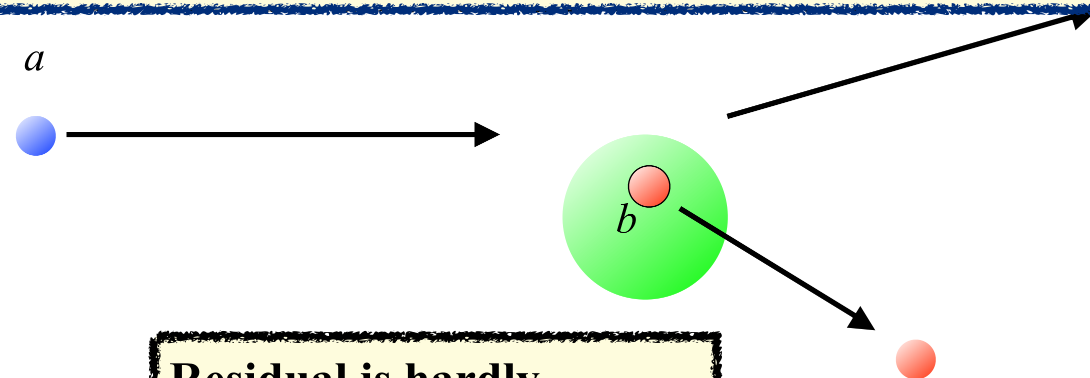
INT Workshop INT-15-58W
**Reactions and Structure of Exotic Nuclei**
March 2−13, 2015

# Quasi-Free Knockout Reaction Studies at RIBF

**Tomohiro Uesaka (RIKEN Nishina Center)**

# Quasifree Scattering (QFS)

**QFS is a powerful and clean experimental probe to nuclear structure, particularly in RI-beam experiments.**




**Residual is hardly disturbed by the reaction.**

**Hydrogen target** **VS.** **Nuclear target ($^{12}C$, $^{9}Be$. . .)**

**Medium energy ( > 200 MeV/u)** **VS.** **Low energy (<100 MeV/u)**

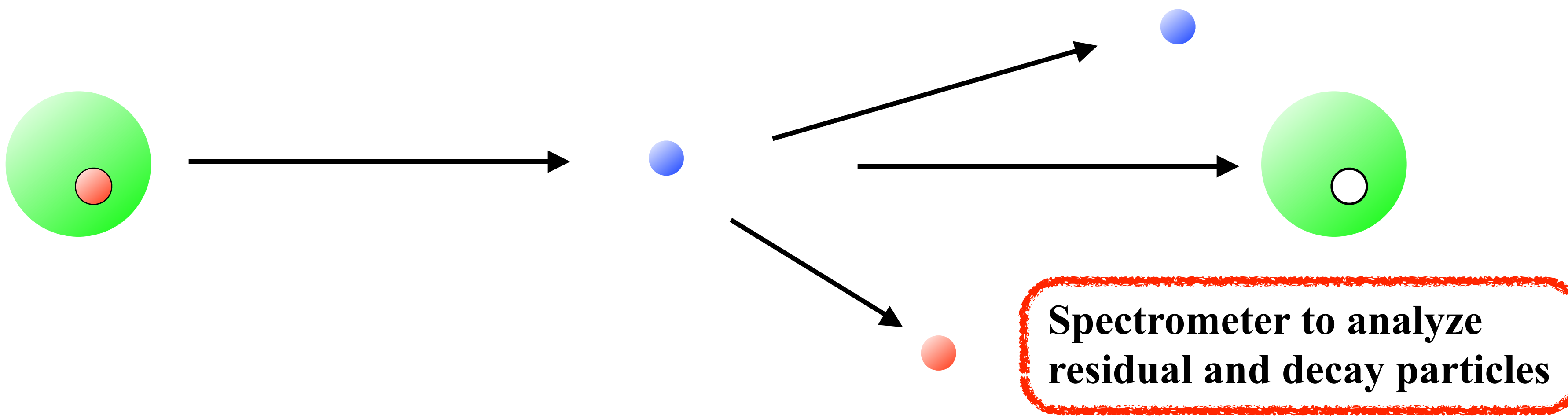
# Outline

1. **Experimental Arrangements for QFS studies**
   - **RI Beam Factory**
   - **SAMURAI**
   - **Special Targets**

2. **QFS as a probe to nuclear structure**
   - **Single-particle spectroscopy : spectroscopic factor. . .**
   - **Nuclear excitation driver : MINOS & fission barrier**
   - **Nuclear Correlation : α Knockout & dineutron**

3. **Summary**

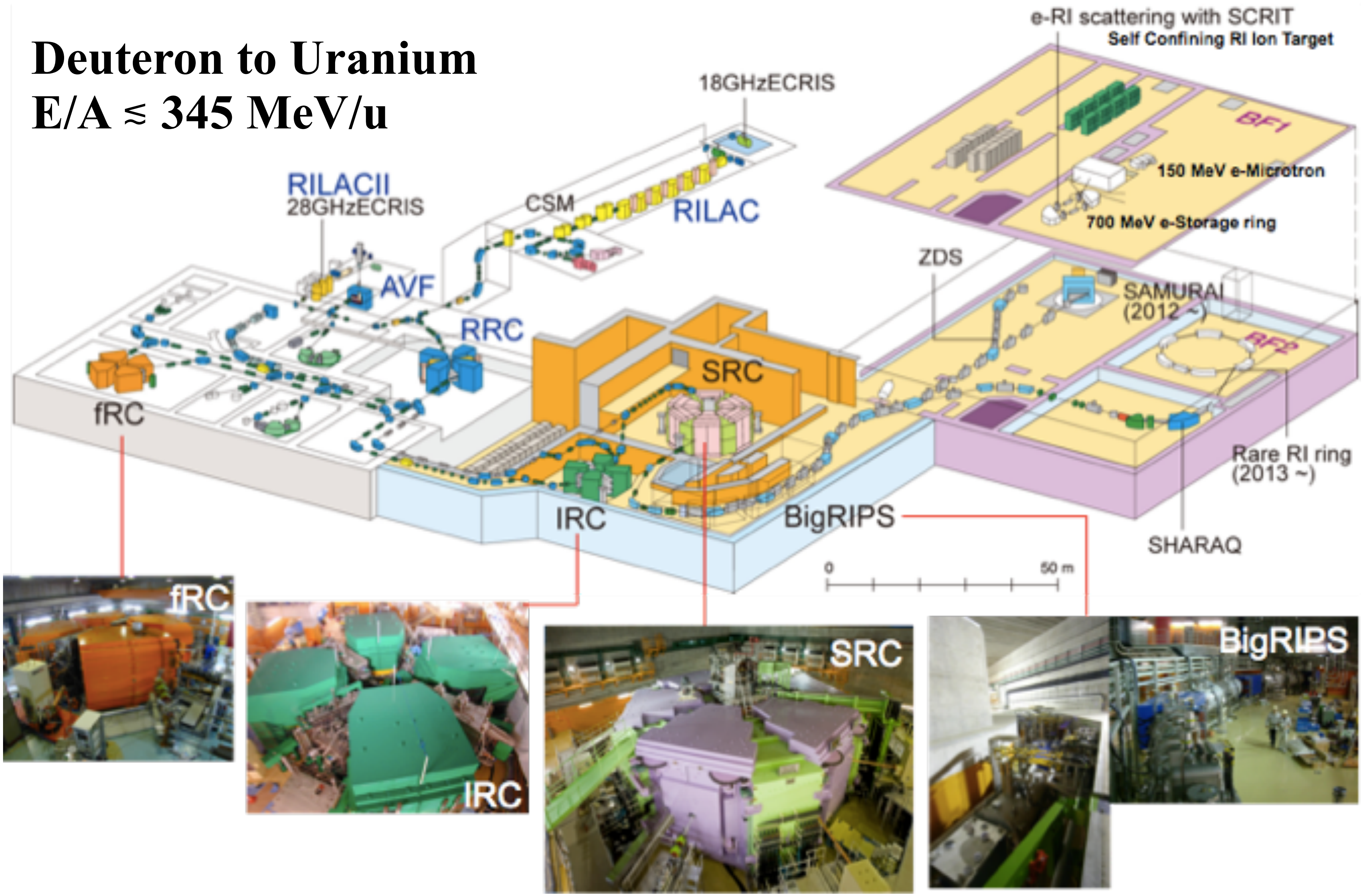
# Experimental Arrangements for QFS exp.




| | | |
|---|---|---|
| Hydrogen target | VS. | Nuclear target ($^{12}C$, $^{9}Be$. . .) |
| Medium energy ( > 200 MeV/u) | VS. | Low energy (<100 MeV/u) |

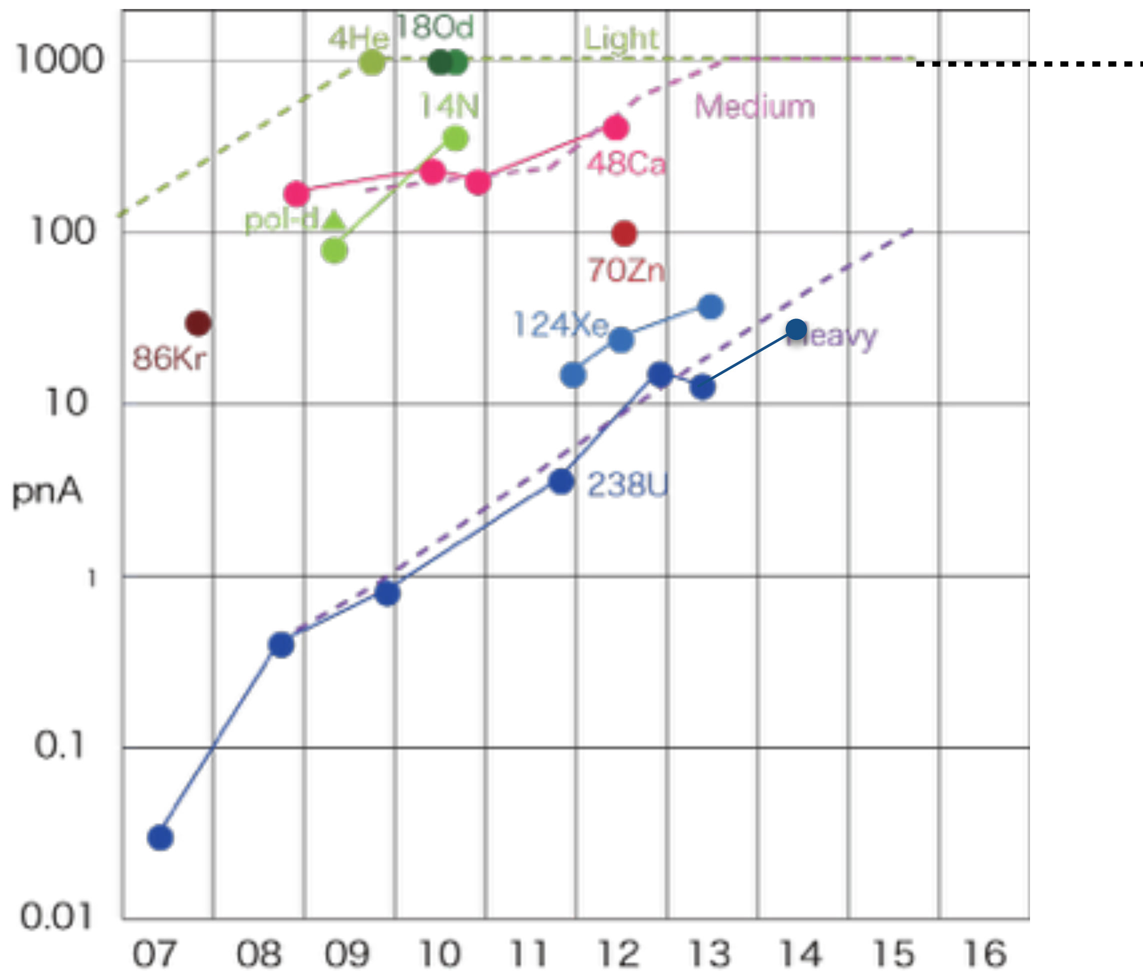
# RI Beam Factory at RIKEN

**Deuteron to Uranium**
**E/A ≲ 345 MeV/u**



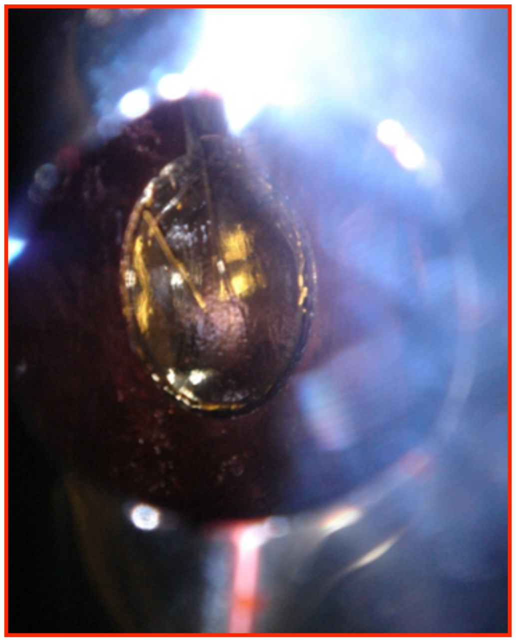
# Beam Intensities at present

| | |
|---|---|
| pol-d(250 MeV/u) | 120 pnA |
| d(250 MeV/u) | 1000 pnA |
| $^{4}$He(320 MeV/u) | 1000 pnA |
| $^{14}$N(250 MeV/u) | 400 pnA |
| $^{18}$O(345 MeV/u) | 1000 pnA |
| $^{48}$Ca(345 MeV/u) | 415 pnA |
| $^{70}$Zn(345 MeV/u) | 100 pnA |
| $^{86}$Kr(345 MeV/u) | 30 pnA |
| $^{124}$Xe(345 MeV/u) | 38 pnA |
| $^{238}$U(345 MeV/u) | 25 pnA |

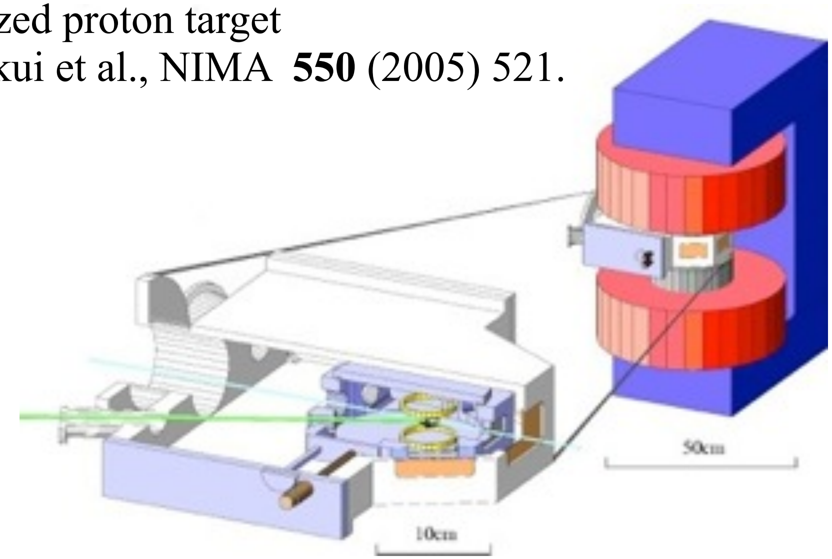


# Special Targets for QFS studies at RIBF

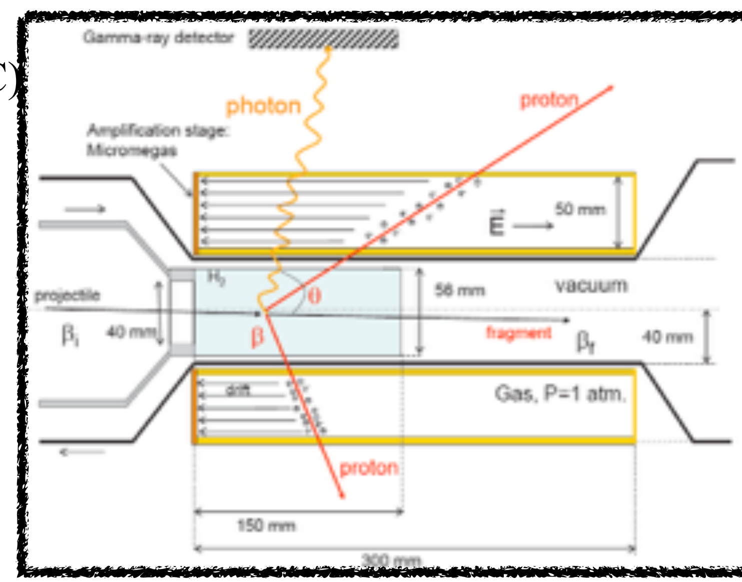
SH-TRICK (solid hydrogen target)
Y. Matsuda et al., NIMA **643** (2011) 6.



