Investigation of direct reactions with active target time projection chambers

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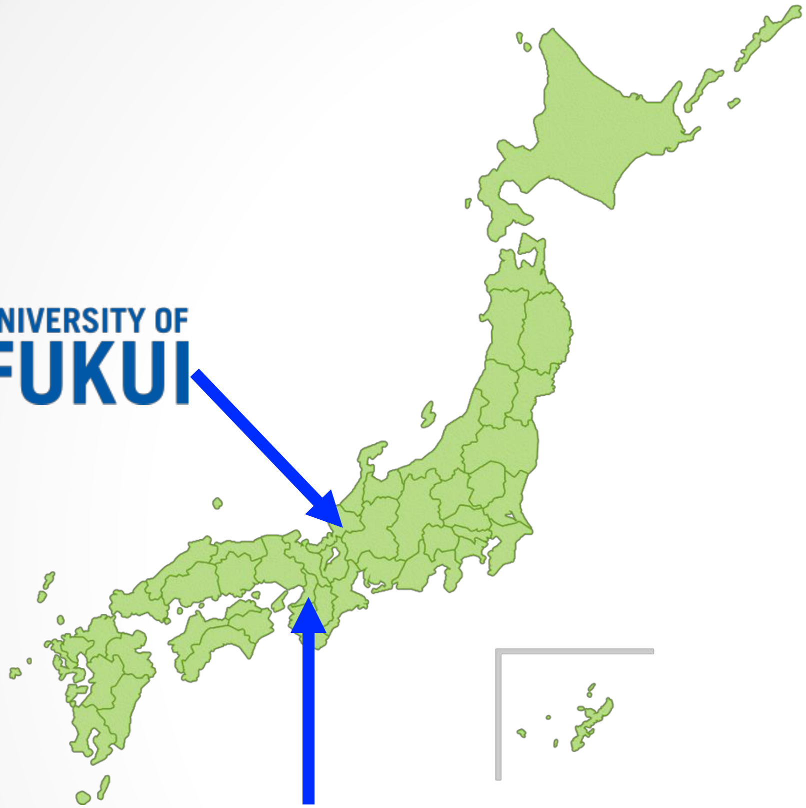
2025/09/03–05 Nuclear Astrophysics Experiments with HIAF

Osaka → Fukui

UNIVERSITY OF FUKUI



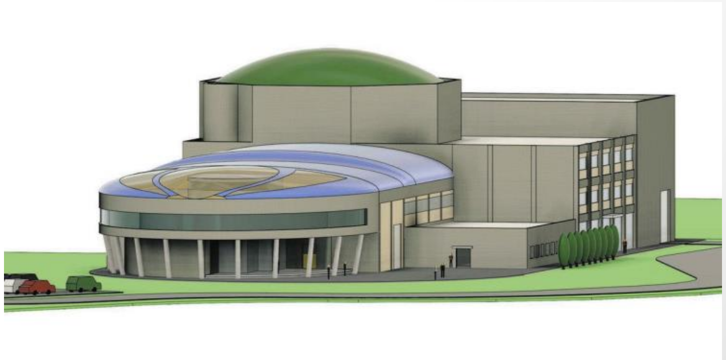
Osaka

福井 (Fukui)

well of happiness

Facilities in Fukui

WERC facility
- ✓ 5 MV tandem
- ✓ 200 MeV synchrotron



New research reactor (in 10 years)

MAIKo active target

Direct reactions

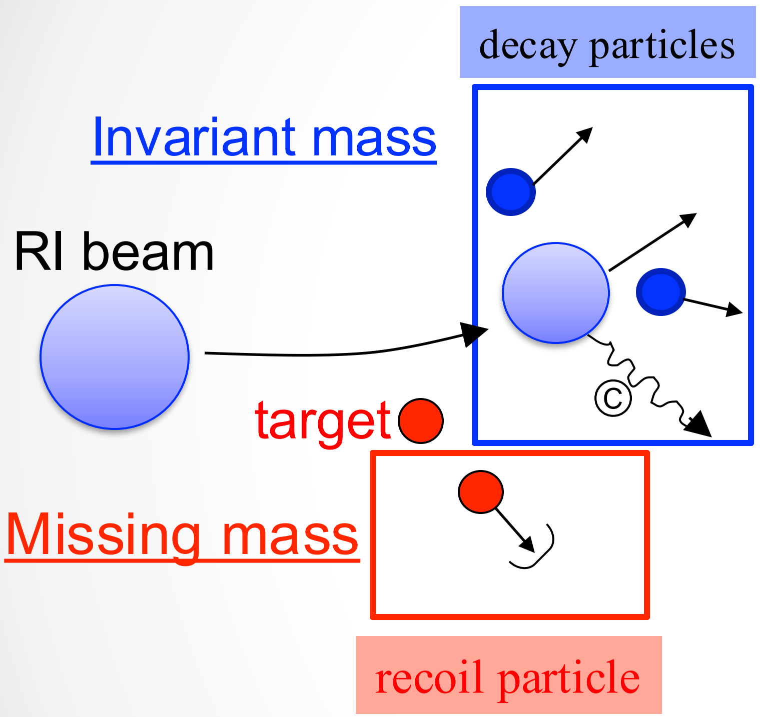
Direct reactions with light ions are very useful tool to investigate nuclear structures.

- Proton, ^{4}He elastic scattering: (p,p), (α,α)
  nuclear density distribution, skin thickness
- Charge exchange reaction: (p,n), (^{3}He,t), (t, ^{3}He), (d,^{2}He)
  Gamow-Teller strength, β decay
- Transfer reaction: (p,d), (p,t), (p,^{3}He), (p,d),…
  shell structure
- Knockout reaction: (p,2p), (p,pα),…
  Ground state configuration, momentum distribution, cluster
- Inelastic scattering: (p,p'), (α,α'), (d,d')
  matrix element: $M \equiv \langle\psi_f||\hat{O}||\psi_i\rangle \quad \sigma \propto |M|^2$
  Overlap between g.s. & excited state → Direct comparison with theory.

Examples

- ✓ (p,p'): Nuclear magicity [M. L. Cortes *et al.*, PRC **97**, 044315 (2018).]
- ✓ (α,α'), (d,d'): Nuclear incompressiblity [T. Li *et al.*, PRL **99**, 162503 (2007).]
- ✓ (α,α'), (d,d'): α cluster [J. Chen *et al.*, PRL **134**, 012502 (2025).]

Inelastic scattering with RI beam



2 methods for spectroscopy

- Invariant mass
  - ✓ Can use a thick target
  - ✓ Small efficiency for detecting all particles.
  - ✓ Ex Spectra are biased.
- Missing mass
  - ✓ Detect the recoil particle only.

non-relativistic formula

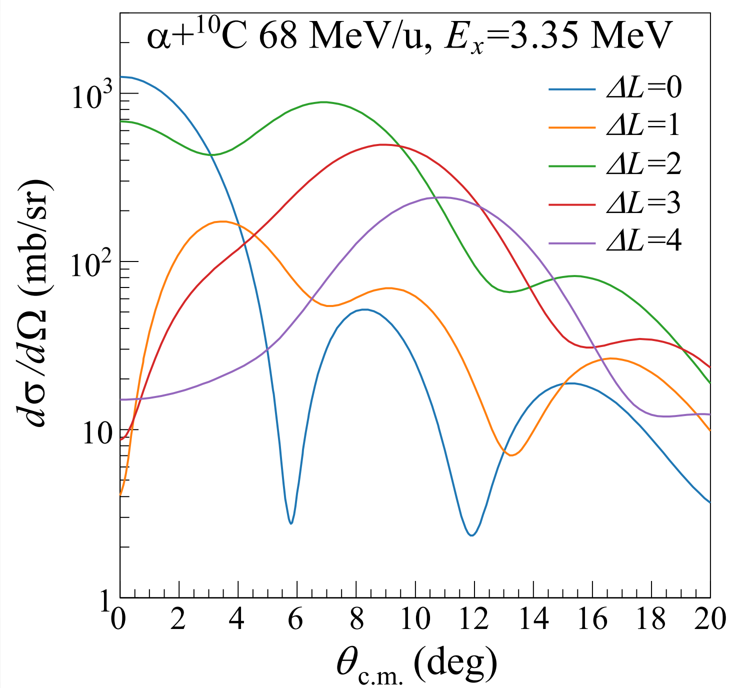
$$E_x = 2\sqrt{\frac{m}{M}E_{\mathrm{beam}}\underline{E_\alpha}}\,\underline{\cos\theta} - \left(1+\frac{m}{M}\right)\underline{E_\alpha}$$

Missing mass can be applied regardless of the decay channel.
Will be especially important for states above particle decay threshold.

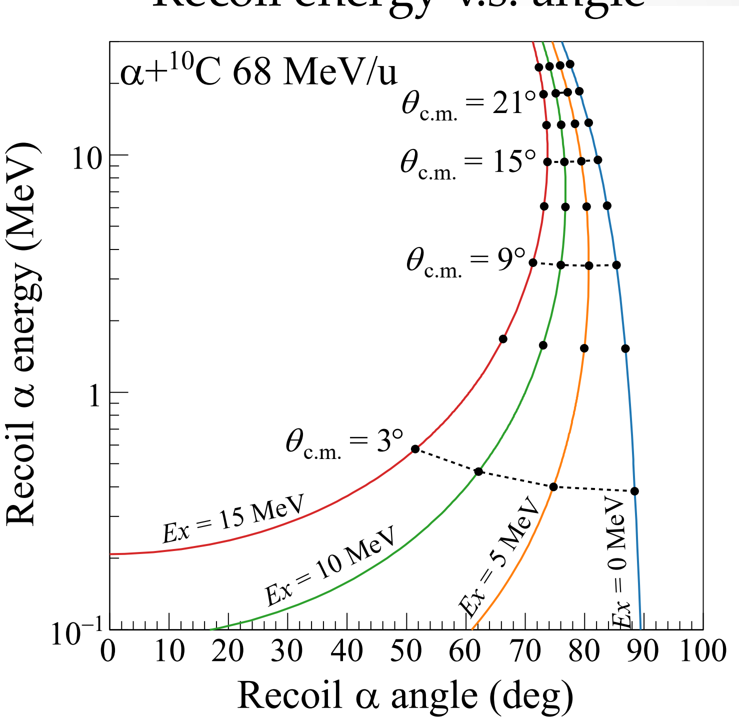
Kinematic condition

Big challenge in RI beam experiments from the kinematic condition.

Differential cross section by DWBA

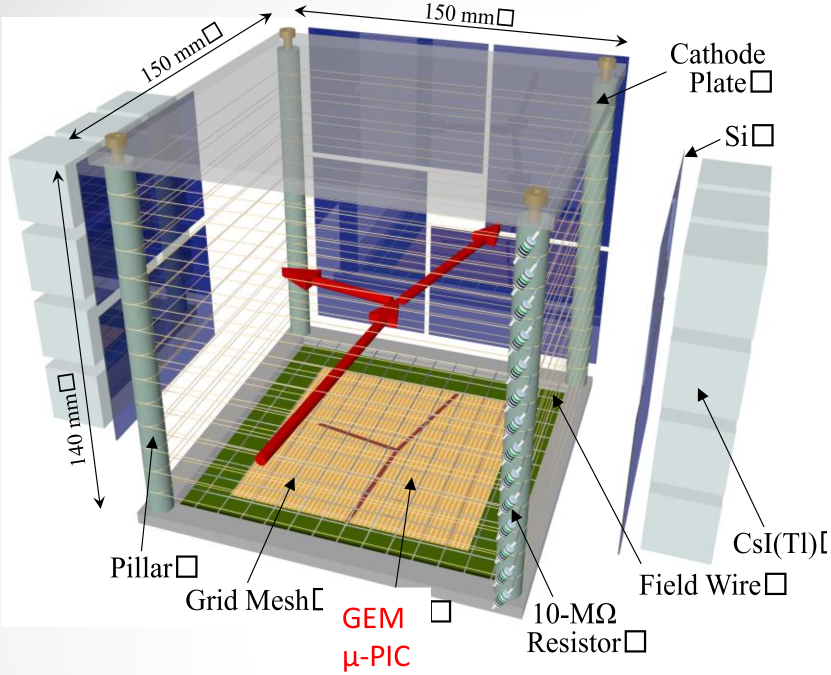


Recoil energy v.s. angle

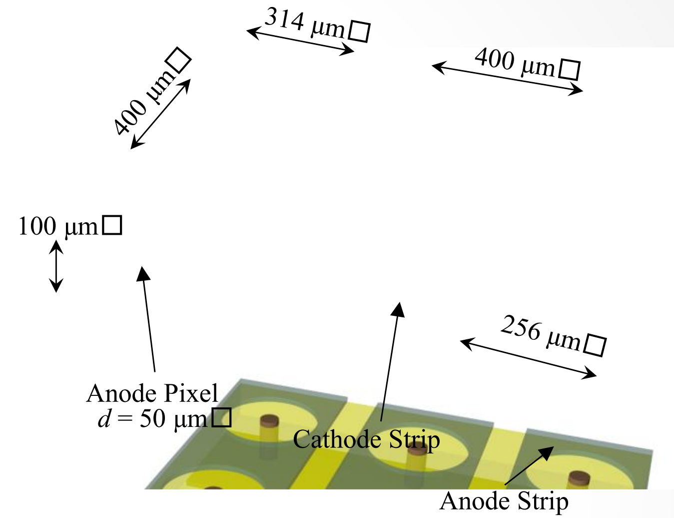


Energy of recoil particle is extremely small (~ 1 MeV).

MAIKo Active Target



μ-PIC for amplification and readout



A. Ochi *et al.*, NIM A **471**, 264 (2001).
T. Furuno *et al.*, NIM A **908**, 215 (2018).

- TPC gas = target gas (He, H_2, D_2, iC_4H_{10}, ...)
- μ-PIC + GEM amplification
  - μ-PIC (gain~1000): 2-dimensional strip readout (400 μm pitch). 256(Anode) + 256(Cathode) = 512 ch.
  - GEM (gain~30): 140 μm pitch, d=70 μm, t=100 μm (thick GEM)
- TPC track → θ_α , range in the gas / Si+CsI → E_α

Development at RCNP since 2011.

First Physics Experiment: ^{10}C

Measurement of neutron quadrupole matrix element in ^{10}C.

$$M_{n(p)} \equiv \langle 2_1^+ || \sum_{n(p)} r^2 Y_2 || 0_1^+ \rangle$$

Physics Motivations for ^{10}C

- ☐ Investigate Z=6 magicity in proton-rich carbon isotopes
  - ✓ Z=6 magicity is proposed in neutron-rich ^{13}C-^{20}C
    - Small B(E2) value, Small proton radius, Large proton separation *E*

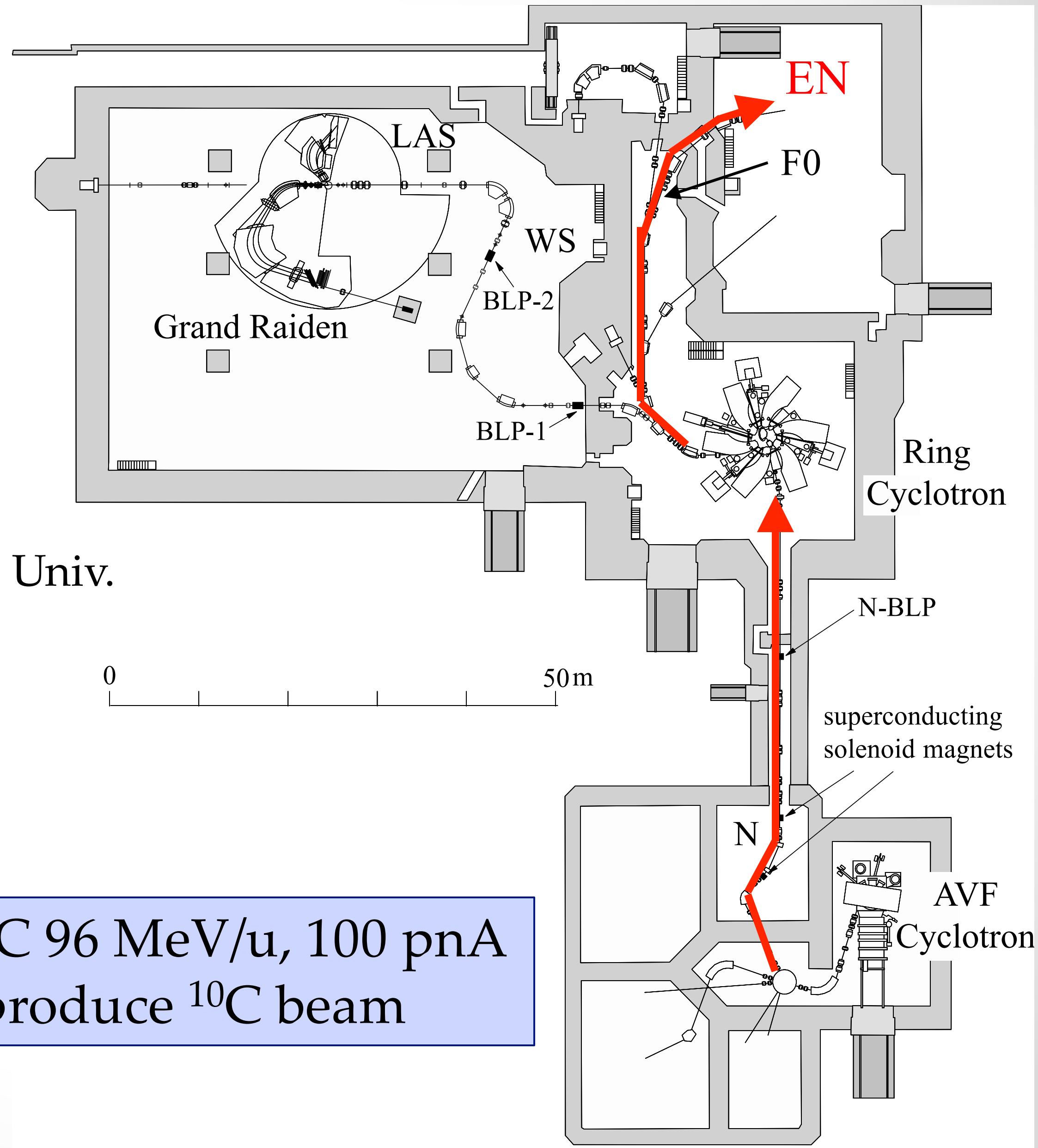
      D. T. Tran, H. J. Ong *et al.*, Nature Com. **9**, 1594 (2018).
  - ✓ Measurement of quadrupole matrix element (M_n, M_p) in ^{10}C

