Formation spectra of deeply bound pionic atoms in the (d,^{3}He) reactions

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YITP workshop on Hadron in Nucleus

Introduction

Deeply bound pionic atom … Useful system to study pion properties at finite density

- Pion-Nucleus optical potential : Strong correlation of parameters

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

- GOR relation + Tomozawa-Weinberg relation

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

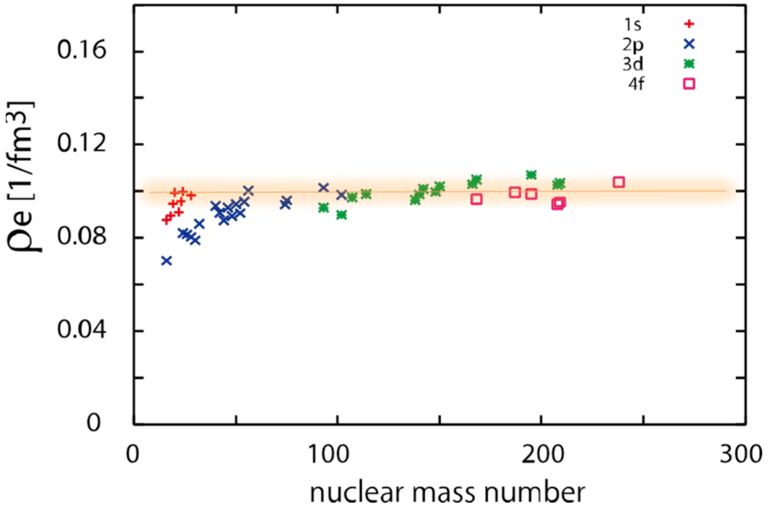
$$\Downarrow$$

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

: Partial Restoration of Chiral Symmetry

K. Suzuki *et al.*, PRL92(04)072302
D. Jido, T. Hatsuda and T. Kunihiro, PLB 670(08)109

- Nuclear density probed by pionic atom : **Only limited at $\rho \simeq 0.6\rho_0$**



N. Ikeno *et al.*, PTP126(11)483

Our Motivation

We want to extract information on pion properties at **various densities**

➡ More Systematic/Accurate information on pionic states from (d,^{3}He) spectra

Our studies

Experimental Data; Systematic/Accurate information

Direct comparison

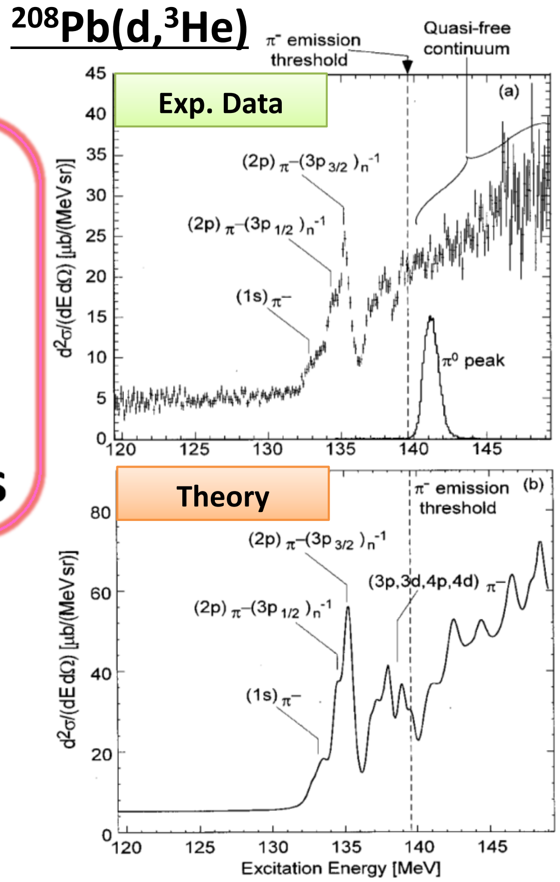
Theoretical Formation Spectrum of pionic atoms

➡ **We know pion properties at various densities**

In this talk

- ^{122}Sn(d,^{3}He) spectra at finite angles
  - Experimental data @RIBF/RIKEN, T. Nishi-san’s talk
- ^{117}Sn(d,^{3}He) spectra
  - Odd-neutron nuclear target $J^{p}=1/2^{+}$
  - Next Experiment @RIBF/RIKEN, K. Itahashi *et al.* RIBF-027
- Updated theoretical calculation
  - Green’s Function Method

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

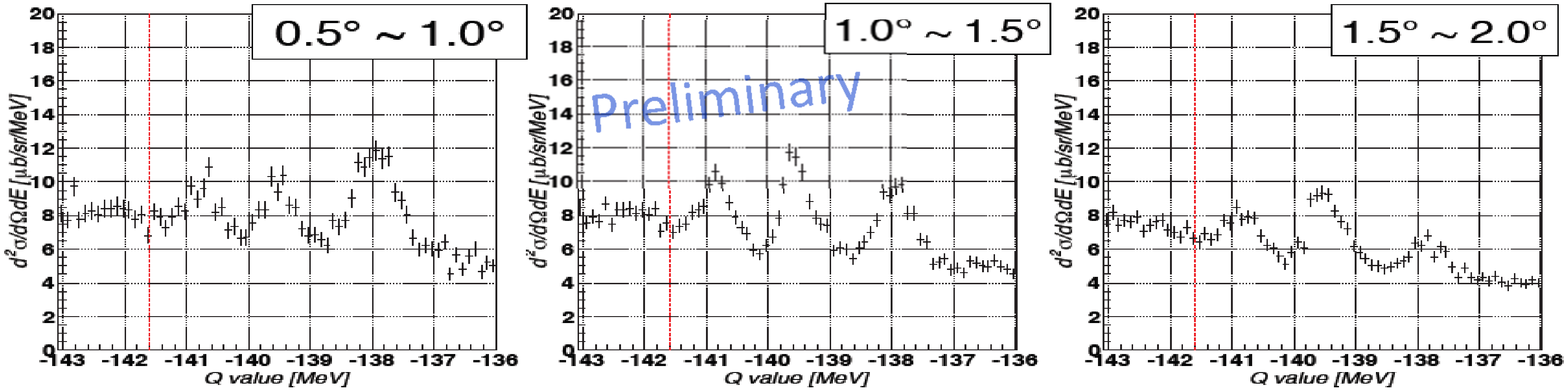


K. Itahashi *et al.*, PRC62(00)025202

^{122}Sn(d,^{3}He) spectra at finite angles

N. Ikeno, H. Nagahiro and S. Hirenzaki, EPJA47 (2011) 161

Experimental Data : JPS 2013 Autumn Meeting, T. Nishi-san's slide



Formulation: Effective Number Approach

- Formation cross section (Bound state + Unbound state)

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

$\Delta E = Q + m_\pi - B_\pi + Sn - 6.787\mathrm{MeV}$

- Elementary cross section $\left(\frac{d\sigma}{d\Omega_{\mathrm{He}}}\right)_{\mathrm{ele}}^{\mathrm{lab}}$: Experimental data (d+n→^{3}He +π^-)
M. Betigeri *et al.*, NPA690(01)473

- Kinematical correction factor:

