Precision spectroscopy of deeply bound pionic states in ^{121,116}Sn

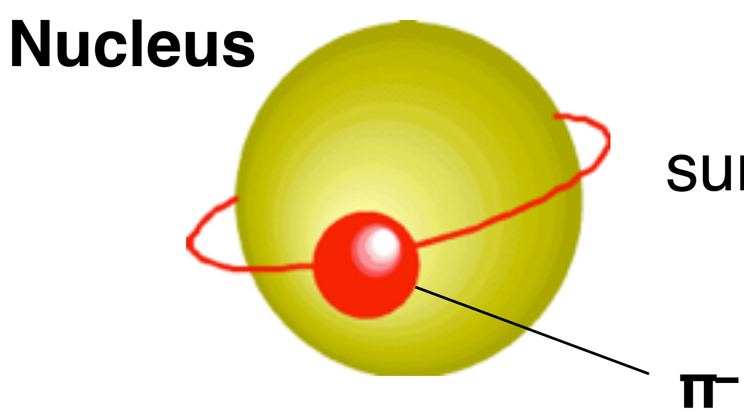
Takahiro Nishi
Advanced Meson Science Laboratory, RIKEN

DeukSoon Ahn, Georg P.A. Berg, Masanori Dozono, Daijiro Etoh, Hiroyuki Fujioka, Naoki Fukuda, Nobuhisa Fukunishi, Hans Geissel, Emma Haettner, Tadashi Hashimoto, Ryugo S. Hayano, Satoru Hirenzaki, Hiroshi Horii, Natsumi Ikeno, Naoto Inabe, Kenta Itahashi* , Sathoshi Itoh, Masahiko Iwasaki, Daisuke Kameda, Shouichiro Kawase, Keichi Kisamori, Yu Kiyokawa, Toshiyuki Kubo, Kensuke Kusaka, Hiroaki Matsubara, Masafumi Matsushita, Shin'ichiro Michimasa, Kenjiro Miki, Go Mishima, Hiroyuki Miya, Daichi Murai, Yohei Murakami, Hideko Nagahiro, Masaki Nakamura, Megumi Niikura, Takahiro Nishi**, Shumpei Noji, Kota Okochi, Shinsuke Ota, Naruhiko Sakamoto, Kimiko Sekiguchi, Hiroshi Suzuki, Ken Suzuki, Motonobu Takaki, Hiroyuki Takeda, Yoshiki K. Tanaka, Koichi Todoroki, Kyo Tsukada, Tomohiro Uesaka, Yasumori Wada, Yuni N. Watanabe, Helmut Weick, Hiroyuki Yamada, Hiroki Yamakami, Yoshiyuki Yanagisawa and Koichi Yoshida

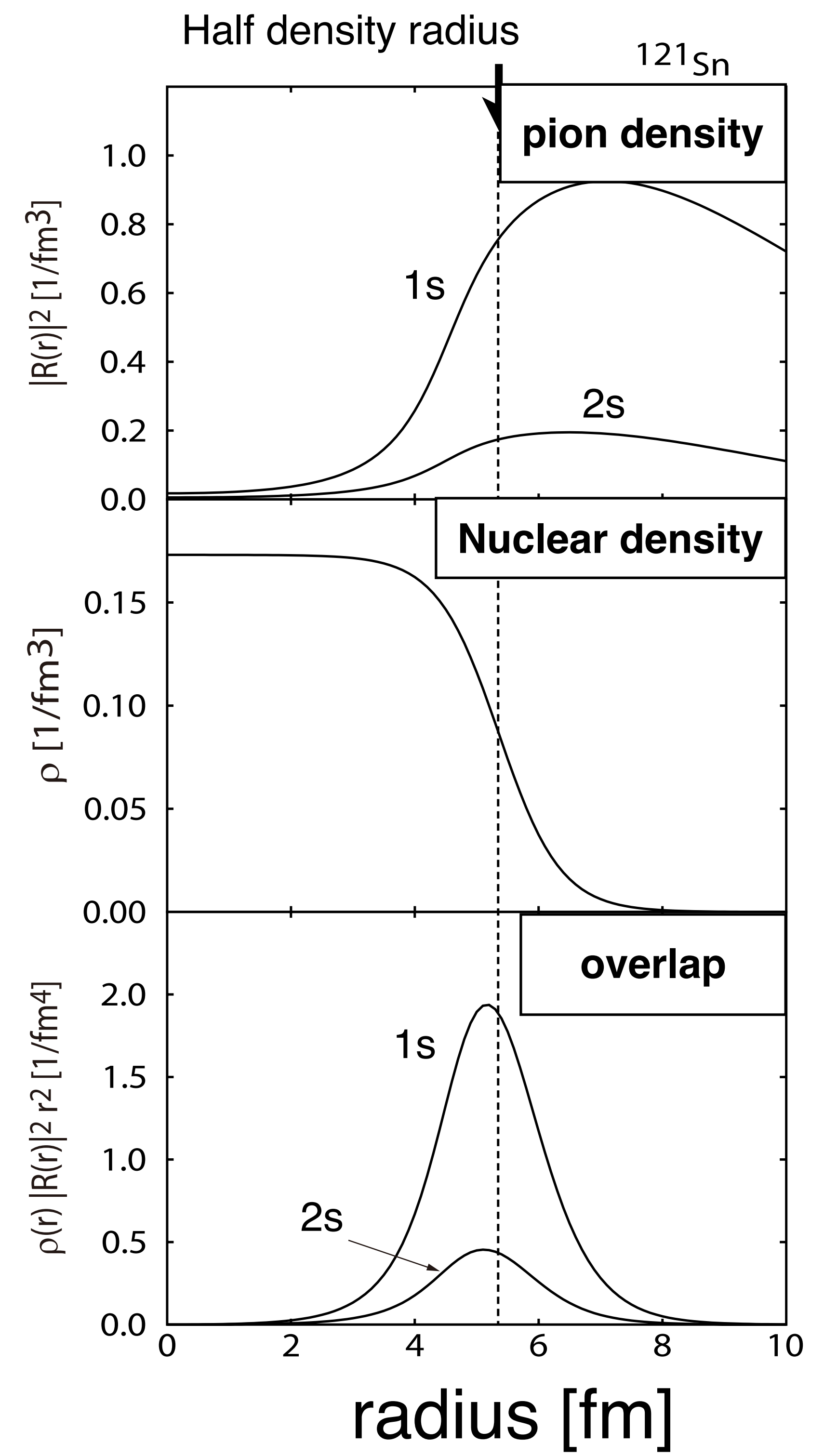
*spokesperson, ** co-spokesperson

University of Tokyo, RIKEN, Nishina Center, University of Notre Dame, Tohoku University, Kyoto University, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Nara Women's University, Osaka University, Stefan Meyer Institute

Deeply bound pionic states



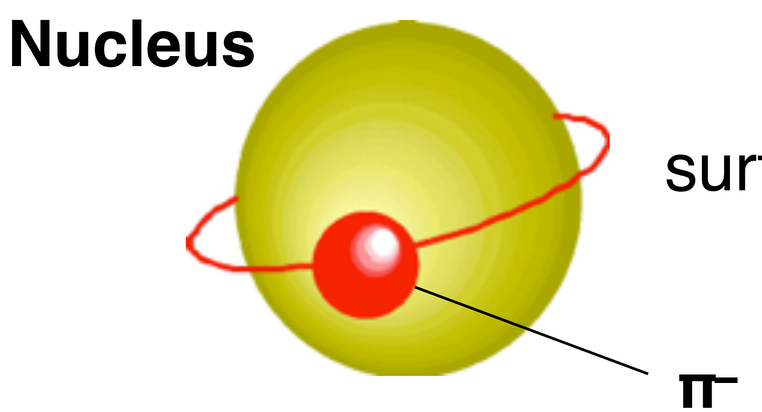
pion orbit :
surface on the nuclei



N. Ikeno *et al.*, PTP126(2011)483.

deeply bound pionic states
→ Large overlap between π and A

Deeply bound pionic states

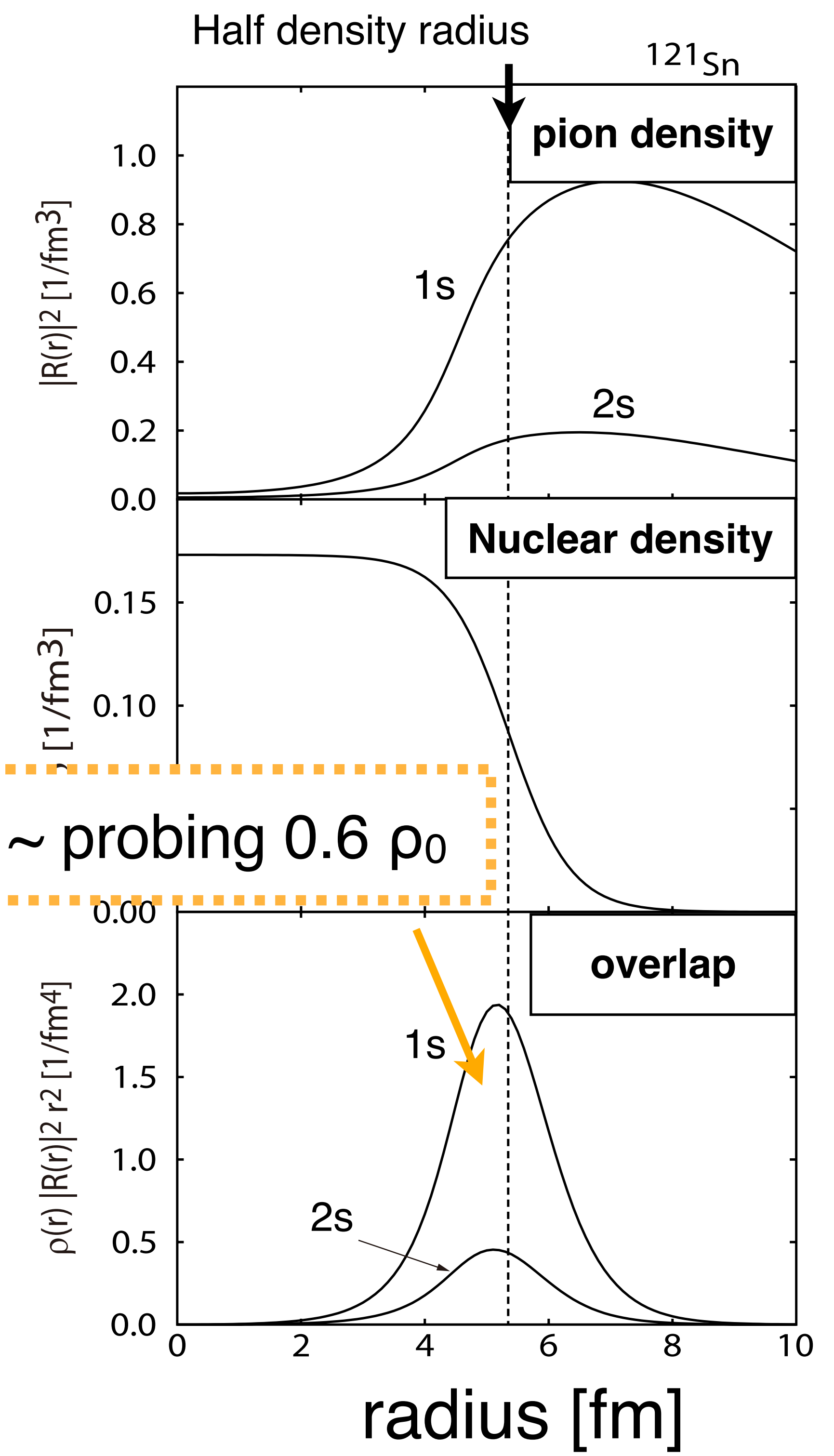


pion orbit :
surface on the nuclei

deeply bound pionic states
→ Large overlap between π and A

good probe for strong interaction at finite ρ

~ probing 0.6 ρ_0



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Strong interaction and pionic states

BE, Γ of 1*s* pionic state
⇔ strong interaction effect

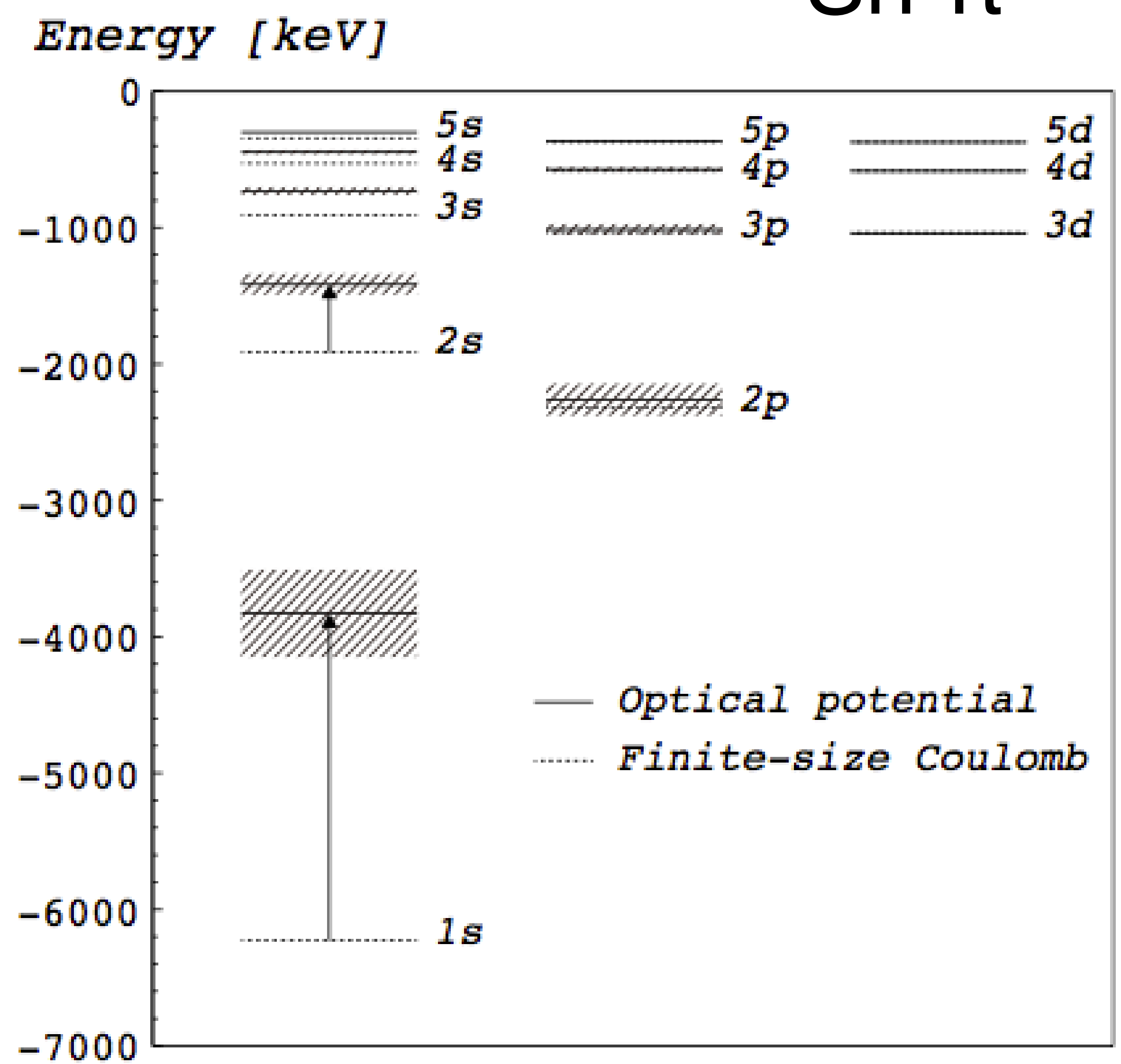
π-A s-wave optical potential (s-wave)

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + b_1\delta\rho\} + \epsilon_2 B_0 \rho^2]$$

$\rho = \rho_p + \rho_n$

$\delta\rho = \rho_p - \rho_n$

$^{121}Sn\text{-}\pi^-$



N. Ikeno et al., Prog. Theor. Phys. 126 (2011) 483.
S. Itoh, Doctoral Dissertation, Univ. of Tokyo (2011)

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π-A s-wave optical potential (s-wave)

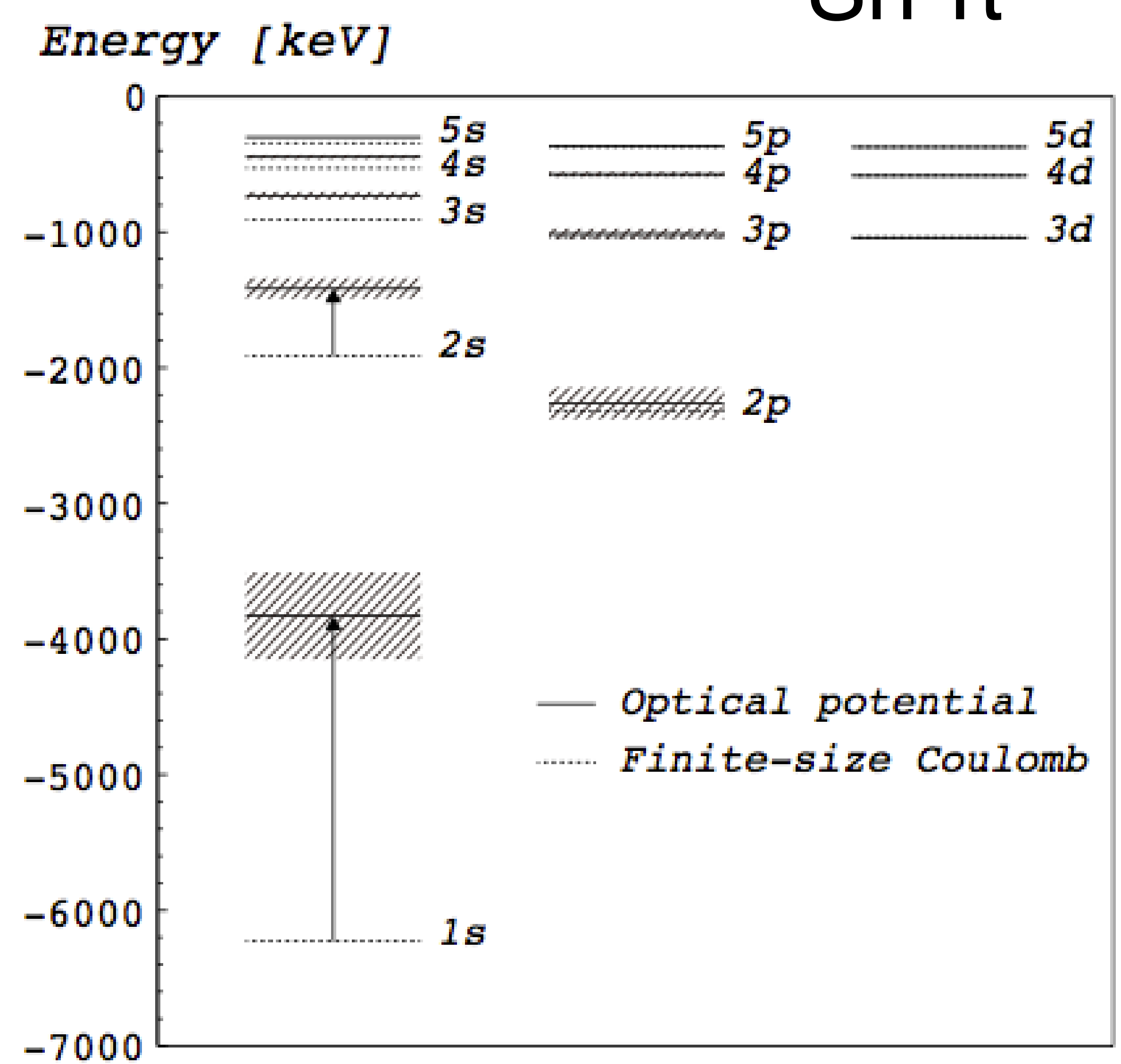
$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + \boxed{b_1}\delta\rho\} + \epsilon_2 B_0 \rho^2]$$

strong relation with quark condensate

↓

Order parameter of chiral symmetry breaking

^{121}Sn-π^-



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Isovector scattering length and quark condensate

