Formation of Deeply Bound Pionic Atoms and Pion Properties in Nuclei

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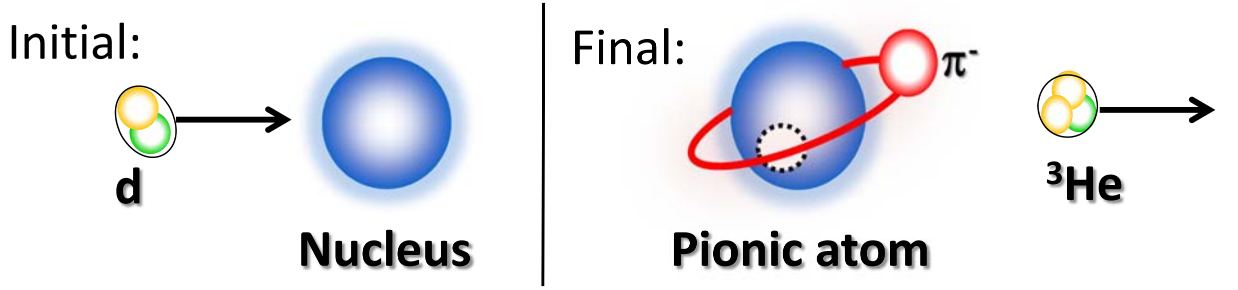
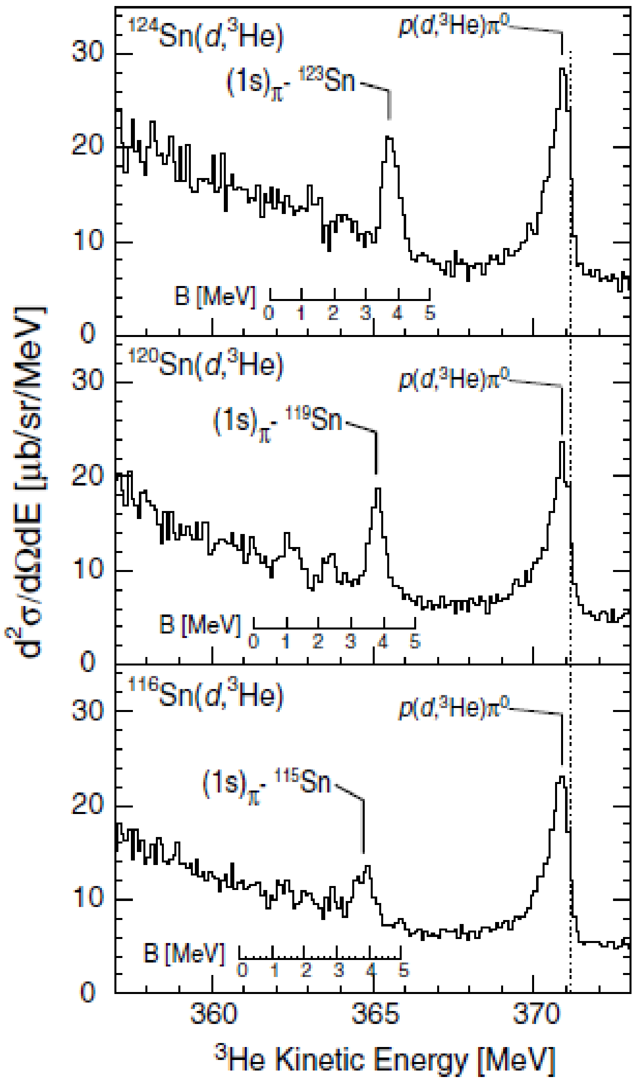
Introduction: Deeply bound pionic atom

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



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



- Pion-Nucleus optical potential

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

- GOR relation + Tomozawa-Weinberg relation

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

$$\Downarrow$$

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

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

What's next?

Interests

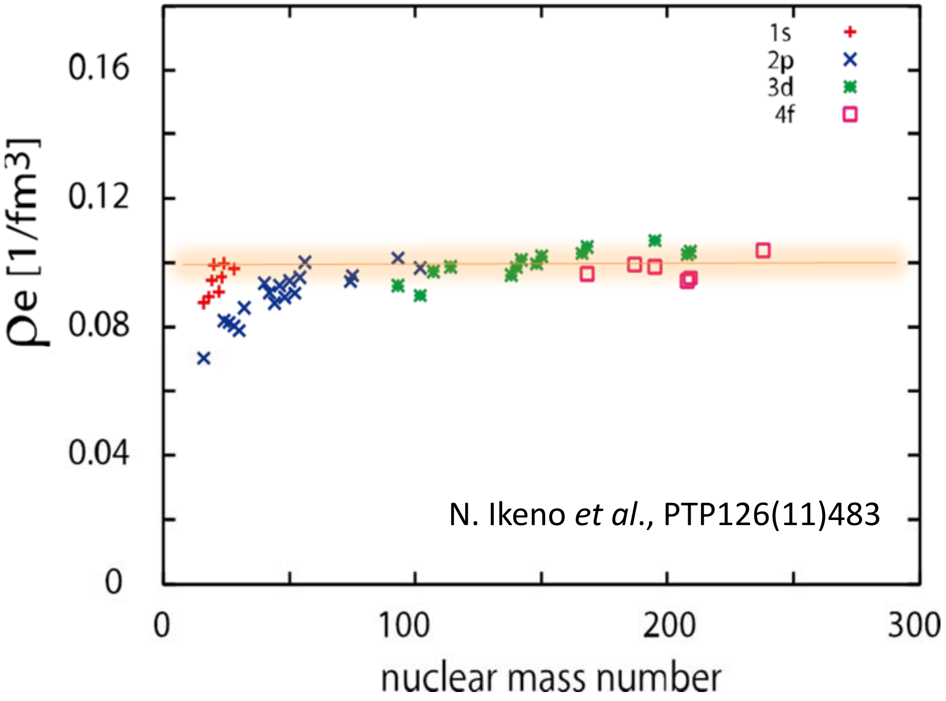
$\bar{q}q$ condensate: More accurate determination
Beyond the linear density approximation (Goda, Jido)
In asymmetric (n or p rich) nuclear matter

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

Difficulties for precise studies

Nuclear density probed by pionic atom

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



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

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

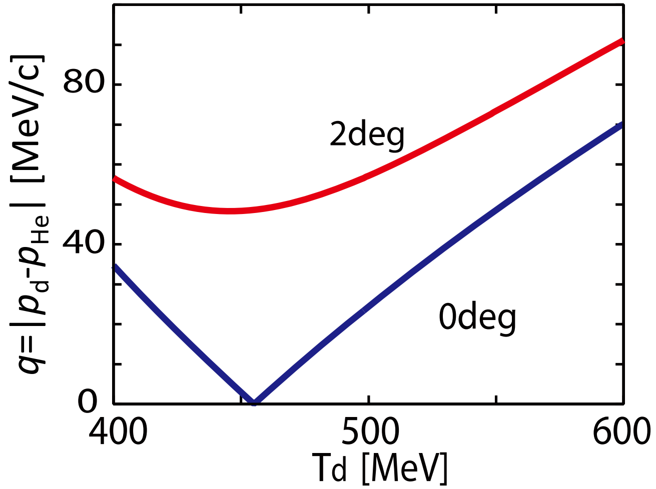
- $\dfrac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} \simeq \dfrac{f_\pi^{*2}}{{f_\pi}^2} \simeq \dfrac{b_1^{\mathrm{free}}}{b_1^*(\rho)} = 0.78 \pm 0.05 \ @\ \rho \simeq 0.6\rho_0$

Our theoretical studies

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

- (d,^{3}He) reaction at finite angles

- Several atomic states in the same nuclei
(=> possible reduction of systematic errors)



- Even + Odd neutron nuclear target

- Systematic 'precise' observation for various nucleus ***including unstable nuclei***

Target Nuclei in the Experiments @GSI

Pb:	**^{205}Pb** **$5/2^-$**	**^{206}Pb** **0^+**	**^{207}Pb** **$1/2^-$**	**^{208}Pb** **0^+**