A. M. Bernstein *et al.*, PRL **42**, 425 (1979).

- ☐ Open shell nuclei: $M_n/M_p \sim 1$ (isoscalar)
- ☐ Proton magic → Proton transition is suppressed, $M_n/M_p > 1$

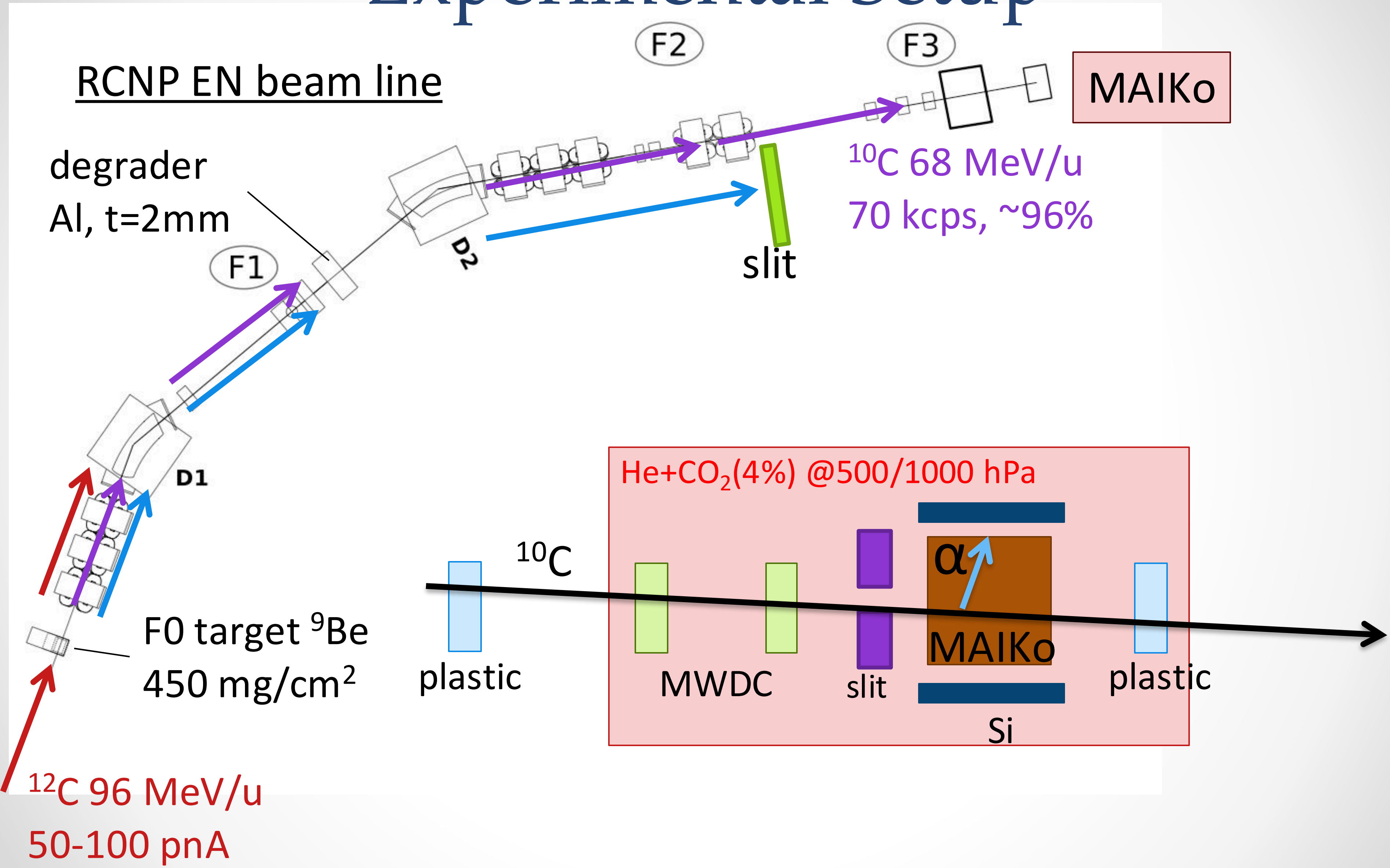
  c.f. ^{16}C: $M_n/M_p = 3.2 \pm 0.7$ [H. J. Ong *et al.*, PRC **78**, 014308 (2008).]
- ☐ Neutron magic → Neutron transition is suppressed, $M_n/M_p < 1$

Experiment at RCNP



Primary beam: ^{12}C 96 MeV/u, 100 pnA
EN beamline to produce ^{10}C beam

Experimental Setup

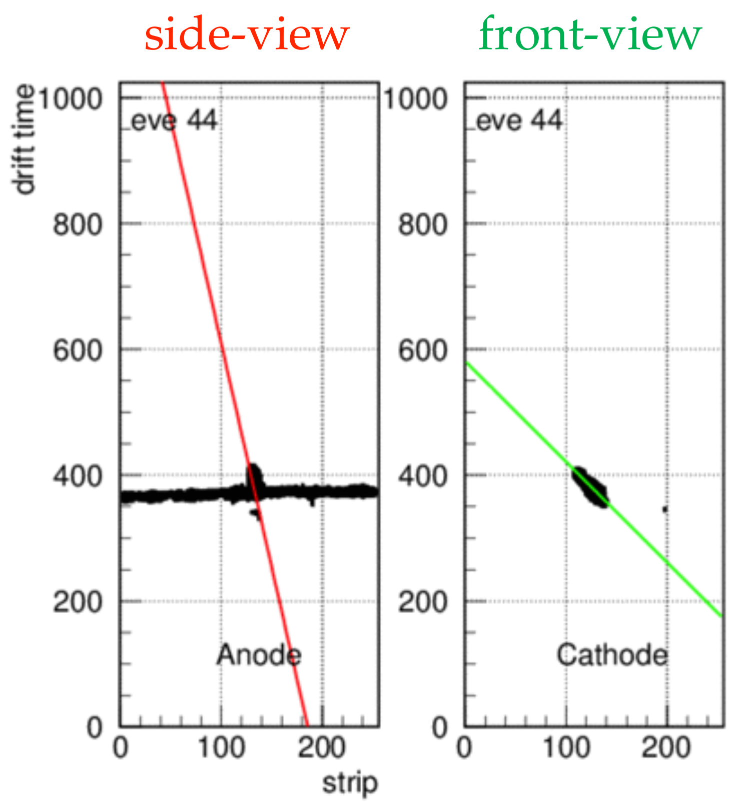


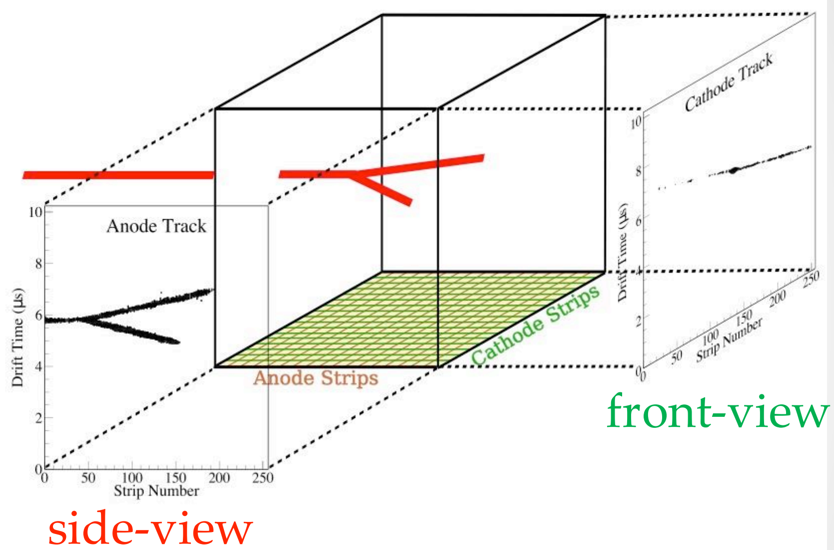
NIM B **70**, 320 (1992).

- NIM A **372**, 489 (1996).

AIP Conf. Proc. **1588**, 146 (2014).

Track Examples

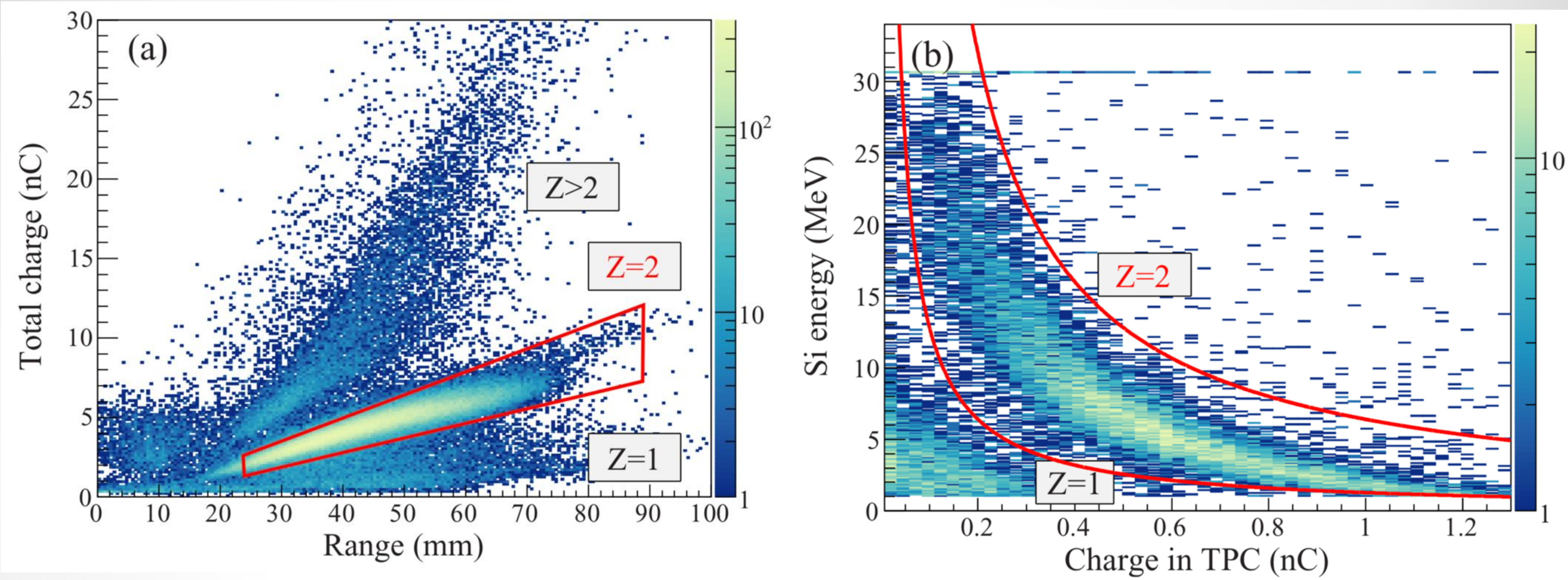




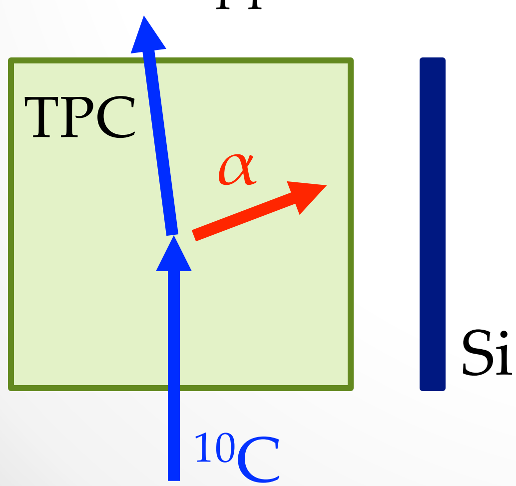
Track finding using Hough transformation

Reconstruct θ_{LAB} and E_{α} of recoil α particles to get the ^{10}C excitation energy and θ_{CM} .

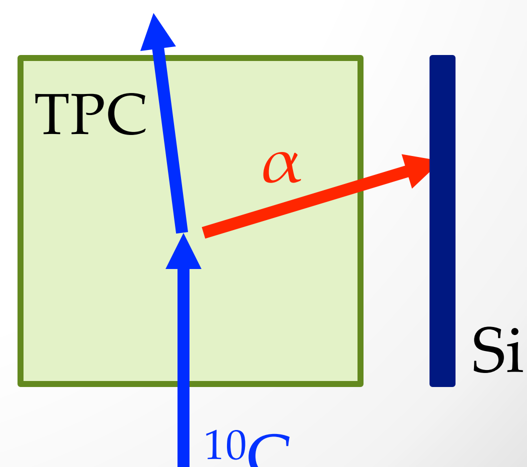
PID of Recoil Particles



Recoil α stopped in TPC

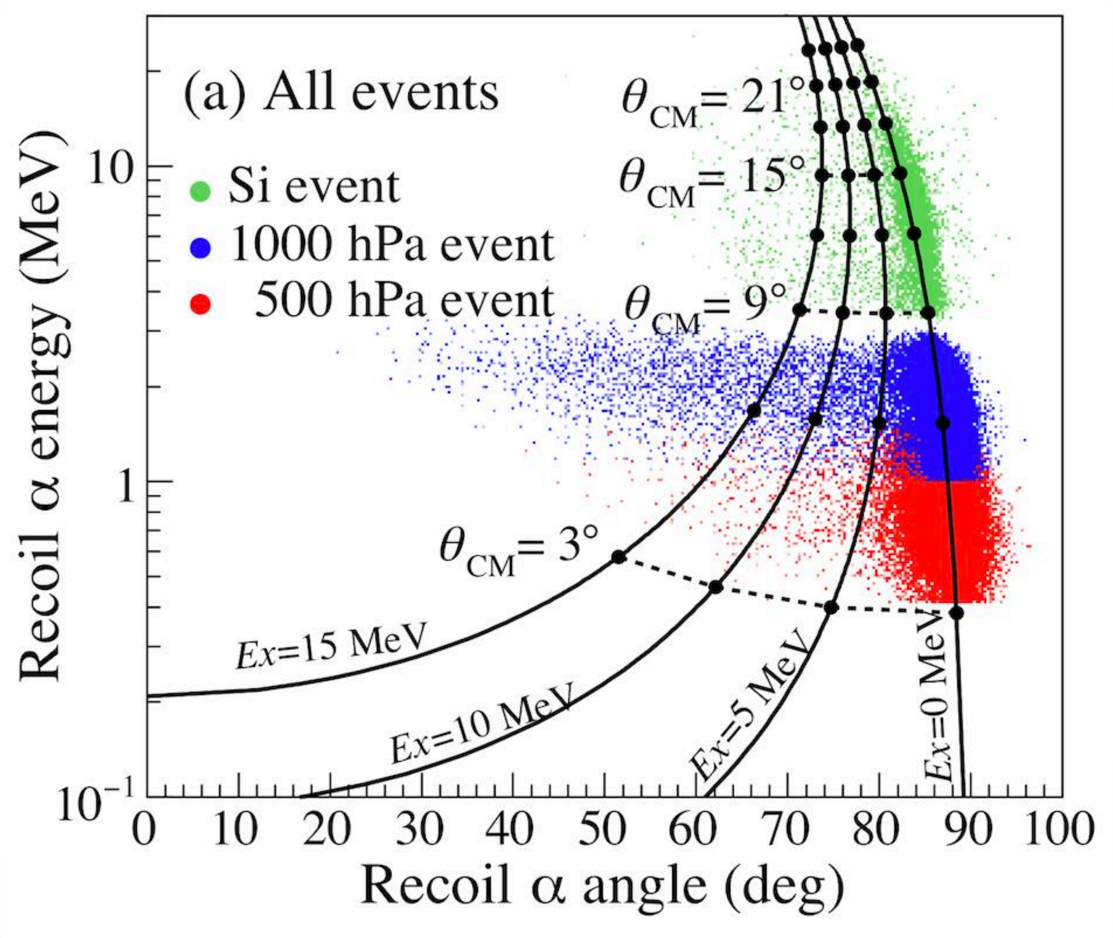


Recoil α hit Si



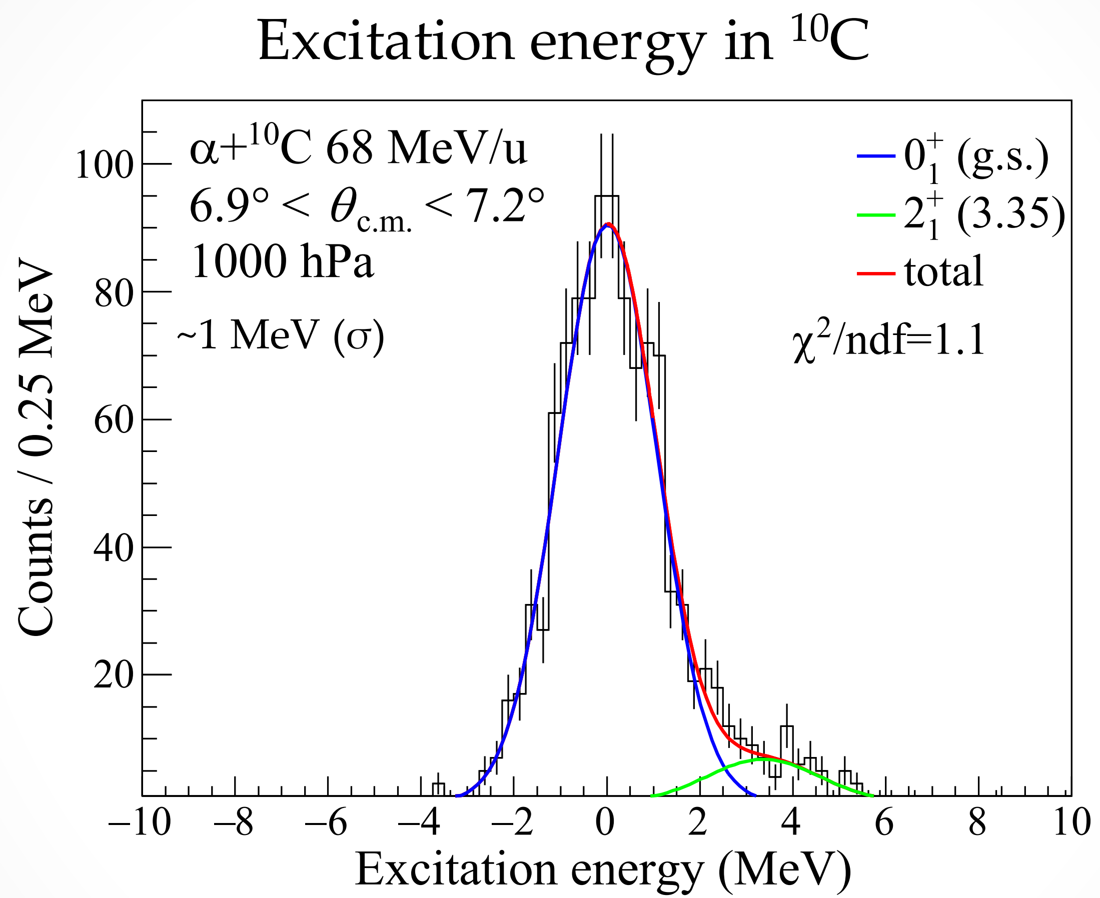
Results

Kinematic plot of recoil α



- ☐ Detection threshold down to 500 keV.
- ☐ Elastic scattering is dominant.