Tomozawa-Weinberg relation

Y.Tomozawa, NuovoCimA46(1966)707.
S.Weinberg, PRL17(1966)616.

$$b_1 \simeq \frac{1}{4(1+m_\pi/M_{Nucleon})}\frac{m_\pi}{2\pi f_\pi^2}$$

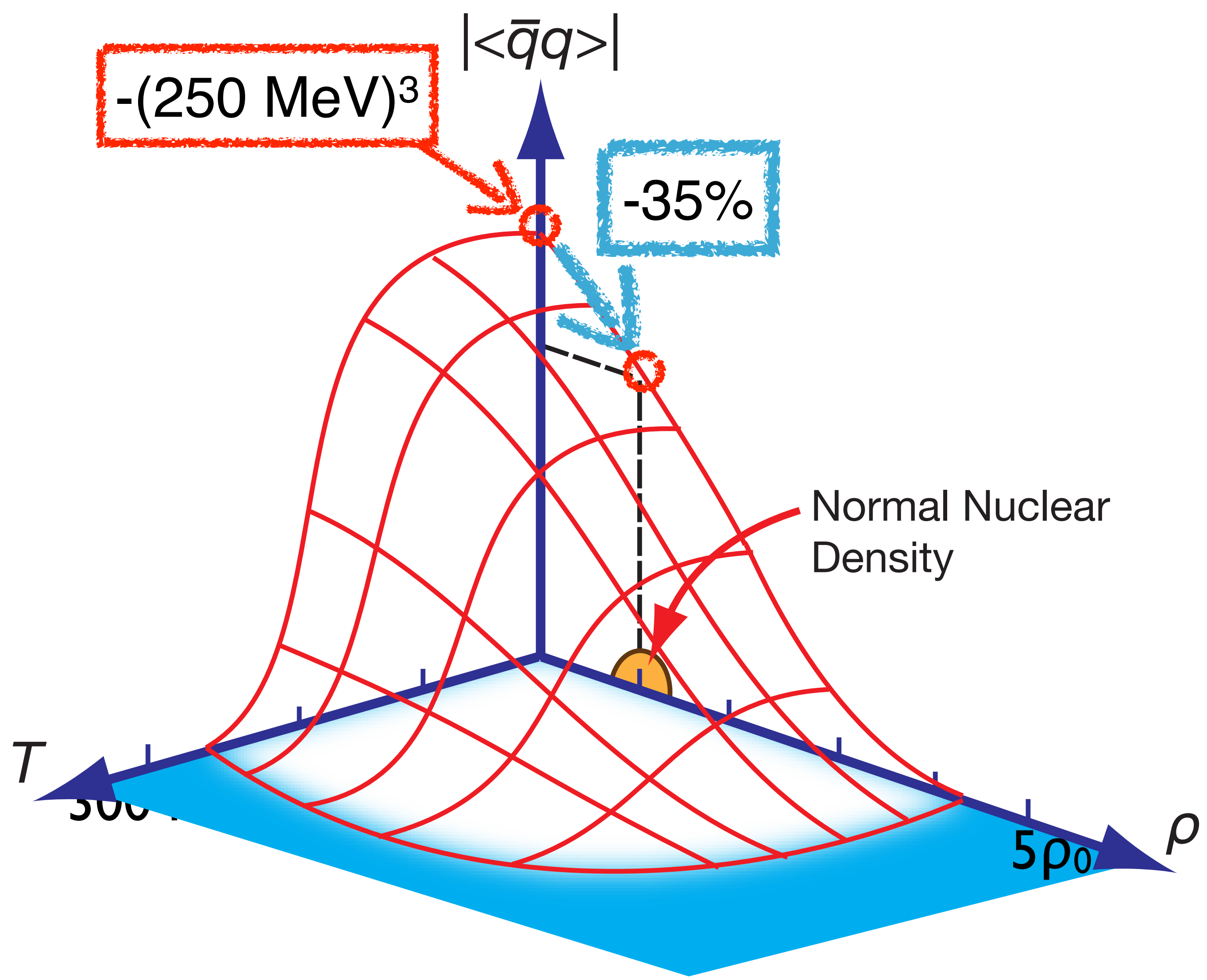
b_1: isovector scattering length

Gell-Mann-Oakes-Renner relation

M. Gell-Mann *et al.*, PR175(1968)2195.

$$f_\pi^2 m_{\pi^\pm}^2 = -m_q\langle\bar{q}q\rangle + O(m_q^2)$$

f_π: pion decay constant



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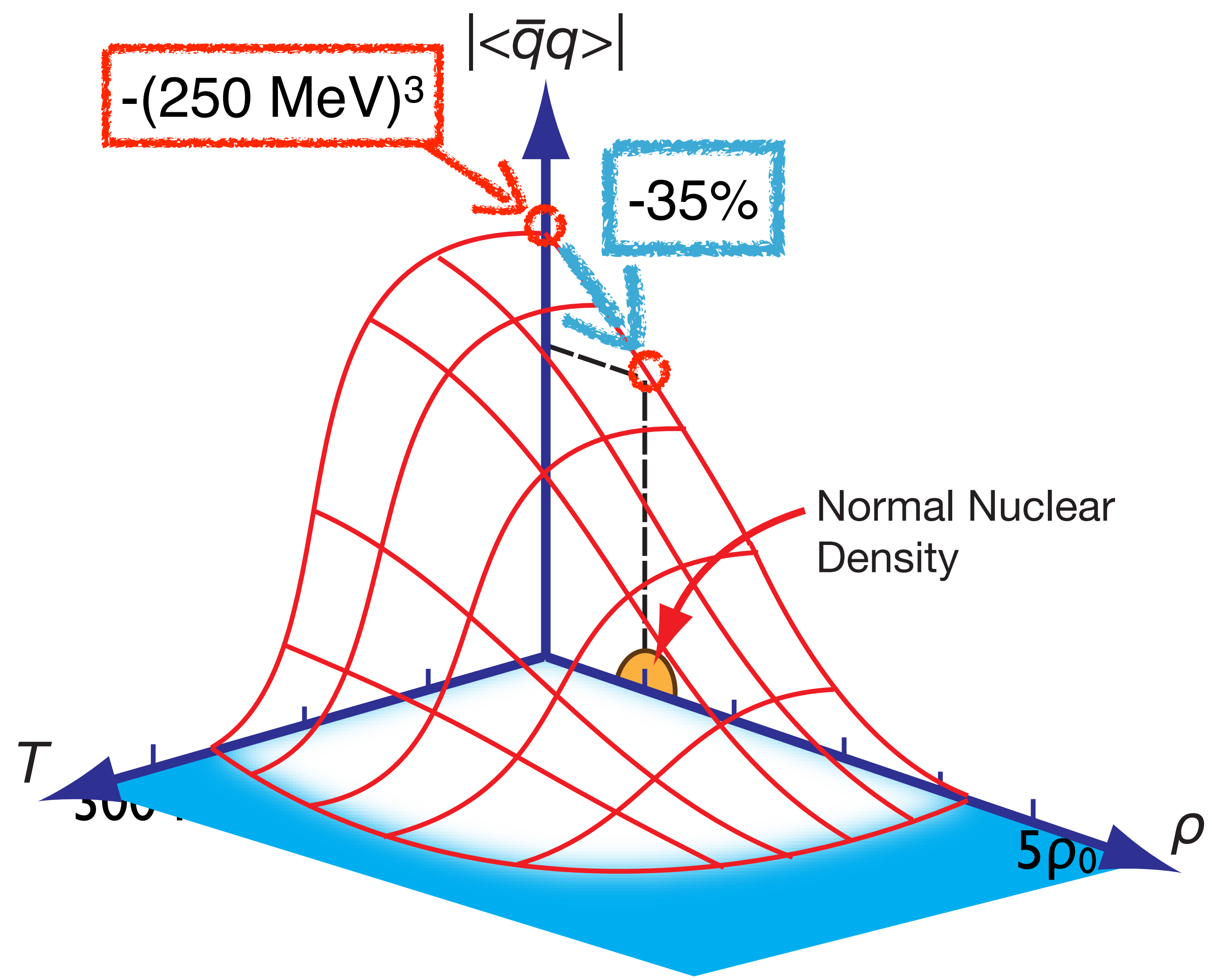
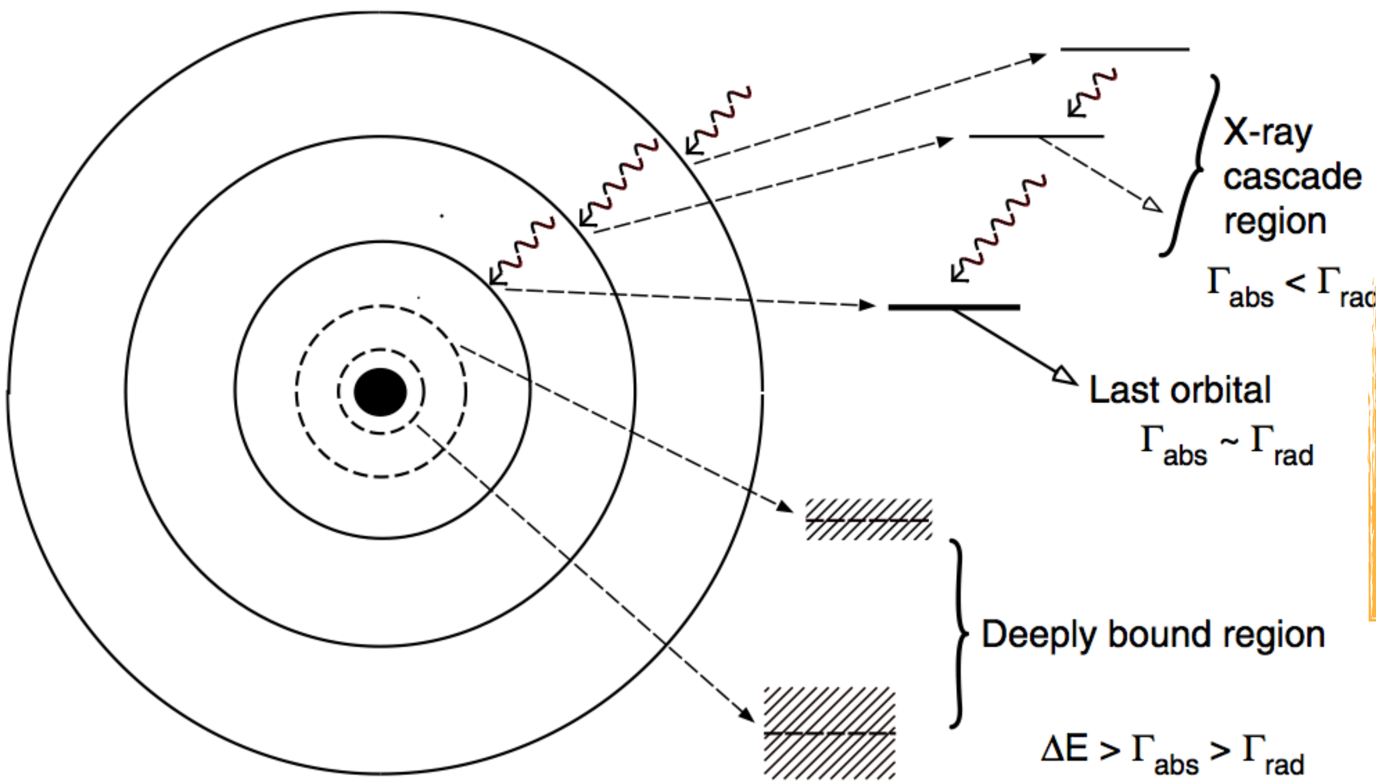
f_π: pion decay constant

$$\frac{\langle \bar{q}q \rangle_{\rho=\rho_0}}{\langle \bar{q}q \rangle_{\rho=0}} \simeq \frac{b_1(\rho = 0)}{b_1(\rho = \rho_0)}$$



W. Weise, NPA553(93)59.

Conventional method; use π^- beam



Yamazaki *et al,* Phys. Rep. 514, 1(2012)

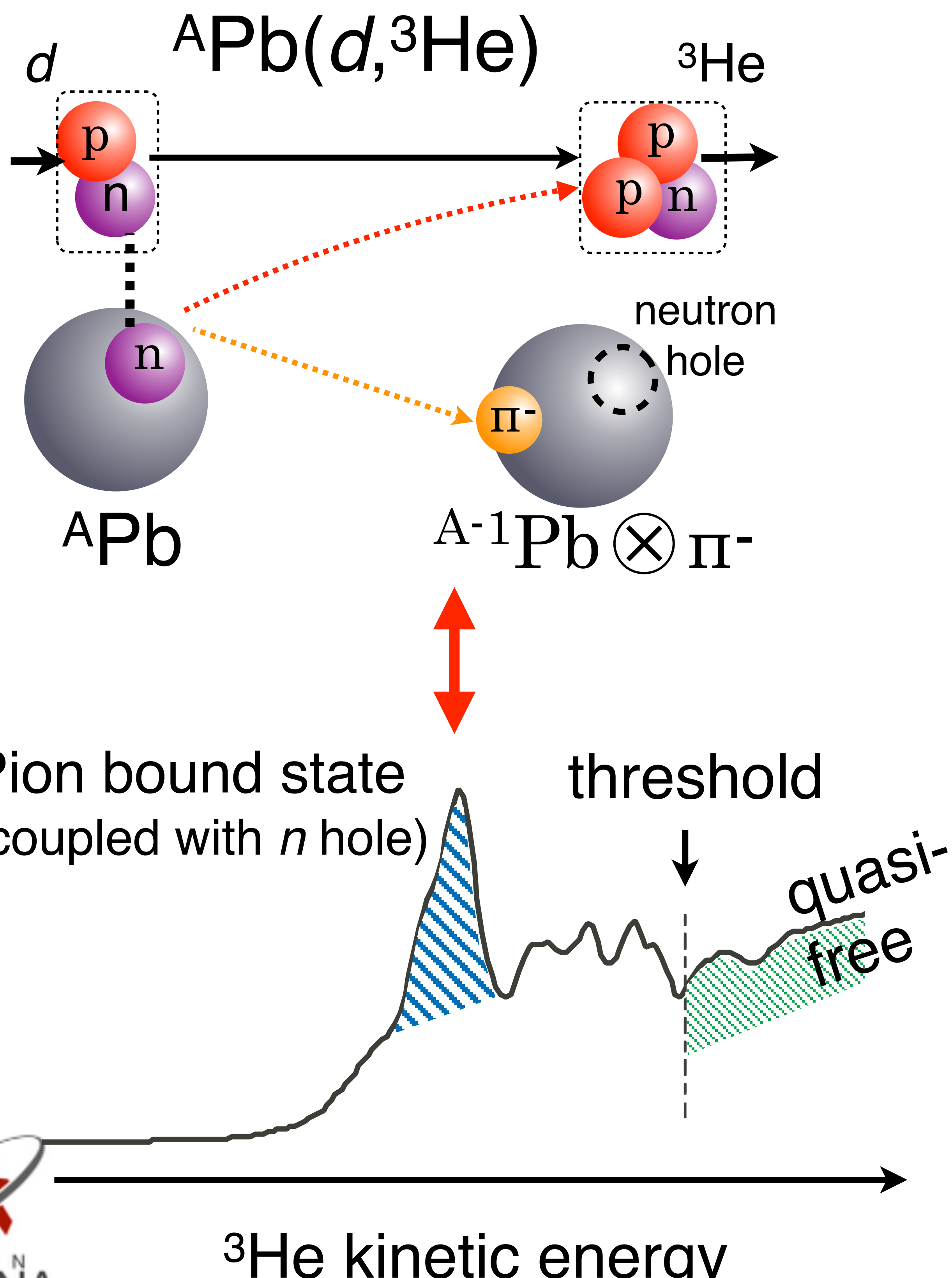
x rays during atomic cascade
→ higher orbits / light nuclei
(~ ^{24}Mg for 1s)

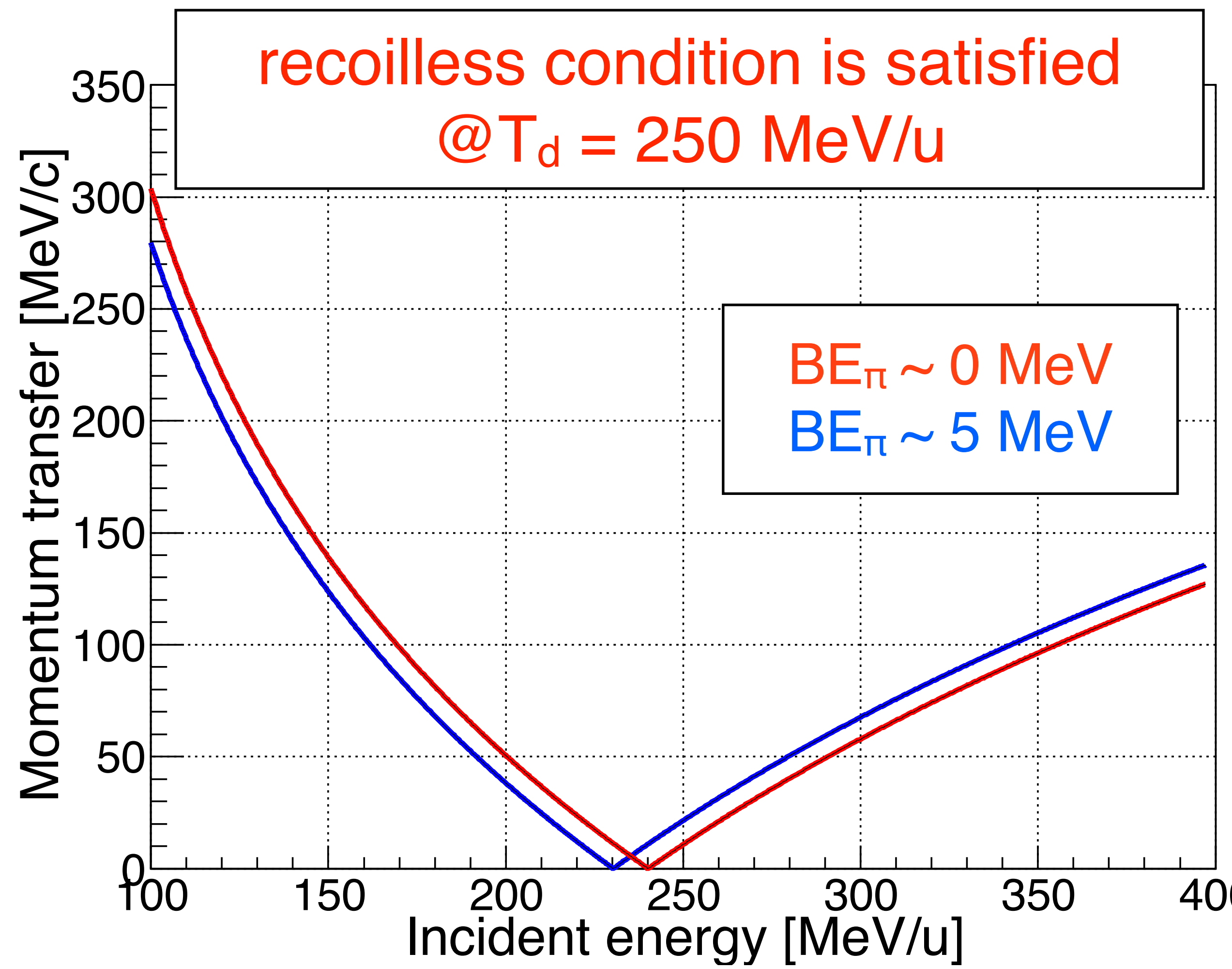
pionic 1s state in H
→ b_1 in vacuum
H. Schröder *et al.*, Eur. Phys. J. C 21, 473 (2001).

