Precision spectroscopy of deeply bound pionic states in tin isotopes at RIBF

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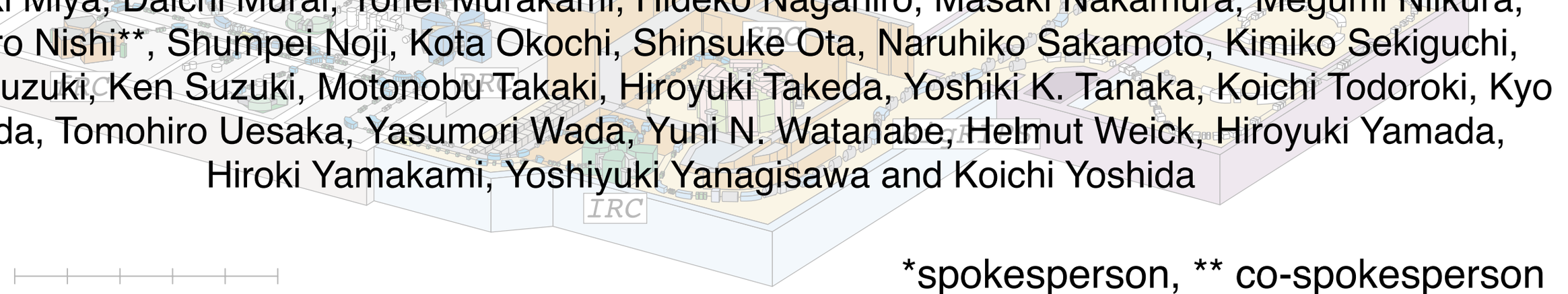

*spokesperson, ** co-spokesperson

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

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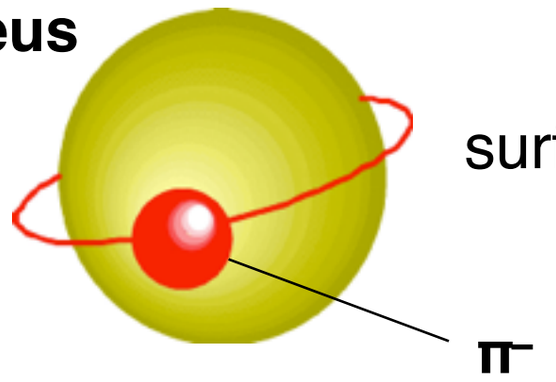
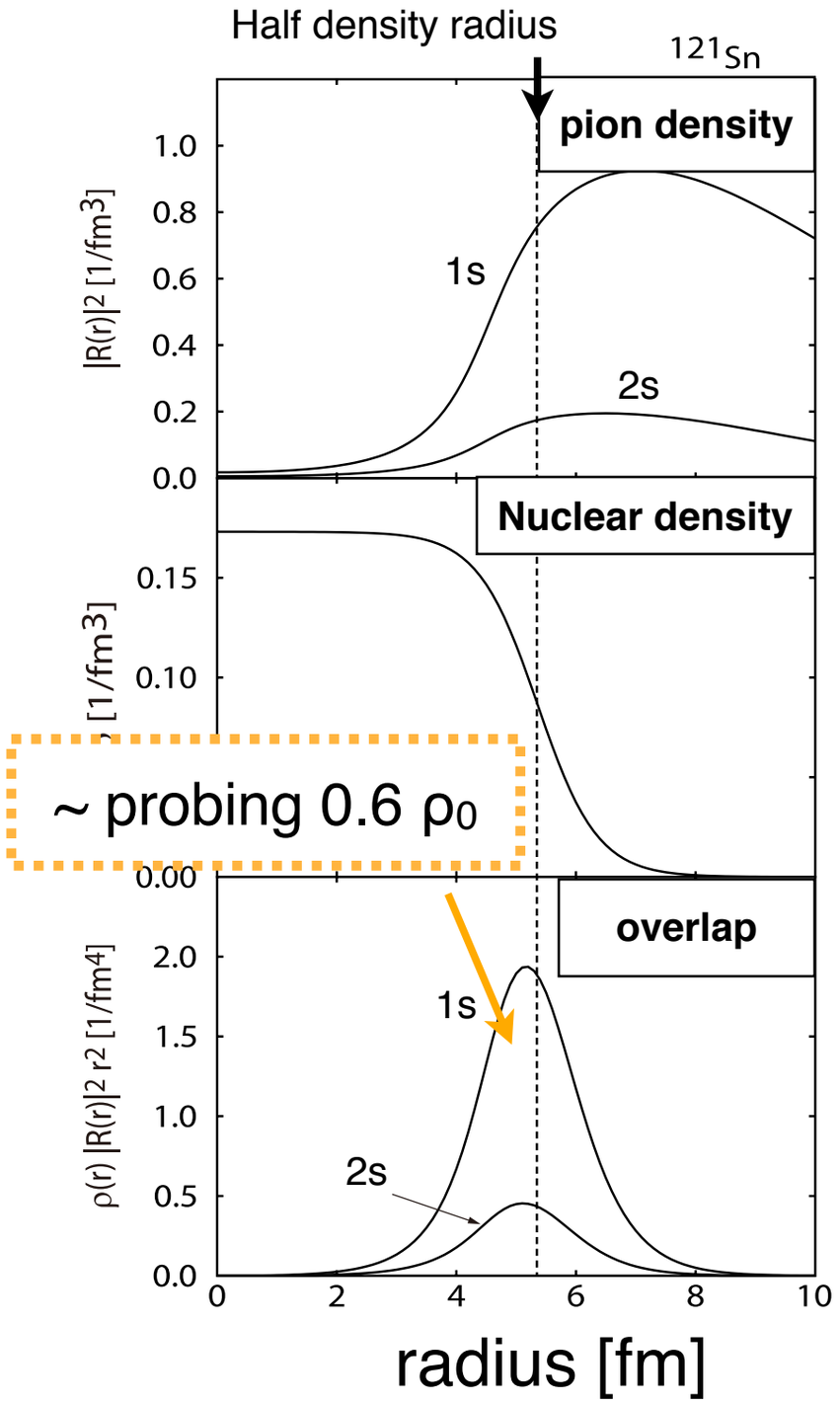
Deeply bound pionic states



pion orbit :
surface on the nuclei

deeply bound pionic states
→ Large overlap between π and A

good probe for strong interaction at finite ρ



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

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Strong interaction and pionic states

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

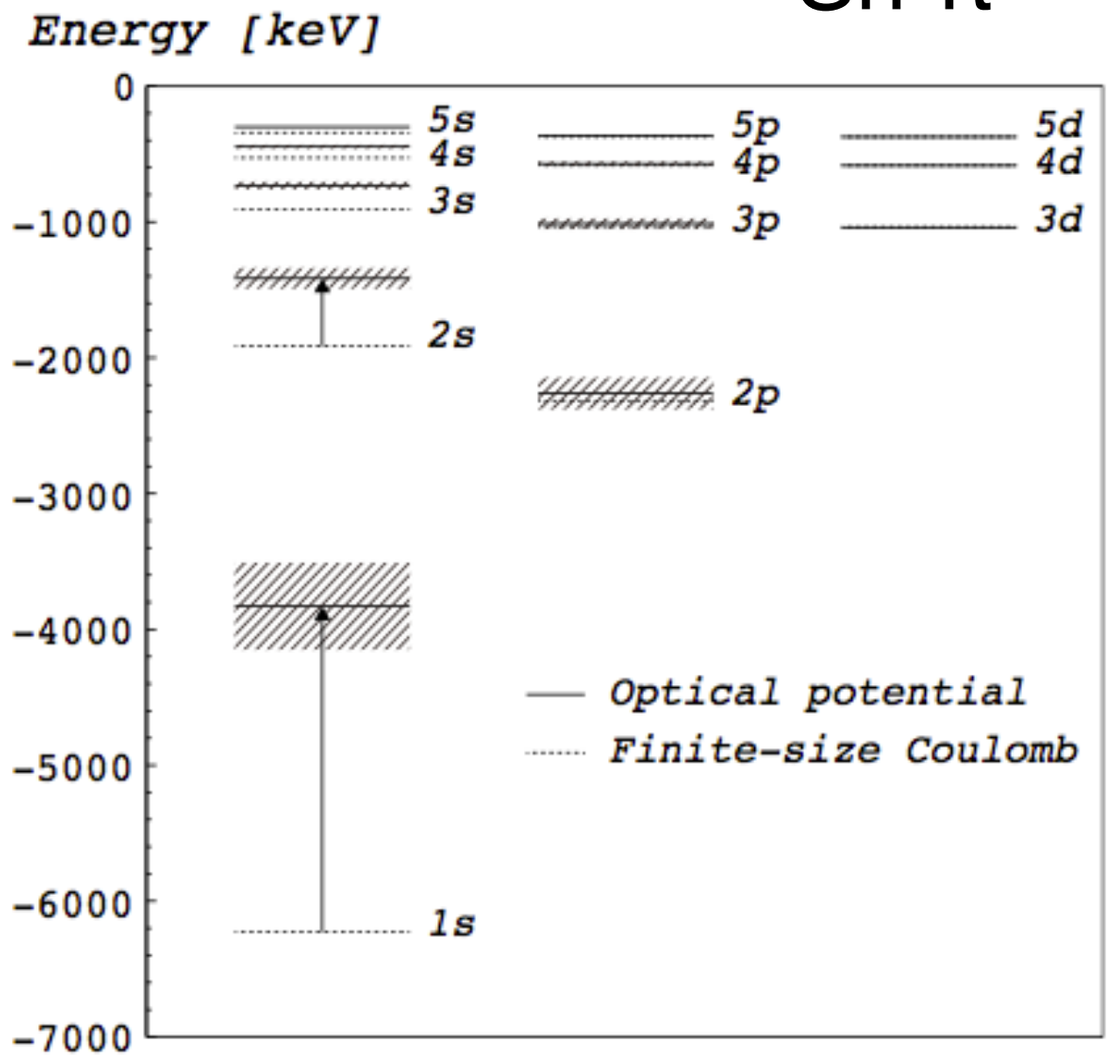
π-A s-wave optical potential (s-wave)

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

$\rho = \rho_p + \rho_n$

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

^{121}Sn-π$^-$



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

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Strong interaction and pionic states

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π-A s-wave optical potential (s-wave)

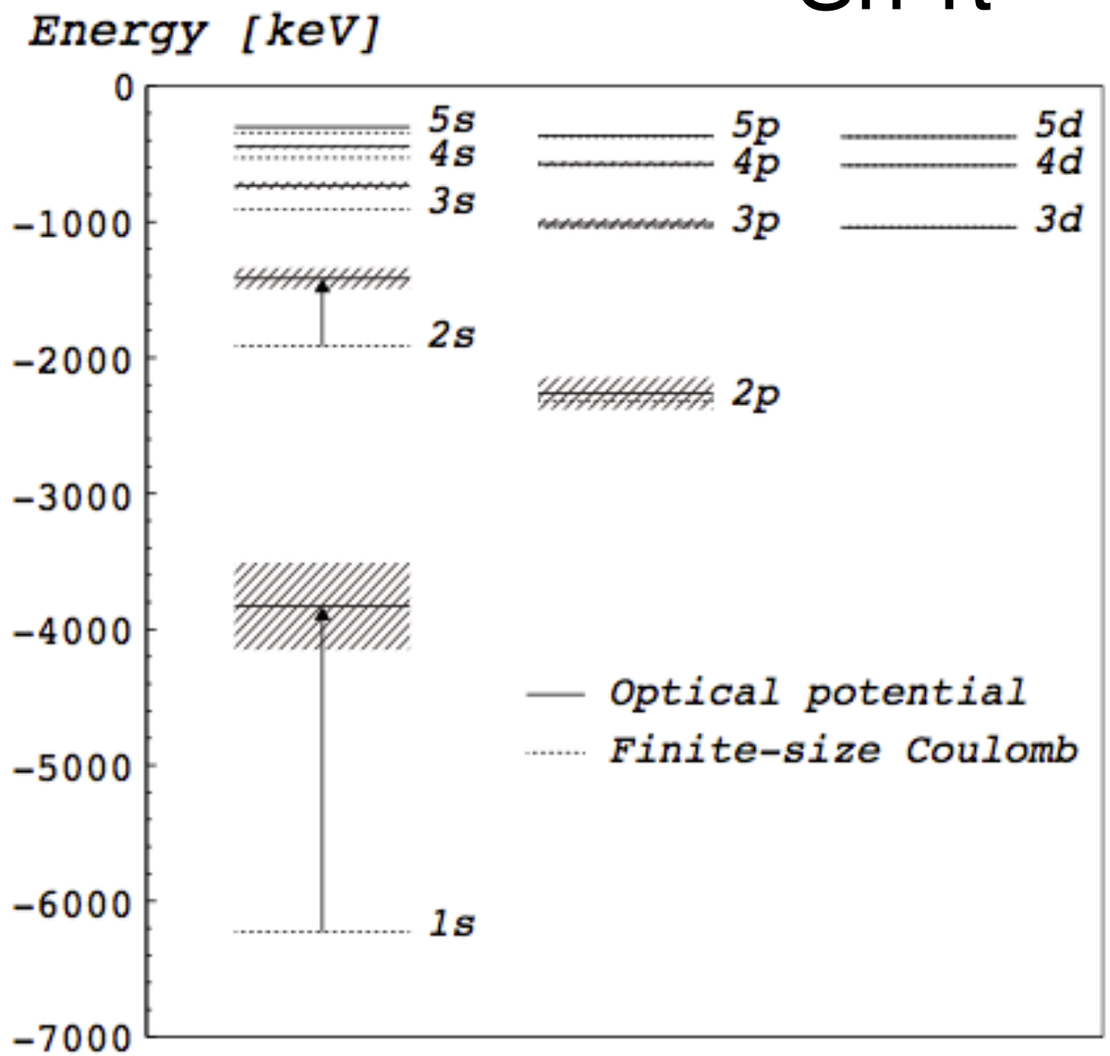
$$V_s(r) = -\frac{2\pi}{\mu}[\epsilon_1\{b_0\rho + b_1\delta\rho\} + \epsilon_2 B_0\rho^2]$$

