Formation of deeply bound pionic atoms and pion properties in nuclei

Natsumi Ikeno (Tottori University)

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)

The 14th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon
July 25-30, 2016 in Kyoto, Japan

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

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

$$\Downarrow$$

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

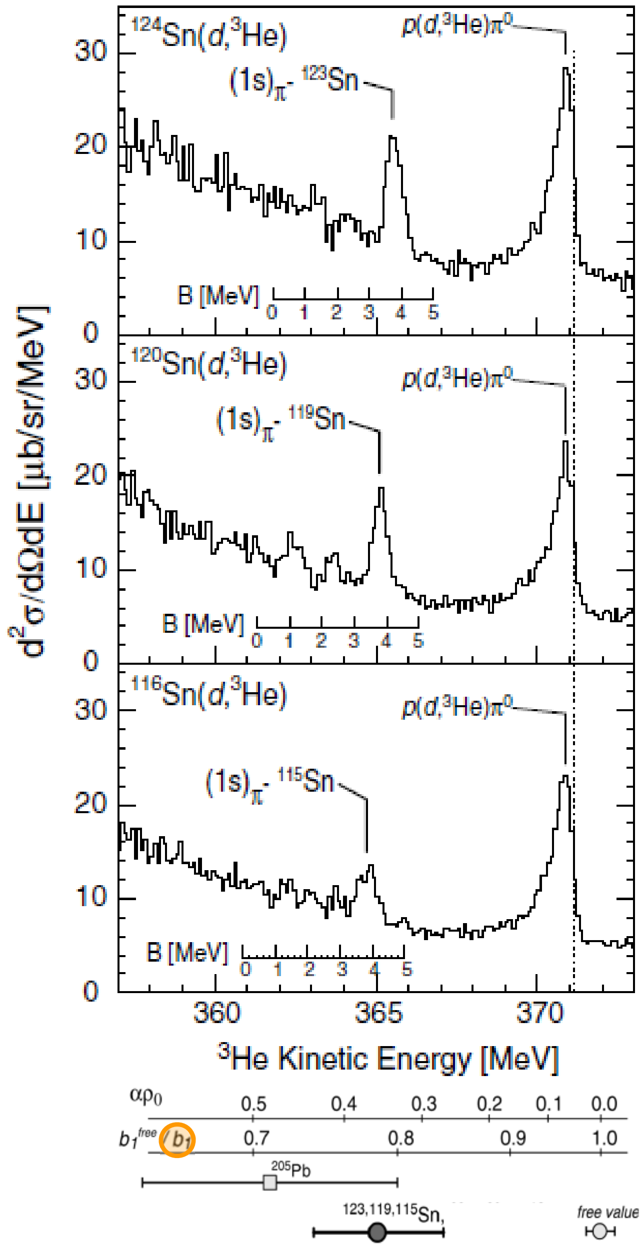
Theoretical basis

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

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

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

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



What's next?

Interests

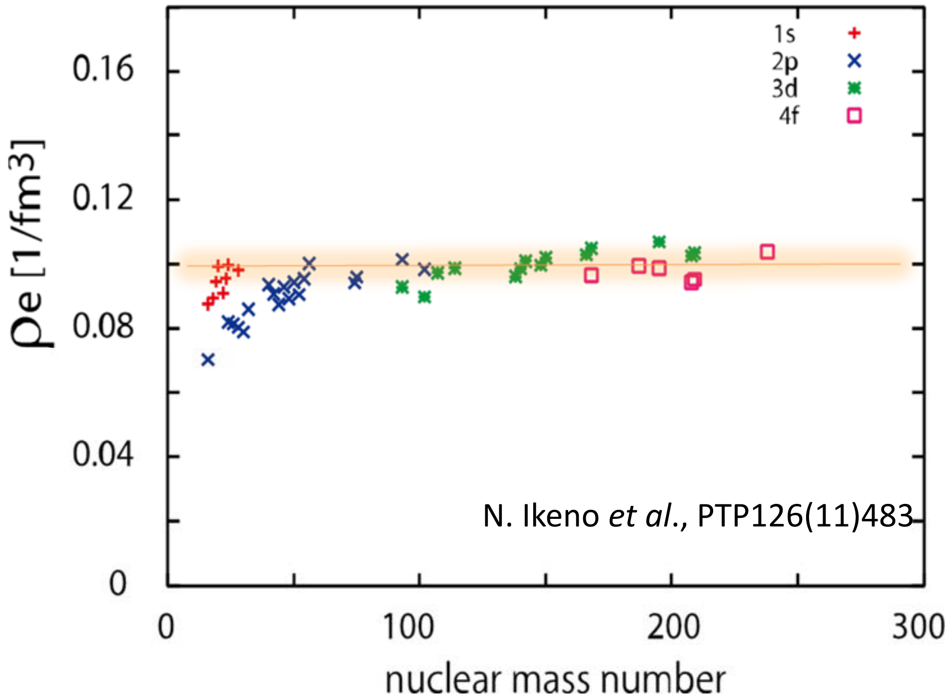
$\bar{q}q$ condensate: More accurate determination

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. $\mathrm{Re}B_0$

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

Motivation and Our theoretical studies

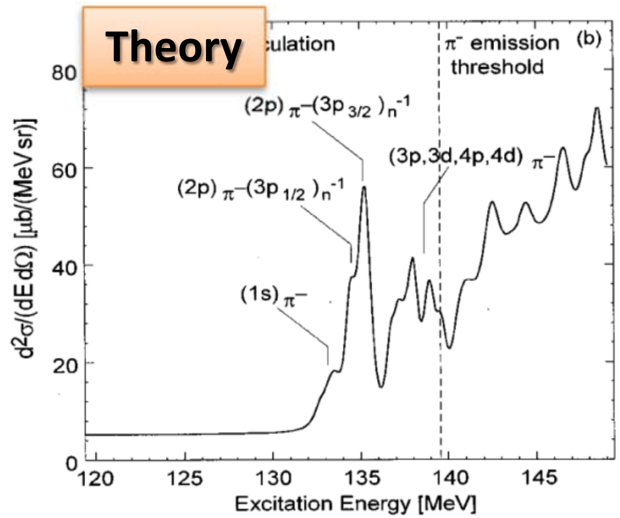
More Systematic/Accurate information on pionic states from the observations is important

Theoretical Formation spectra

- Various targets: Even + Odd neutron nuclear
- Reaction angle: 0 - 3 deg.
- Formation reaction: (d,^{3}He), (p,2p) reaction
- Formation Spectra in Green's function Method

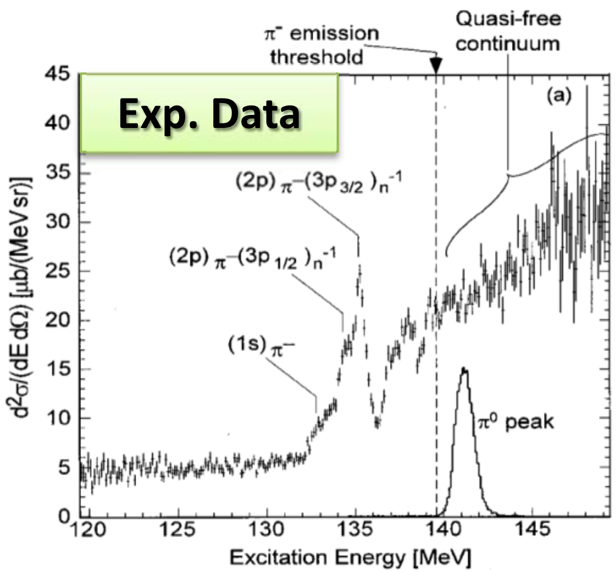
- ✓ ^{122}Sn(d,^{3}He) spectra: Even target
- ✓ ^{117}Sn(d,^{3}He) spectra: Odd target
- ✓ ^{117}Sn(p, 2p) spectra: Odd target

^{208}Pb(d,^{3}He)



S. Hirenzaki *et al.,* PRC44(91)2472

Direct comparison



K. Itahashi *et al.,* PRC62(00)025202

Finite angle, Odd target studies

- **$(d,^3He)$ reaction at finite angles**

Matching condition: $L = [\ell_\pi \otimes \ell_n^{-1}] \simeq qR$

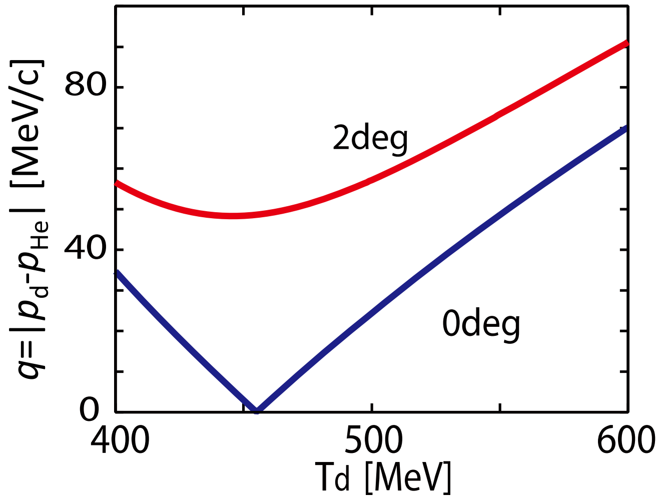
Forward angle: Near recoilless condition (q ~ 0)

Finite angles: Larger momentum transfer

- Several atomic states (ex. 1s, 2s, 2p) in the same nuclei

=> Possible reduction of systematic errors

Neutron density ambiguities   Experimental uncertainties



- **Even + Odd neutron nuclear target**

- Systematic 'precise' observation for various nucleus

Target Nuclei in the Experiments @GSI

Even-Even Nucleus: $J^P=0^+$

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^+

Experiments @RIBF/RIKEN

Interests of Odd target $J^p=1/2^+$

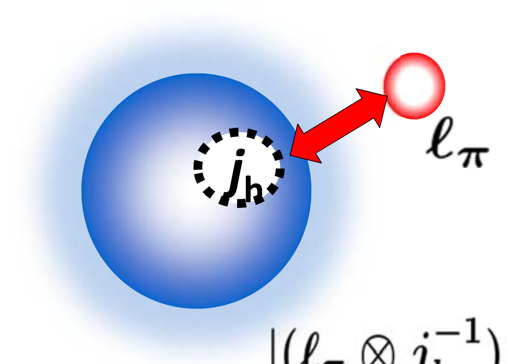
``Pionic state $[\pi^- \otimes 0^+]$ ***free from residual interaction effect"***