for deep orbit in heavy nuclei
absorption is faster

This method cannot produce "deeply-bound" pionic atom…

Production method; (d,³He) reaction





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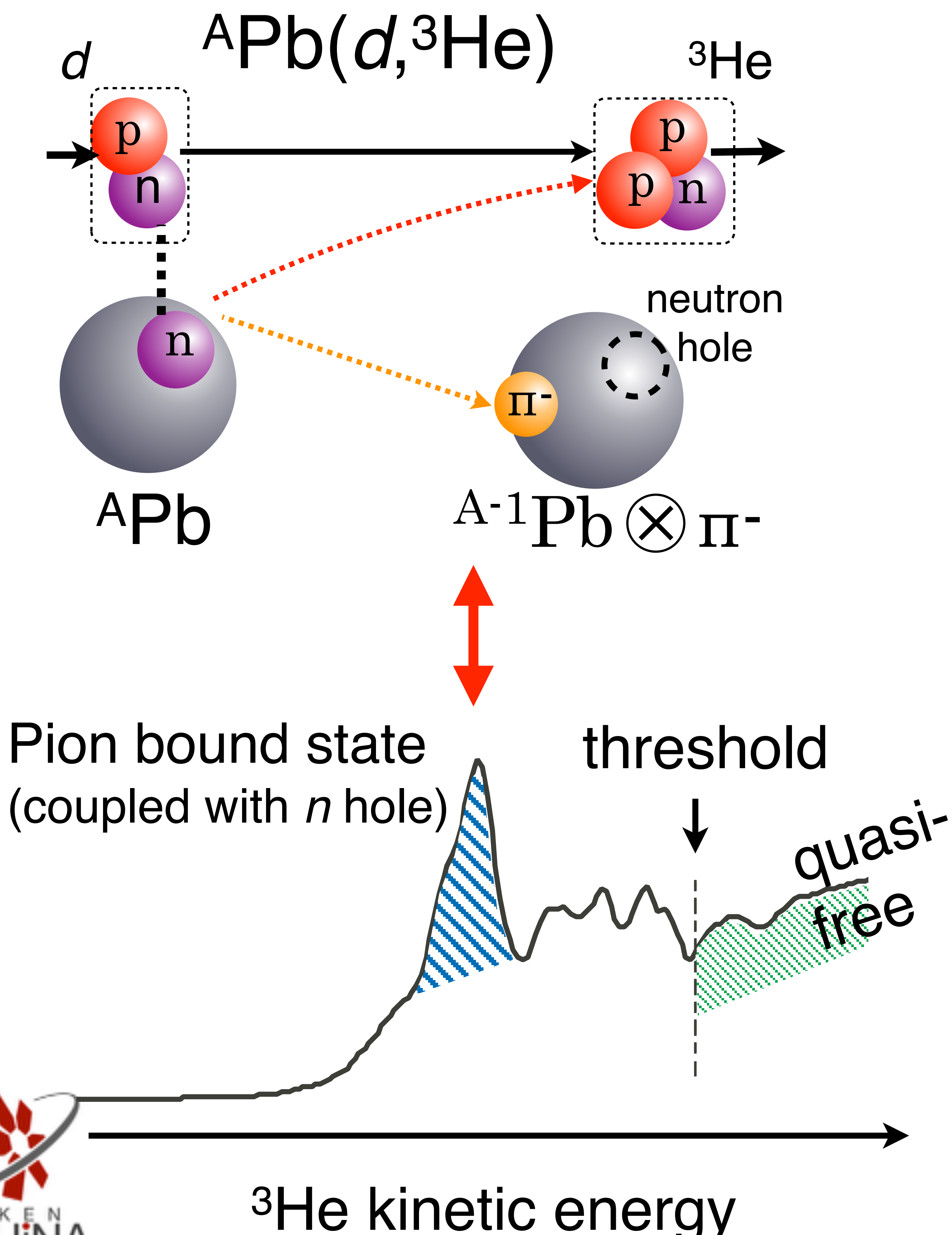
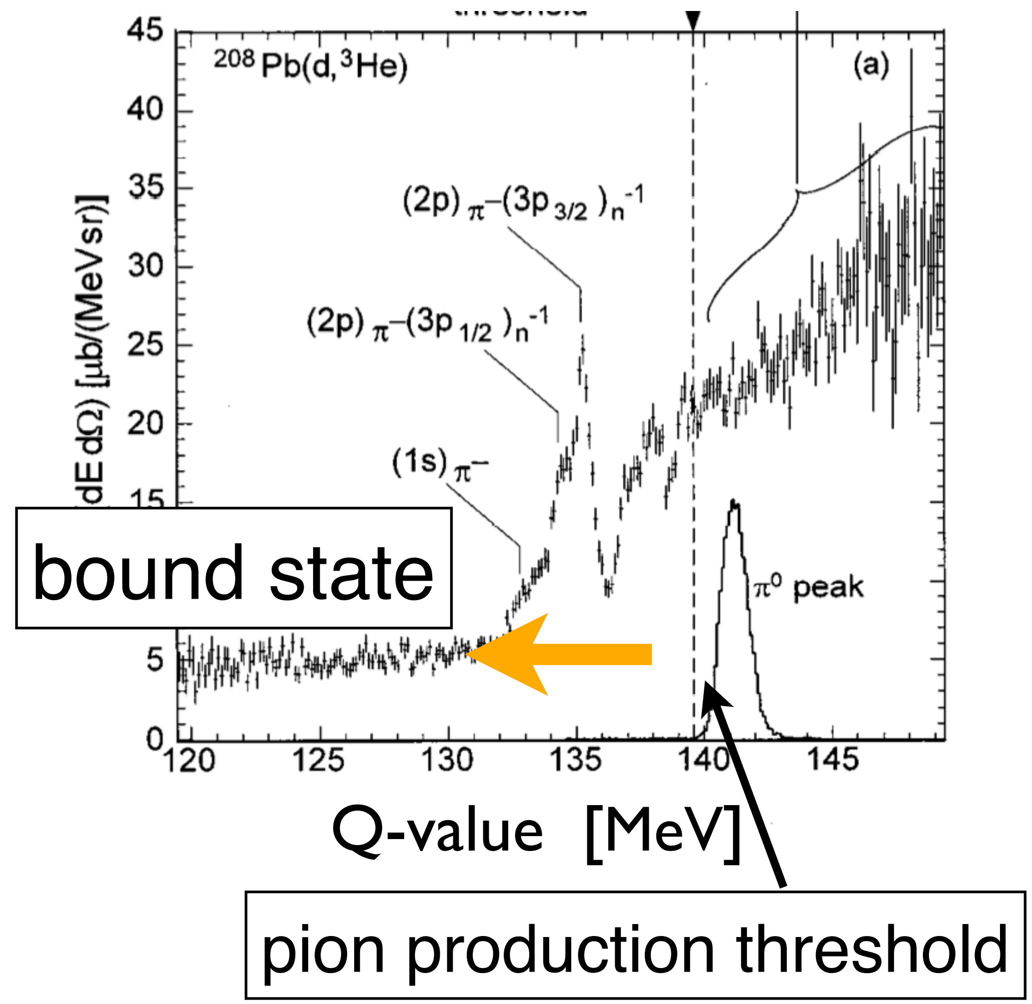
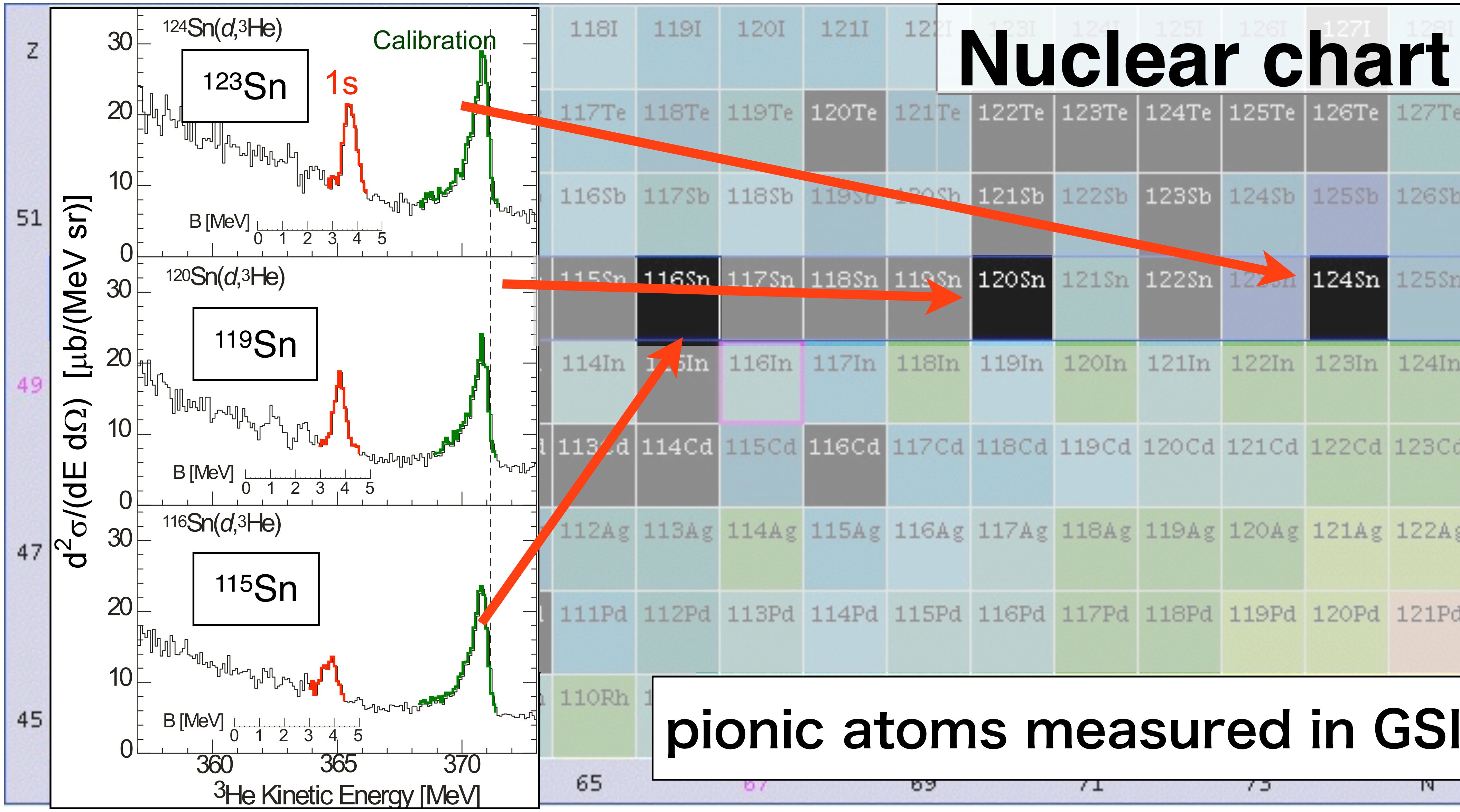


experimental spectrum
for pionic ^{207}Pb@GSI



K. Itahashi, et al.,
Phys. Rev. C62 (2000) 025202

Deeply bound pionic atoms at GSI



K. Suzuki et al., PRL92 072302 (2004)

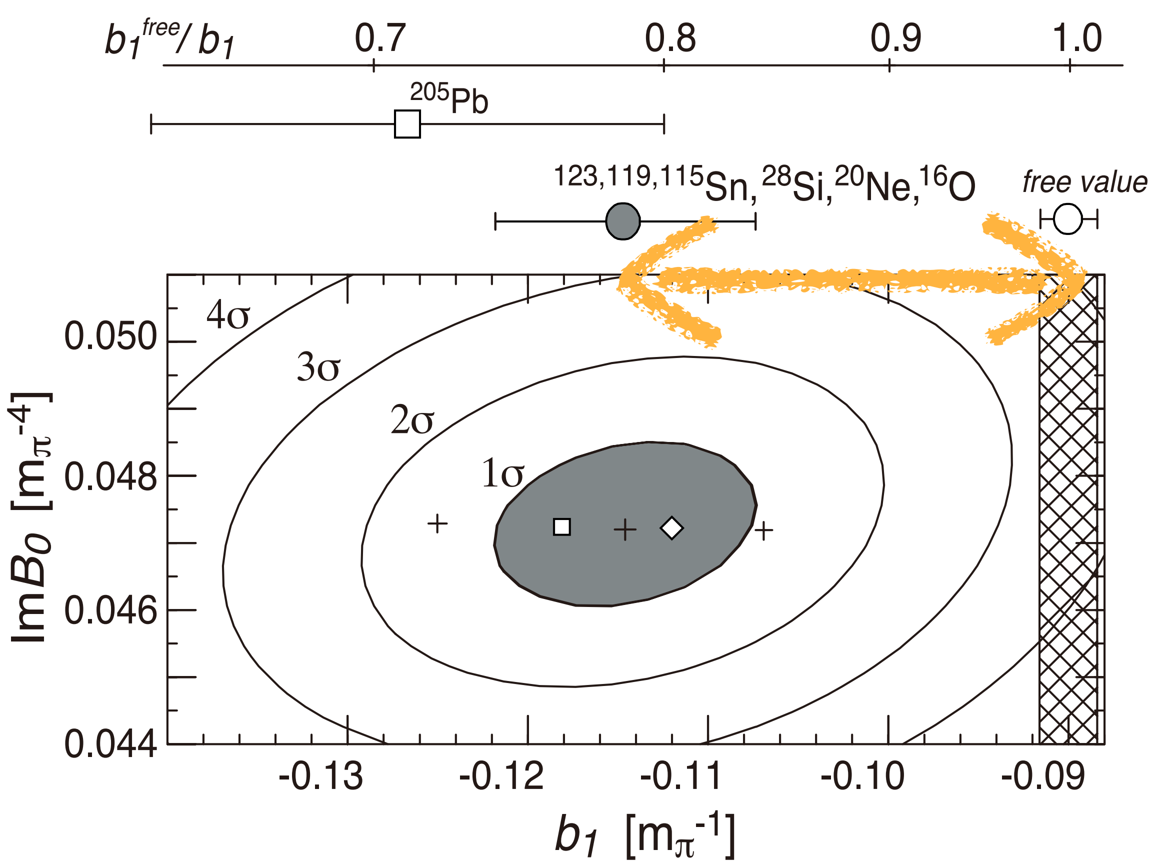
NuDat

Systematic study of pionic Sn isotopes

~ **3 month** measurement for 3 isotopes

Extract b_1 from experimental data

Contour plot of χ^2



$$\frac{b_1^{\rm free}}{b_1} = 0.78 \pm 0.05$$ → $$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle} \approx 0.66 \pm 0.06$$

cf. theoretical prediction ~ 0.65

π-A s-wave optical potential

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + b_1\delta\rho\} + \epsilon_2 B_0\rho^2]$$

※ b_0 , ReB_0 are deduced from data of light / symmetric pionic atoms

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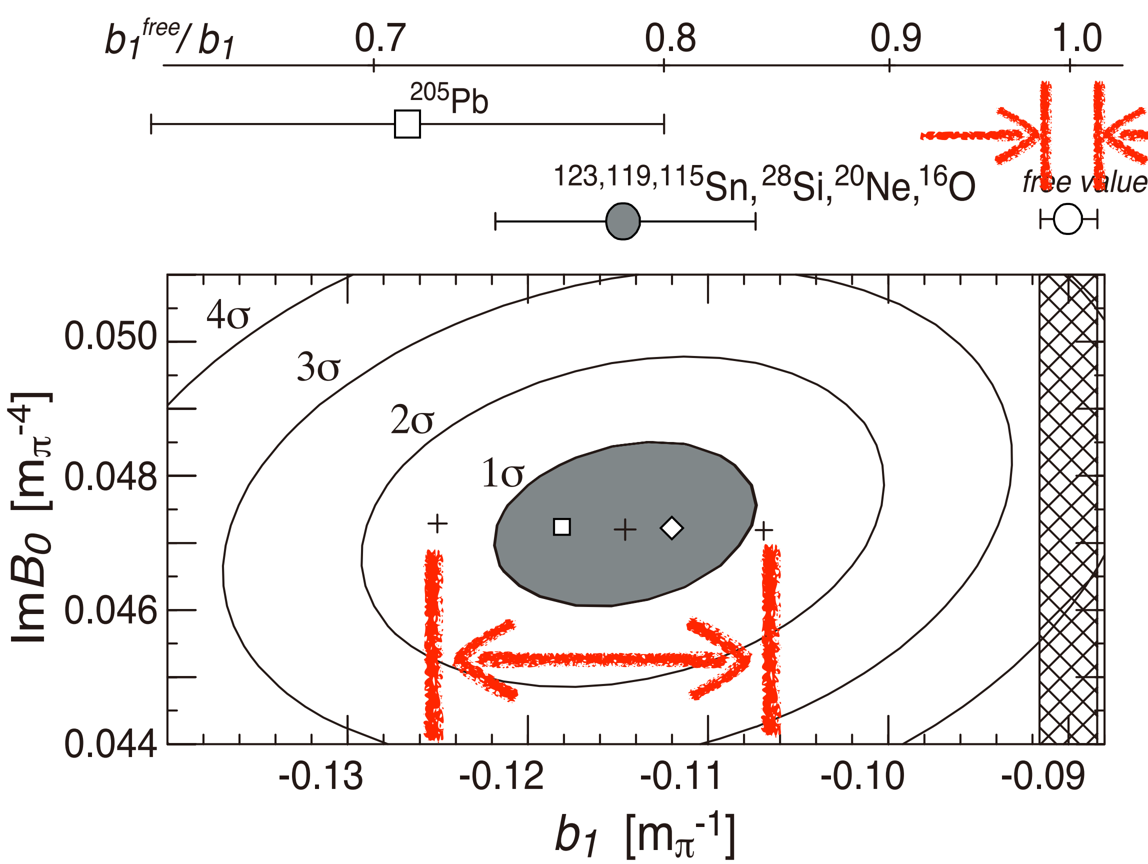
Extract b_1 from experimental data

Contour plot of χ^2



$$\frac{b_1^{\rm free}}{b_1} = 0.78 \pm 0.05 \quad \rightarrow \quad \frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle} \approx 0.66 \pm 0.06$$

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π-A s-wave optical potential

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + b_1\delta\rho\} + \epsilon_2 B_0\rho^2]$$

