APCTP Focus Program in Nuclear Physics 2021
Part I: Hadron properties in a nuclear medium from the quark and gluon degrees of freedom.,
14 - 16 July, 2021, Online Meeting (ZOOM)（9 AM - 12 AM, Asia/Seoul and Asia/Tokyo Timezone）

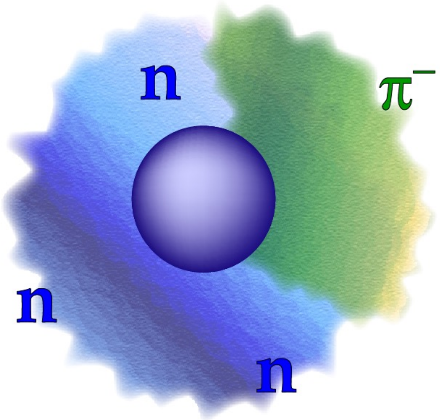
Structure and formation of mesic atoms and mesic nuclei

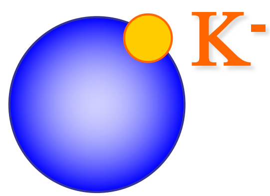
Satoru Hirenzaki (Nara Women's University, Japan)

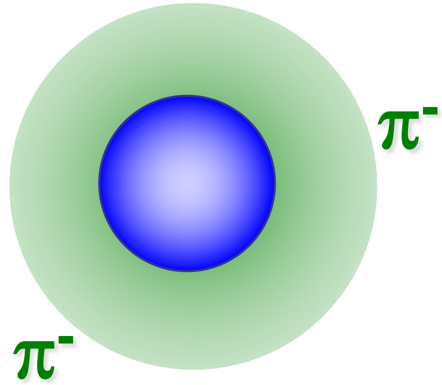
15 July 2021 Thursday, 11:35 (30min.)
(Asia/Seoul and Asia/Tokyo Timezone)

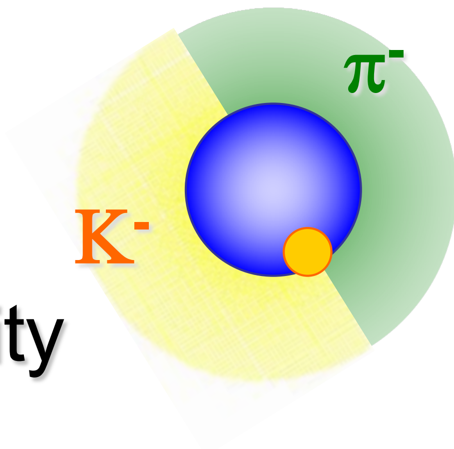
【0】Introduction

(1) Meson in nucleus, Exotic systems









(2) Baryon resonances at finite density

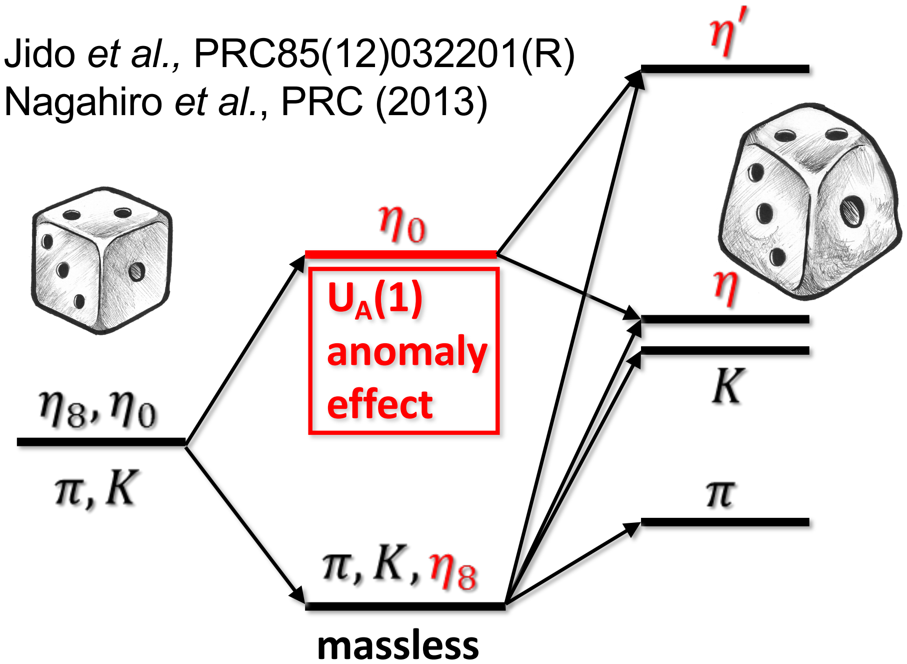
$N^*(1535)$ $\Lambda(1405)$ 、、

【0】Introduction

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)



