Structure and Formation of deeply bound pionic atoms

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Collaboration with

Theoretical side: J. Yamagata-Sekihara, H. Nagahiro, D. Jido, S. Hirenzaki
Experimental side: K. Itahashi , T. Nishi, H. Fujioka

- N. Ikeno, R. Kimura, J. Yamagata-Sekihara, H. Nagahiro, D. Jido, K. Itahashi, L. S. Geng, S. Hirenzaki, PTP126, 483 (2011)
- N. Ikeno, H. Nagahiro, S. Hirenzaki, EPJA47, 161 (2011)
- N. Ikeno, J. Yamagata-Sekihara, H. Nagahiro, S. Hirenzaki, PTEP2013, 063D01 (2013)
- N. Ikeno, J. Yamagata-Sekihara, H. Nagahiro, S. Hirenzaki, PTEP2015, 033D01 (2015)

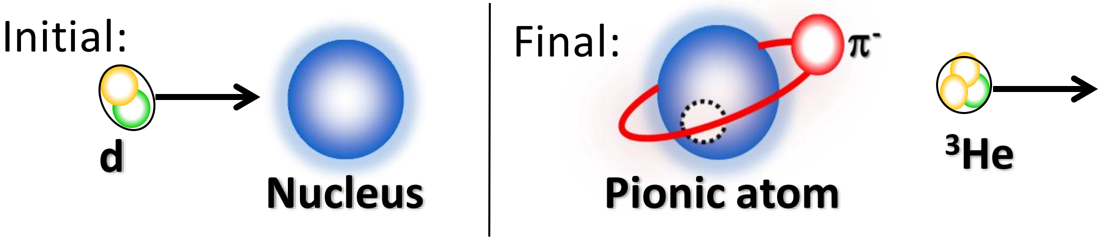
Meson in Nucleus (MIN2016),
July 31- August 2, 2016, Panasonic Hall, Yukawa Institute for Theoretical Physics, Kyoto University

Deeply bound pionic atom

π^- meson-Nucleus system:

Coulomb + Strong Interaction

- (d,^{3}He) reaction: Pionic 1s states in $^{115, 119, 123}$Sn



- Pion-Nucleus optical potential

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

- GOR relation + Tomozawa-Weinberg relation

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

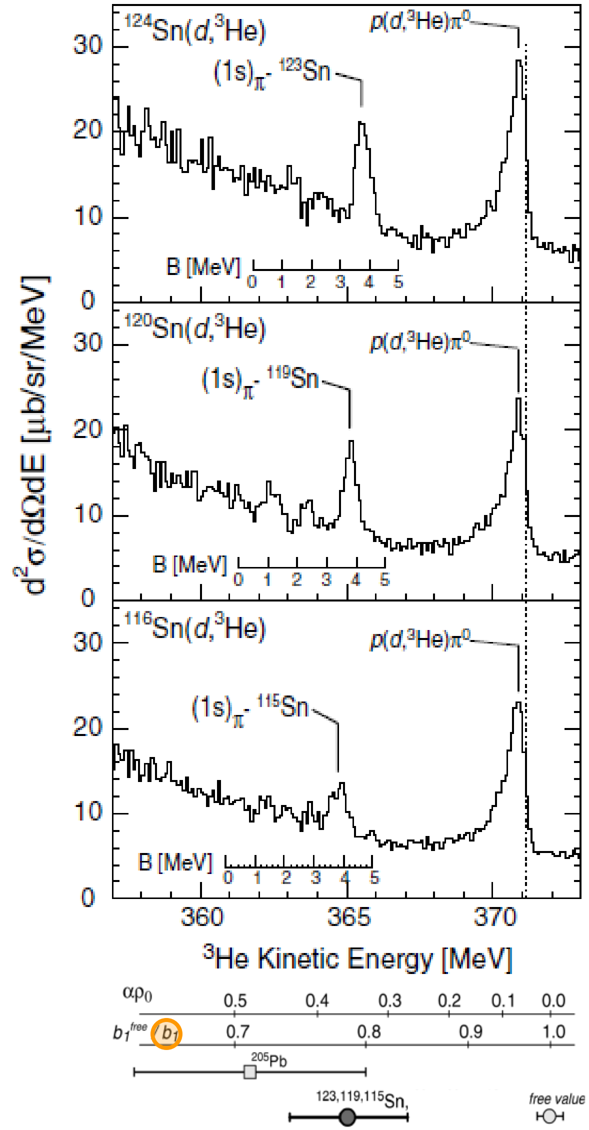
$$\sim 0.67 \ @ \ \rho = \rho_0$$

Theoretical basis

E.E. Kolomeitsev, N. Kaiser, W. Weise, PRL90(03)092501

D. Jido, T. Hatsuda, T. Kunihiro, PLB670(08)109

K. Suzuki *et al.*, PRL92(04)072302



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

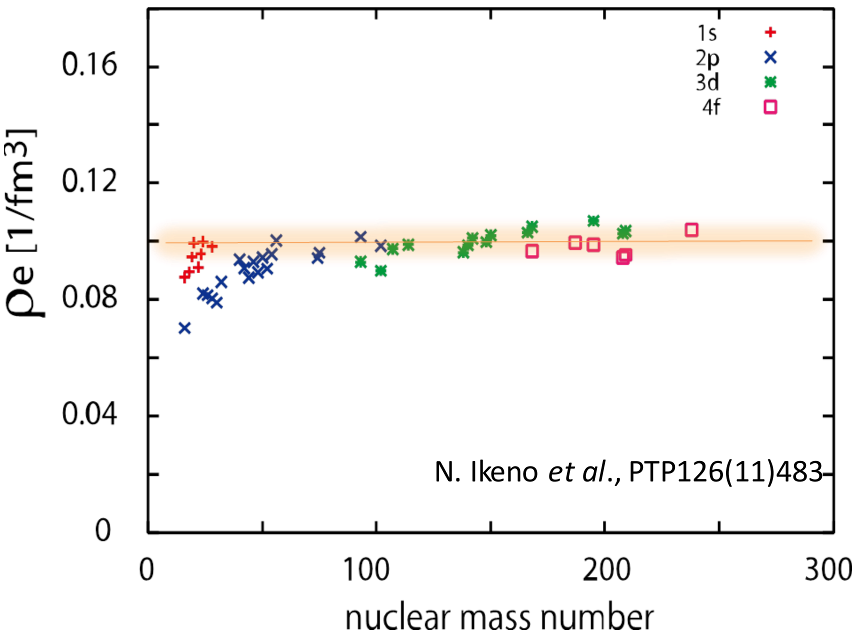
What's next?