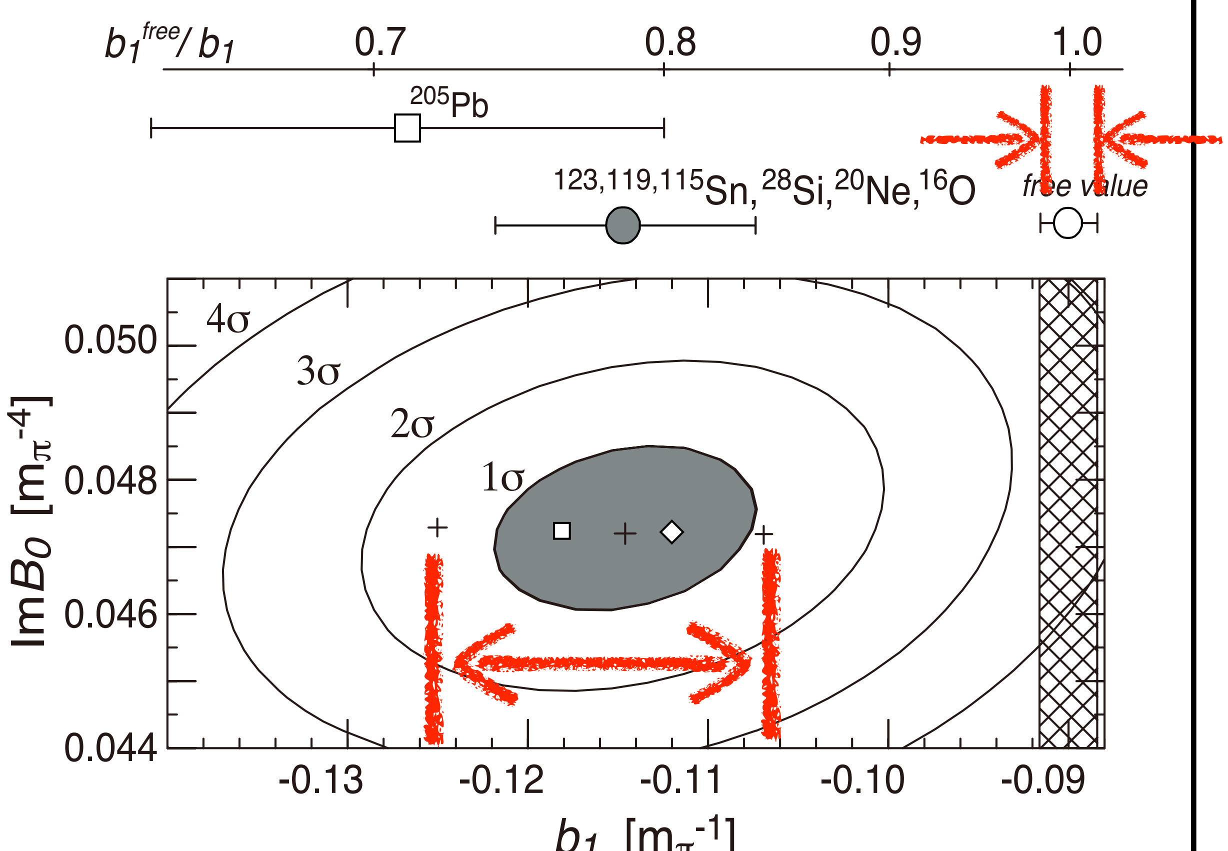
error of b_1 in medium is still large compared with that in vacuum!!
two main sources are

- **experimental error**
- **neutron distribution ambiguities**

※ b_0 , $\mathrm{Re}B_0$ are deduced from data of light / symmetric pionic atoms

Extract b_1 from experimental data

Contour plot of χ^2



$$\frac{b_1^{\text{free}}}{b_1} = 0.78 \pm$$

cf. theo

π-A s-wave optical potential

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error of b_1 in medium is still large
compared with that in vacuum!!
two main sources are

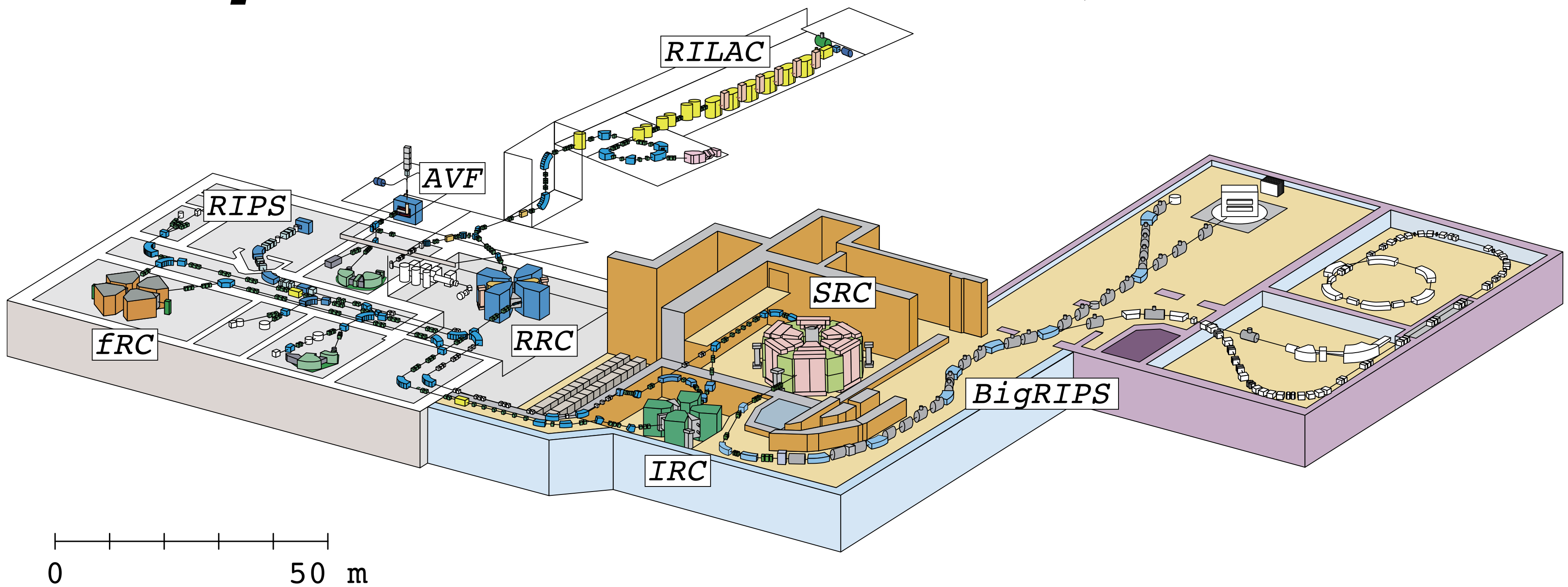
- **experimental error**
- **neutron distribution ambiguities**

To extract b_1 with higher precision

improve resolution

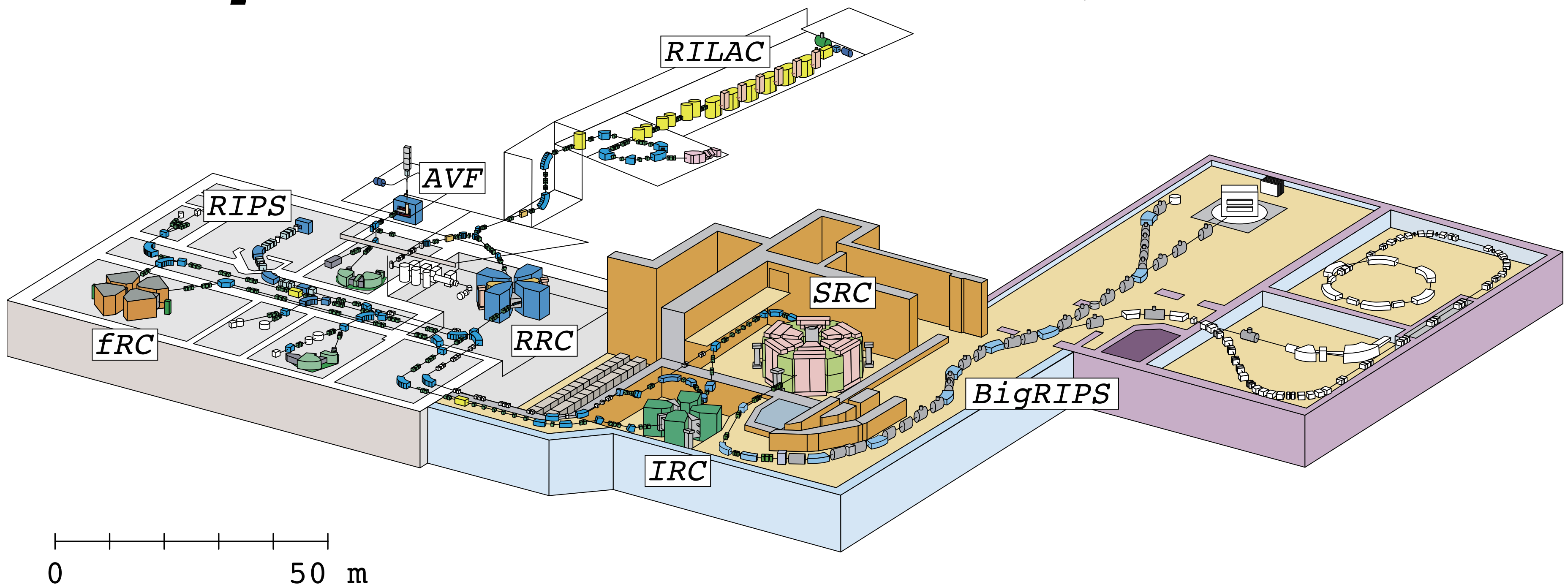
More isotopes

Experiment at RIBF, RIKEN



	GSI	RIBF	Improvement
intensity	~ 10^{11}/ 6 s (1 spill)	~ 10^{12}/ s	**×60**
angular acceptance (H / V)	15 / 10 mrad	40 / 60 mrad	×16
resolution (FWHM)	400 keV	**~ 600 keV**	↘ factor 1.5 ~ 2

Experiment at RIBF, RIKEN



	GSI	RIBF	Improvement
intensity	~ 10^{11}/ 6 s (1 spill)	~ 10^{12}/ s	× 60
angular acceptance (H / V)	15 / 10 mrad	40 / 60 mrad	×16
resolution (FWHM)	400 keV	200 ~ 300 keV	improve

by dispersion matching optics

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First production experiment in 2014 @ RIKEN (11 days)

More people were working…

aim of the experiment

- improve the resolution ~ 300 keV
- first step of the systematic study with enough statistics

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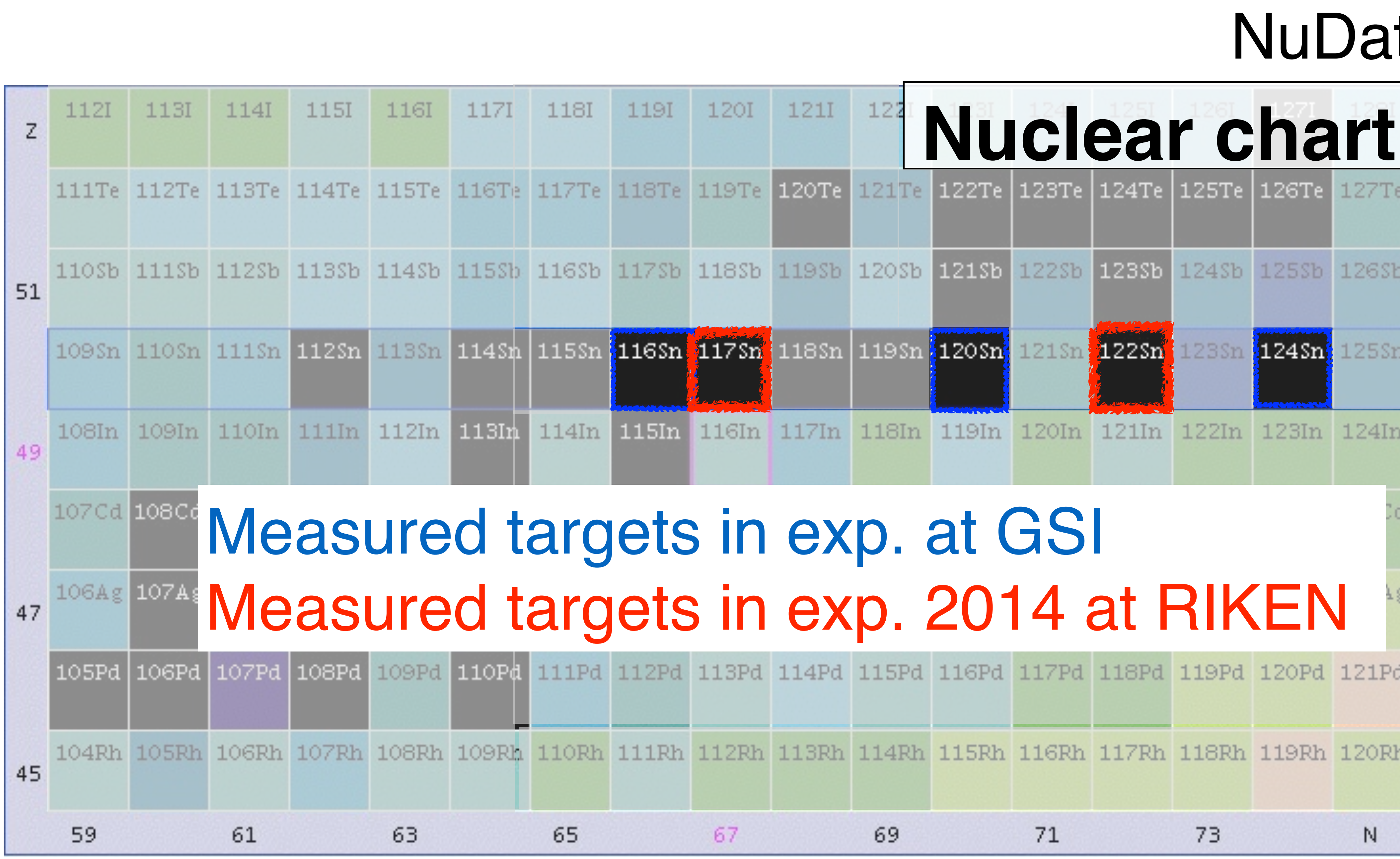
First production experiment in 2014 @ RIKEN (11 days)



^{122}Sn: relatively large cross section

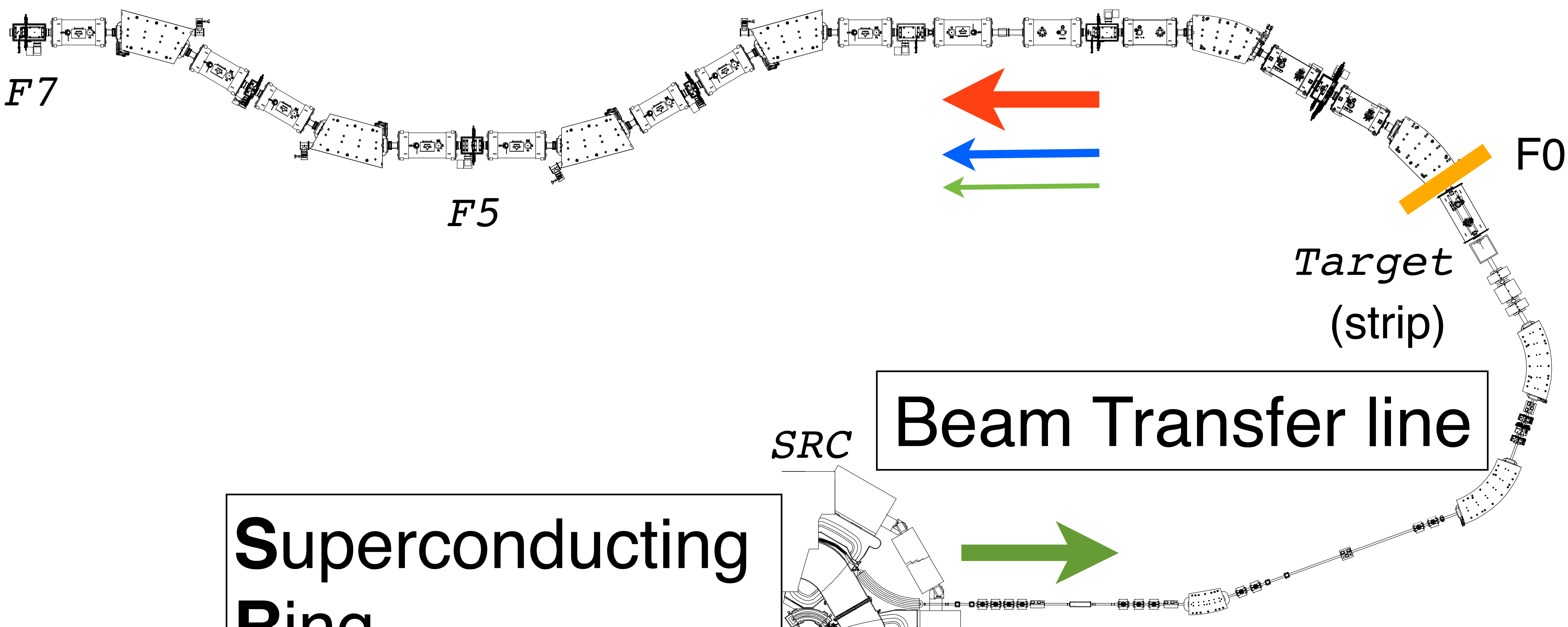
^{117}Sn: first odd-A target (even-A pionic Sn)

Experimental setup

RIKEN Fragment Separator
BigRIPS

^{3}He ~ 10^2Hz
(signal)

p ~ 10^5 Hz
(break up/ background)