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

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

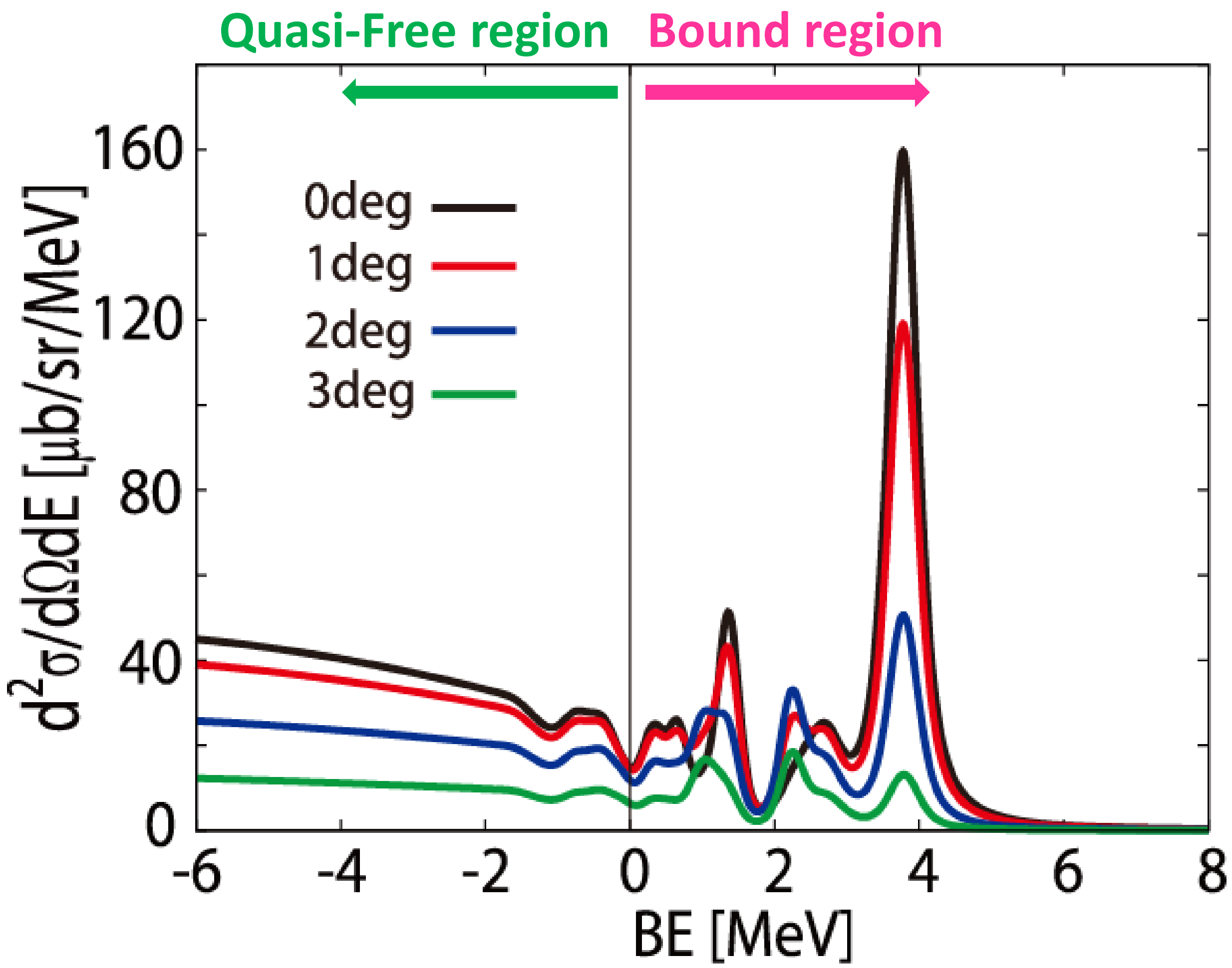
N. Ikeno, H. Nagahiro and S. Hirenzaki, EPJA47 (2011) 161

- Effective Number:

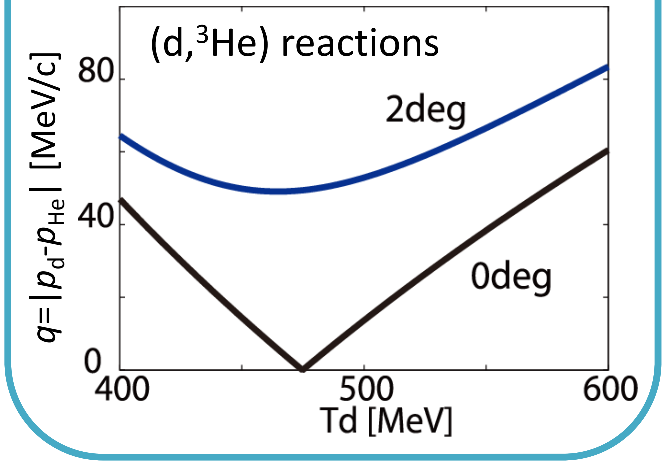
$$N_{\mathrm{eff}} = \sum_{JMm}\left|\int d\vec{r}e^{i\vec{q}\cdot\vec{r}}D(\vec{r})\xi^\dagger_{\frac{1}{2}m}[\phi^*_{\ell_\pi}(\vec{r})\otimes\psi_{j_n}(\vec{r})]_{JM}\right|^2$$

Numerical results

- ^{122}Sn(d,^{3}He) spectra at Finite angles



Momentum transfer



Energy resolution
ΔE=300keV

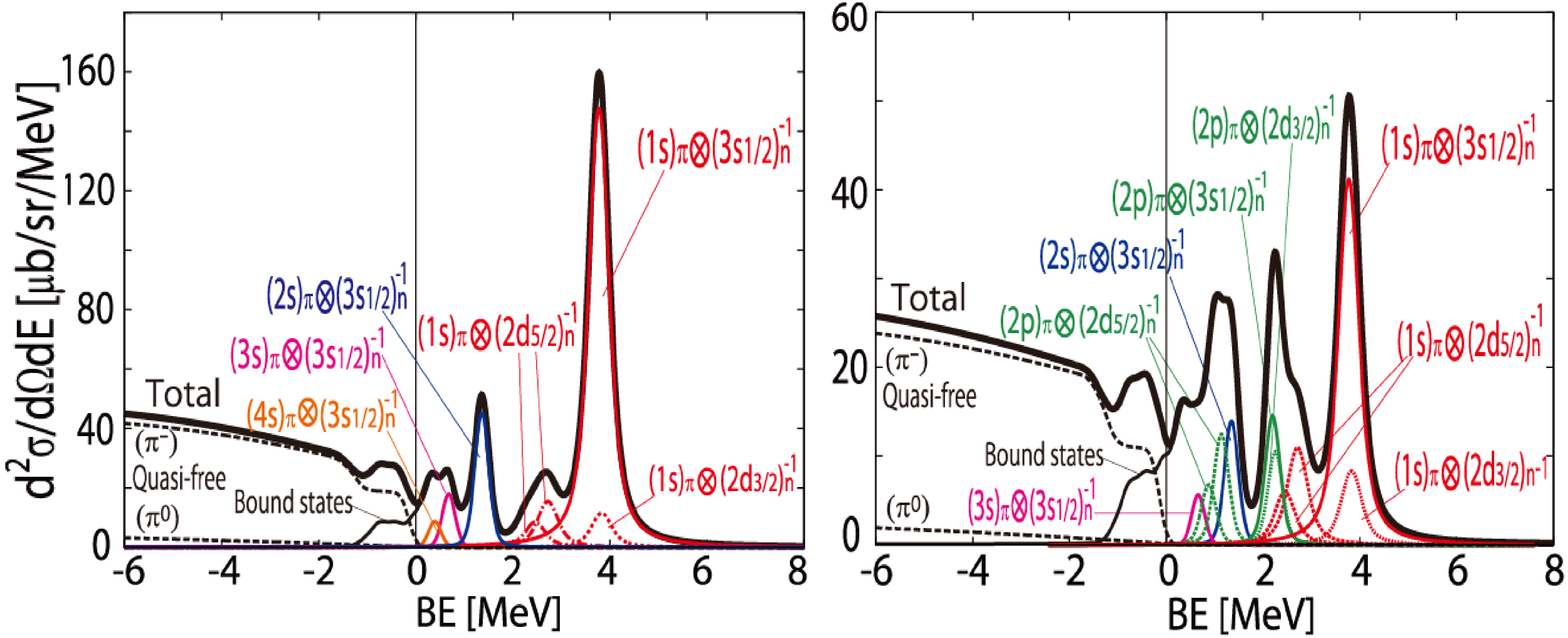
Neutron wave function:
H. Koura *et al*., NPA671(2000)96

Spectra have a strong angular dependence.