Even-Even Nucleus: $J^p=0^+$

Final state: pion particle - neutron hole $[\pi \otimes n^{-1}]$

S. Hirenzaki *et al.* PRC60(99)058202;
N. Nose-Togawa *et al.* PRC71(05)061601(R)

^{116}Sn complex energy shift		
j_h^{-1}	1s [keV]	2p [keV]
$3s_{1/2}^{-1}$	-15.4-4.2i	**J=1/2** -4.0-1.1i
		J=3/2 -4.0-1.1i
$2d_{3/2}^{-1}$	-15.9-4.8i	**J=1/2** -9.1-3.1i
		J=3/2 0.3+0.3i
		J=5/2 -5.2-1.8i
Exp. Error ± 24 [keV] @GSI		

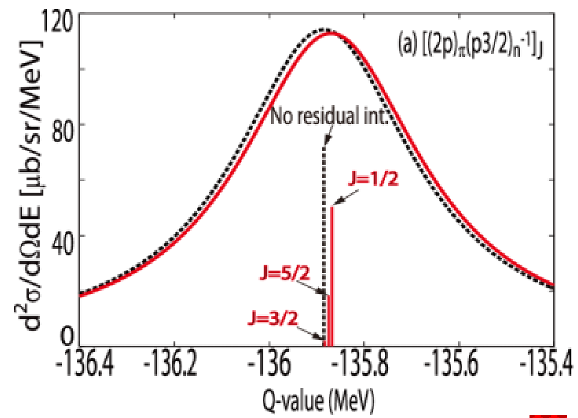


$|(\ell_\pi \otimes j_h^{-1})_J\rangle$

``Residual interaction effect"

- Level splitting between different J state
- Energy shift

Additional difficulty to determine B.E. and parameters in V_{opt}



[Exp. Error] vs. [Shift due to Residual Int.]

➡ Observation of pionic states free from these effects is very important to obtain more accurate information from data.

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:

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

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

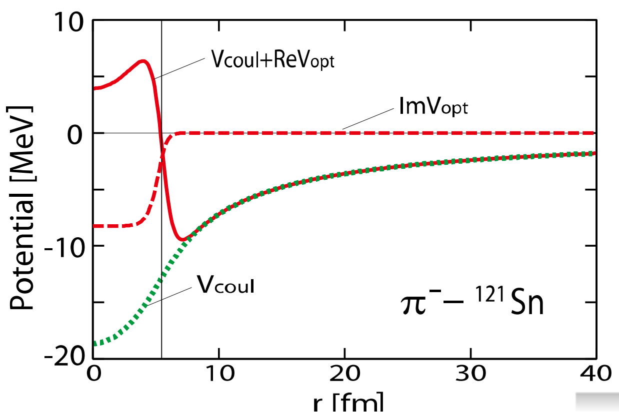
- Effective Number:

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

Different formulation for **Even-** and **Odd-** neutron nuclear targets

- Klein Gordon equation

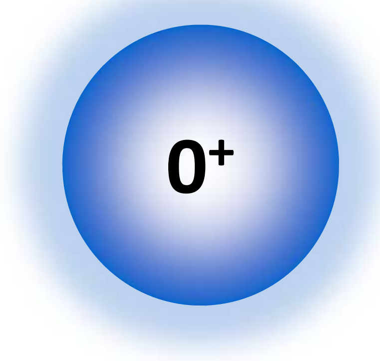
$$[-\nabla^2+\mu^2+2\mu V_{\rm opt}(r)]\phi(\mathbf{r}) = [E-V_{\rm coul}(r)]^2\phi(\mathbf{r})$$



Formulation: Effective Number

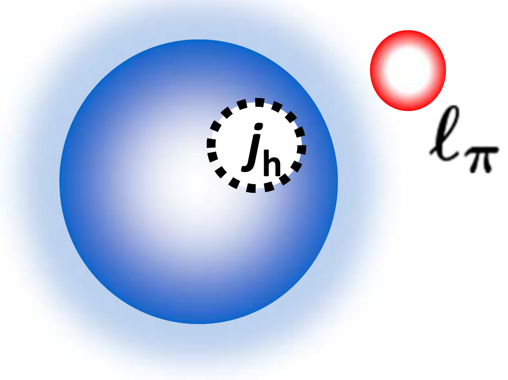
Even target: ^{122}Sn (0^+)

Initial:



$$|0^+\rangle$$

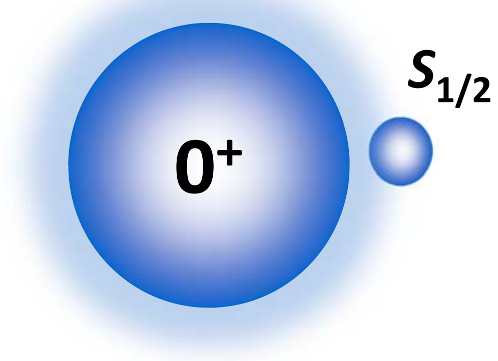
Final:



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

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

Initial:



Reasonable Assumption

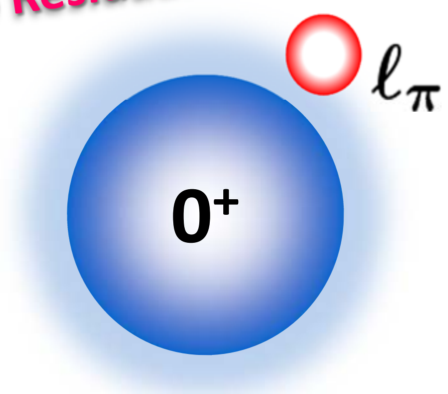
$$|s_{1/2} \otimes 0^+\rangle$$

Final:

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

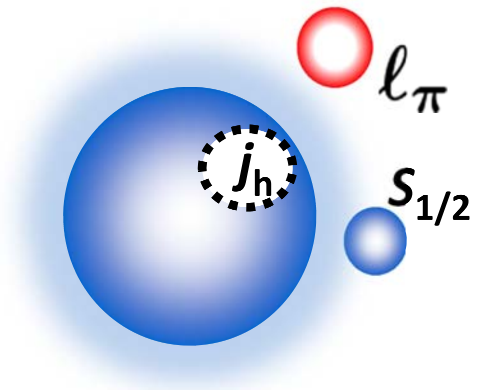
(2) neutron pick-up j_h orbit from other than $s_{1/2}$

``No Residual Interaction"



$$|(\ell_\pi \otimes 0^+)\rangle$$

+



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

➢ Realistic neutron configurations for the target and the daughter nucleus: Exp. Data

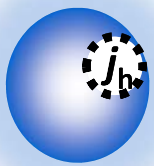
Even target: ^{122}Sn (0^+)

Excited level of ^{121}Sn

Exp. Data: ^{122}Sn(d,t)^{121}Sn

E. J. Schneid et al., Phys. Rev. 156 (1967) 1316

Neutron hole orbit j_h	Ex [MeV]
3s1/2	0.06
2d3/2	0.00
2d5/2	1.11
	1.37
1g7/2	0.90
1h11/2	0.05



- ✓ Many excited levels
- ✓ Large excitation energies (Ex)

➡ **Pionic atom formation spectra: Expected to be Complicated and broad spectra**

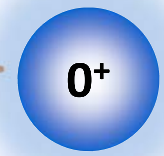
Odd target: ^{117}Sn ($1/2^+$)

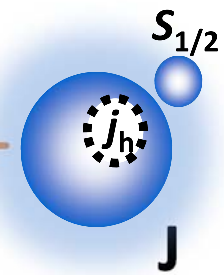
Excited level of ^{116}Sn

Exp. Data: ^{117}Sn(d,t)^{116}Sn,

J. M. Schippers et al., NPA510(1990)70

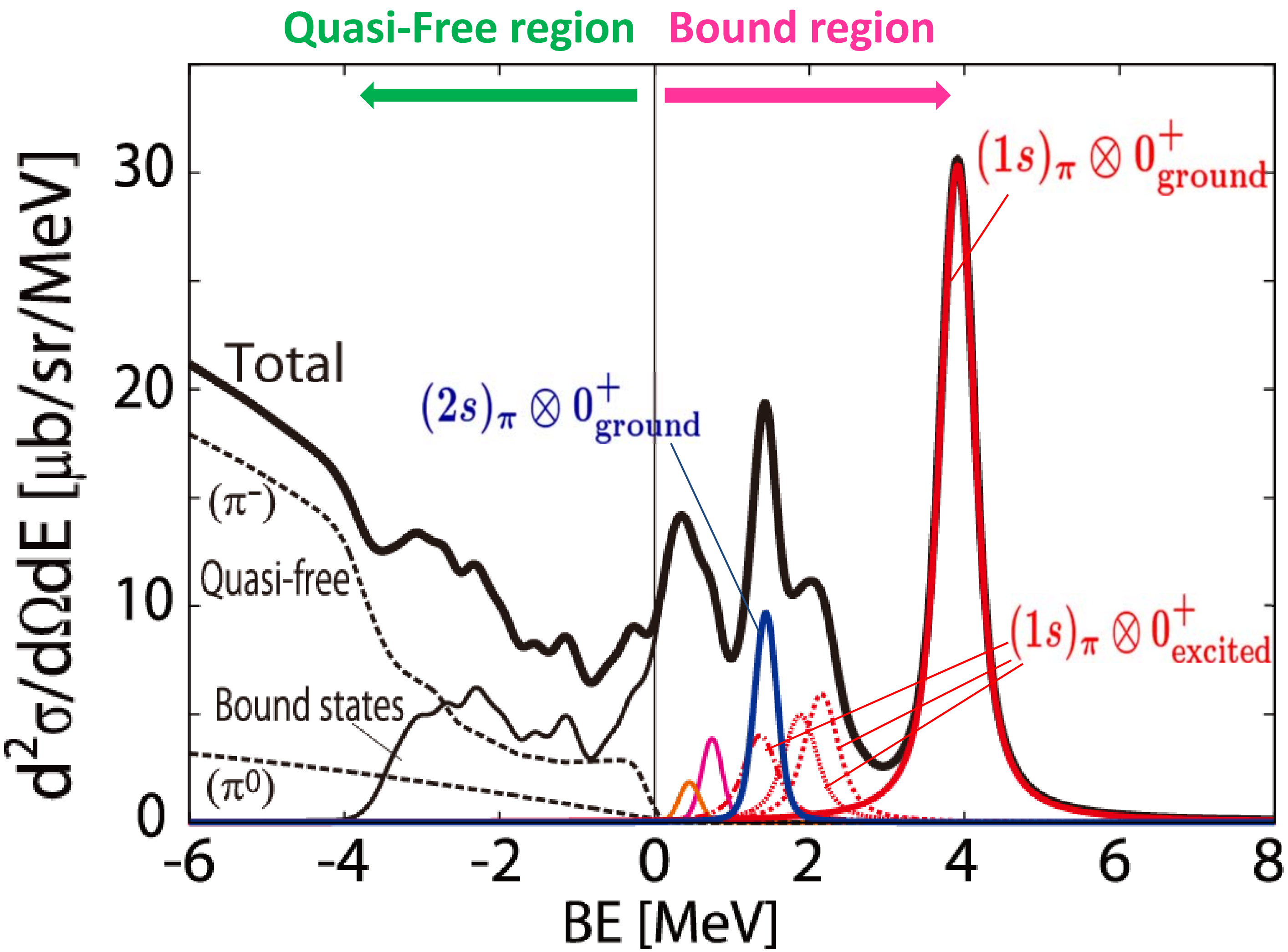
J^p	Neutron hole orbit j_h	Ex [MeV]
0+	3s1/2	0.00
		1.76
		2.03
		2.55
1+	2d3/2	2.59
		2.96
2+	2d3/2 and 2d5/2	1.29
		2.23
		3.23
		3.37
		3.47
		3.59
		3.77
		3.95
3+	2d5/2 and 1g7/2	3.00
		3.42
		3.71
	1g7/2	3.18
4+	1g7/2	2.39
		2.53
		2.80
		3.05
		3.10
5-	1h11/2	2.37
6-	1h11/2	2.77