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

【0】Introduction

【1】Pionic Atom and $\sigma_{\pi N}$

with high-precision data at RIBF/RIKEN

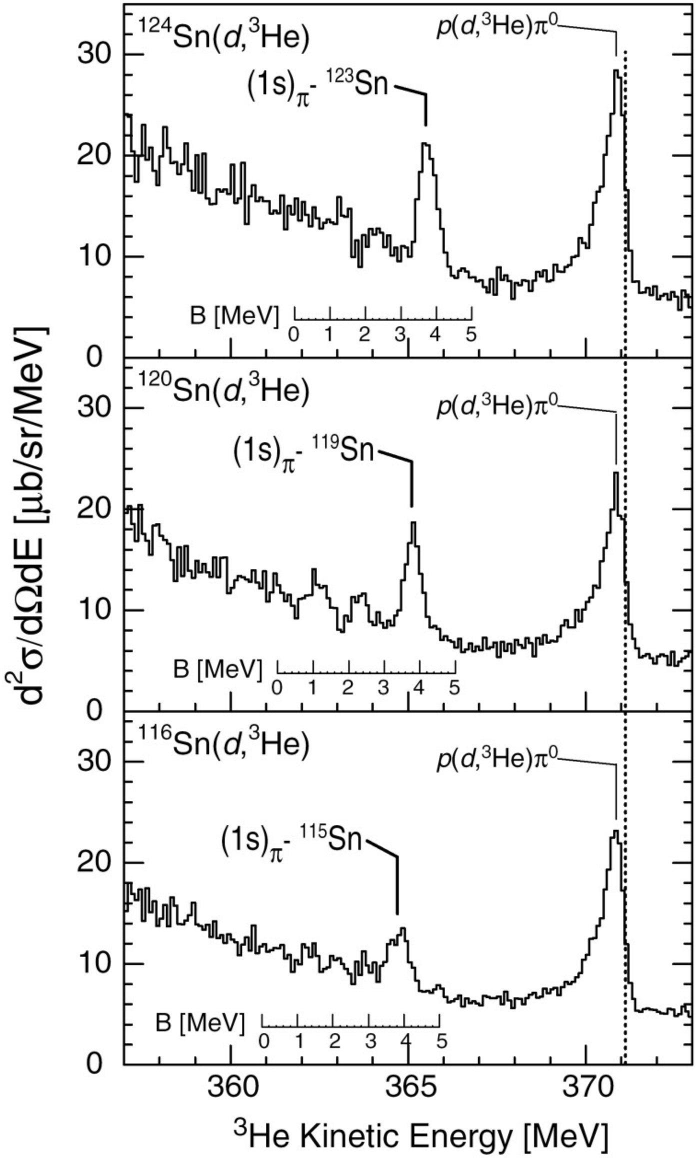
【2】Residual Interaction effects

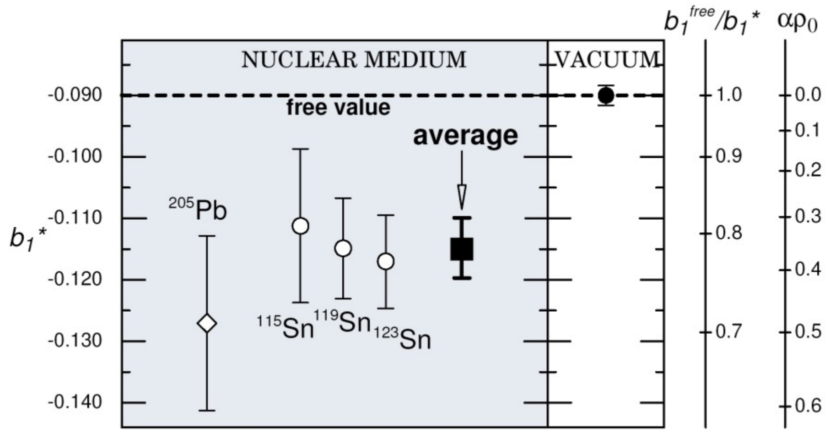
to mesic Atoms and mesic Nuclei

【3】Possibility to higher densities than ρ_0

【4】Summary

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





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

GOR relation + Tomozawa-Weinberg Relation

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

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

Sensitivity of the deeply bound pionic atom observables to the pion-nucleon sigma term $\sigma_{\pi N}$

By Natumi Ikeno (Tottori univ.), S. H.

$$\left[-\nabla^2 + \mu^2 + 2\mu V_{\rm opt}(r)\right]\phi(\vec{r}) = \left[E - V_{\rm em}(r)\right]^2 \phi(\vec{r}),$$

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

$$\begin{aligned} b(r) &= \varepsilon_1[b_0\rho(r) + b_1[\rho_n(r) - \rho_p(r)]], \\ c(r) &= \varepsilon_1^{-1}[c_0\rho(r) + c_1[\rho_n(r) - \rho_p(r)]], \\ L(r) &= \left\{1 + \frac{4}{3}\pi\lambda[c(r) + \varepsilon_2^{-1}C_0\rho^2(r)]\right\}^{-1}, \end{aligned}$$

$$b_1(\rho) = b_1^{\rm free}\left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho\right)^{-1}, \qquad b_0(\rho) = b_0^{\rm free} - \varepsilon_1 \frac{3}{2\pi}(b_0^{\rm free2} + 2b_1^2(\rho))\left(\frac{3\pi^2}{2}\rho\right)^{1/3}$$

Tomozawa-Weinberg, GOR. Weise.