Polarized proton target
T. Wakui et al., NIMA **550** (2005) 521.



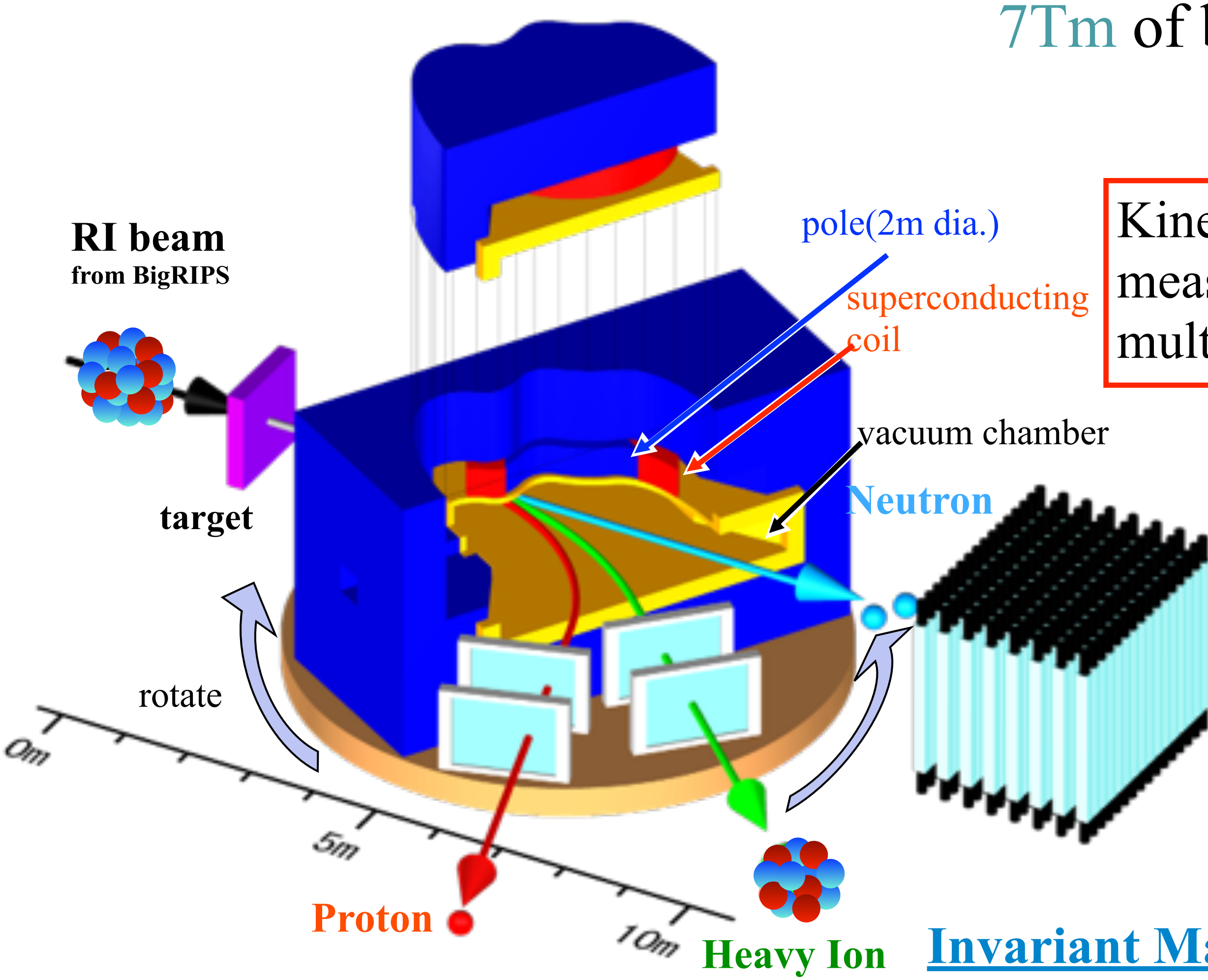

MINOS
(thick H target with TPC)
A. Obertelli et al.




Review on H targets for RI-beam experiments.
A. Obertelli and T. Uesaka, EPJA **47** (2011) 105.

# SAMURAI

**S**uperconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam with 7Tm of bending power



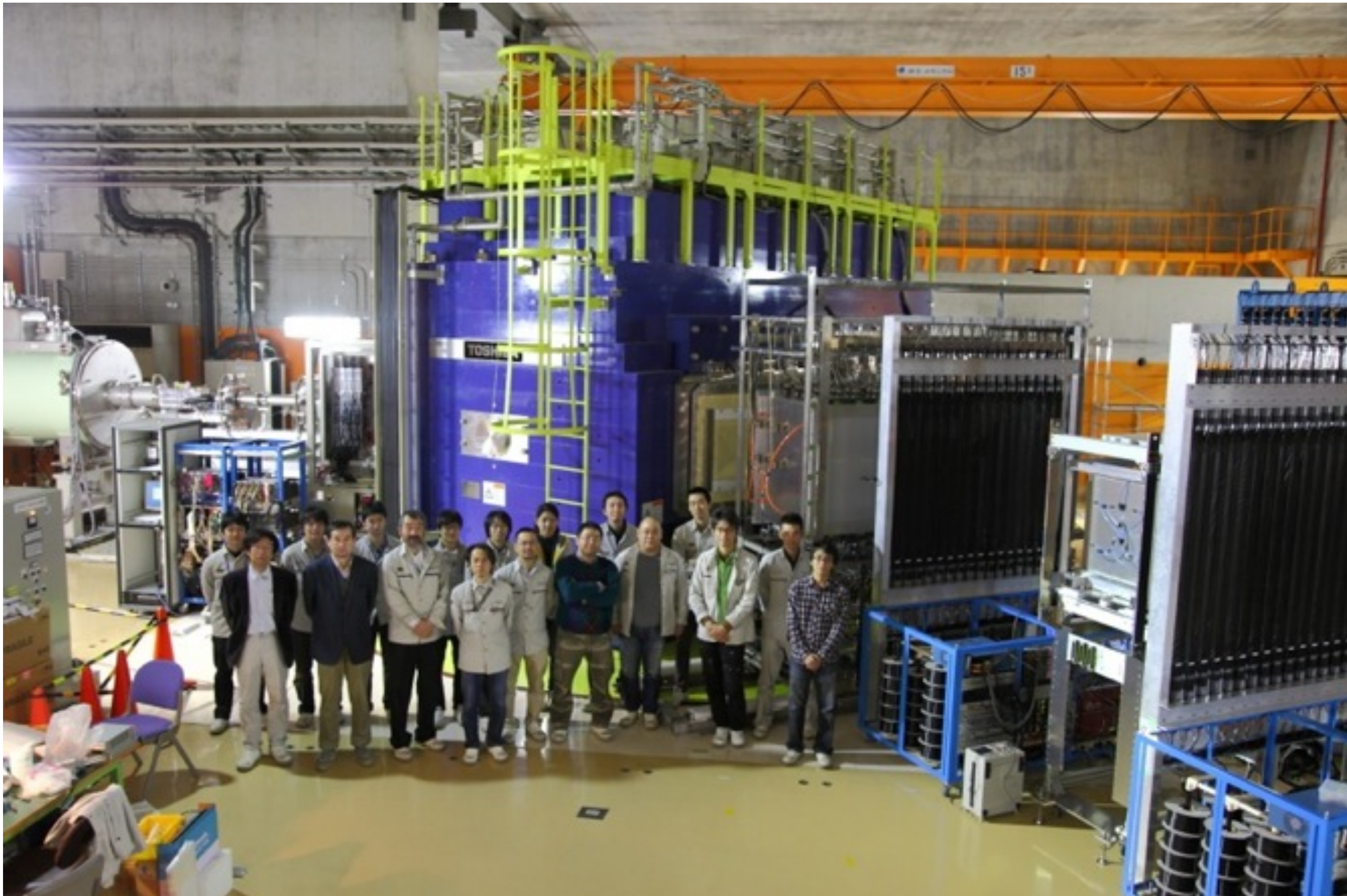

Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

**Invariant Mass Measurement**

**Missing Mass Measurement**

# SAMURAI (2012~)



# Experimental programs @RIBF

**Single-particle state spectroscopy**

(p,2p)/(p,pn) knock-out for neutron-rich He, Li, C isotopes
T. Kobayashi et al.,
(p,2p) knockout for Oxygen isotopes with pol. target
T. Uesaka, S. Kawase, L. Tang et al.,

**Reaction driver**

MINOS-DALI2 (SEASTAR) Campaign
P. Doornenbal, A. Obertelli et al., $2^+$ spectroscopy
MINOS-SAMURAI
Y. Kondo et al., Spectroscopy of $^{28}O$
(p,2p) delayed fission of neutron-rich Pb, Bi, Po isotopes
D. Muecher et al.,

**Correlation in nuclei**

Two neutron momentum correlation in Borromean nuclei
Y. Kubota, A. Corsi et al.
Alpha cluster states in neutron-rich Be isotopes via (p,pα) reaction
D. Beaumel et al.

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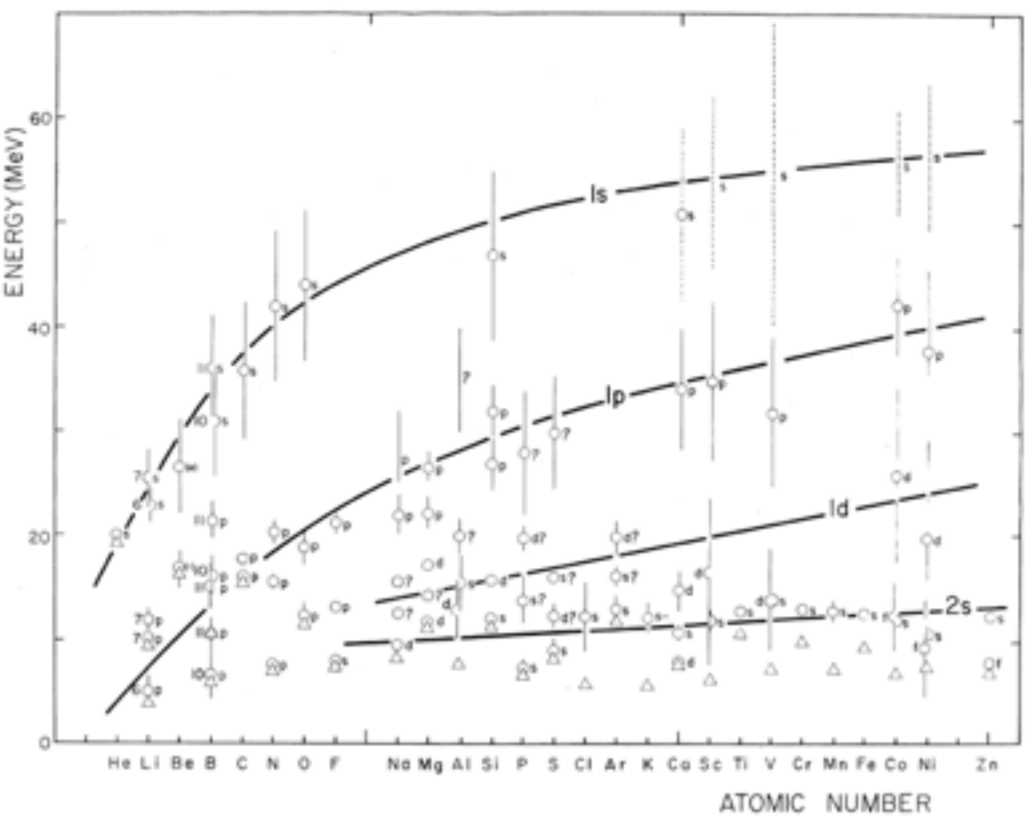
$$|\Phi\rangle = \sum_{i,j} C_i \underline{|\phi; njl, S_N\rangle}_i |\Psi_j\rangle$$

1) Selectively populate single-particle states

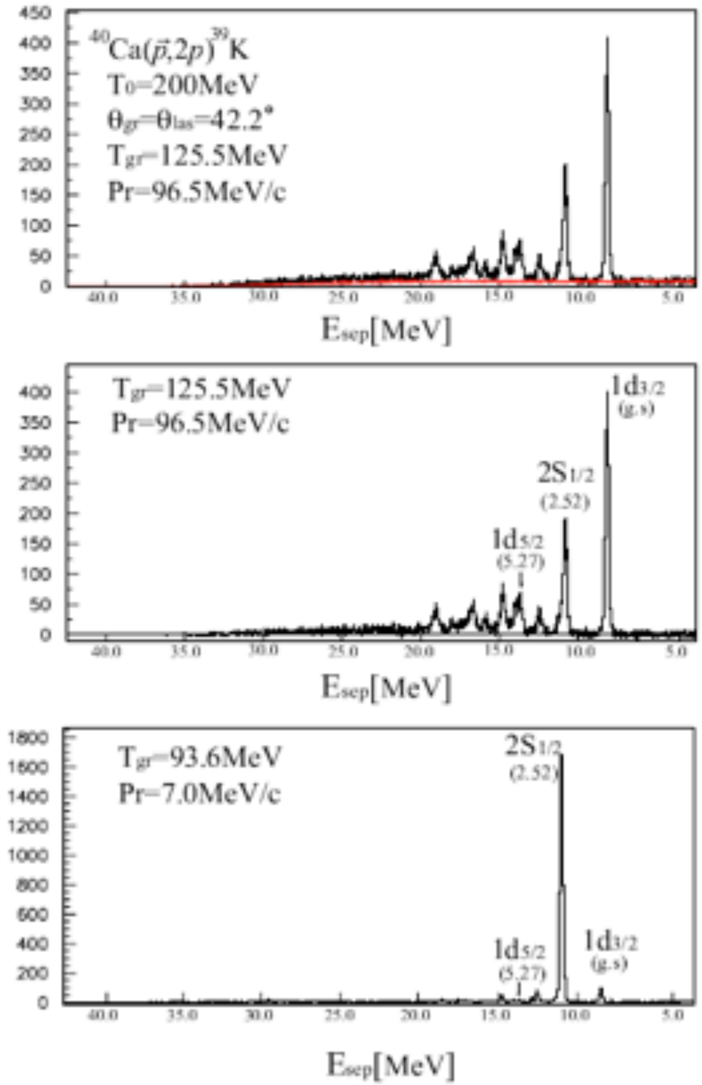
medium-energy substitute of transfer reactions

# QFS as a tool of hole-state spectroscopy

Jacob and Maris,
Rev. Mod. Phys. 45 (1973) 6.

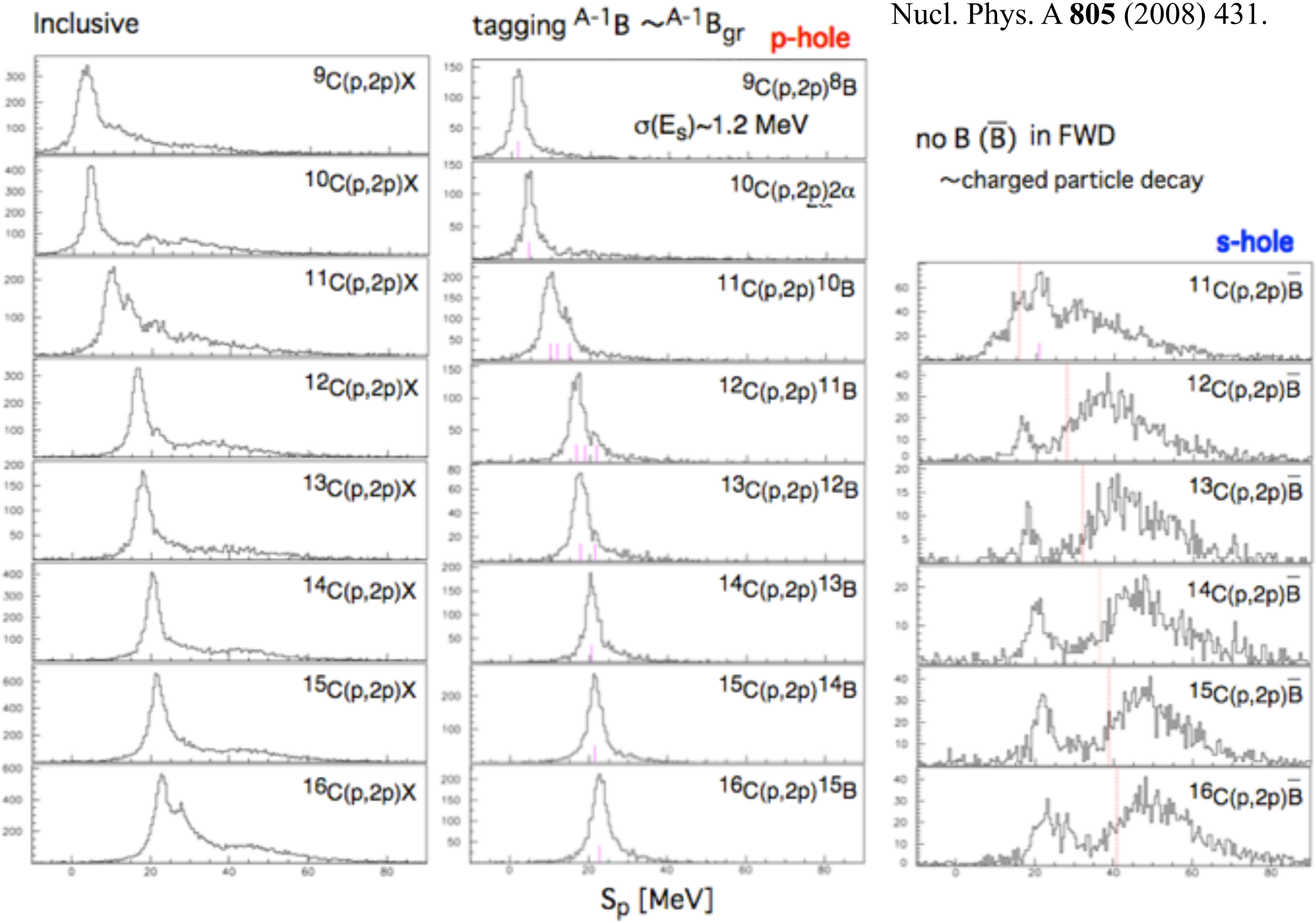



Nagasue, Noro et al.