Interests

$\bar{q}q$ condensate: More accurate determination
Beyond the linear density approximation
In asymmetric (n or p rich) nuclear matter

➔ Aspects of symmetry and pion properties in ``*various conditions (densities)*"

Difficulties for precise studies



Nuclear density probed by pionic atom

: Only limited to $\rho \simeq 0.6\rho_0$

- Strong correlation of parameters
  b_0 vs. $\mathrm{Re}B_0$

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

Our studies

Theoretical Formation spectra

- Various targets: Even + Odd neutron nuclear
  - Systematic 'precise' observation for various nucleus

Pb:	^{205}Pb $5/2^-$	^{206}Pb 0^+	^{207}Pb $1/2^-$	^{208}Pb 0^+						
Sn:	^{115}Sn $1/2^+$	^{116}Sn 0^+	^{117}Sn $1/2^+$	^{118}Sn 0^+	^{119}Sn $1/2^+$	^{120}Sn 0^+	^{121}Sn $3/2^+$	^{122}Sn 0^+	^{123}Sn $11/2^-$	^{124}Sn 0^+

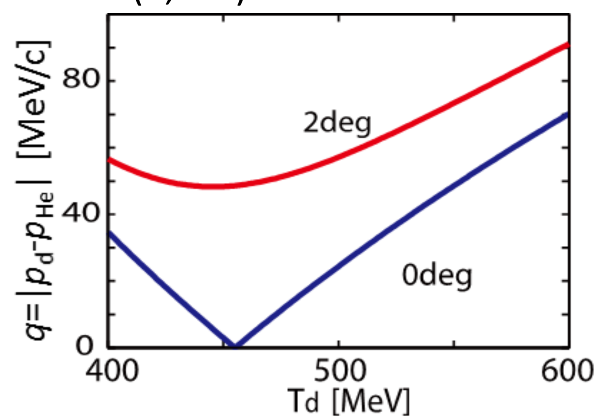
Even-Even Nucleus: $J^p=0^+$ Target Nuclei in the Experiments @GSI

Experiments @RIBF/RIKEN (^{117}Sn, ^{122}Sn)

- Reaction angle:
  - Several atomic states in the same nuclei

  => possible reduction of systematic errors

(d,^{3}He) reaction



- Various formation reaction:
  - (d,^{3}He) reaction @RIBF/RIKEN
  - (p,2p) reaction @RCNP

- Some thoughts of pionic atoms in proton rich nuclei

Formulation: Effective Number Approach

- Formation cross section (Bound state + Quasi-free production)

$$\left(\frac{d^2\sigma}{dE_{\rm He}d\Omega_{\rm He}}\right)_A^{\rm lab} = \left(\frac{d\sigma}{d\Omega_{\rm He}}\right)_{\rm ele}^{\rm lab} \sum_{ph} K \left(\frac{\Gamma}{2\pi}\frac{1}{\Delta E^2+\Gamma^2/4}N_{\rm eff} + \frac{2p_\pi E_\pi}{\pi}N_{\rm eff}\right)$$

$\Delta E = Q + m_\pi - BE + Sn - 6.787\text{MeV}$

- Elementary cross section $\left(\frac{d\sigma}{d\Omega_{\rm He}}\right)_{\rm ele}^{\rm lab}$ **:**

Experimental data (d+n→^{3}He +π^-)

M. Betigeri *et al.*, NPA690(01)473

- Kinematical correction factor:

$$K = \left[\frac{|\vec{p}_{\rm He}^{A}|}{|\vec{p}_{\rm He}|}\frac{E_n E_\pi}{E_n^A E_\pi^A}\left(1+\frac{E_{\rm He}}{E_\pi}\frac{|\vec{p}_{\rm He}|-|\vec{p}_d|\cos\theta_{d\rm He}}{|\vec{p}_{\rm He}|}\right)\right]^{\rm lab}$$

Difference of kinematics between

d+n→^{3}He + π^- and A(d,^{3}He)(A-1)$\otimes\pi^-$

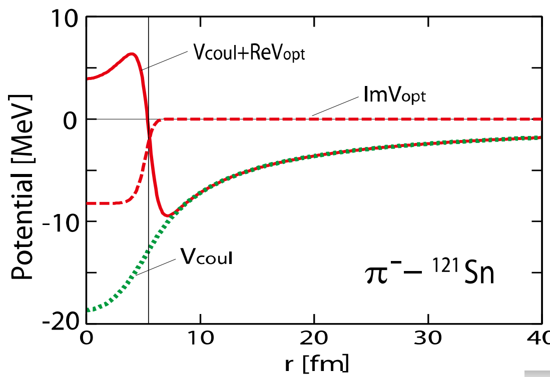
- Effective Number:

$$N_{\rm eff} = \sum_{JMm}\left|\int d\vec{r} e^{i\vec{q}\cdot\vec{r}} D(\vec{r})\xi^\dagger_{\frac{1}{2}m}[\phi^*_{\ell_\pi}(\vec{r})\otimes\psi_{j_n}(\vec{r})]_{JM}\right|^2$$

Different formulation for Even- and Odd- neutron nuclear targets

- Klein Gordon equation

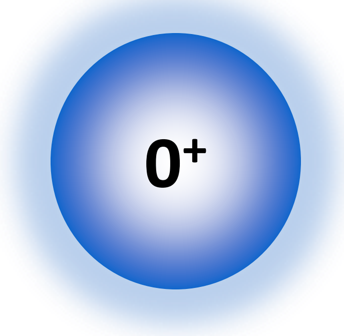
$$[-\nabla^2+\mu^2+2\mu V_{\rm opt}(r)]\phi(\mathbf{r}) = [E-V_{\rm coul}(r)]^2\phi(\mathbf{r})$$



