

Measurement of deeply bound pionic states using the $(p, {}^2\text{He})$ reaction at RCNP

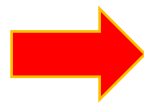
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collaborators

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Deeply bound pionic atom

- Binding energy and width of pionic atom



Partial restoration of
chiral symmetry

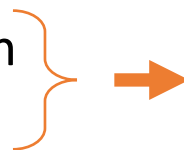
- s-wave pion-nucleus potential

$$U_s(r) = -\frac{2\pi}{\mu} \left[\varepsilon_1 \{ b_0 \rho(r) + b_1 [\rho_n(r) - \rho_p(r)] \} + \varepsilon_2 B_0 \rho^2(r) \right]$$

$$\mu = m_\pi M / (m_\pi + M), \quad \varepsilon_1 = 1 + m_\pi / M, \quad \varepsilon_2 = 1 + m_\pi / 2M$$

$$\rho_n(r): \text{neutron density, } \rho_p(r): \text{proton density, } \rho(r) = \rho_n(r) + \rho_p(r)$$

Gell-Mann-Oakes-Renner relation
Tomozawa-Weinberg relation



$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx \frac{b_1^{\text{free}}}{b_1(\rho)}$$

$$U_s(r) = -\frac{2\pi}{\mu} [\varepsilon_1 \{b_0 \rho(r) + b_1 [\rho_n(r) - \rho_p(r)]\} + \varepsilon_2 B_0 \rho^2(r)]$$