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

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} \simeq \frac{f_\pi^{*2}}{f_\pi^{2}} \simeq \frac{b_1^{\rm free}}{b_1^*(\rho)} = 0.78 \pm 0.05 \ @ \ \rho \simeq 0.6\rho_0$$ ➔ σ ~ 45MeV

χ^2 fitting for (all) atomic data (BE, Width) $\sigma_{\pi N}^{\rm FG} = 57 \pm 7$ MeV,

E. Friedman and A. Gal, Phys. Lett. B **792**, 340 (2019).
E. Friedman and A. Gal, Acta Phys. Polon. B **51**, 45-54 (2020).

$\sigma_{\pi N}$ values

$$\sigma_{\pi N} = \frac{\bar{m}_q}{2m_N} \sum_{u,d} \langle N|\bar{q}q|N\rangle \qquad \bar{m}_q = \frac{m_u + m_d}{2}$$

Nucleon charges with dynamical overlap fermions

PHYSICAL REVIEW D **98,** 054516 (2018)

N. Yamanaka* et al., (JLQCD Collaboration)

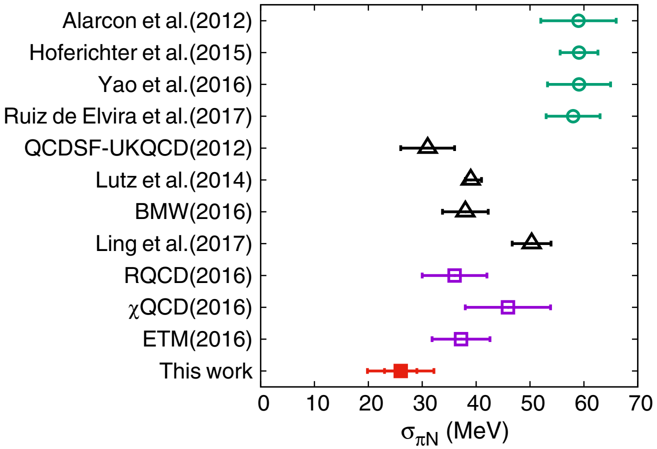


FIG. 13. Our result for $\sigma_{\pi N}$ (filled square) compared with those from recent direct evaluations in lattice QCD (open squares, RQCD [9], χQCD [8], ETM [11]), analyses of lattice QCD data using Feynman-Hellmann theorem (black triangles, QCDSF-UKQCD [7], Lutz *et al.* [74], BMW [10], Ling *et al.* [75]) and phenomenological studies (open circles, Alarcón *et al.* [12], Hoferichter *et al.* [13], Yao *et al.* [15], Ruiz de Elvira *et al.* [16]). As for our result, the smallest error bar denotes the statistical one, and the largest one also takes into account those due to the extrapolation and the discretization.

The nucleon sigma term from lattice QCD

R. Gupta, S. Park, M. Hoferichter, E. Mereghetti, l

B. Yoon and T. Bhattacharya, [arXiv:2105.12095 [hep-lat]].

arXiv:2105.12095v1 [hep-lat] 25 May 2021

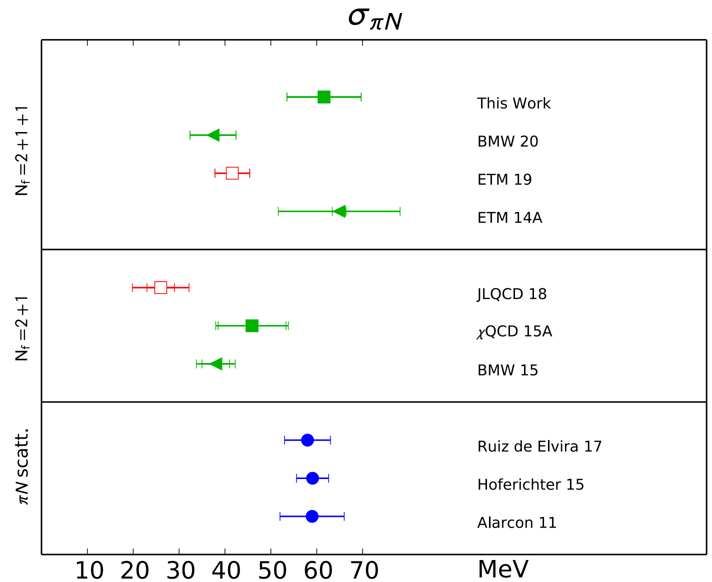


FIG. 8. Results for $\sigma_{\pi N} = m_{ud} g_S^{u+d}$ from 2+1- and 2+1+1-flavor lattice calculations. The BMW 20 result from 1+1+1+1-flavor lattices is listed along with the other 2+1+1-flavor calculations for brevity. Following the FLAG conventions, determinations via the direct approach are indicated by squares and the FH method by triangles. Also, the symbols used for lattice estimates that satisfy the FLAG criteria for inclusion in averages are filled green, and those not included are open red. The references from which lattice results have been taken are: JLQCD 18 [60], χQCD 15A [57], BMW 15 [56], ETM 14A [63], ETM 19 [61], and BMW 20 [62]. Phenomenological estimates using πN scattering data (blue filled circles) are from Alarcon 11 [28], Hoferichter 15 [31], and Ruiz de Elvira 17 [37].