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

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^+**

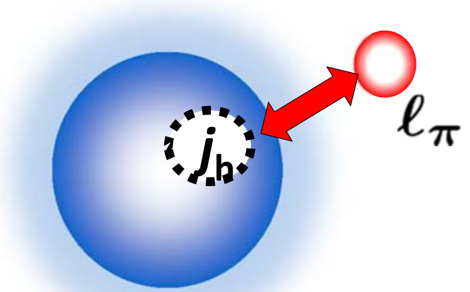
Interests of Odd target $J^p=1/2^+$

``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)



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

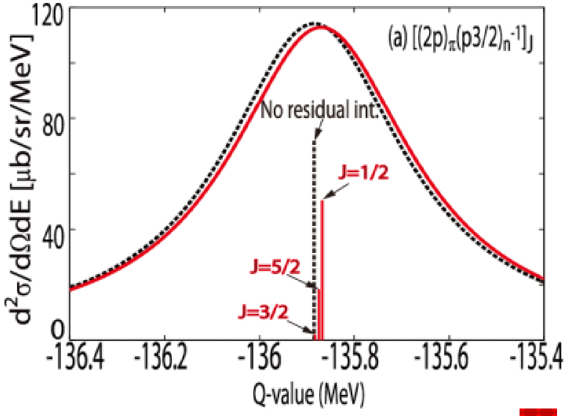
``Residual interaction effect''

- Level splitting between different J state
- Energy shift

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

^{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			



[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)

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

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

- 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)$\otimes\pi^-$

- Effective Number:

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

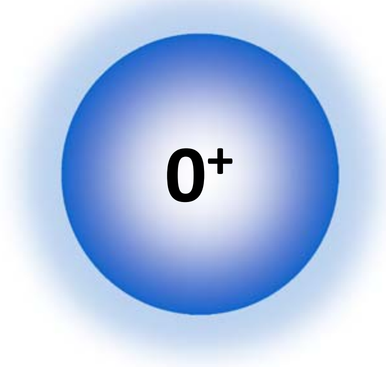
Different formulation for **Even-** and **Odd-** neutron nuclear targets

Formulation: Effective Number

Acknowledgement
H. Nakada-san

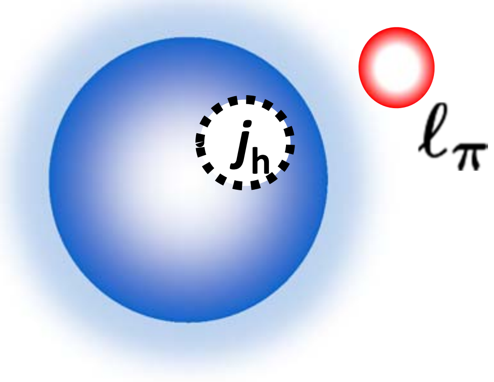
Even target: ^{122}Sn (0^+)

Initial:



$|0^+\rangle$

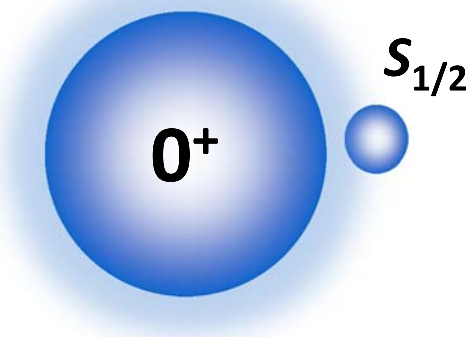
Final:



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

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

Initial:



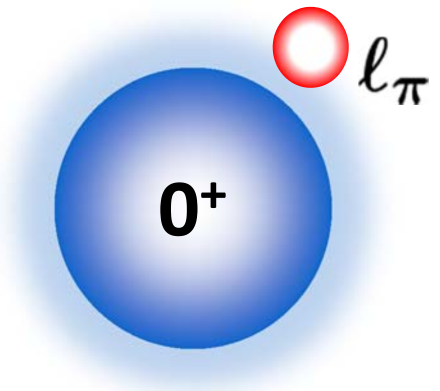
Reasonable Assumption

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

Final:

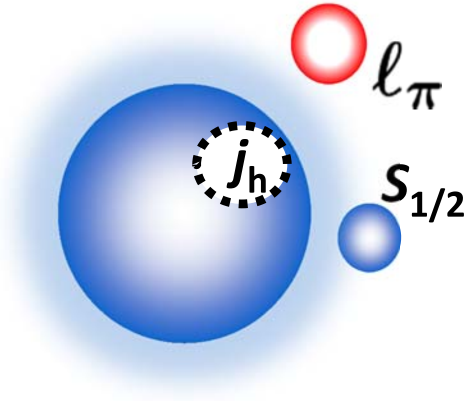
(1) neutron pick-up from $s_{1/2}$ orbit

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



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

+



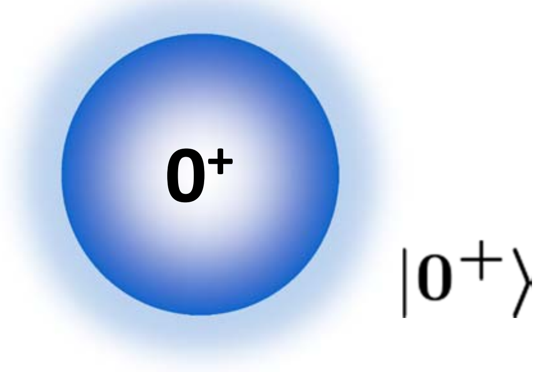
$|(\ell_\pi \otimes [s_{1/2} \otimes j_h^{-1}]_J)_{J_f}\rangle$

Formulation: Effective Number

Acknowledgement
H. Nakada-san

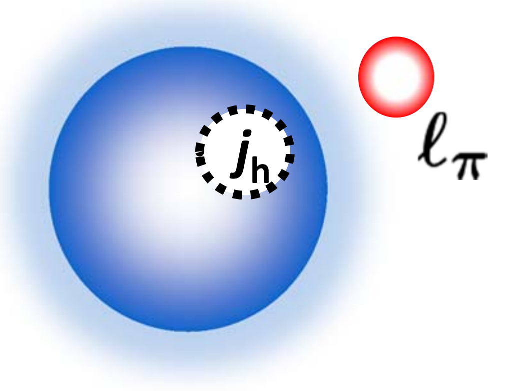
Even target: ^{122}Sn (0^+)

Initial:



$|0^+\rangle$

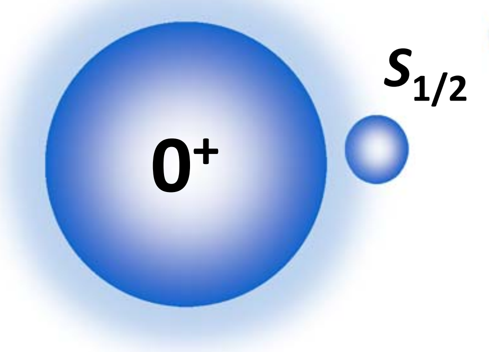
Final:



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

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

Initial:



Reasonable Assumption

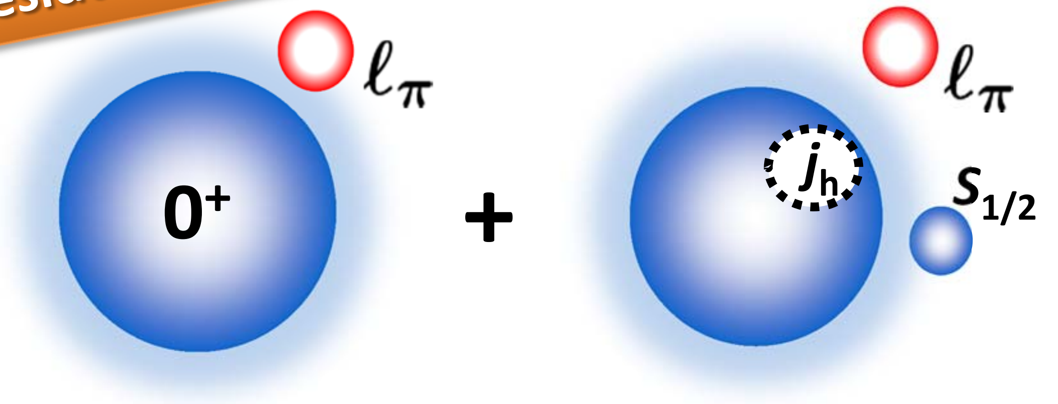
$|s_{1/2} \otimes 0^+\rangle$

Final:

(1) neutron pick-up

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

No Residual Interaction



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

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

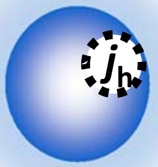
Even target: ^{122}Sn (0^+)

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

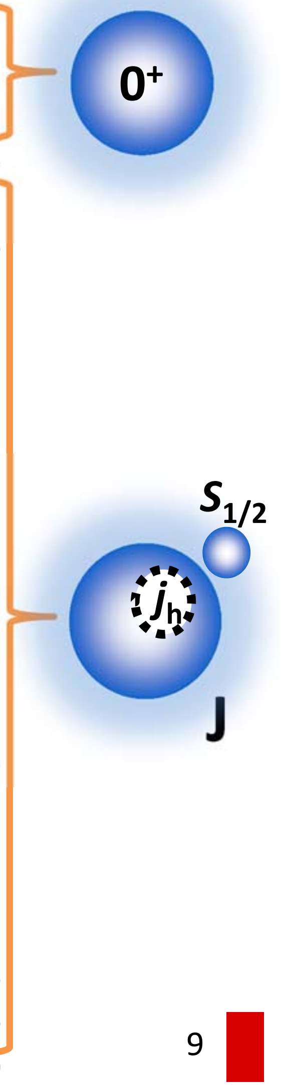
Odd target: ^{117}Sn ($1/2^+$)

Excited level of ^{116}Sn

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

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

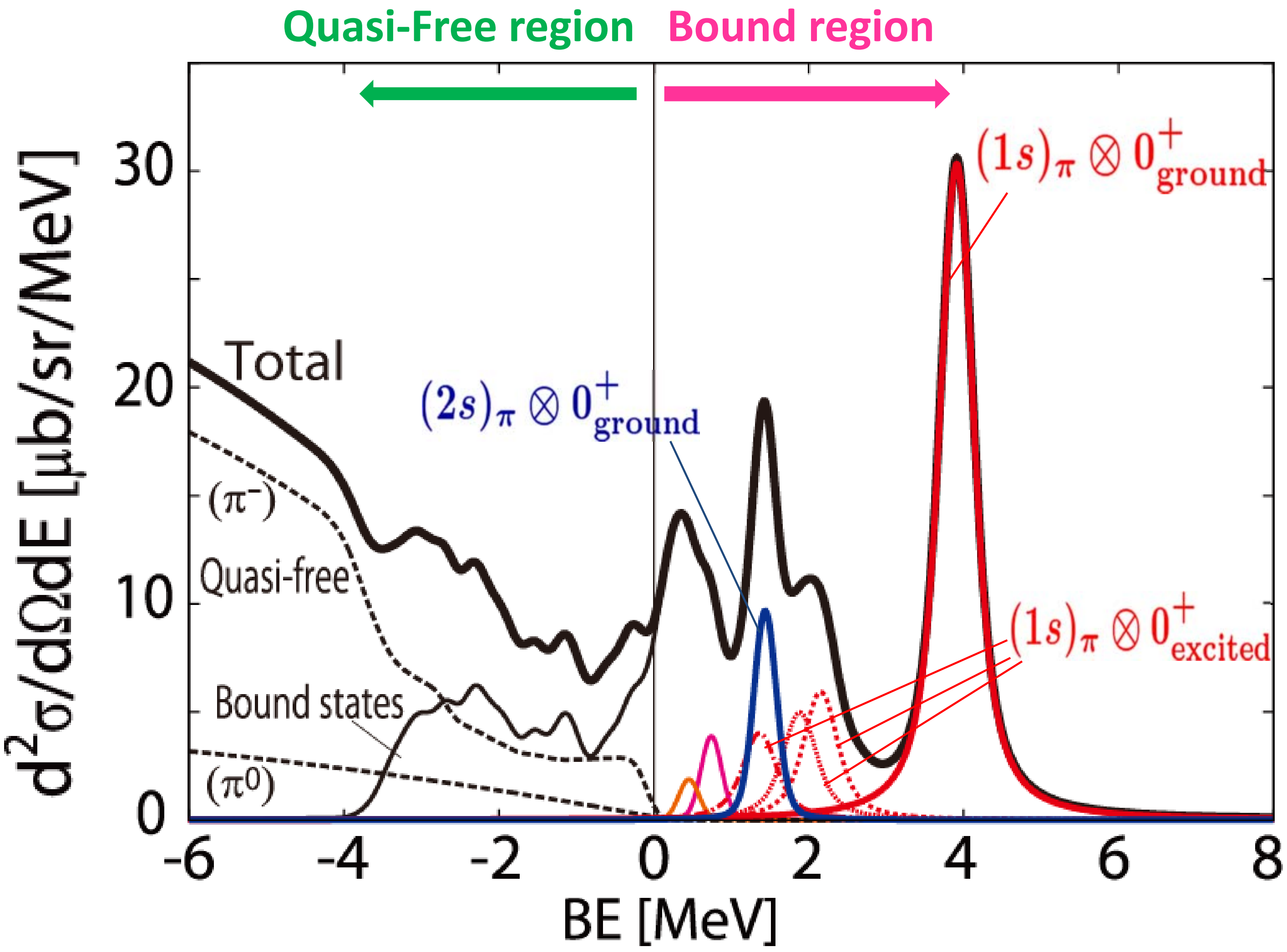
J^p	Neutron hole orbit j_h	Ex [MeV]
0+	3s1/2	0.00
		1.76
		2.03
		2.55
1+	2d3/2	2.59
		2.96
2+	2d3/2 and 2d5/2	1.29
		2.23
		3.23
		3.37
		3.47
		3.59
		3.77
		3.95
3+	2d5/2 and 1g7/2	3.00
		3.42
		3.71
	1g7/2	3.18
4+	1g7/2	2.39
		2.53
		2.80
		3.05
		3.10
5-	1h11/2	2.37
6-	1h11/2	2.77



Numerical Results: Odd target

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

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



Energy resolution
ΔE=300keV

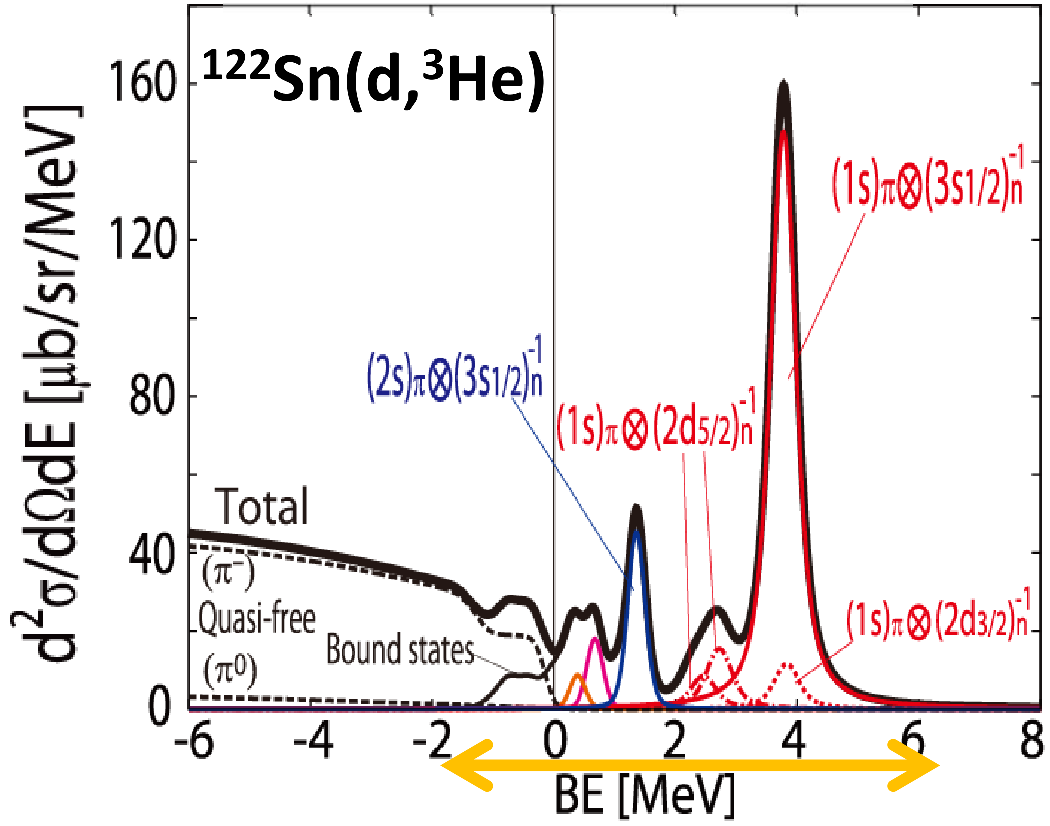
Dominant
Subcomponent:
$$[(n\ell)_\pi \otimes J^P]$$