Density dependence

→ Need to study isotope / isotone dependence

| | | | | | | | | | | | | | | | | | | | | |
|----------------------------------|-------------------------------------|---------------------------------|----------------------------------|------------------------------------|---------------------------------|----------------------------------|----------------------------------|--|------------------------------------|---------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|--|------------------------------------|--|------------------------------------|------------------------------------|-----------------------------------|------------------------------------|
| Cs117 8.4 s (9/2+) EC * | Cs118 14 s 2 ECp,ECα,... * | Cs119 43.0 s 9/2+ EC * | Cs120 64 s 2 EC * | Cs121 155 s 3/2(+) EC * | Cs122 21.0 s 1+ EC * | Cs123 5.94 m 1/2+ EC * | Cs124 30.8 s 1+ EC * | Cs125 45 m (1/2+) EC | Cs126 1.64 m 1+ EC | Cs127 6.25 h 1/2+ EC | Cs128 3.66 m 1+ EC | Cs129 32.06 h 1/2+ EC | Cs130 29.21 m 1+ EC,β- * | Cs131 9.689 d 5/2+ EC | Cs132 6.479 d 2+ EC,β- * | Cs133 7/2+ 100 | Cs134 2.0648 y 4+ EC,β- * | Cs135 2.3E+6 y 7/2+ β- * | Cs136 13.16 d 5+ β- * | Cs137 30.07 y 7/2+ β- |
| Xe116 59 s 0+ EC | Xe117 61 s 5/2(+) ECp | Xe118 3.8 m 0+ EC | Xe119 5.8 m (5/2+) EC | Xe120 40 m 0+ EC | Xe121 40.1 m 5/2(+) EC | Xe122 20.1 h 0+ EC | Xe123 2.08 h (1/2)+ EC | Xe124 1.6E+14 y 0+ ECEC 0.10 | Xe125 16.9 h (1/2)+ EC * | Xe126 0+ 0.09 | Xe127 36.4 d 1/2+ EC * | Xe128 0+ 1.91 | Xe129 1/2+ 26.4 * | Xe130 0+ 4.1 | Xe131 3/2+ 21.2 * | Xe132 0+ 26.9 * | Xe133 5.243 d 3/2+ β- * | Xe134 0+ 10.4 * | Xe135 9.14 h 3/2+ β- * | Xe136 2.36E21 y 0+ 8.9 |
| I115 1.3 m (5/2+) EC | I116 2.91 s 1+ EC * | I117 2.22 m (5/2+) EC | I118 13.7 m 2- EC * | I119 19.1 m 5/2+ EC | I120 81.0 m 2- EC * | I121 2.12 h 5/2+ EC | I122 3.63 m 1+ EC * | I123 13.27 h 5/2+ EC | I124 4.1760 d 2- EC | I125 59.408 d 5/2+ EC | I126 13.11 d 2- EC,β- * | I127 5/2+ 100 | I128 24.99 m 1+ EC,β- * | I129 1.57E7 y 7/2+ β- * | I130 12.36 h 5+ β- * | I131 8.02070 d 7/2+ β- * | I132 2.295 h 4+ β- * | I133 20.8 h 7/2+ β- * | I134 52.5 m (4)+ β- * | I135 6.57 h 7/2+ β- |
| Te114 15.2 m 0+ EC | Te115 5.8 m 7/2+ EC * | Te116 2.49 h 0+ EC | Te117 62 m 1/2+ EC * | Te118 19.1 m 0+ EC | Te119 19.1 m 1/2+ EC * | Te120 0+ 0.096 | Te121 16.78 d 1/2+ EC * | Te122 0+ 2.603 | Te123 1E+13 y 1/2+ EC * | Te124 0+ 4.816 | Te125 1/2+ 7.139 | Te126 0+ 18.95 | Te127 9.35 h 3/2+ β- * | Te128 2.2E24 y 0+ β,β- 31.69 | Te129 69.6 m 3/2+ β- * | Te130 7.9E20 y 0+ β- 33.80 | Te131 25.0 m 3/2+ β- * | Te132 3.204 d 0+ β- * | Te133 12.5 m (3/2)+ β- * | Te134 41.8 m 0+ β- |
| Sb113 6.67 m 5/2+ EC | Sb114 3.49 m 3+ EC | Sb115 2.80 h 5/2+ EC | Sb116 15.8 m 3+ EC * | Sb117 19.1 m 5/2+ EC | Sb118 3.6 m 1+ EC * | Sb119 38.19 h 5/2+ EC * | Sb120 15.89 m 1+ EC * | Sb121 5/2+ 57.36 | Sb122 2.7238 d 2- EC,β- * | Sb123 7/2+ 42.64 | Sb124 60.20 d 3- β- * | Sb125 2.7582 y 7/2+ β- * | Sb126 12.46 d (8)- β- * | Sb127 3.85 d 7/2+ β- * | Sb128 9.01 h 8- β- * | Sb129 4.40 h 7/2+ β- * | Sb130 39.5 m (8)- β- * | Sb131 23.03 m (7/2+) β- * | Sb132 2.79 m (4)+ β- * | Sb133 6.57 h (7/2+) β- |
| Sn112 0+ 0.97 | Sn113 115.09 d 1/2+ EC * | Sn114 0+ 0.65 | Sn115 1/2+ 0.34 | Sn116 0+ 14.53 | Sn117 1/2+ 7.68 | Sn118 0+ 24.23 | Sn119 1/2+ 8.59 | Sn120 0+ 32.59 | Sn121 27.06 h 3/2+ β- * | Sn122 0+ 4.63 | Sn123 129.2 d 11/2- β- * | Sn124 0+ 5.79 | Sn125 9.64 d 11/2- β- * | Sn126 1E+5 y 0+ β- * | Sn127 2.10 h (11/2)- β- * | Sn128 59.07 m 0+ β- * | Sn129 2.23 m (3/2+) β- * | Sn130 3.72 m 0+ β- * | Sn131 56.0 s (3/2+) β- * | Sn132 39.7 s 0+ β- |
| In114 2.8047 9/2+ EC * | In115 14.97 m 1+ EC,β- * | In116 71.9 s 9/2+ EC * | In117 71.9 s 1+ EC,β- * | In118 4.1E+14 y 9/2+ β- * | In119 14.10 s 4.3 | In120 4.32 m 3/2+ β- * | In121 3.0 s 1+ β- * | In122 2.4 m 9/2+ β- * | In123 3.08 s 1+ β- * | In124 2.51 s 9/2+ β- * | In125 1.3 s 1+ β- * | In126 3.6 s 9/2+ β- * | In127 3.11 s 3+ β- * | In128 2.36 s 9/2(+) β- * | In129 1.60 s 3(+) β- * | In130 1.09 s (9/2+) βn * | In131 0.84 s (3+) βn * | In132 0.61 s (9/2+) βn * | In133 0.32 s 1(-) βn * | In134 0.282 s (9/2+) βn * |