strong relation with quark condensate

↓

Order parameter of chiral symmetry breaking

^{121}Sn-π$^-$



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

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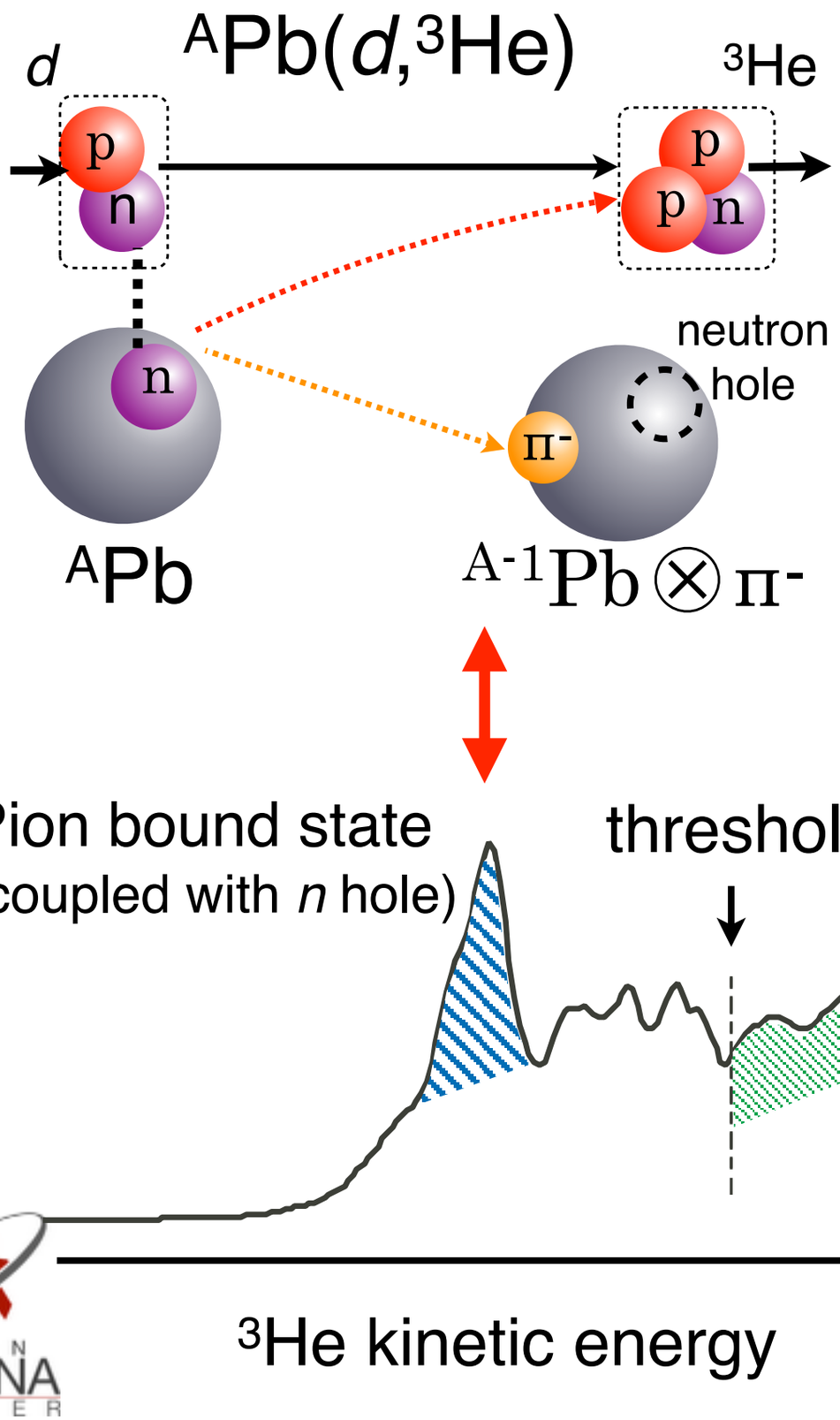
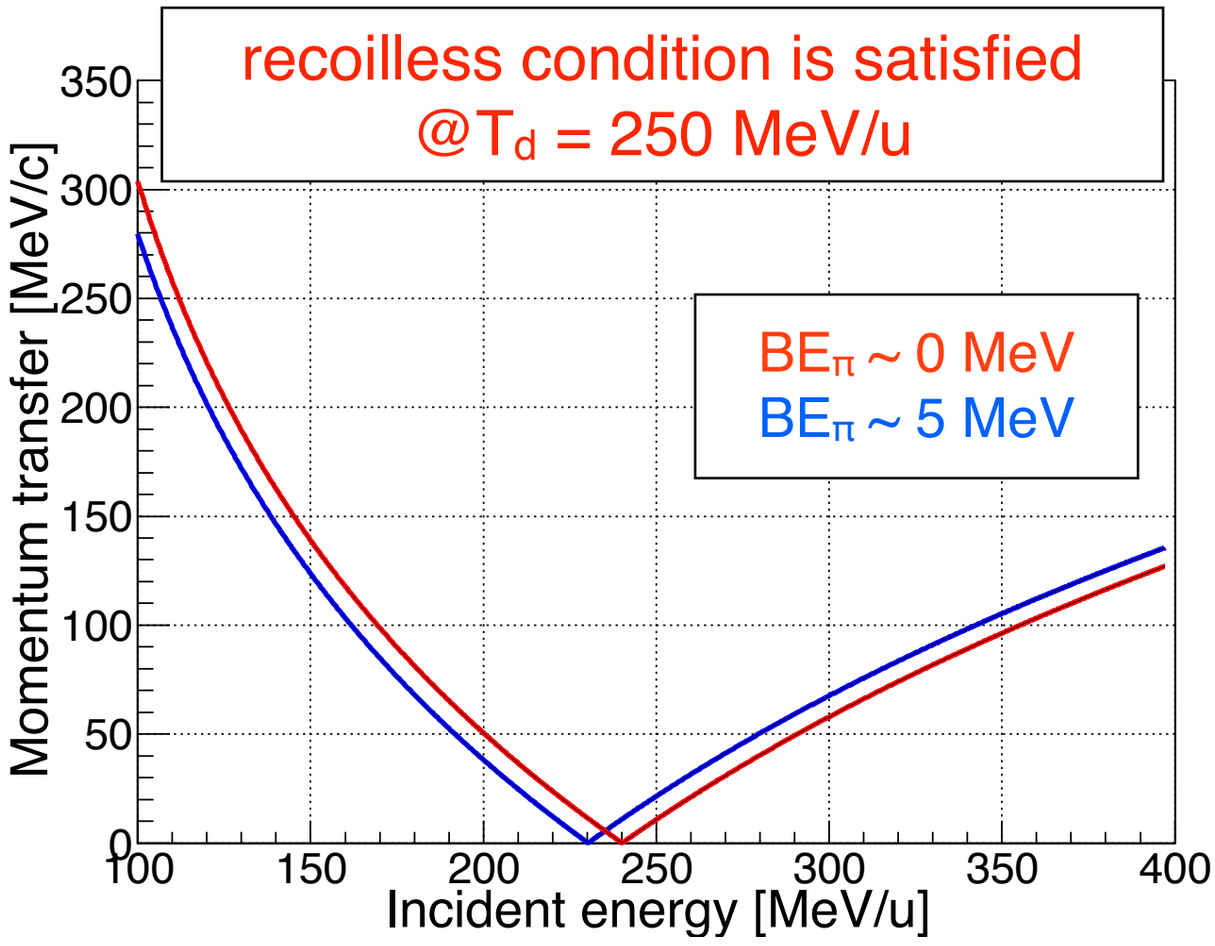
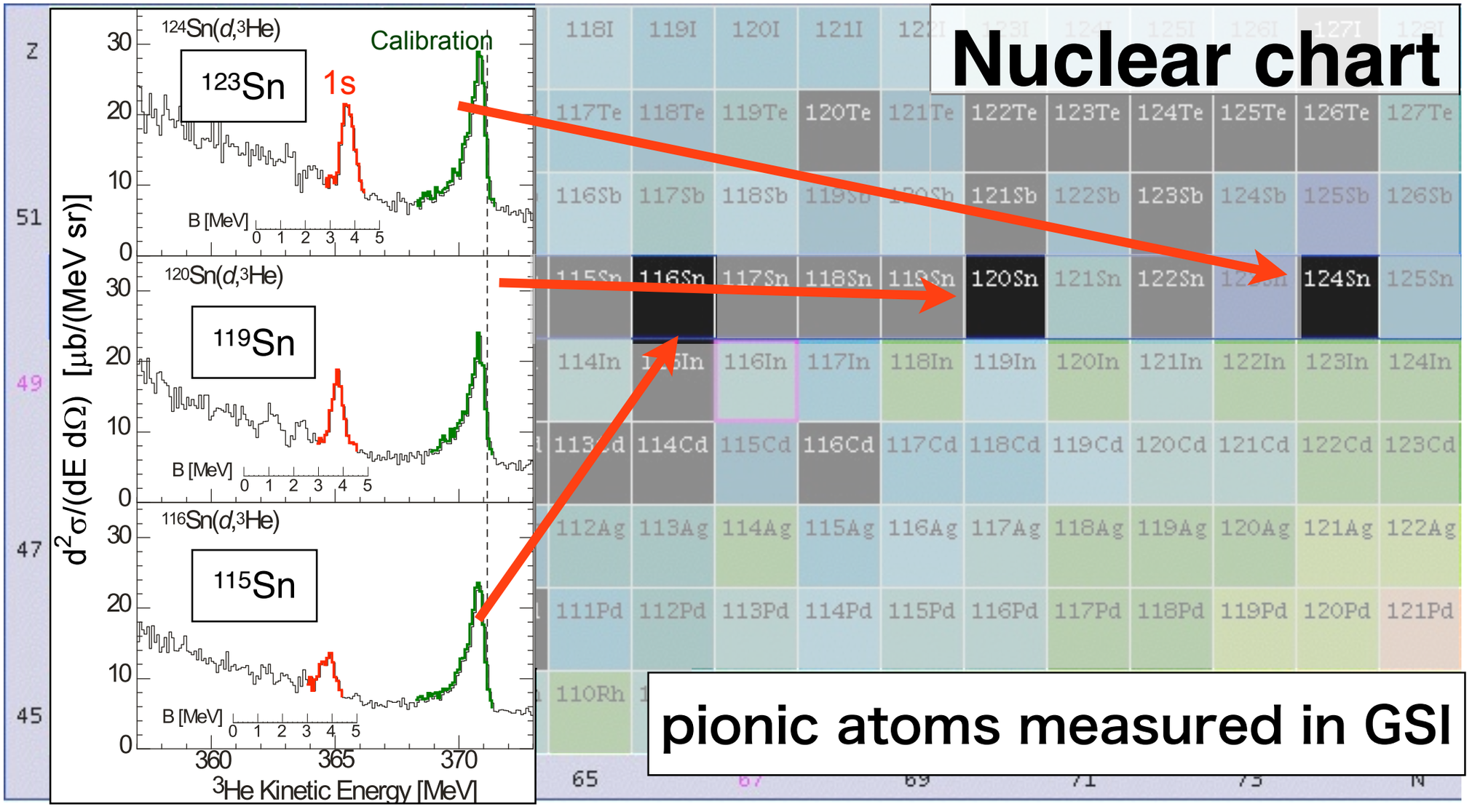
Production method; (d,^{3}He) reaction





Deeply bound pionic atoms at GSI



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

Systematic study of pionic Sn isotopes

~ **3 month** measurement for 3 isotopes

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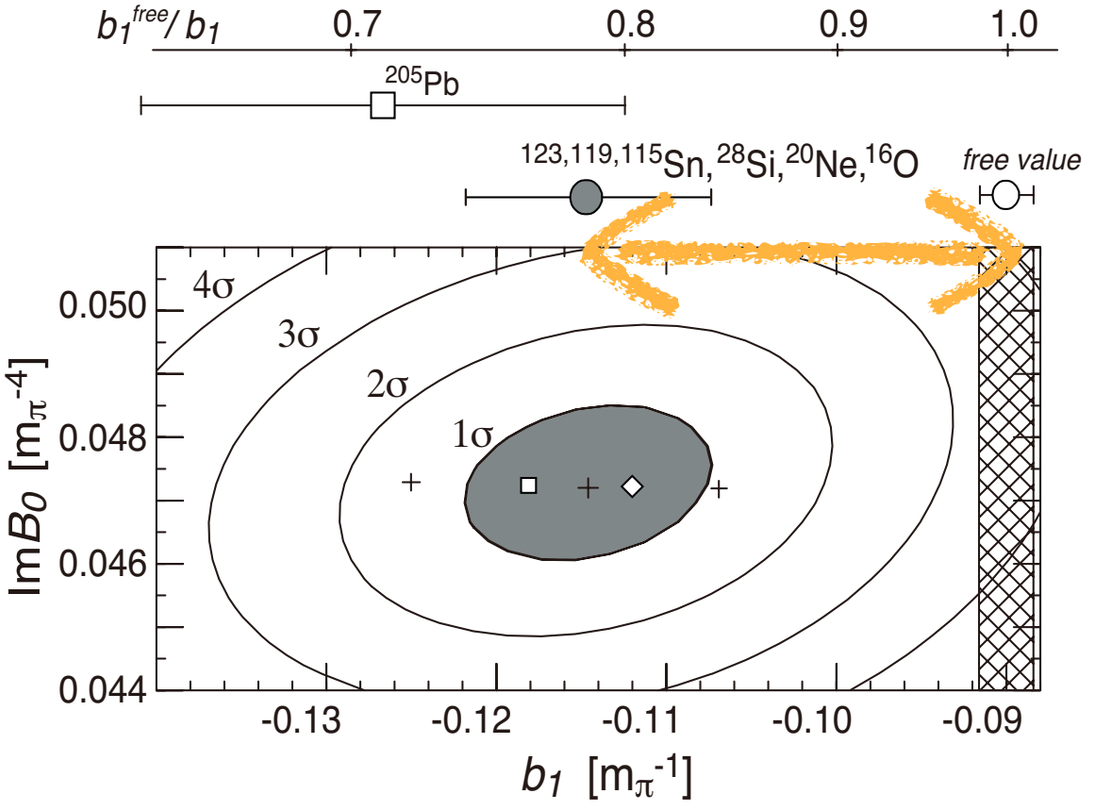
Extract b_1 from experimental data