(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

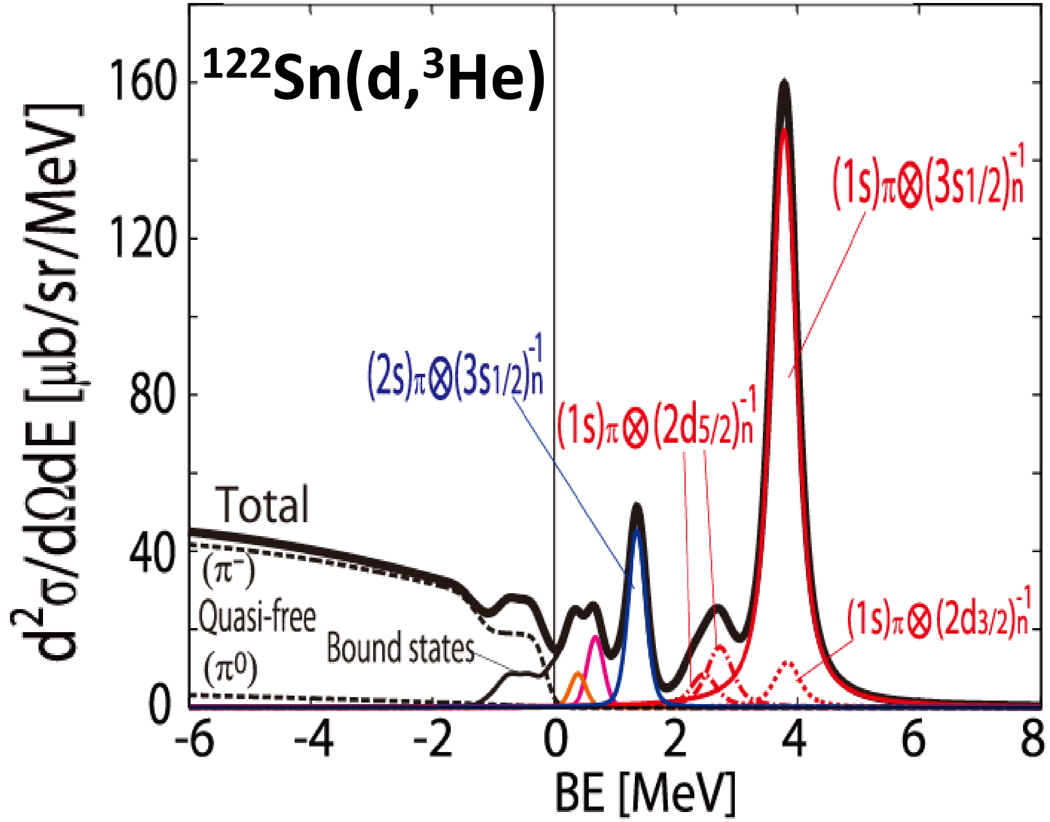
Dominant Subcomponent:
$[(n\ell)_\pi \otimes J^P]$