Cf. $\sigma_{\pi N}^{\rm FG} = 57 \pm 7$ MeV,

Latest Data @ RIKEN

Spectroscopy of Pionic Atoms in $^{122}Sn(d,{}^3He)$ Reaction and Angular Dependence of the Formation Cross Sections

PHYSICAL REVIEW LETTERS **120,** 152505 (2018)

T. Nishi, K. Itahashi et al., (piAF Collaboration)

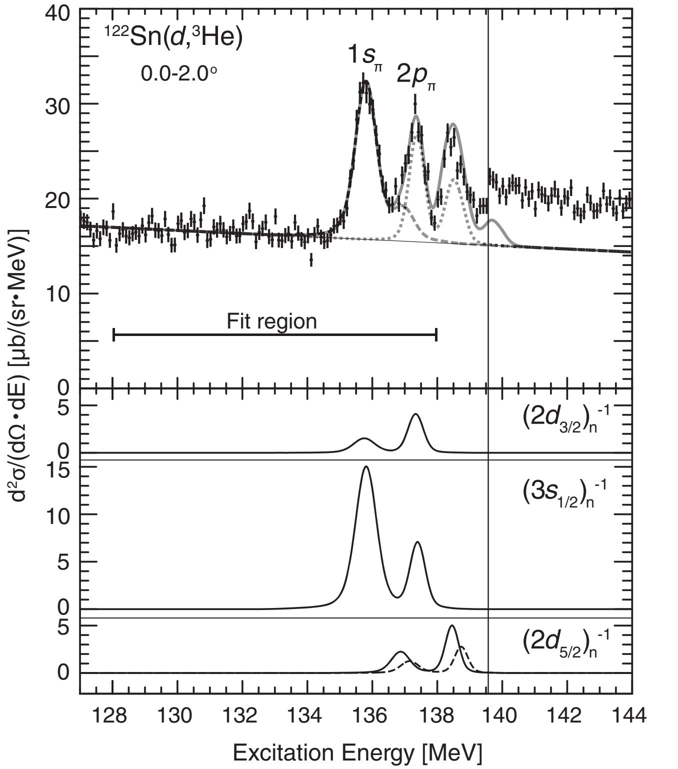


FIG. 2. (Top panel) Measured excitation spectrum of the $^{122}Sn(d,{}^3He)$ reaction at the angular range of $0 < \theta < 2°$. Three distinct peaks are observed in the region $E_{ex} = [134, 139]$ MeV. The left and middle peaks are mainly originating from formation of pionic $1s$ and $2p$ states, respectively. The right peak is partly contributed from the other pionic states ($2s$, $3p$, and $3s$). The spectrum is fitted in the region indicated. The fitting curve and contributions from the $1s$ and the $2p$ states are presented by solid, dashed, and dotted lines, respectively. (Bottom panel) Decom-

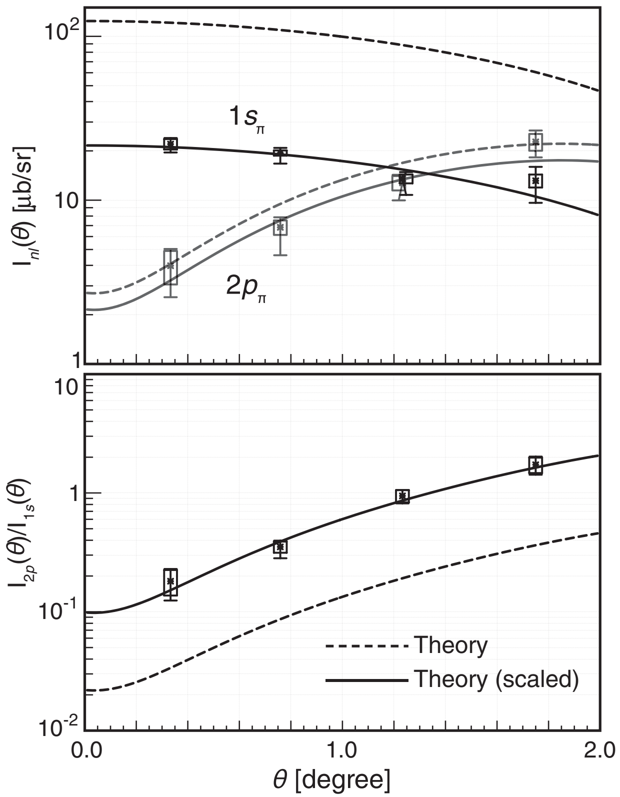


FIG. 4. (Top panel) Determined pionic-nl-state formation cross sections $I_{nl}(\theta)$ for different θ ranges. Statistical errors are shown by the boxes and systematic errors in addition by the bars. The deduced cross sections are compared with the theoretical calculations [19,28]. (Bottom panel) $I_{2p}(\theta)/I_{1s}(\theta)$. Systematic errors are canceled by taking the ratios.

$$B_{1s} = 3.828 \pm 0.013(\text{stat})^{+0.036}_{-0.033}(\text{syst})\ \text{MeV},$$
$$\Gamma_{1s} = 0.252 \pm 0.054(\text{stat})^{+0.053}_{-0.070}(\text{syst})\ \text{MeV},$$
$$B_{2p} = 2.238 \pm 0.015(\text{stat})^{+0.046}_{-0.043}(\text{syst})\ \text{MeV},$$

Even New Exp. @ RIKEN June 2021

K. Itahashi[a]
(piAF Collaboration)

Proposal Update and Extension Request for NP1512-RIBF135

High Precision Spectroscopy of Pionic Atoms in Tin Isotopes by $(d,{}^3He)$ reactions

Characteristic information from Deeply Bound Pionic Atoms

＊ multi-state (1s, 2p, 2s) observation for each nuclei

＊Cross section data (Formation spectra)

＊High sensitivity (expected) to the sigma term

（＊Long isotope chain information for Sn ）

Sensitivity of the deeply bound pionic atom observables to the pion-nucleon sigma term $\sigma_{\pi N}$

By Natumi Ikeno (Tottori univ.)