Contour plot of χ^2



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

cf. theoretical prediction ~ 0.65

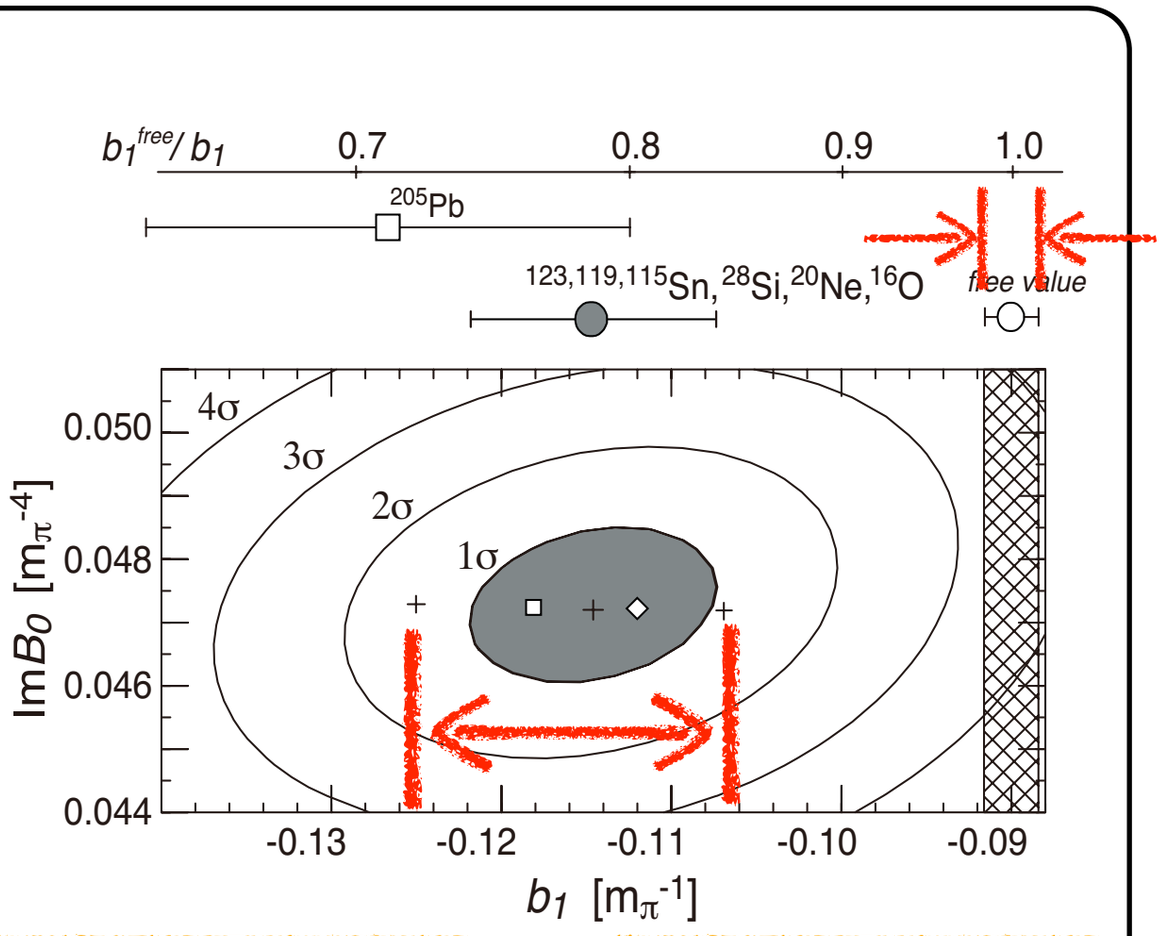
π-A s-wave optical potential

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

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

Extract b_1 from experimental data

Contour plot of χ^2



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

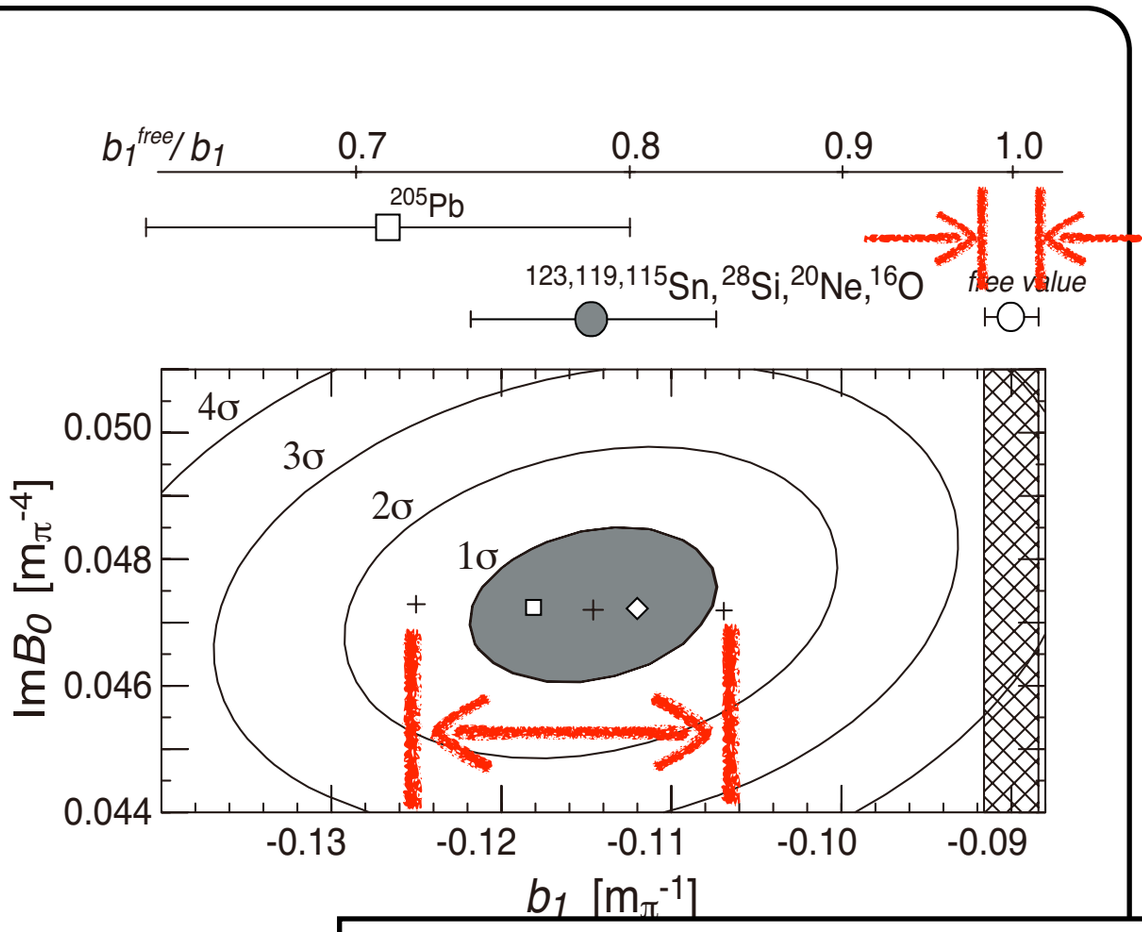
error of b_1 in medium is still large compared with that in vacuum!!
two main sources are

- **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



$$\frac{b_1^{\rm free}}{b_1} = 0.78 \pm ($$

cf. theo

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**

To extract b_1 with higher precision
improve resolution / calibration
More isotopes

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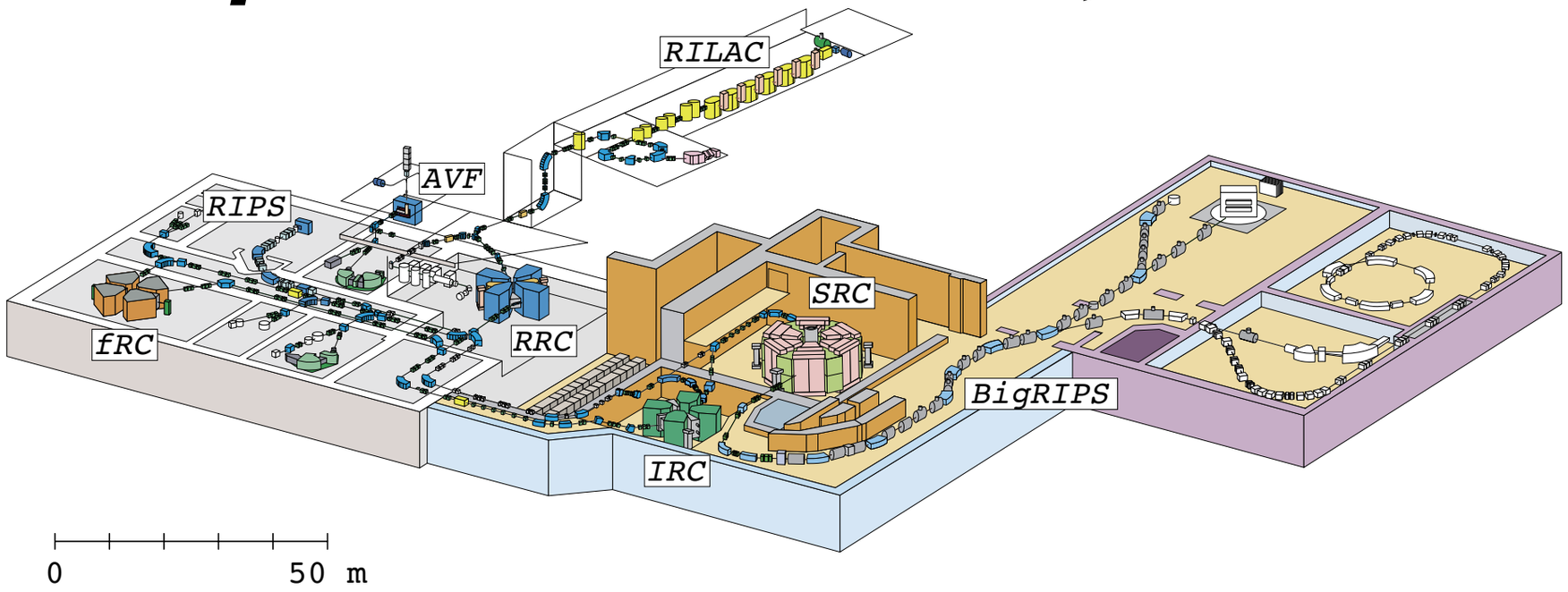
Experiment at RIBF, RIKEN



	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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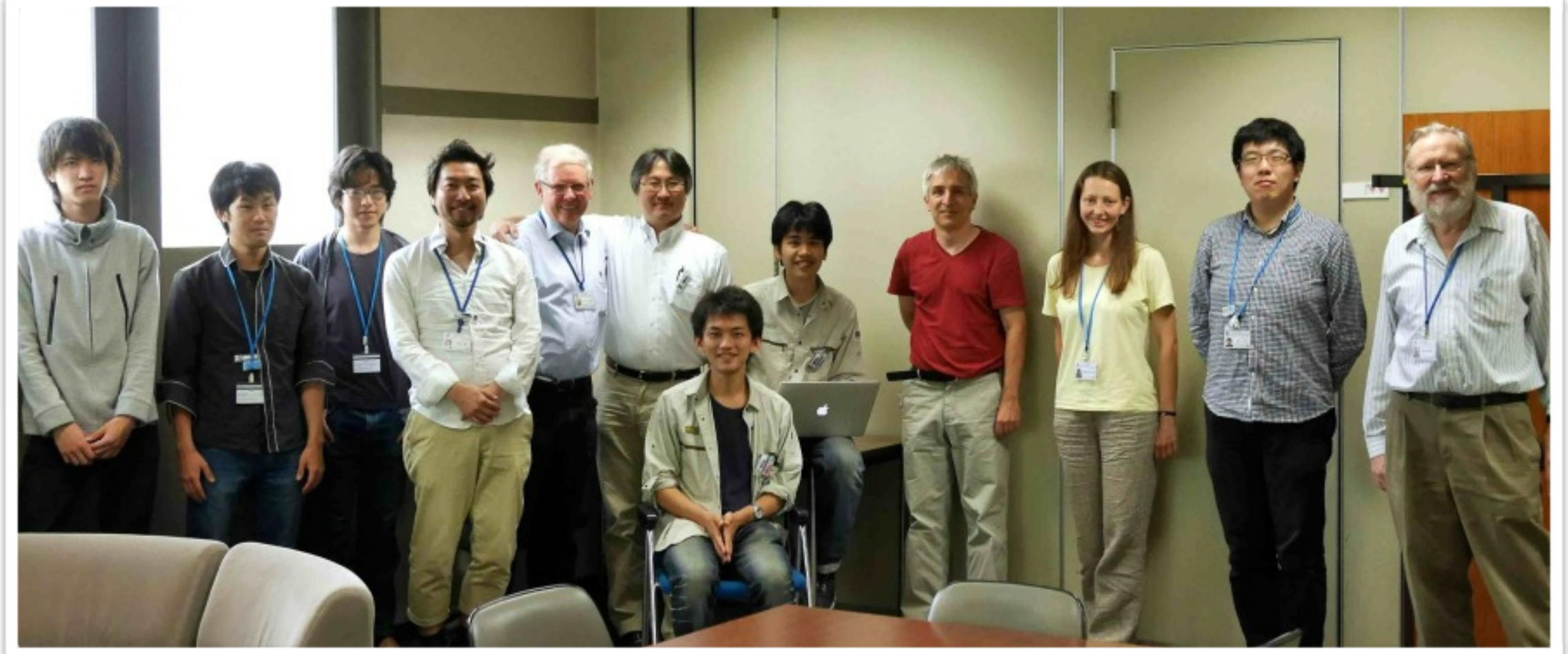
First production experiment in 2014 @ RIKEN (11 days)