Beam Transfer line

Superconducting
Ring
Cyclotron

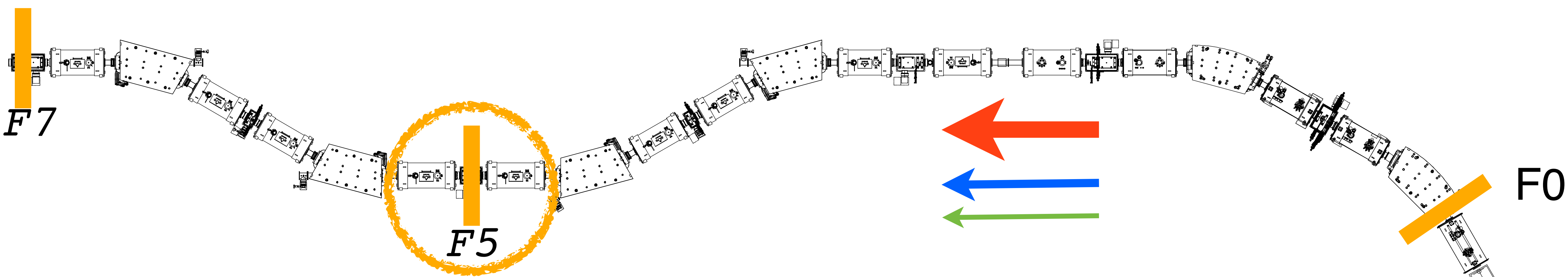
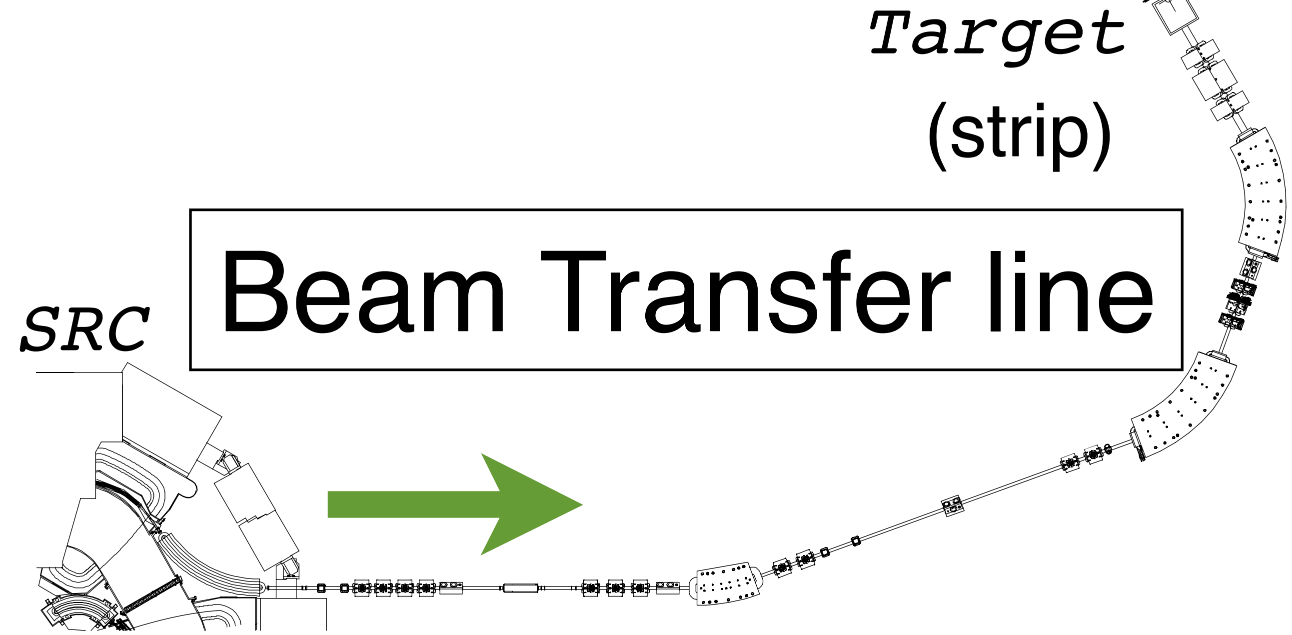
d beam 250 MeV/u
~ 10^{12} /s

Experimental setup

RIKEN Fragment Separator
BigRIPS

^{3}He ~ 10^{2}Hz
(signal)

p ~ 10^{5} Hz
(break up/ background)

BigRIPS

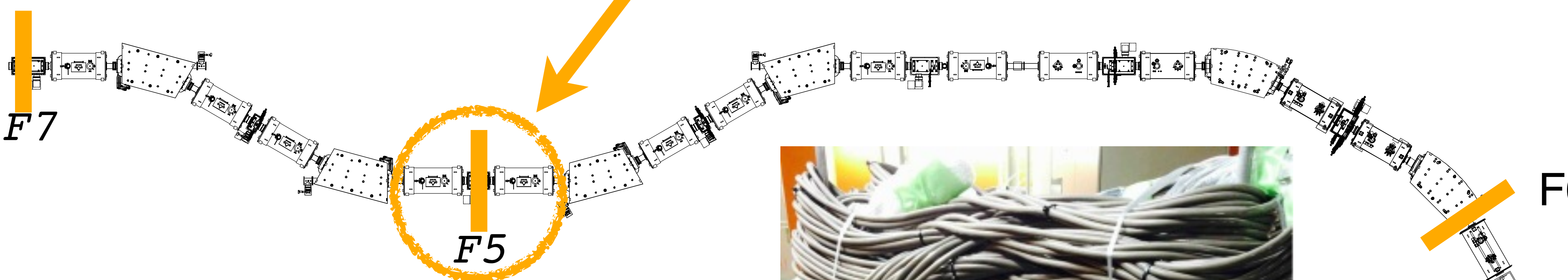
d beam 250 MeV/u
~ 10^{12} /s

Experimental setup: detectors

Tracking by **MWDC**

^{3}He ~ 10^2Hz (signal)

p ~ 10^5 Hz (break up/ background)



Measured position, angle@F5

+

transfer matrix

P_{3He} + reaction angle at target

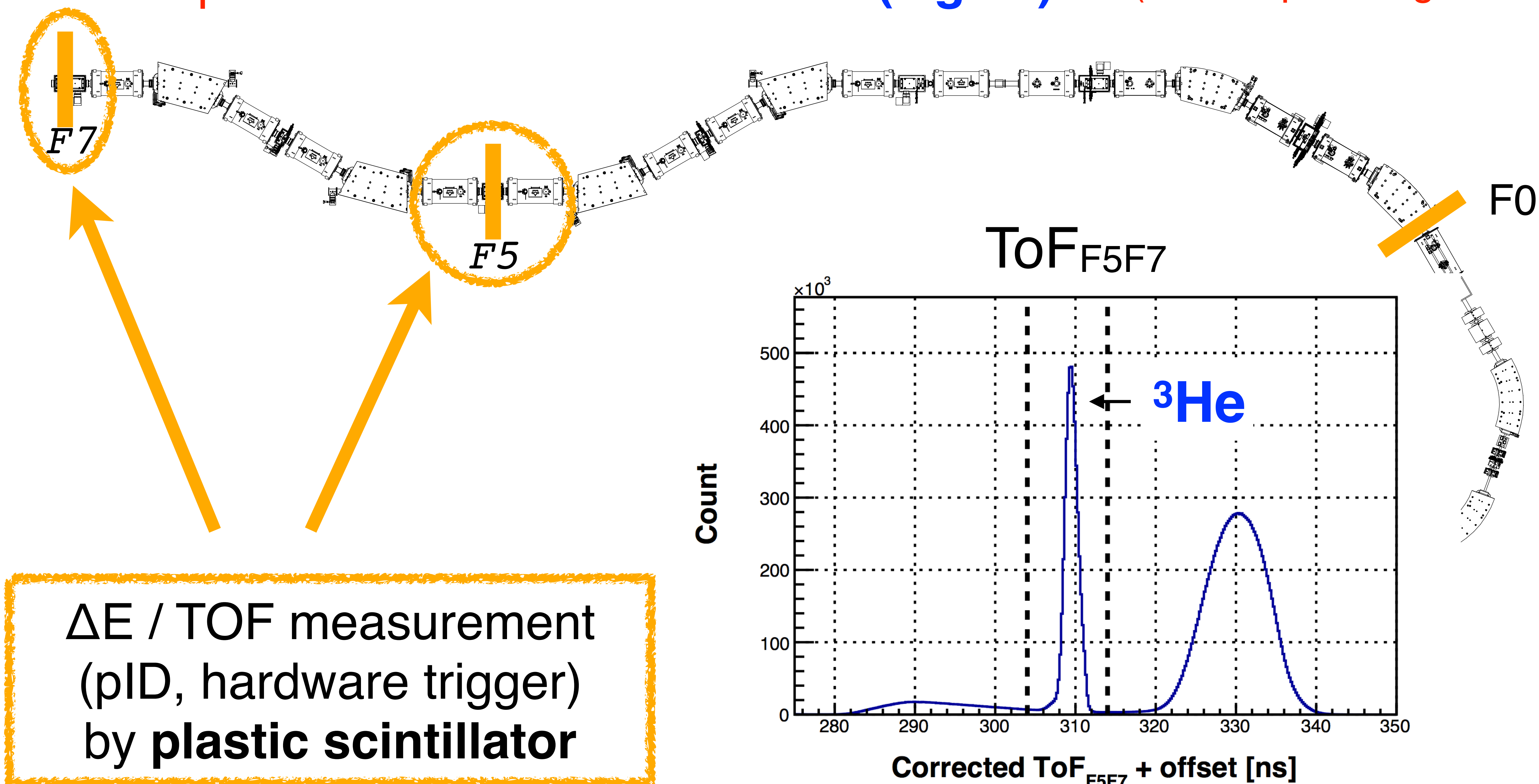
Multi Wire Drift Chamber

Experimental setup: detectors

large part of p:
swept out in F5 - F7

^{3}He ~ 10^2Hz
(signal)

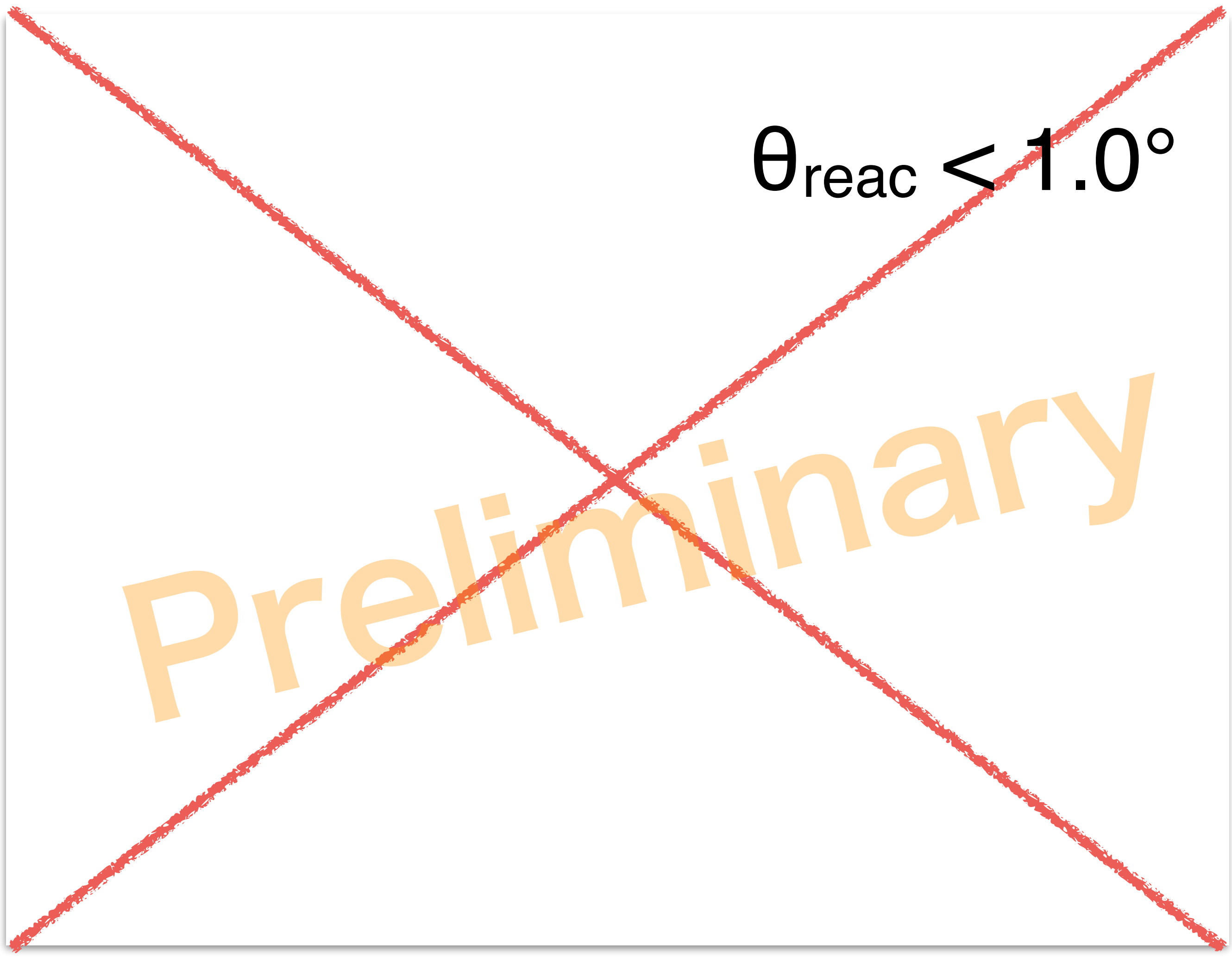
p ~ 10^5 Hz
(break up/ background)



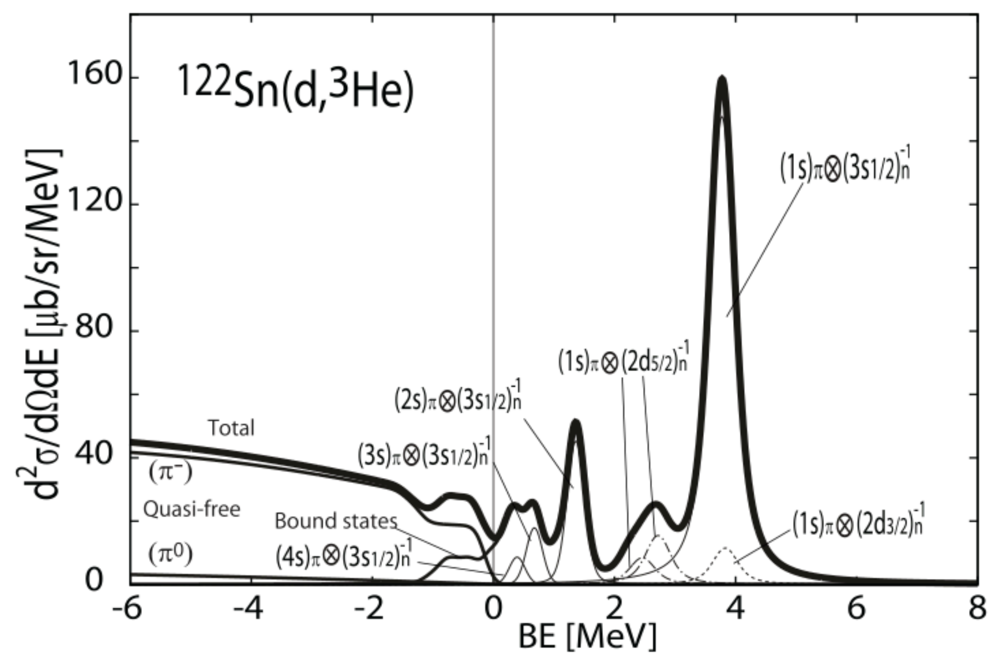
ΔE / TOF measurement
(pID, hardware trigger)
by **plastic scintillator**

Production run: ^{122}Sn target

δp/p spectrum of ^{3}He



cf. theoretical spectrum (0°)

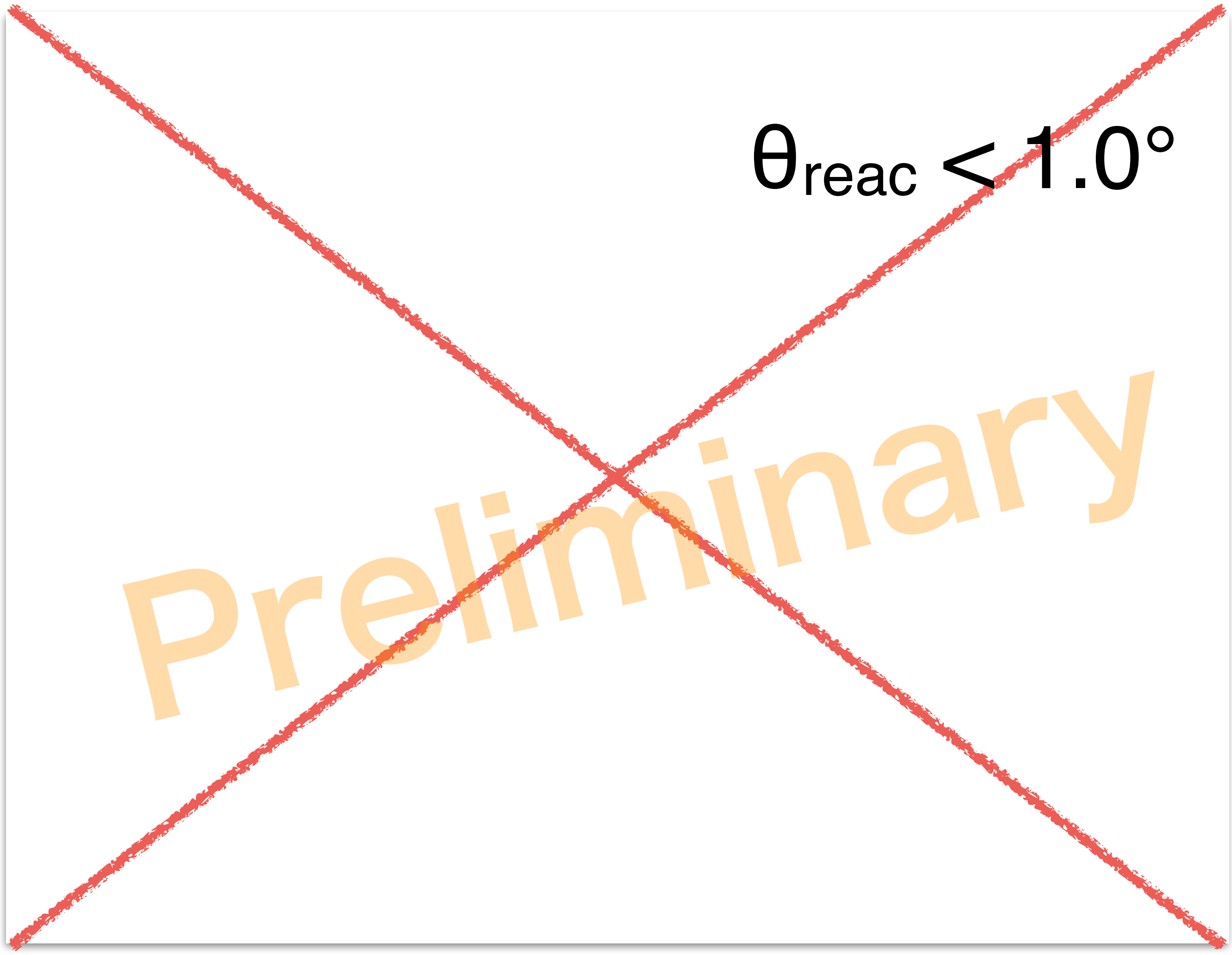


ikeno et al, Prog.Theor.Phys. 126 (2011)

- The spectrum seems to achieve the best resolution among the past deeply-bound pionic atom experiment.
- The spectrum seems consistent with the theoretical calc. qualitatively.

Production run: ^{117}Sn target

δp/p spectrum of ^{3}He



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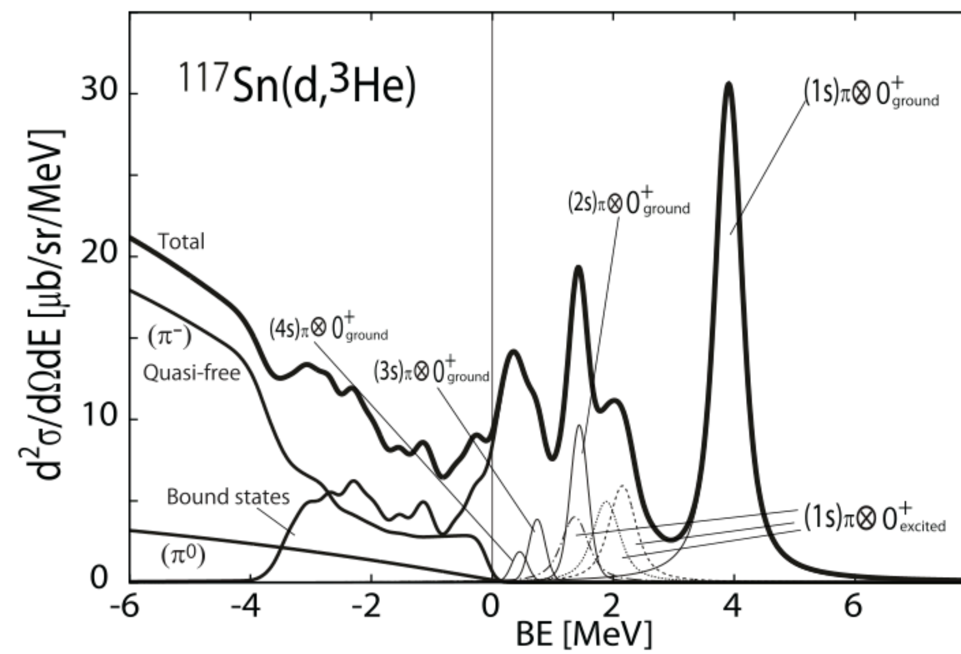

ikeno et al, Prog. Theor. Exp. Phys. 063D01 (2013)

- The first observation of pionic Sn with even-number A.
- The spectrum seems consistent with the theoretical calc. qualitatively.