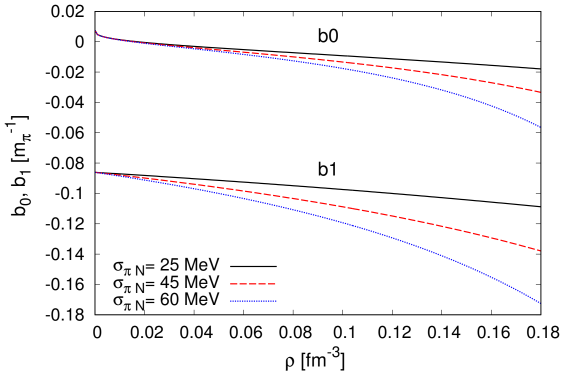


FIG. 1: Density dependence of the $b_0(\rho)$ and $b_1(\rho)$ for the different $\sigma_{\pi N}$ term.

$$b_1(\rho) = b_1^{\rm free}\left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho\right)^{-1},$$

$$b_0(\rho) = b_0^{\rm free} - \varepsilon_1 \frac{3}{2\pi}(b_0^{\rm free2} + 2b_1^2(\rho))\left(\frac{3\pi^2}{2}\rho\right)^{1/3}$$

∗ High sensitivity to σ value

∗ σ determination from new deeply bound pionic atom data

(d,3He) spectra

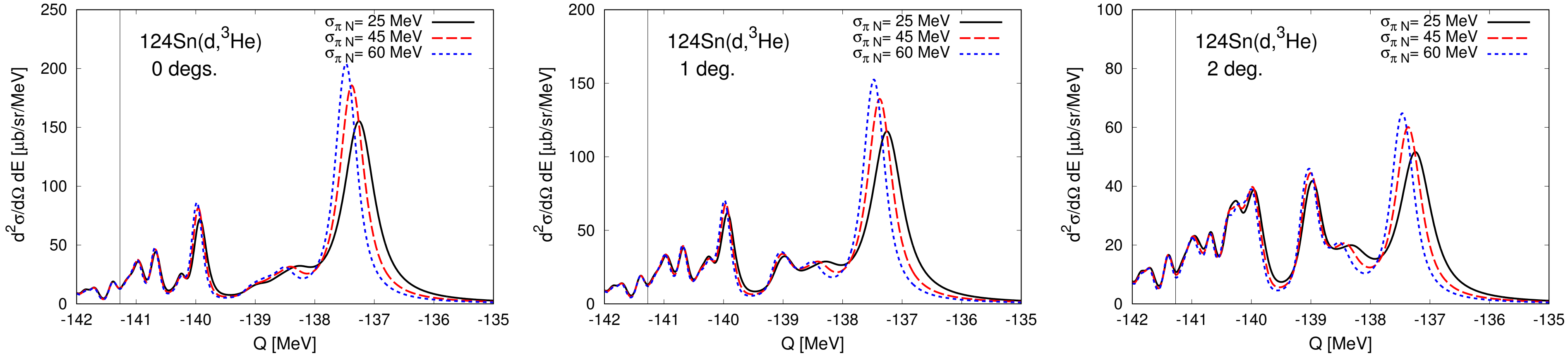


FIG. 4: Formation cross section in the ^{124}Sn(d,^{3}He) reaction for the different angles. Left, middle and right panel is the result for $\theta_{\rm dHe} = 0^\circ, 1^\circ, 2^\circ$, respectively. The calculations are done with the parameter set (I). Experimental energy resolution is assumed to be $\Delta E = 150$ keV

【0】Introduction

【1】Pionic Atom and $\sigma_{\pi N}$
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【2】Residual Interaction effects
to mesic Atoms and mesic Nuclei

【3】Possibility to higher densities than ρ_0

【4】Summary

Residual Interaction Effects (π) results at 1999 and 2005

$(\pi \text{ particle}) \otimes (\text{n-hole})$ states (Boson ⊗ Fermion-hole)