aim of the experiment

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

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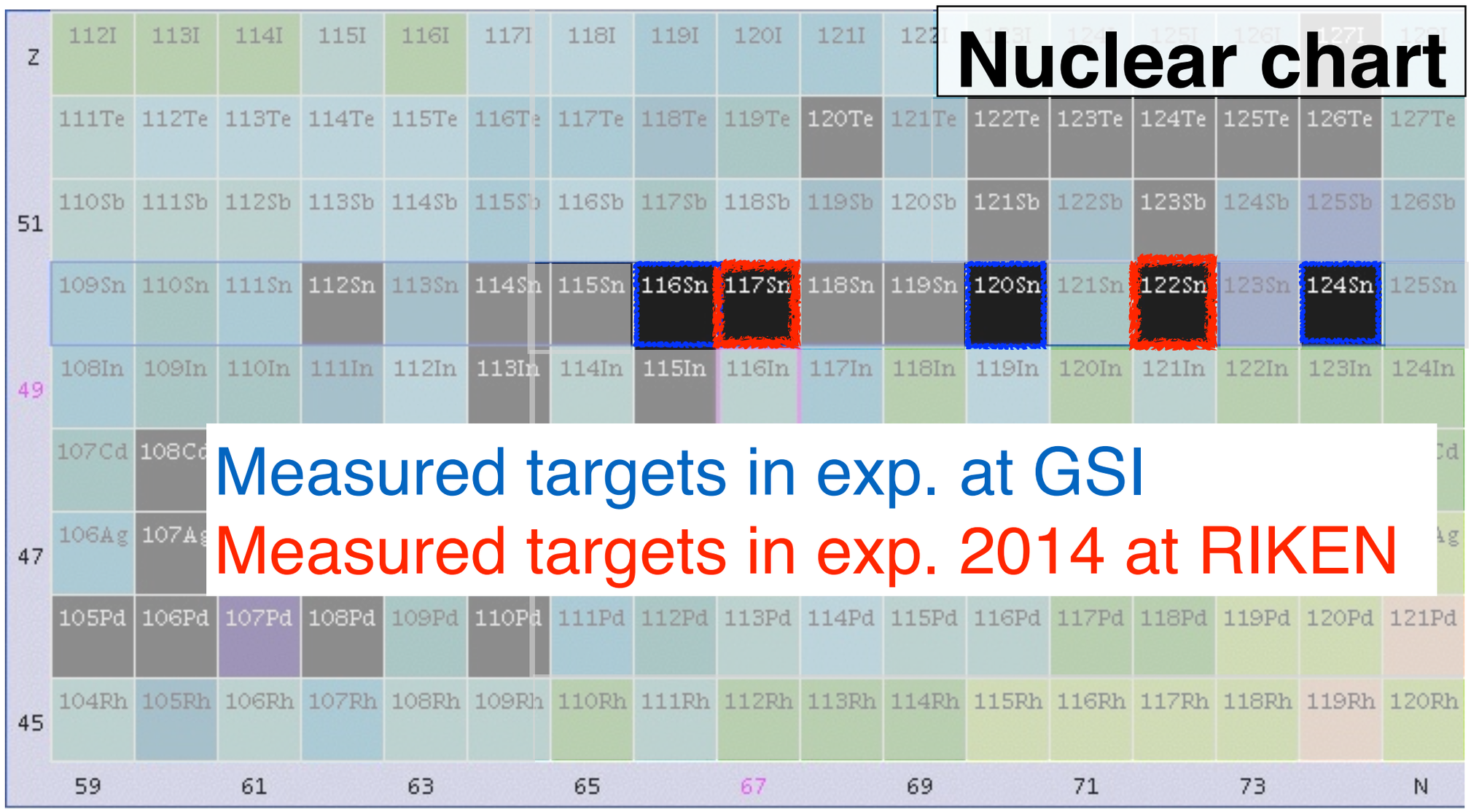
First production experiment in 2014 @ RIKEN (11 days)



^{122}Sn: relatively large cross section

^{117}Sn: first odd-A target

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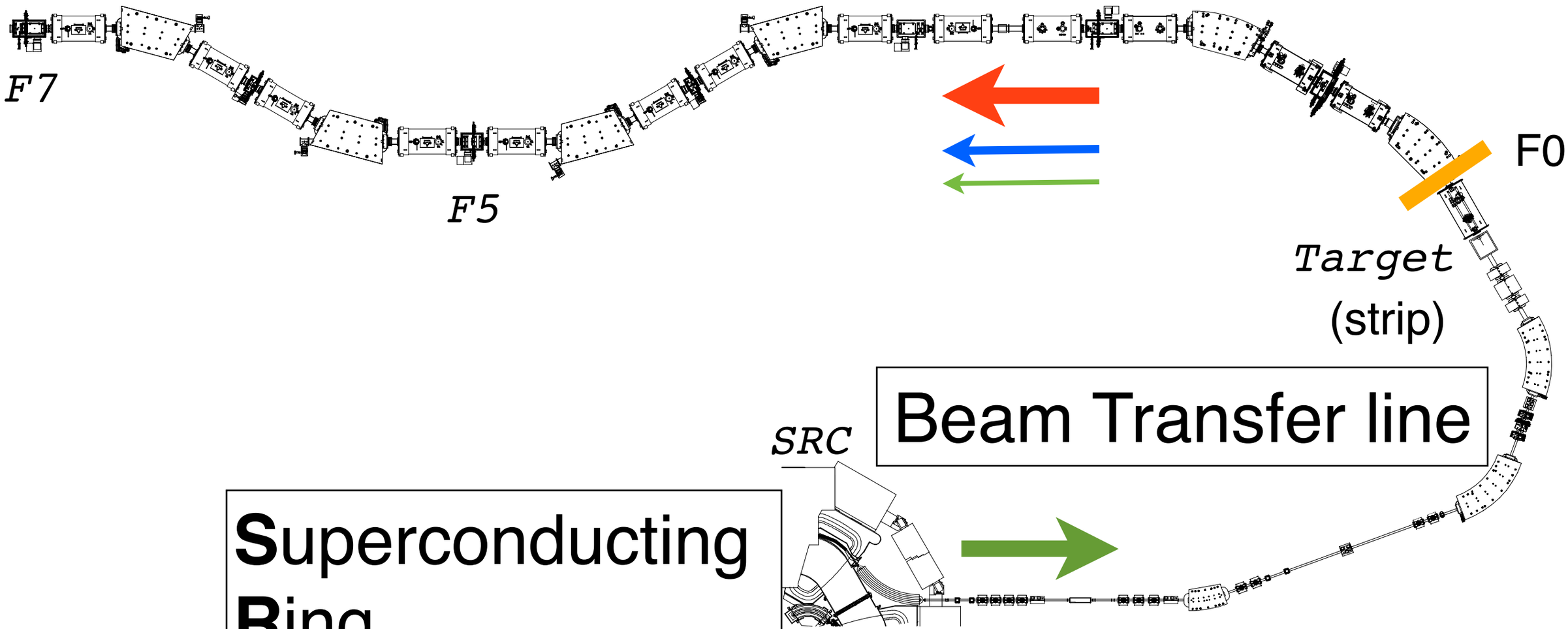
Experimental setup

RIKEN Fragment Separator
BigRIPS

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

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



Beam Transfer line

Superconducting
Ring
Cyclotron

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

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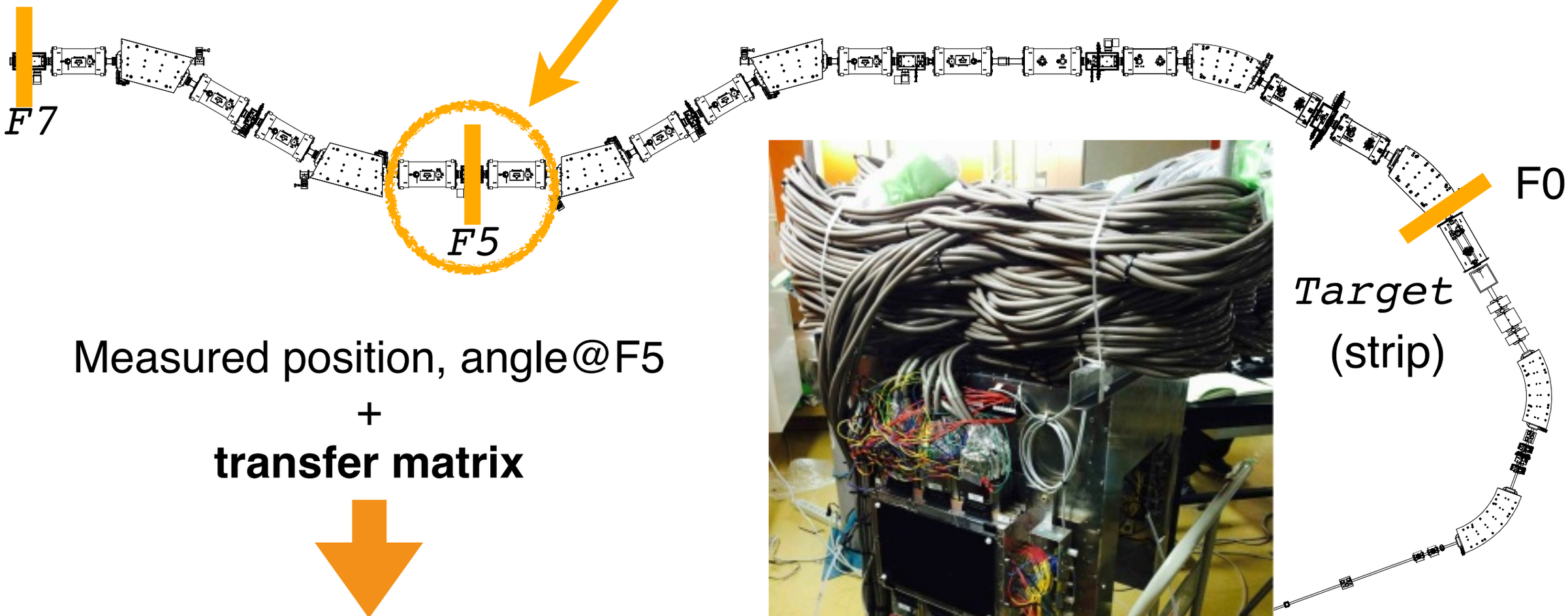
Experimental setup: detectors