GSI, RIKEN

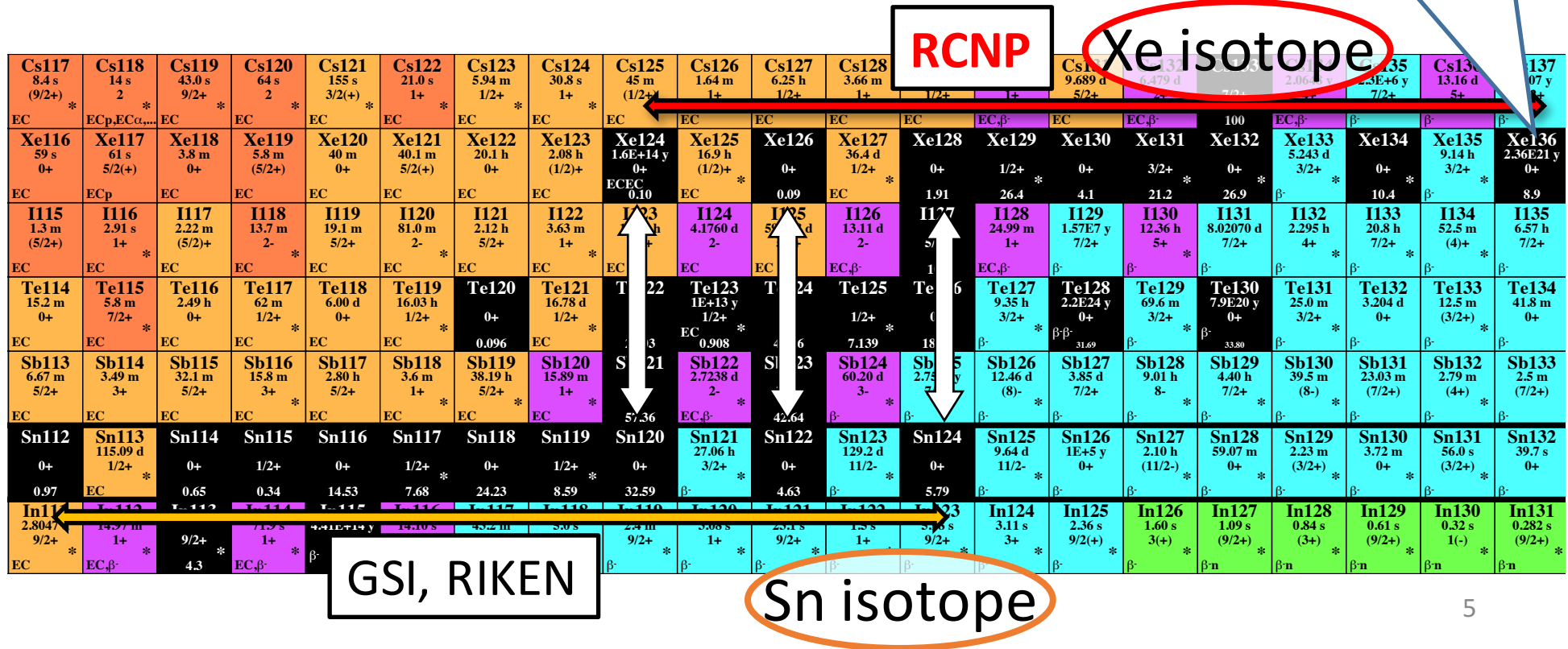
Sn isotope

- Xe : gas target
 - hard to use at GSI or RIKEN

→ RCNP (Research Center for Nuclear Physics)