@HIMAC

T. Kobayashi et al.,
Nucl. Phys. A **805** (2008) 431.



# Oxygen Isotopes (to start with)

**Z=8: proton magicity**

**$^{16}$O: most intensively studied nucleus**

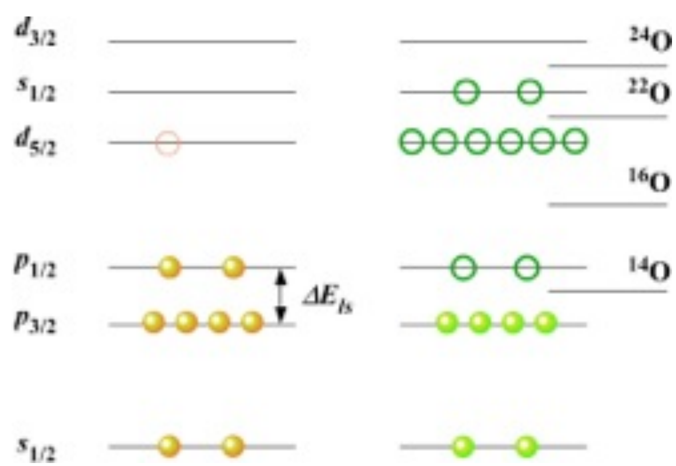
Ando and Bando, PTP **66** (1981) 227.
Pieper and Pandharipande, PRL **70** (1993) 2541.

**Within the reach of recent rigorous calculations with realistic NN(+3N) interactions.**

C. Barbieri, PLB **643**, 268 (2006).
G. Hagen *et al.*, PRC **80**, 021306(R) (2009).
S. Fujii et al. PRL **103**, 182501 (2009).

Table 1: Experimental values of the spin-orbit splittings in $^{16}$O

| | Proton | Neutron |
|---|---|---|
| $\Delta E_{1p_{1/2}-1p_{3/2}}$ | 6.32 MeV | 6.18 MeV |
| $\Delta E_{1d_{3/2}-1d_{5/2}}$ | 5.10 MeV | 5.09 MeV |



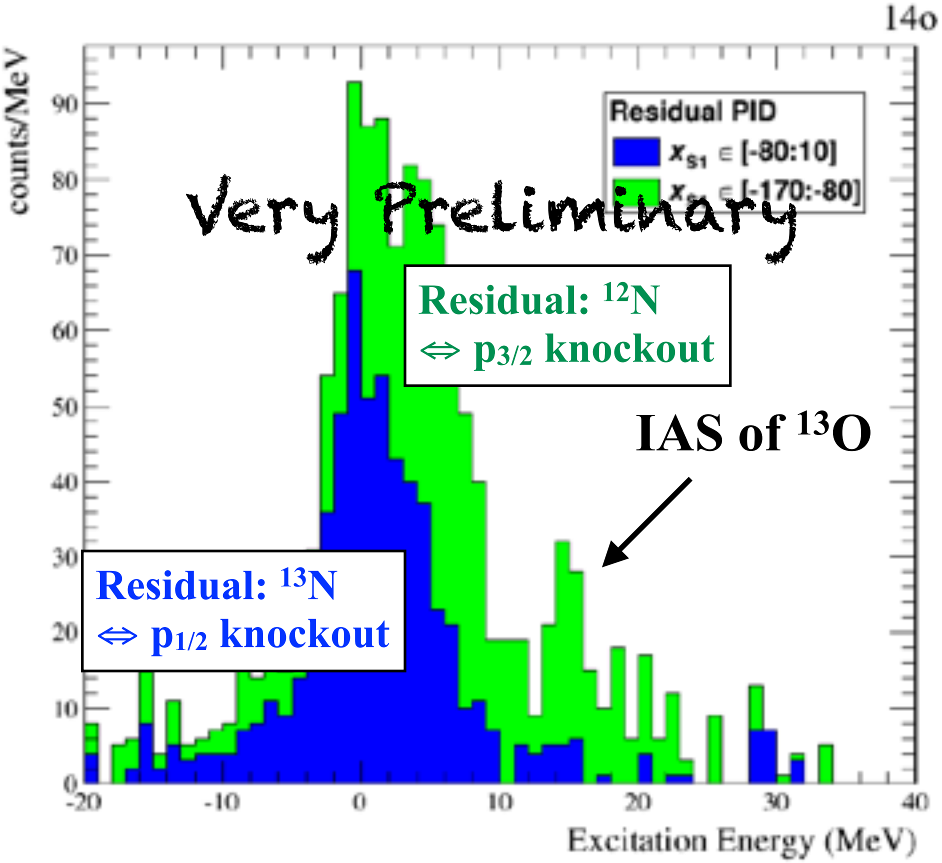


**$^{18}$O : Experiment at RCNP**

**$^{14,22-24}$O : Experiment at RIBF**

# $^{14,22,24}O(\vec{p},2p)$@RIBF

$^{14}O(p,2p)$






**Analyses to improve resolution and determination of spectroscopic factor are in progress.**

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**MINOS-SAMURAI**

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**D. Muecher et al.,**

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$$|\Phi\rangle = \sum_{i,j} C_i \underline{|\phi; njl, S_N\rangle_i} \underline{|\Psi_j\rangle}$$

1) Selectively populate single-particle states

medium-energy substitute of transfer reactions

2) Efficiently produce excited state of a nucleus "nuclear reaction driver"

large cross section, large luminosity (target thickness)

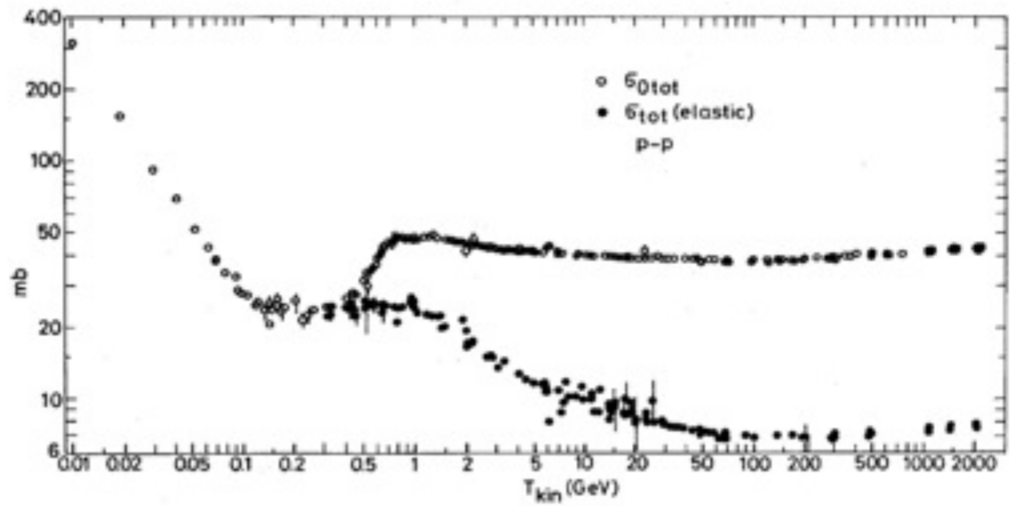
# QFS in RI-Beam Experiments

- **Large cross section**

  **practically N-N scattering**

  **$\sigma \sim N_{participant} \times 25$ mb**

  **# $\sigma_{inela} < 1$mb**




- **Large momentum transfer process**

  **Recoil particles have large energies (> several tens of MeV)**
  **→ thick target can be used.**

- **All the residual particles are detectable.**

  **⇔ normal kinematics experiments where detection of heavy residual is not easy.**

# MINOS

A. Obertelli (Saclay)

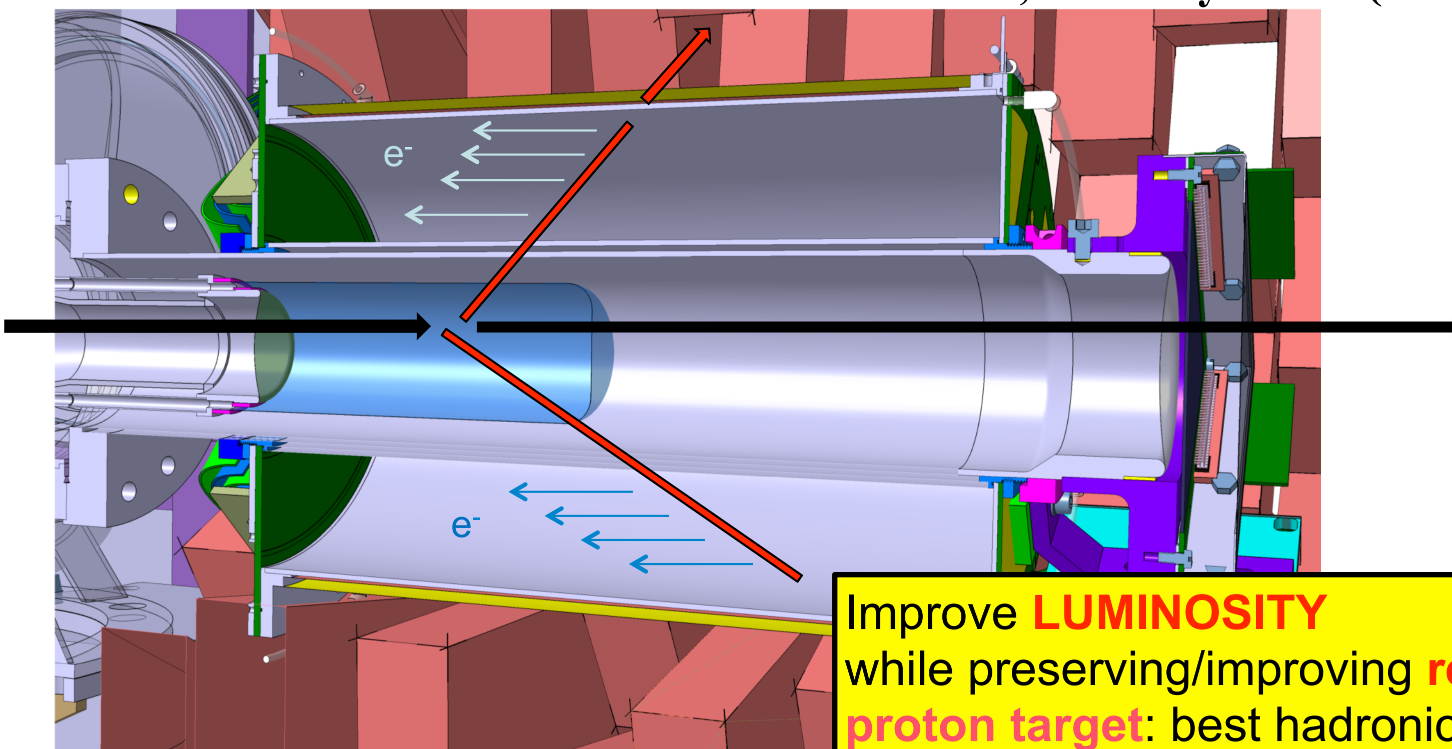
**A project to pursue the highest efficiency in reaction experiments**

**Proton-induced knockout reaction**

$\times$

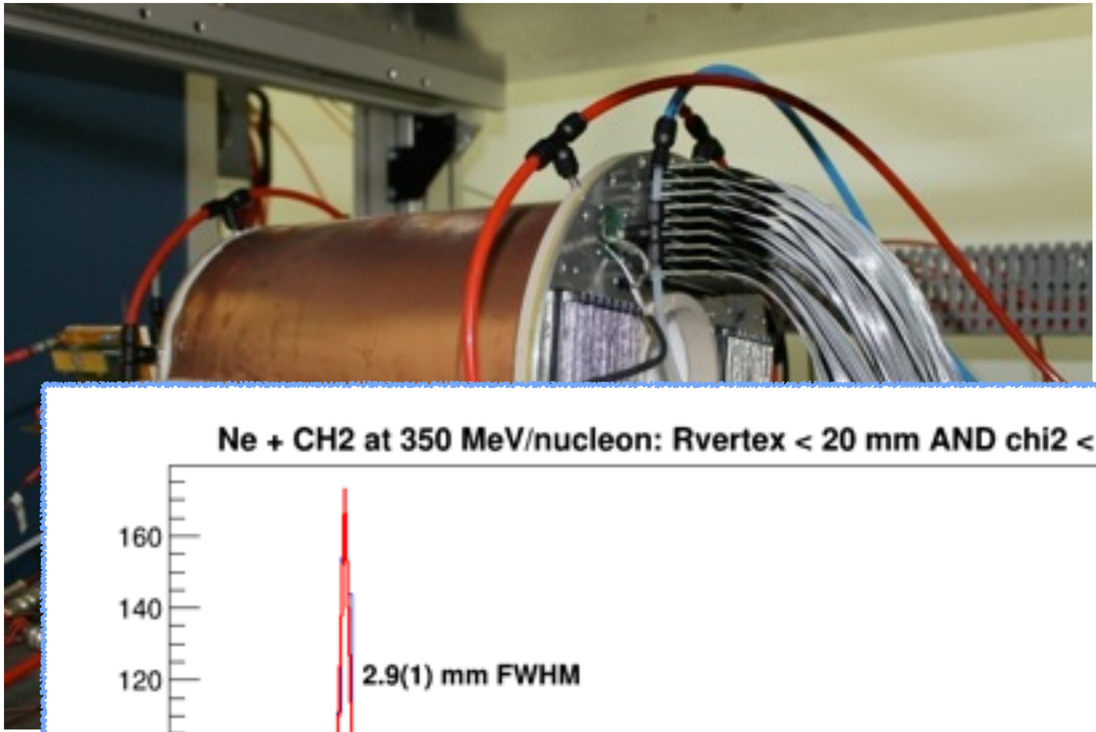
**15-cm liquid hydrogen target (1 mol target!!)**

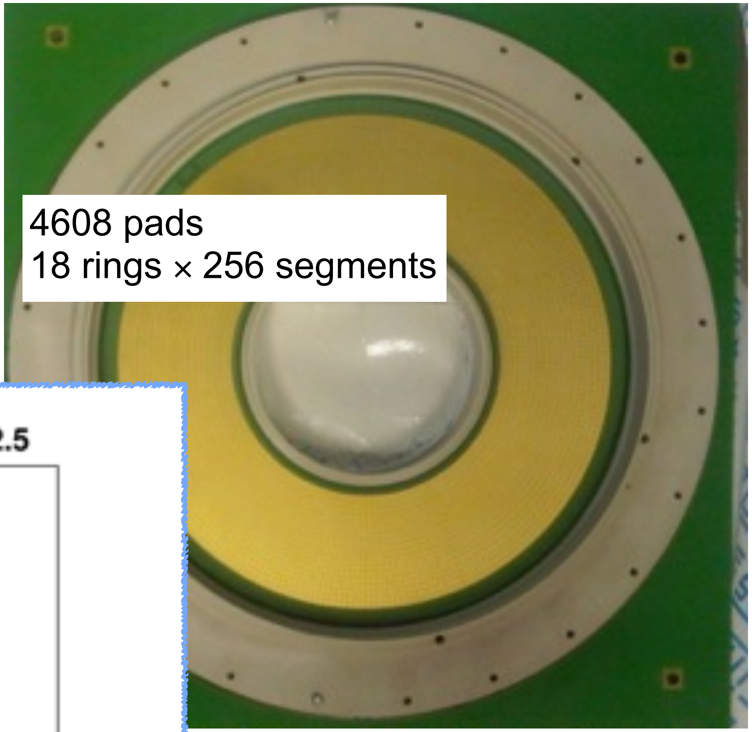
**Alexandre Obertelli et al., Eur. Phys. J. A (2014) 50:8.**