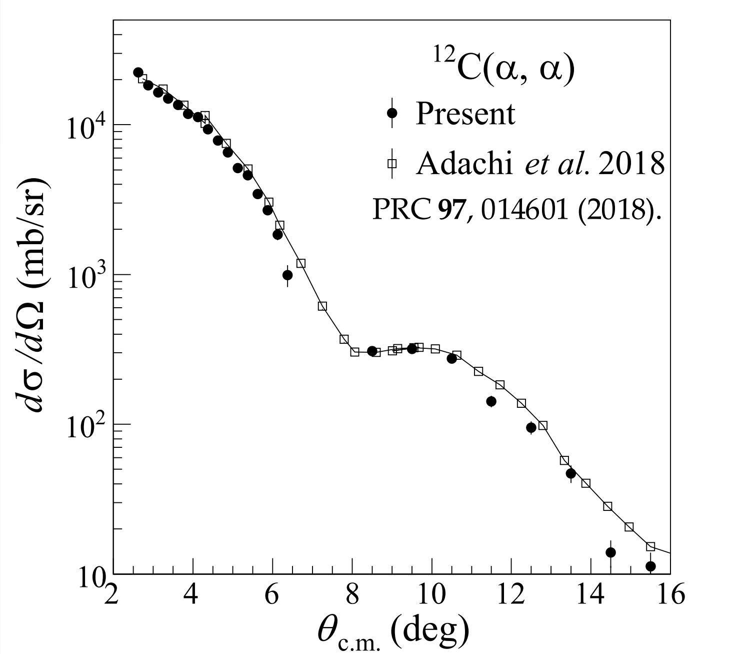
Results



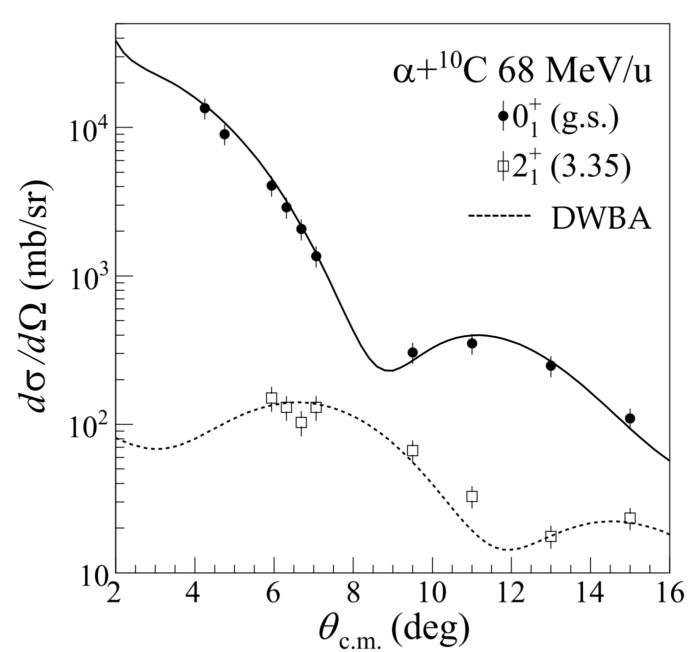
Obtained the 0_1^+ (g.s.) and 2_1^+ (3.35 MeV) yields.

Cross Sections for Low E_x

$^{12}C + \alpha$



$^{10}C + \alpha$



- $^{12}C + \alpha$ → Consistent with the previous result
  - ✓ MAIKo measurement is reliable.
- $^{10}C + \alpha$ elastic and inelastic
  - ✓ Elastic → Effective α-N interaction, density distribution
  - ✓ Inelastic → Neutron transition matrix element M_n

$$M_n = 6.9 \pm 0.7\ \text{(fit)}\ \pm 1.2\ \text{(sys)}\ \text{fm}^2$$

Matrix element in ^{10}C

A. M. Bernstein *et al.*, PRL **42**, 425 (1979).

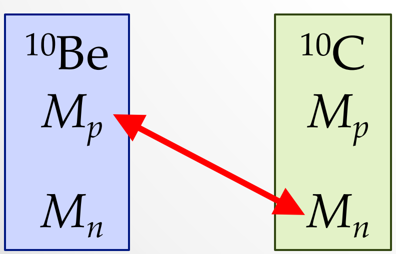
- open shell nuclei: $M_n/M_p \sim 1$(isoscalar)
- proton magic → proton transition is suppressed: $M_n/M_p > 1$
  c.f. ^{16}C $M_n/M_p = 3.2 \pm 0.7$ [H. J. Ong *et al.*, PRC **78**, 014308 (2008).]
- neutron magic → neutron transition is suppressed: $M_n/M_p < 1$

$$M_n = 6.9 \pm 0.7 \text{ (fit) } \pm 1.2 \text{ (sys) fm}^2$$

$$M_p = \frac{1}{e}\sqrt{B(E2; 0_1^+ \to 2_1^+)} = 6.63(11)\ \text{fm}^2$$ PRC **86**, 014312 (2012).

$$M_n/M_p(^{10}\text{C}) = 1.05 \pm 0.11 \text{ (fit) } \pm 0.17 \text{ (sys)}$$

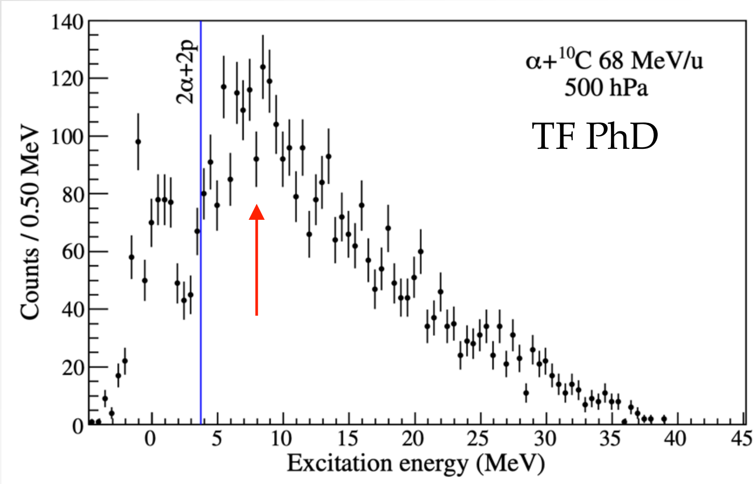
Proton magicity is hindered in ^{10}C

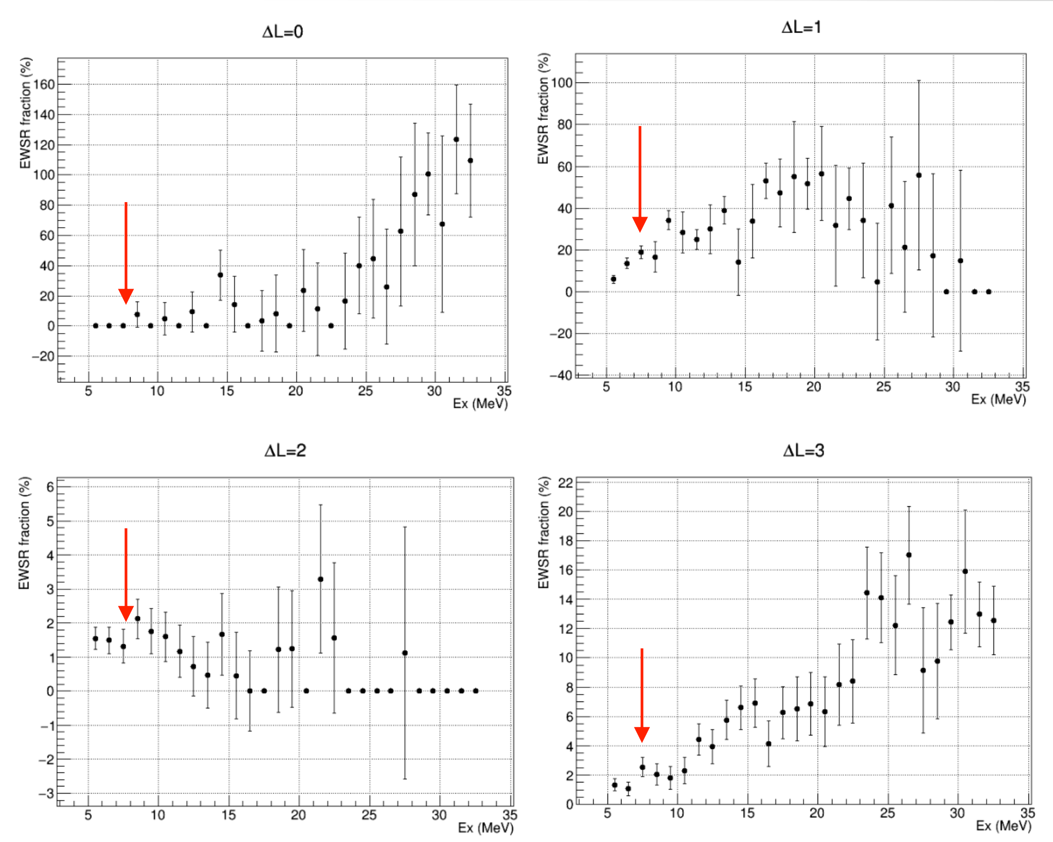


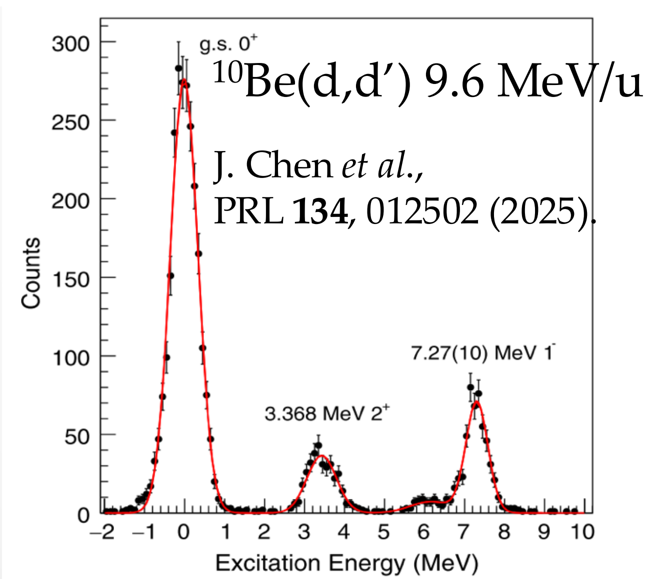
✓ ^{10}Be proton matrix element: $M_p(^{10}\text{Be}) = 6.78 \pm 0.11$ fm^2
[E. A. McCutchan *et al.*, PRL **103**, 192501 (2009).]

$M_n(^{10}\text{C}) = M_p(^{10}\text{Be})$ → mirror symmetry is conserved

High E_x spectrum







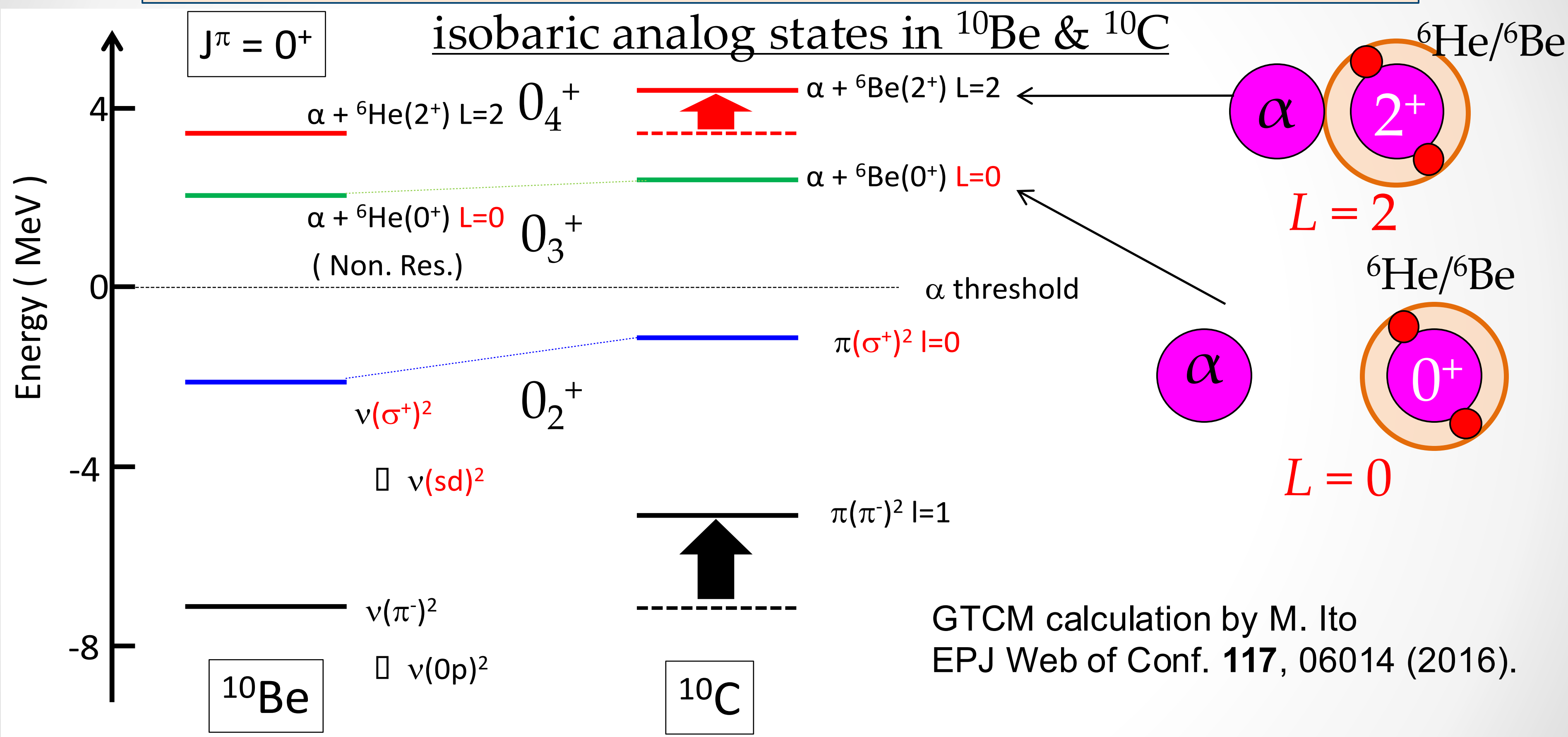
E_x~7 MeV → E1 dominant?

To assign the J^{π}, multi-pole decomposition analysis (MDA) is required.

- ✓ Divide the *Ex* spectrum into different $\theta_{CM.}$
- ✓ Compare $d\sigma/d\Omega$ with the DWBA calculations.

The mirror system of ^{10}C & ^{10}Be

The mirror system will give a new approach to α clusters.



GTCM calculation by M. Ito
EPJ Web of Conf. **117**, 06014 (2016).

- Energy shift will be observed in 0_4^+ states (α+^{6}He/^{6}Be with L=2).
  → *Thomas-Ehrman shift (TES)* of "cluster structures"
- The T-E shift unveil the inner structures of the clusters.