→ Residual Interaction Effects

- For Pb (S wave int. only) Mixing probability $\lesssim 0.2\%$

$$\Delta E \sim 0\text{–}20\text{keV} << \text{Exp. Error}$$

S. Hirenzaki, H. Kaneyasu, K. Kume, H. Toki, Y. Umemoto,

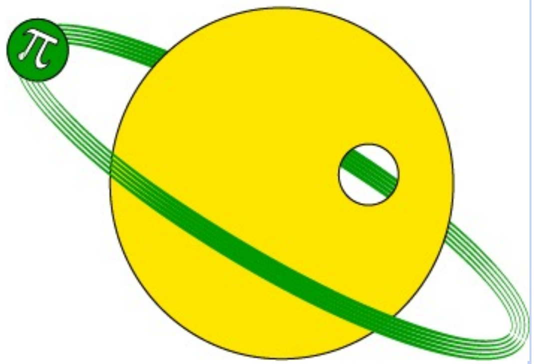
PRC60(99)058202

- For Sn (S+P wave int.)

$$\Delta E \lesssim \text{Exp. Error}$$

N. Nose-Togawa, H. Nagahiro, S. Hirenzaki, K. Kume,

PRC71(05)061601



NOW ∗ Better data for mesic atoms

∗ Mesic nuclear states

Residual interaction effects on mesic atoms and mesic nuclei

N. Nose-Togawa (RCNP, Osaka),

N. Ikeno (Tottori) , J. Yamagata-Sekihara (Kyoto Sangyou univ.) , S. H.

$$\langle \phi_{\xi'}, N_\beta; J|H|\phi_\xi, N_\alpha; J\rangle = (\omega_\xi - \varepsilon_\alpha)\delta_{\xi,\xi'}\delta_{\alpha,\beta} + \langle \phi_{\xi'}, N_\beta; J|\hat{V}|\phi_\xi, N_\alpha; J\rangle$$

$$V = -\frac{2\pi}{m_\pi}[b_0 + b_1\boldsymbol{\tau}\cdot\mathbf{I} + (c_0 + c_1\boldsymbol{\tau}\cdot\mathbf{I})\nabla\cdot\nabla]\delta(\mathbf{r}).$$

$$\begin{aligned}
&\langle \phi_{\xi'}, N_\beta; J|\hat{V}|\phi_\xi, N_\alpha; J\rangle \\
&= -\frac{1}{2m_\pi}(-1)^{-J+j_\alpha+j_\beta+1/2}\sqrt{(2j_\alpha+1)(2j_\beta+1)(2\ell_\alpha+1)(2\ell_\beta+1)(2\ell'_\pi+1)(2\ell_\pi+1)} \\
&\times \sum_L (-1)^L \left\{ \begin{array}{ccc} \ell'_\pi & j_\beta & J \\ j_\alpha & \ell_\pi & L \end{array} \right\} \left\{ \begin{array}{ccc} \ell_\alpha & j_\alpha & \frac{1}{2} \\ j_\beta & \ell_\beta & L \end{array} \right\} (\ell_\beta 0 \ell_\alpha 0 \mid L0)(\ell_\pi 0 \ell'_\pi 0 \mid L0) \\
&\times \Bigg[(b_0+b_1) \int_0^\infty drr^2 R^*_{\ell_\beta}(r) R_{\ell_\alpha}(r) R_{\ell'_\pi}(r) R_{\ell_\pi}(r) \\
&\quad + (c_0+c_1) \int_0^\infty drr^2 R^*_{\ell_\beta}(r) R_{\ell_\alpha}(r) \\
&\quad \times \left\{ \left(\frac{\mathrm{d}R_{\ell'_\pi}(r)}{\mathrm{d}r}\right)\left(\frac{\mathrm{d}R_{\ell_\pi}(r)}{\mathrm{d}r}\right) + \frac{\ell_\pi(\ell_\pi+1) + \ell'_\pi(\ell'_\pi+1) - L(L+1)}{2}\frac{R_{\ell'_\pi}(r)R_{\ell_\pi}(r)}{r^2} \right\} \Bigg] .
\end{aligned}$$

Residual Interaction Effects

* Important to deduce sub-hadronic info. from spectroscopy precisely

Ex.) Kaon case

* Coexistence of atomic states and nuclear states

* Shifts and configuration mixing for mesic nucleus states (maybe large ?)

* Even mixing between atomic and nuclear states ??

Residual interaction effects on mesic atoms and mesic nuclei

N. Nose-Togawa (RCNP, Osaka),
N. Ikeno (Tottori) , J. Yamagata-Sekihara (Kyoto Sangyou univ.) , S. H.

∗ Some Preliminary results for kaon case (Kaon-115Sn)

【model space (Potential based on Chiral Unitary model)】
n-hole : s1/2, d3/2, d5/2, g7/2, h11/2
K nucl: 1s, 2s, 2p, K Atom: 1s, 2s, 3s, 4s, 2p, 3p, 4p, 3d, 4d

【maximum energy shift 】

Nuclear (2s)x(s012) (j=1/2)	Shift[keV]=	-332.03016	-790.41411
Atomic (2p)x(d032) (j=1/2)	Shift[keV]=	11.61673	1.07724

【Level Mixing：larger than 0.1 fraction for Sn115 】
(two level mix for j=5/2: (2p nuclear, d3/2) and (2p nuclear g7/2))
∗ |1>= 0.31921 |2p nuclear, d3/2> + 0.63809 |2p nuclear, g7/2>
∗ |2>= 0.67889 |2p nuclear, d3/2> + 0.28909 |2p nuclear, g7/2>