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

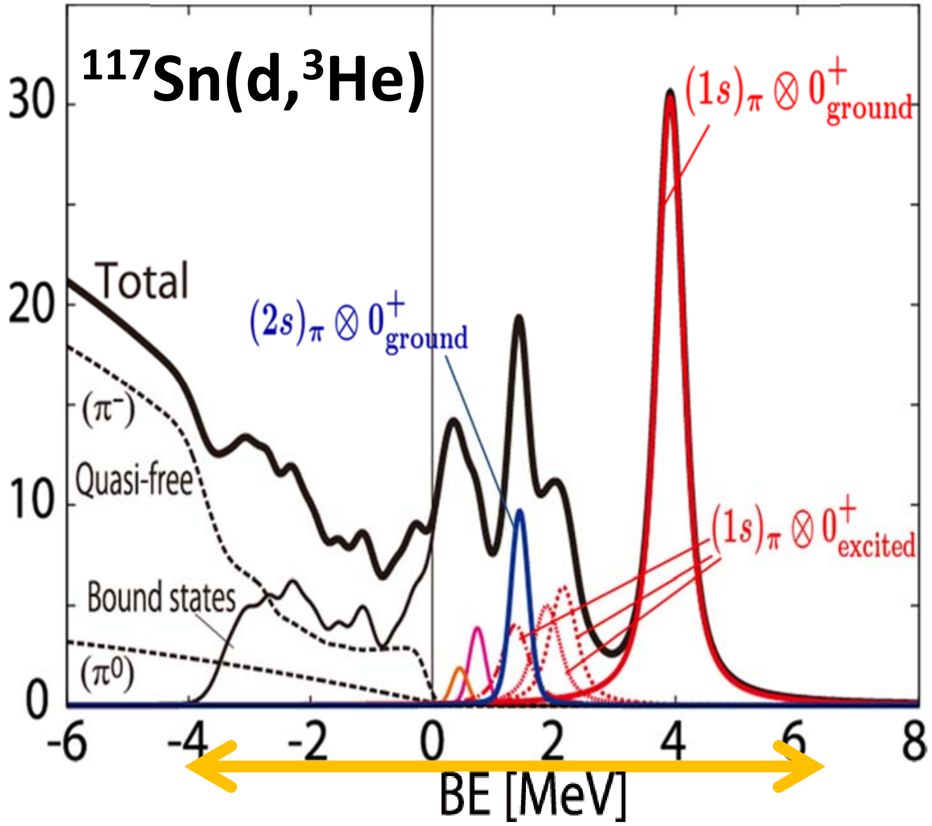
Numerical Results: Even vs. Odd target

0 degrees

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



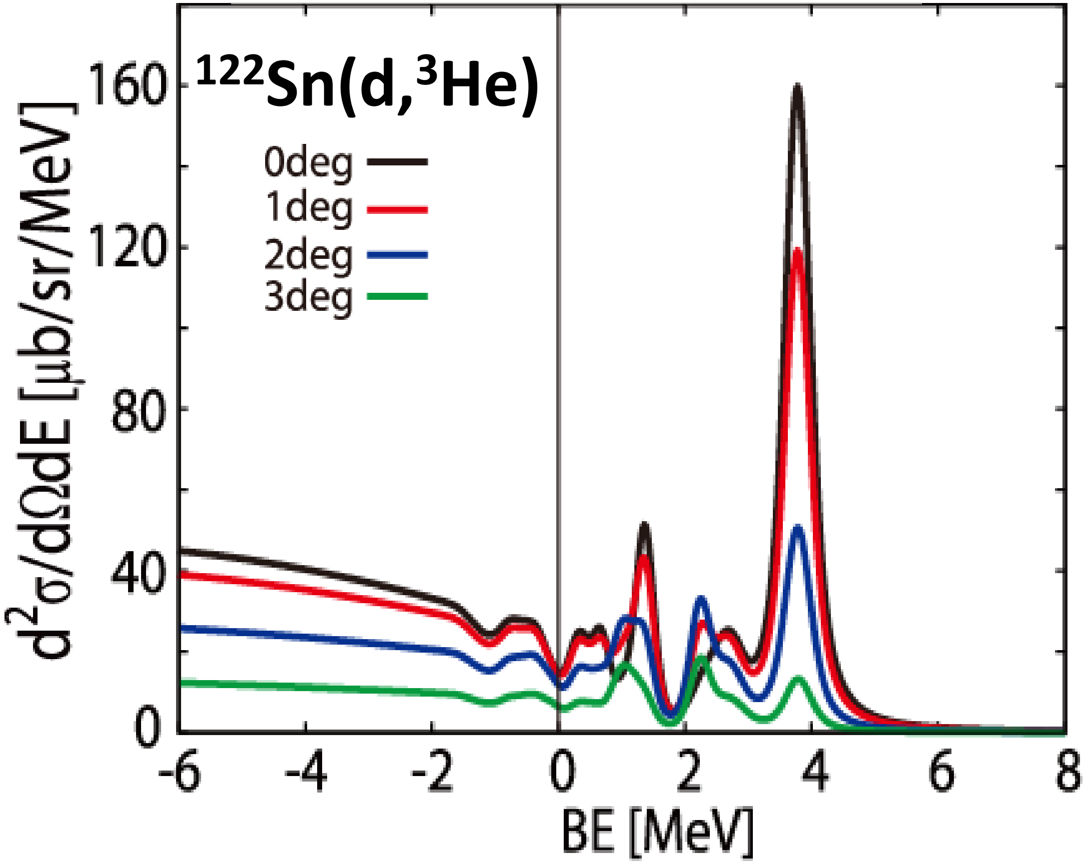
Odd target: ^{117}Sn ($1/2^+$)



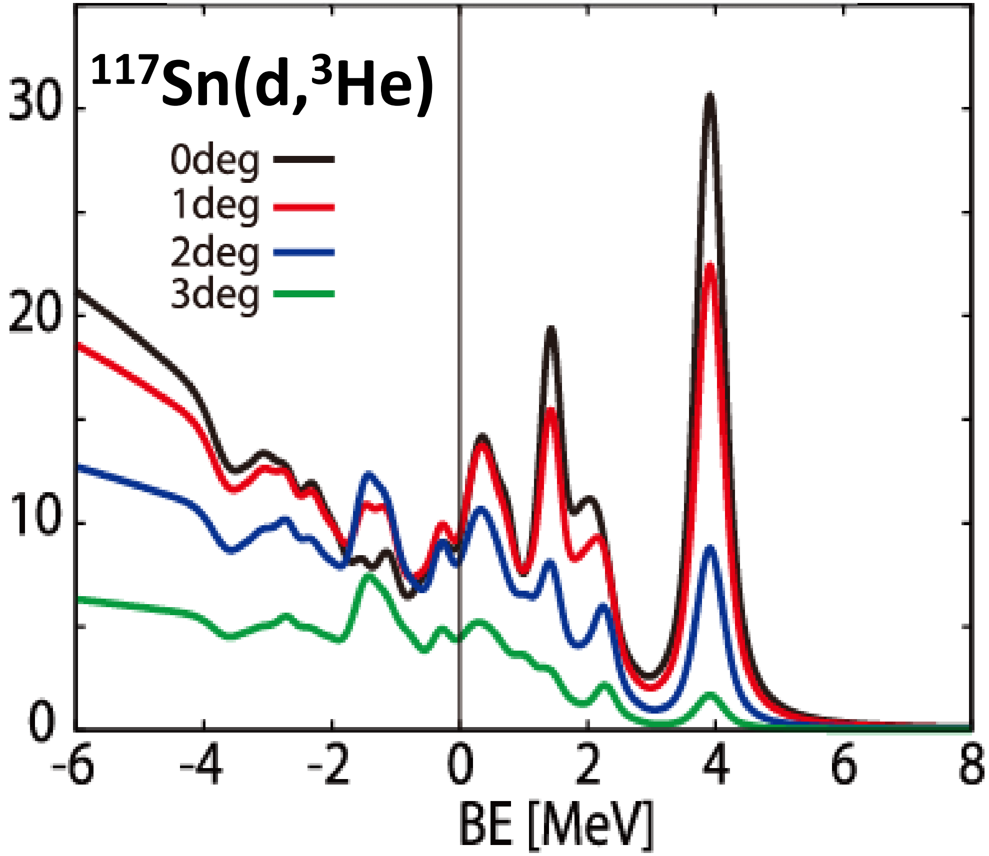
- Pionic 1s state formation with neutron s-hole state is large in both spectra.
- Bound pionic state formation spectra in ^{117}Sn(d,^{3}He) are spread over wider energy range.
- Absolute value of cross section in ^{117}Sn(d,^{3}He) is smaller.