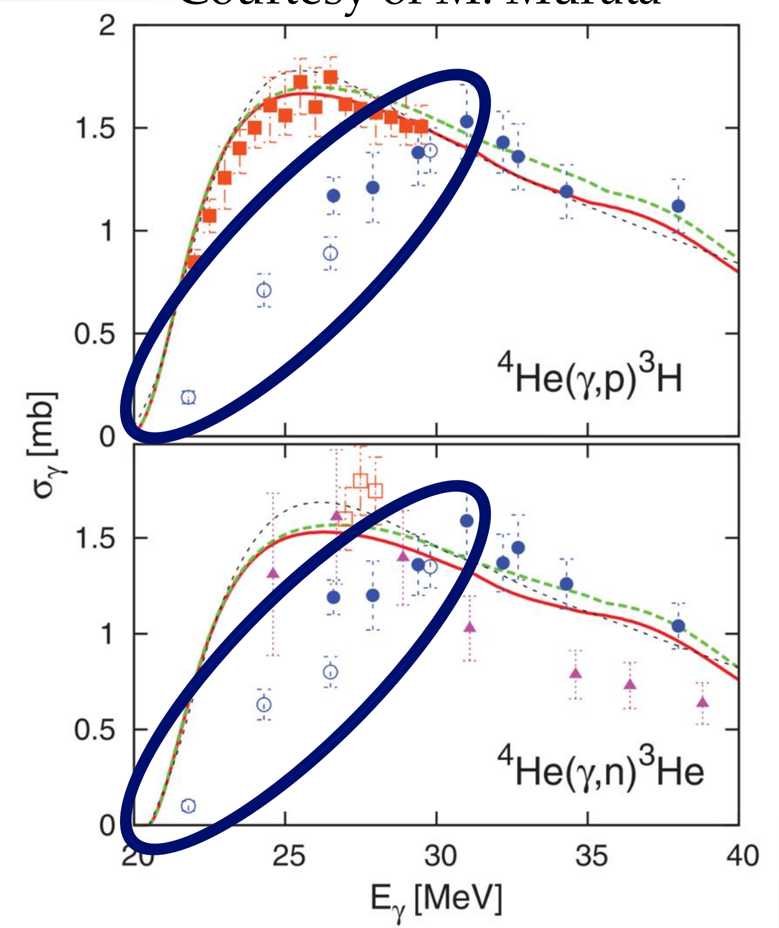
Recent Activities with MAIKo

Photo-disintegration of ^{4}He

^{4}He disintegration by gamma rays: ^{4}He(γ,p), ^{4}He(γ,n)

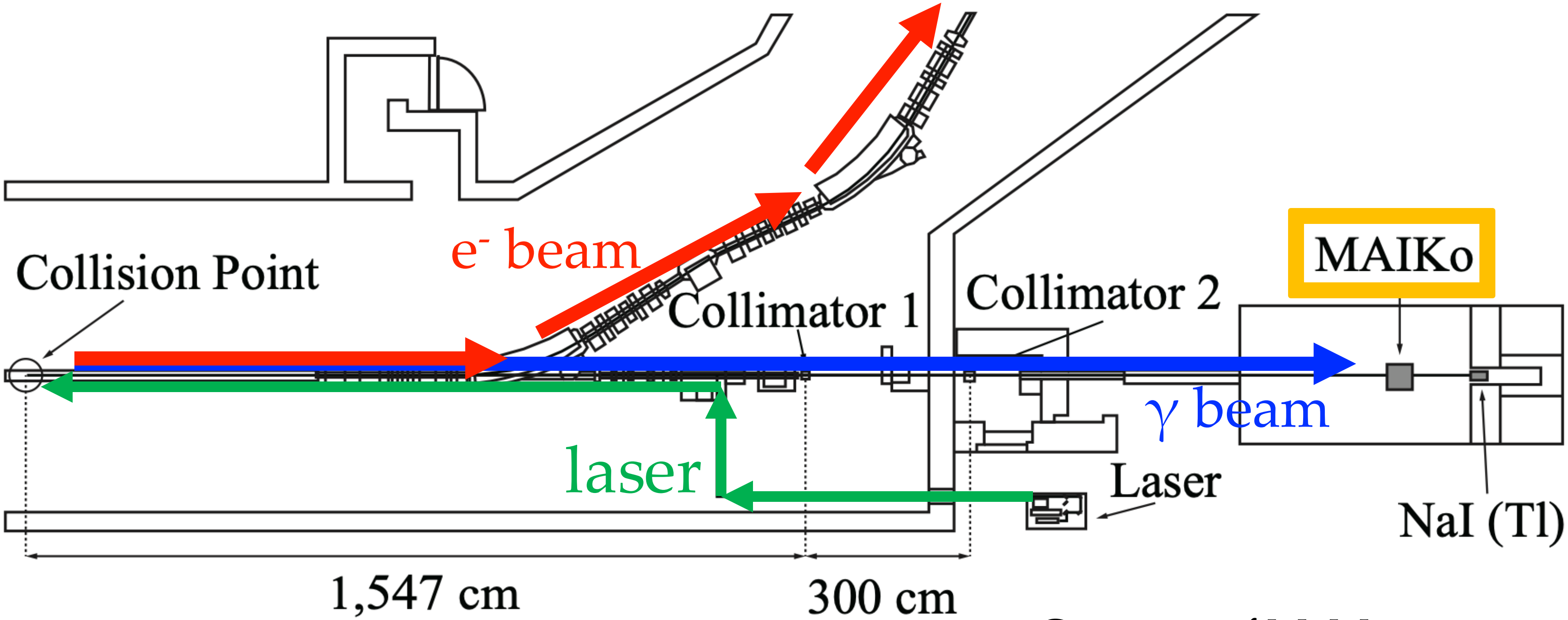
- ✓ Benchmark for the few-body calculations.
- ✓ Connection to the Big-Bang nucleosynthesis.
- ✓ Inputs to the ν-process: ^{4}He(ν,ν′p) and ^{4}He(ν,ν′n)

Courtesy of M. Murata

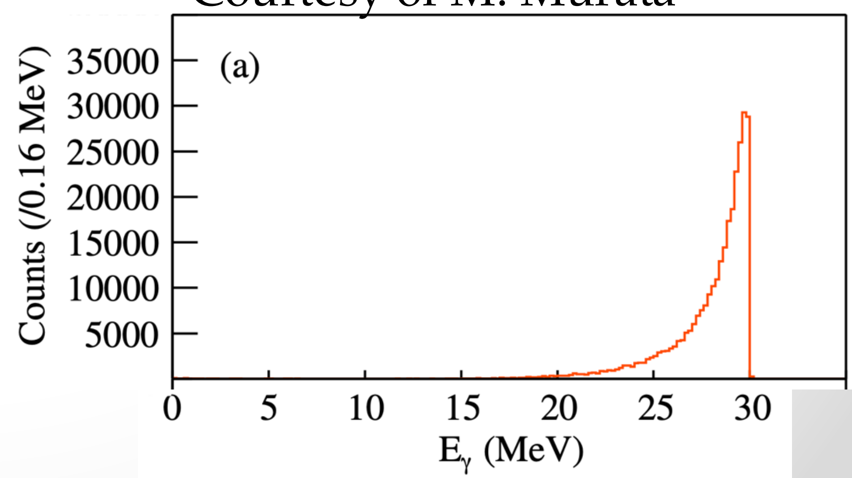


- ➢ Lack of experimental data over wide range of E_γ.
- ➢ Recent results By Shima *et al*. have no GDR peak.
  (PRC 72, 04404)

New-SUBARU facility

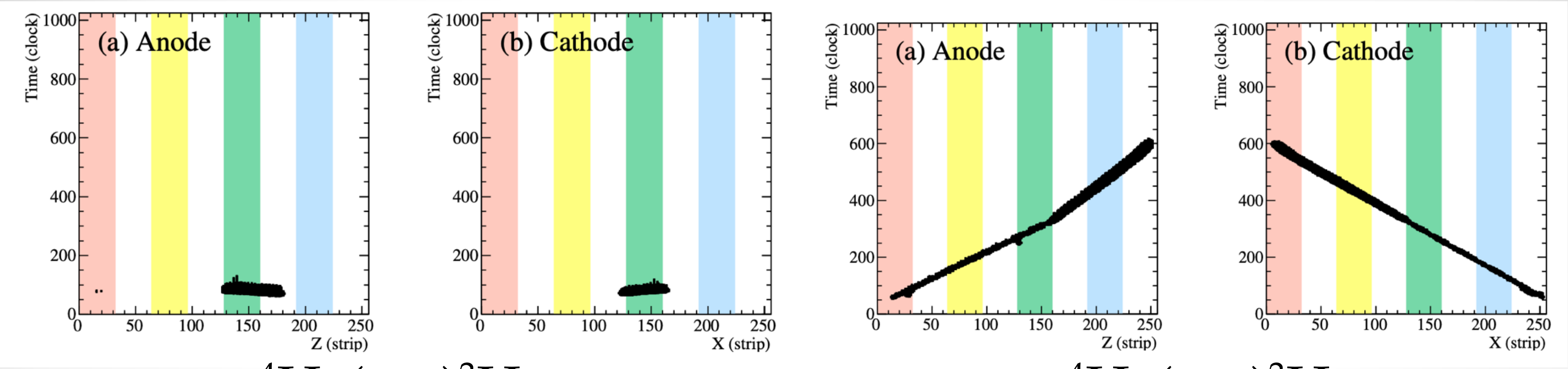


Courtesy of M. Murata



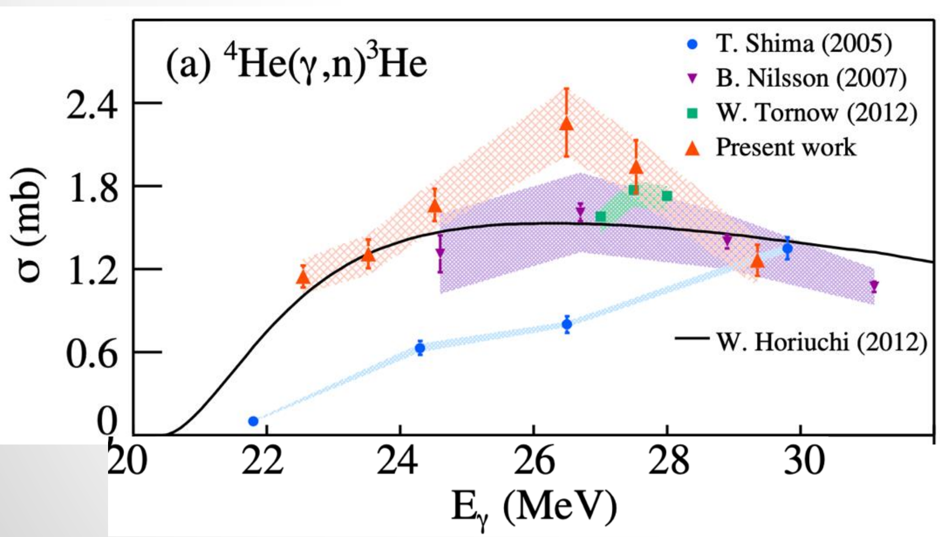
- ✓ Electron beam: 0.7–1.5 GeV, 250 mA
- ✓ γ beam energy: 0.5–73 MeV
- ✓ γ beam intensity: 10^5–10^6 cps
- ✓ Quasi mono-energy ($\Delta E/E<10\%$).

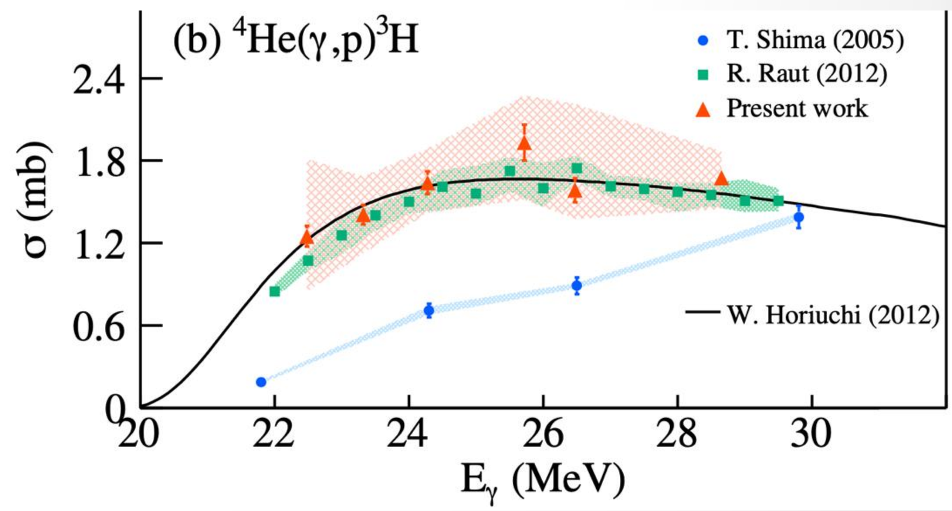
New-SUBARU Results



$^{4}He(\gamma,n)^{3}He$

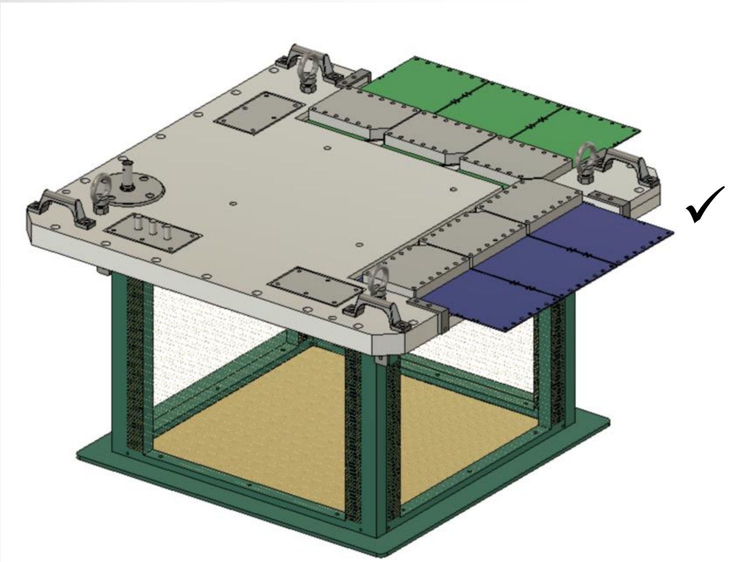
$^{4}He(\gamma,p)^{3}H$





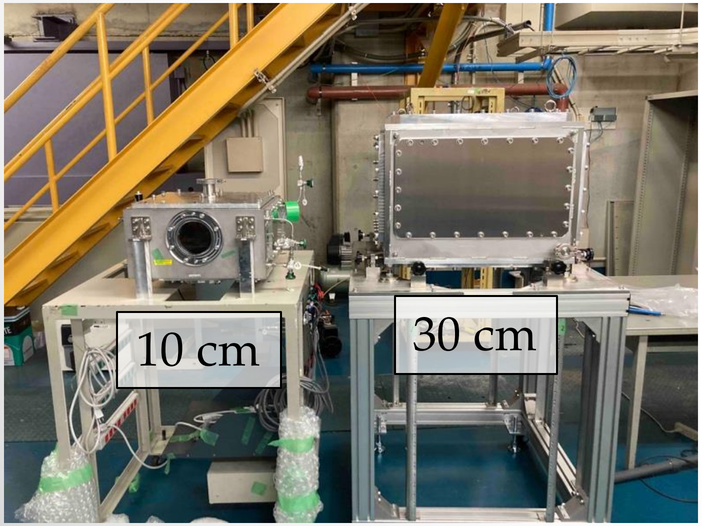
M. Murata, TF *et al.*, Phys. Rev. C **107**, 064317 (2023).
Ph. D. thesis

Upgrade to MAIKo+



Size of the TPC: 10 cm → 30 cm

✓ ×3 target thickness, ×3 detection efficiency
→ ×10 statistics
1536 ch   Future: upgrade to SAMPA

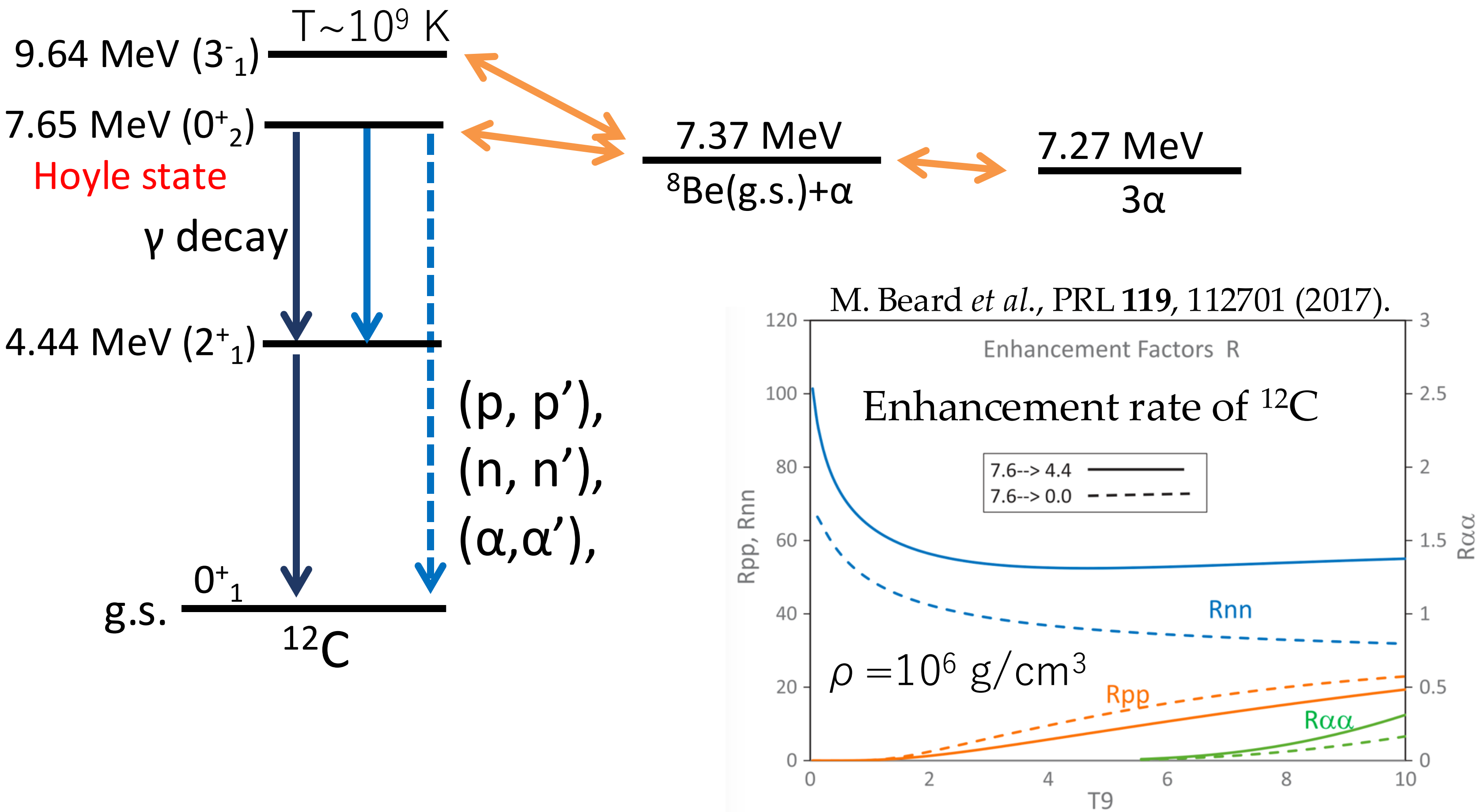


Physics programs

- Search for α cluster structures
- $^{12}C(n,n')$ measurement
- Resonant scattering for astro physics

Triple α under high density

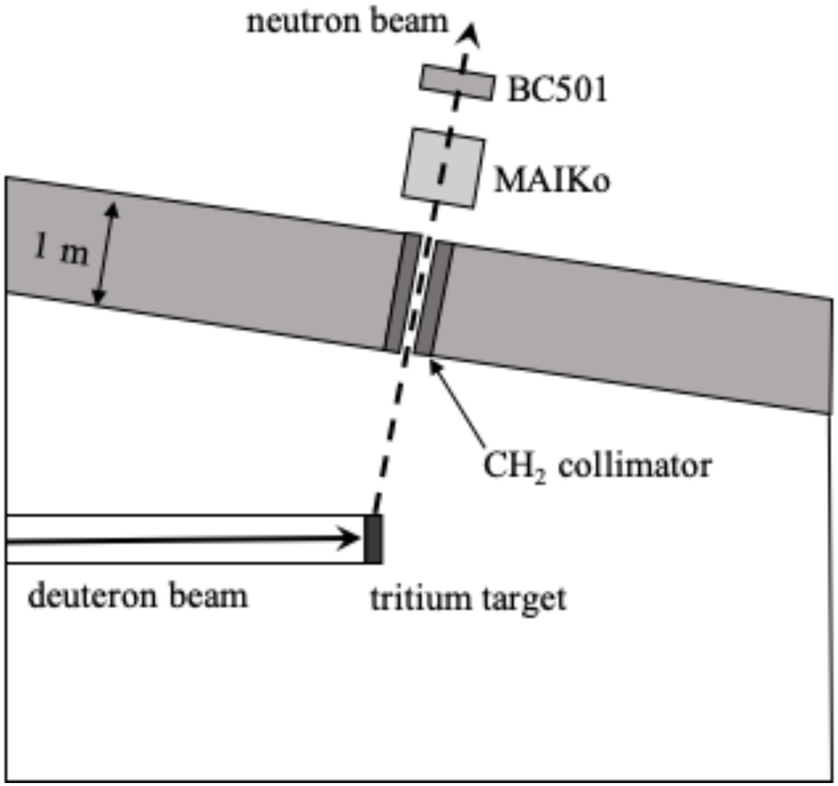
In high density environments, triple α reaction rate is enhanced by de-excitation of (n,n'), (p,p'), (α , α ').