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

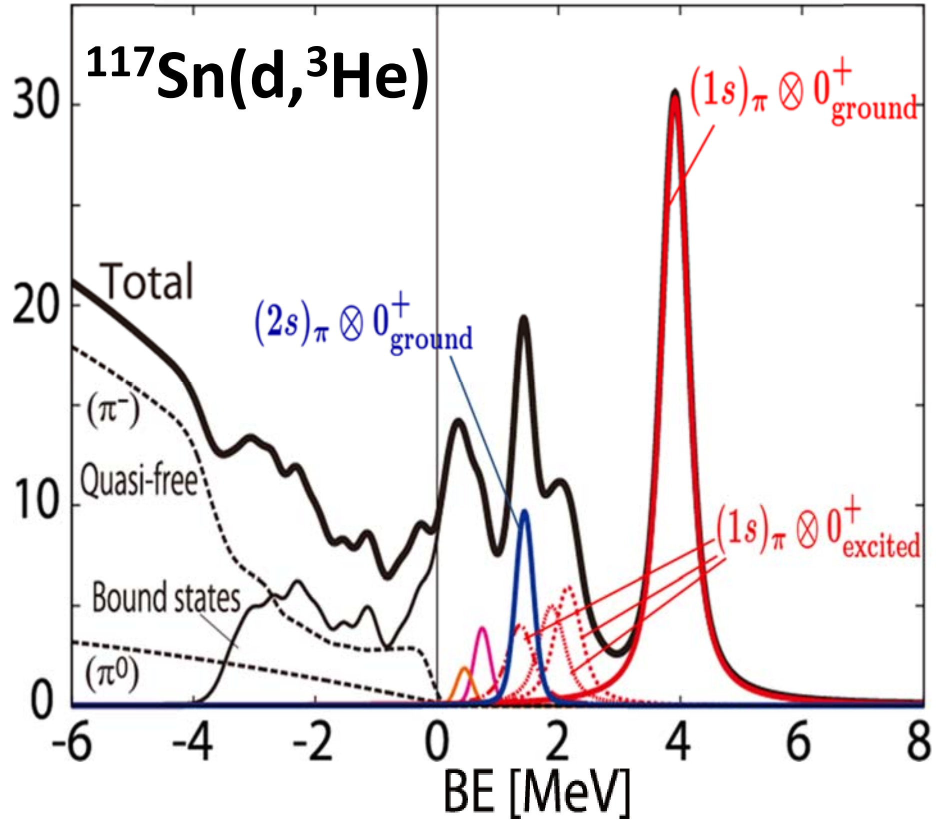
(d,^{3}He) spectra: Even vs. Odd target

0 degrees

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



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

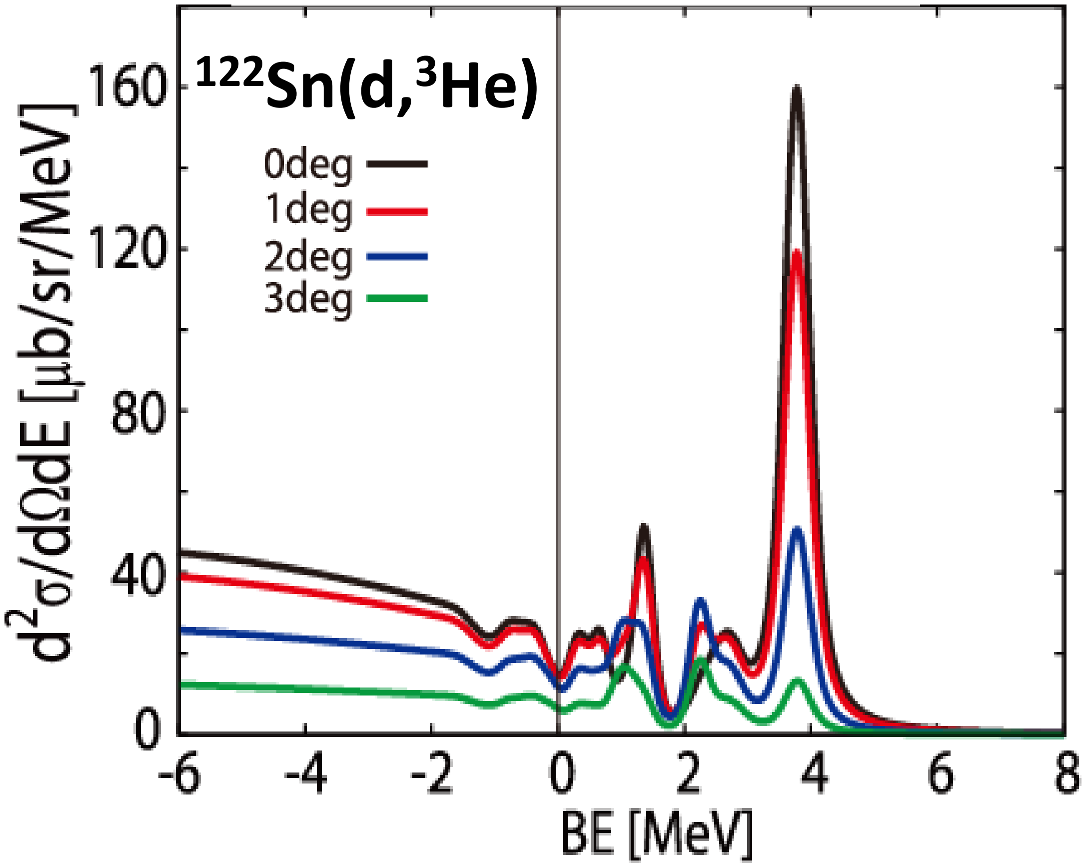


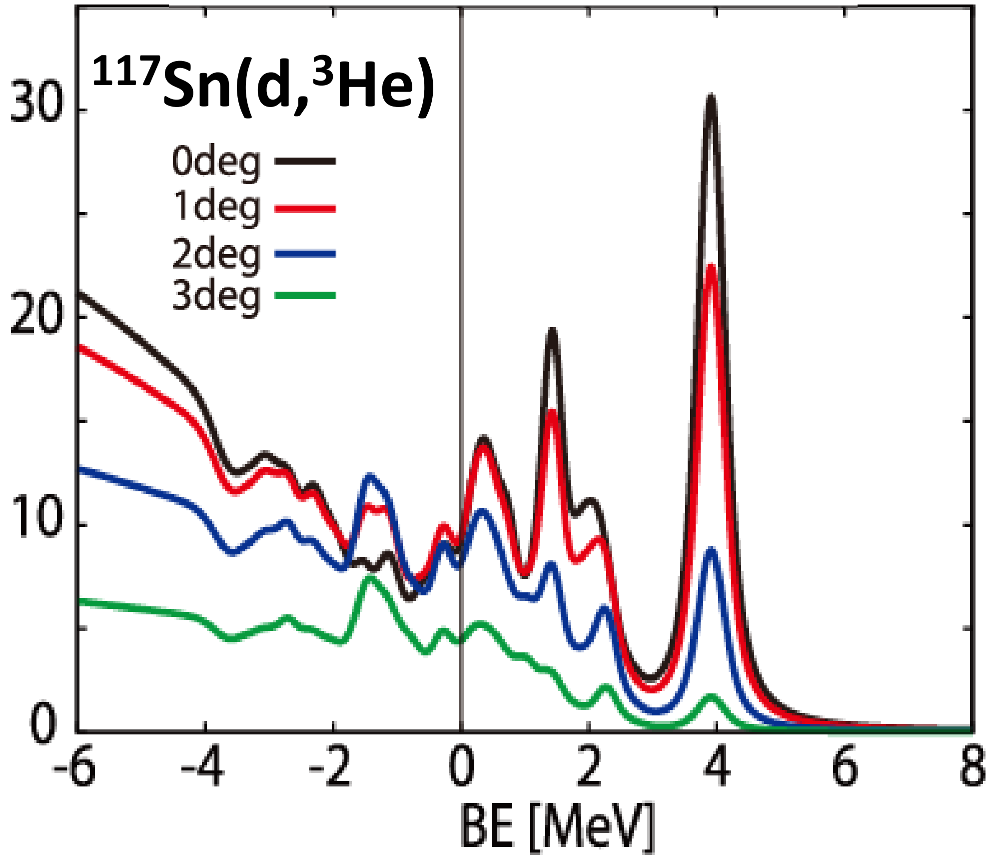
- Pionic 1s state formation with neutron s-hole state is large in both spectra.
- Bound pionic state formation spectrum in ^{117}Sn(d,^{3}He) spread over wider energy range.
- Absolute value of cross section in ^{117}Sn(d,^{3}He) is smaller.

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

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

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





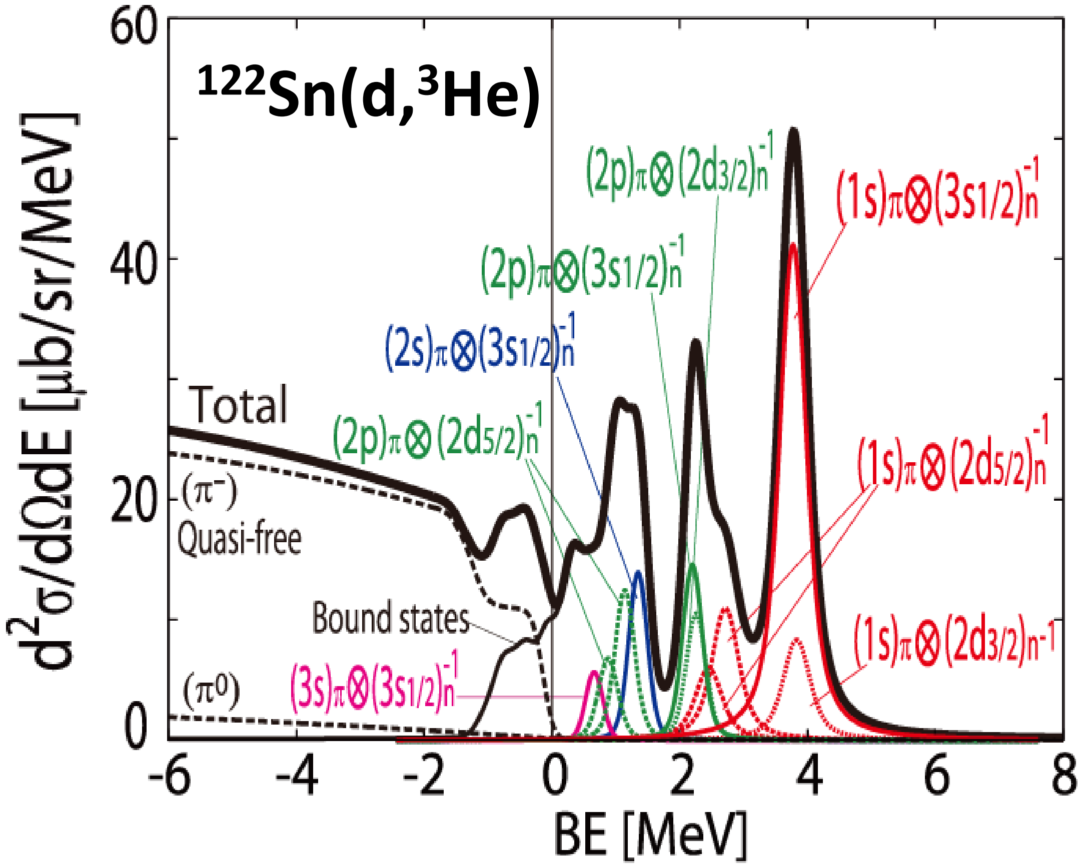
- Both spectra have strong angular dependence.

  - Sharpe structure - Overall strength

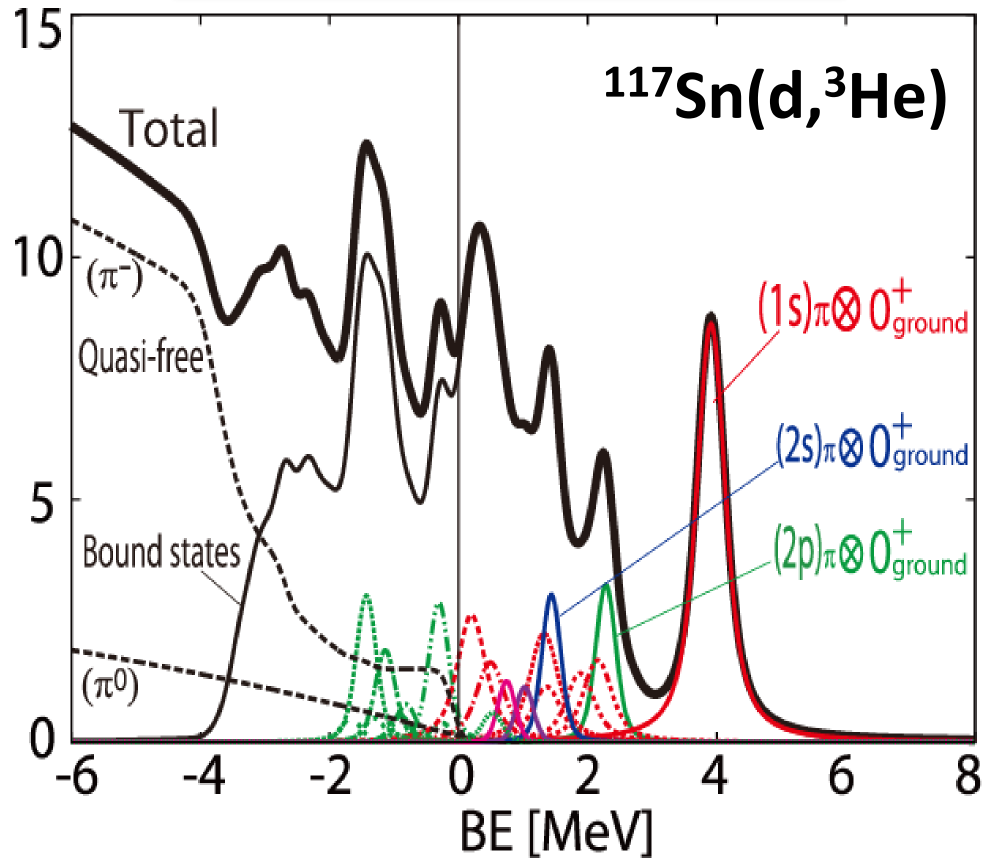
$(d,^{3}He)$ spectra: Even vs. Odd target

2 degrees

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



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



Even target:

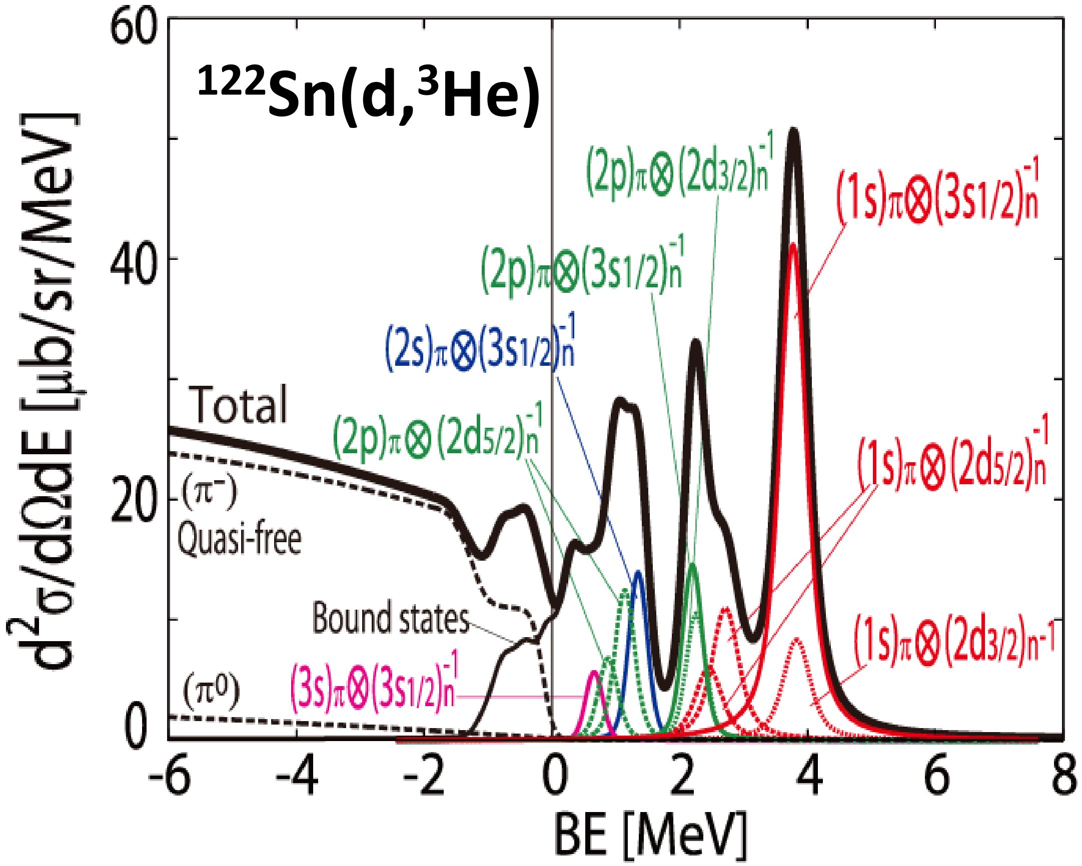
Simultaneous observation of several pionic ***1s***, ***2s*** and ***2p*** states at forward and finite angles