Isotope / isotone study

N = 82 :
magic number

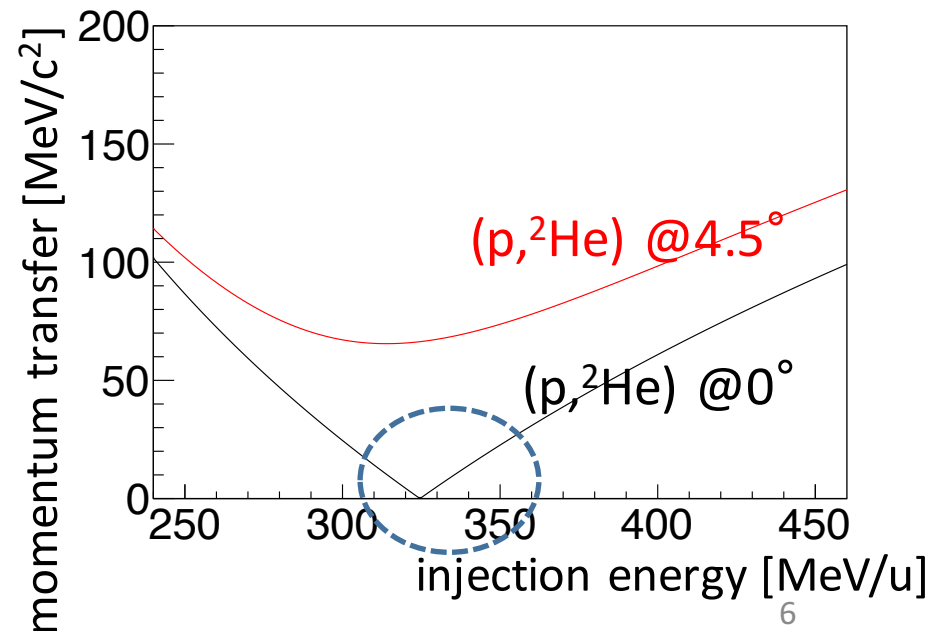
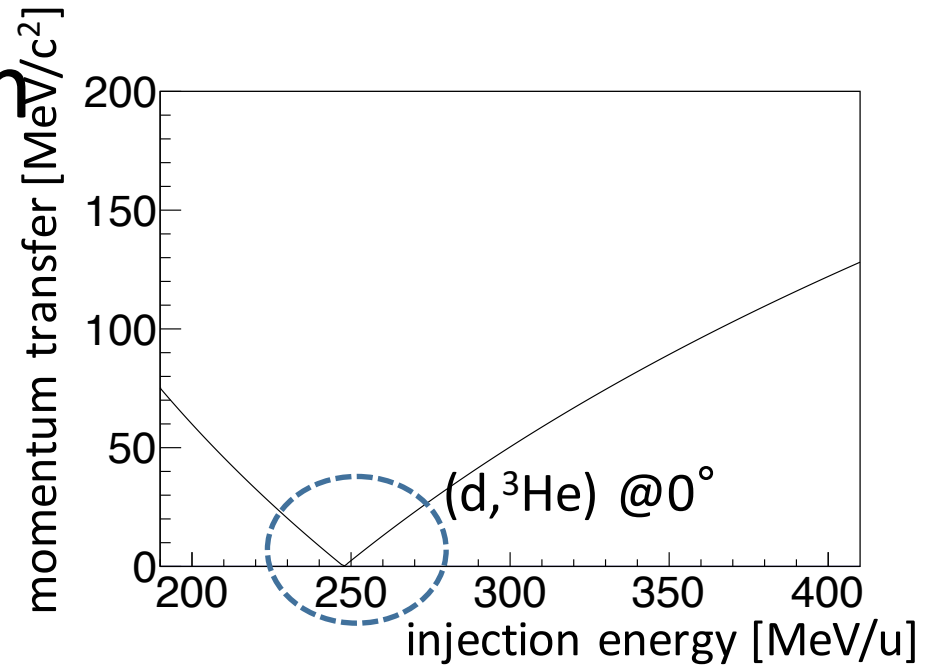


Choice of the reaction

- recoilless condition
Beam energy
 - $(d, {}^3\text{He}) \sim 250 \text{ MeV/u}$
 - $(p, {}^2\text{He}) \sim 330 \text{ MeV}$