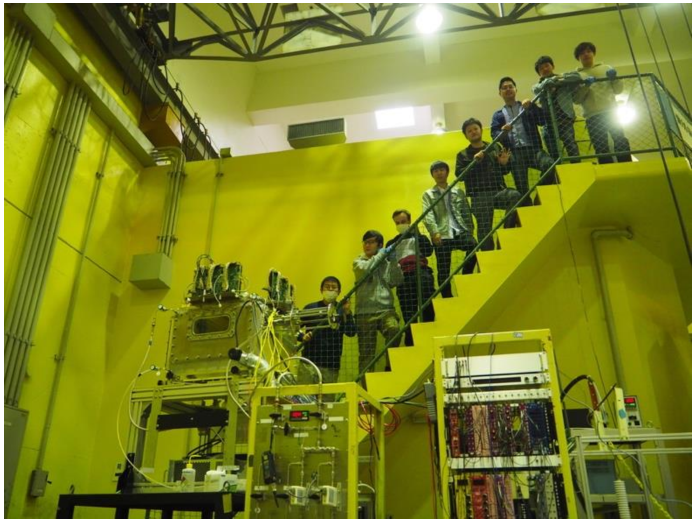


Measurement of ^{12}C(n.n')^{12}C$_{Hoyle}$

Test experiment

Test measurement using 14 MeV neutron beam at OKTAVIAN, Osaka Univ.
(Main exp. → ~10 MeV)

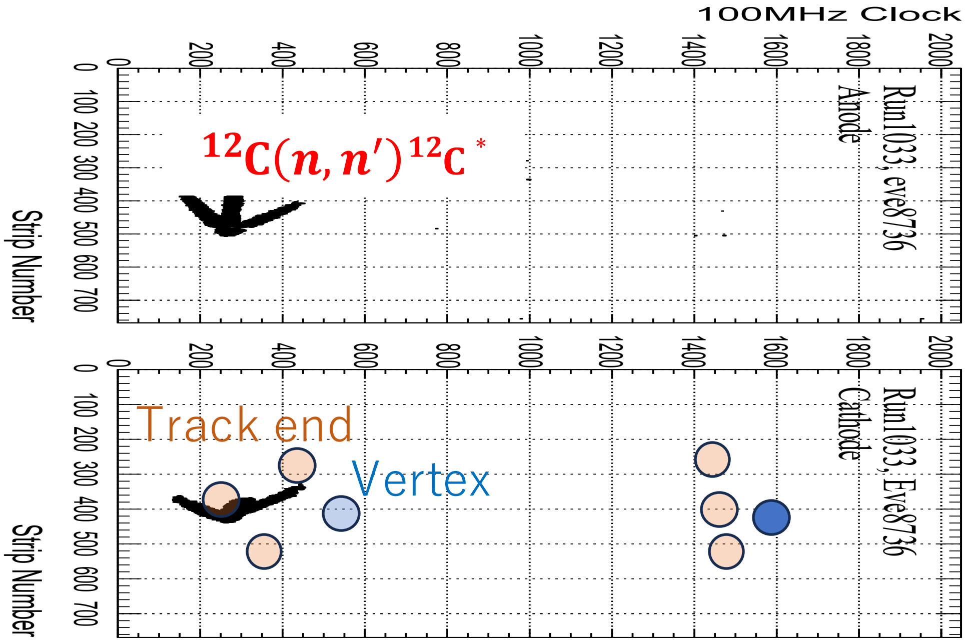


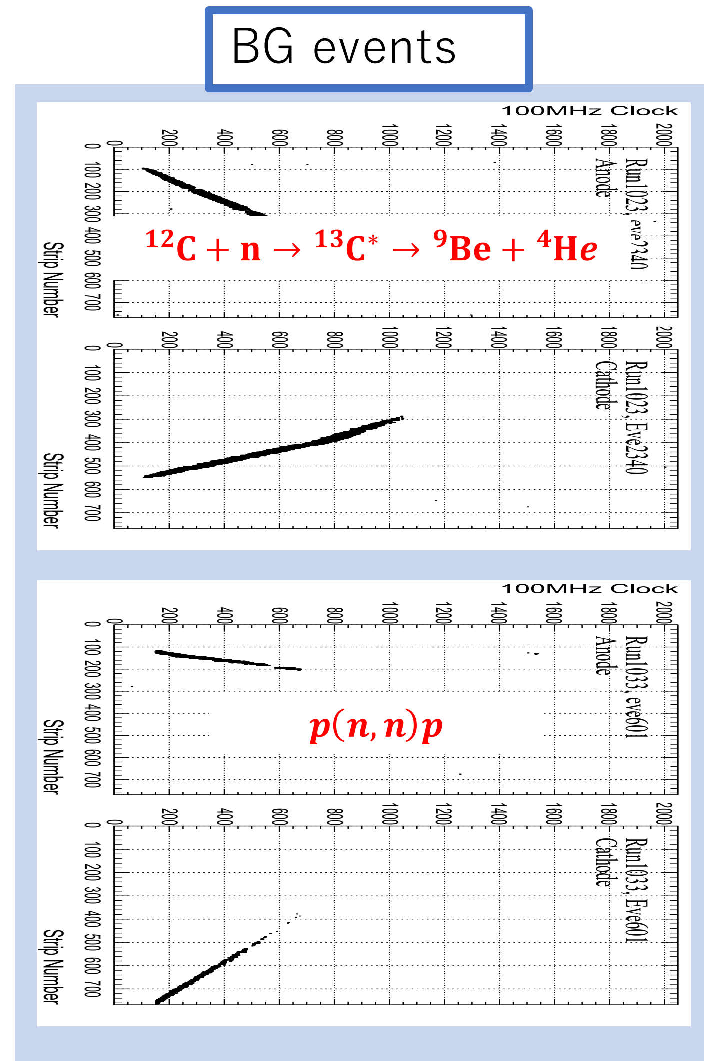


neutron

- ✓ d + t → ^{4}He + n (14 MeV)
- ✓ Collimated beam (~5 kHz)
- ✓ MAIKo gas: iC_4H_{10}(10%) + H_2(90%) 0.1 atm

Track analysis





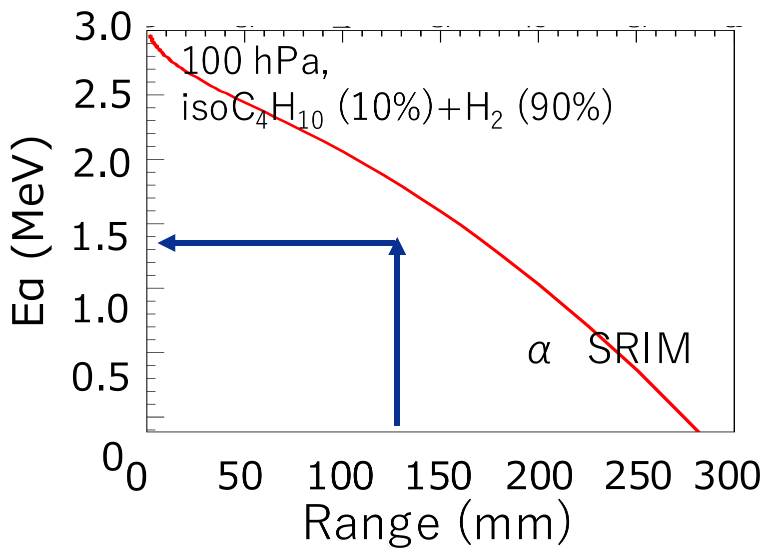
Courtesy of Y. Lin

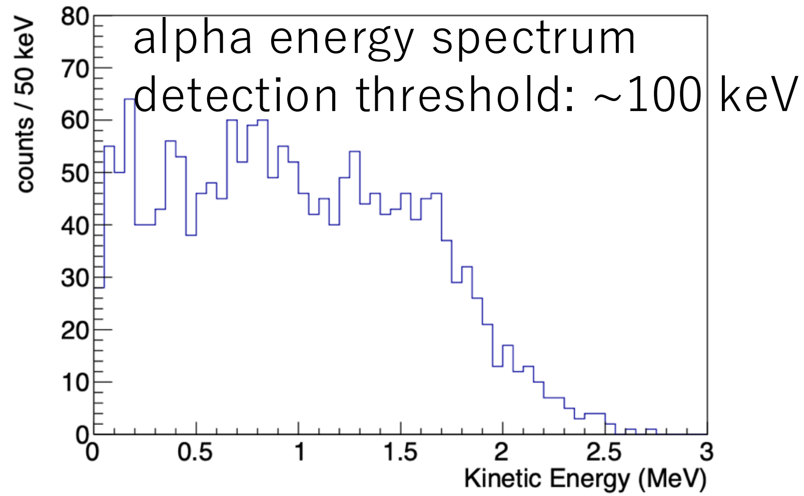
<u>Tracking analysis</u>

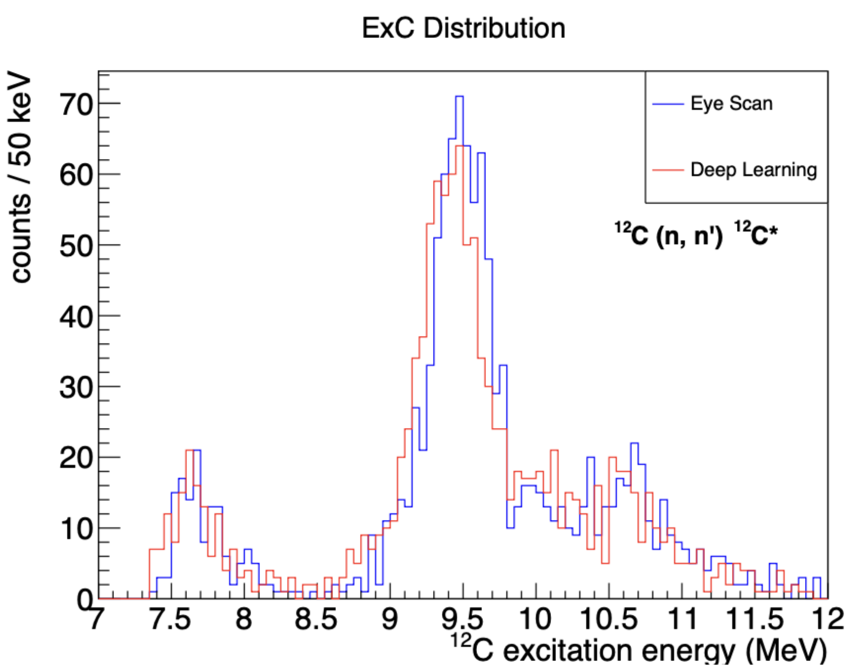
- ✓ 3 α decay event / BG events
- ✓ Position of the vertex & track end
  → Invariant mass

- ✓ Eye-scan analysis → 68,000 events with 14 people
- ✓ Deep learning trained by eye-scanned data.