Formulation: Effective Number

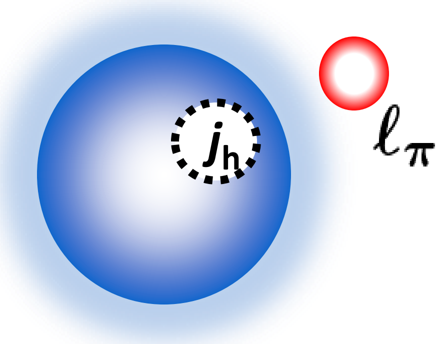
Even target: ^{122}Sn (0^+)

Initial:



$|0^+\rangle$

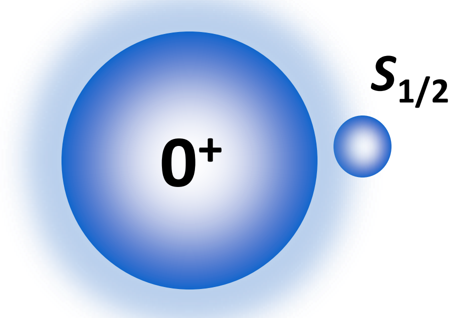
Final:



$|(\ell_\pi \otimes j_h^{-1})_J\rangle$

Odd target: $^{117,\,119}$Sn ($1/2^+$)

Initial:



Reasonable Assumption

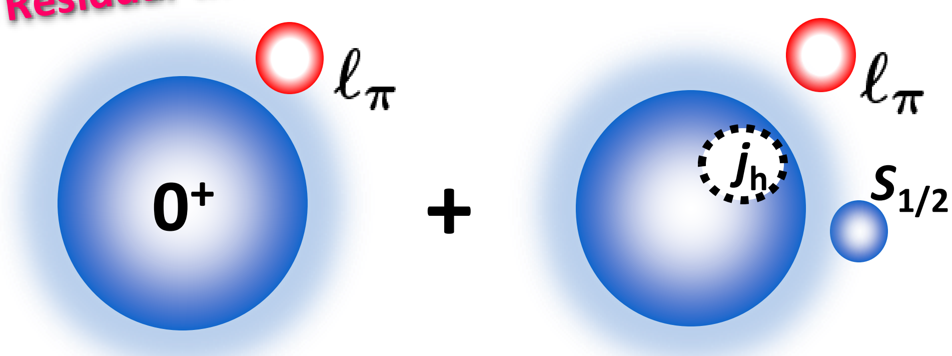
$|s_{1/2} \otimes 0^+\rangle$

Final:

(1) neutron pick-up from $s_{1/2}$ orbit

(2) neutron pick-up j_h orbit from other than $s_{1/2}$

``No Residual Interaction"

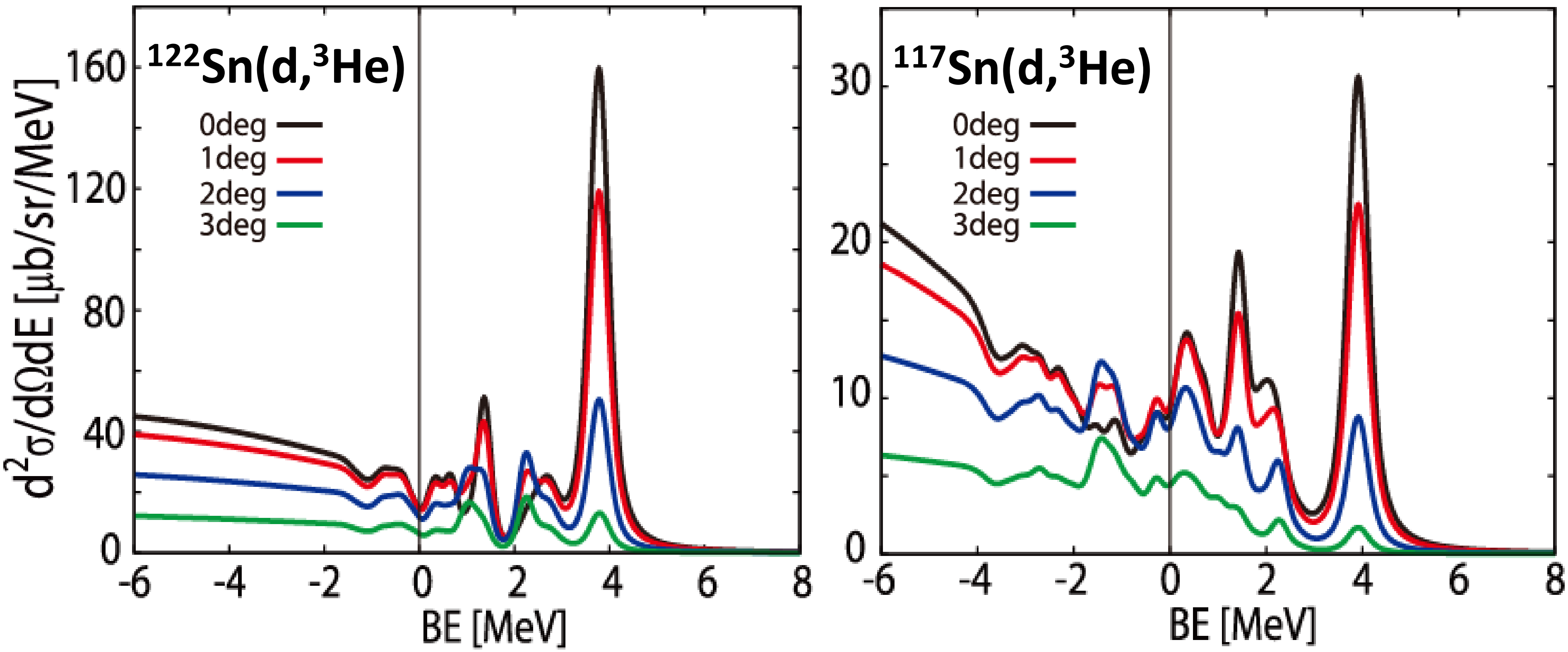


$|(\ell_\pi \otimes 0^+)\rangle$ $|(\ell_\pi \otimes [s_{1/2} \otimes j_h^{-1}]_J)_{J_f}\rangle$