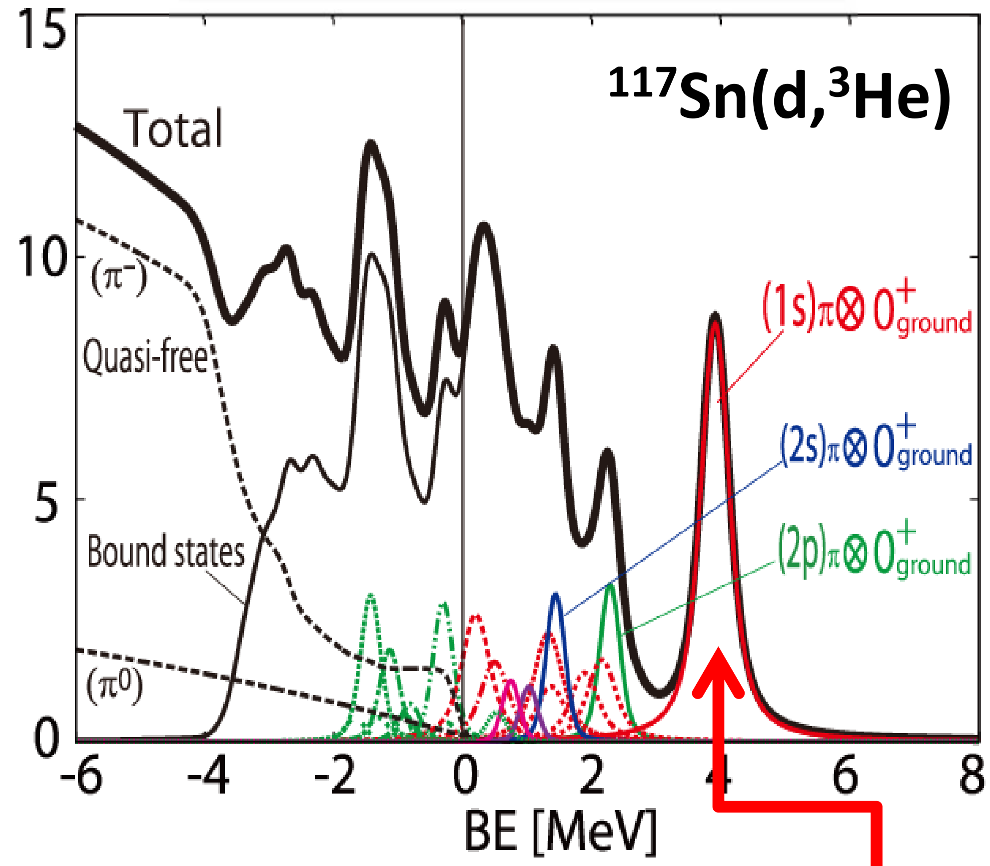
(d,^{3}He) spectra: Even vs. Odd target

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

Experimental studies: piAF project

K. Itahashi *et al.*,
RIBF-027, RIBF-054

Pionic Atom Spectroscopy @RIBF/RIKEN

- ✓ Higher statistics, better resolution
- ✓ Angular dependence of spectra

By T. Nishi-san's talk

∗ Pilot Experiment in October 2010 : ^{122}Sn(d,^{3}He) reaction
∗ Main Experiment in June 2014 : ^{122}Sn, ^{117}Sn targets

K. Itahashi-san's slide

Different reaction: (p,2p) @RCNP

H. Fujioka *et al.*,
RCNP E451

Pionic Atom Spectroscopy @RNCP

- ✓ Different reaction from (d,^{3}He) reaction
- ✓ Different angle at 0 deg. and 4.5 deg.
- ✓ Higher statistics, better resolution

By Y. Watanabe-san's talk

Future plan

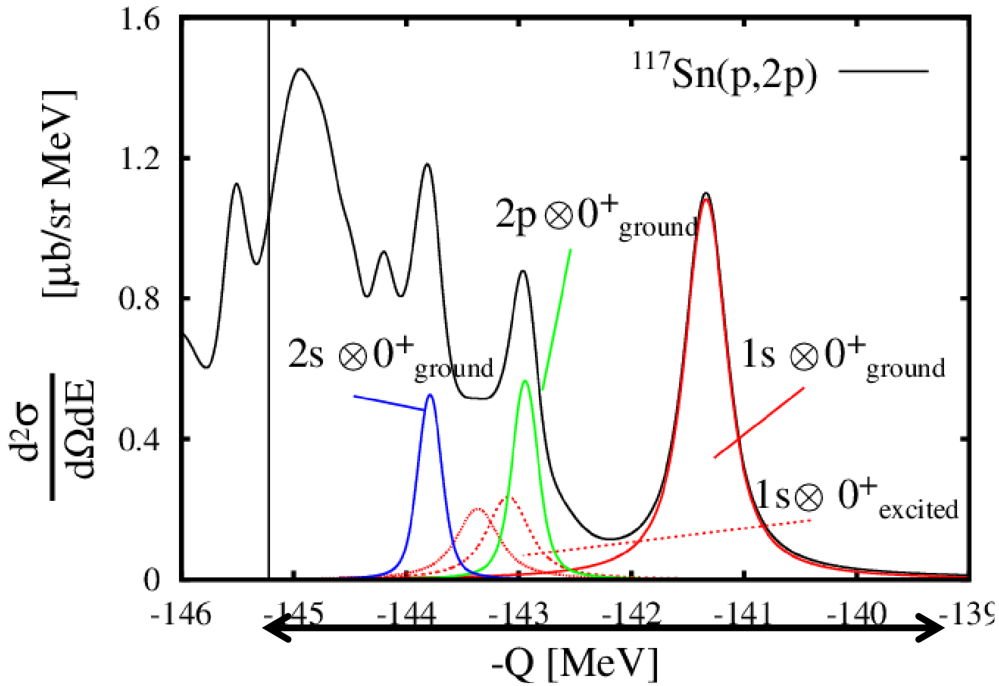
- ✓ Unstable nuclear targets
- ✓ Open angle reaction …

Theory study: J. Yamagata-Sekihara, N. Ikeno, S. Hirenzaki

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

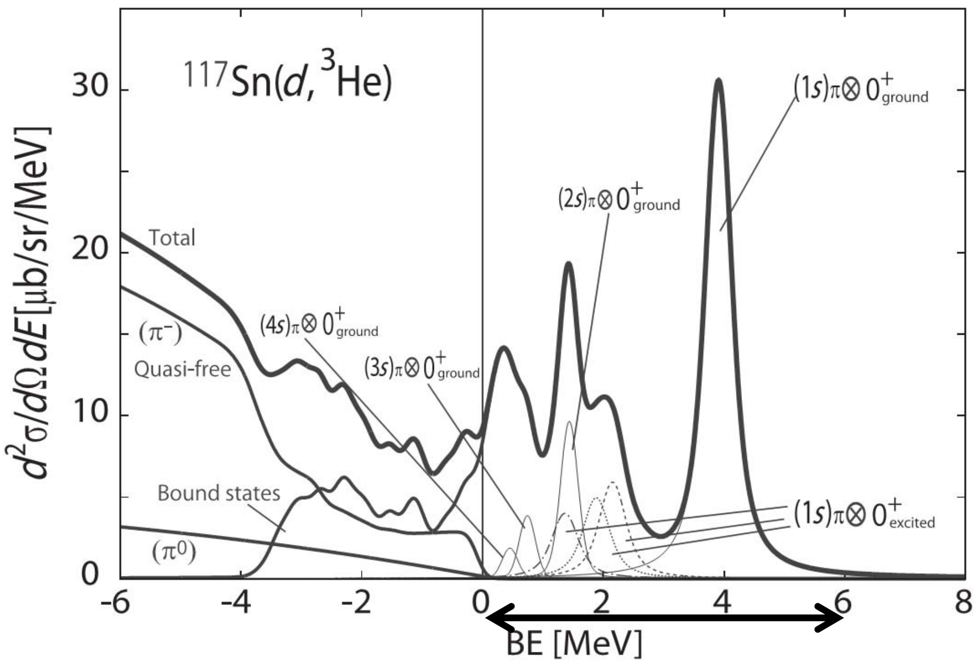
$$^{117}\mathrm{Sn}(p,2p)@T_p = 392\ \mathrm{MeV}$$

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 momentum transfer
- Absolute value is smaller

Updated theoretical spectra by Green's Function Method

Future Experiments @RIBF/RIKEN and RCNP

Recent developments in experimental techniques

-> Possibility of obtaining data with significantly better accuracy

- ✓ Better Energy Resolution
- ✓ Precise Shapes of Spectrum
  - Various nuclear targets,
  - Finite angles reactions, …

↓

Improvements in theoretical calculation for the (d,^{3}He) reactions for pionic atom formation

- Green's Function Method

Formulation: Green's Function Method

- Formation cross section O. Morimatsu, K. Yazaki, NPA435(85)727, NPA483(88)493

$$\left(\frac{d^2\sigma}{dE_{\mathrm{He}}d\Omega_{\mathrm{He}}}\right)_A^{\mathrm{lab}} = \left(\frac{d\sigma}{d\Omega_{\mathrm{He}}}\right)_{\mathrm{ele}}^{\mathrm{lab}} \times -\frac{1}{\pi}\mathrm{Im}\sum_f \left[\tau_f^\dagger G(E)\tau_f \times K\right]$$

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

- Kinematical correction factor *K*

- Green's function for π^- interacting with the nucleus

$$G(E,\vec{r},\vec{r}') = \langle n^{-1}|\phi_\pi(\vec{r})\frac{1}{E-H_\pi+i\varepsilon}\phi_\pi^\dagger(\vec{r}')|n^{-1}\rangle$$

- transition amplitude

$$\tau_f(\vec{r}) = \chi_f^*(\vec{r})\xi_{1/2,m_s}^*\left[Y_{\ell_\pi}^*(\hat{\vec{r}})\otimes\psi_{j_n}(\vec{r})\right]_{JM}\chi_i(\vec{r})$$

Advantages:

(i) We can include Bound and Quasi-free contributions simultaneously.