Analysis in progress including other mesic nuclear systems

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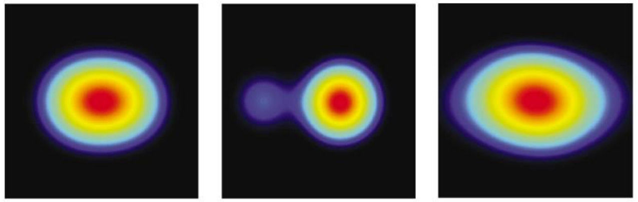
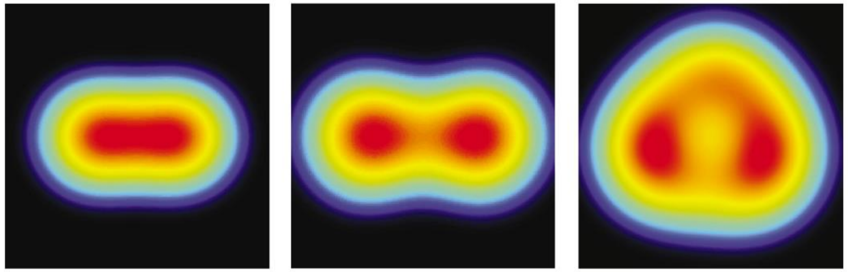
Nuclear Compression in K-nucleus case

Dote, Horiuchi, Akaishi, Yamazaki,
PRC70(04)044313

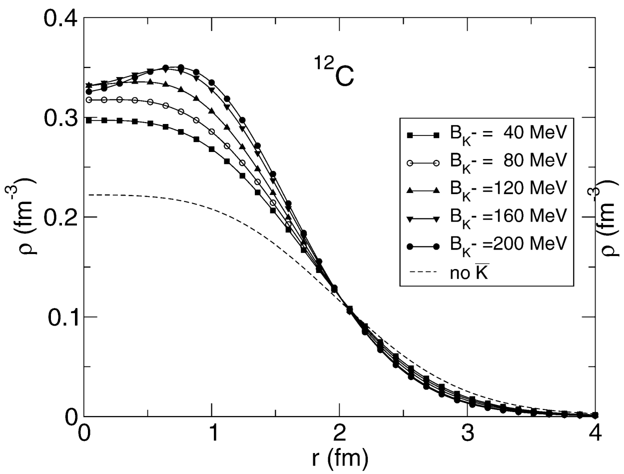


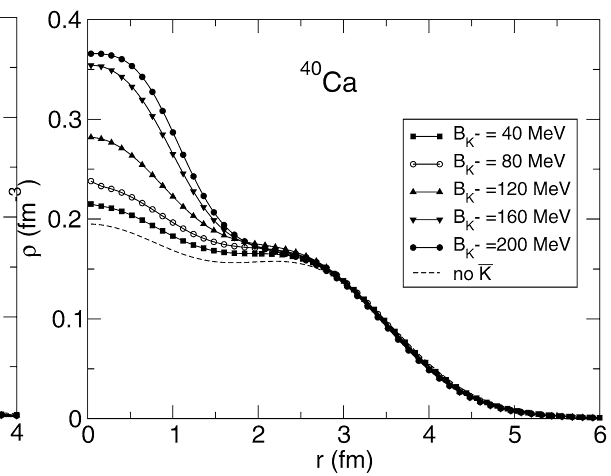
ppnK$^-$ pppK$^-$ pppnK$^-$

De



^{6}BeK$^-$ ^{9}BK$^-$ ^{11}CK$^-$





RMF(Relativistic Mean Field) Model
J. Mares, E. Friedman, A. Gal,
NPA770(06)84

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

η(958) case

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)