Results: Ex reconstruction



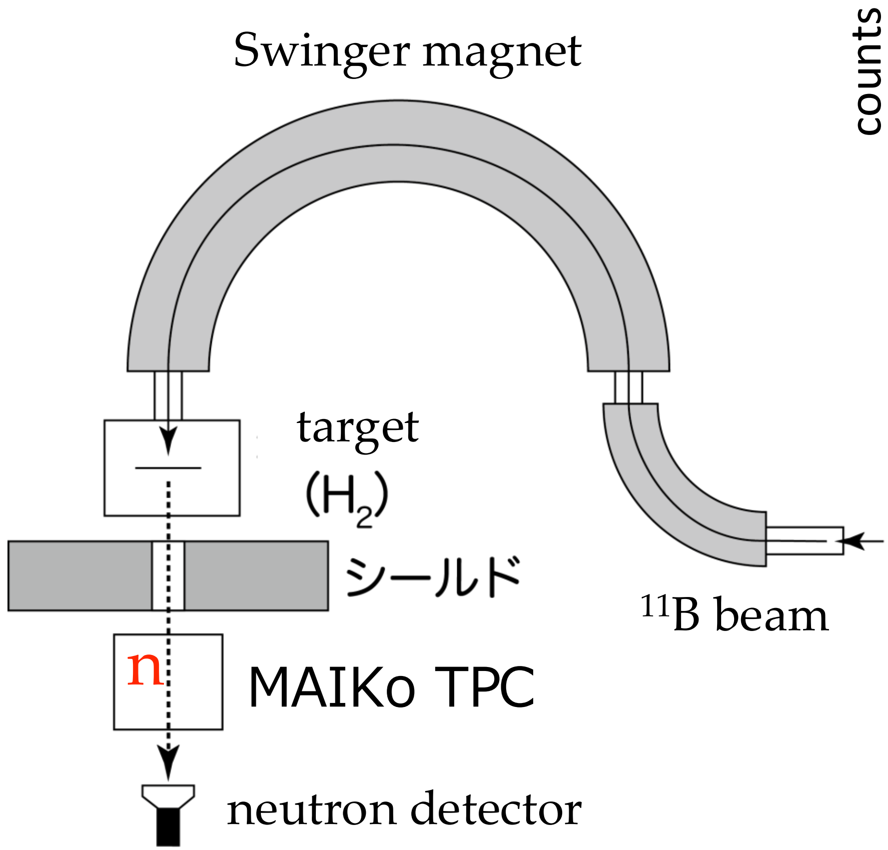




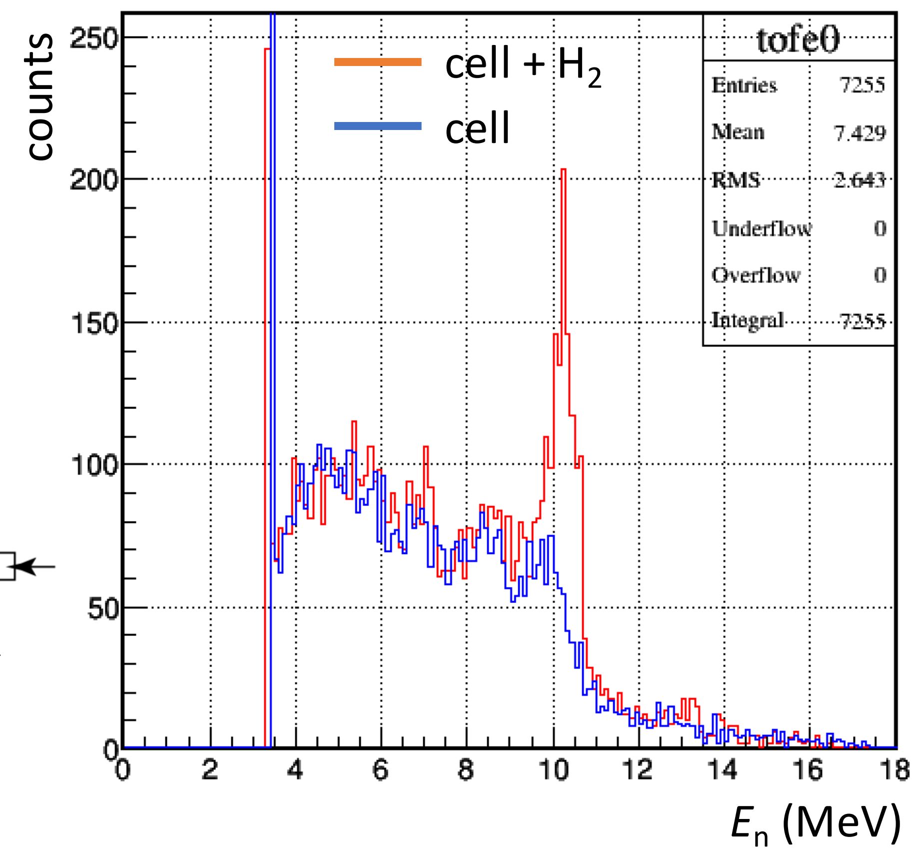
Physics experiment at RARiS

Measurement at En~10 MeV will be carried out in CYRIC (RARI

Experiment at CYRIC



Energy spectrum of the neutron beam

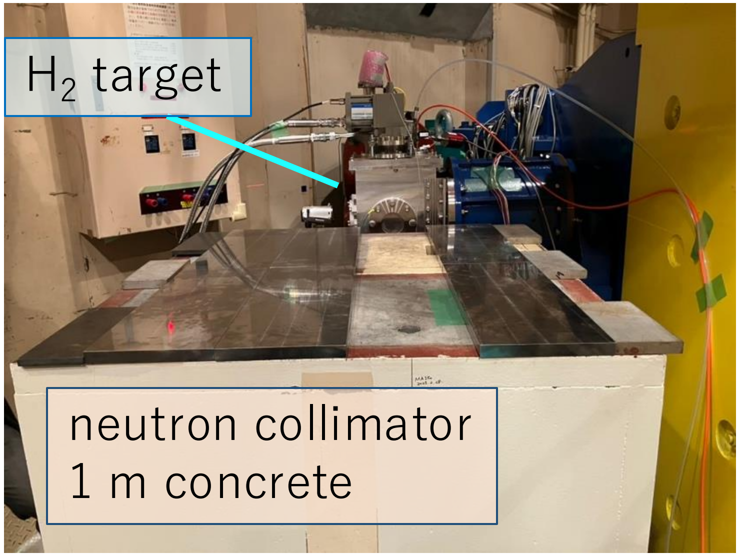


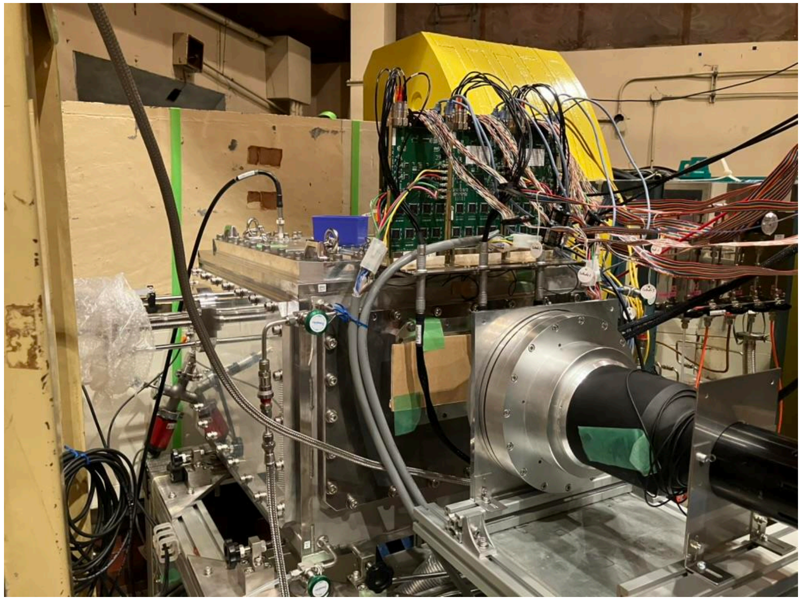
A. Nakagawa, master theses (2020).

Energy of the neutron beam can be tuned
by changing the angle of the swinger magnet.

Physics experiment at RARiS

Feb. 2025: Transportation from RCNP to Tohoku (~620 km)

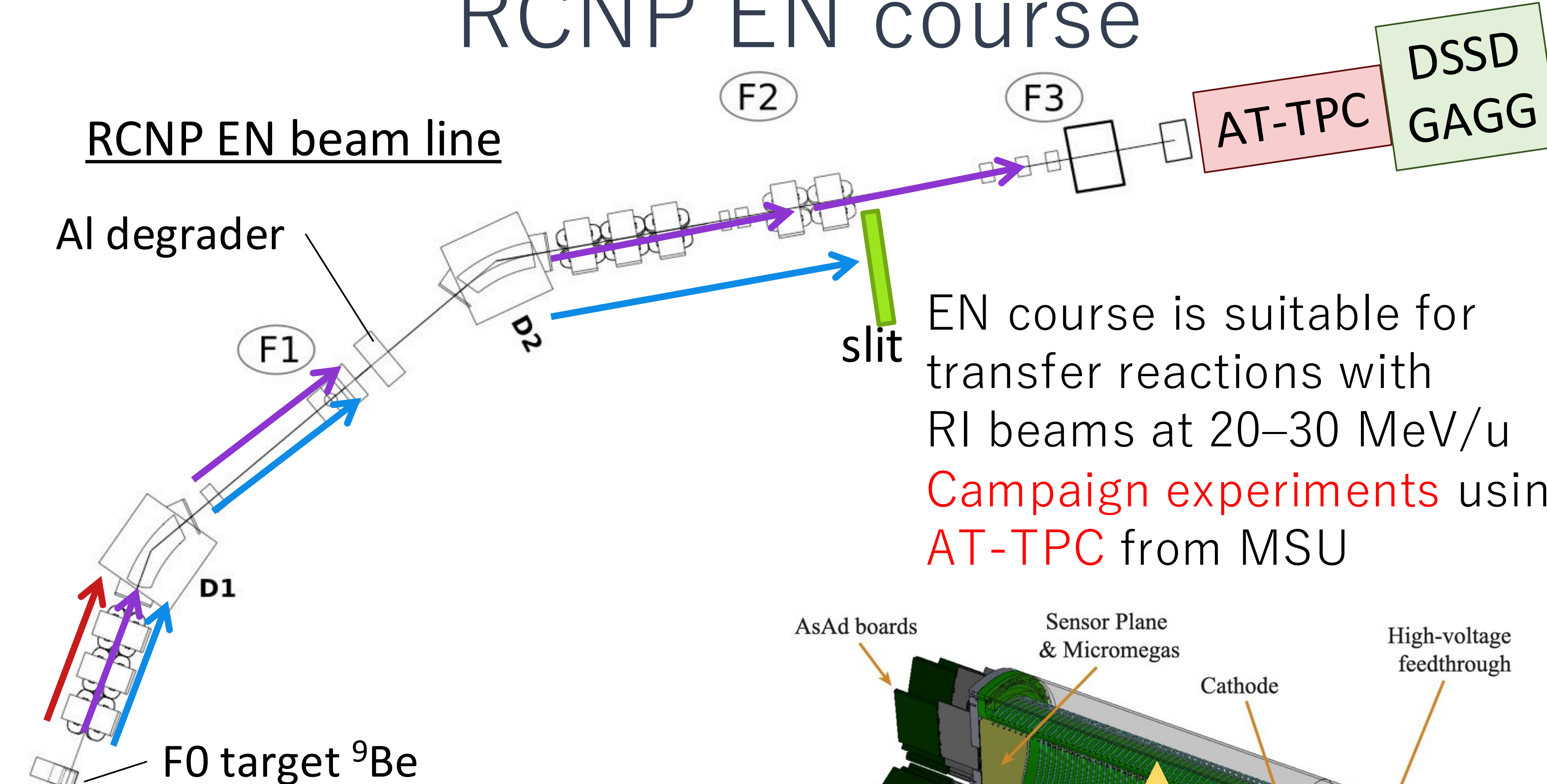




Beam time will be next month!
En = 8–13 MeV

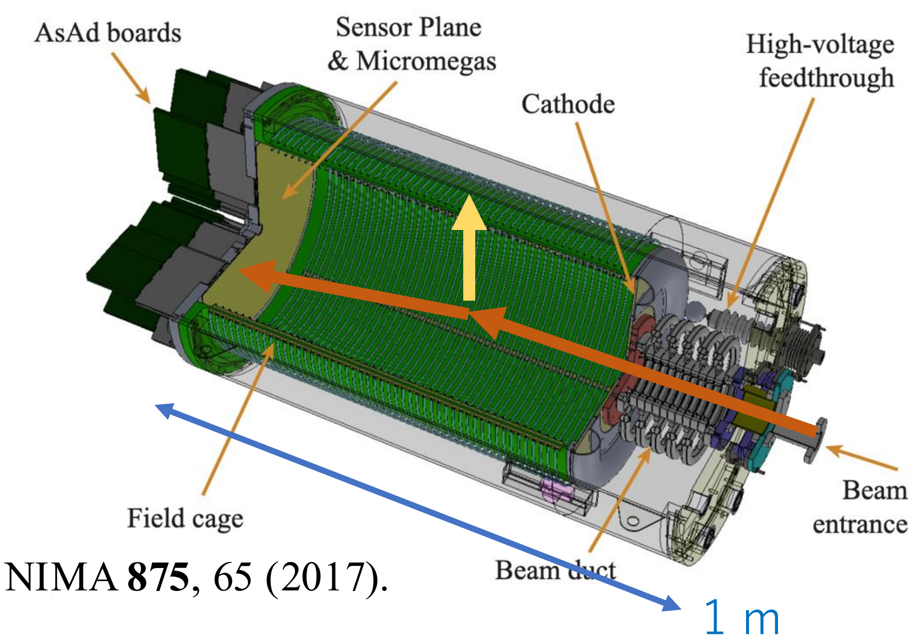
AT-TPC campaign at RCNP

RCNP EN course



EN course is suitable for transfer reactions with RI beams at 20–30 MeV/u

Campaign experiments using AT-TPC from MSU



NIMA **875**, 65 (2017).

AT-TPC campaign program

Measurement of deuteron induced reactions.

Approved experiments

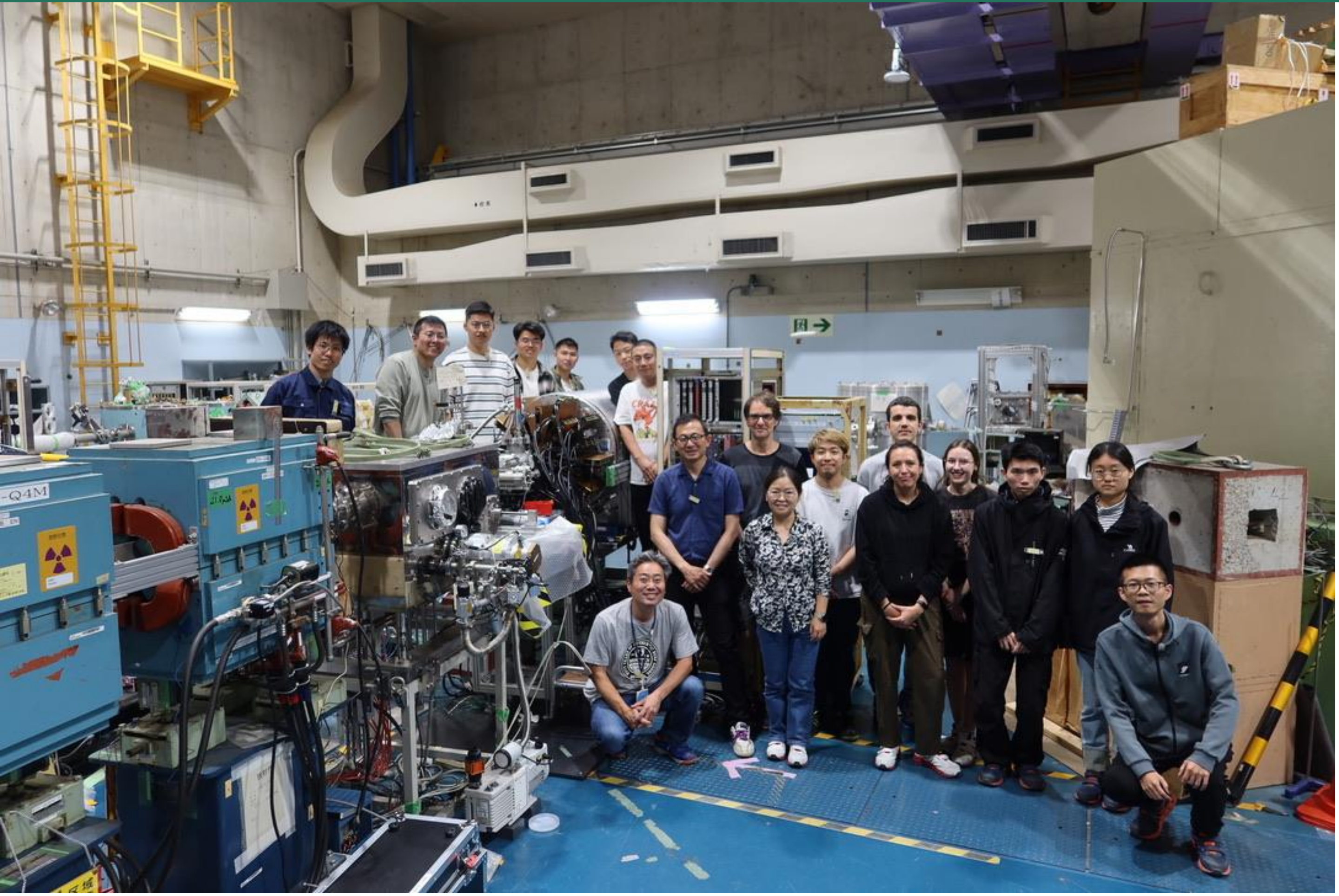
Project started in 2018.

Exp	Spokes person	Primary beam	Reaction	Approved days
Commission	H.J. Ong, T. Kawabata, W. Mittig	18O?		
E510	B. Dominguez, D. Suzuki, Y. Ayyad	22Ne @50 MeV/u	17C(d,p)	5.5 days
E534	H.J. Ong, D. Suzuki, B. Dominguez	18O @60 MeV/u	17N(d,3He) @45 MeV/u	4 days
E535	C. Santamaria, A. Macchiavelli, H.J. Ong	18O @60 MeV/u	13,15B(d,3He) @33 MeV/u	6 days
E546	T. Kawabata	12C @~~50~~ 70 MeV	12C+12C --> 24Mg* --> 6α	6 days
E565	J. Chen, D. Bazin	18O @60 MeV/u	12Be(d,p)	6 days
E581	J. Lou, Y. Ye	18O @60 MeV/u	11Be(d,3He)	5 days

Physics motivations

- (d,^{3}He), (d,p) reactions: Single particle states to shell closure.
- (d,^{6}Li), (d,d') reactions: Cluster configuration.
- Resonant scattering: α condensed (BEC) states.
- And more...

Collaboration

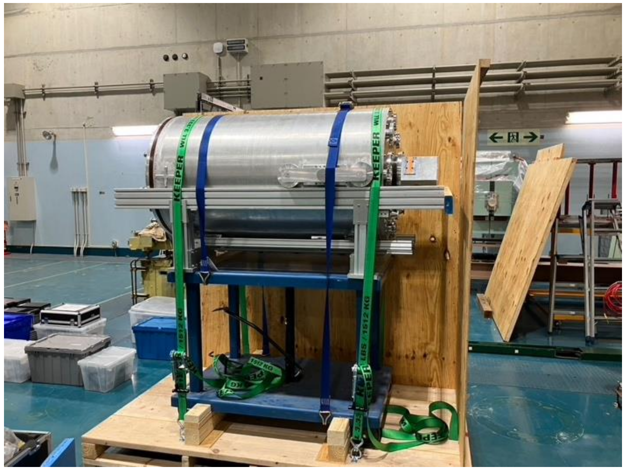


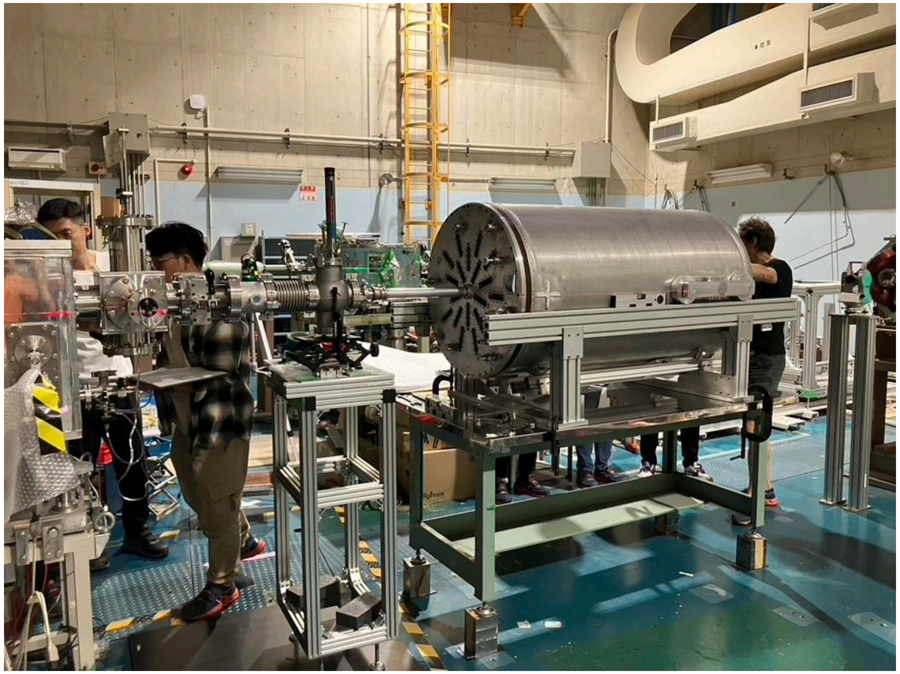
2025/05/15

UNIVERSITY OF FUKUI
大阪大学 THE UNIVERSITY OF OSAKA
MICHIGAN STATE UNIVERSITY Founded 1855
IMP
PEKING UNIVERSITY 1898
SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY 南方科技大学
THE UNIVERSITY OF TENNESSEE KNOXVILLE
OAK RIDGE National Laboratory
UNIVERSIDADE DA CORUÑA
SIGILLUM REG UNIVERSITAT COMPOSTELLAN
V.A.S.T
UTokyo
MORGAN STATE UNIVERSITY
香港大學 THE UNIVERSITY OF HONG KONG