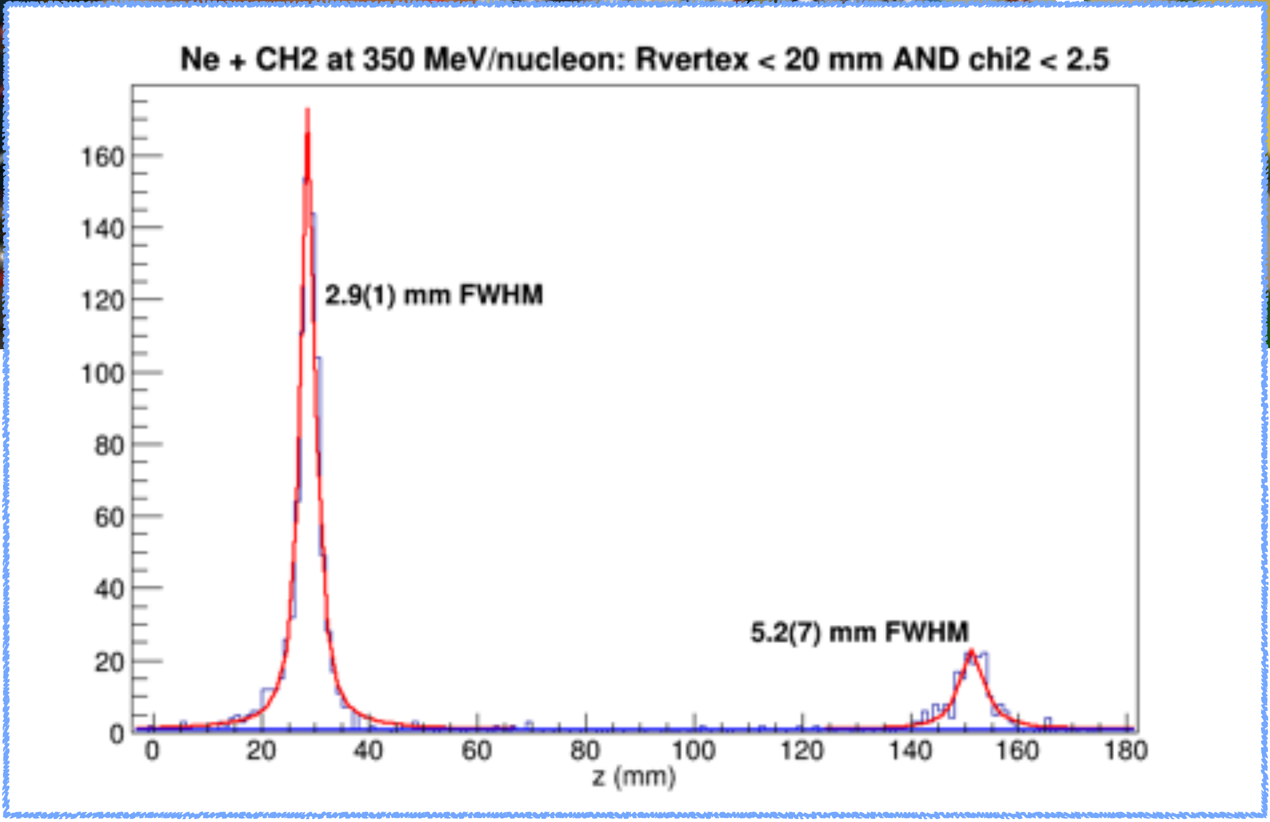

Improve **LUMINOSITY**
while preserving/improving **resolution**
**proton target**: best hadronic probe

# The Time Projection Chamber






Micromegas detector

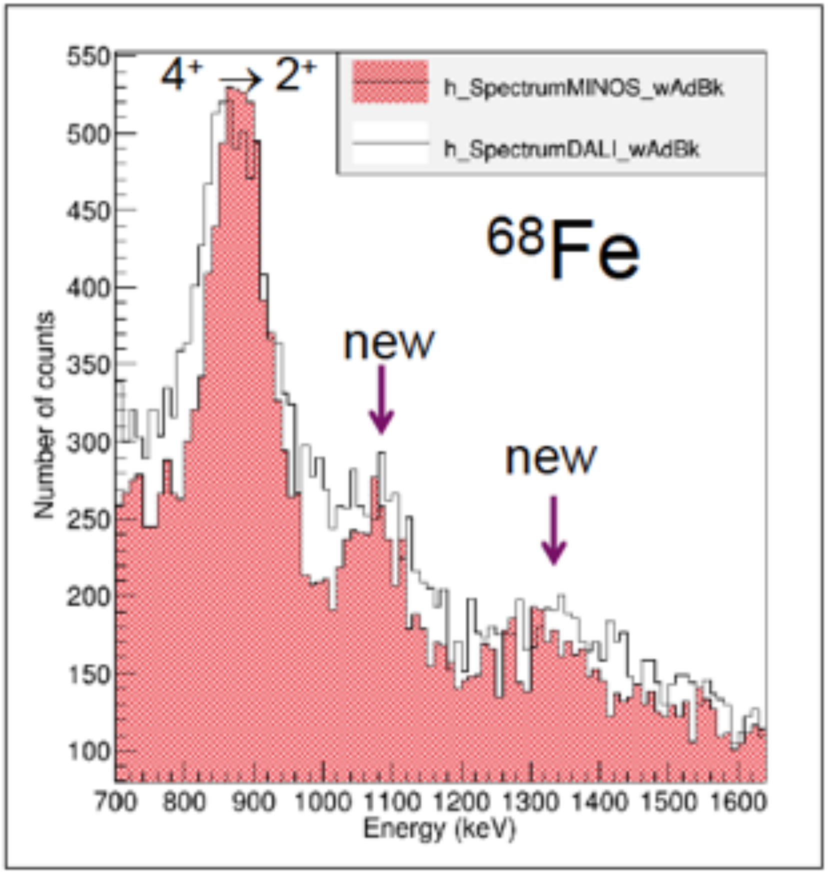


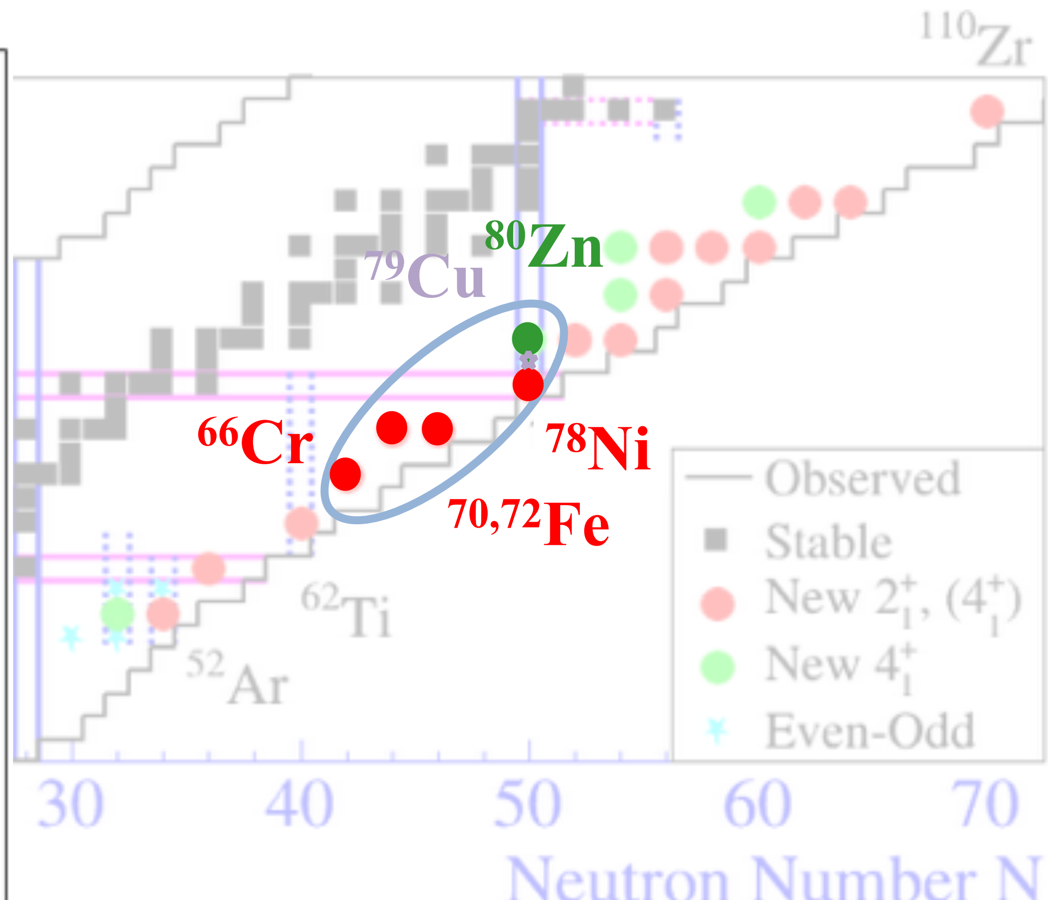

courtesy of Obertelli

# Shell Evolution and Search for Two-plus Energies At the RIBF (SEASTAR) – a RIKEN Physics program

Spokespersons: P. Doornenbal (RIKEN), A. Obertelli (CEA, RIKEN)

20 hours of beam time

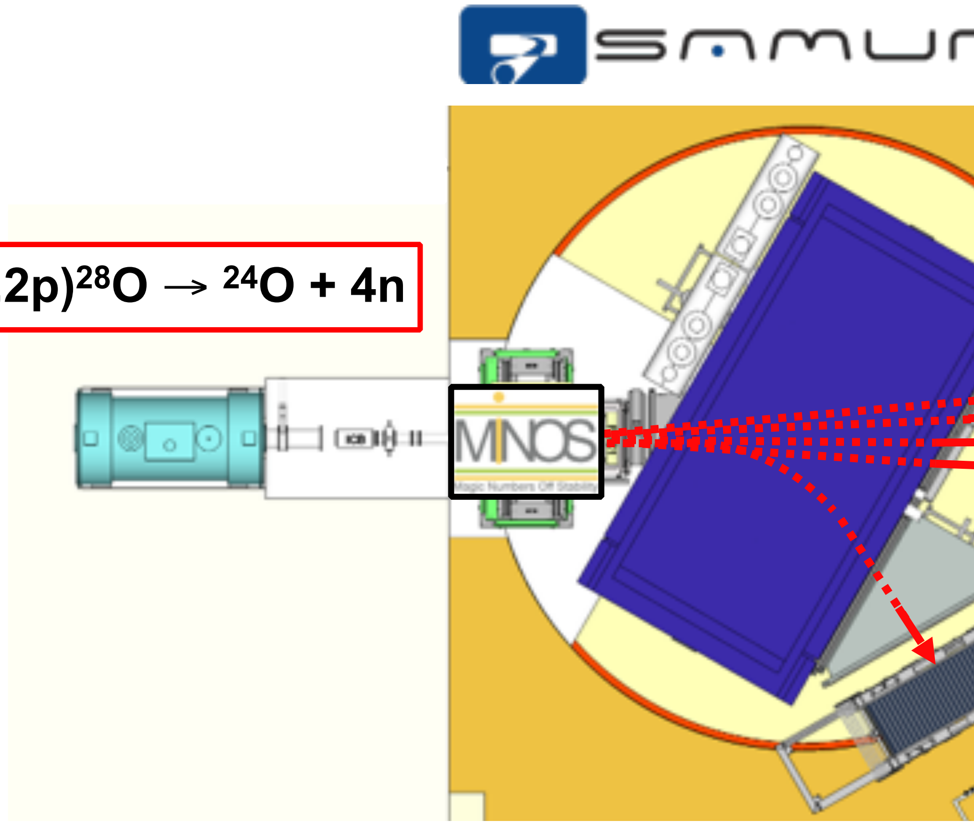


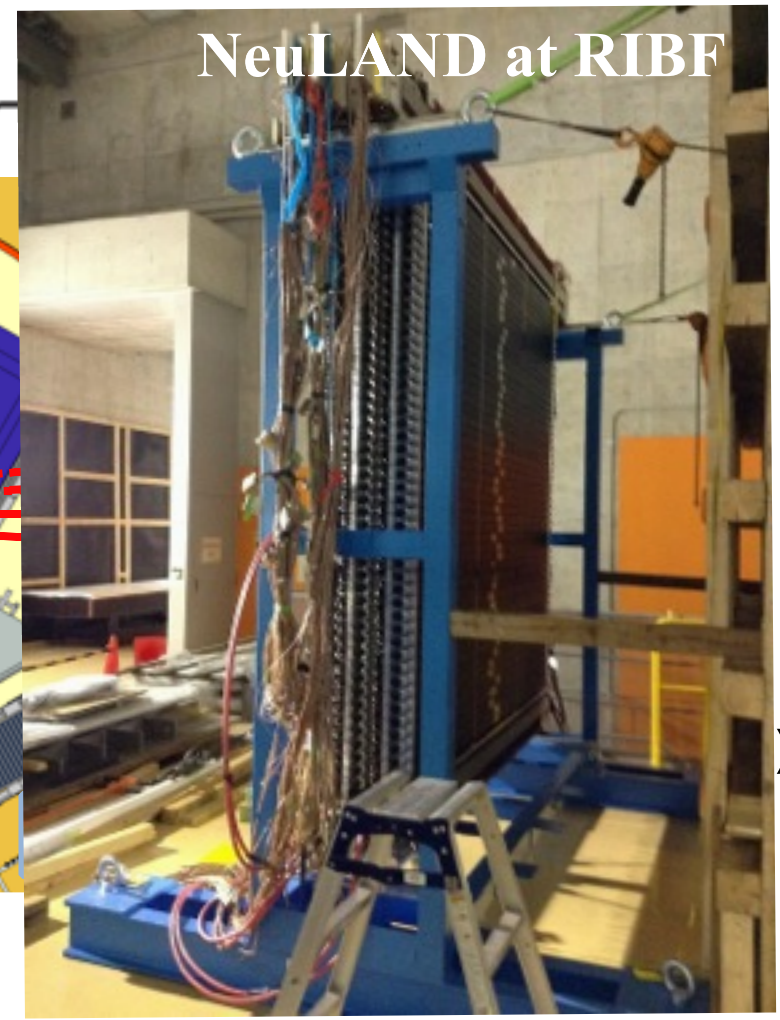



# Go far beyond the dripline

**SAMURAI + MINOS (2014–) + NeuLAND (2015–2018)**

$^{29}F(p,2p)^{28}O \rightarrow ^{24}O + 4n$




Y. Kondo (TITech) et al.

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1) Selectively populate single-particle states

medium-energy substitute of transfer reactions

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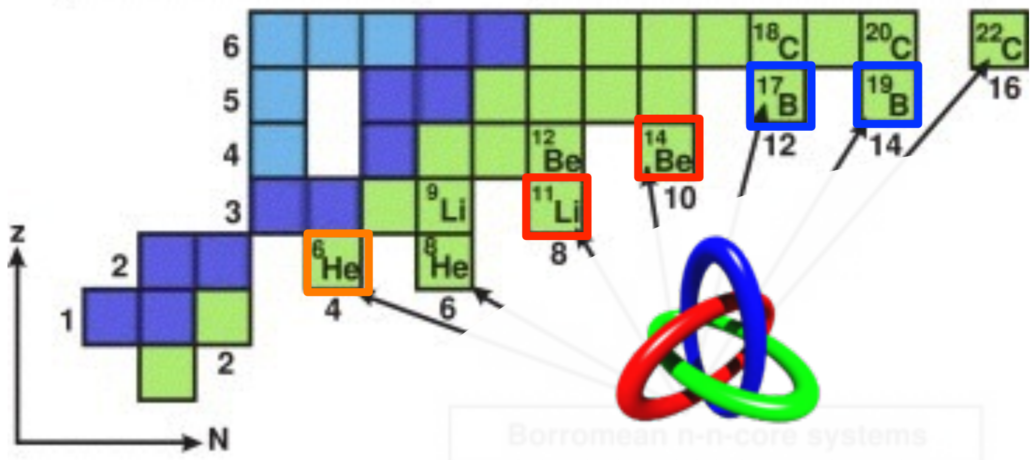
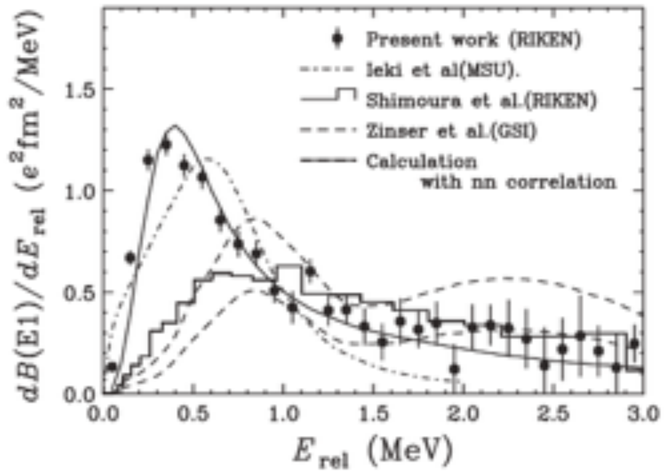
large cross section, large luminosity (target thickness)

3) Can be a probe to nuclear correlation

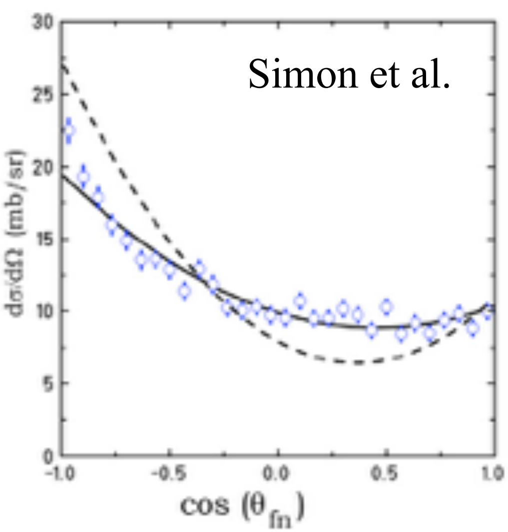
# Two-neutron Correlation in Borromean Nuclei



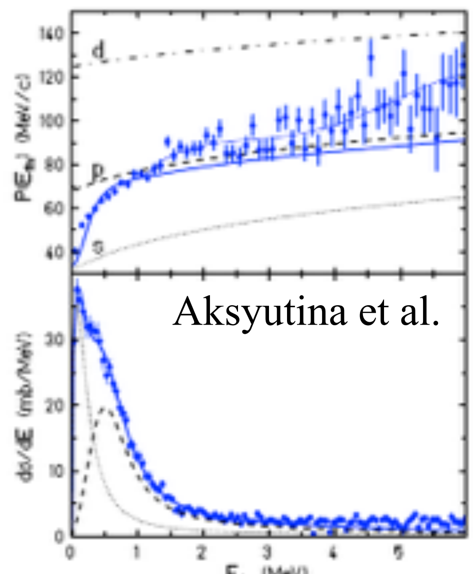

Nakamura et al.