Numerical results

- Dominant Subcomponent $[(n\ell)_\pi \otimes (n\ell_j)_n^{-1}]$

Energy resolution
ΔE=300keV



0 degrees

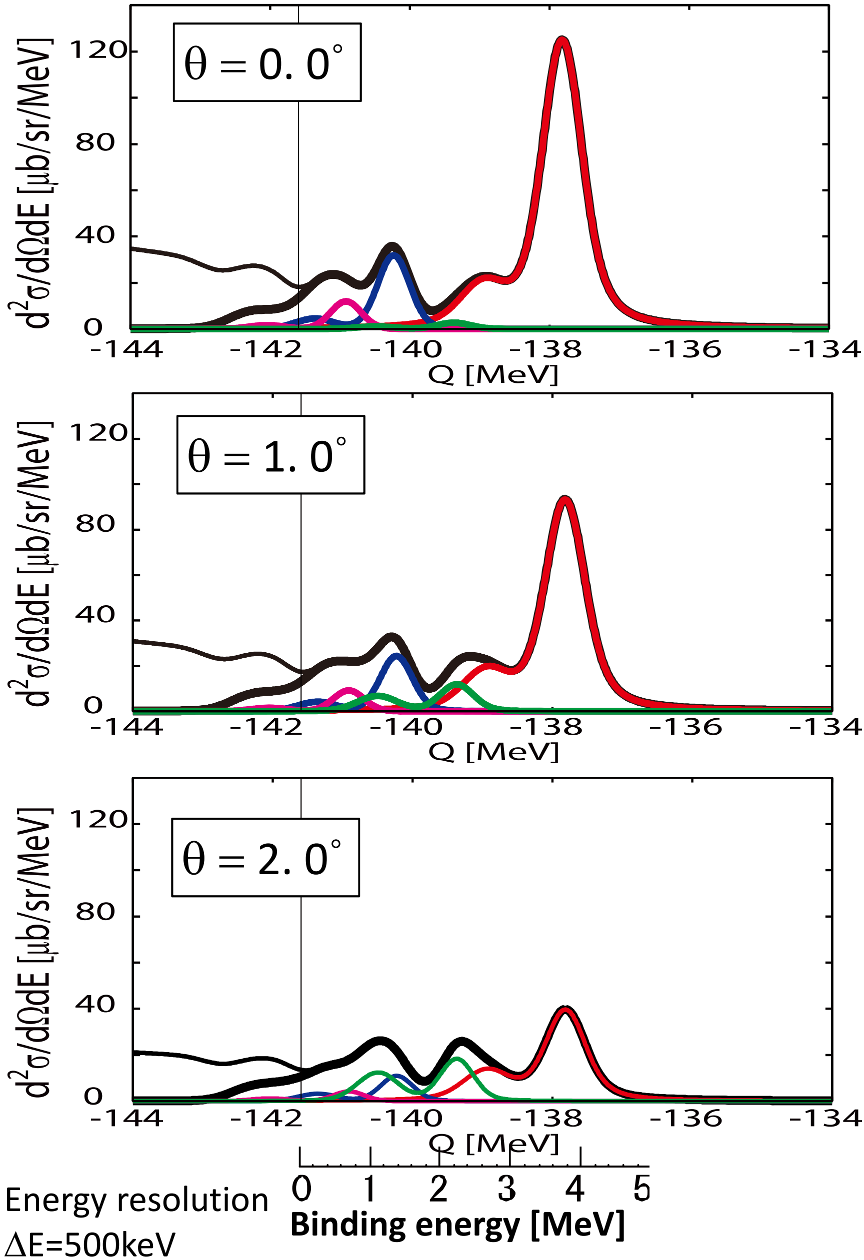
2 degrees

We can obtain information on deeply bound pionic **2*p*** state in addition to **1*s*** and **2*s*** states.

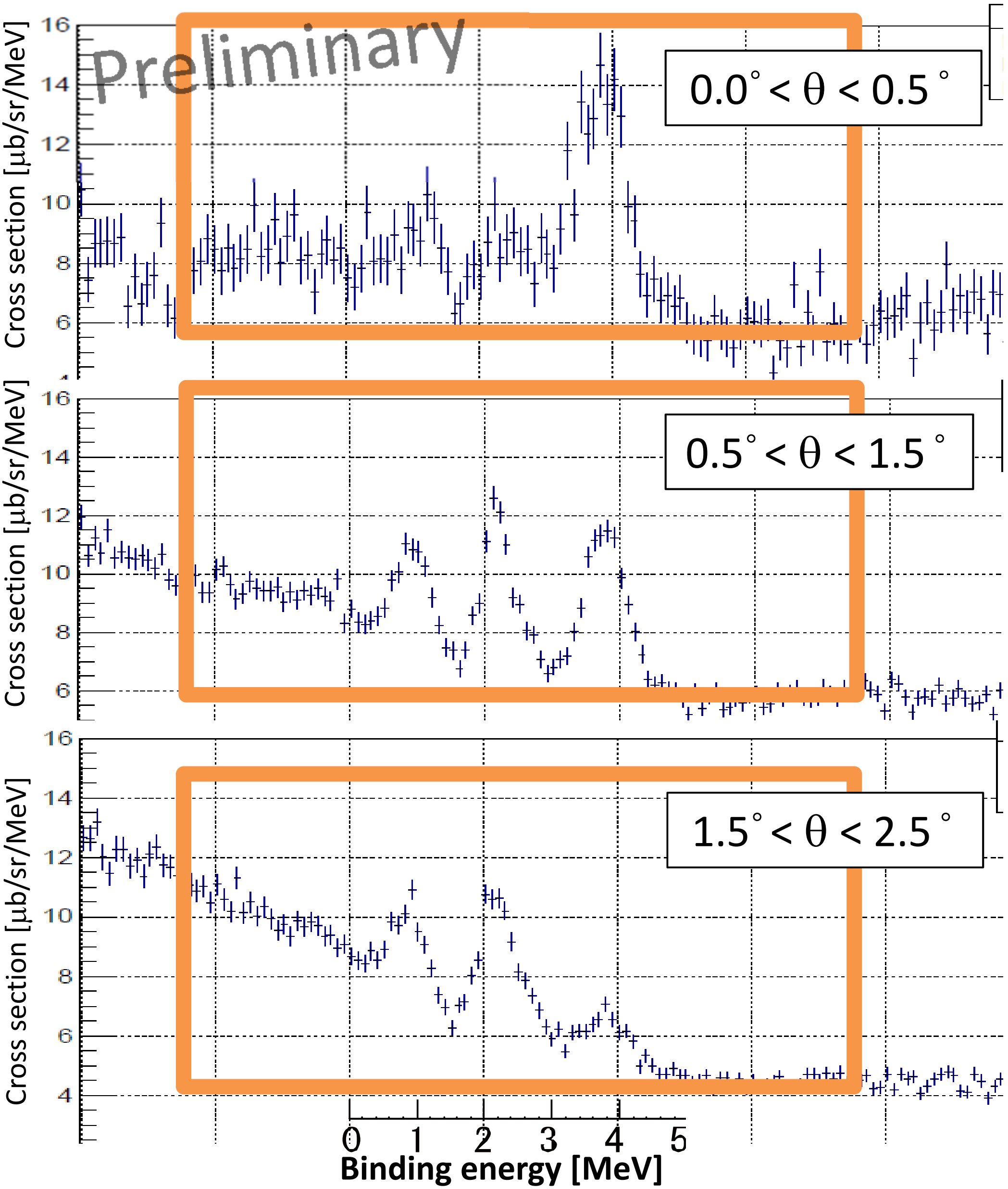
This will be important to reduce uncertainties in neutron distribution.

Theory vs. Experiment

T. Nishi, private communication



Energy resolution
ΔE=500keV



^{117}Sn(d,^{3}He) spectra:
Odd-neutron nuclear target

N. Ikeno , J. Yamagata-Sekihara, H. Nagahiro and S. Hirenzaki, PTEP(2013) 063D01

Interests of Odd target

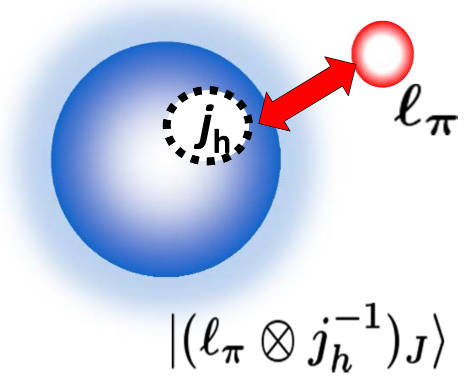
Odd-neutron nuclear target: J^p=1/2$^+$

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

- Pionic atom spectroscopy on the wider region in nuclear chart
- Pionic state free from residual interaction effect $[\pi^- \otimes 0^+]$

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

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



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

``Residual interaction effect''

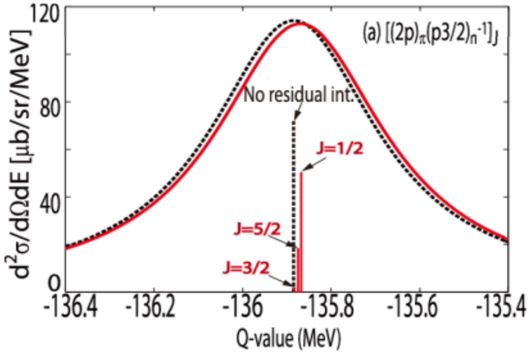
- Level splitting between different J state
- Energy shift

Additional difficulty to determine B.E. and parameters in V$_{\text{opt}}$

^{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



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

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

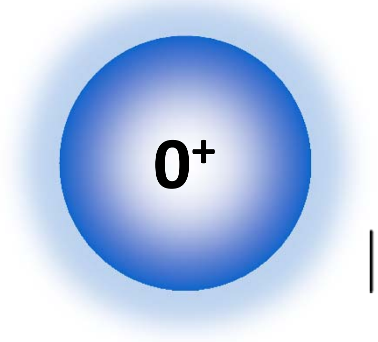
Observation of pionic states free from these effects is very important to obtain more accurate information from data.