Available at RCNP

pionic atoms with $(p, {}^2\text{He})$
@RCNP

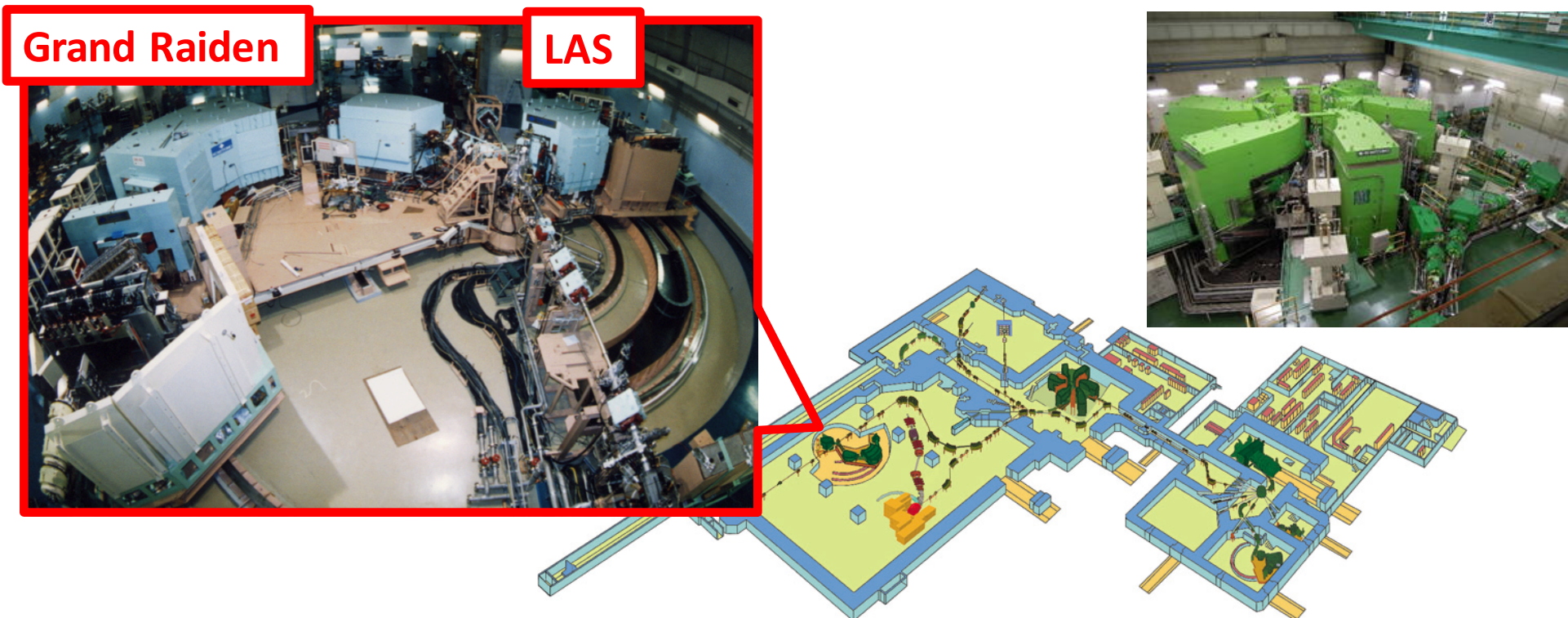


RCNP (Research Center for Nuclear Physics)

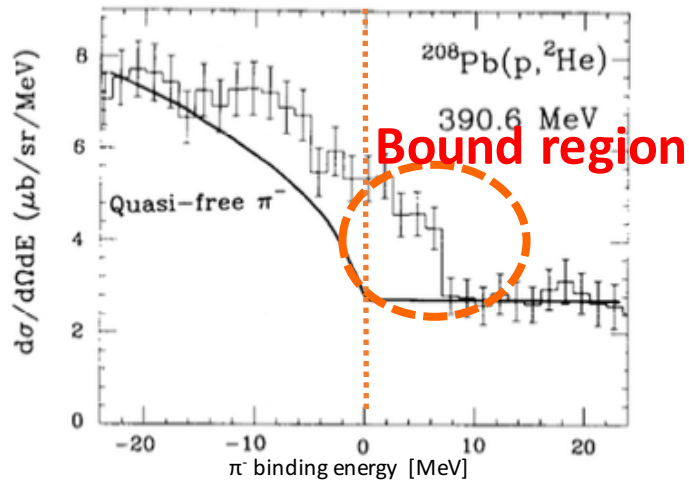
- AVF cyclotron + ring cyclotron
- The two-arm spectrometer :

Proton energy :
up to 400 MeV

Grand Raiden / LAS (Large Acceptance Spectrometer)