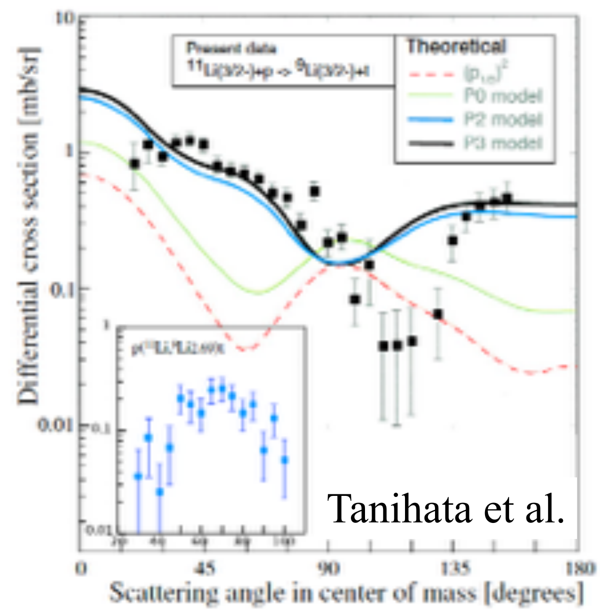

Simon et al.




Aksyutina et al.




Tanihata et al.



# What we have learned from the previous experiments

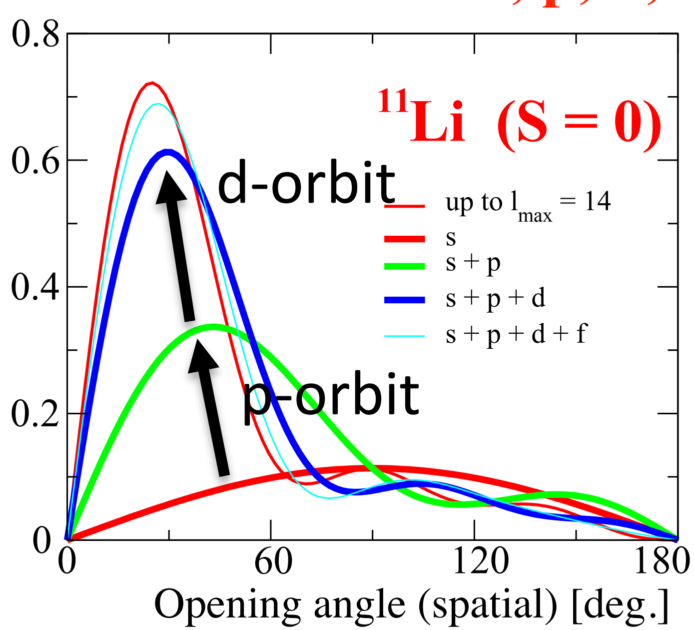
- **Dineutron correlation exists.**
- **In $^{11}Li$, contributions of s- and p-orbits are about half-and-half.**

# Is there any room for further studies?

- **Dineutron correlation exists.**
- **In $^{11}$Li, contributions of s- and p-orbits are half-and-half.**

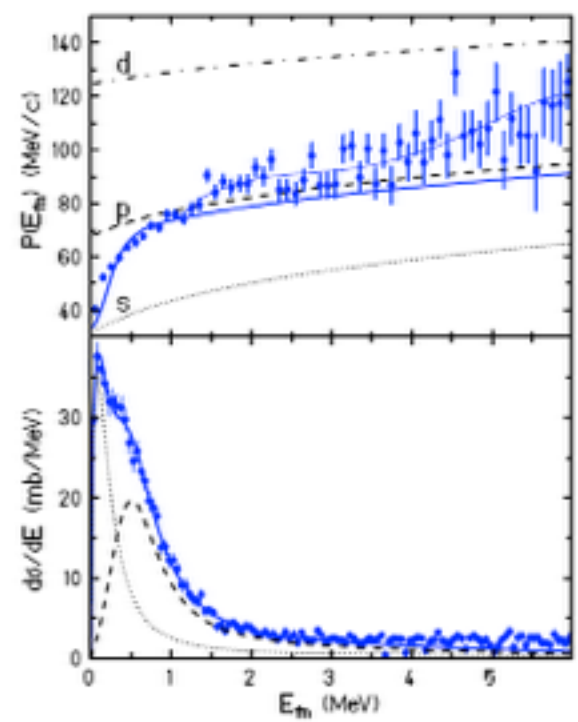
- **What is the role played by higher multipole?**

  **Interference between s, p, d, f. . .**




K. Hagino, in private communications

Aksyutina et al.



# Is there any room for further studies?

- **Dineutron correlation exists.**
- **In $^{11}$Li, contributions of s- and p-orbits are half-and-half.**

- **What is the role played by higher multipole?**

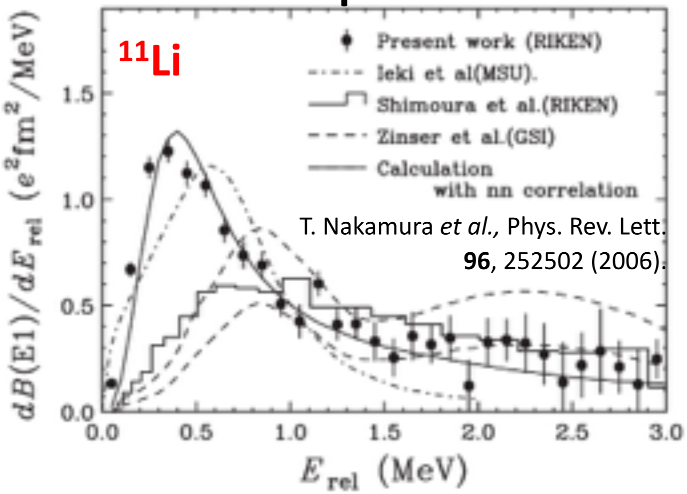
  **Interference between s, p, d, f. . .**

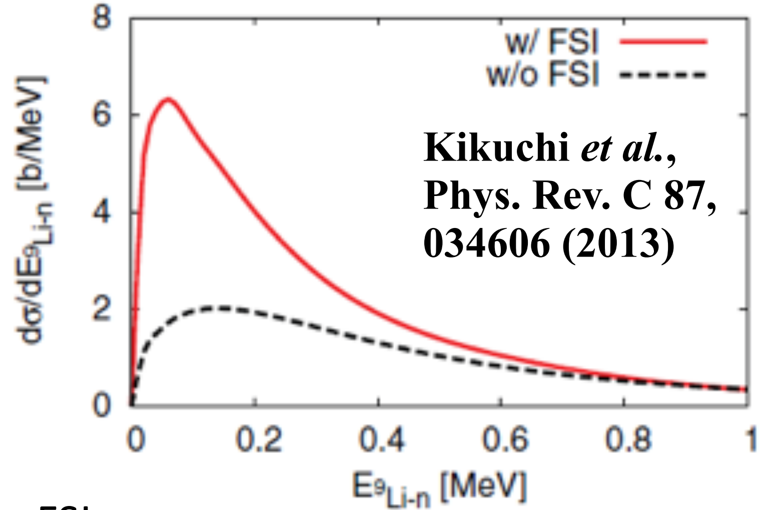
- **Does excited core play a role?**

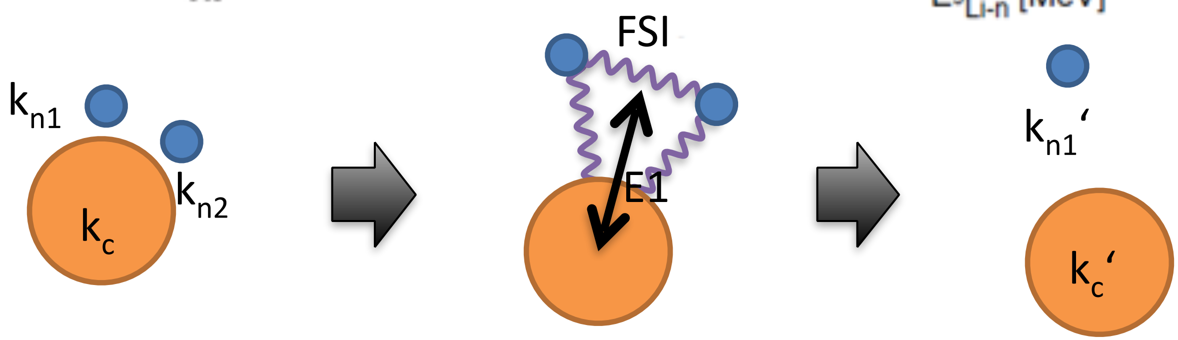
$$\left|\Phi_{g.s.}\right\rangle = \left|\mathrm{core}\right\rangle \otimes \left(\alpha\left|s_{1/2}^2\right\rangle + \beta\left|p_{1/2}^2\right\rangle + \gamma\left|d_{5/2}^2\right\rangle + \ldots\right) + \left|\mathrm{core}^*\right\rangle \otimes \left(\alpha'\left|s_{1/2}^2\right\rangle + \beta'\left|p_{1/2}^2\right\rangle + \gamma'\left|d_{5/2}^2\right\rangle + \ldots\right) + \ldots$$

# Struggle with Final State Interactions

**Coulomb breakup**



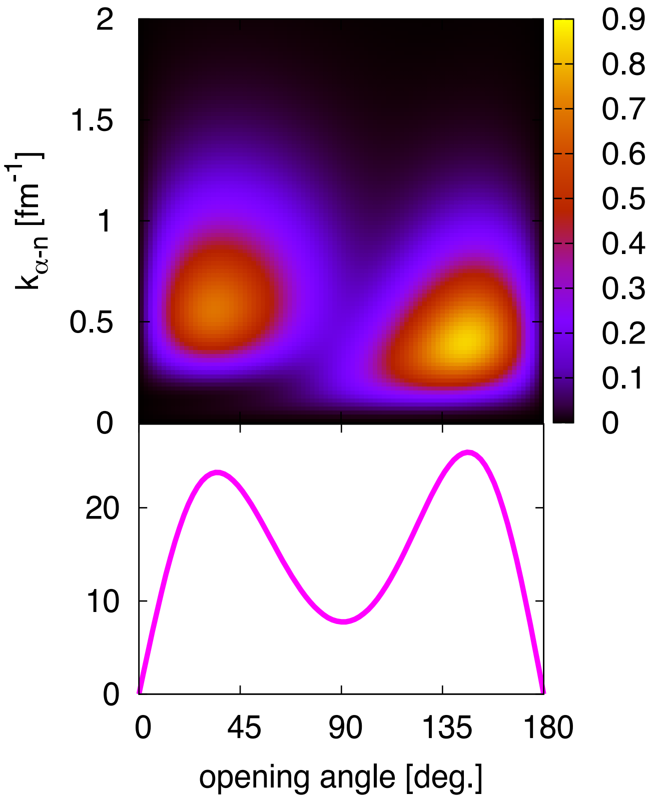

Spectra can be largely distorted by FSI

**We have to employ a reaction with minimum FSI.**

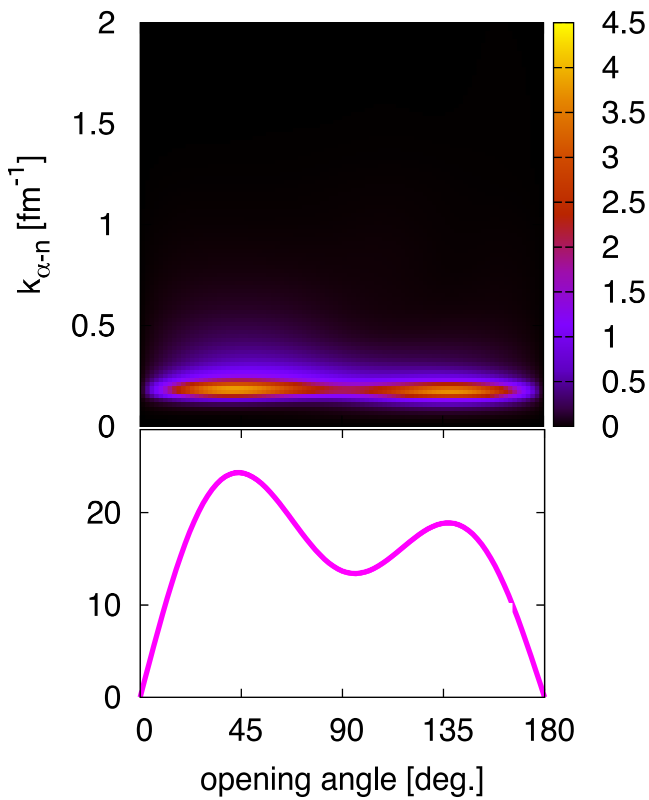
# How can we observe the dineutron?

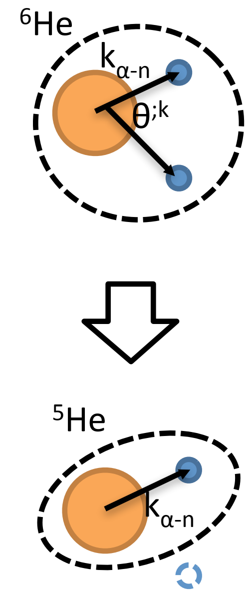
In collaboration with Yuma Kikuchi and K. Ogata

Ground-state (~~Observable~~)




After (p,pn) reaction (Observable)




Signature seems to be weak . . . .