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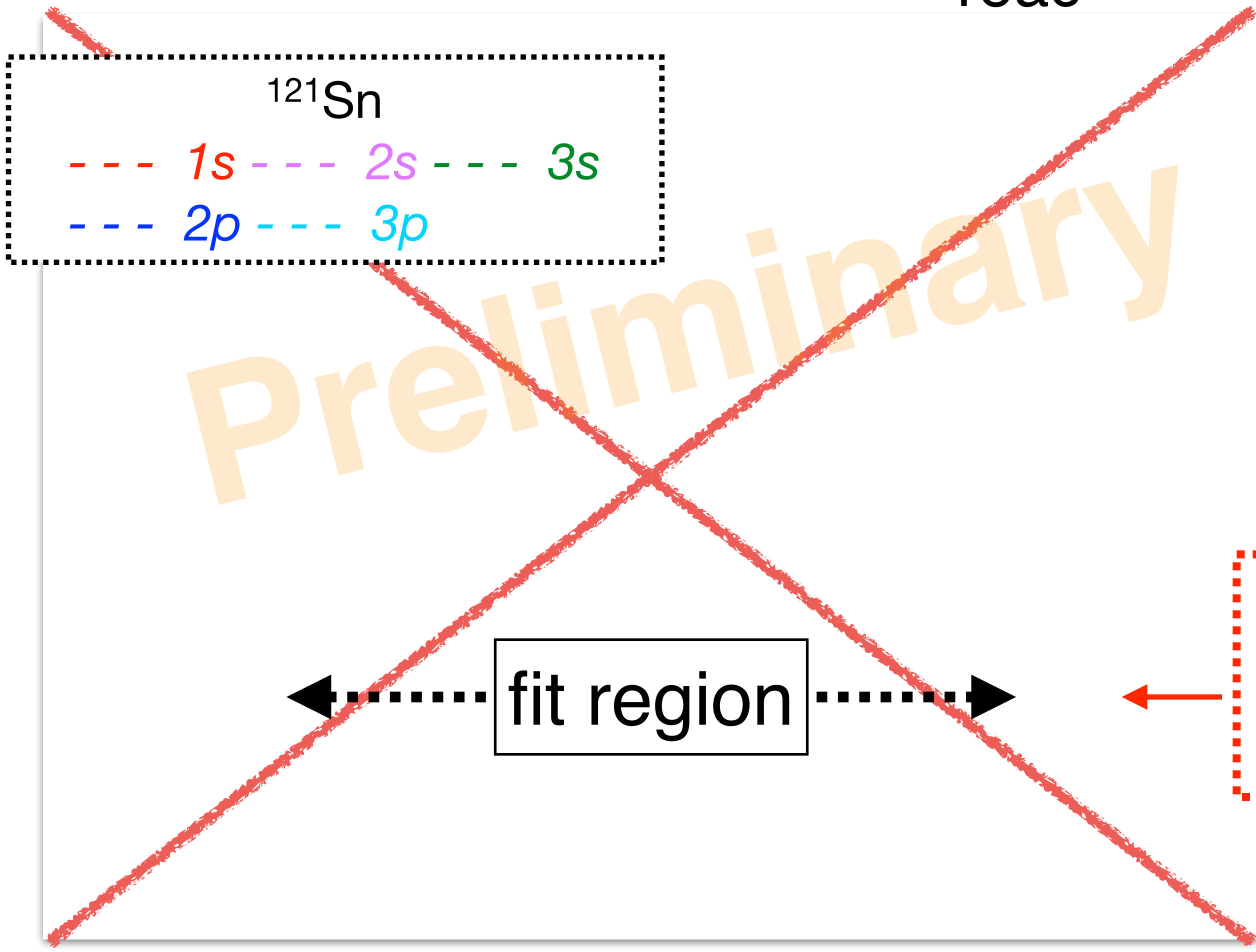
Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



blue solid line : fit function

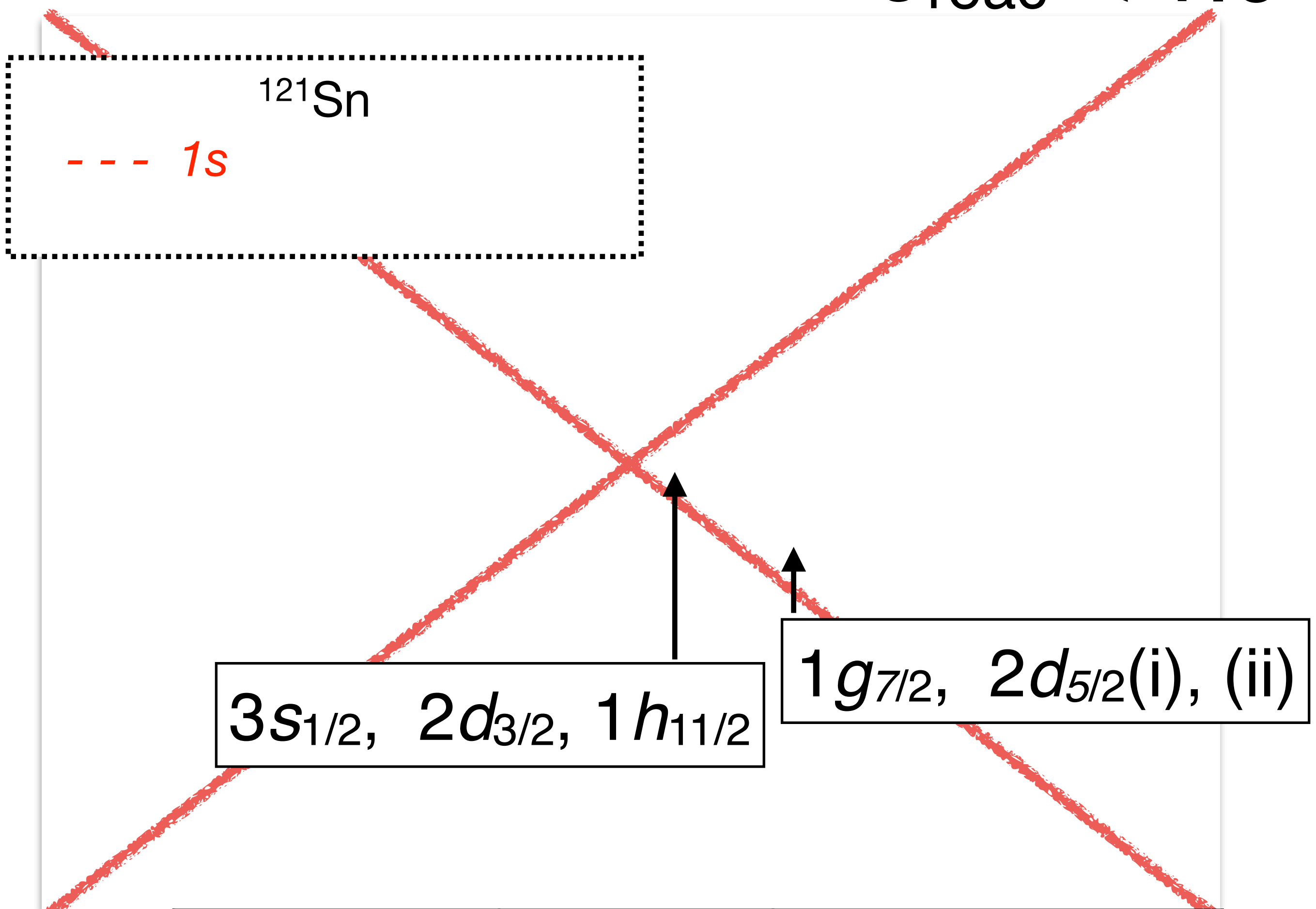
quasi-free π^-
production threshold
139.57 MeV

The E_{ex} spectrum is fit by the function with several components
→ deduce binding energies and widths of pionic states

※ calibration of E_{ex} is still on going…

Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



neutron hole	Eex [MeV]	relative strength for pionic 1*s* state
2	0.000	0.09
1	0.006	0.001
3	0.060	**1**
1	0.926	0.003
2	1.121	0.12
2	1.403	0.06

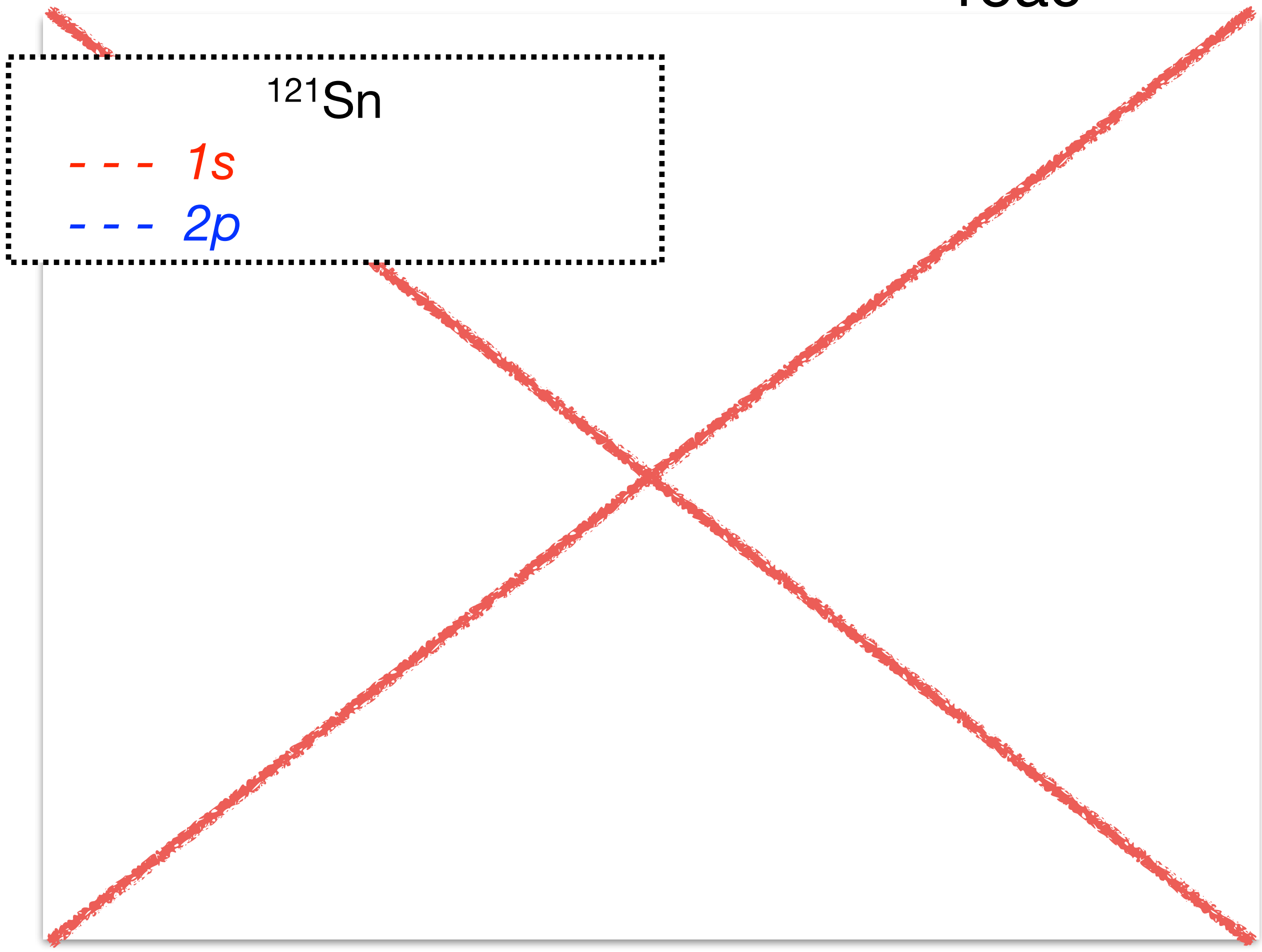
background (solid line / flat)

\+ 1*s* pionic state (dashed line)

each pionic state
→ several configuration
with different neutron holes
each configuration
→ Voigtian / σ_{exp} is fixed

Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$

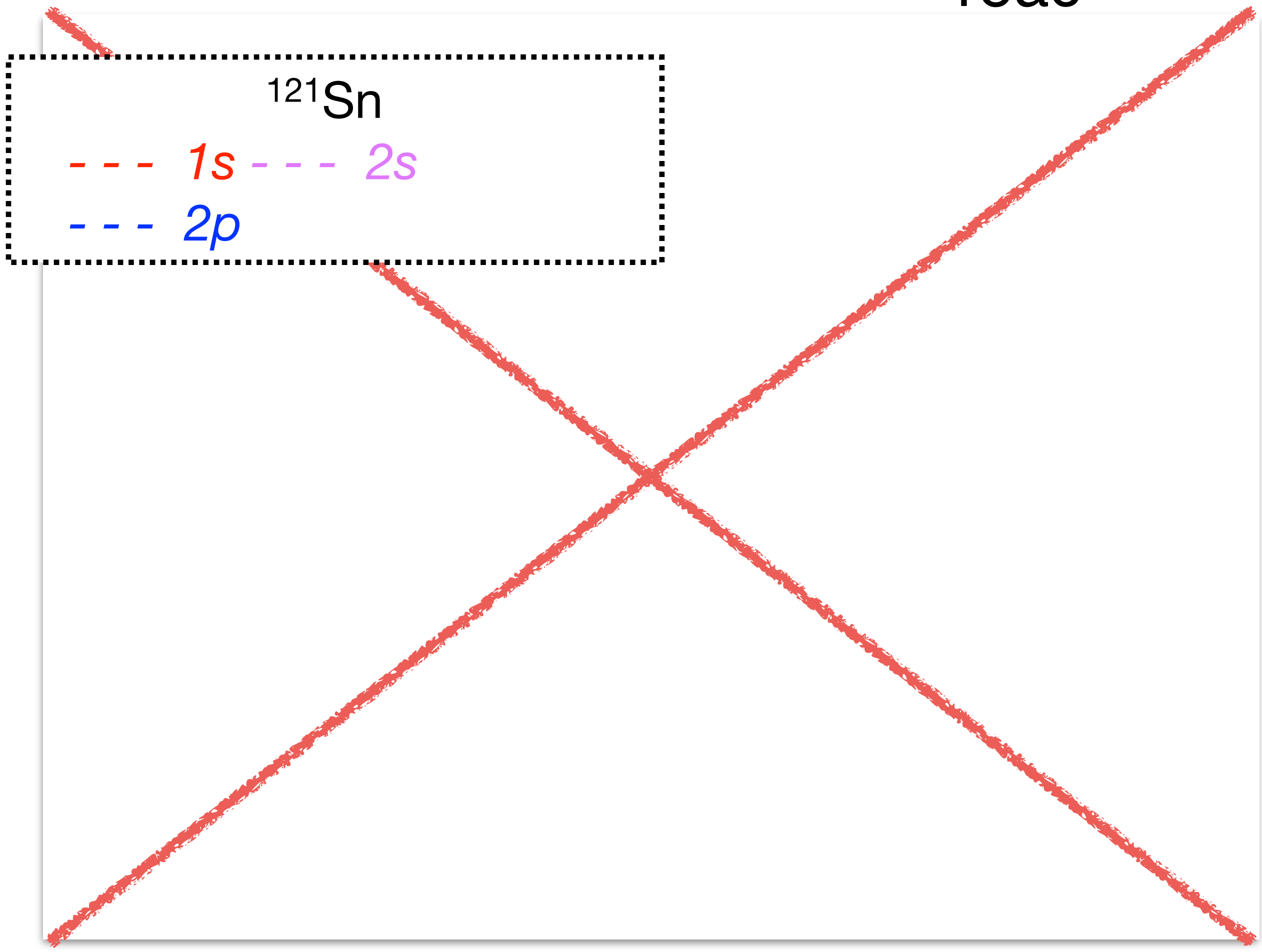


background (solid line / flat)

+ 1*s* pionic state (dashed line)
+ 2*p* pionic state (dashed line)

Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



background (solid line / flat)

+ 1*s* pionic state (dashed line)
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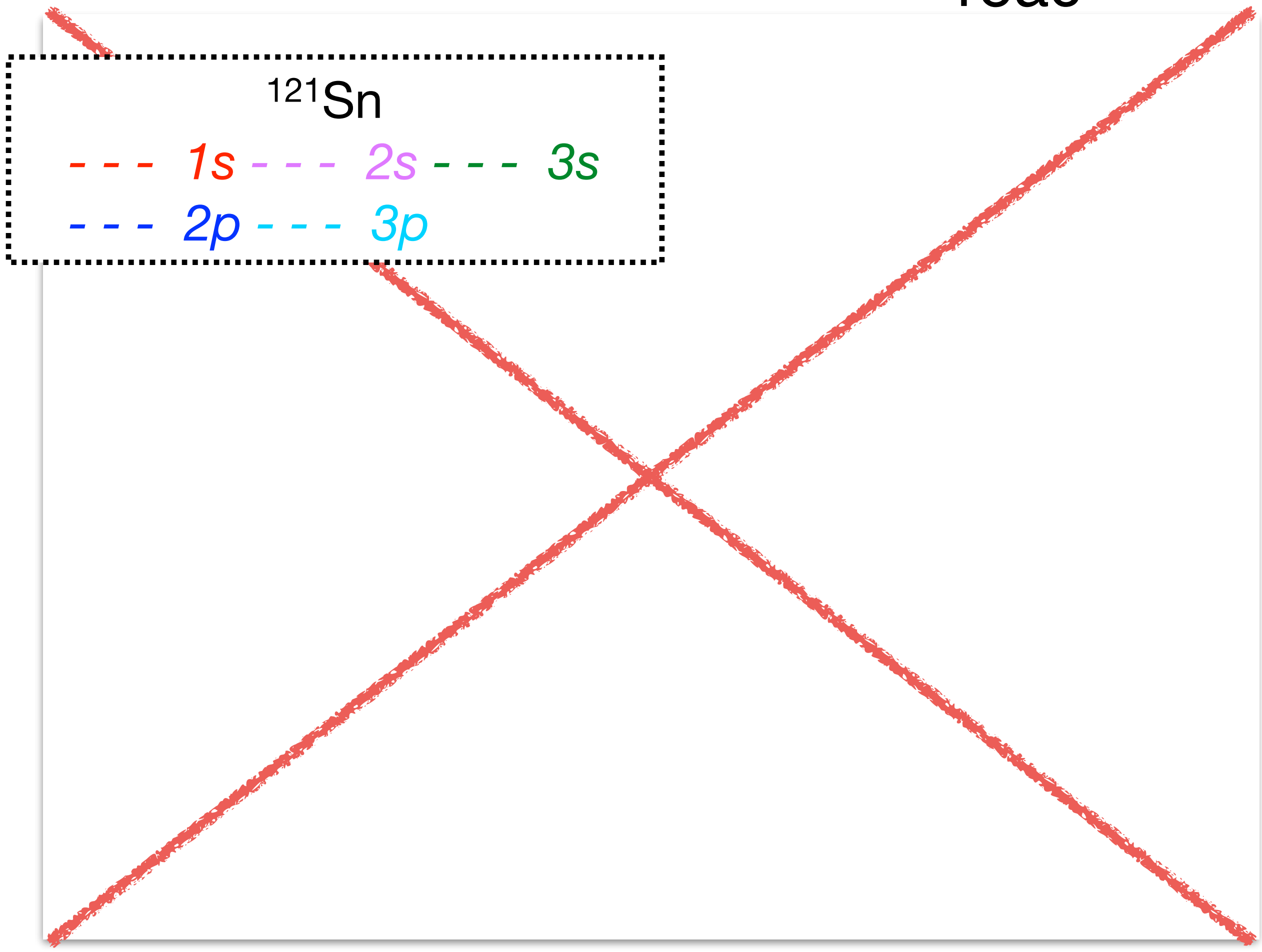


background (solid line / flat)