Formulation: Even vs. Odd target

- Effective Number

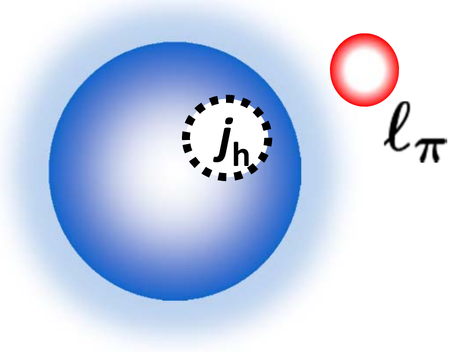
Even target: ^{122}Sn (0^+)

Initial:



$|0^+\rangle$

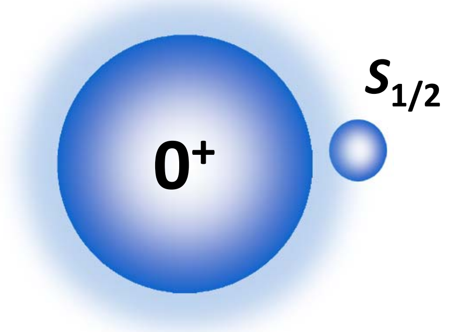
Final:



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

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

Initial:



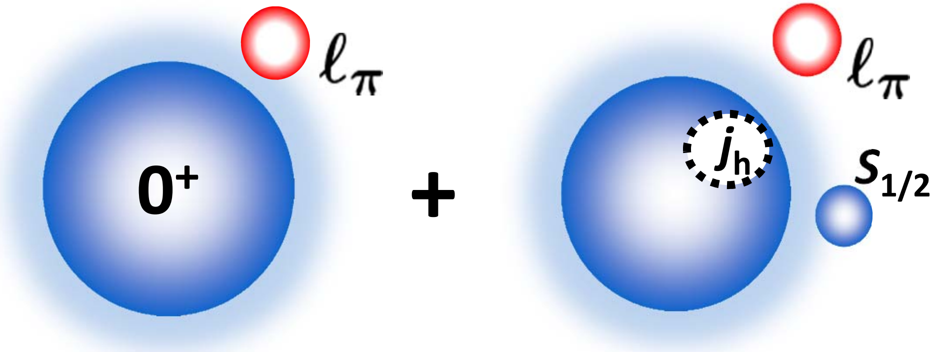
Assumption

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

Final:

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

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



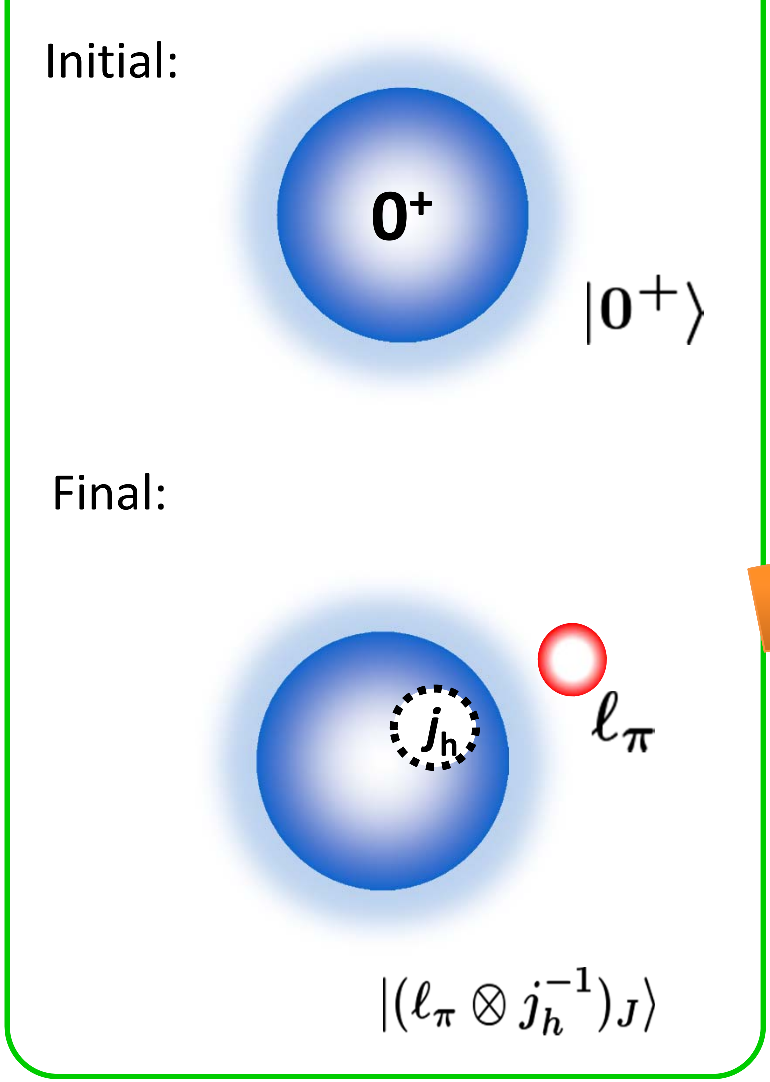
$|(\ell_\pi \otimes 0^+)\rangle$

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

Formulation: Even vs. Odd target

- Effective Number

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



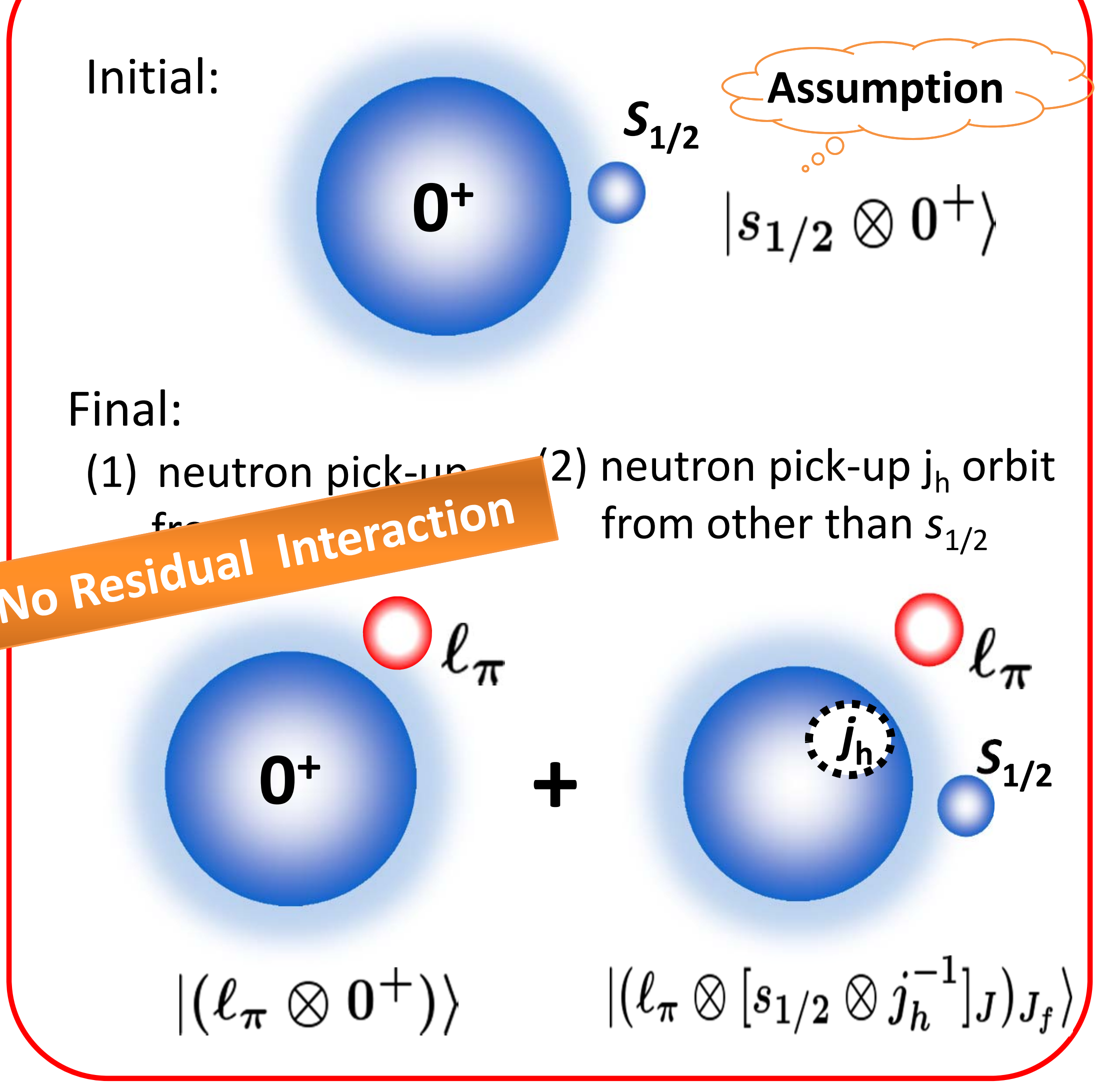
Initial:

$|0^+\rangle$

Final:

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

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



Initial:

Assumption

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

Final:

(1) neutron pick-up
fr

(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

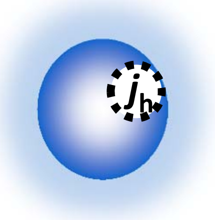
Even target: ^{122}Sn (0^+)

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

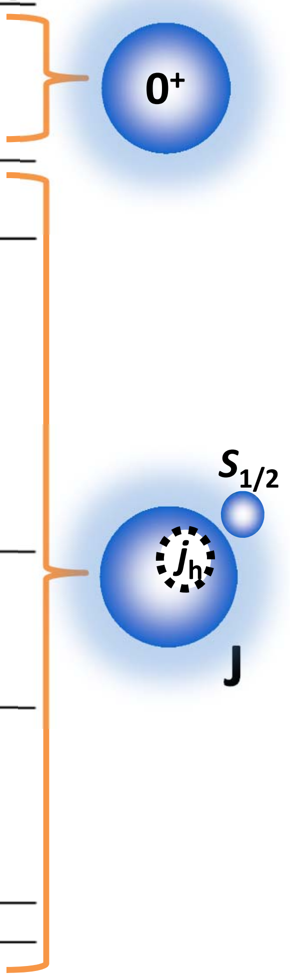
Odd target: ^{117}Sn ($1/2^+$)

Excited level of ^{116}Sn

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

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

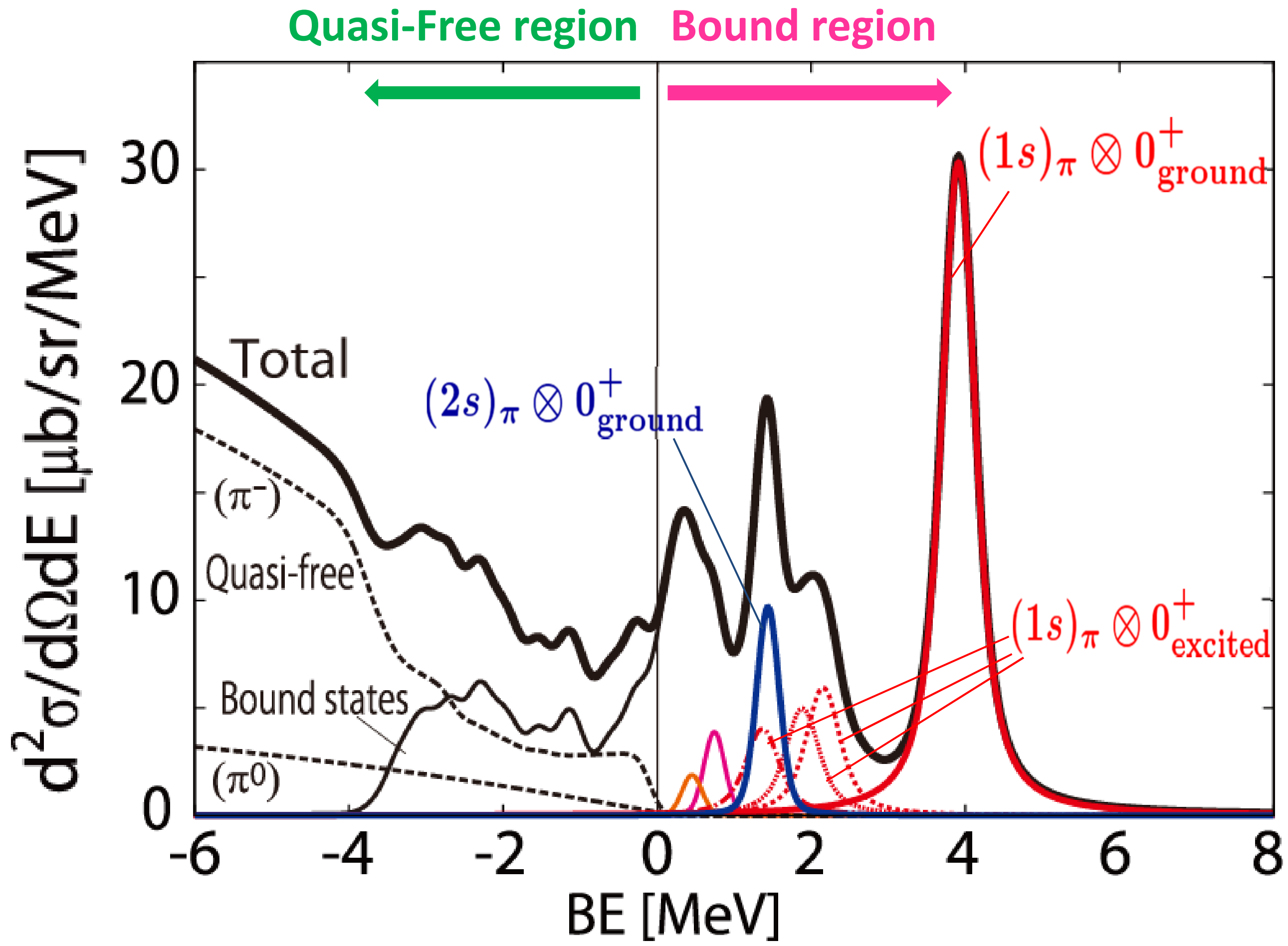
J^p	Neutron hole orbit j_h	Ex [MeV]
0+	3s1/2	0.00
		1.76
		2.03
		2.55
1+	2d3/2	2.59
		2.96
2+	2d3/2 and 2d5/2	1.29
		2.23
		3.23
		3.37
		3.47
		3.59
		3.77
		3.95
3+	2d5/2 and 1g7/2	3.00
		3.42
		3.71
	1g7/2	3.18
4+	1g7/2	2.39
		2.53
		2.80
		3.05
		3.10
5-	1h11/2	2.37
6-	1h11/2	2.77



Numerical Results: Odd target

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

Neutron wave function:
H. Koura *et al*., NPA671(2000)96



Energy resolution
ΔE=300keV

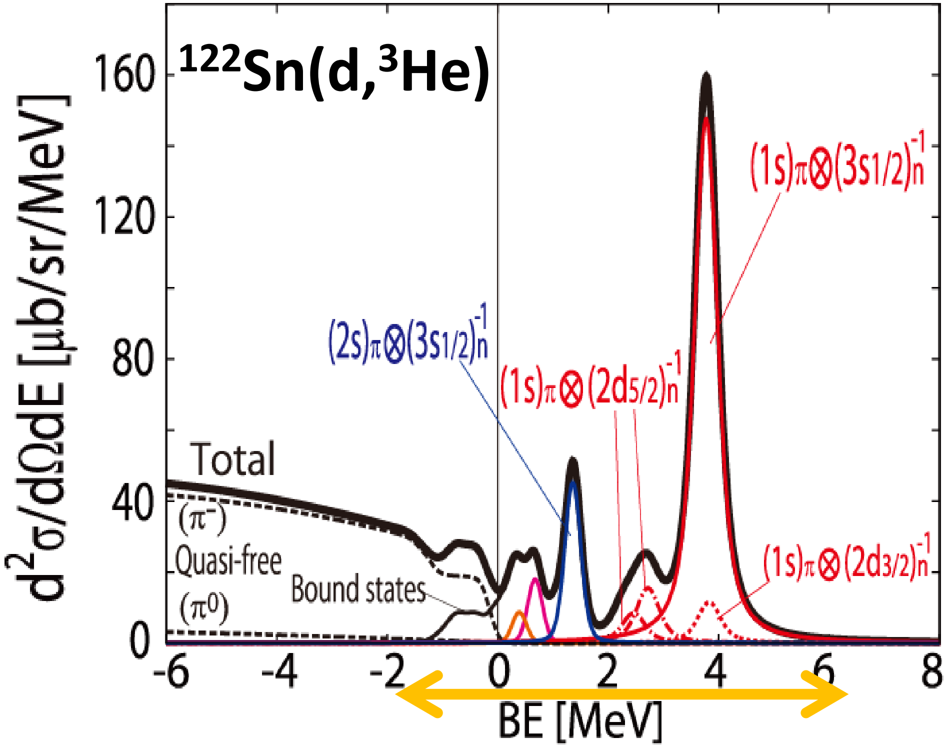
Dominant
Subcomponent:
$$[(n\ell)_\pi \otimes J^P]$$