(ii) We can include an infinite number of Bound State contributions.

(iii) We do not assume Lorentz distribution as the shape of peak structure.

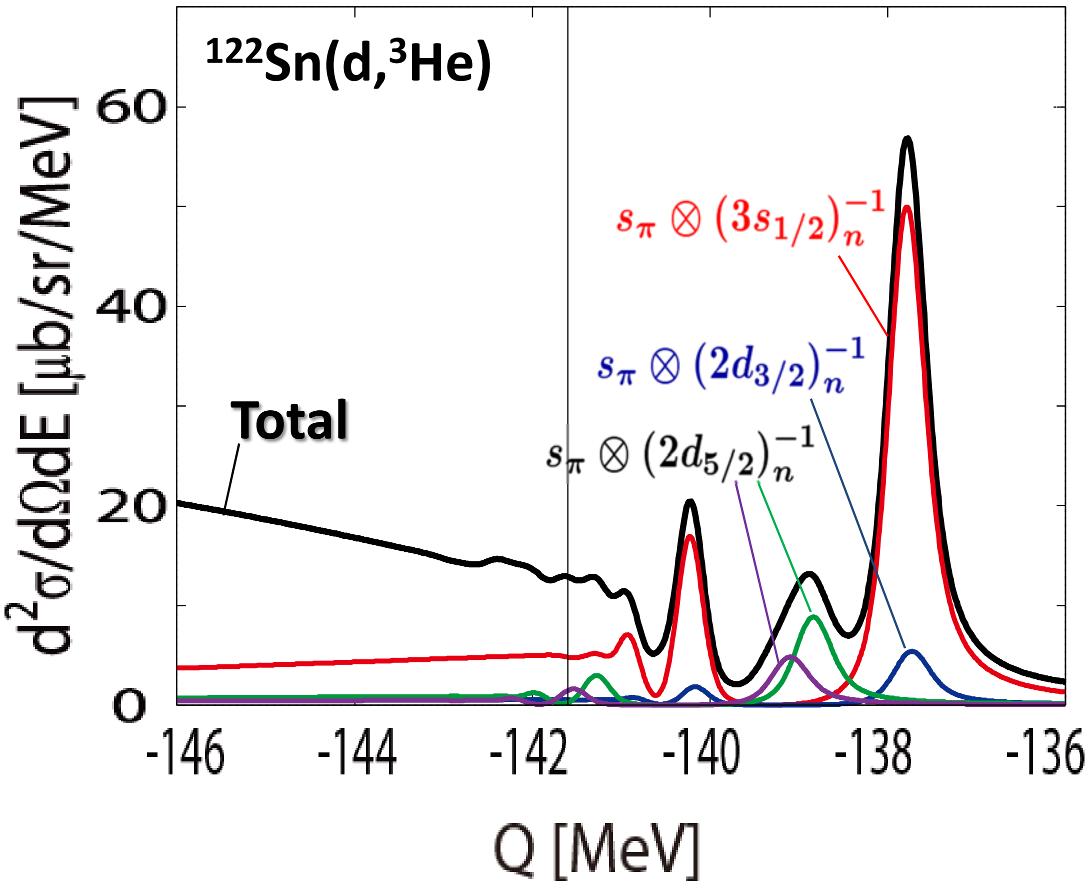
Numerical results: Green vs. Neff

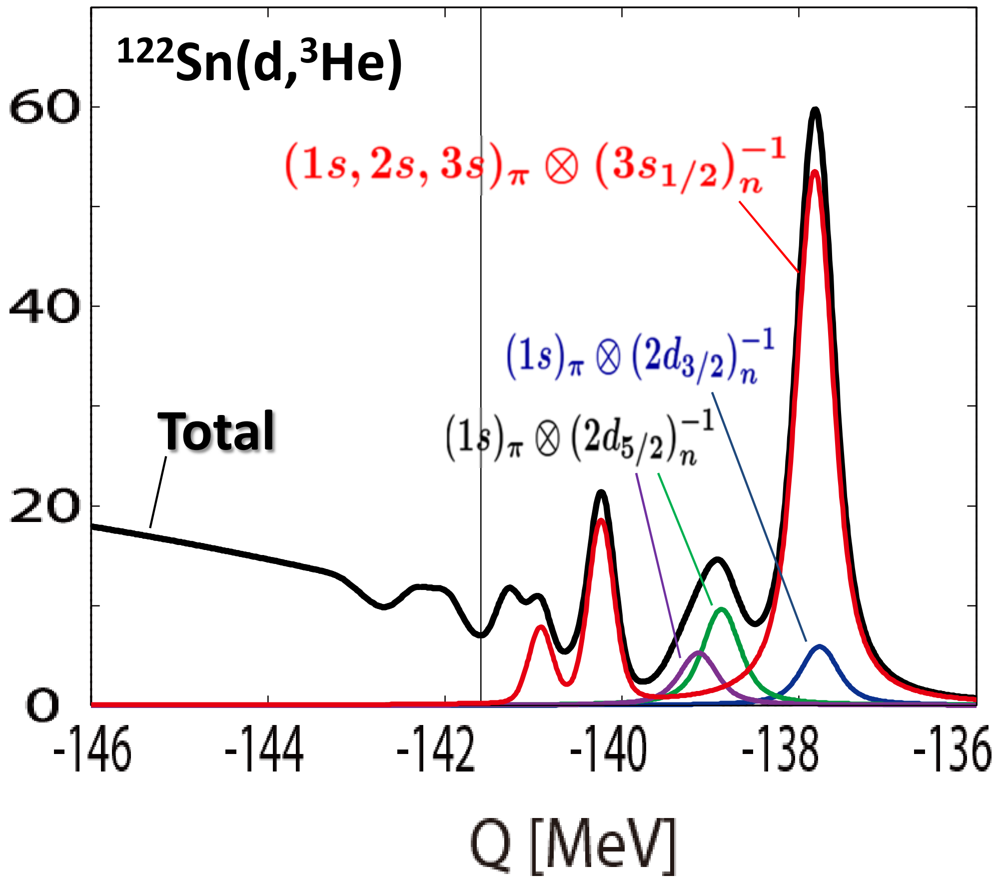
Energy resolution
ΔE=300keV

- $^{122}Sn(d,^3He)$ spectra at 0 degrees

Neutron wave function:
Harmonic Oscillator

Green **Neff**





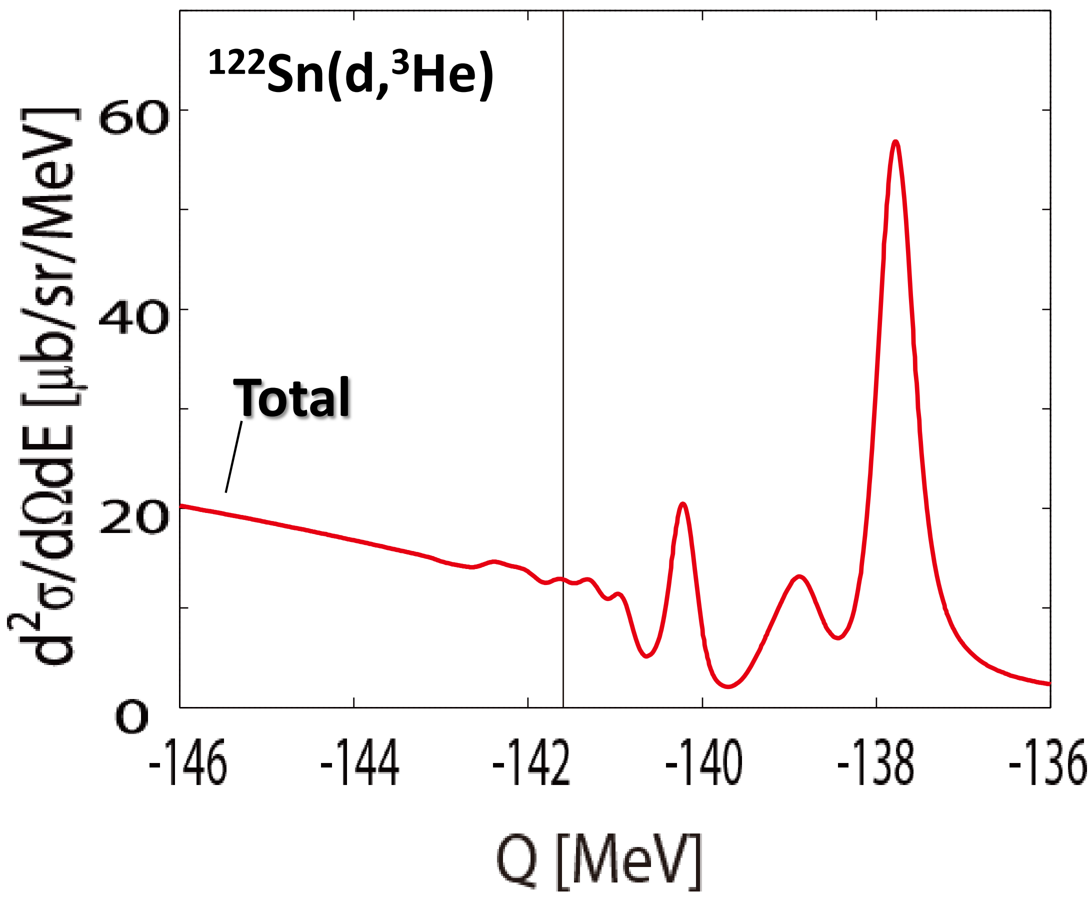
Both Methods seem to provide the very similar spectra.