+ 1*s* pionic state (dashed line)
+ 2*p* pionic state (dashed line)
+ 2*s* pionic state (dashed line)
+ 3*p*, 3*s* state (dashed line)

Fitting parameter

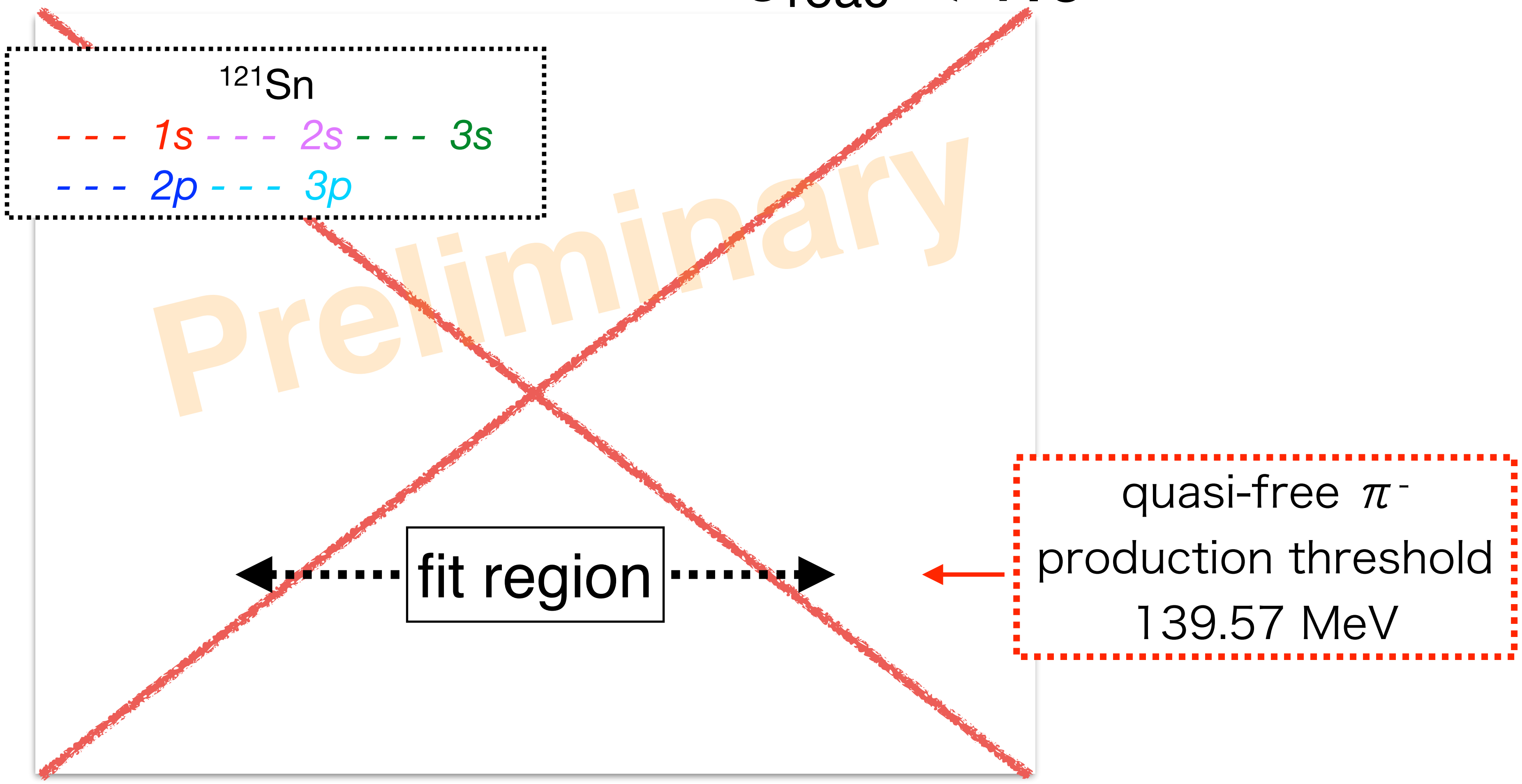
- relative strength of each state
- BE_{1s}, BE_{2p}, BE_{2s}
- Γ_{1s}, Γ_{2p}

Fixed parameter

- BE_{3p}, BE_{3s}
- Γ_{2s}, Γ_{3p}, Γ_{3s}

Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



Deduced BE_{1s}, Γ_{1s}, BE_{2p}

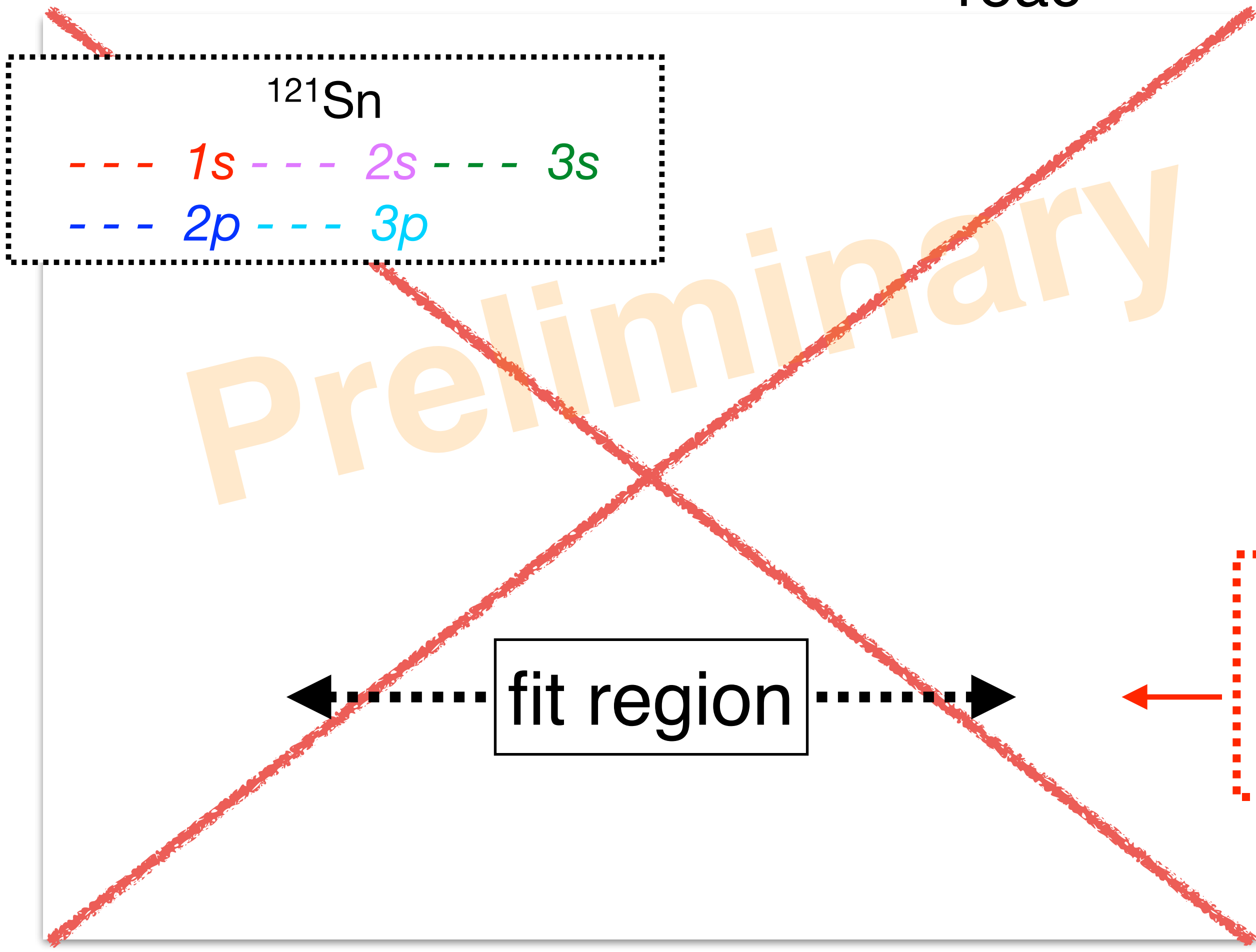
→ b_1, $\mathrm{Im}B_0$ in π-A s-wave optical potential

$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho(r) + b_1\delta\rho(r)\} + \epsilon_2 B_0\rho(r)^2\}].$$

※ b_0 , $\mathrm{Re}B_0$ are deduced from data of light / symmetric pionic atoms

Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



quasi-free π^-
production threshold
139.57 MeV

Deduced BE_{1s}, Γ_{1s}, **BE_{2p}**

→ b_1, ImB_0 in π-A s-wave optical potential

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Fitting of the E_{ex} spectrum : ^{117}Sn target

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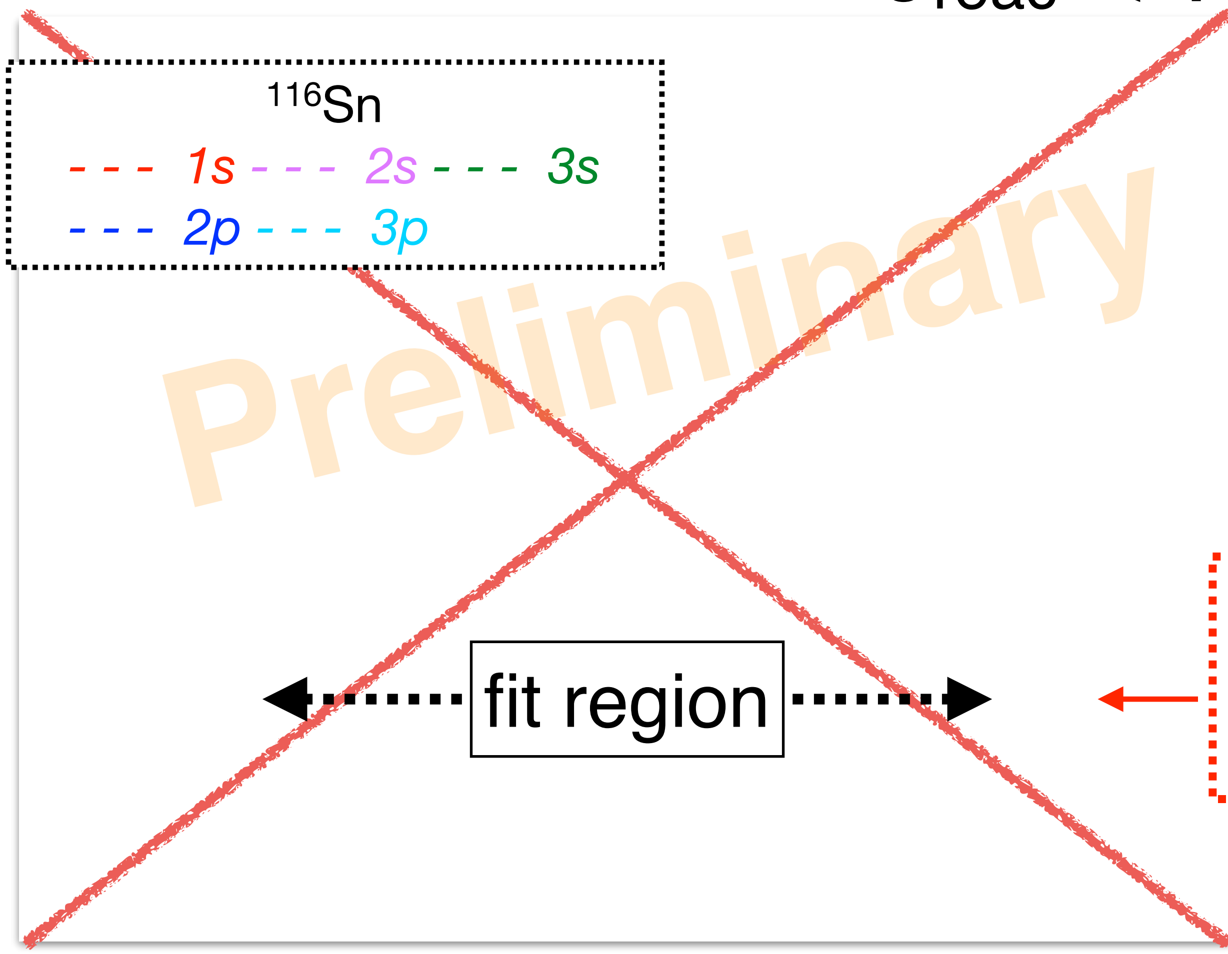

quasi-free π^- production threshold 139.57 MeV

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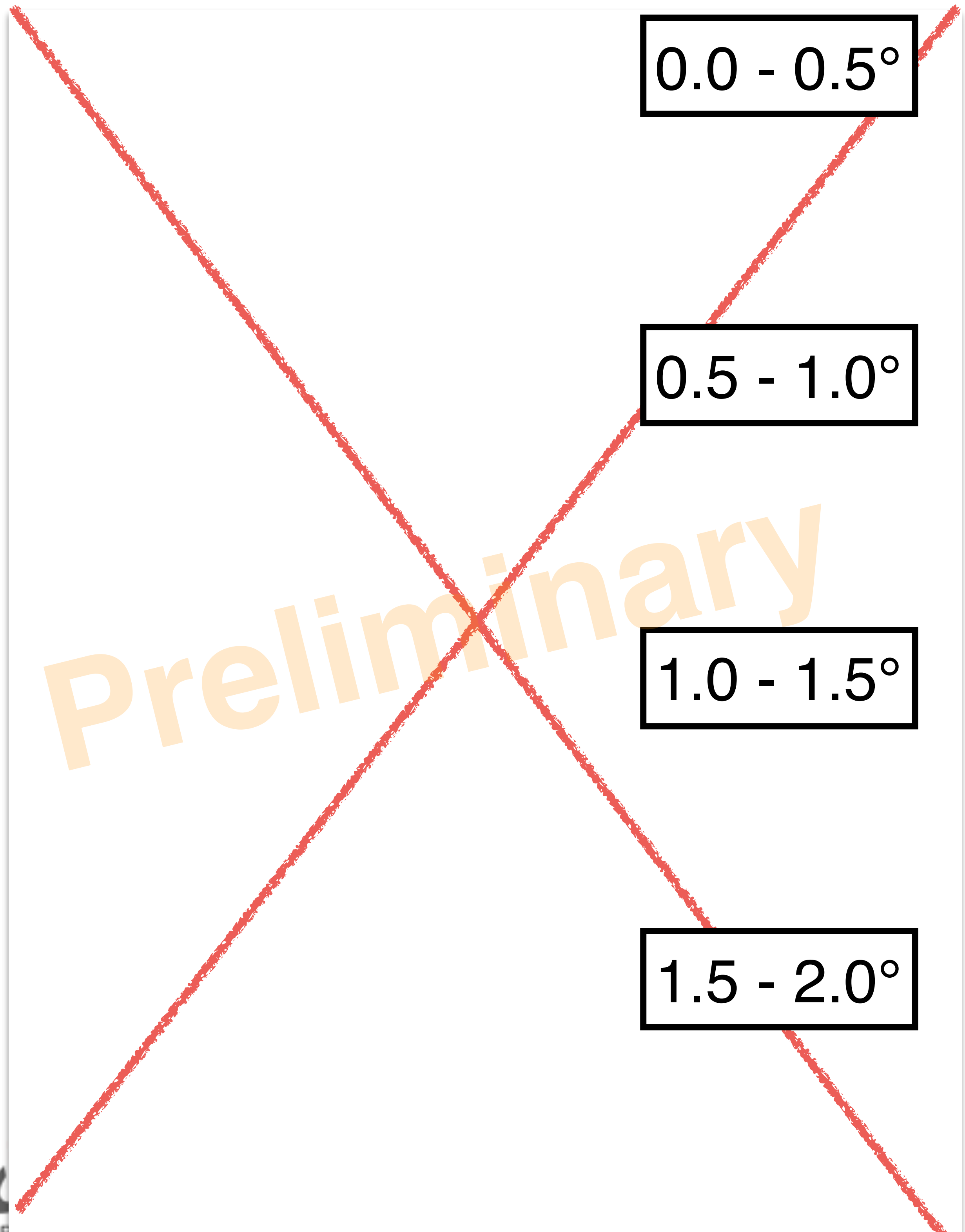
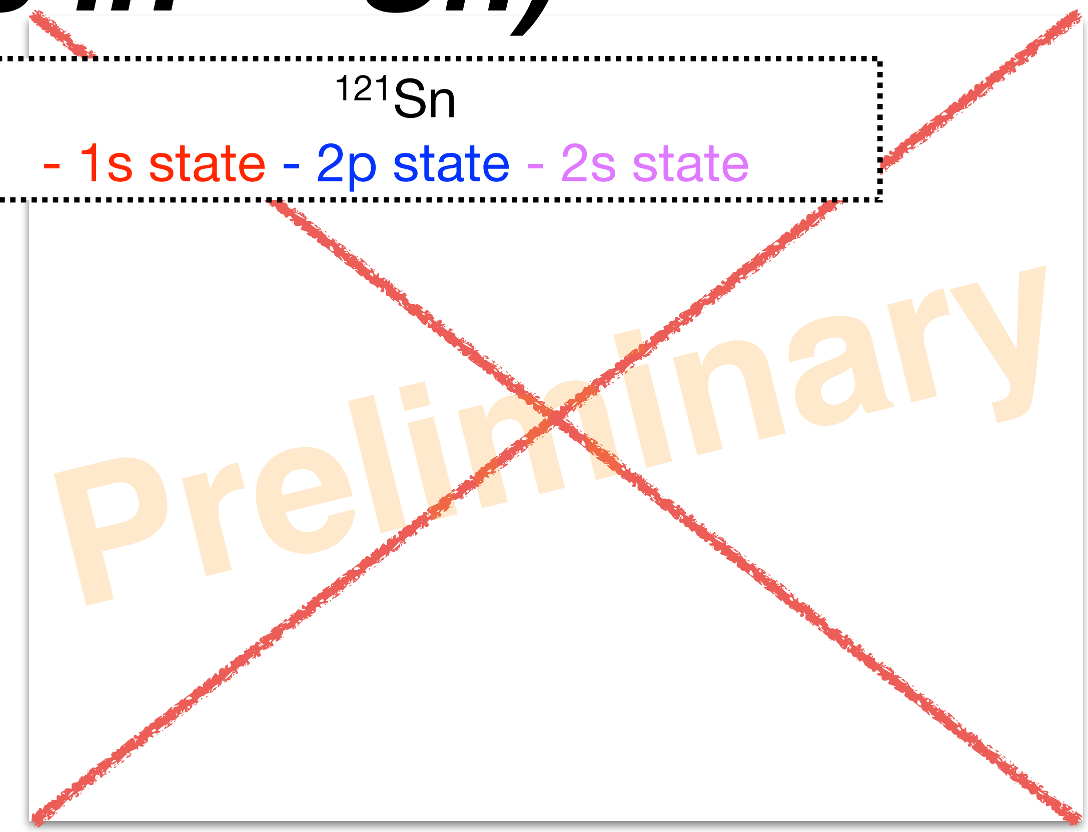
※ b_0 , ReB_0 are deduced from data of light / symmetric pionic atoms