Tracking by **MWDC**

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

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



Measured position, angle@F5

+

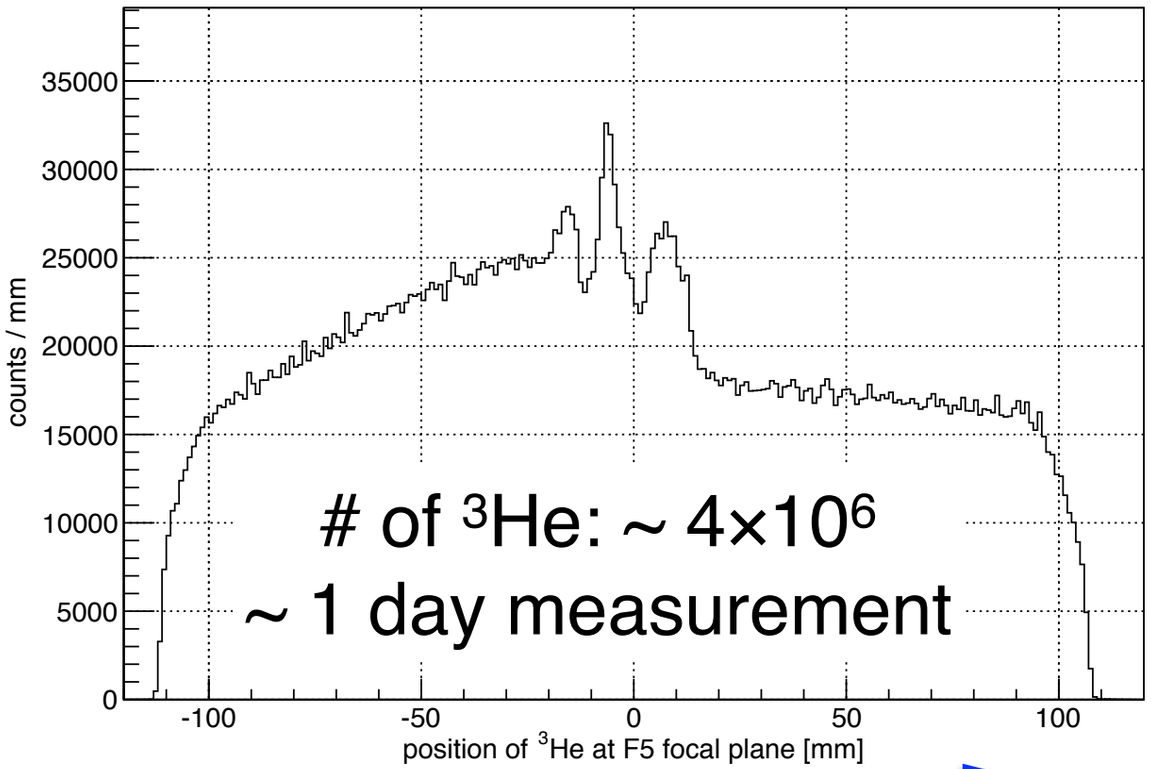
transfer matrix

P_{3He} + reaction angle at target

Multi Wire Drift Chamber

Production run: ^{122}Sn target

position spectrum of ^{3}He



High P_{3He}

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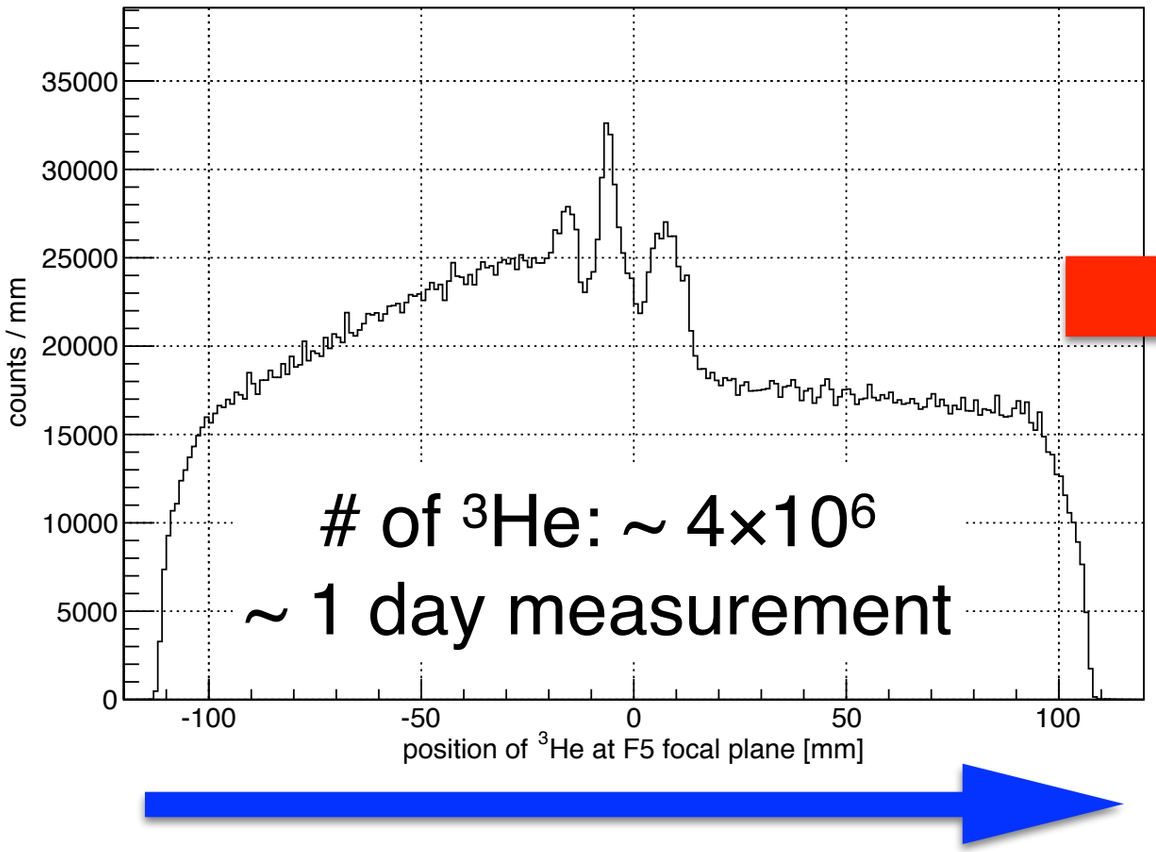
Production run: ^{122}Sn target

position spectrum of ^{3}He



High P_{3He}

Eex spectrum of ^{121}Sn

bound state of π in ^{121}Sn

$\theta_{reac} < 1.0°$

Preliminary

High P_{3He}

quasi-free π production threshold

The spectrum seems to achieve the best resolution among the past deeply-bound pionic atom experiment.

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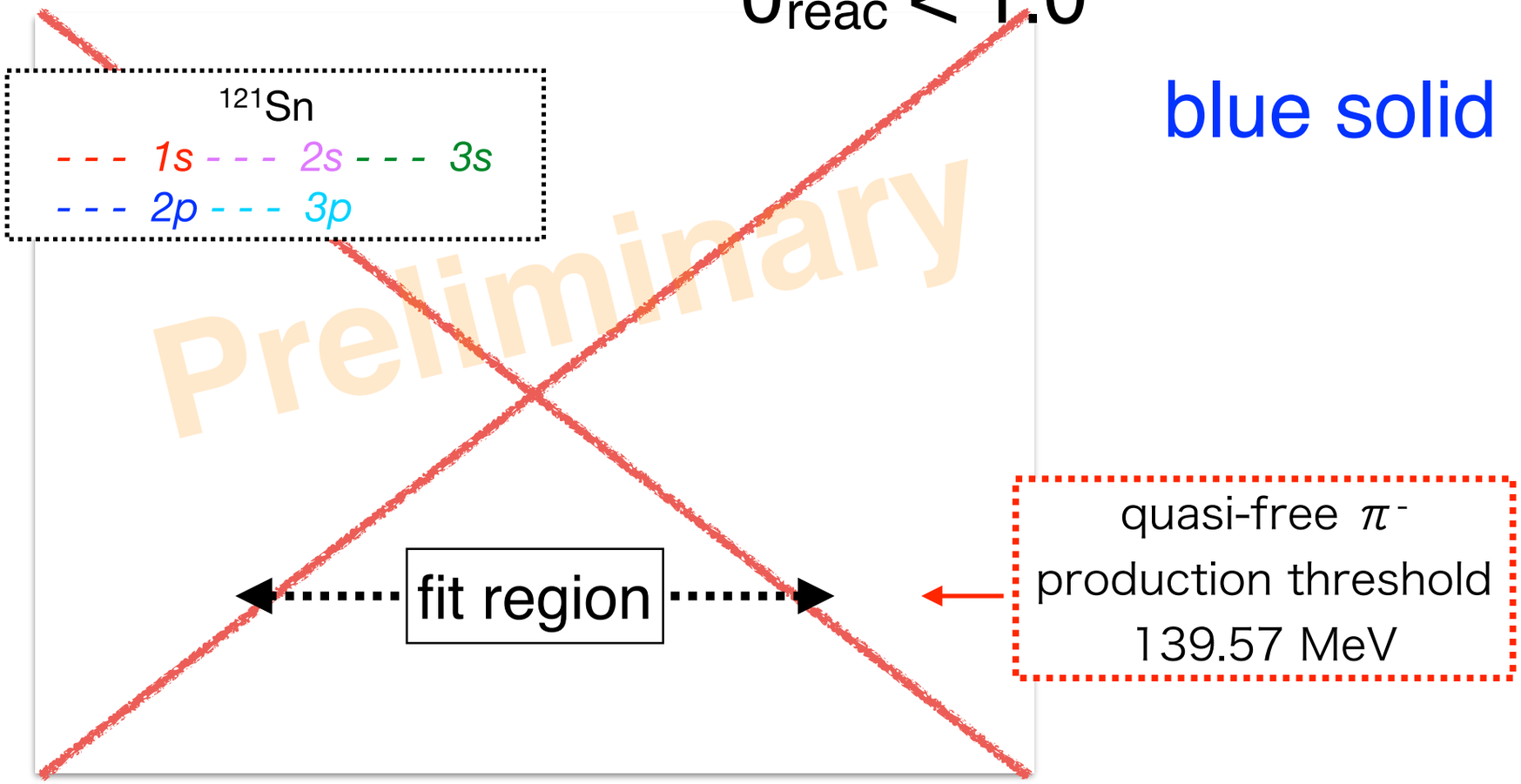
Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



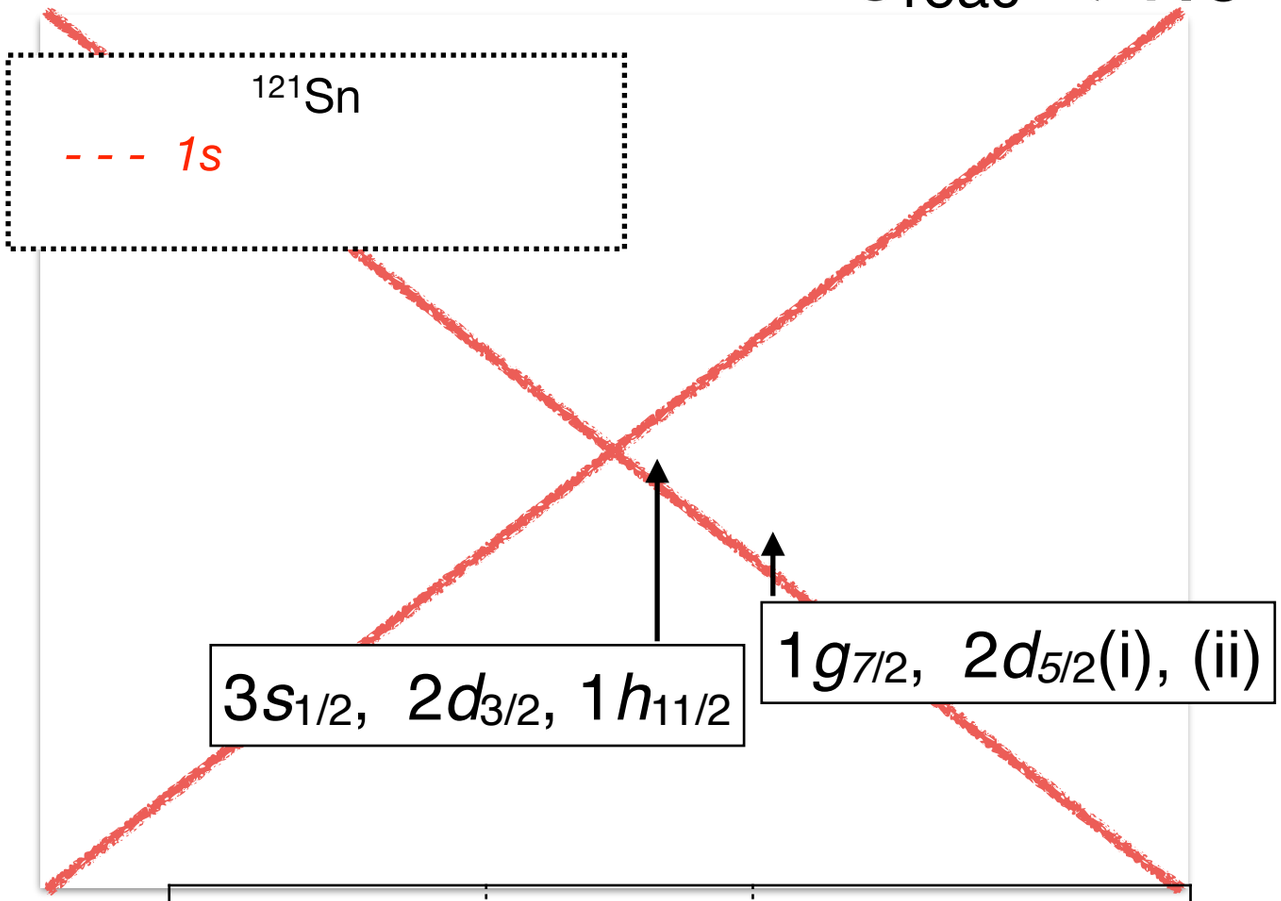
blue solid line : fit function

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

$\theta_{reac} < 1.0°$



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

neutron hole	Eex [MeV]	relative strength for pionic 1*s* state
$2d_{3/2}$	0.000	0.09
$1h_{11/2}$	0.006	0.001
$3s_{1/2}$	0.060	**1**
$1g_{7/2}$	0.926	0.003
$2d_{5/2}$ (i)	1.121	0.12
$2d_{5/2}$ (ii)	1.403	0.06

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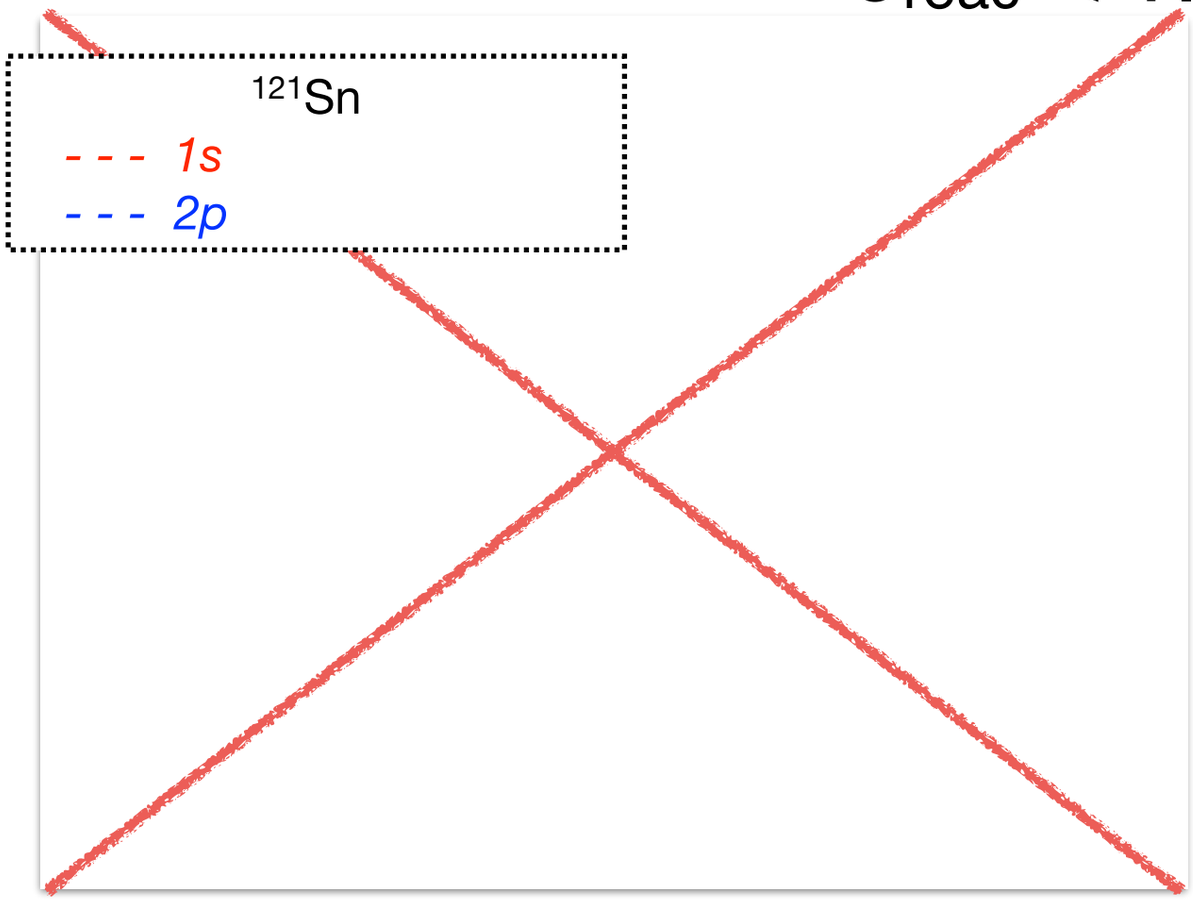
Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



background (solid line / flat)

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

\+ 2*p* pionic state (dashed line)