← smeared out by $k_{core\text{-}n}$ integration

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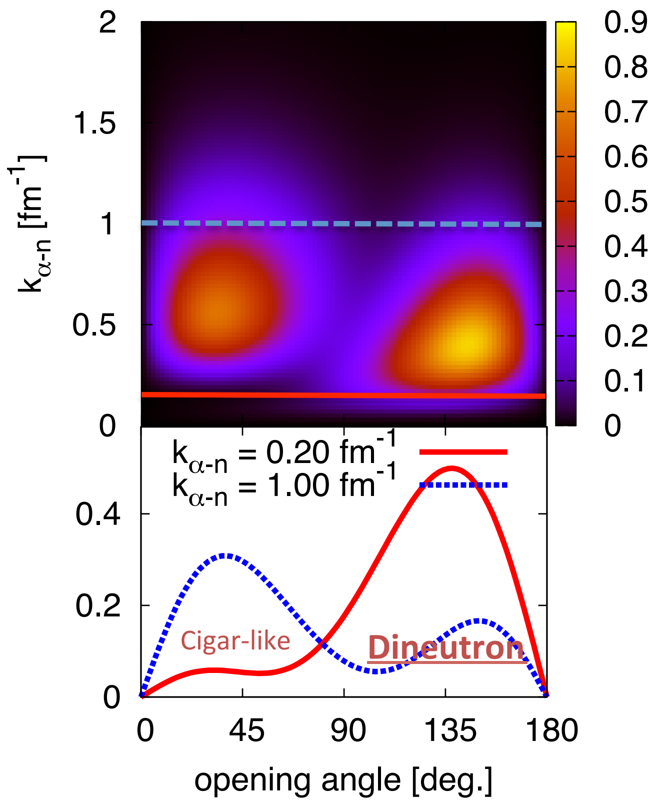


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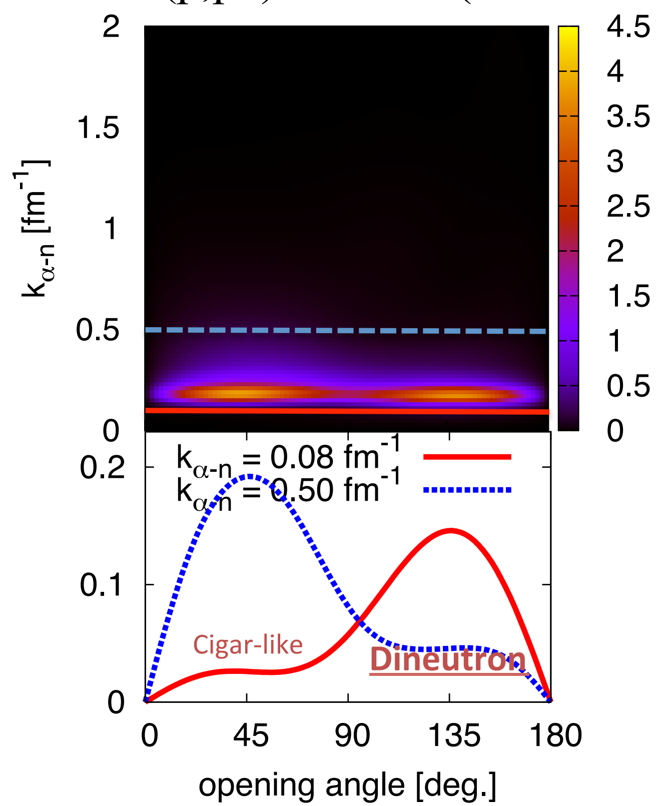
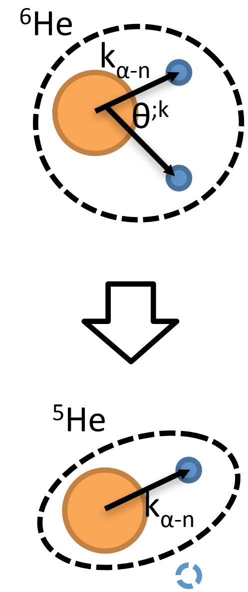



**Clearer signatures of dineutron correlations!**

**Dineutron-like for small $k_{core-n}$ ⇔ Cigar-like for large $k_{core-n}$**

# The cleanest and the most complete approach to the dineutron correlation

- $^{11}$Li, $^{14}$Be, $^{17}$B(*p*,*pn*) neutron knockout reaction (at E/A~250 MeV) with high momentum transfer (q > 2 fm$^{-1}$)

  Free from three-body final state interaction

- Kinematically (too) complete experiment

  Detect all the particles, including γ-ray

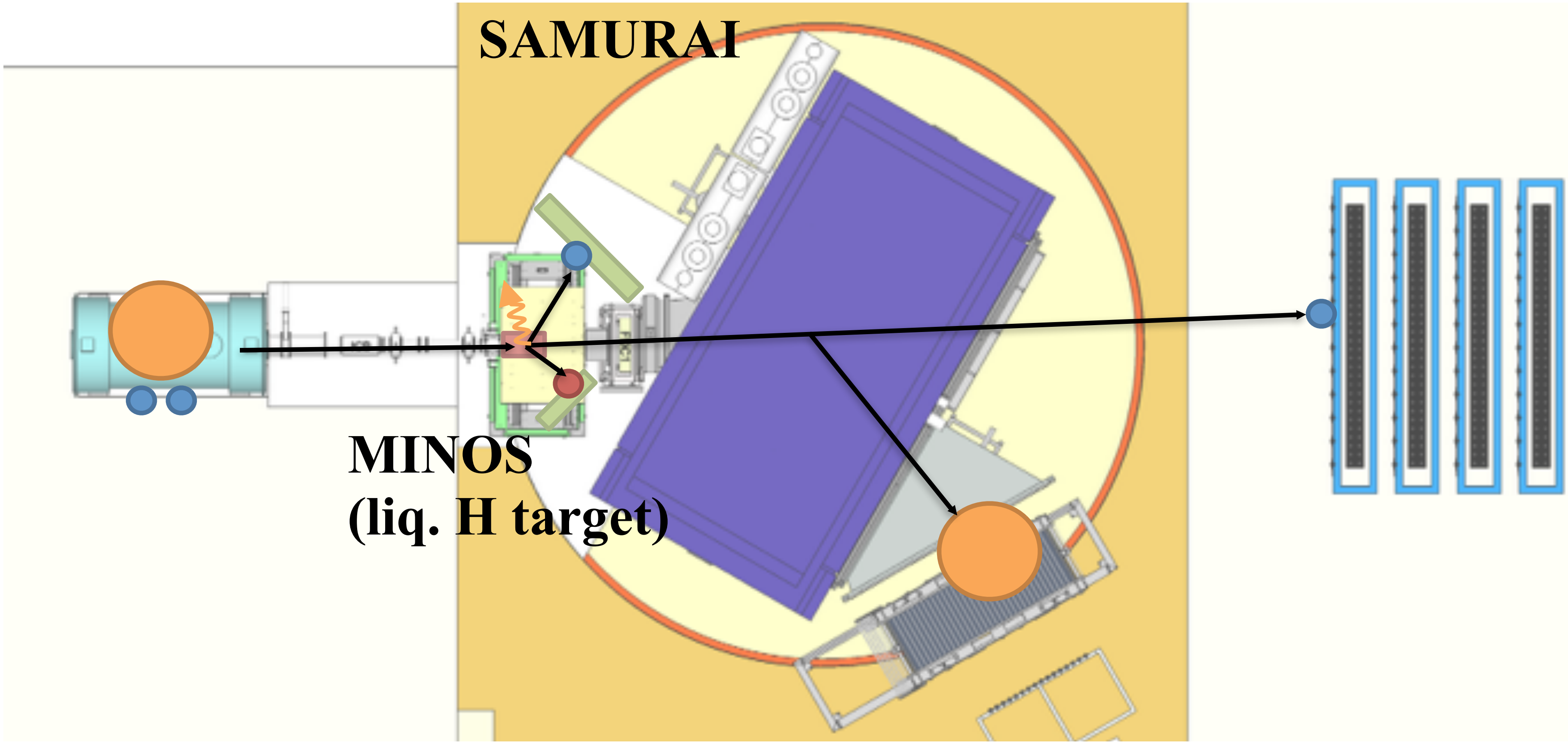


**Tradeoff**

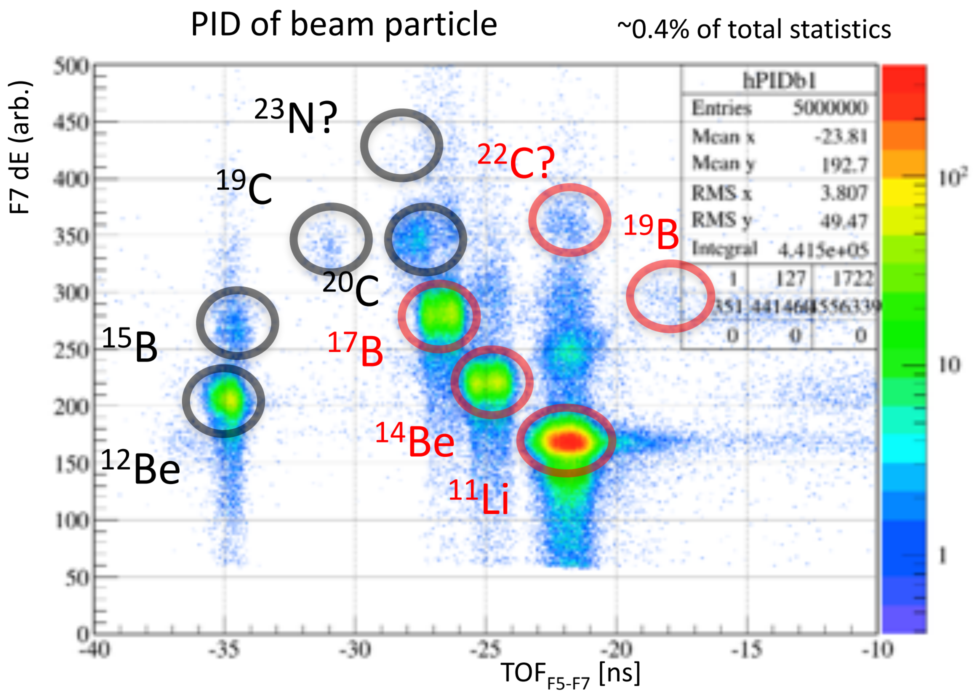
low experimental efficiency

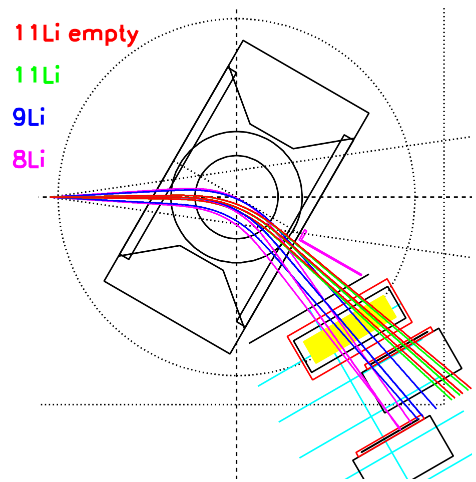
→ remedied by high luminosity by use of high-intensity beams at RIBF and a thick liquid hydrogen target of MINOS!

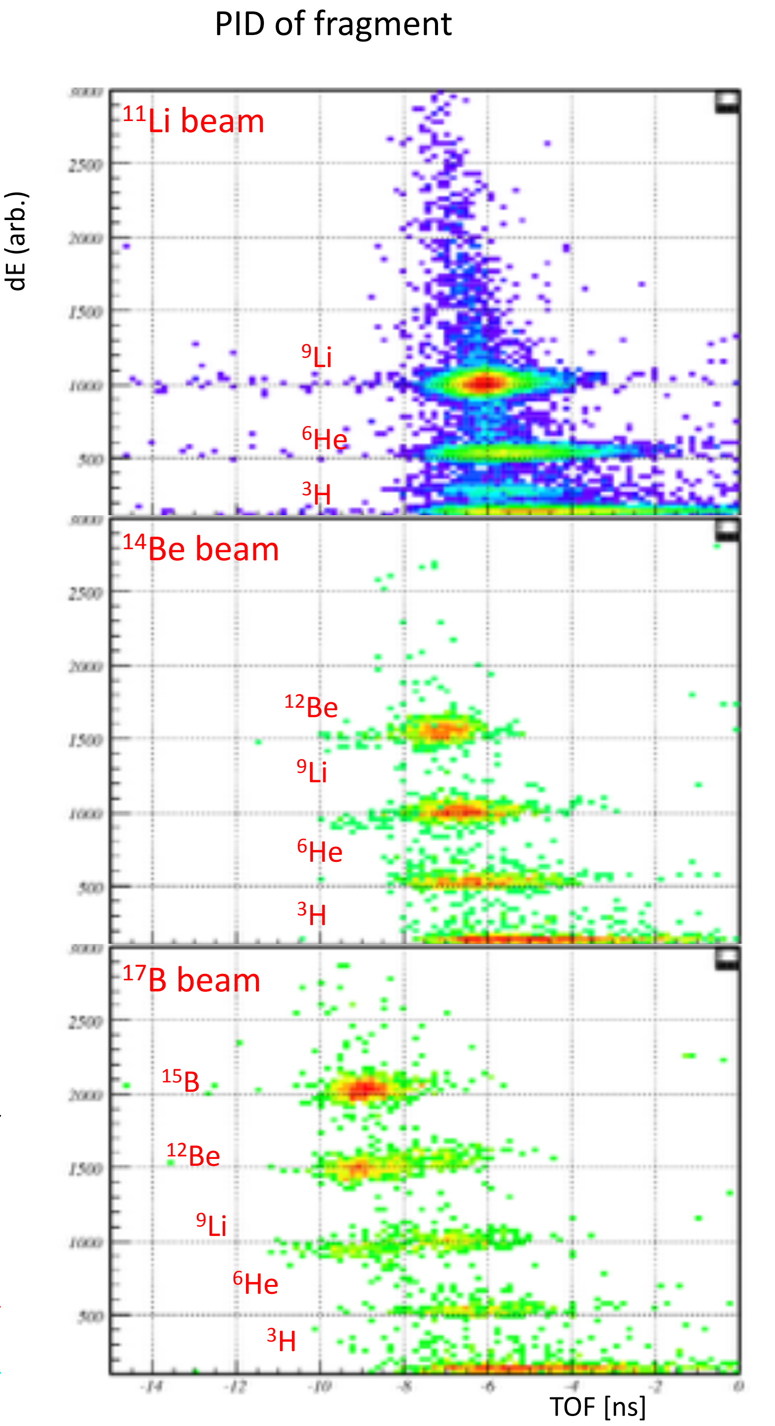
# Experimental setup for (p,pn)



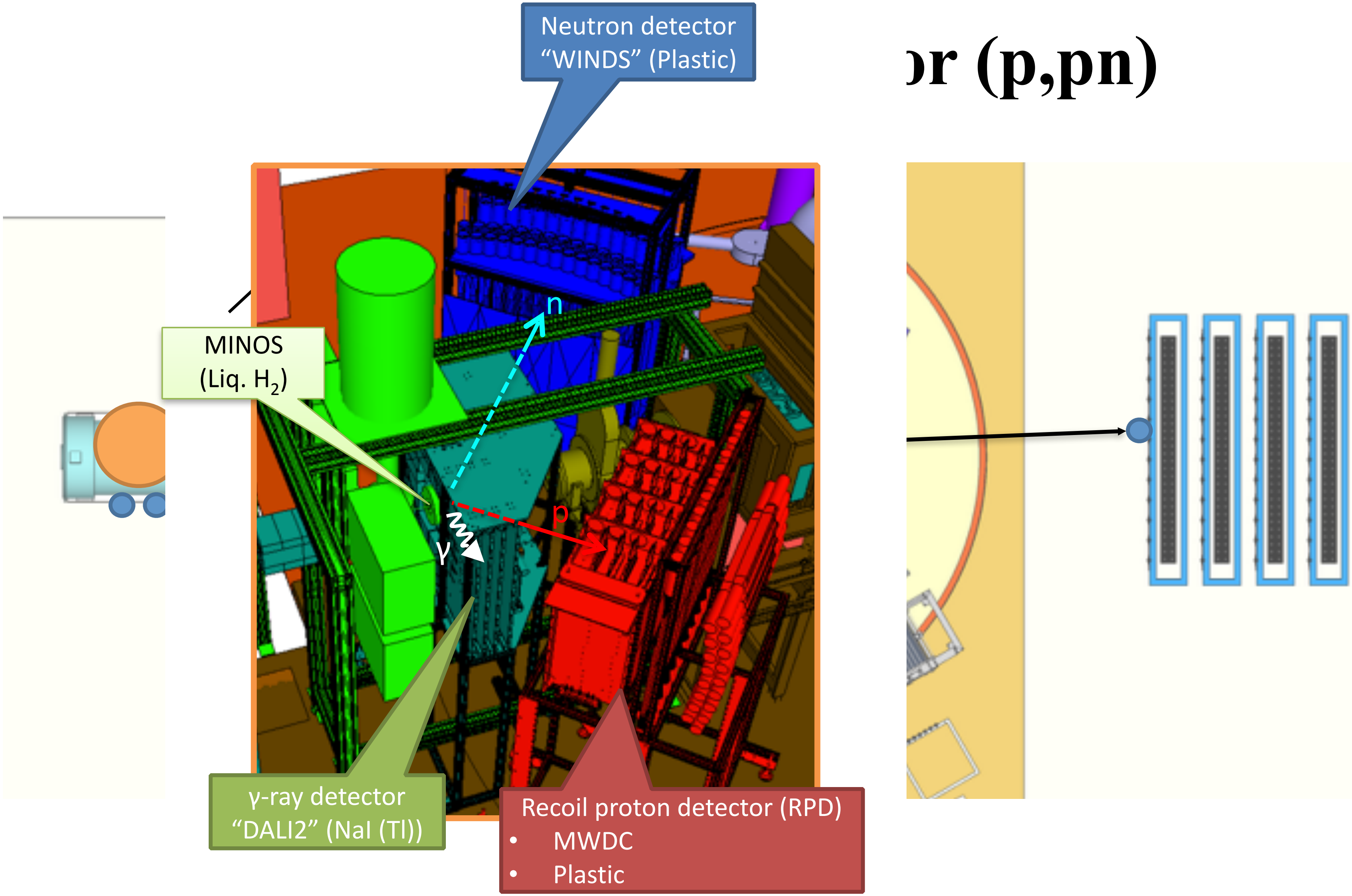
# Particle Identification



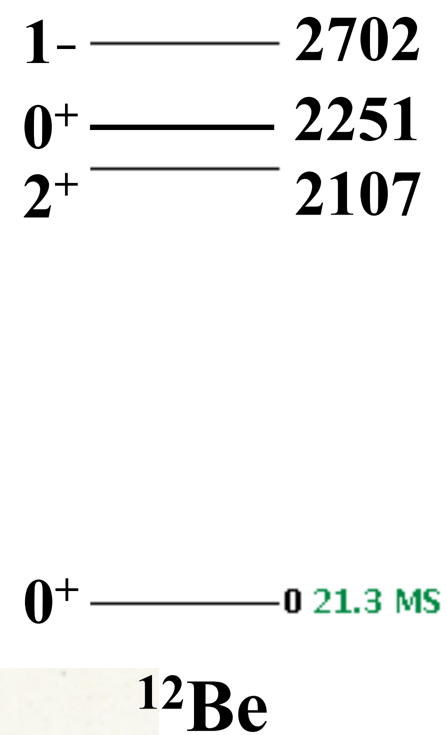
# r (p,pn)