(d,^{3}He) spectra at Finite angles

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

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

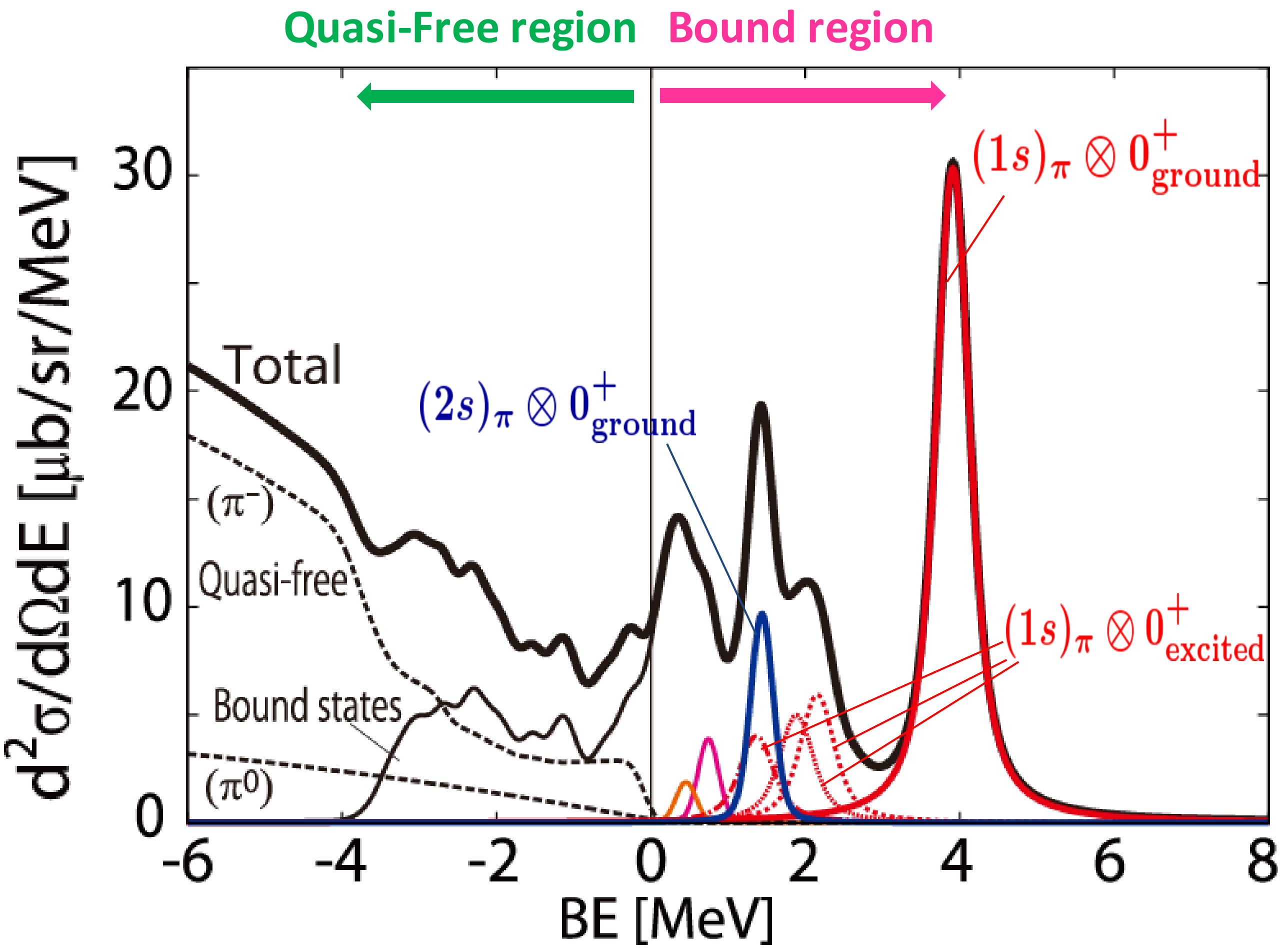


- Both spectra have strong angular dependence.
  - Sharpe structure
  - Overall strength

(d,^{3}He) spectra: Odd target

- ^{117}Sn(d,^{3}He) spectra at 0 degrees

Neutron wave function:
H. Koura *et al.*, NPA671(00)96



Energy resolution
ΔE=300keV

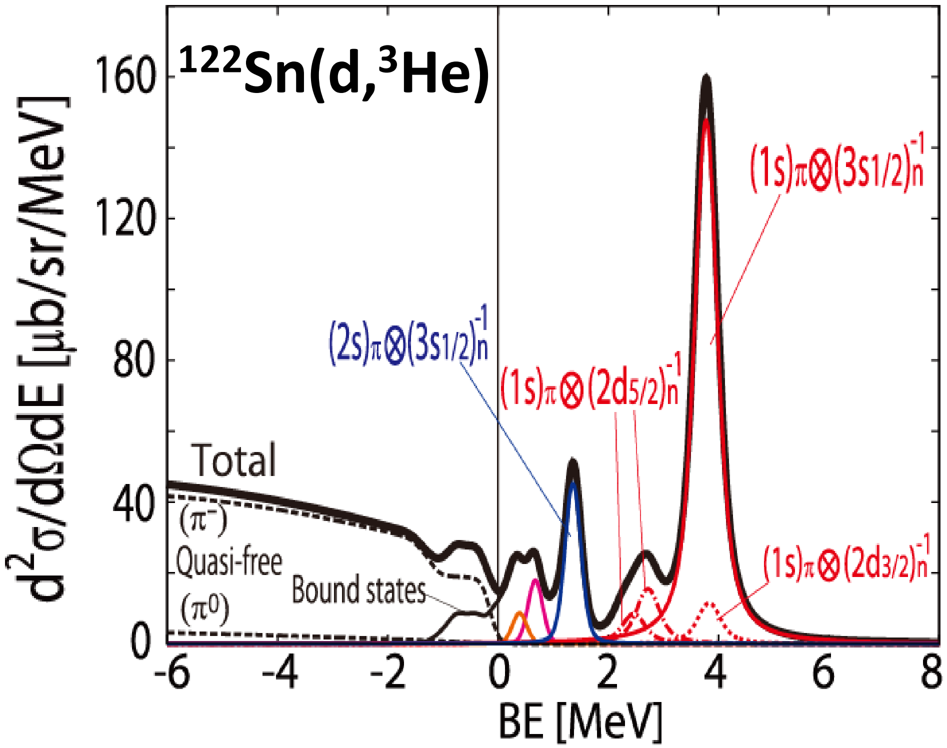
Dominant Subcomponent:
$$[(n\ell)_\pi \otimes J^P]$$