40 members in total
Japan ・ China ・ USA ・ Spain ・ Vietnam ・ Hongkong

Installation in May 2025

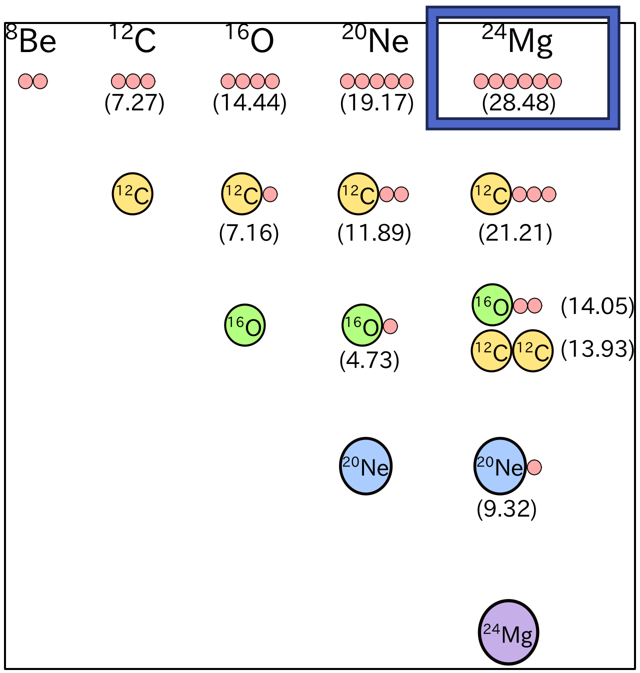


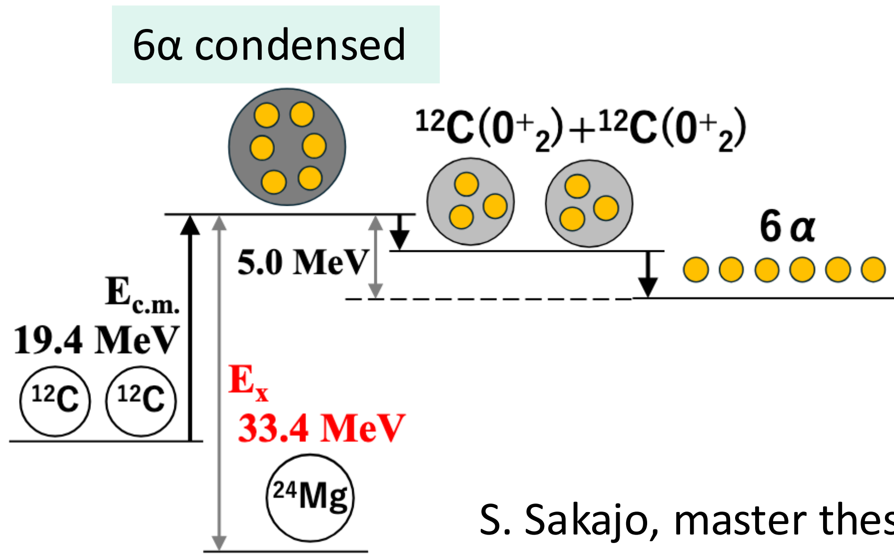


C_3D_8 gas for the deuterium target.
Cost: 25,000 USD for 200 L.

First measurement in July

Search for 6α condensed state in ^{24}Mg by ^{12}C + ^{12}C scattering.

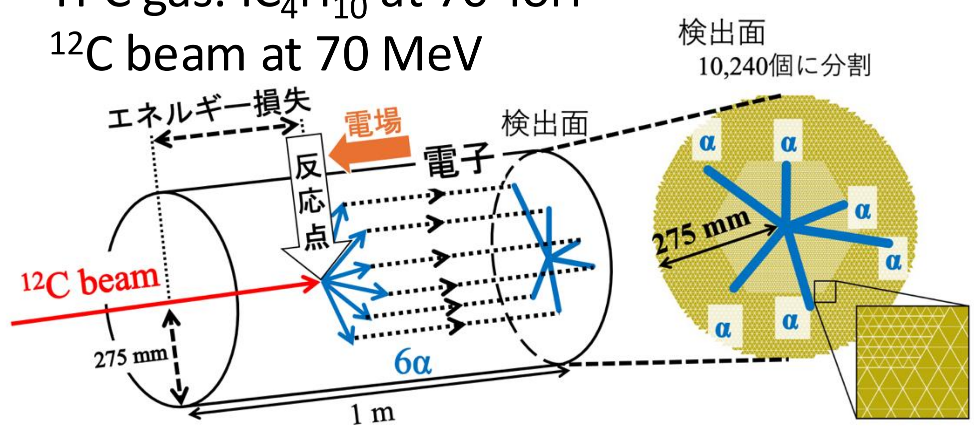




S. Sakajo, master thesis (2025).

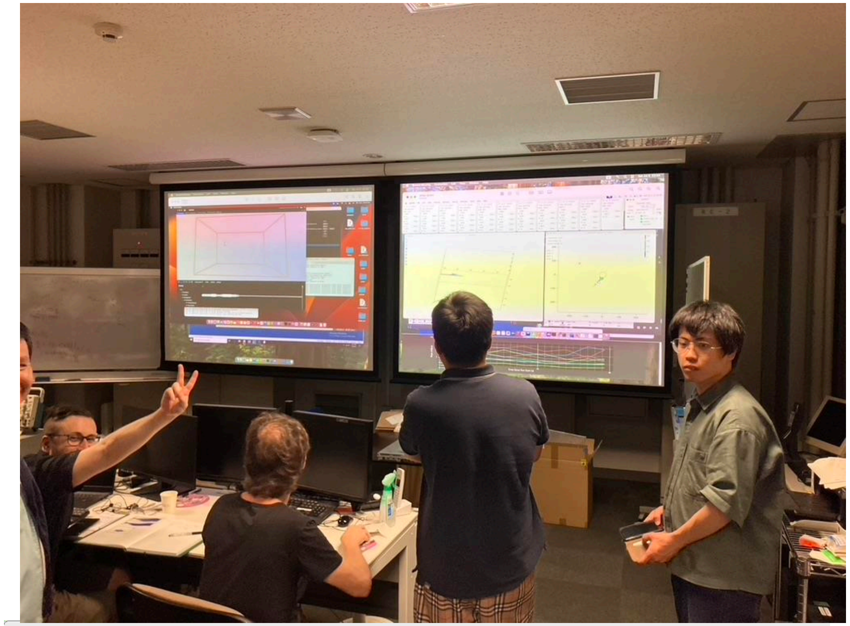
TPC gas: iC_4H_{10} at 70 Torr

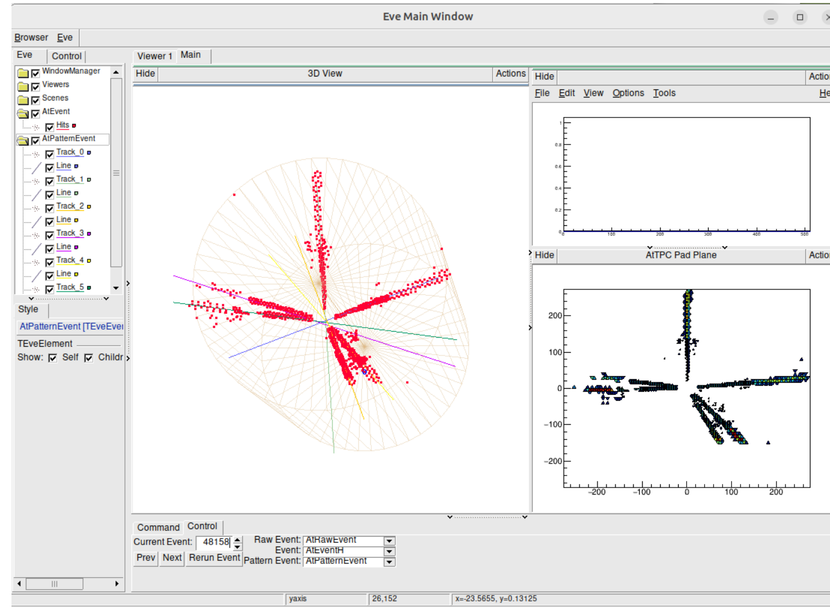
^{12}C beam at 70 MeV

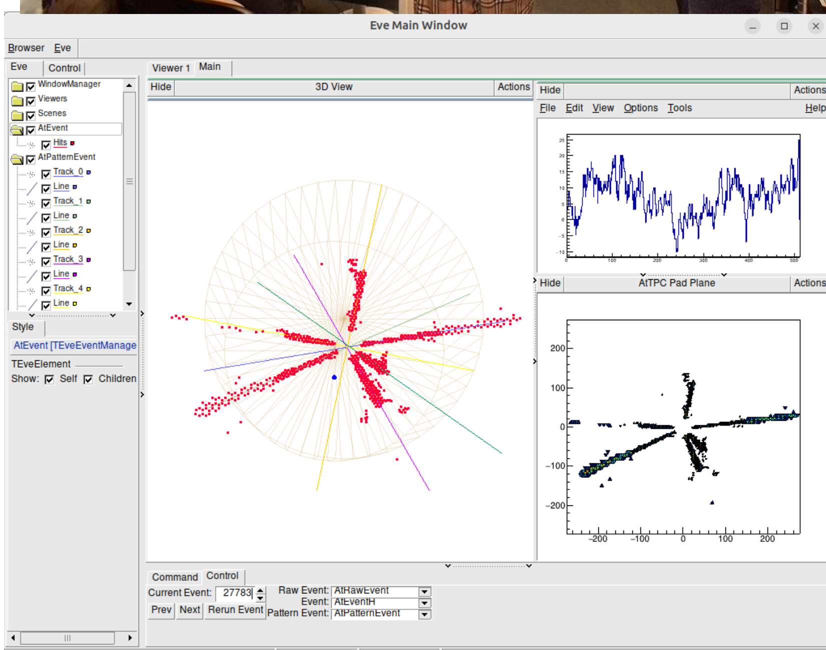


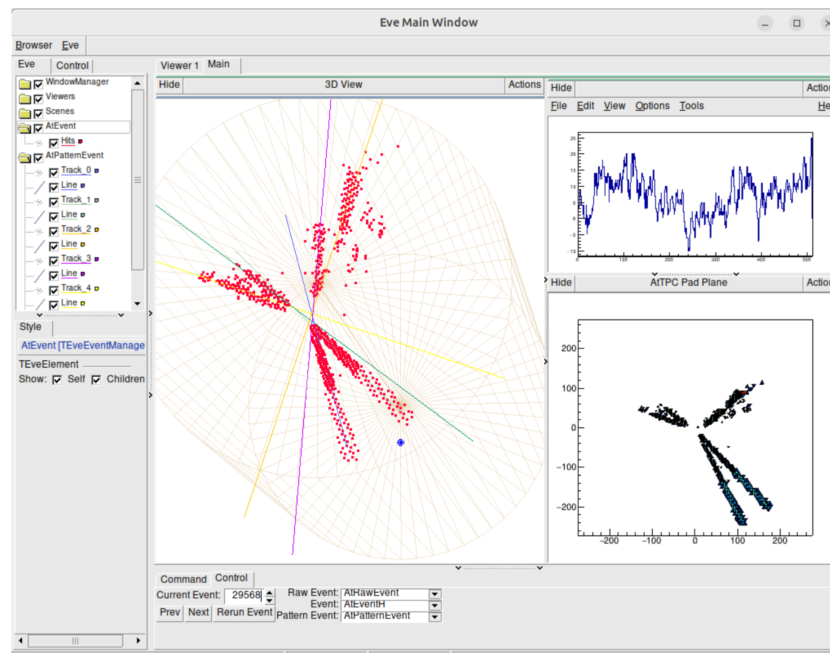
- Thick target method with ^{12}C beam (E_{cm} < 35 MeV).
- Depth in the TPC → E_{cm}
- Detect 6 α particles with AT-TPC.

Online data

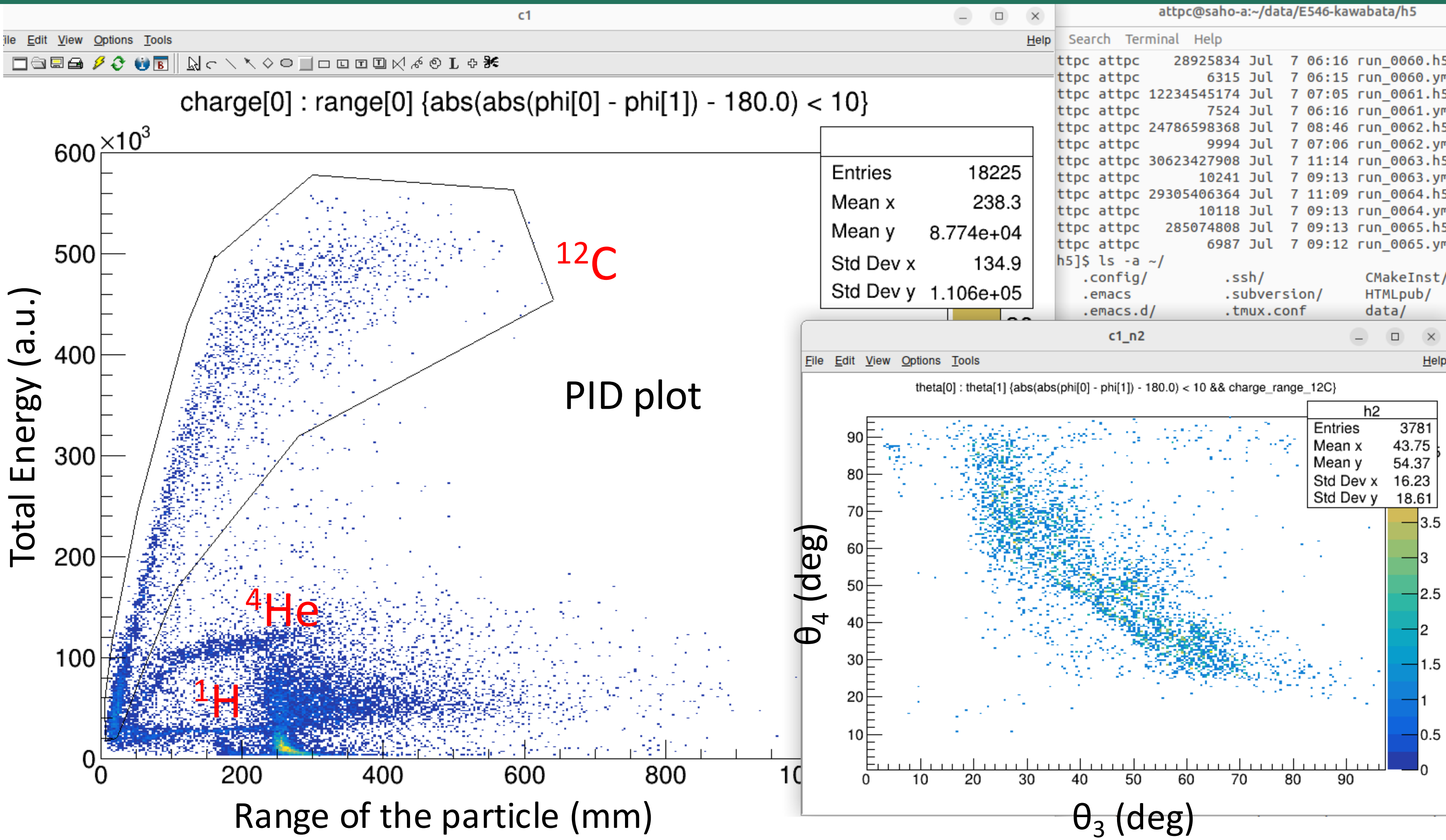



Eve Main Window
3D View
AtTPC Pad Plane
Current Event: 48158
Raw Event: AtRawEvent
Event: AtEventH
Pattern Event: AtPatternEvent


Eve Main Window
3D View
AtTPC Pad Plane
Current Event: 27783
Raw Event: AtRawEvent
Event: AtEventH
Pattern Event: AtPatternEvent


Eve Main Window
3D View
AtTPC Pad Plane
Current Event: 29568
Raw Event: AtRawEvent
Event: AtEventH
Pattern Event: AtPatternEvent

Online analysis

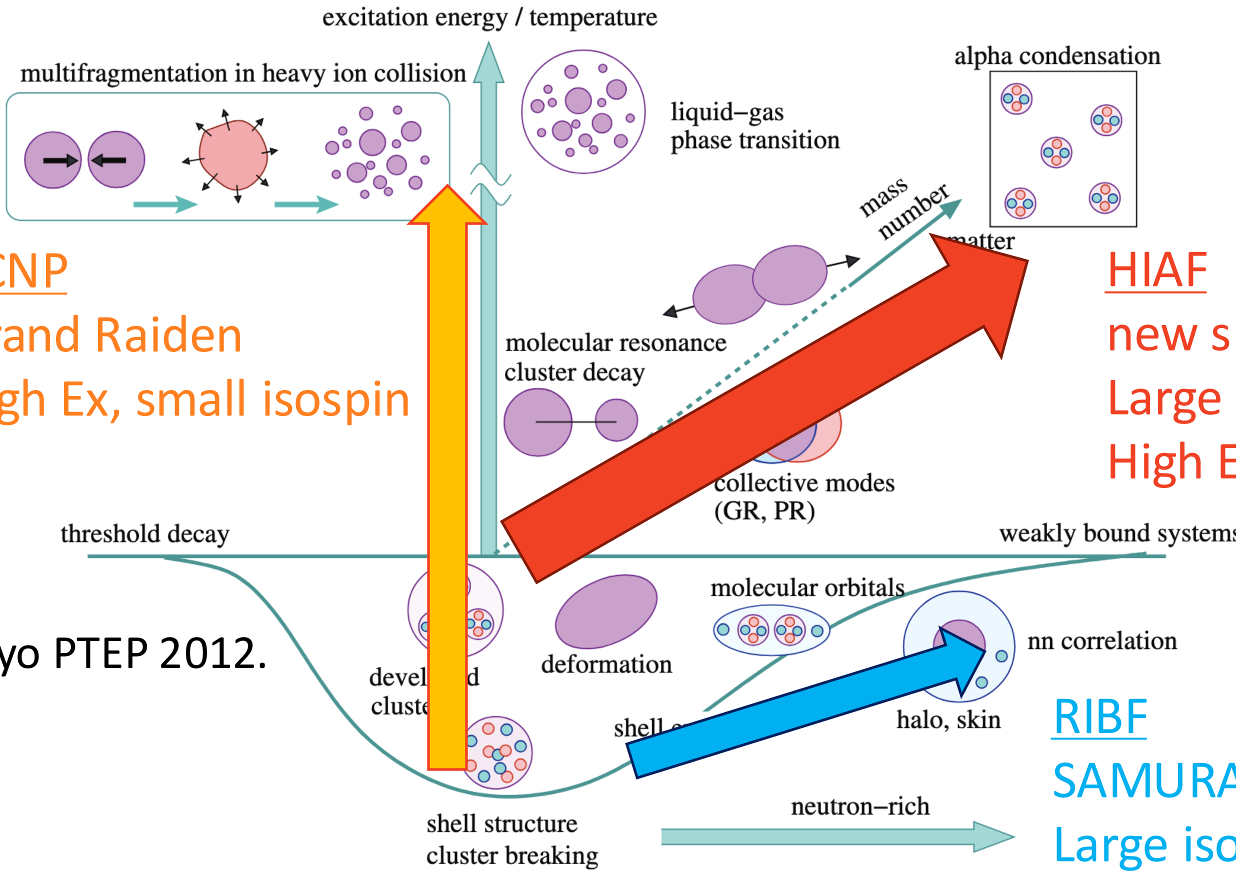


Clearly see the ^{12}C+^{12}C elastic.