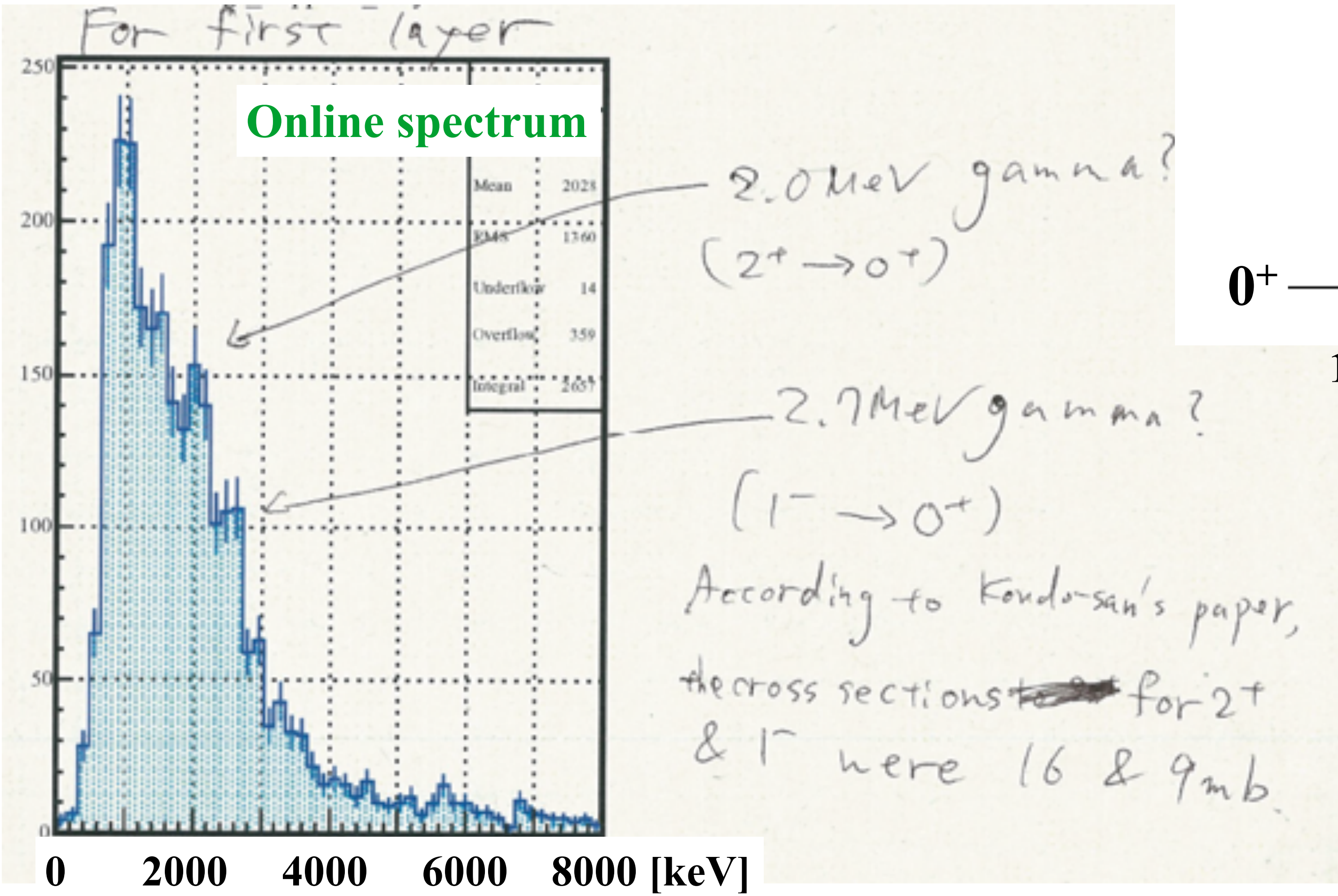


Neutron detector
"WINDS" (Plastic)
n
MINOS
(Liq. $H_2$)
p
γ
γ-ray detector
"DALI2" (NaI (Tl))
Recoil proton detector (RPD)
• MWDC
• Plastic

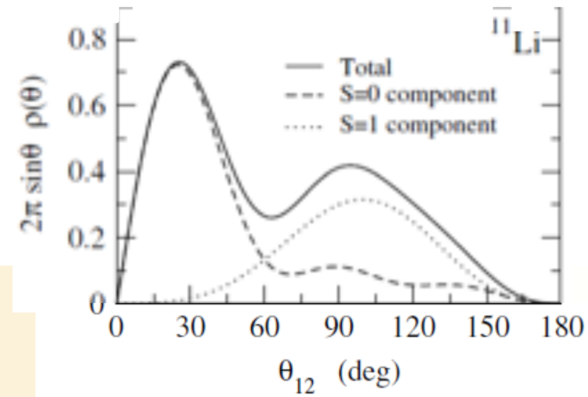
# Excited core in $^{14}$Be

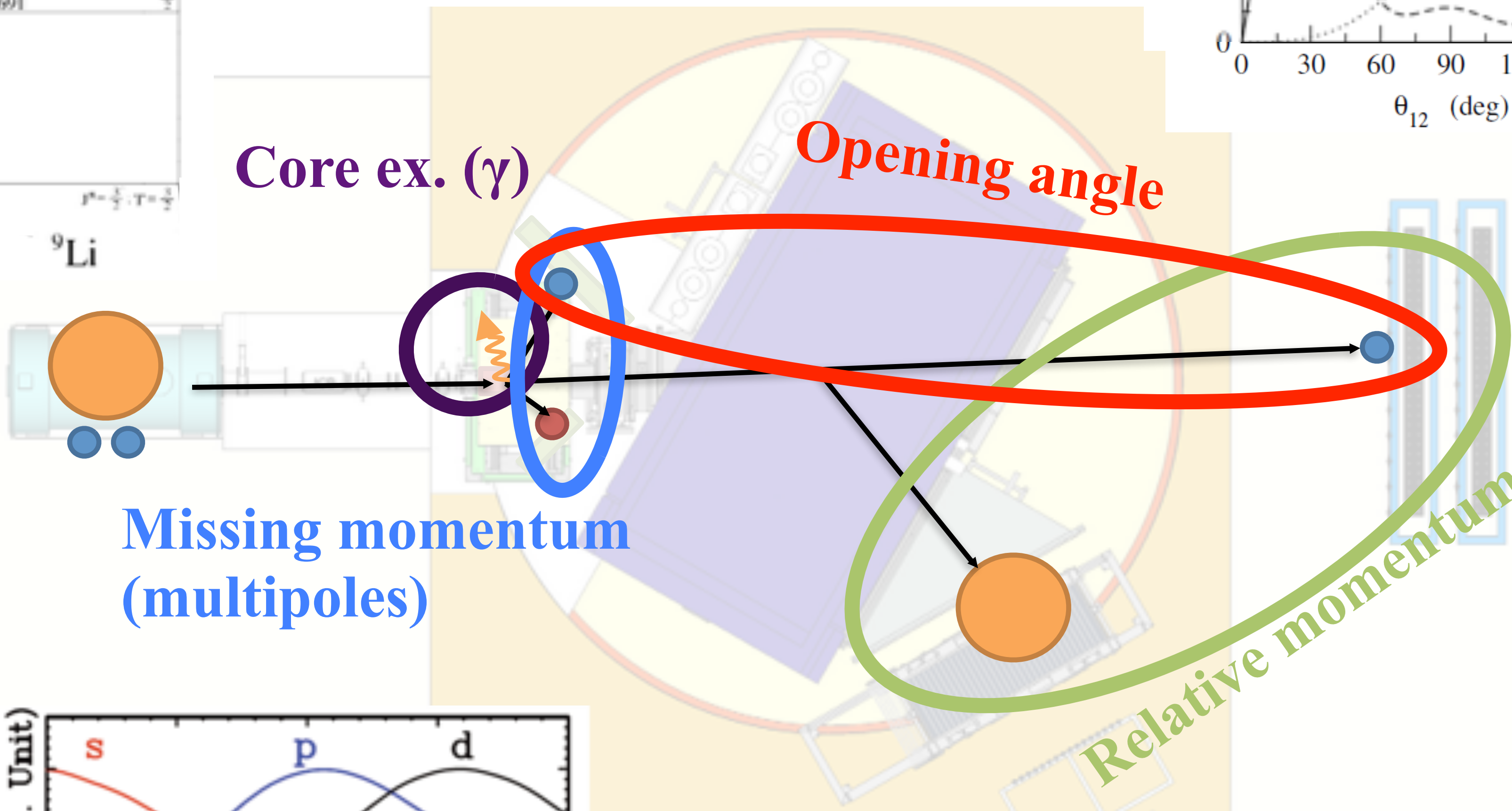
- Does excited core play a role?

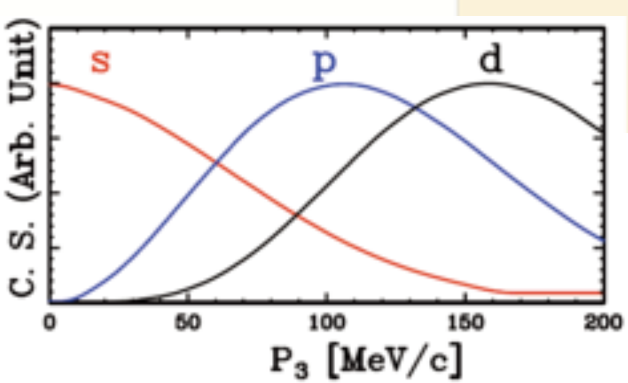


# Observables

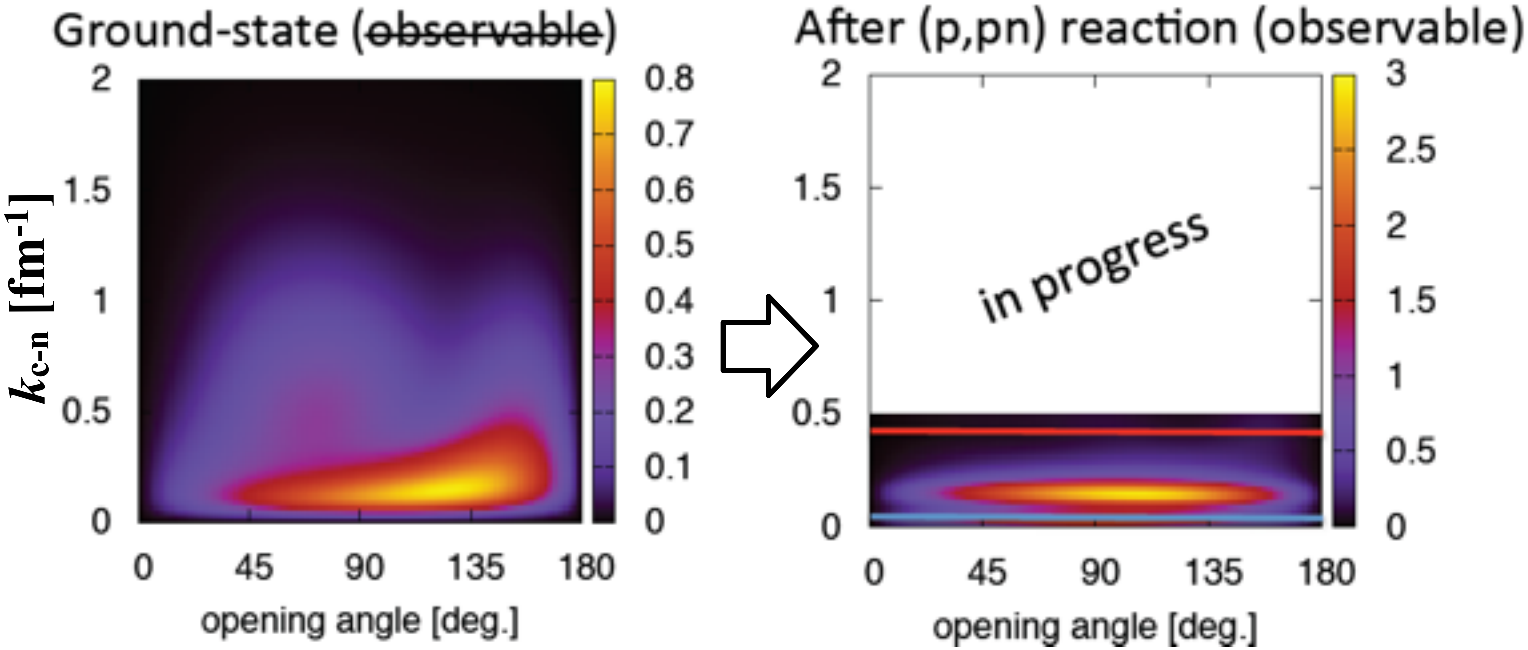



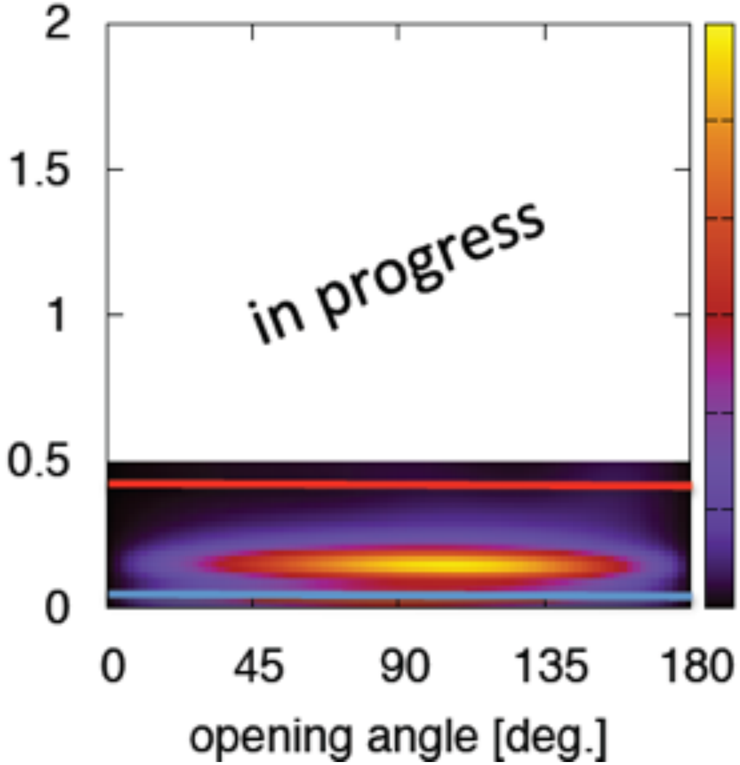
# How can we observe the dineutron?