- We can see clear peak structure of $[(1s)_\pi \otimes {}^{116}\mathrm{Sn}(0^+)]$.
  - No residual interaction effect

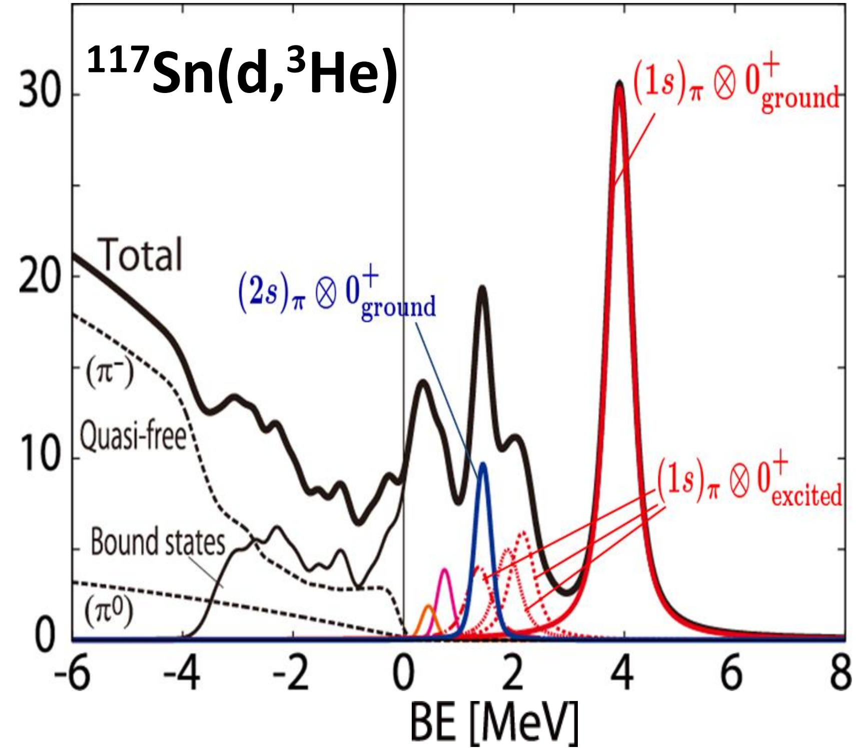
(d,^{3}He) spectra: Even vs. Odd target

0 degrees

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



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

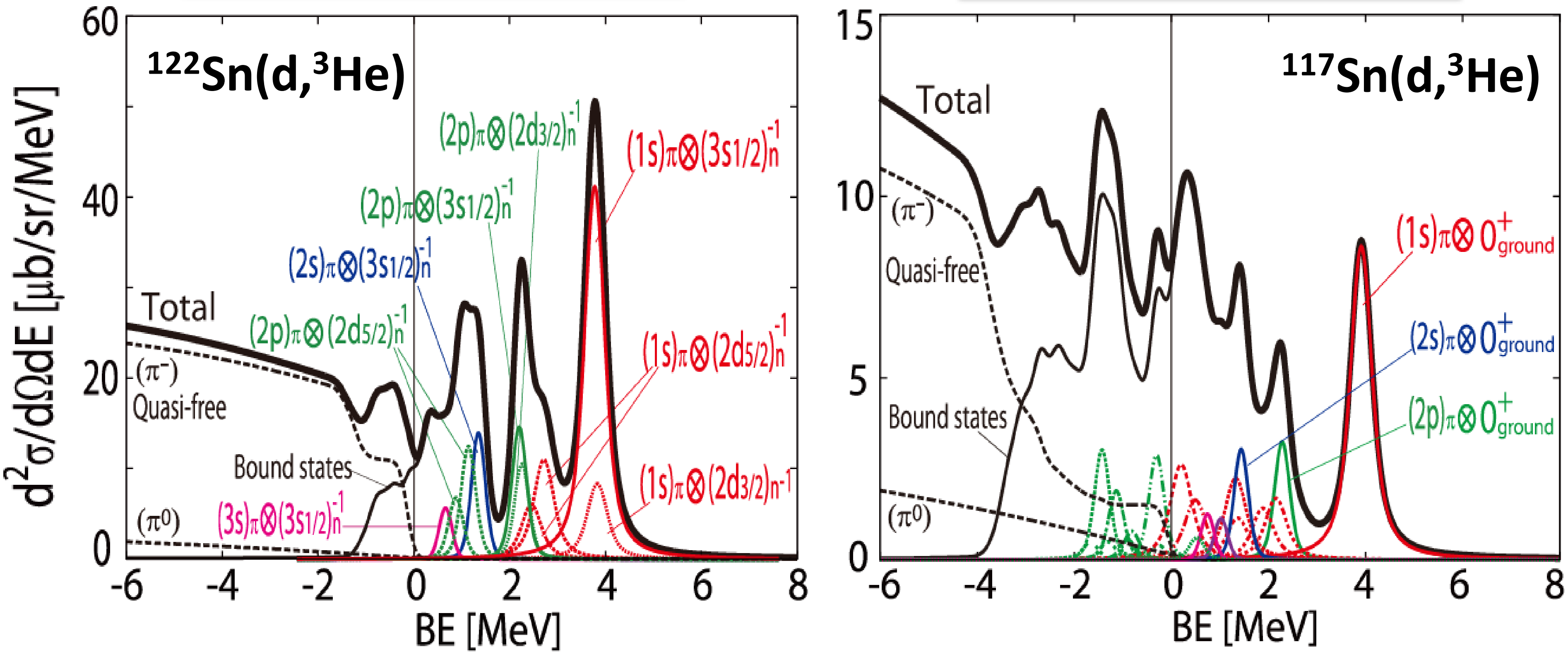


- Pionic 1s state formation with neutron s-hole state is large in both spectra.
- Bound pionic state formation spectra in ^{117}Sn(d,^{3}He) are spread over wider energy range.
- Absolute value of cross section in ^{117}Sn(d,^{3}He) is smaller.