Numerical results: Green vs. Neff

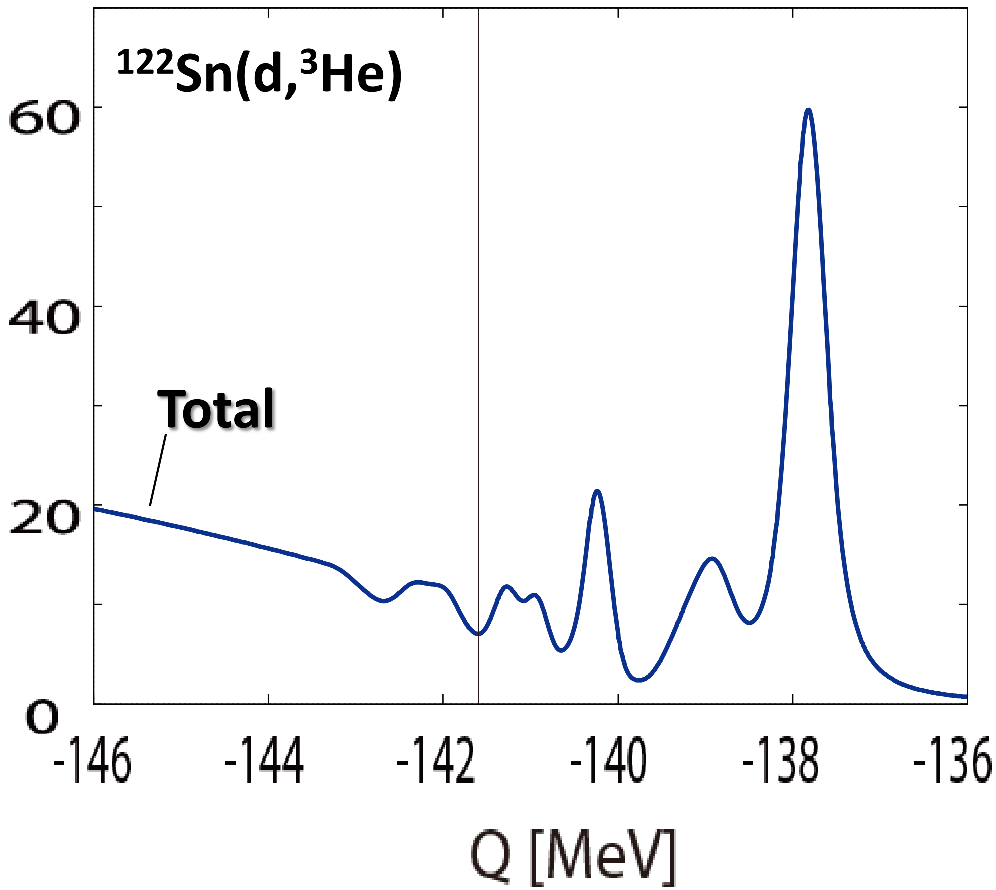
➢ ^{122}Sn(d,^{3}He) spectra at 0 degrees

Energy resolution
ΔE=300keV

Green



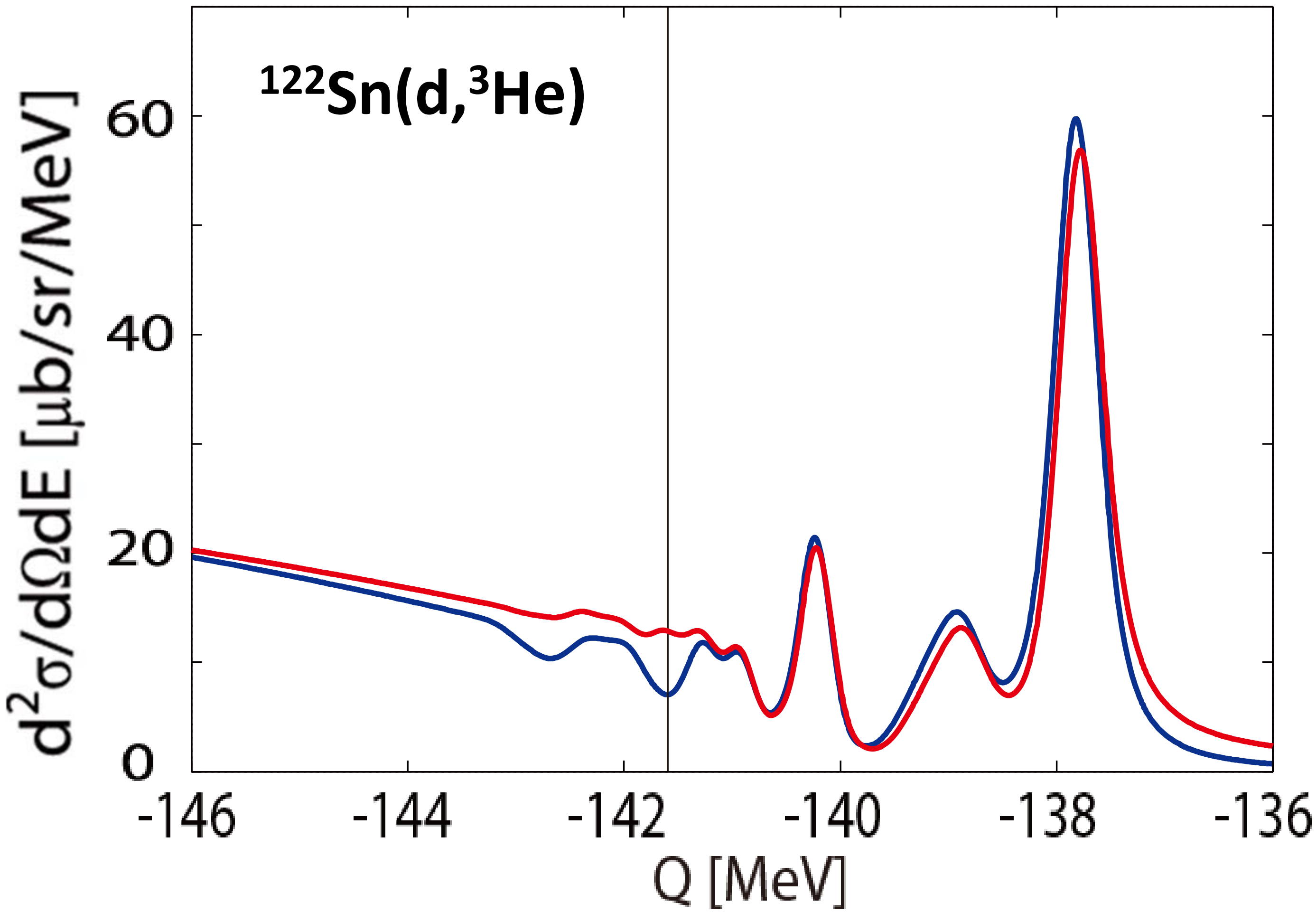
Neff



Numerical results: Green vs. Neff

- $^{122}Sn(d,^{3}He)$ spectra at 0 degrees

Energy resolution
ΔE=300keV



<u>Differences between both spectra</u>

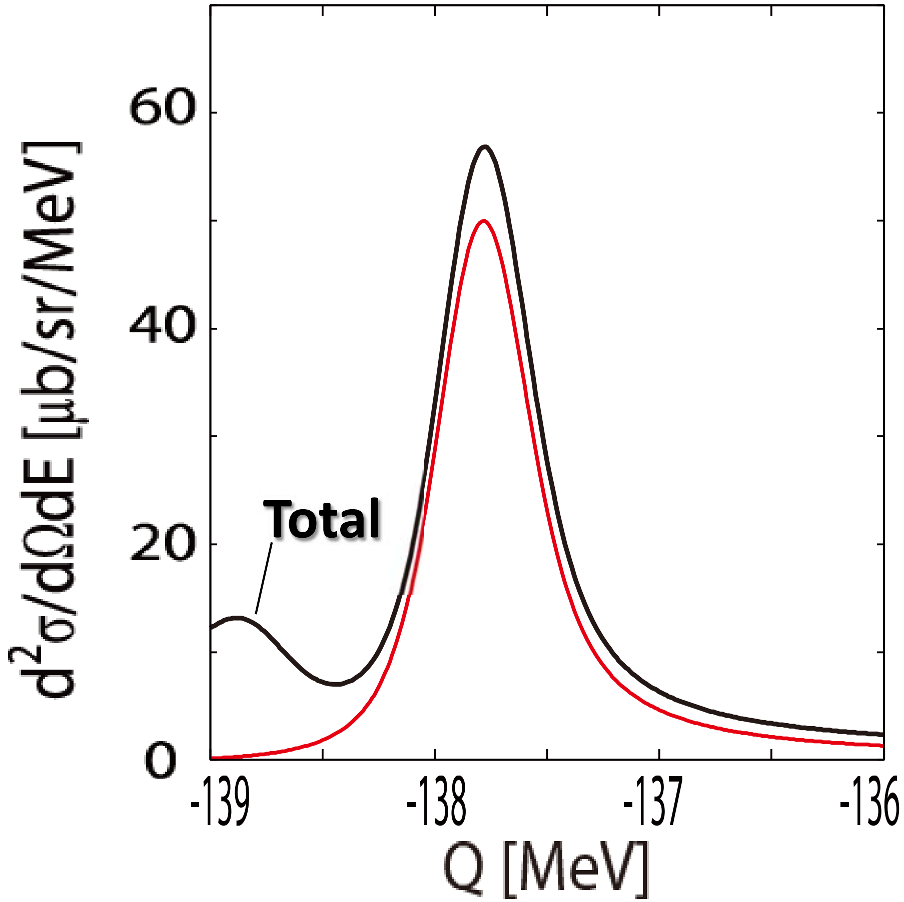
(1)Near threshold (2) Height and position of peak (3) Tail of peak structure