Numerical Results: Finite angles

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



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

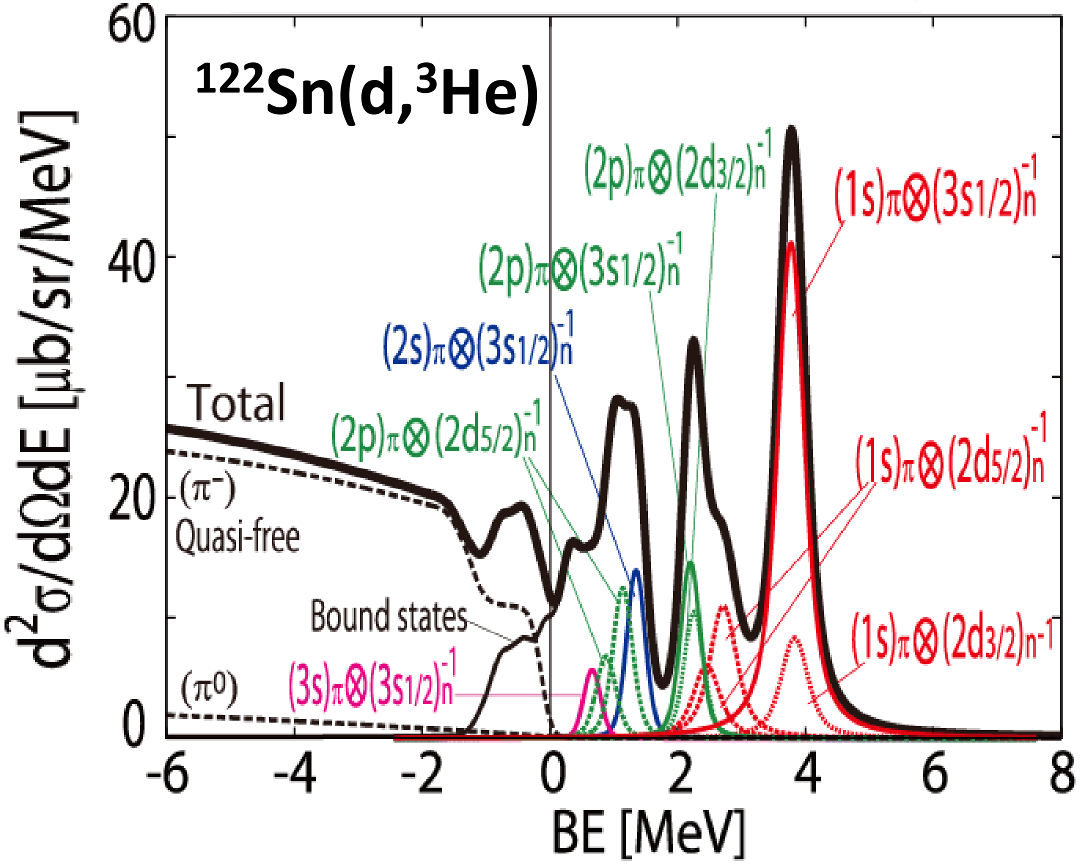


- Both spectra have strong angular dependence.