(d,^{3}He) spectra: Even vs. Odd target

2 degrees

Even target: ^{122}Sn (0^+) | **Odd target: ^{117}Sn ($1/2^+$)**



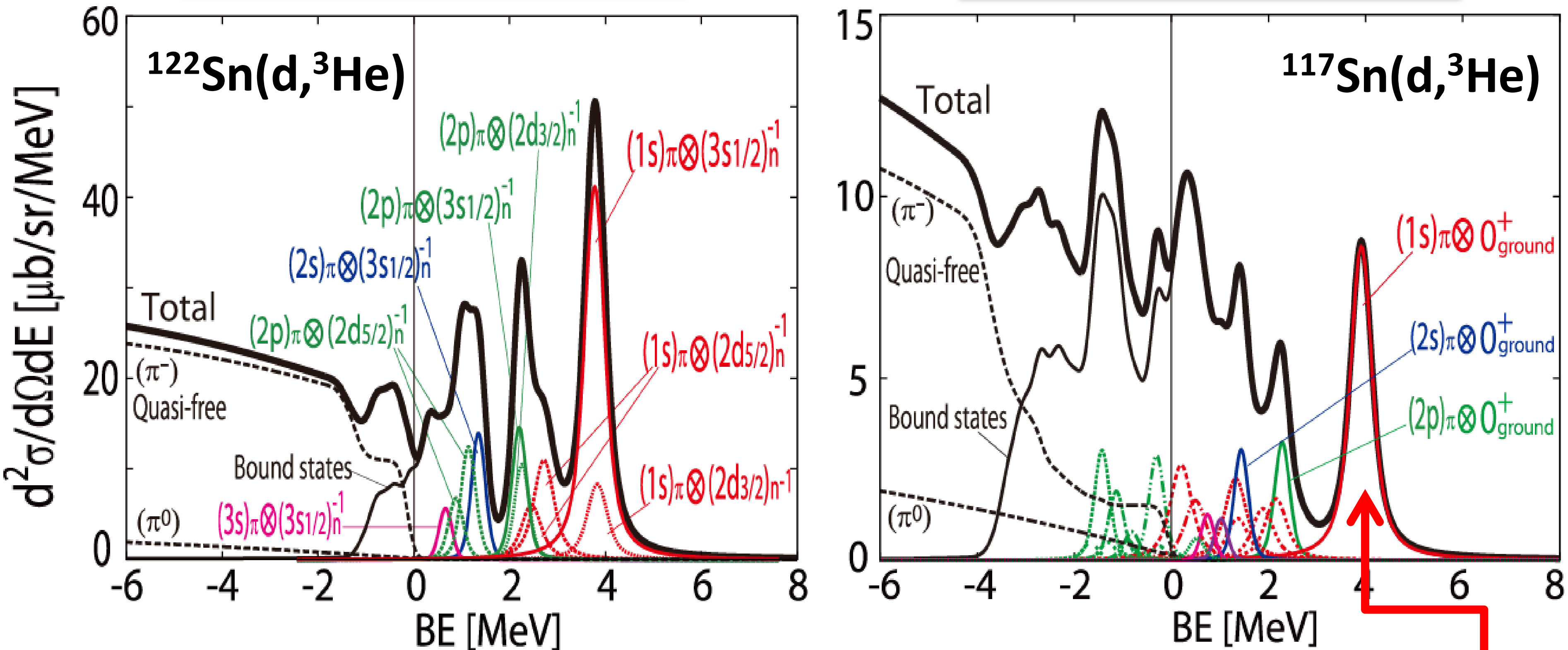
Even target:

Simultaneous observation of several pionic **1*s***, **2*s*** and **2*p*** states at forward and finite angles

(d,^{3}He) spectra: Even vs. Odd target

2 degrees

Even target: ^{122}Sn (0$^+$) | **Odd target: ^{117}Sn (1/2$^+$)**



Odd target:

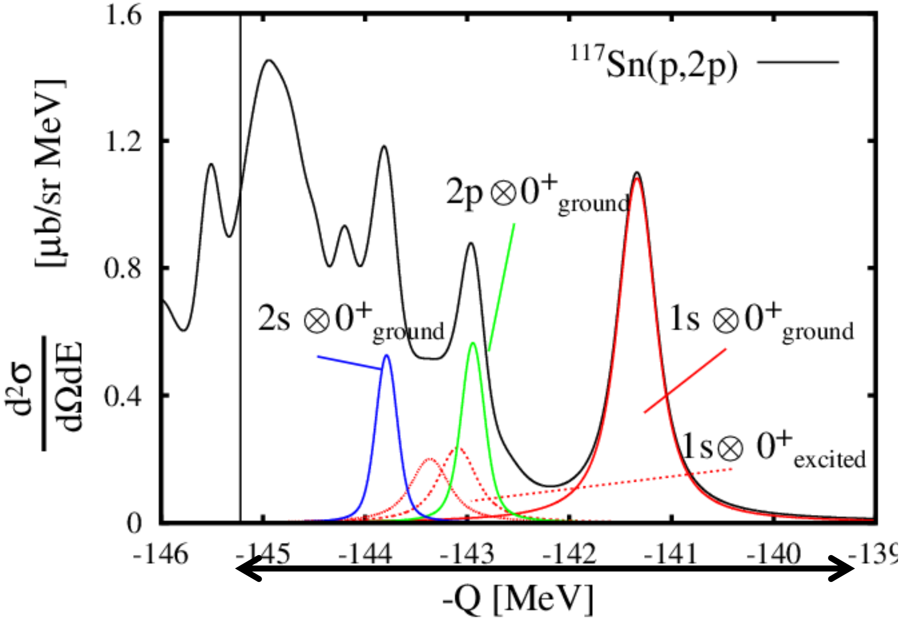
Isolated peak and single subcomponent (No residual interaction effect)