Other beamtimes with RI beams will be performed in autumn.

Possible Project at HIAF

Structures of light unstable nuclei



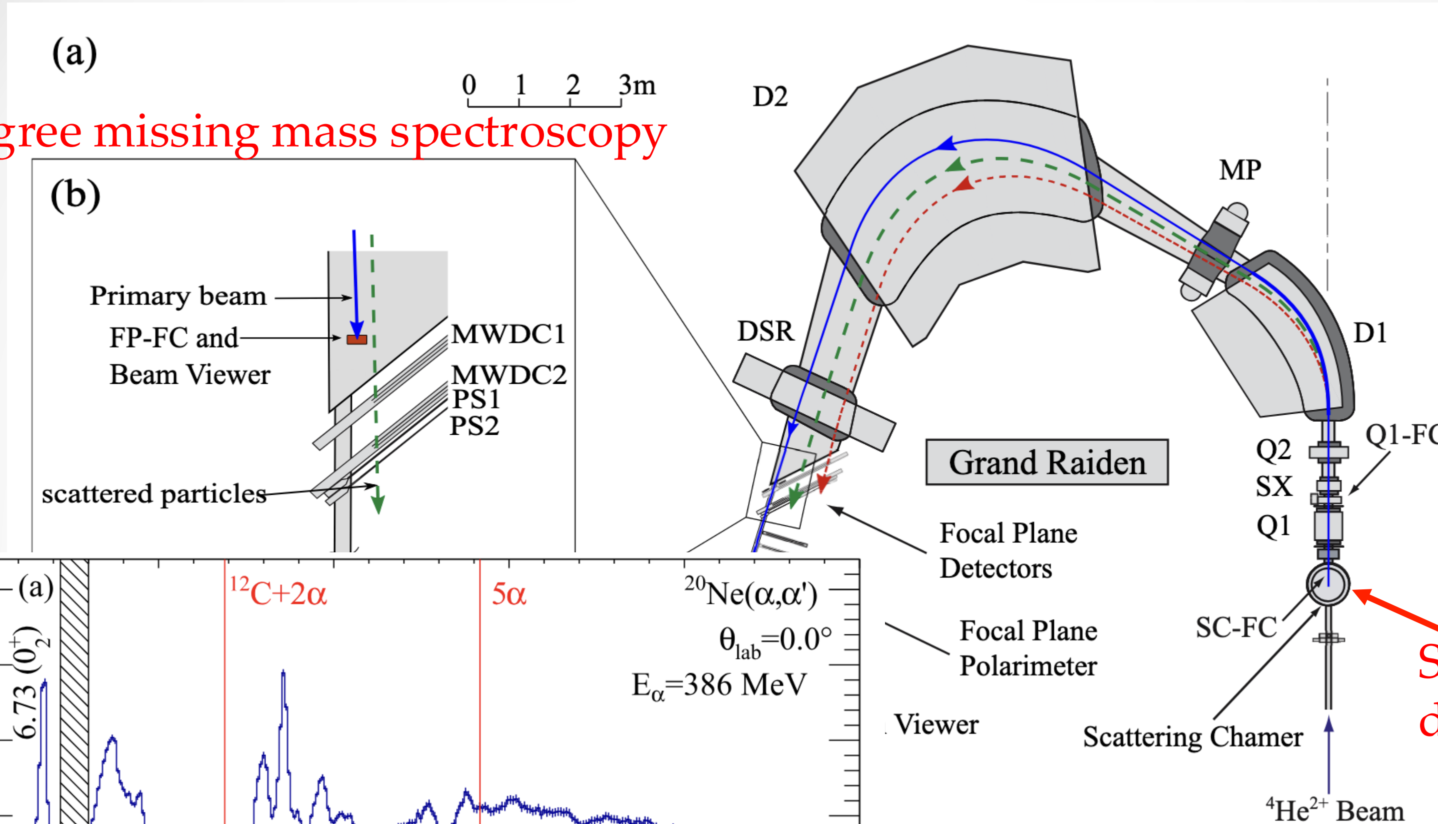
RCNP
Grand Raiden
High Ex, small isospin

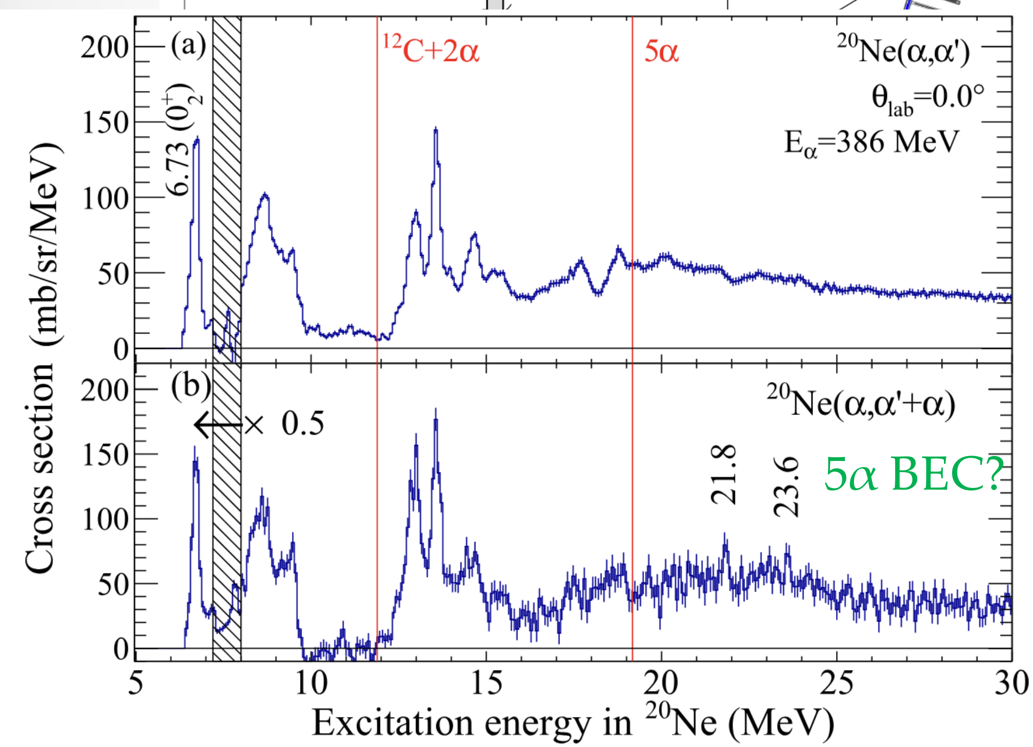
HIAF
new spectrometer
Large isospin
High Ex

Y. Kanada-En'yo PTEP 2012.

RIBF
SAMURAI
Large isospin
Limited Ex

Stable nucleus measurement

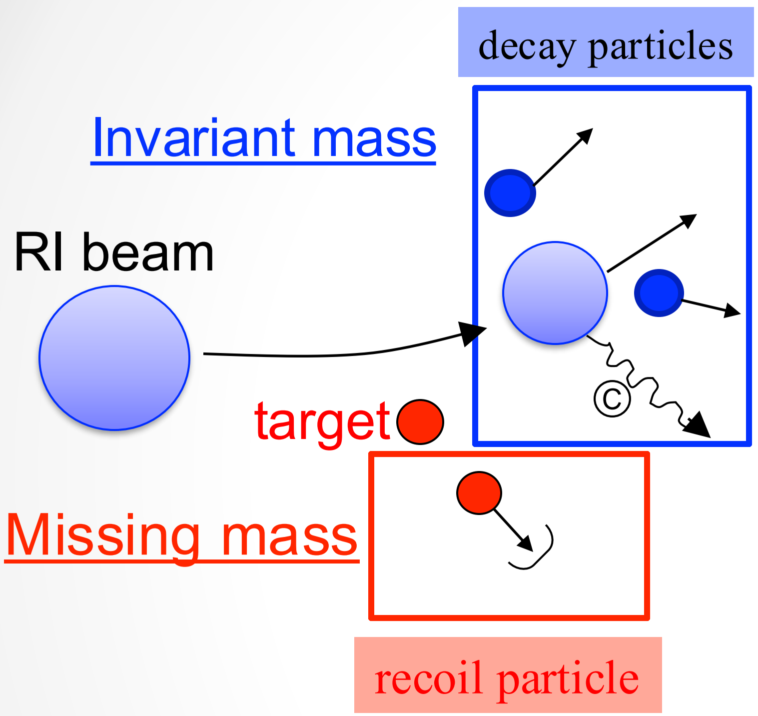


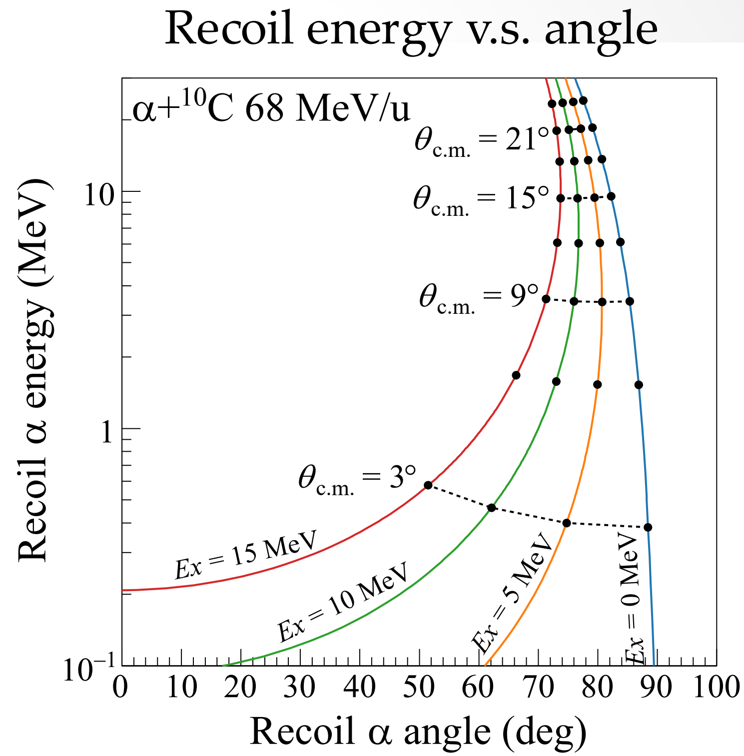


S. Adachi *et al*, PLB **819**, 136411 (2021).
B. Zhou *et al*., Nat. Comm. **14**, 8206 (2023).

- ✓ Missing mass at $\theta_{cm} = 0°$
- ✓ Decay particle measurement

RI beam measurement



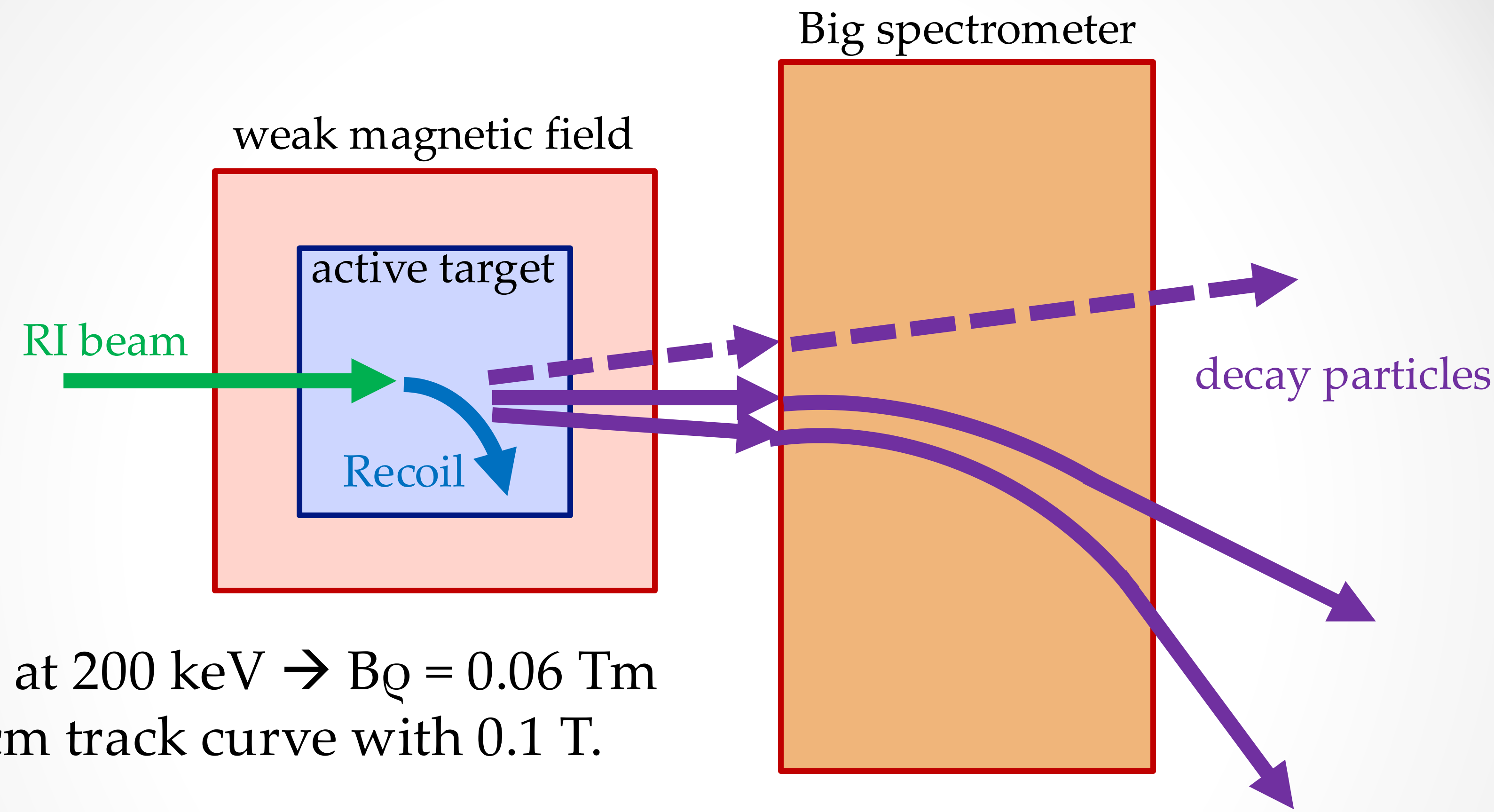


Detect both recoil and decay particles.

Spectroscopy at $\theta_{cm} = 0^{\circ}$

- ✓ $\theta_{lab} = 0^{\circ}$ (same as RI beam)
- ✓ E_{α} ~ 200 keV
  much smaller Bρ than RI beam

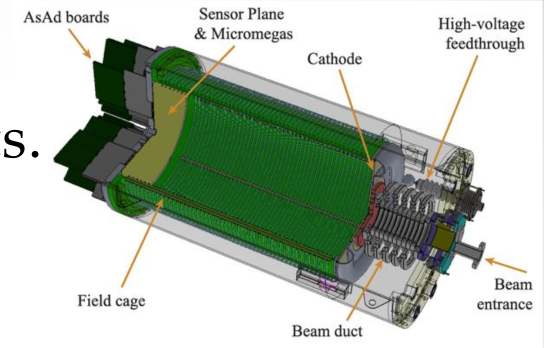
New measurement at HIAF



✓ ^4He at 200 keV → Bϱ = 0.06 Tm
10 cm track curve with 0.1 T.

Unique and powerful instruments

Cylindrical vs cubic



Cylinder type

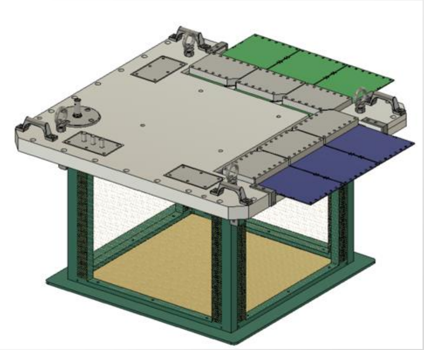
- 😃 Can be extended without increasing electronics.
- 😃 Large target thickness.
- 😃 Installed inside the solenoid magnet.

- 😢 Cannot operate with high-rate beam: up to O(1 kHz)
- 😢 Need to disable the center region → Larger detection threshold

➢ Suitable with extremely low-intensity RI beam.

Cube type

- 😃 Can operate with high-intensity beam: O(10^5–10^6 Hz)
- 😃 Without disabling the center region: low-energy recoil
- 😢 Need more electronics to enlarge
- 😢 Smaller target thickness



➢ Suitable to decrease the detection threshold.

➢ Never used inside a spectrometer.