Pionic atom at RCNP : (p,²He)



N. Matsuoka et al.,
Phys. Lett. B 359 (1995) 39.

- 1990s

- Bound states was formed
- Energy level couldn't be determined
- resolution : 700 keV (FWHM)

Improvement of
the resolution

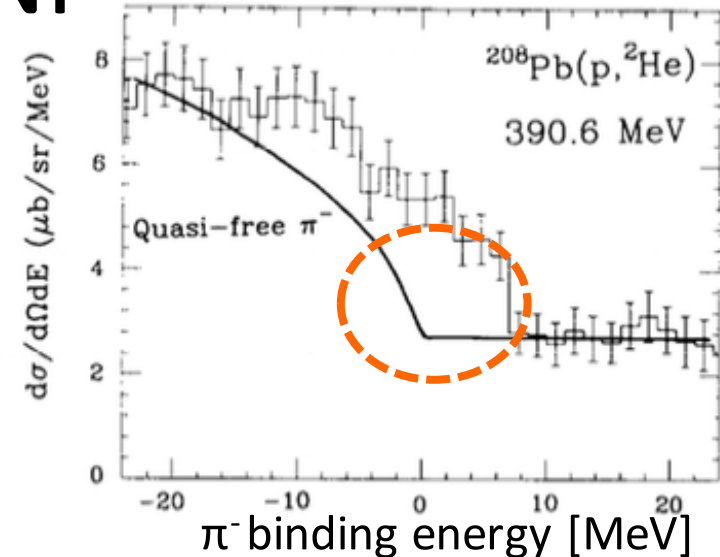


determination of
the binding energy
and the width

(p,²He) reaction at RCNP

Previous experiment

- LAS :
 - resolution 700 keV (FWHM)
 - acceptance : 2.4 msr
- Beam intensity : 0.5~1 nA



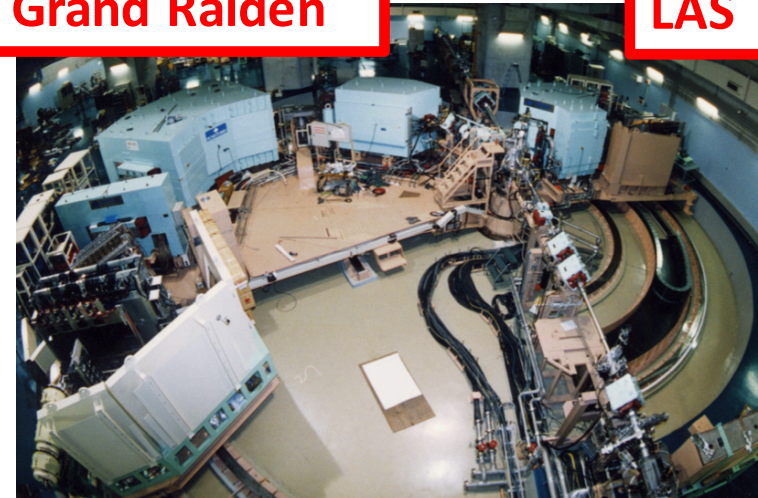
π^- binding energy [MeV]
N. Matsuoka et al.,
Phys. Lett. B 359 (1995) 39.

New experiment

- Grand Raiden
 - resolution ~ 250 keV (FWHM)
 - acceptance : 0.04 msr
- Beam intensity : ~ 30 nA