➔ This pionic 1s state is preferable for extracting accurate information on pion properties

(p,2p) spectra vs. (d,^{3}He) spectra: Odd target

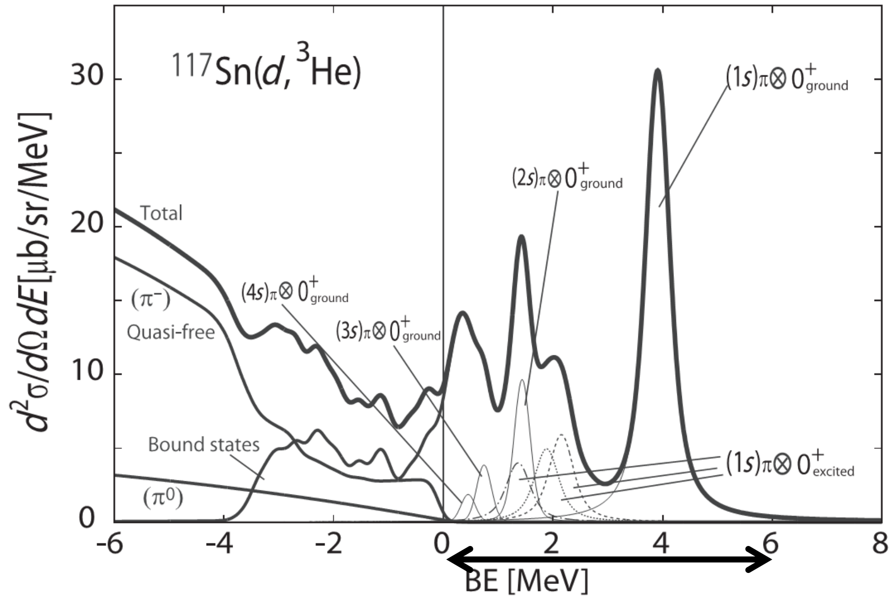
$^{117}\mathrm{Sn}(p,2p)@T_p = 392\ \mathrm{MeV}$

Calculated by J. Yamagata-Sekihara, N. Ikeno, S. Hirenzaki



$^{117}\mathrm{Sn}(d,^3\mathrm{He})@T_d = 500\ \mathrm{MeV}$

N. Ikeno, J. Yamagata-Sekihara, H. Nagahiro, S. Hirenzaki, PTEP2013(13)06D01



(p,2p) reaction:

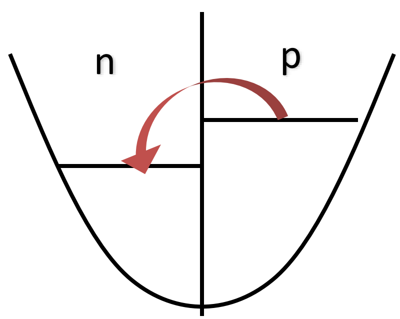
- Subcomponent of 2p state is large due to larger momentum transfer
- Absolute value is smaller

Pionic atoms in Proton rich nuclei

- Possible one-body decay by $\pi^- + p \rightarrow \pi^0 + n$
- Decay mode of pionic Hydrogen

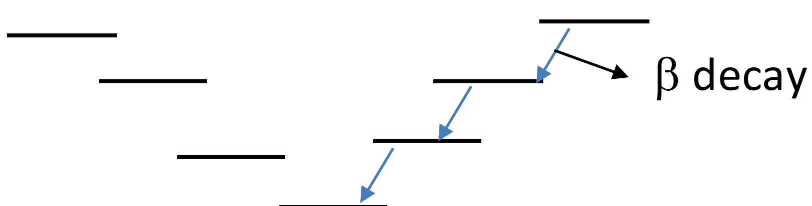
(This process is possible because $m_{\pi^-} + m_p > m_{\pi^0} + m_n$)

- Possible Enhancement in Proton-rich nuclei



Different E_F
→ Larger phase space for
$\pi^- + p \rightarrow \pi^0 + n$ process

Isobar Energy level



β decay Q-value from Isotope table
= 1 ~ 10 MeV

Pionic atoms in Proton rich nuclei

- Interests
  - Additional decay mode (Imaginary potential)

    → Different atomic structure? Different effective density?
  - Nuclear dependence of **1 body** vs. **2 body**?
  - $\pi^- + p \rightarrow \pi^0 + n$, $\pi^0 \rightarrow 2\gamma$ at finite density?

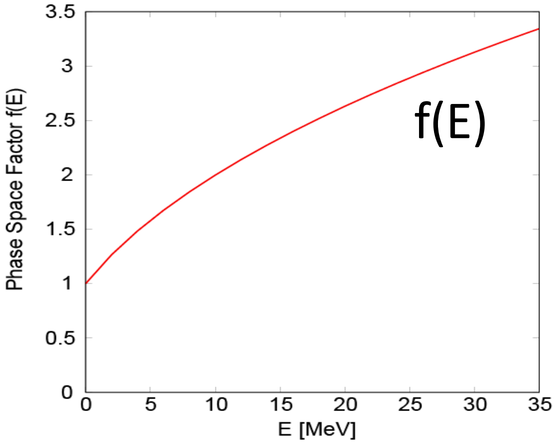
    (π^0 → 2γ)
  - Exclusive information by the selection rules of

    π atom formation reaction (Matching condition) and Nuclear matrix elements $M_{fi} = < f|\hat{O}|i >$?