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

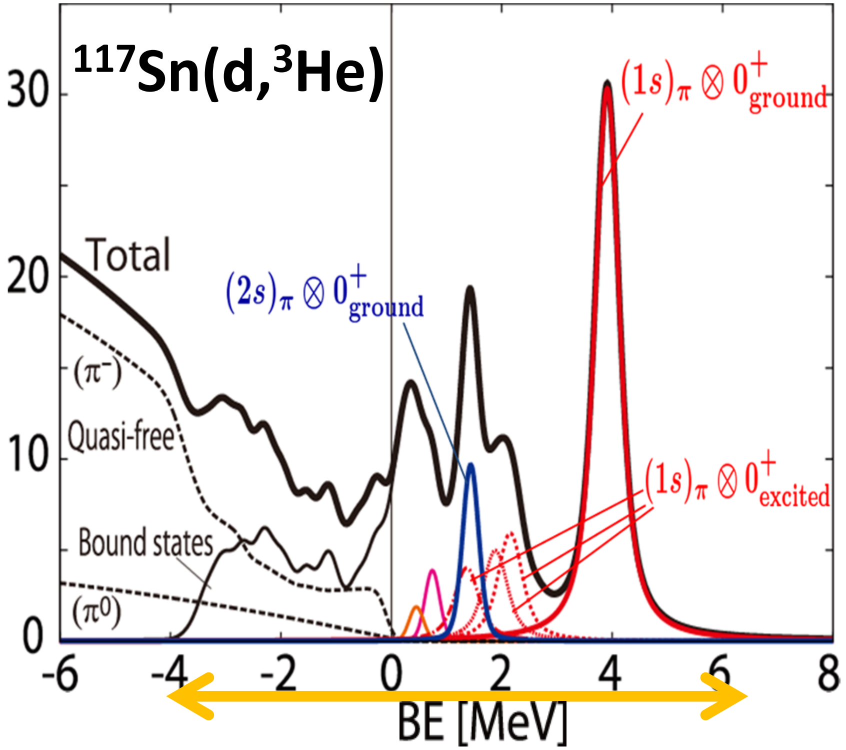
Numerical Results: Even vs. Odd target

0 degrees

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



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

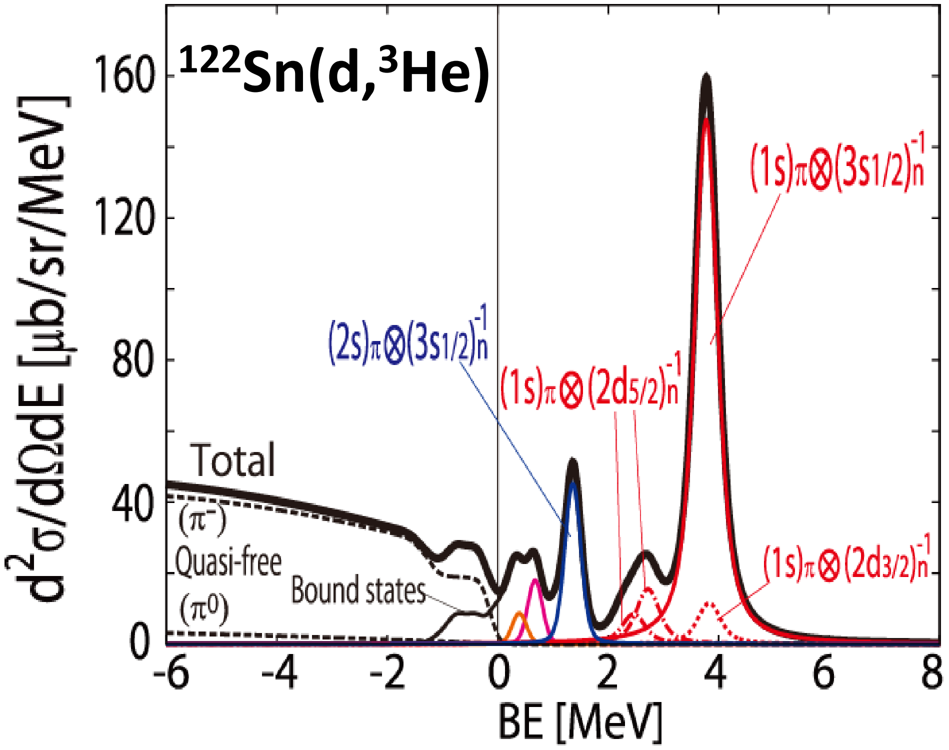


- Pionic 1s state formation with neutron s-hole state is large in both spectra.
- Bound pionic state formation spectra in ^{117}Sn(d,^{3}He) are spread over wider energy range.
- Absolute value of cross section in ^{117}Sn(d,^{3}He) is smaller.

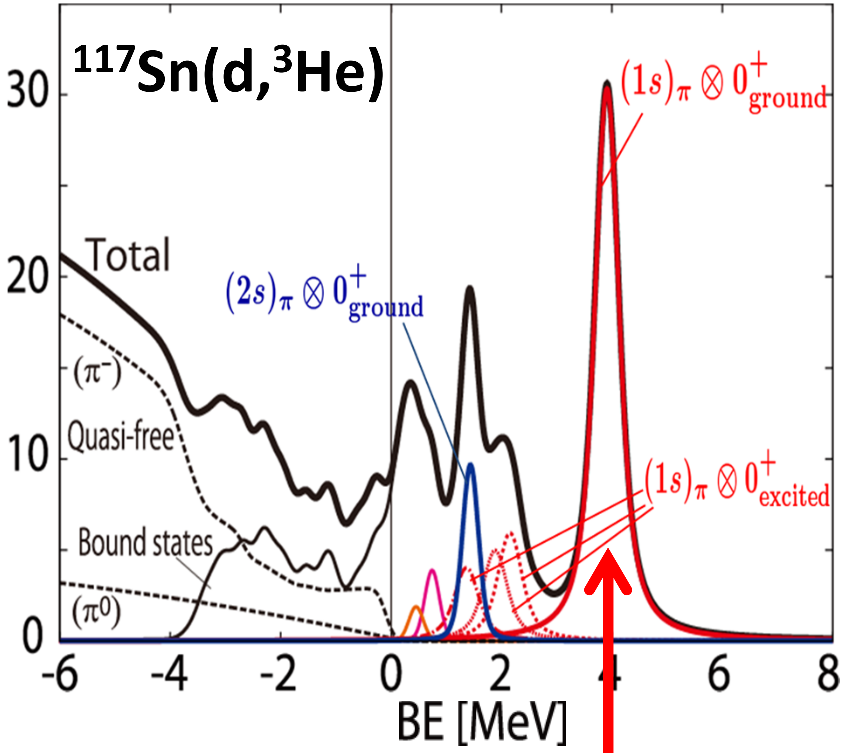
Numerical Results: Even vs. Odd target

0 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 BE and parameters in V_{opt}

Updated theoretical calculation:

Spectra calculated by Green’s Function Method

N. Ikeno , J. Yamagata-Sekihara, H. Nagahiro, S. Hirenzaki, in preparation

Future Experiments @RIBF/RIKEN

✓ Better Energy Resolution
✓ More Precise Shapes of Spectrum

- Various nuclear targets, - Finite angles reactions, …

We need to update the theoretical spectra.

Formulation: Green's Function Method

➢Formation cross section

O. Morimatsu, K. Yazaki, NPA435(85)727, NPA483(88)493

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

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

- 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

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

$$\chi_f^*(\vec{r})\chi_i(\vec{r}) = \exp\left(i\vec{q}\cdot\vec{r}\frac{m_C}{m_C+m_\pi}\right)F(\vec{r})$$

Advantages:

✓ We can include Bound and Quasi-free contributions simultaneously.

✓ We can include an infinite number of Bound State contributions.

✓ We do not assume Lorentz distribution as the shape of peak structure.