1.6 times larger central density for 1s state

‘Compression’ general phenomena

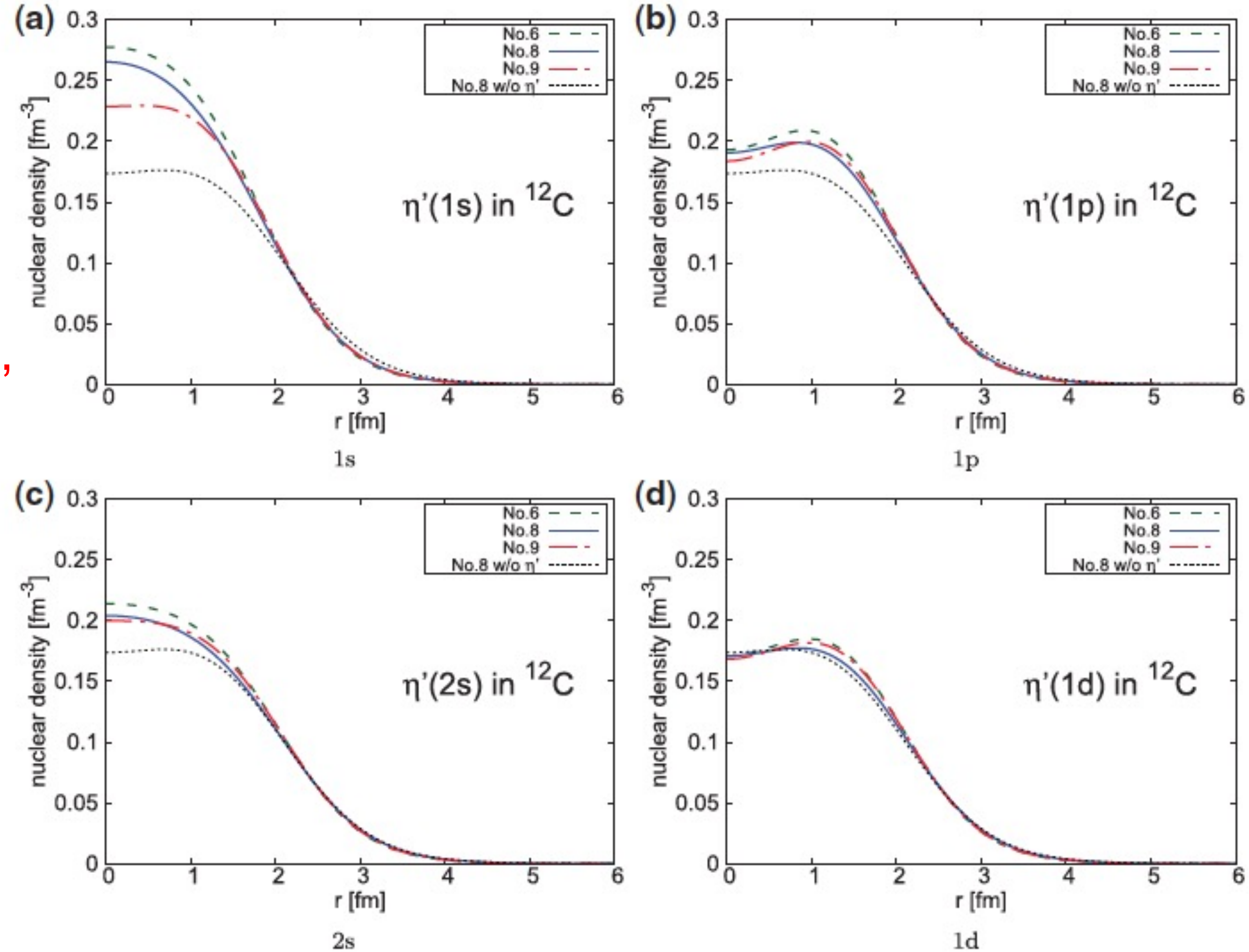
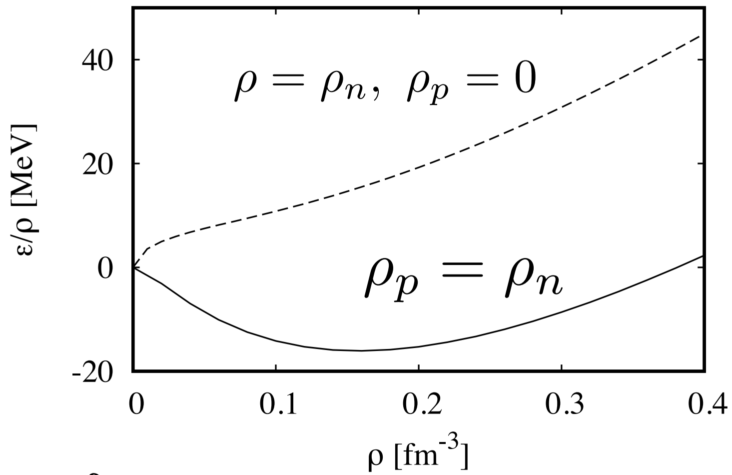


Fig. 8. Nuclear density profiles of the η' bound systems in ^{12}C obtained with parameter sets 6, 8, and 9. The dotted line stands for the density distribution of the normal nucleus ^{12}C without η' calculated with parameter set 8.

* Systematic study for the various systems

Thomas-Fermi model
Oyamatsu, NPA561(93)181



$$E_{\rm nucleus}[\rho] = \int d^3r \epsilon(\rho_n(\vec{r}), \rho_p(\vec{r})) + F_0 \int d^3r |\nabla\rho(\vec{r})|^2 + \frac{e^2}{2}\int d^3r \int d^3r' \frac{\rho_p(\vec{r})\rho_p(\vec{r'})}{|\vec{r}-\vec{r'}|}$$

$$\rho = \frac{\rho_0}{1+\exp((r-c)/a)} \times {\rm Factor} + \frac{\rm A}{(\pi {\rm b}^2)^{3/2}} \exp\left(-\frac{\rm r^2}{\rm b^2}\right) \times (1 - {\rm Factor})$$

$$E_{\rm total}[\rho] = E_{\rm nucleus}[\rho] + E_{\rm meson}[\rho]$$

- From systematic study by Thomas-Fermi

Compression is general and more significant for

∗ Lighter nuclei

∗ Heavier meson

∗ Stronger attraction

→ Effects could be significant enough for
'HEAVY' meson bound systems in light nuclei
to probe higher densities by the bound meson

【4】Summary

∗ Deeply bound Pionic atoms

Sensitivity to the σ term

(within the linear dependence to ρ)

∗ Residual interaction effects

Mesic nuclear states, configuration mixing

Importance to deduce meson properties from the bound meson spectra

∗ Possibility to the higher densities than normal nucleus

Heavier meson bound states in Lighter nuclei could be interesting

(access to various 'non-linear density dependence' ?)