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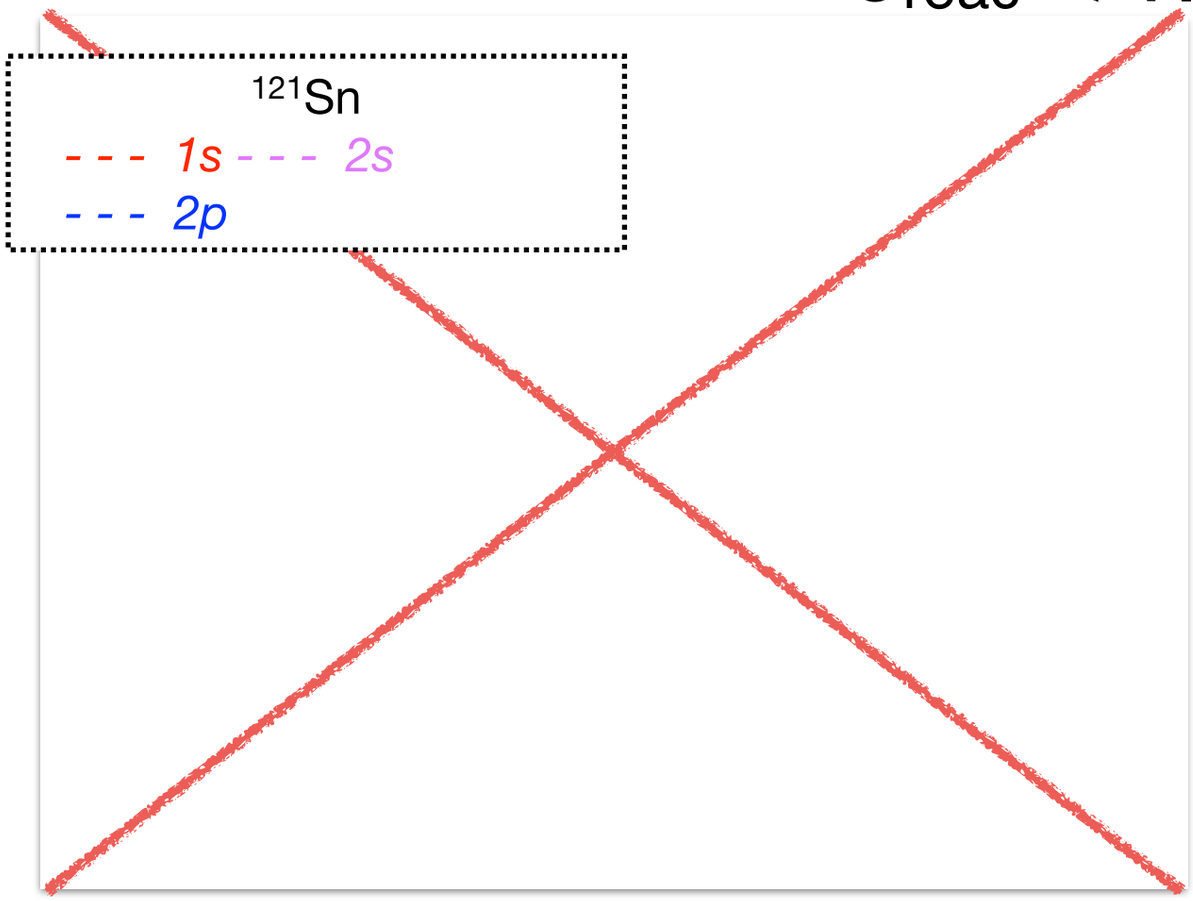
Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



background (solid line / flat)

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

\+ 2*p* pionic state (dashed line)

\+ 2*s* pionic state (dashed line)

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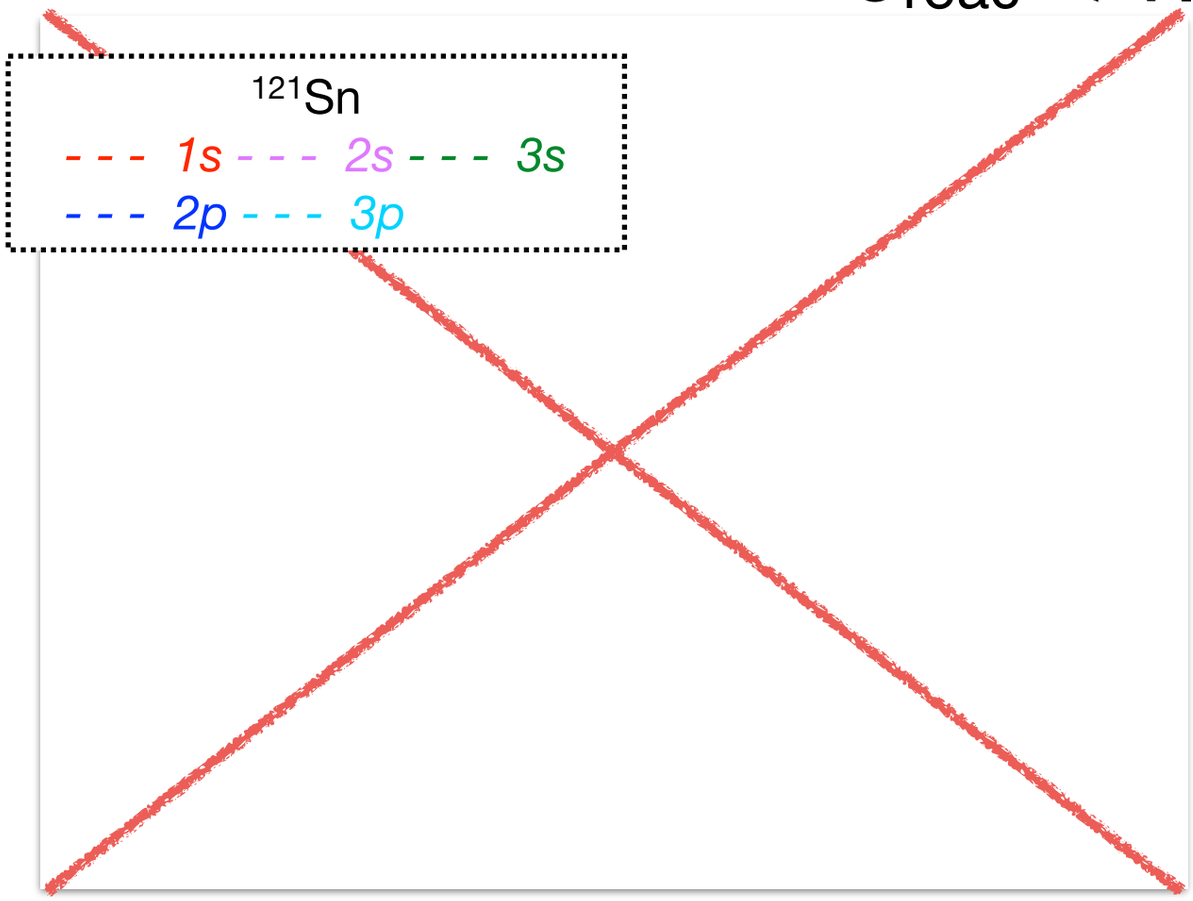
Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



background (solid line / flat)

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

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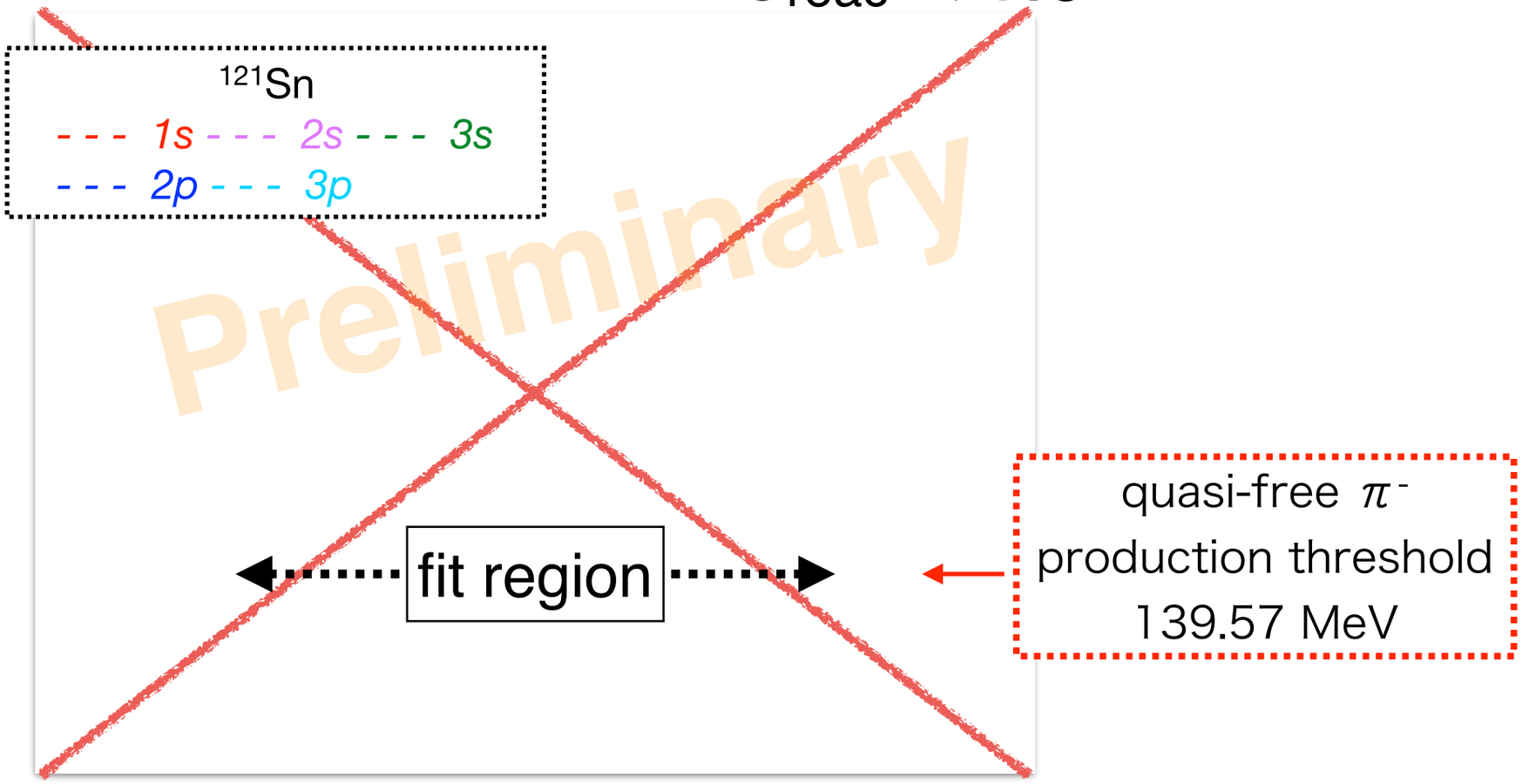
Fitting of the E_{ex} spectrum : ^{122}Sn target

$\theta_{reac} < 1.0°$



Deduced BE_{1s}, Γ_{1s}, BE_{2p}

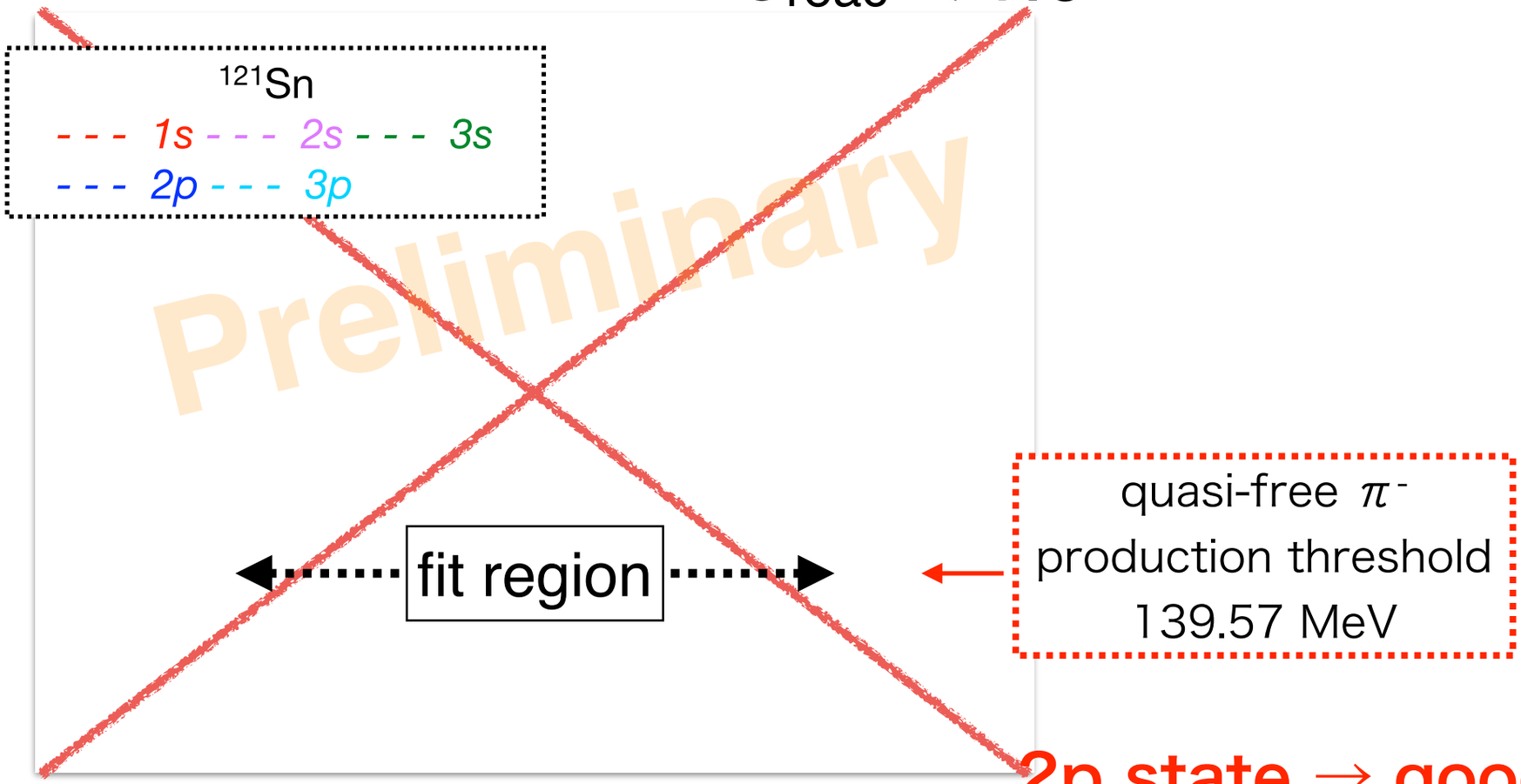
→ b_1, ImB_0 in π-A s-wave optical potential