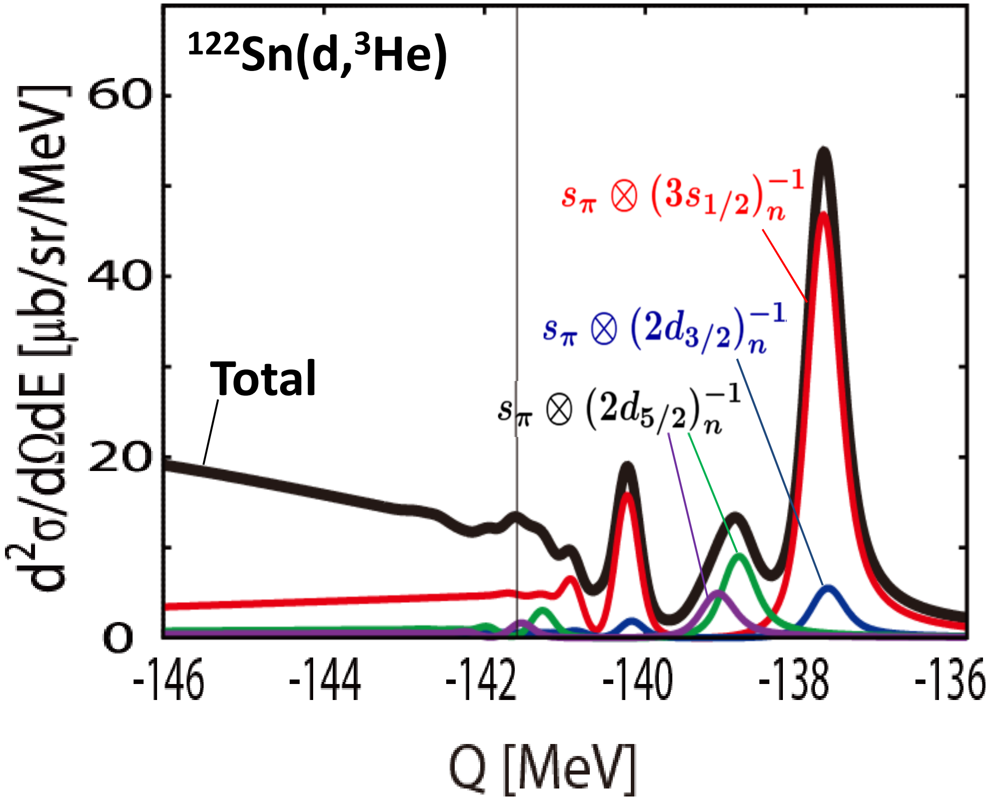
Numerical results: Green vs. Neff

Energy resolution
ΔE=300keV

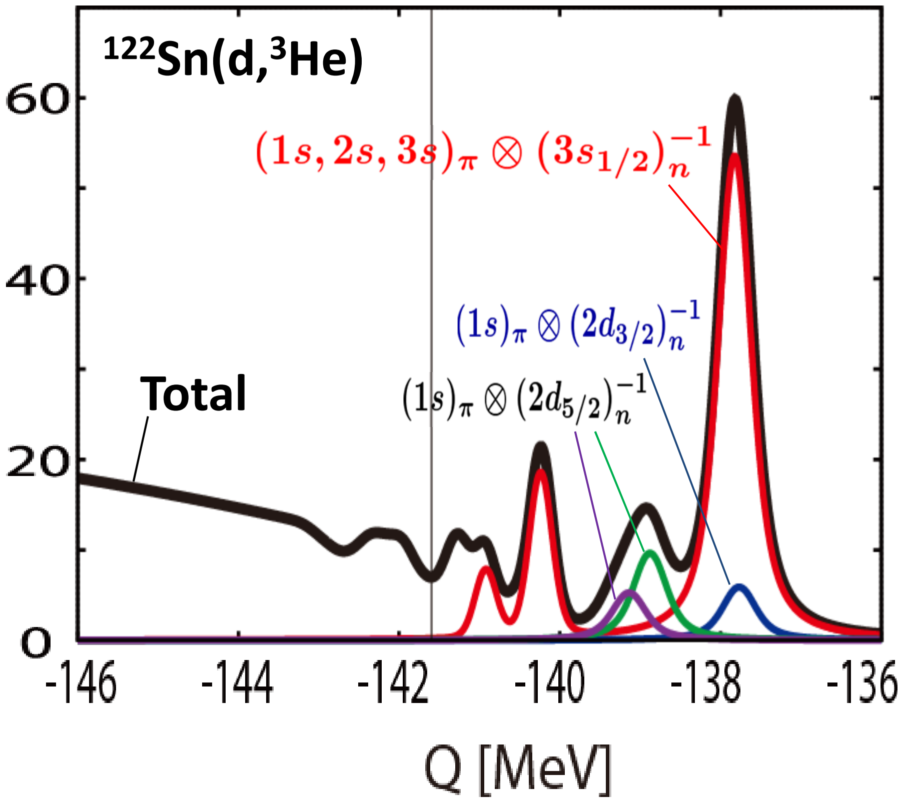
- ^{122}Sn(d,^{3}He) spectra at 0 degrees

Neutron wave function:
Harmonic Oscillator

Green



Neff



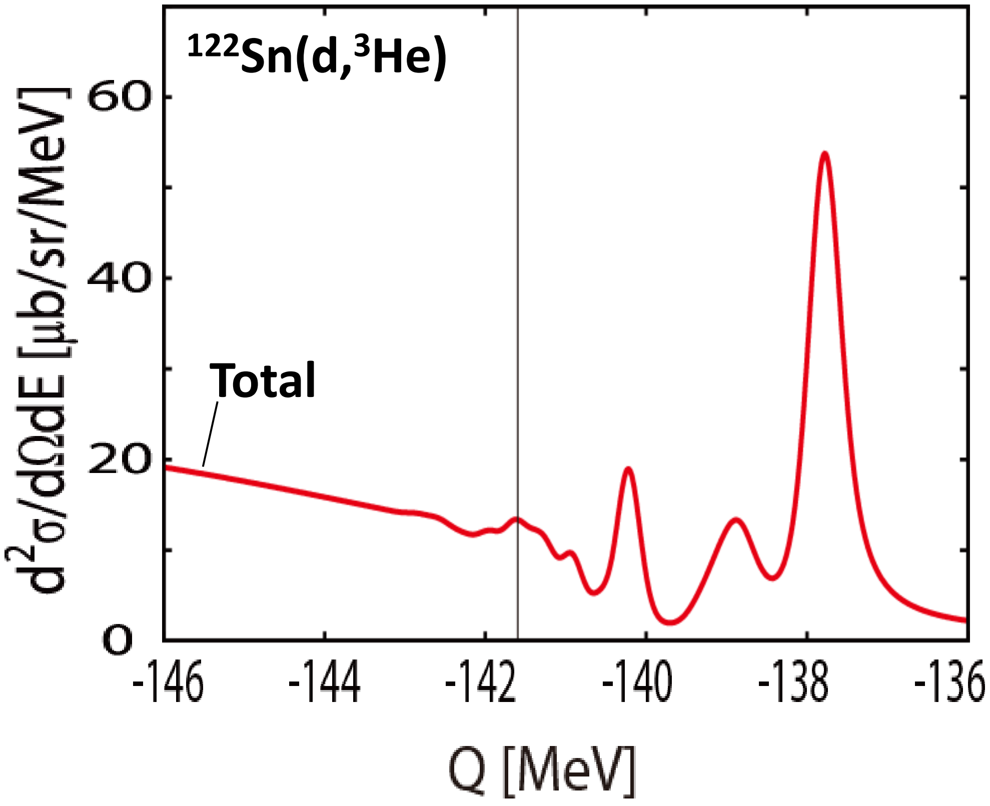
Both Methods seem to provide the very similar spectra.

Numerical results: Green vs. Neff

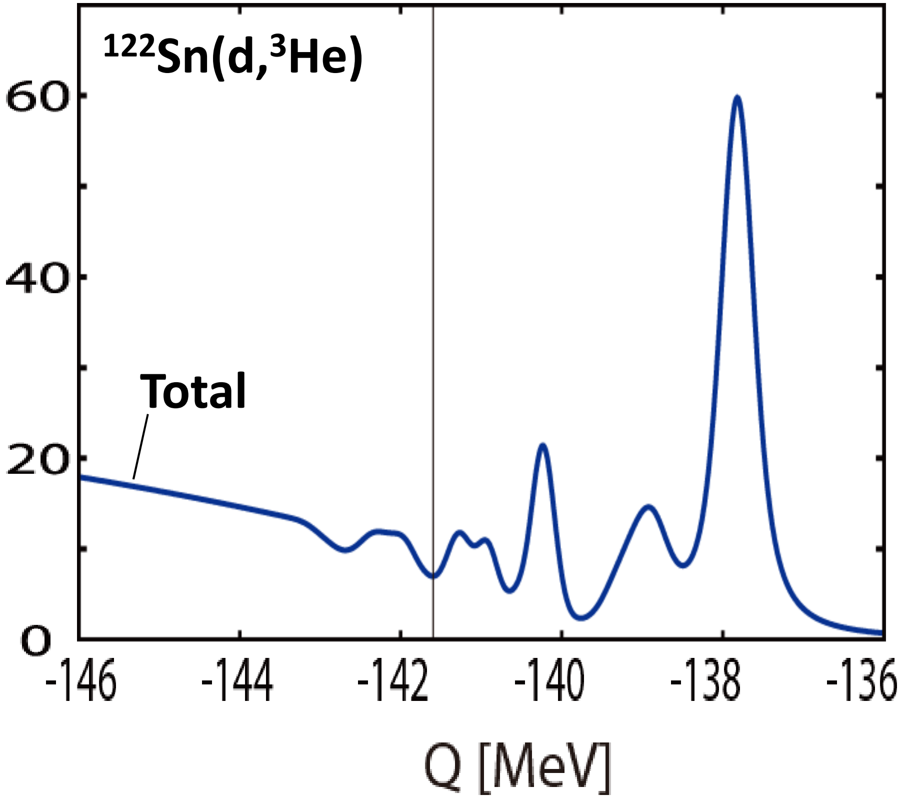
- ➢ ^{122}Sn(d,^{3}He) spectra at 0 degrees