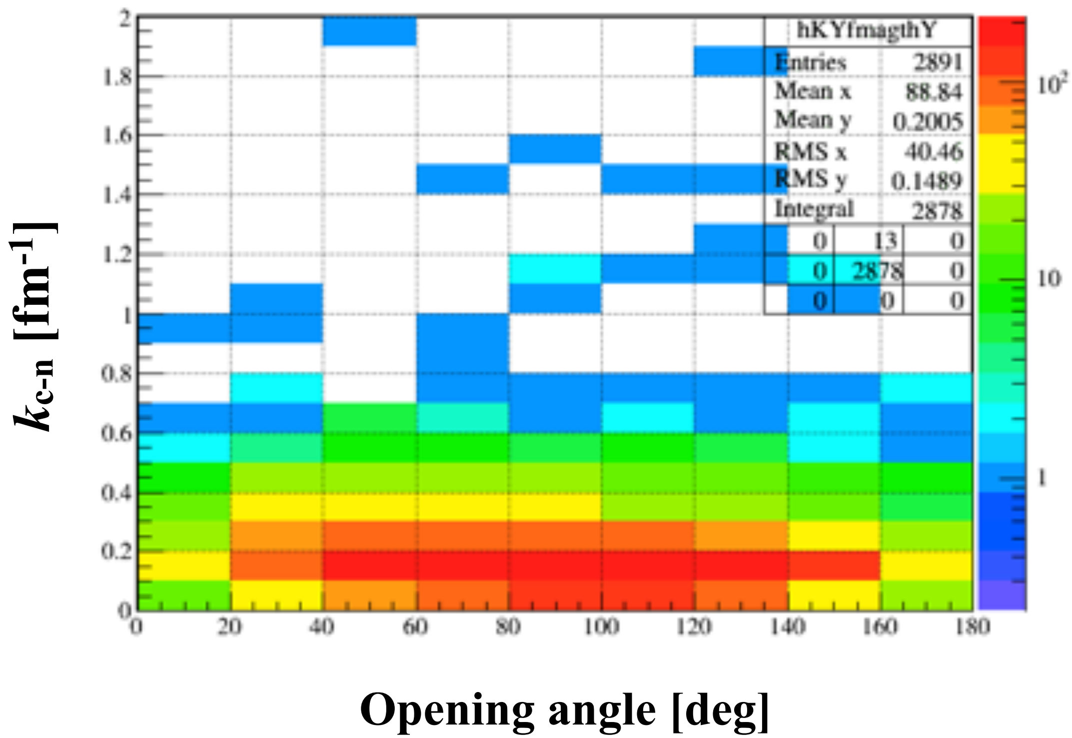
**Case of $^{11}Li$**

**In collaboration with Yuma Kikuchi and K. Ogata**

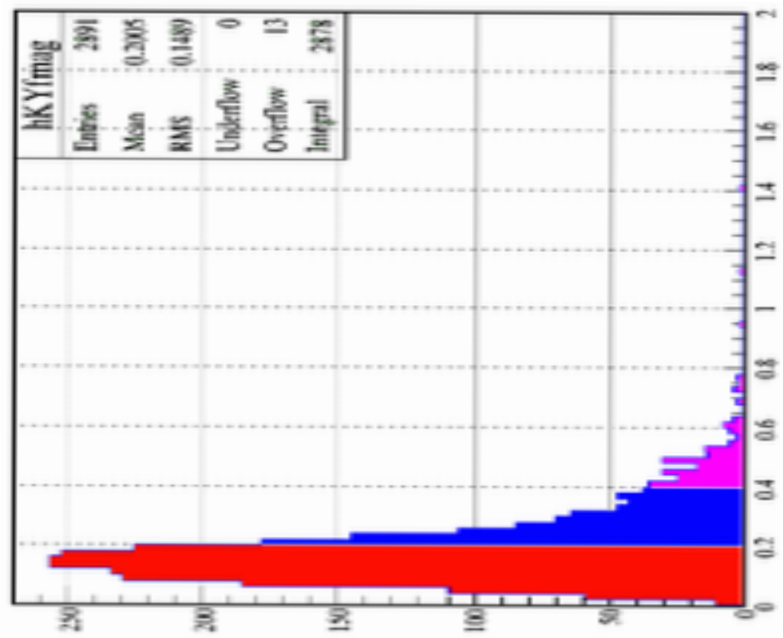


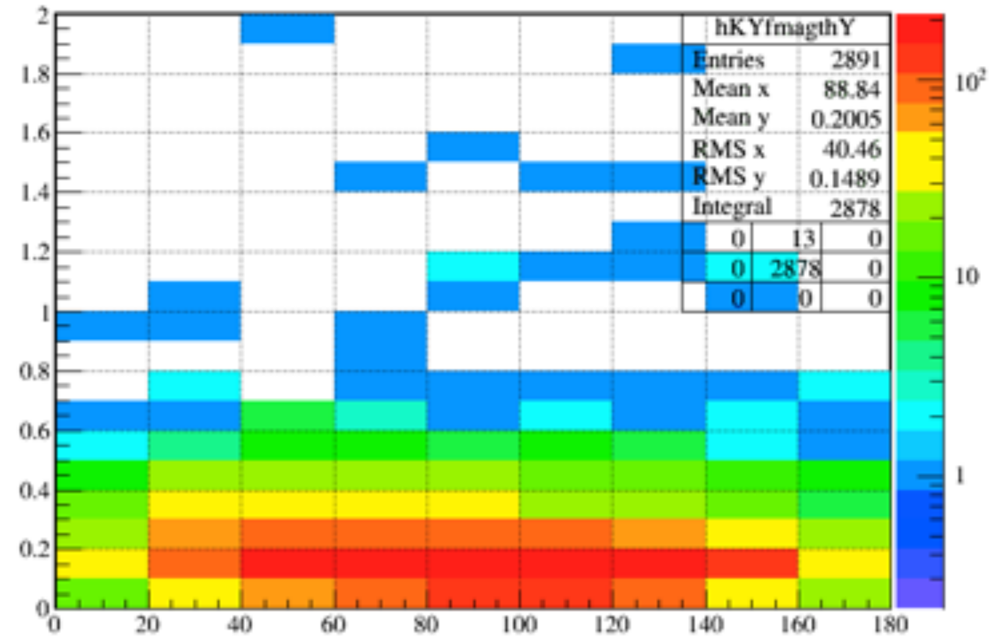

# How can we observe the dineutron?



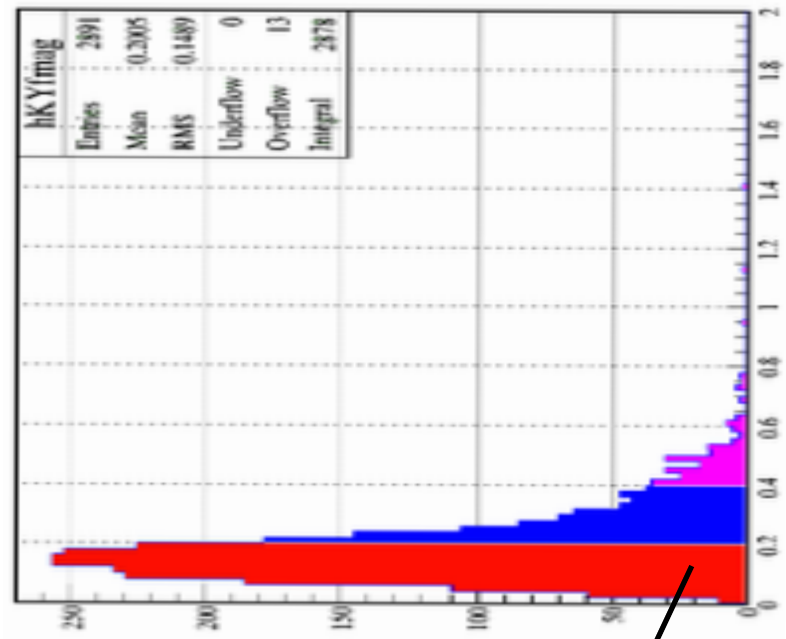
# How can we observe the dineutron?

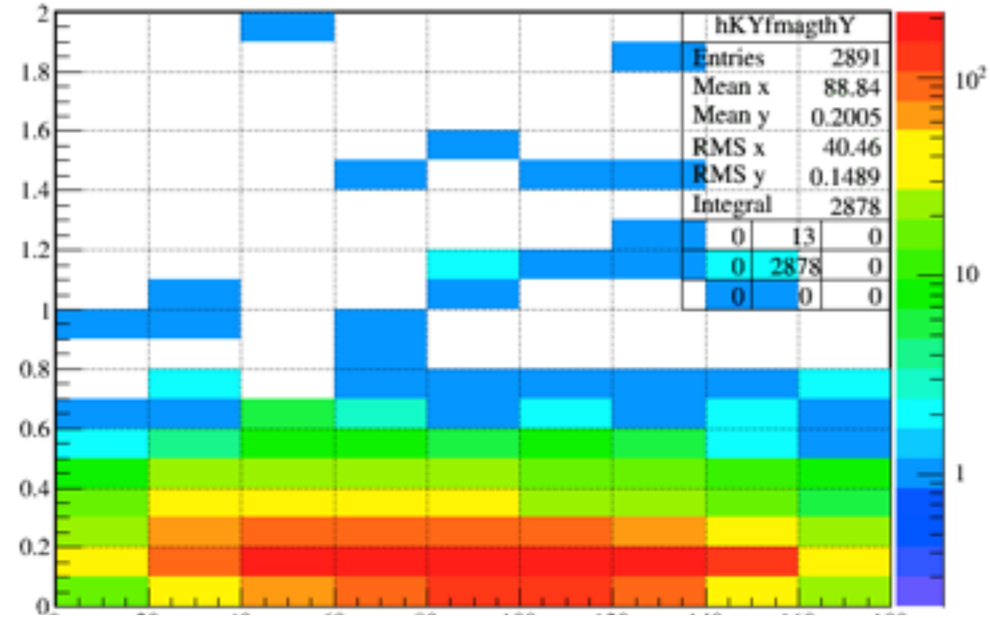


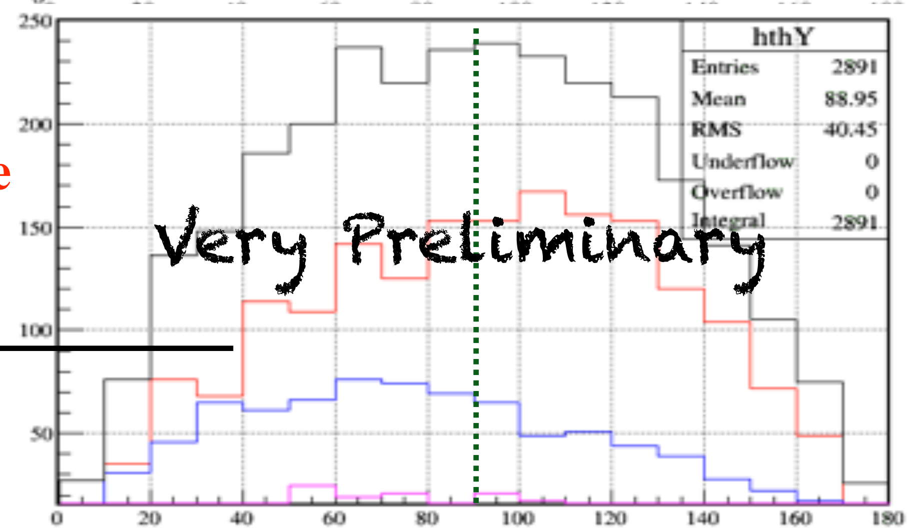




Opening angle [deg]

# How can we observe the dineutron?



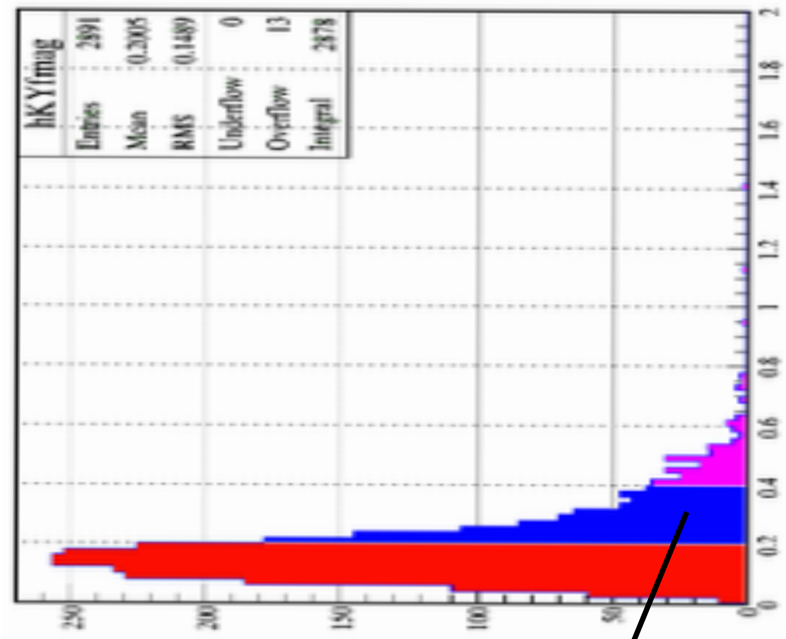



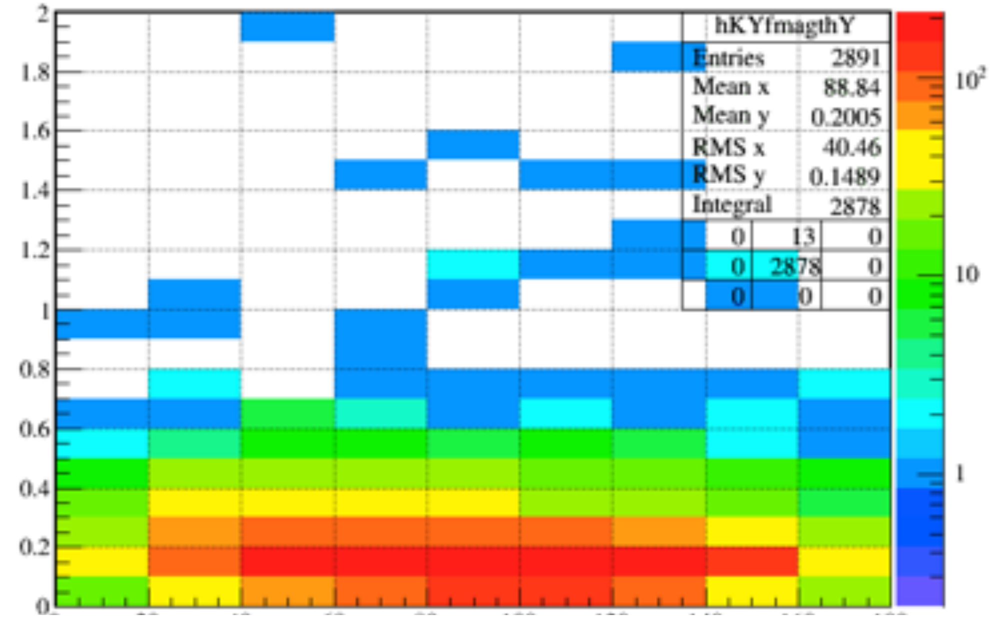

Opening angle [deg]

**Small $k_{c\text{-}n}$**
**⇔ neutron is far away from the core**

**Enhancement in the large $\theta_{nn}$ region**
**⇒ dineutron-like**

# How can we observe the dineutron?



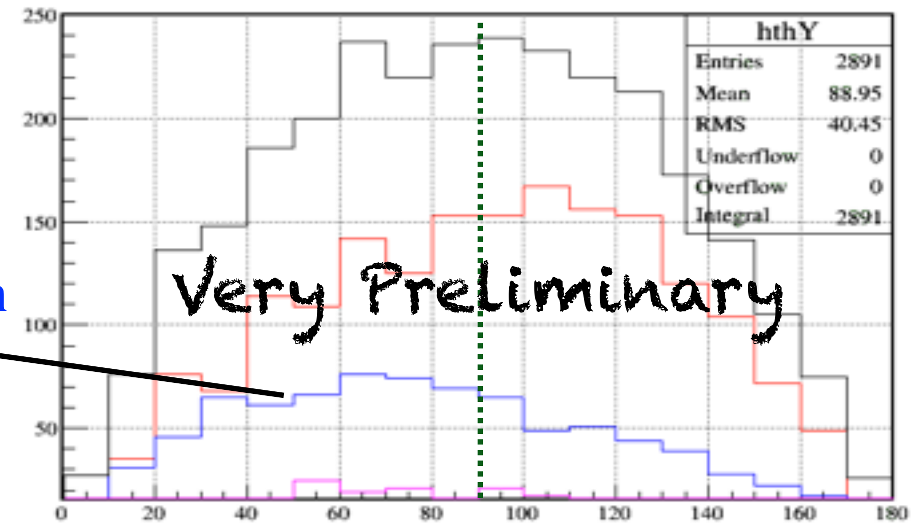




Large $k_{c\text{-}n}$

⇔ neutron is close to the core.

Enhancement in the small $\theta_{nn}$ region

⇒ cigar-like




Opening angle [deg]

# Summary

**Quasi-free scattering is a good tool to probe structure of unstable nuclei.**

**Single-particle spectroscopy : spectroscopic factor. . .**

**Nuclear excitation driver : MINOS & fission barrier**
**Nuclear Correlation : α Knockout & dineutron**

**(p,pn) reaction with a large momentum transfer**

**The cleanest and the most complete experiment to probe dineutron correlation**

**Minimization of 3-body FSI**

**γ-ray detection for tagging core excitation**

**High statistics enabled with RIBF × MINOS**