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

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

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

$\theta_{reac} < 1.0°$



2p state → good calibration peak

Deduced BE_{1s}, Γ_{1s}, **BE_{2p}**

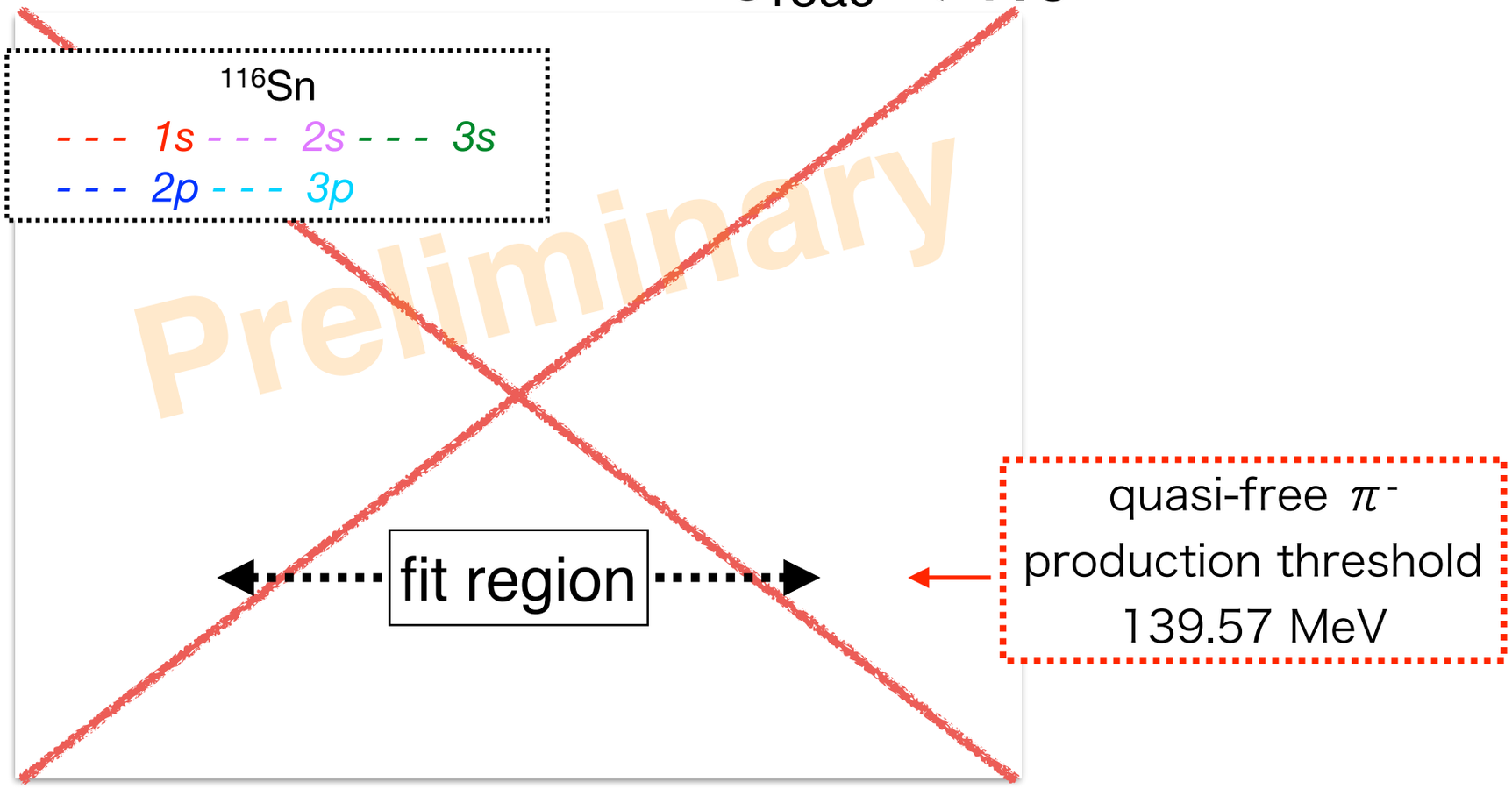
→ b_1, ImB_0 in π-A s-wave optical potential

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

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

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

$\theta_{reac} < 1.0°$



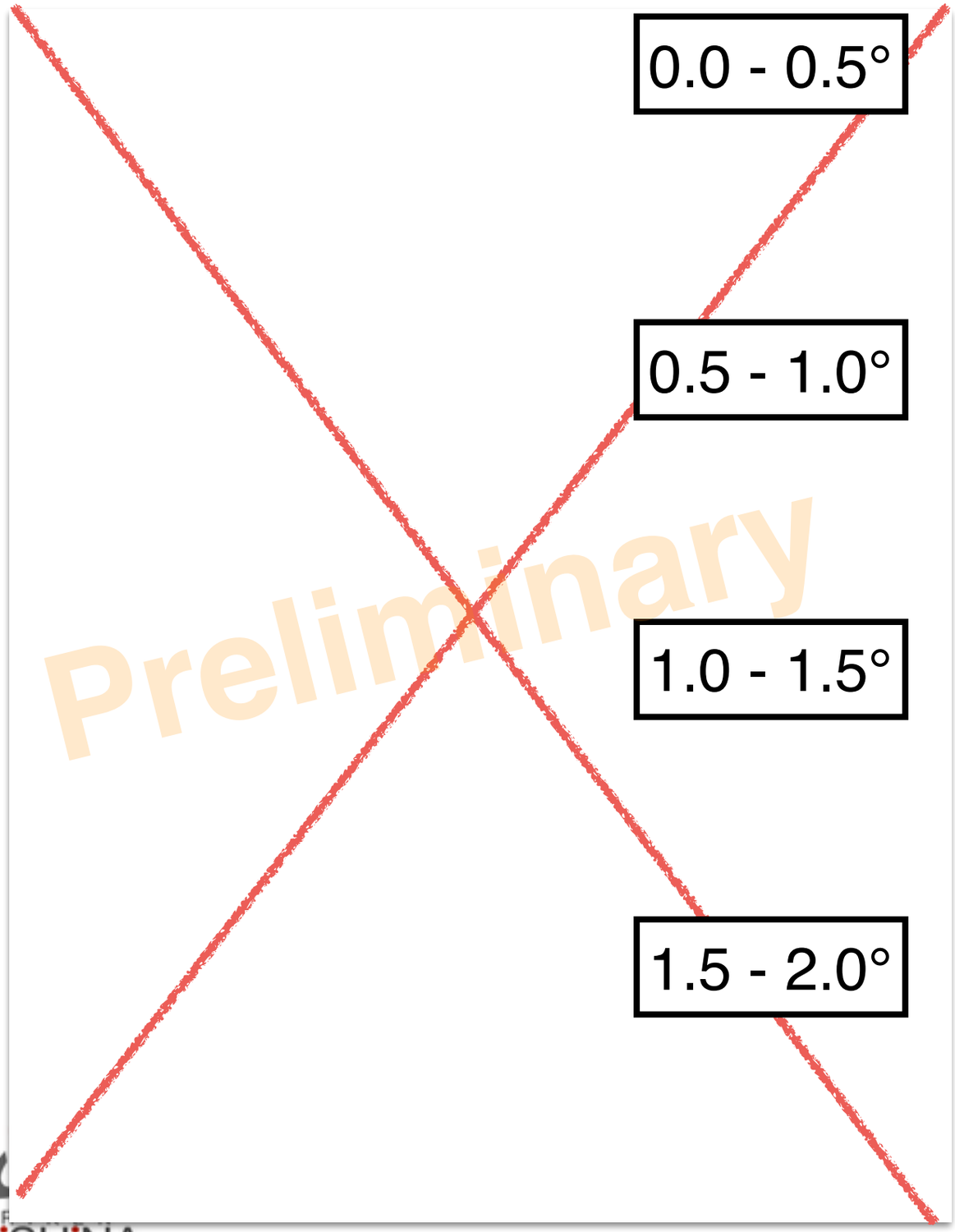
Deduced BE_{1s}, Γ_{1s}, BE_{2p}

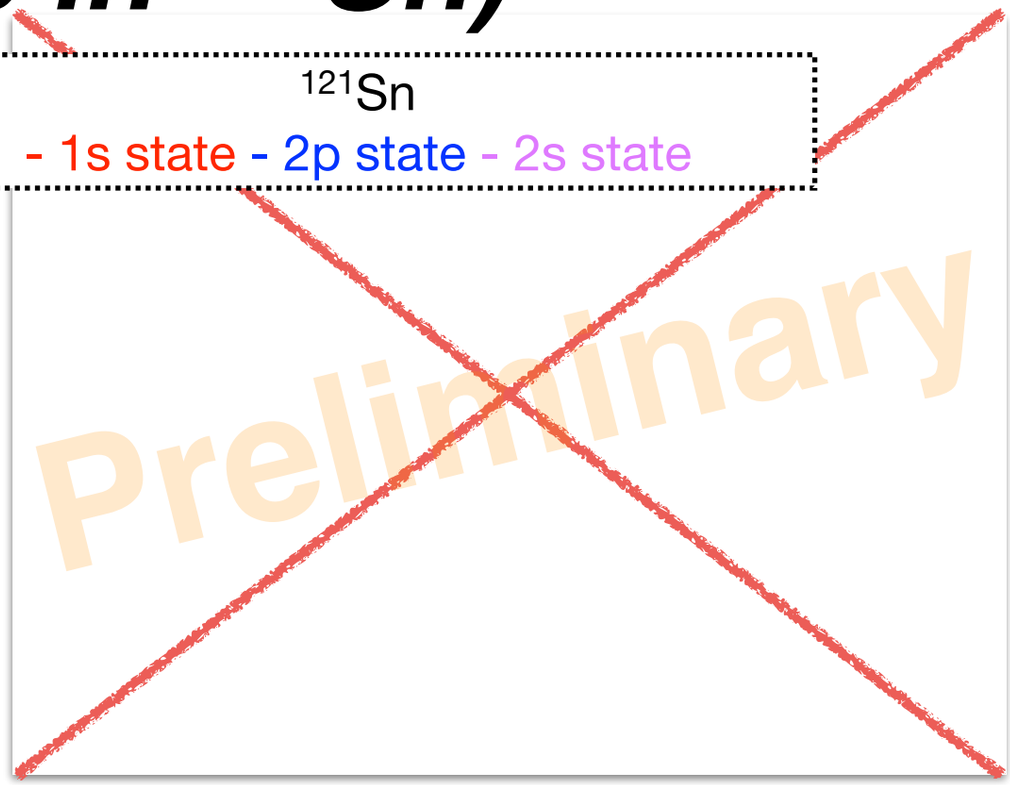
→ b_1, ImB_0 in π-A s-wave optical potential