Energy resolution
ΔE=300keV

Green



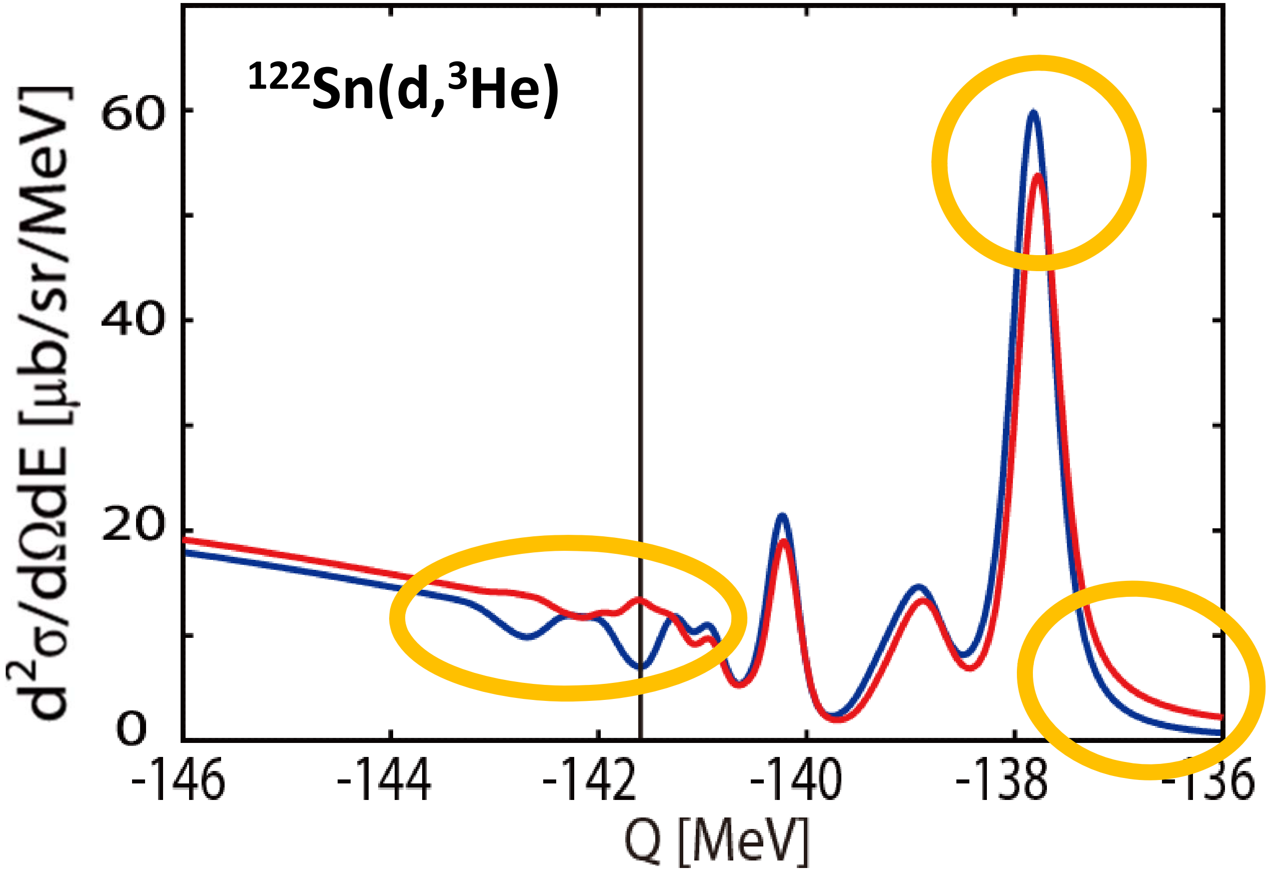
Neff



Numerical results: Green vs. Neff

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

Energy resolution
ΔE=300keV



Differences between both spectra

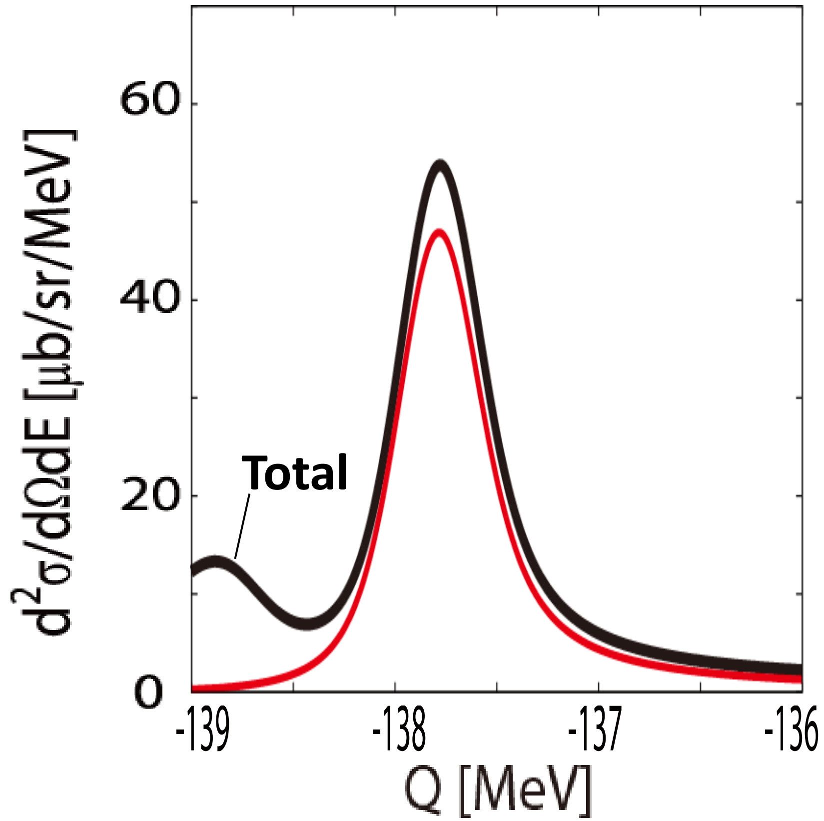
(1)Near threshold, (2)Height and position of peak, (3)Tail of peak structure

Numerical results: Green vs. Neff

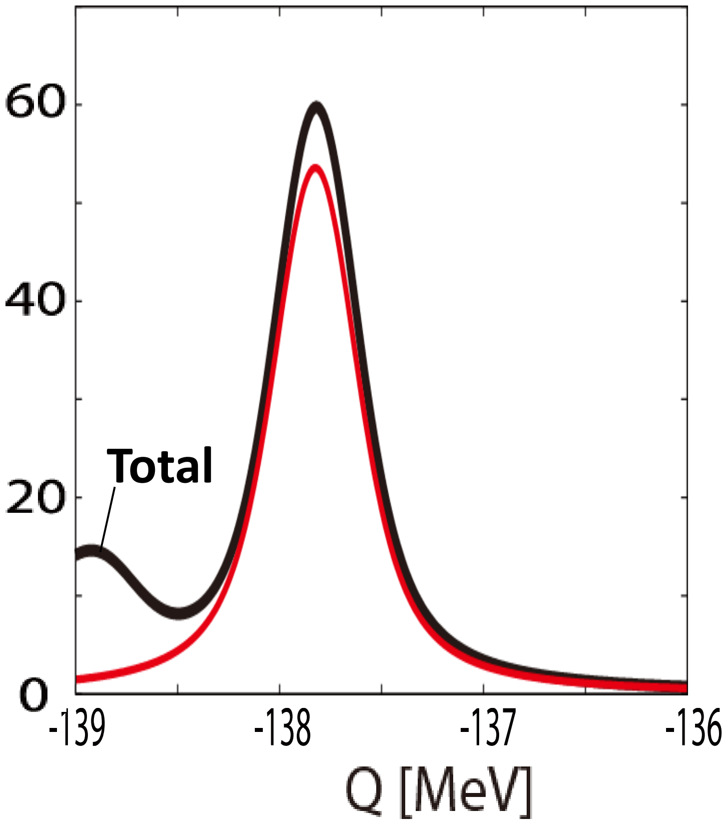
Energy resolution
ΔE=300keV

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

Summary Theoretical Formation Spectra of pionic atoms

- **^{122}Sn(d,^{3}He) spectra at finite angles**
  - ✓ Spectra have strong angular dependence.
  - ✓ Different subcomponents dominate at different angles.
    $(1s)_\pi$, **$(2s)_\pi$**: 0 degrees, **$(2p)_\pi$**: 2degrees
  - → Simultaneous observation of various states in one nuclide (Good!)
  - ✓ Comparison with theory and experiment at finite angles
    - **Qualitative** behavior --- reasonable agreements
    - **Quantitative** behavior --- some problems

- **^{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.
  - ✓ Absolute value of cross section are significantly smaller.

- **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.