Preliminary Calculation

- Evaluation of the one body decay potential
  - Imaginary part of π^- p scattering length from ΔE and Γ of pionic hydrogen
  - Enhancement of imaginary part by phase space factor f(E)

$$f(E) = \frac{M_{01}^3}{M_1^3}\sqrt{\frac{[M_1^2-(m_{\pi^0}+m_n)^2][M_1^2-(m_n-m_{\pi^0})^2]}{[M_{01}^2-(m_{\pi^0}+m_n)^2][M_{01}^2-(m_n-m_{\pi^0})^2]}} \times \theta(M_1 - m_{\pi^0} - m_n)$$



(- Nuclear Matrix element is not yet considered)

  - Additional term in pion-nucleus optical potential

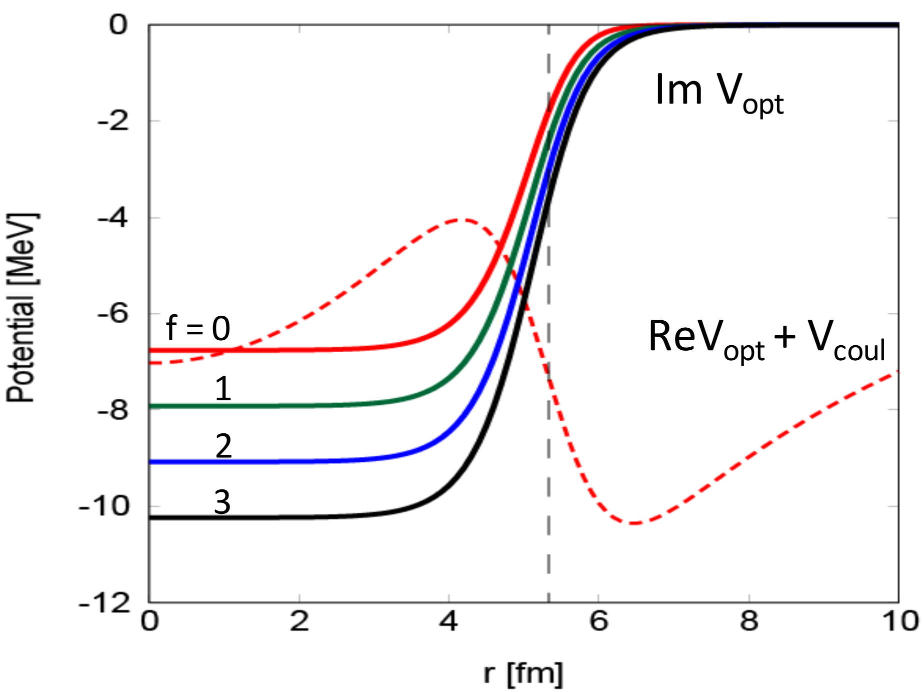
$$2\mu V_{\rm opt}^s(r) = -4\pi[\varepsilon_1\{b_0\rho(r)+b_1\delta\rho(r)\}+\varepsilon_2 B_0\rho^2(r)] -4\pi\varepsilon_1 b_{1b} f(E)\rho_p(r)$$

Preliminary Calculation (π atom structure)

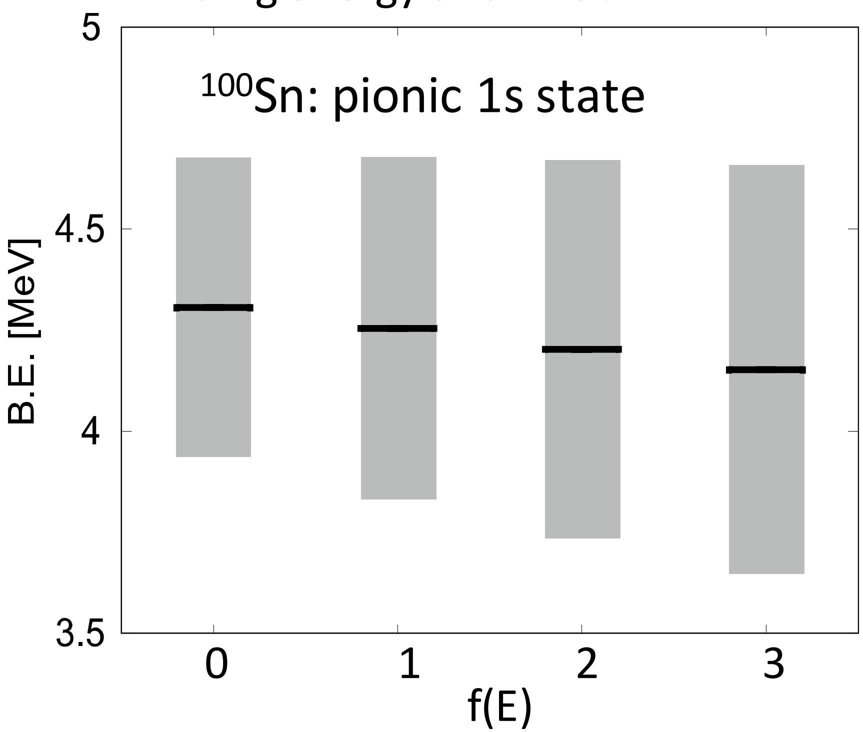
- pion-nucleus optical potential

$$2\mu V^{s}_{\text{opt}}(r) = -4\pi[\varepsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \varepsilon_2 B_0\rho^2(r)] - 4\pi\varepsilon_1 b_{1b} f(E)\rho_p(r)$$

Potential



Binding energy and Width



<u>π-^{100}Sn (EXTREMELY proton rich case)</u>

Summary　Theoretical Formation Spectra of pionic atoms

- **Finite angles: ^{122}Sn(d,^{3}He) spectra**
  - ✓ Different subcomponents dominate at different angles.
    $(1s)_\pi$, **$(2s)_\pi$**: 0 degrees, **$(2p)_\pi$**: 2degrees
  - → Simultaneous observation of various states in one nuclide (Good feature)

- **^{117}Sn(d,^{3}He) spectra: Odd-neutron nuclear target**
  - ✓ We can see clear peak structure of $[(1s)_\pi \otimes {}^{116}\mathrm{Sn}(0^+)]$.
    - No residual interaction effect
  - → More precise information than that of even target case can be expected.

- **Pionic atoms in Proton rich nuclei**
  - ✓ Possible one-body decay channel
  - ✓ Preliminary Results
  - ✓ New Information?

By comparing theory with the high resolution future experimental data for various targets and reaction angles,
we expect to know pion properties at various densities.