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

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

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

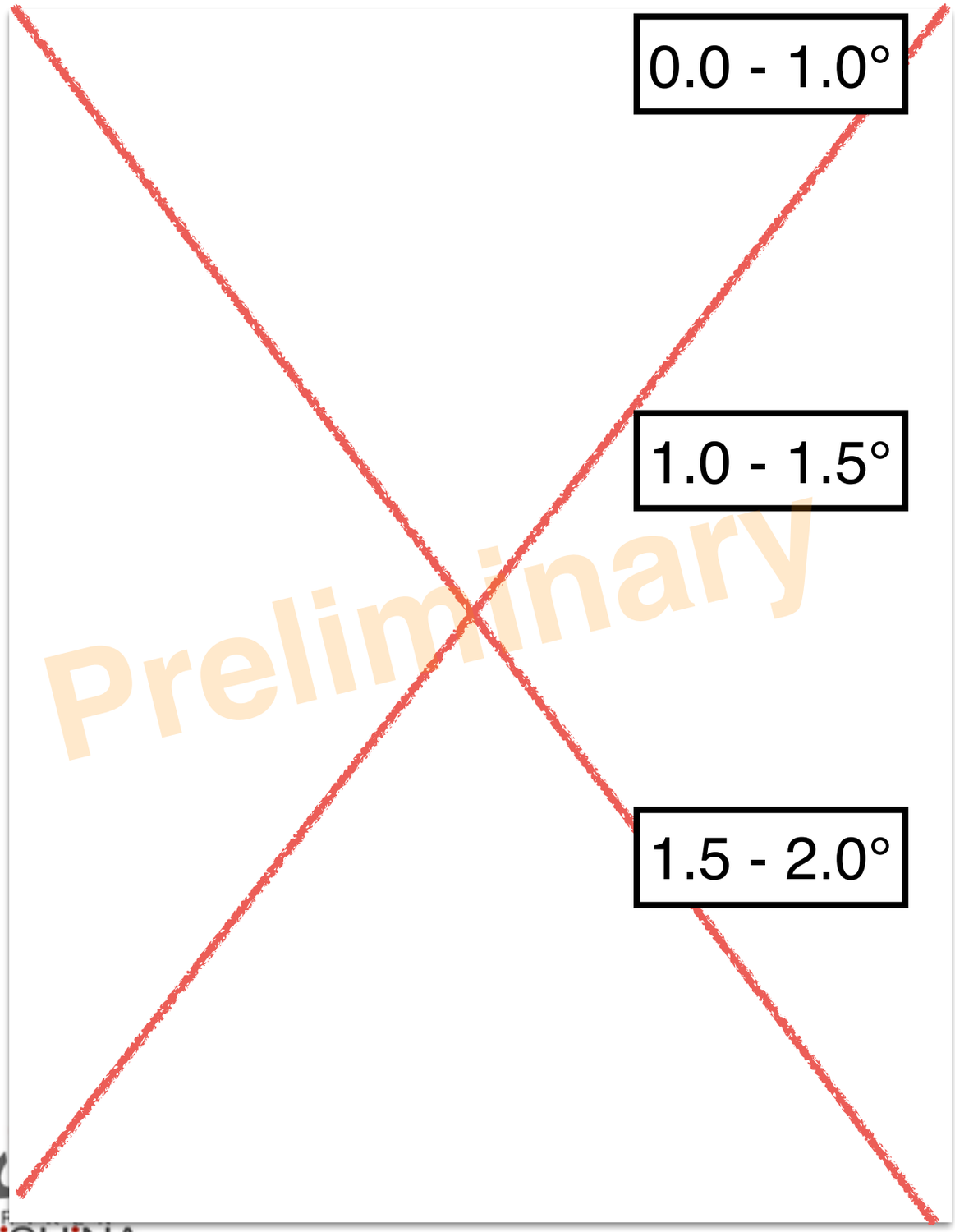


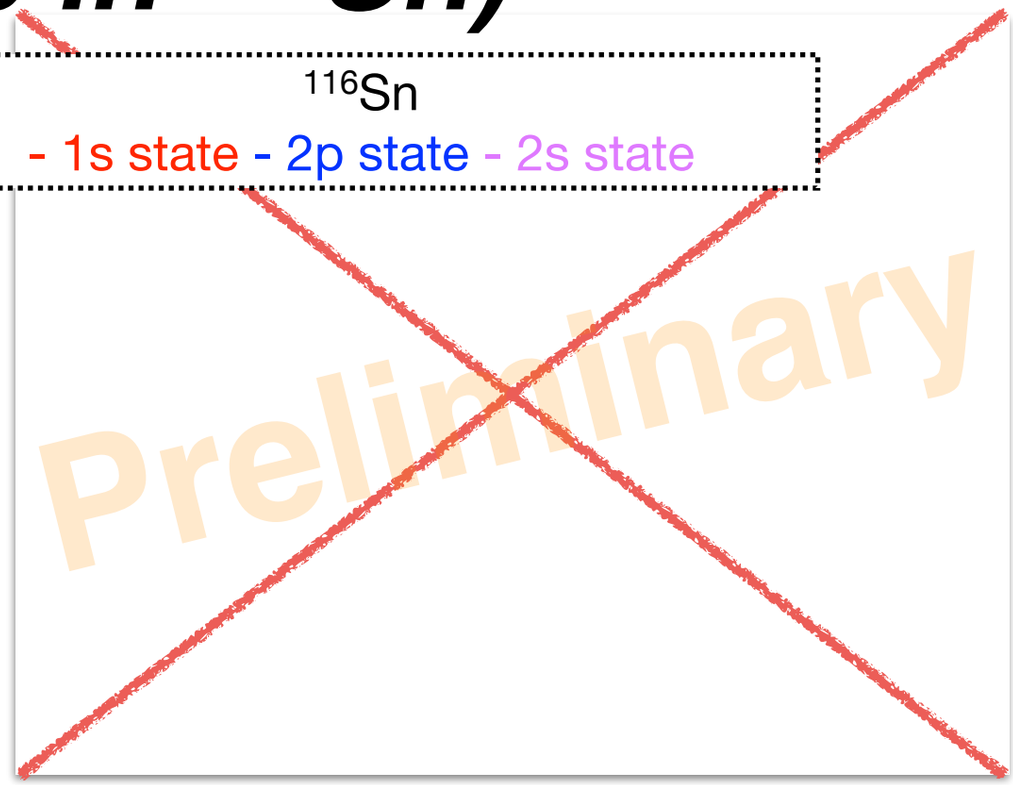


s state decrease dσ/dΩ ⟷ p state increase dσ/dΩ

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)

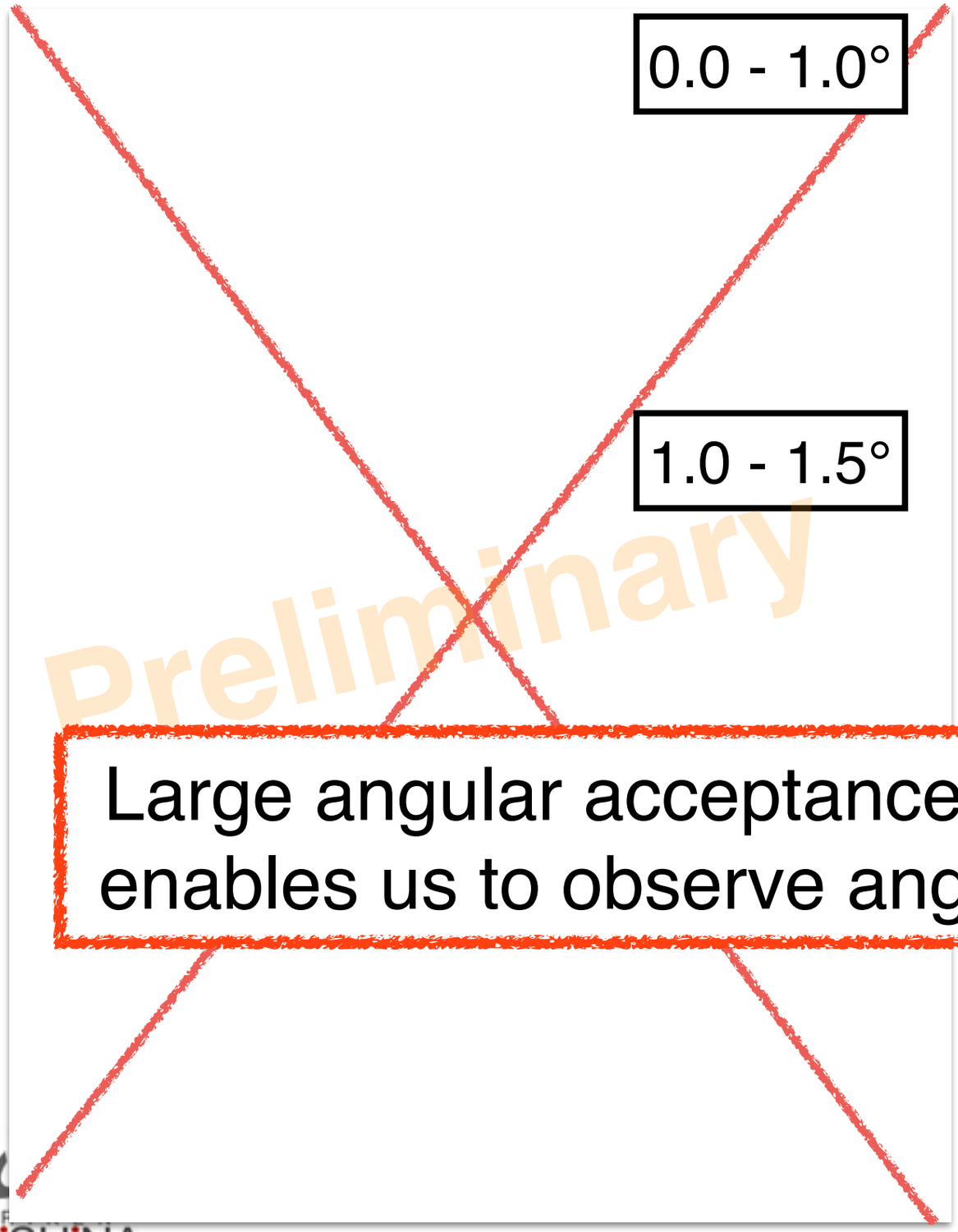


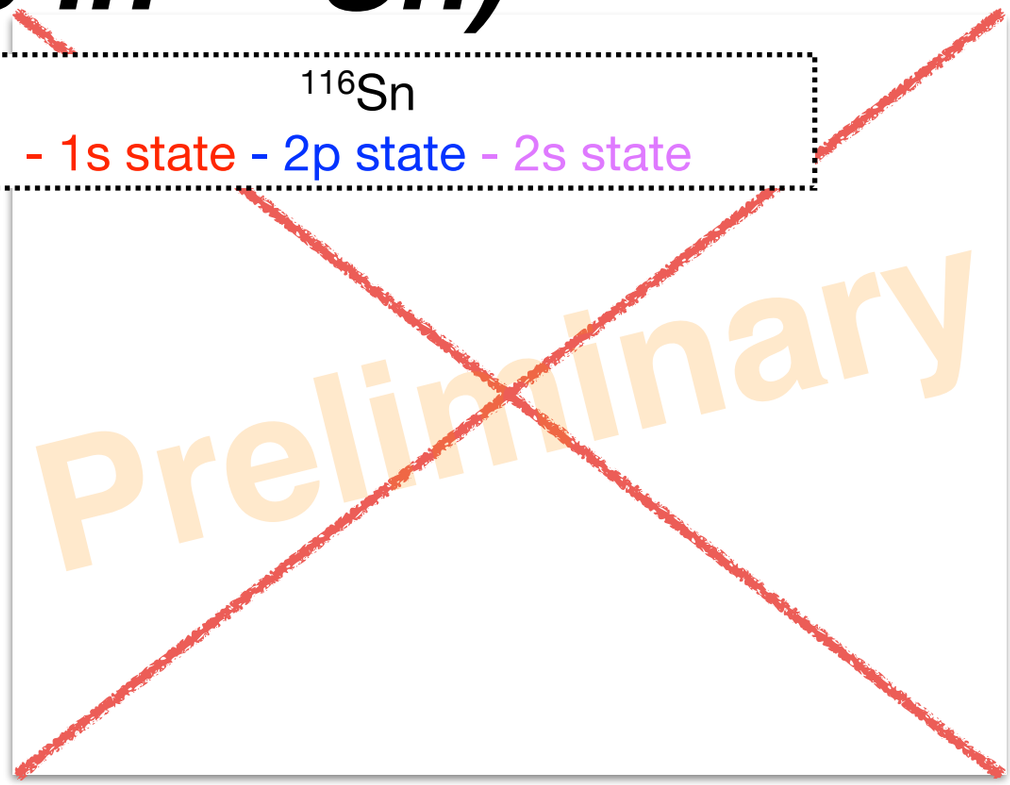


s state
decrease dσ/dΩ ⟷ p state
increase dσ/dΩ

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)





Large angular acceptance of the spectrometer@RIKEN enables us to observe angular dependence of $d^2\sigma/dEd\Omega$

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

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 ^{122,116}Sn, and succeed in
  - improvement of the resolution,
  - observation of the pionic 1s, 2p and 2s states in $^{121,\ 116}$Sn,
  - observation of angular dependence of these states.
- Analysis to deduce b_1 from measured BE_{1s}, Γ_{1s} , BE_{2p} is in progress.

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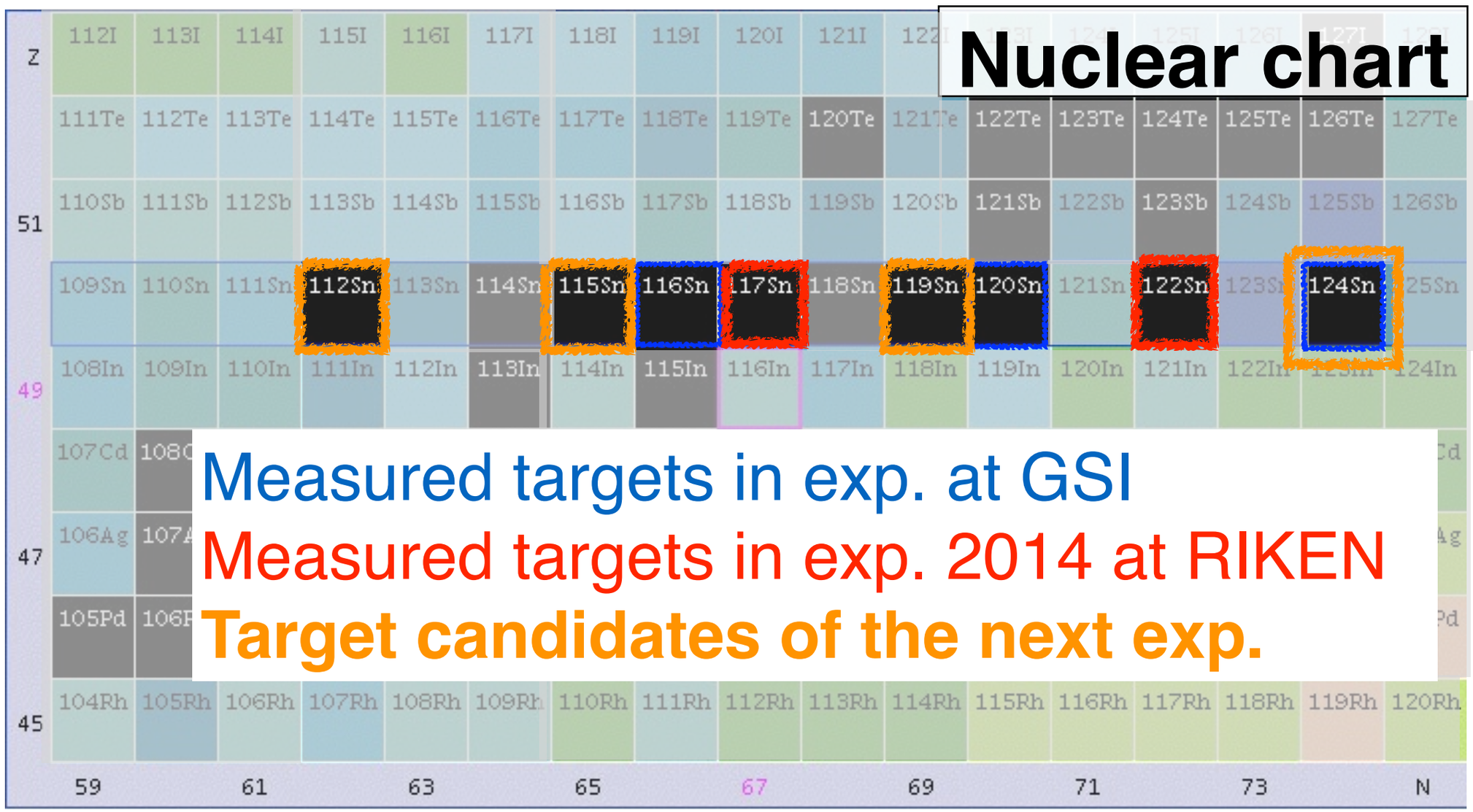
(Near) future works



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>

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