Grand Raiden

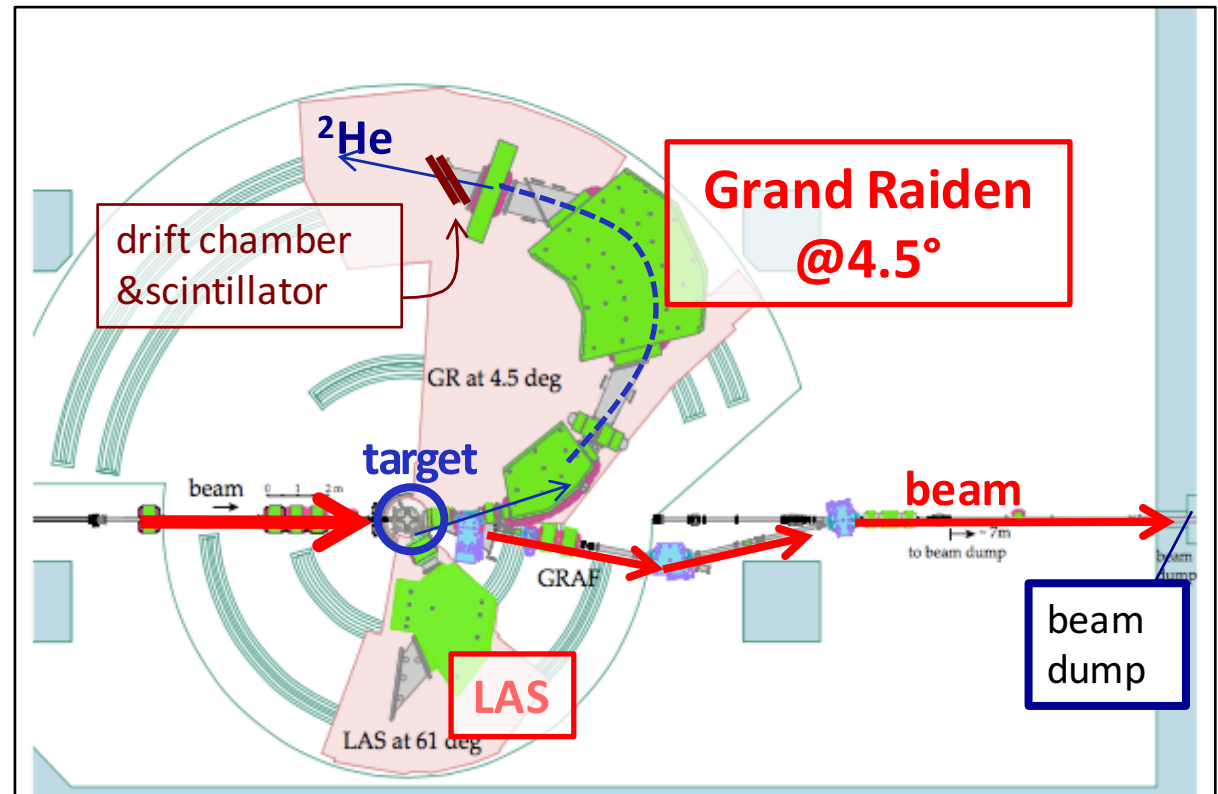
LAS



Experimental setup

- Grand Raiden → Resolution: 200~250 keV (FWHM)
 - uncertainty of reaction vertex
 - beam resolution

- Intense beam :
30 nA



Schedule / Future plan

Phase 0 (2015 – 2016)