θ_{reac} dependence of each components (pionic states in ^{121}Sn)

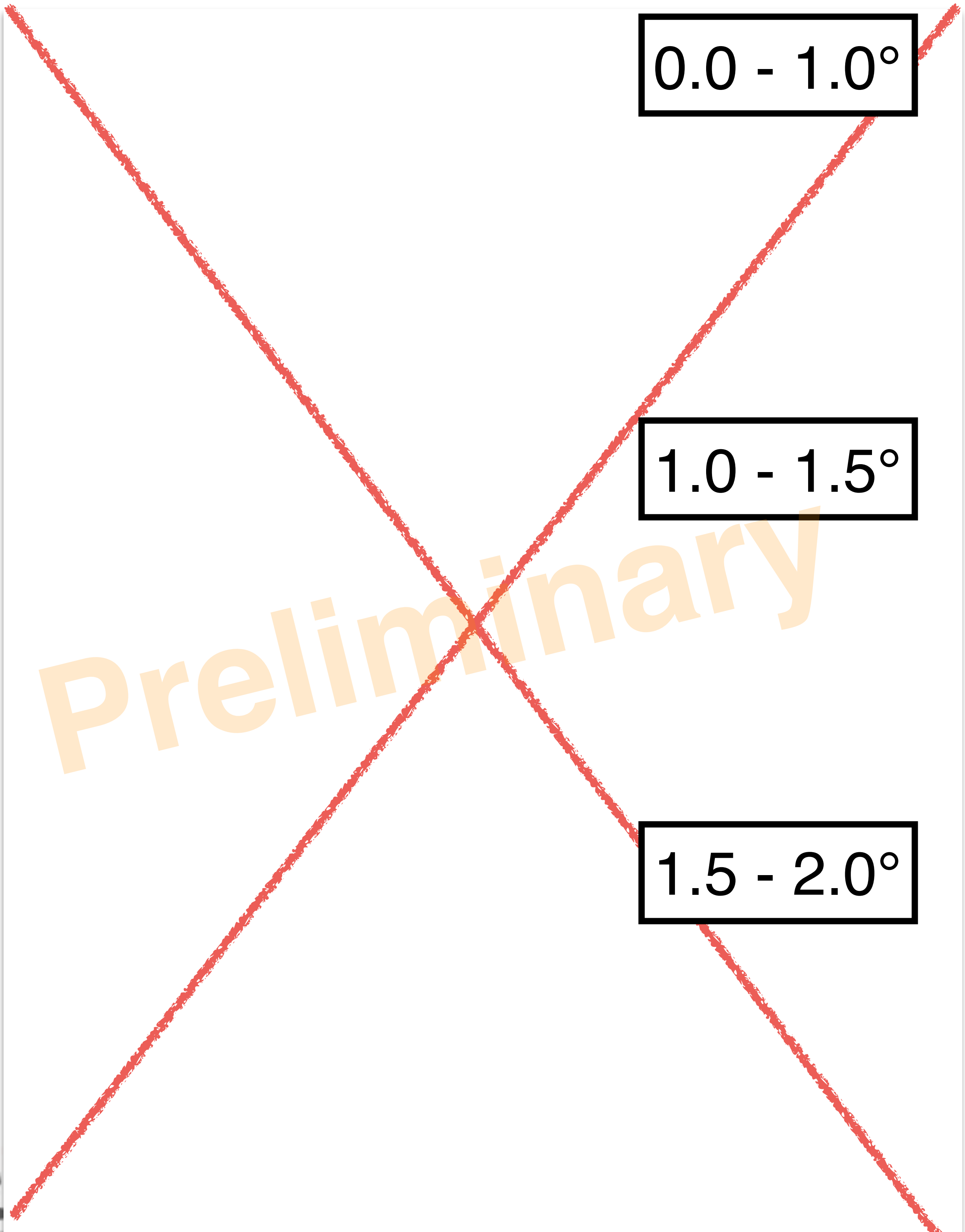


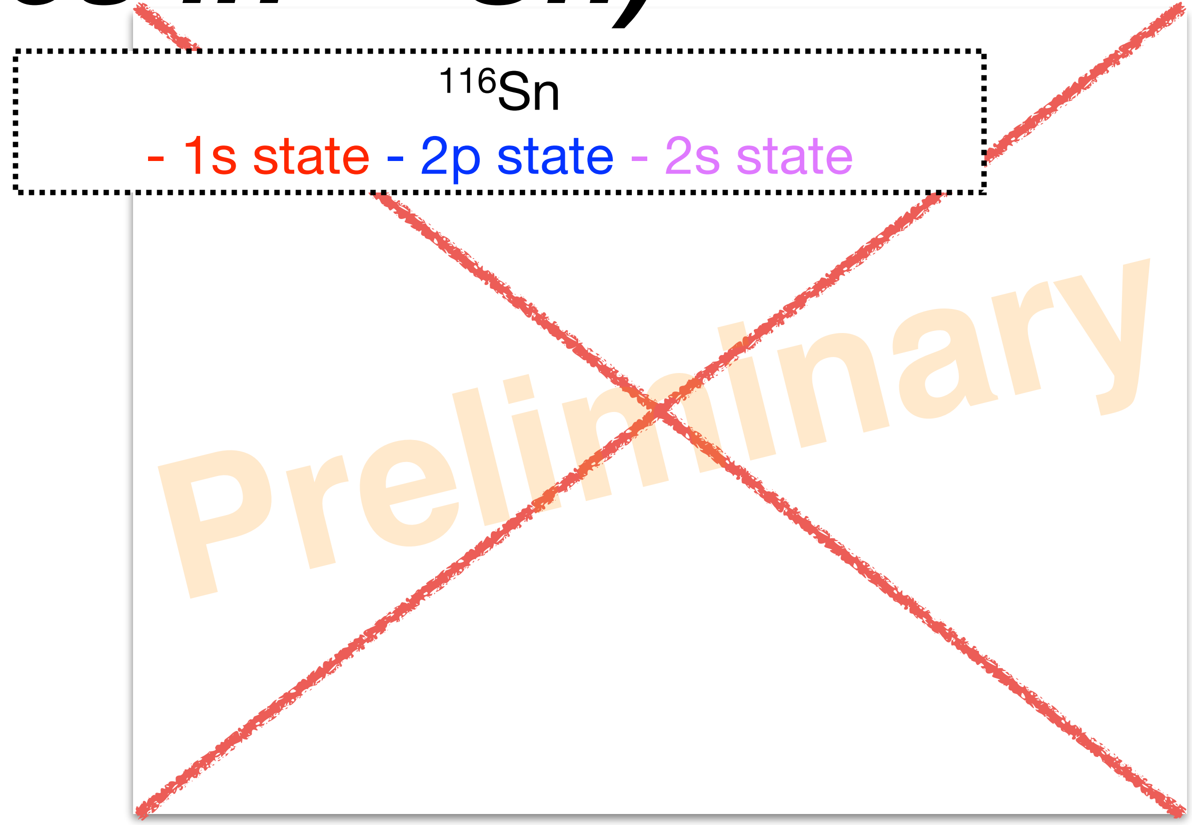


Solid line : theoretical prediction
(N. Ikeno, private communication / normalized)

Large θ_{reac}
→ large momentum transfer
→ large angular momentum transfer
→ **finite n state increase (2p)**

θ_{reac} dependence of each components (pionic states in ^{116}Sn)

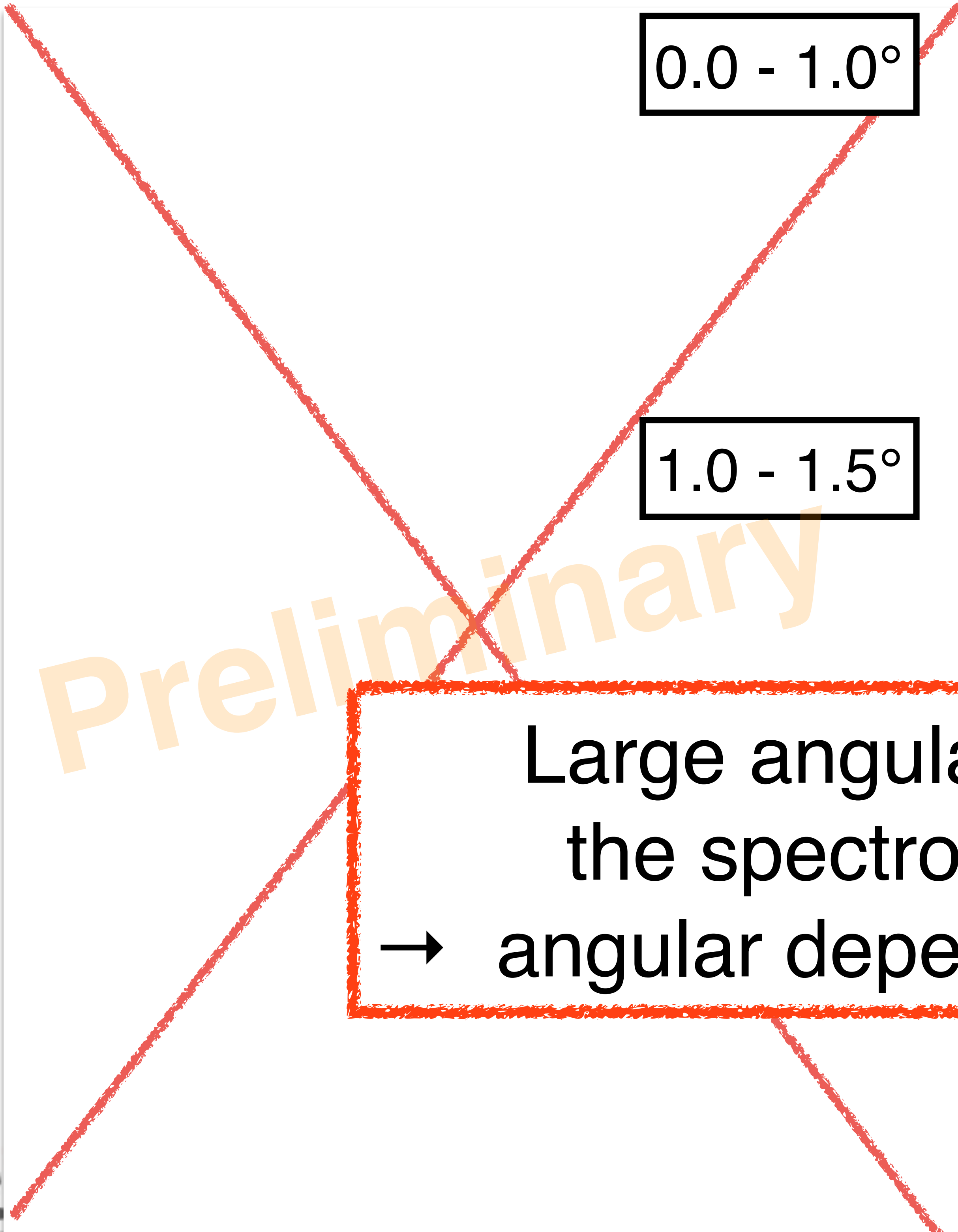


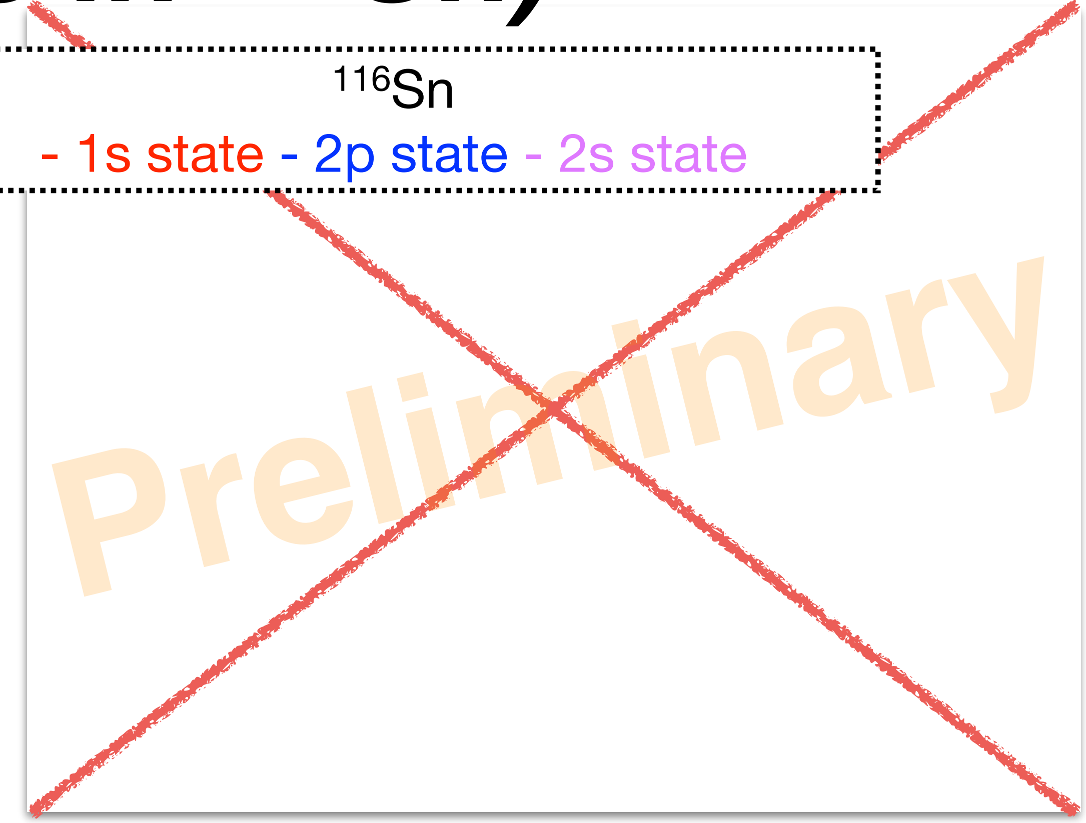


Solid line : theoretical prediction
(N. Ikeno, private communication / normalized)

Large θ_{reac}
→ large momentum transfer
→ large angular momentum transfer
→ **finite n state increase (2p)**

θ_{reac} dependence of each components (pionic states in ^{116}Sn)





Solid line : theoretical prediction
...on / normalized)

Large angular acceptance of the spectrometer@RIKEN → angular dependence of $d^2\sigma/dEd\Omega$

...sfer
→ large angular momentum transfer
→ **finite n state increase (2p)**

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Summary

- Deeply-bound pionic atom is good probe for QCD in finite density, especially for quark condensate via b_1 parameter in π - A potential.
- To determine the b_1 precisely, experiments of pionic Sn isotopes are on going at RIKEN.
- In the first exp. , we measured with the target of ^{117,122}Sn, and succeed in
  - improvement of the resolution,
  - observation of the pionic 1s, 2p and 2s states (at least) in $^{121,\ 116}$Sn,
  - observation of angular dependence of these states.
- Analysis to deduce b_1 from measured BE_{1s}, BE_{2p}, Γ_{2s} is in progress.

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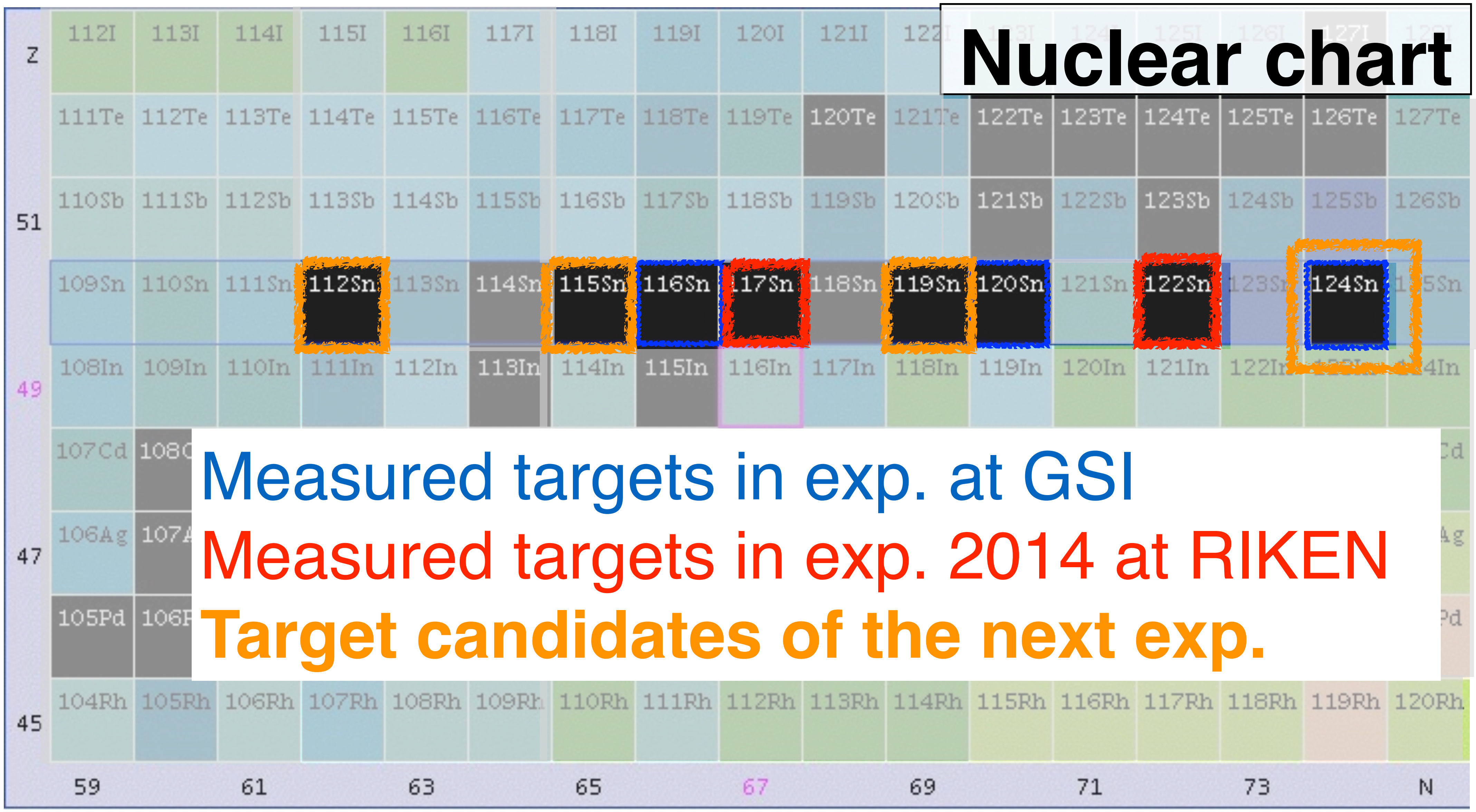
(Near) future works

NuDat



The next exp. are already approved in PAC at RIKEN with wider range of isotopes.

<u>The exp. will be performed in a few years.</u>