Numerical results: Green vs. Neff

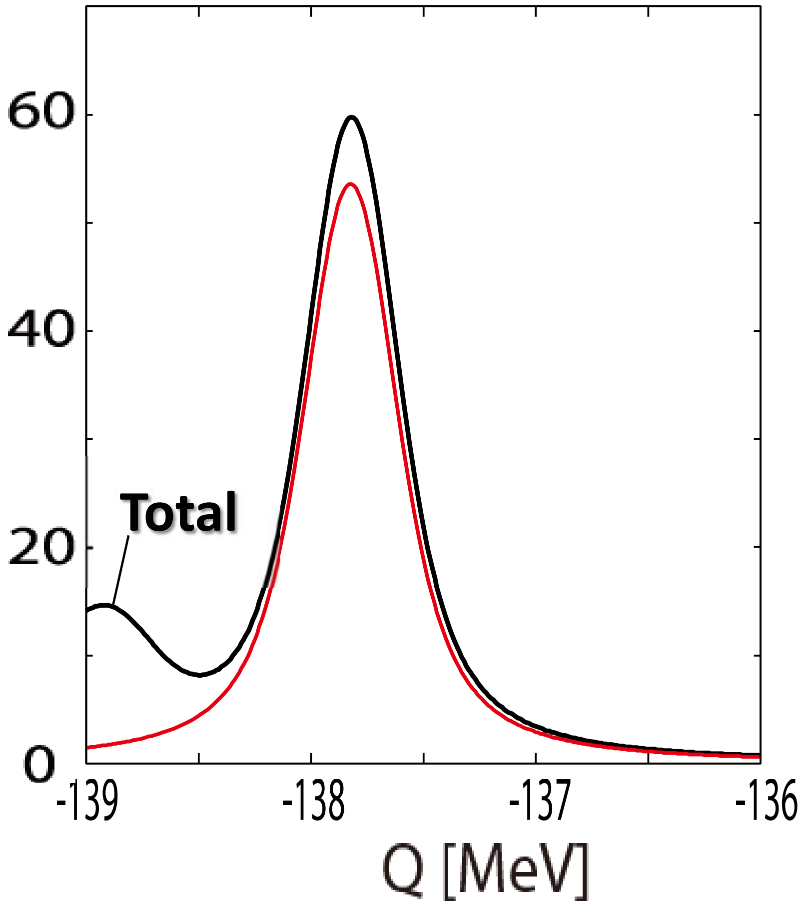
Energy resolution
ΔE=300keV

We focus on subcomponent of $(1s)_{\pi} \otimes (3s_{1/2})_{n}^{-1}$

Green



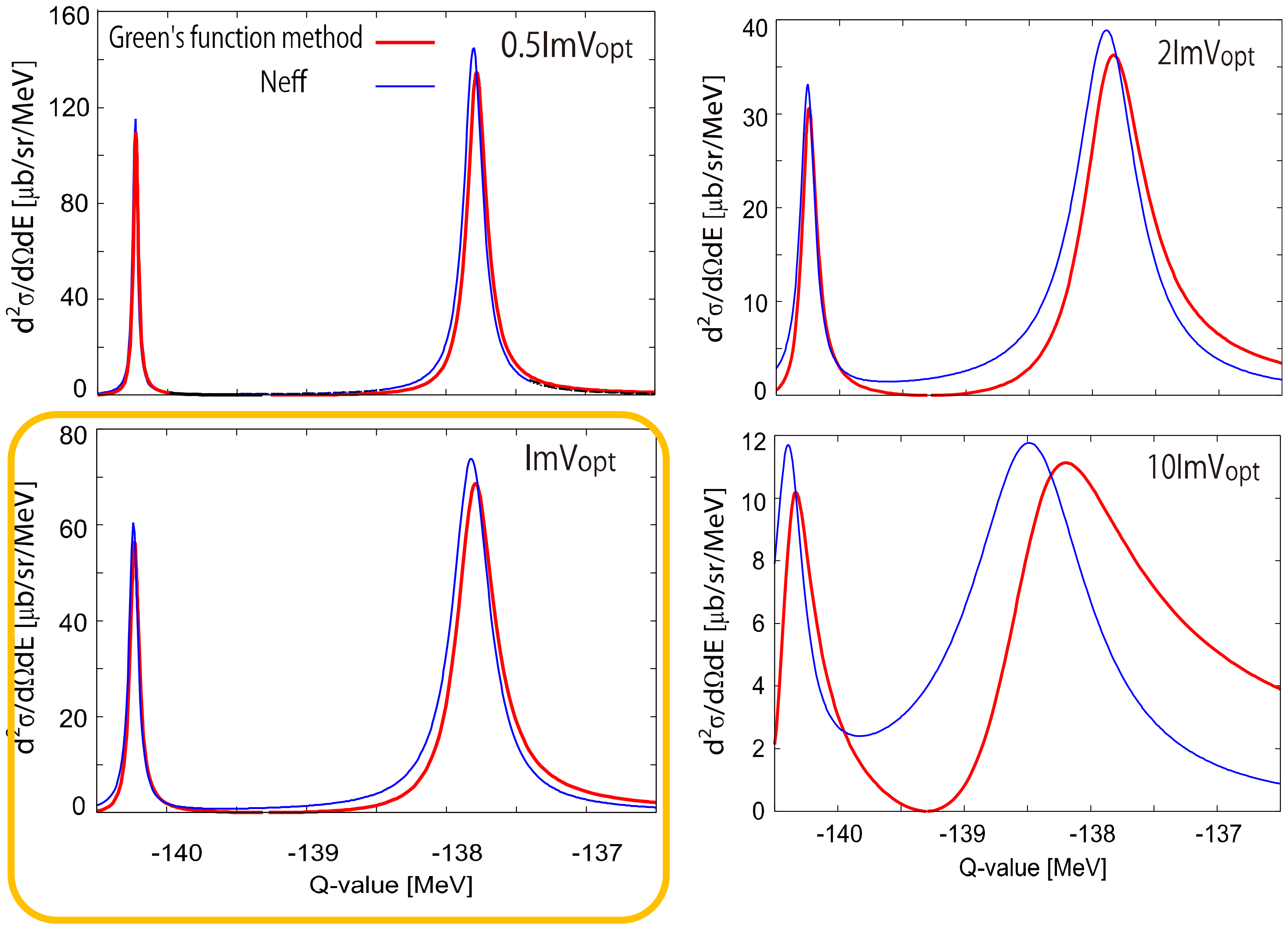
Neff



Different behavior of peak structure (Green: Asymmetric, Neff: Symmetric)

➔ **Precise theoretical spectrum is important to deduce pion properties in nuclei from future high resolution experiment**

Numerical results: Green vs. Neff



Large ImV_{opt}
-> peak position is shift

Discrepancy Green vs. Neff
ImVopt: around 10 keV
10 ImVopt : Very large

Errors of B.E. >20 keV: Neff is a good method

Summary Theoretical Formation Spectra of pionic atoms

- **$^{122}Sn(d,^{3}He)$ spectra at finite angles**
  - ✓ 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 $[(1s)_{\pi} \otimes {}^{116}Sn(0^{+})]$.
    - No residual interaction effect
  - → More precise information than that of even target case can be expected.

- **Updated Theoretical Calculation**
  - $^{122}Sn(d,^{3}He)$ spectra calculated by Green's Function Method
  - ✓ We get more precise formation spectrum theoretically which is suited to be compared with high resolution future experimental data.

- **New reaction (p,2p) ongoing**

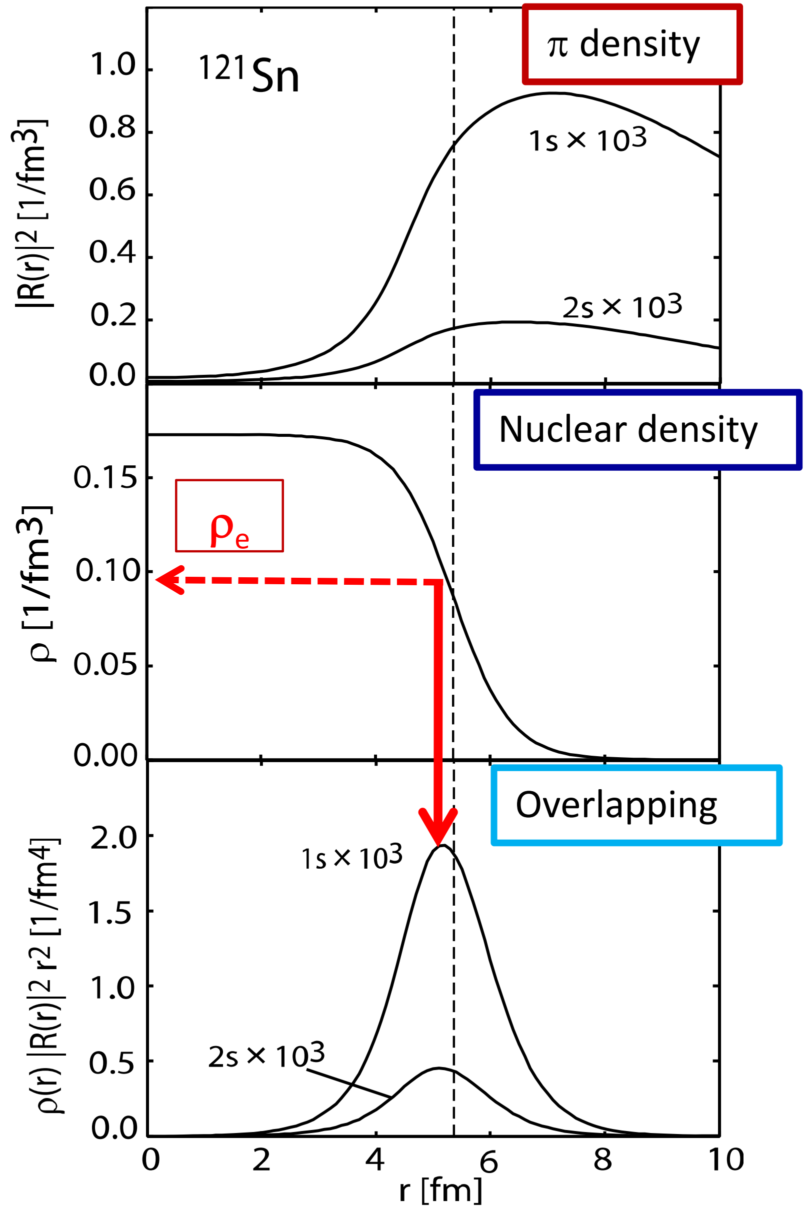
By comparing theory with new experimental data,
we expect to know pion properties at various densities.

Formulation: Effective Nuclear Density ρ_e

Where does pion probe?

Effective nuclear density ρ_e :

Nuclear density at the radial coordinate r_e , where the overlapping density has the maximum value.



Overlapping density:

$$\underbrace{\rho(r)}_{N}\underbrace{|R_{n\ell}(r)|^2}_{\pi}r^2$$

T. Yamazaki, S. Hirenzaki, PLB557(03)20

Formulation: Structure

- Klein Gordon equation

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

- Pion-Nucleus Optical Potential

$$2\mu V_{\text{opt}}(r) = \underbrace{-4\pi[b(r)+\varepsilon_2 B_0\rho^2(r)]}_{\text{s-wave term}} + \underbrace{4\pi\nabla\cdot[c(r)+\varepsilon_2^{-1}C_0\rho^2(r)]L(r)\nabla}_{\text{p-wave term}}$$

$$b(r) = \varepsilon_1\{b_0\rho(r) + b_1[\rho_n(r)-\rho_p(r)]\}$$

$$c(r) = \varepsilon_1^{-1}\{c_0\rho(r) + c_1[\rho_n(r)-\rho_p(r)]\}$$

$$L(r) = \{1+\tfrac{4}{3}\pi\lambda[c(r)+\varepsilon_2^{-1}C_0\rho^2(r)]\}^{-1}$$

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R. Seki, K. Masutani, PRC27(83)2799
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