- Test experiment – feasibility study

Phase 1

- Pilot experiment
 - target : ^{124}Sn
- Proposal was submitted

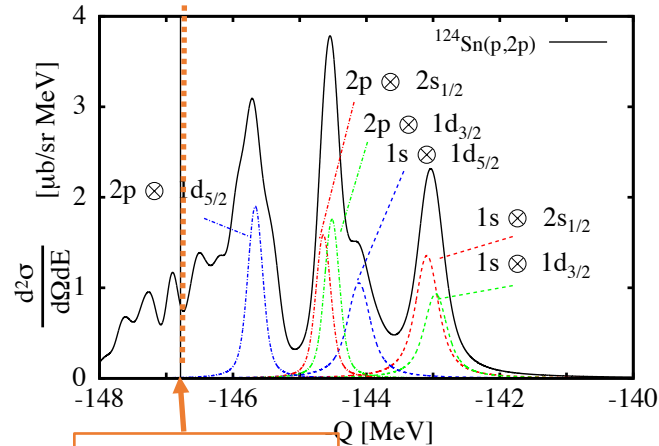
Phase 2

- Target : Xe

Phase 1 experiment – expected spectrum

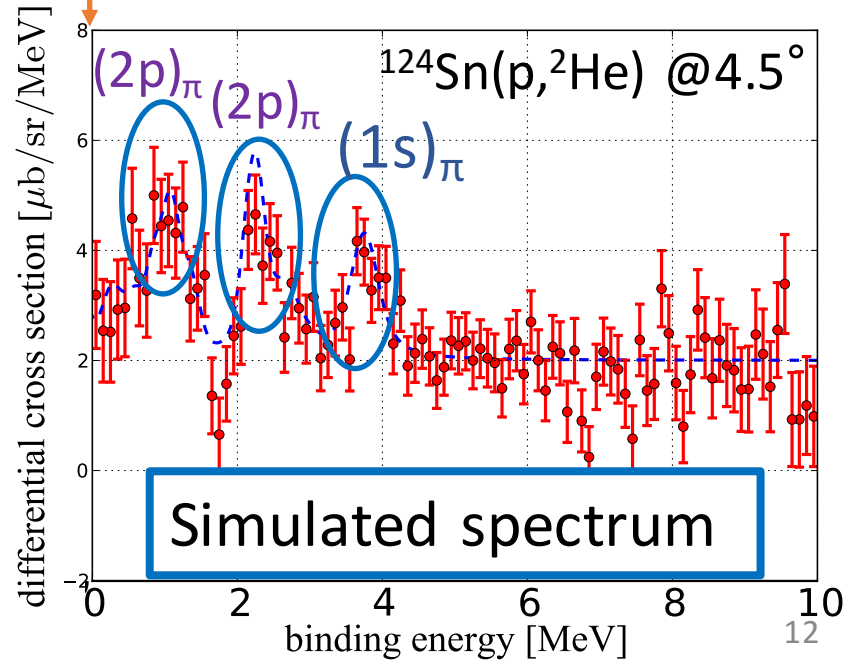
- Grand Raiden @4.5°
- ^{124}Sn target
(30 mg/cm²)
- 350 MeV proton beam
- Beam intensity :
30 nA, 10days

Observe 3 peaks



Theoretical calculation
J. Yamagata-Sekihara,
N. Ikeno, and
S. Hirenzaki,
private communication.

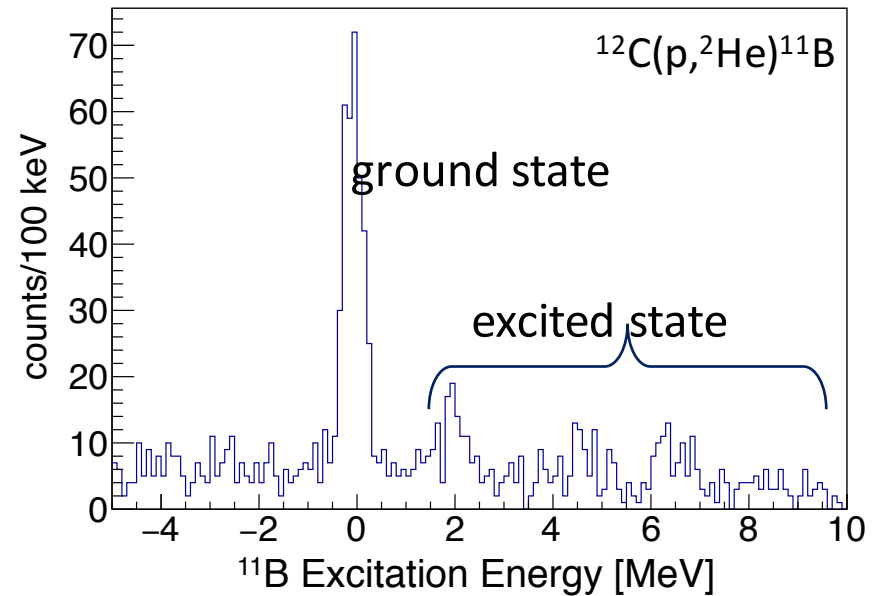
πB=0 [MeV]



Simulated spectrum


Feasibility study

- Detection of ^2He at Grand Raiden
 - Observed $^{12}\text{C}(p,^2\text{He})^{11}\text{B}$



- Test for intense beam
- Background measurement
- How to check the beam stability
- Optics study

Summary

- (d,³He) – GSI, RIKEN
- (p,²He) – RCNP
 - Possible to use Gas target
 - high precision measurement
 - Grand Raiden – high resolution
- Test experiment at RCNP
- Proposal was submitted
- Target : ¹²⁴Sn  Xe isotopes (future plan)