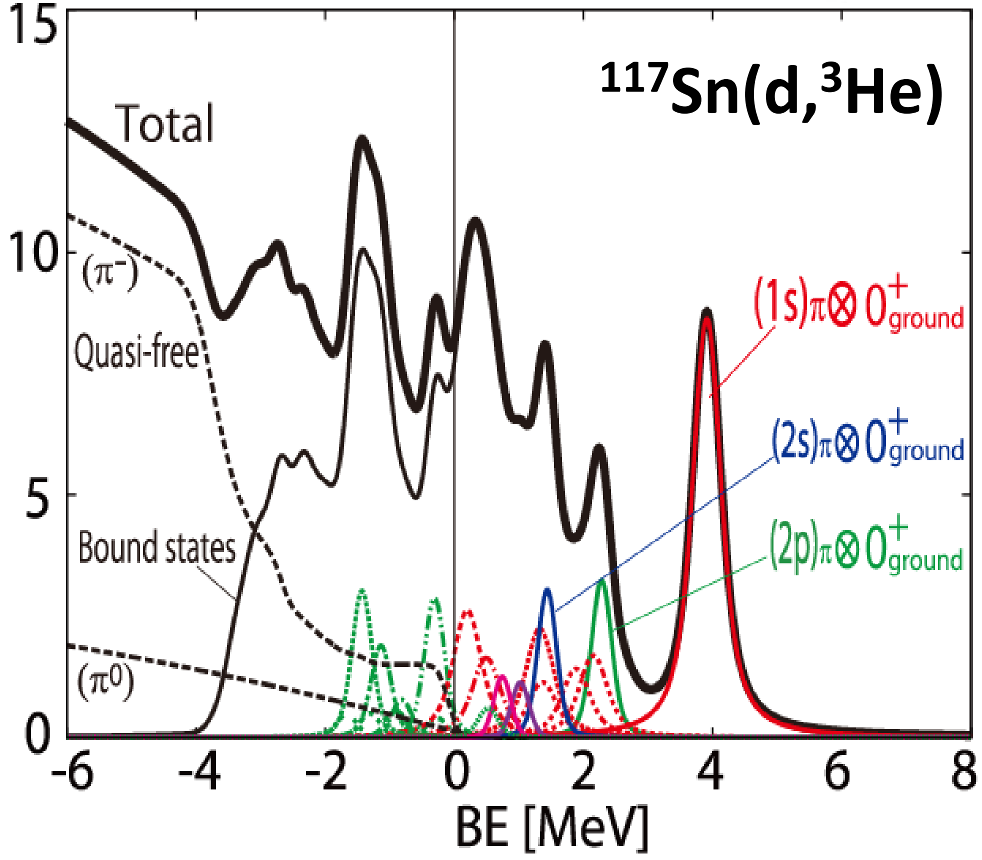
Numerical Results: Even vs. Odd target

2 degrees

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



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



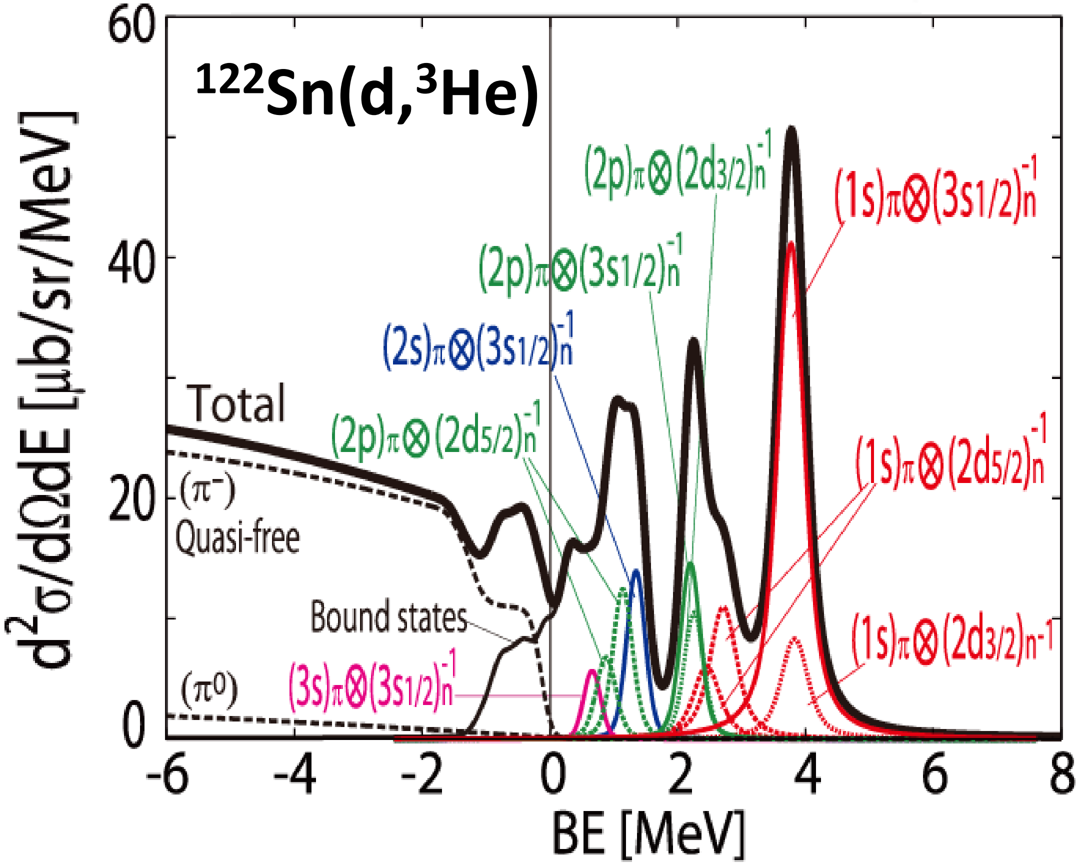
Even target:

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

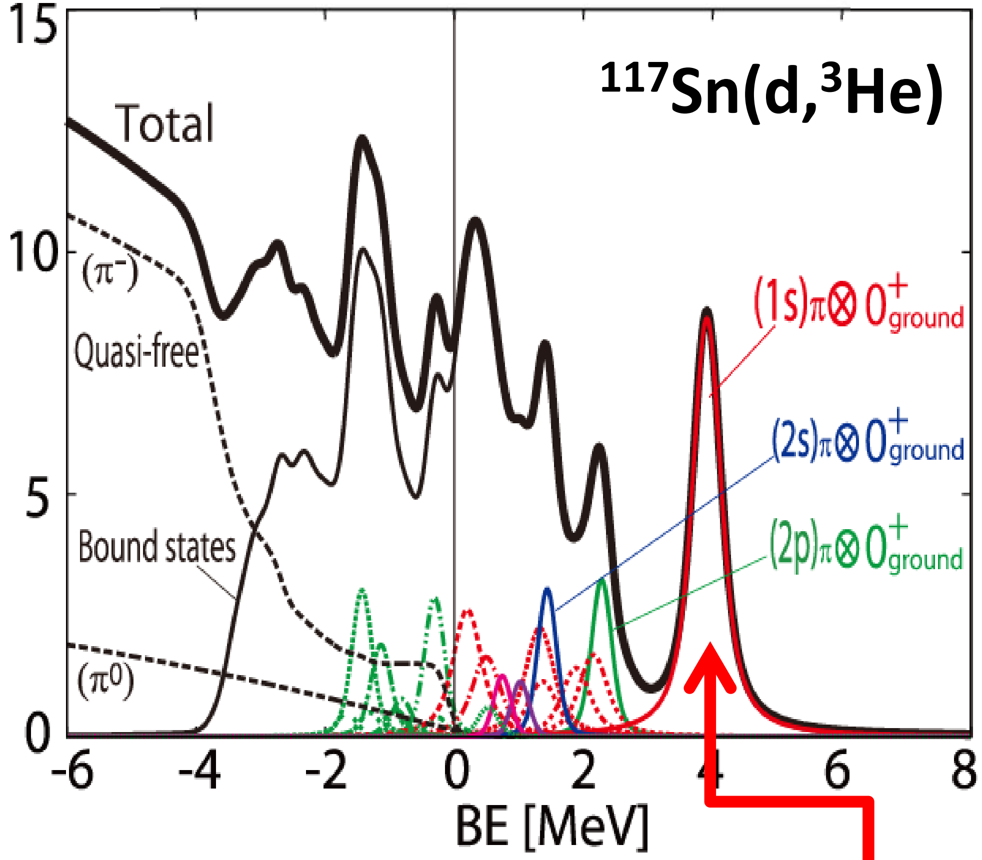
Numerical Results: Even vs. Odd target

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

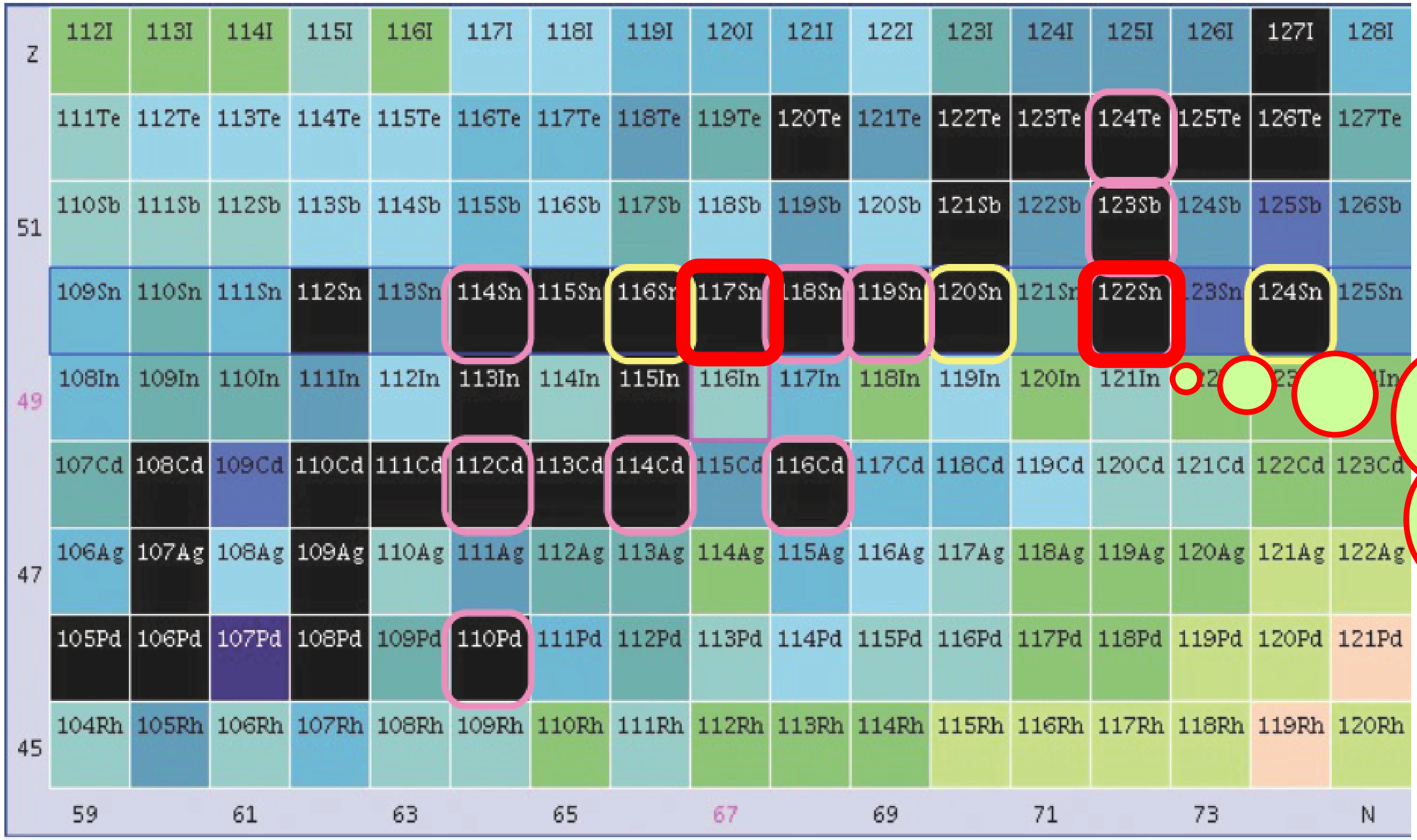
Pionic Atom Spectroscopy @RIBF/RIKEN

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

- Higher statistics, better resolution
- Angular dependence of spectra

＊Pilot Experiment in October 2010 : ^{122}Sn(d,^{3}He) reaction

S. Itoh, Doctor Thesis, University of Tokyo, December (2011).



Z	112I	113I	114I	115I	116I	117I	118I	119I	120I	121I	122I	123I	124I	125I	126I	127I	128I
	111Te	112Te	113Te	114Te	115Te	116Te	117Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te
51	110Sb	111Sb	112Sb	113Sb	114Sb	115Sb	116Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb
	109Sn	110Sn	111Sn	112Sn	113Sn	114Sn	115Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn
49	108In	109In	110In	111In	112In	113In	114In	115In	116In	117In	118In	119In	120In	121In	22	23	4In
	107Cd	108Cd	109Cd	110Cd	111Cd	112Cd	113Cd	114Cd	115Cd	116Cd	117Cd	118Cd	119Cd	120Cd	121Cd	122Cd	123Cd
47	106Ag	107Ag	108Ag	109Ag	110Ag	111Ag	112Ag	113Ag	114Ag	115Ag	116Ag	117Ag	118Ag	119Ag	120Ag	121Ag	122Ag
	105Pd	106Pd	107Pd	108Pd	109Pd	110Pd	111Pd	112Pd	113Pd	114Pd	115Pd	116Pd	117Pd	118Pd	119Pd	120Pd	121Pd
45	104Rh	105Rh	106Rh	107Rh	108Rh	109Rh	110Rh	111Rh	112Rh	113Rh	114Rh	115Rh	116Rh	117Rh	118Rh	119Rh	120Rh
	59		61		63		65		67		69		71		73		N

Main Experiment
May-June 2014 :
^{122}Sn, ^{117}Sn targets

K. Itahashi, EXA2014

K. Itahashi-san's slide

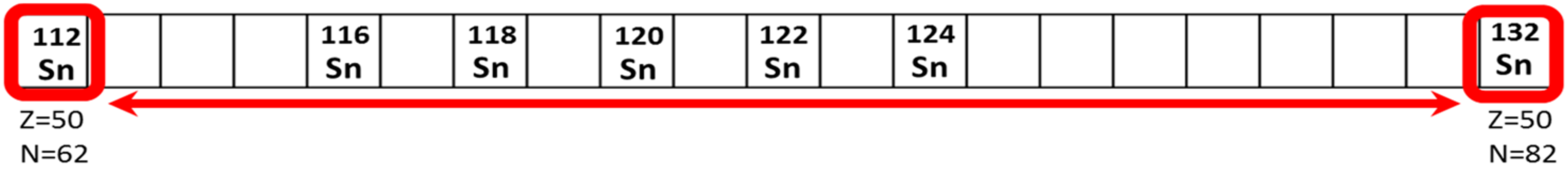
New theoretical studies of pionic atoms

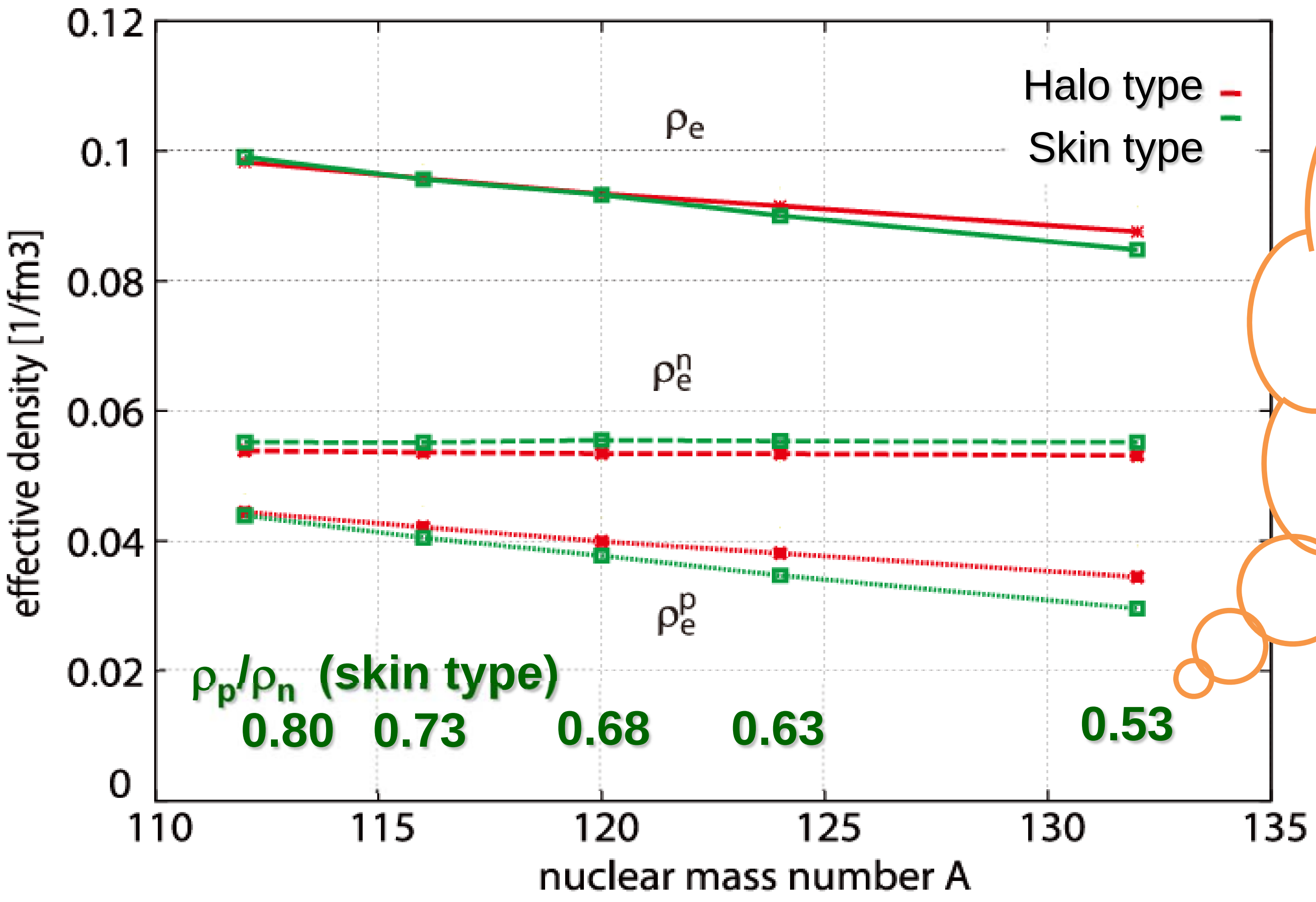
Collaboration

N. Ikeno, J. Yamagata-Sekihara, H. Nagahiro,
D. Jido, H. Fujioka, K. Itahashi, S. Hirenzaki

Pionic atom in unstable nuclei

- Nuclear densities probed by pionic 1s states in $^{112\text{-}132}$Sn

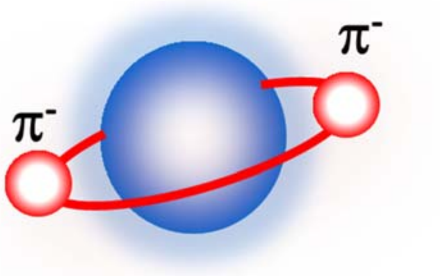




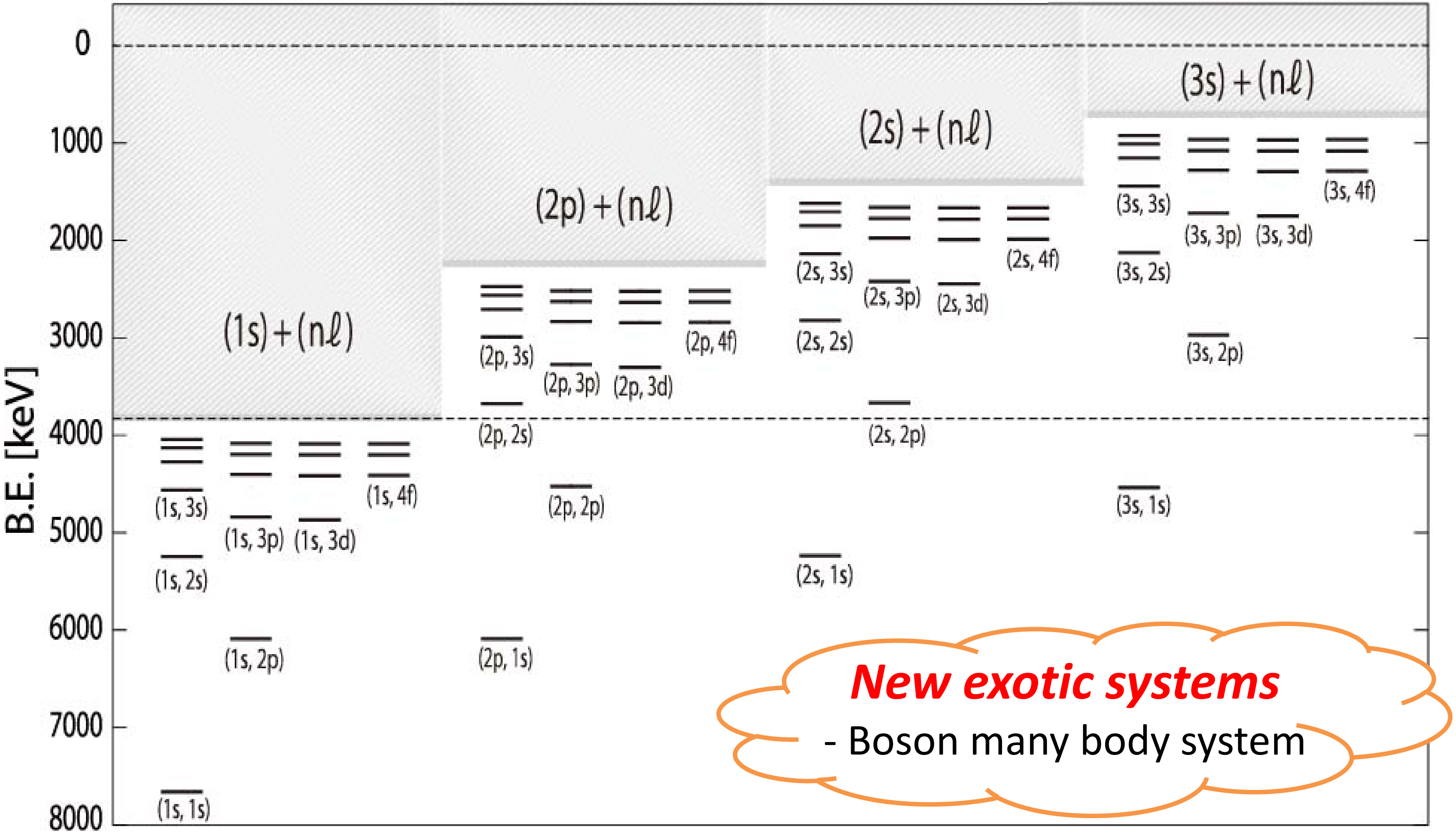
Relatively large variation of ρ_p/ρ_n ratio

Information in asymmetric nuclear matter

Double pionic atoms



- Structure of Double pionic atoms of ^{121}Sn

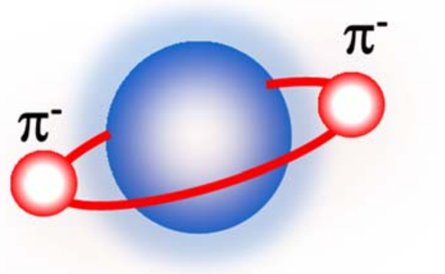


New exotic systems

- Boson many body system

- Formations by (π^-,p) reaction → future work

Double pionic atoms



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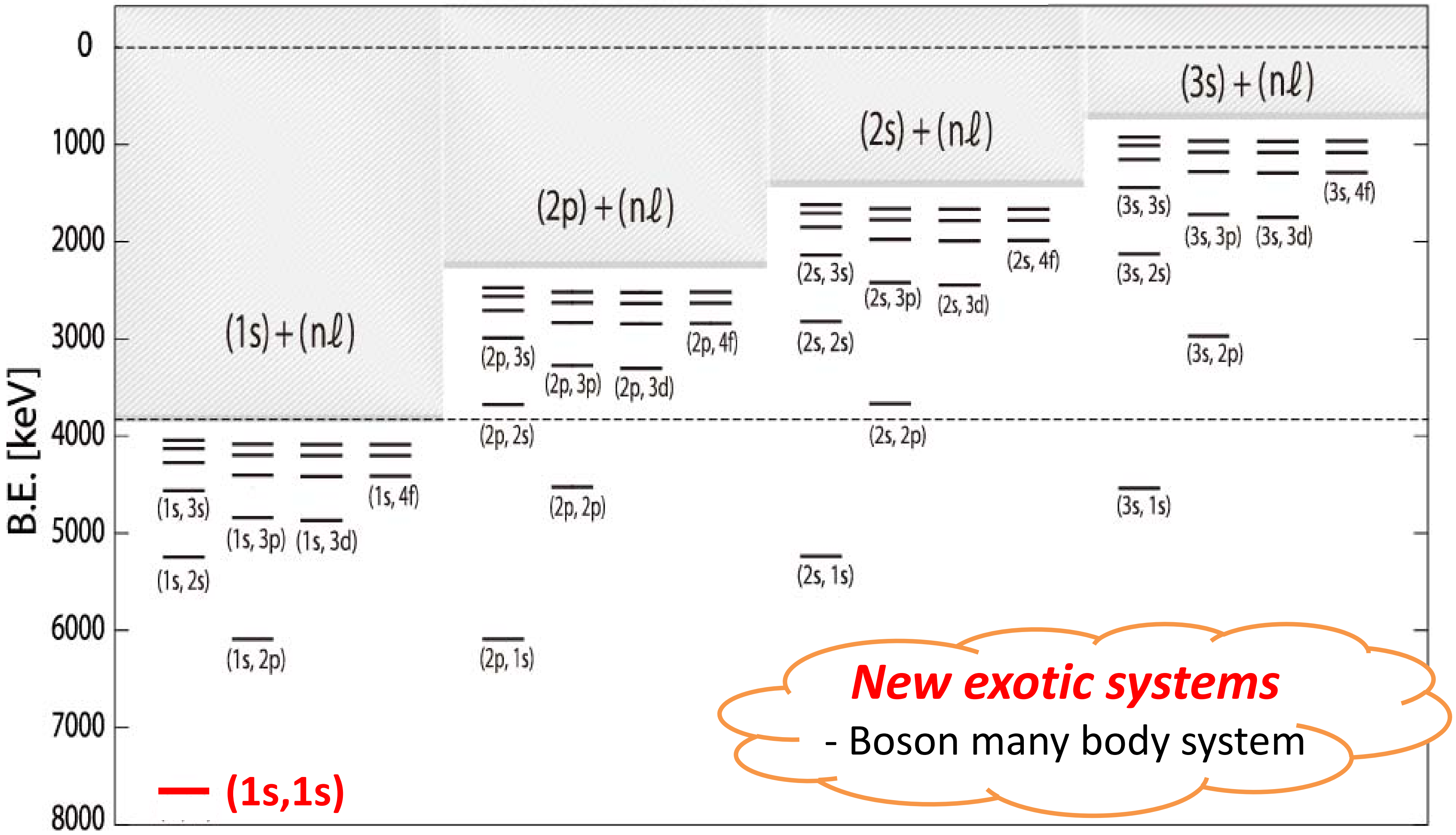

New exotic systems

- Boson many body system

- Formations by (π^-,p) reaction → future work

Summary

- **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.

- **New theoretical studies**
  - ☐ Pionic atom in unstable nuclei
    - ✓ Information at various ρ and ρ_p/ρ_n ratio
  - ☐ Double pionic atom
    - ✓ New exotic many body systems

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.