Two-Neutron Momentum Correlation in Borromean Nuclei

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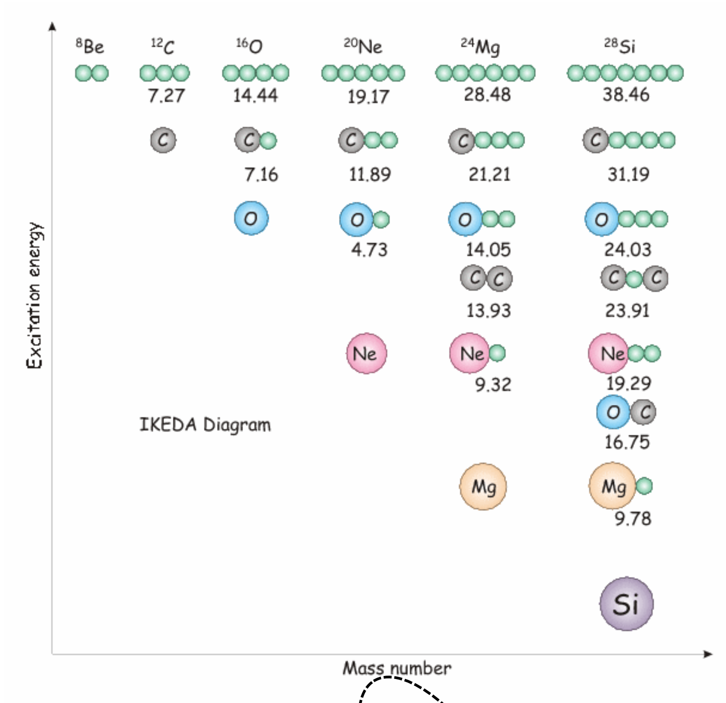
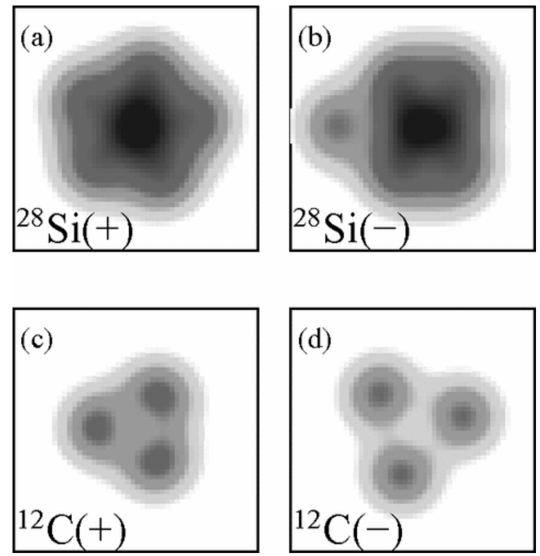
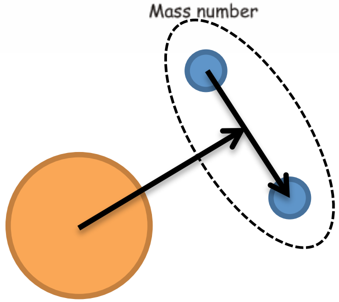
Theoretical support from Y. Kikuchi (*RIKEN*) and K. Ogata (*RCNP*)

How can we SEE clustering?

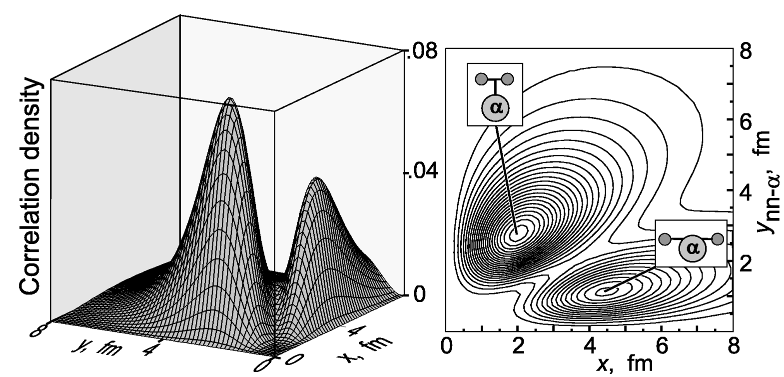




Y. Kanada-En'yo *et al.*, Phys. Rev. C 84, 014313



To our knowledge, nobody has SEEN it.
We will demonstrate how to do it.



Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett. 82, 4996

Steps to SEE clustering

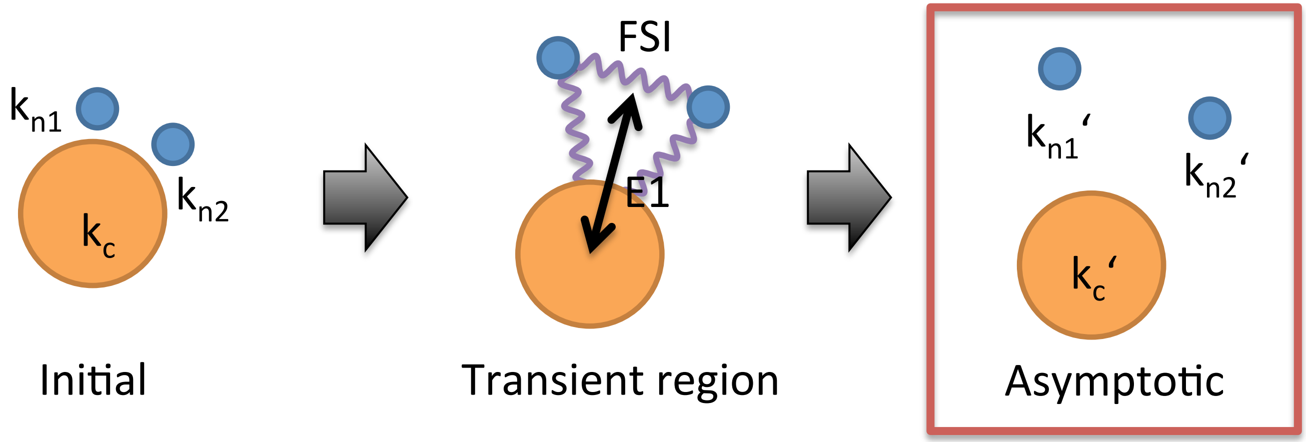
1. Break
   – Nuclear reaction → break the nucleus into clustering ingredients
2. Measure
   – Momenta of all the ingredients after the reaction
3. **Connect**
   – **Measured (asymptotic) momenta → initial momenta in nucleus**
4. Represent
   – Appropriate coordinate

These four steps are essential.

The “connection” is the key.

“Connection”

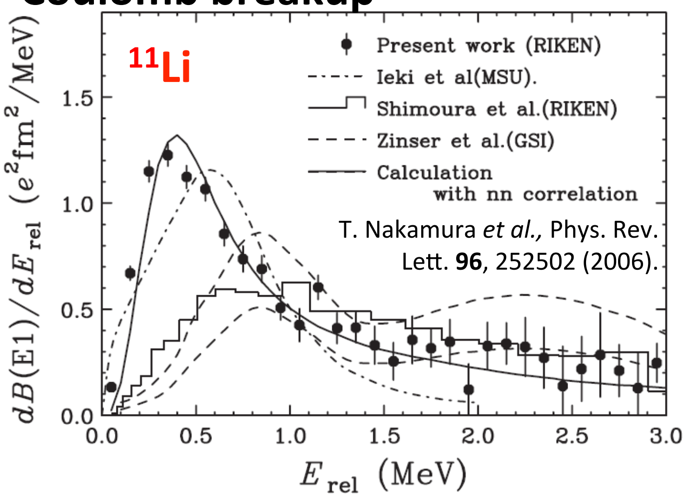
Initial momentum ≠ asymptotic momentum

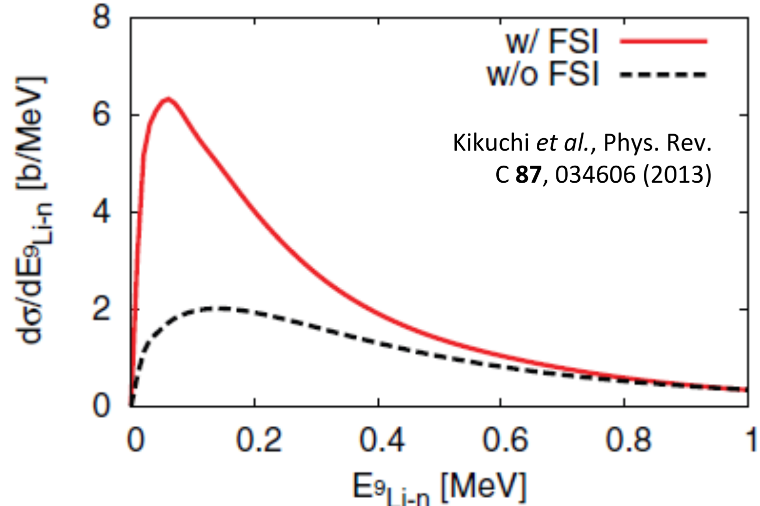


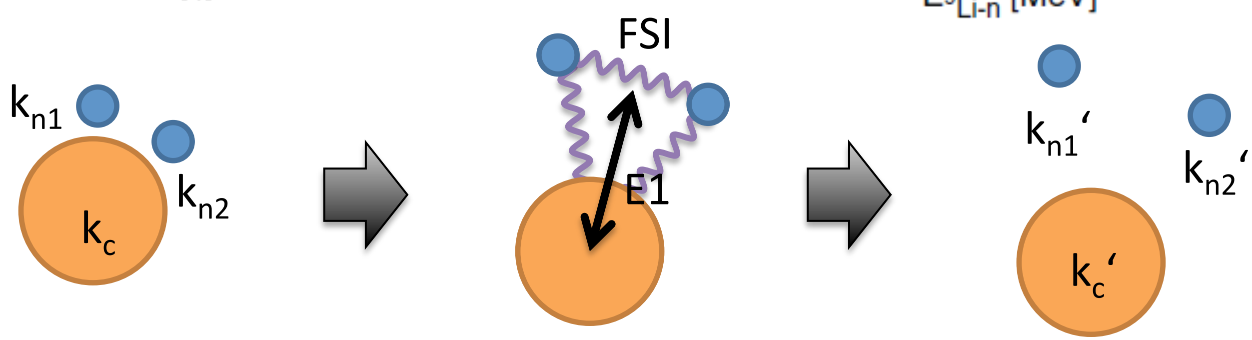
Because of final state interaction (FSI)

Effect of FSIs

Coulomb breakup







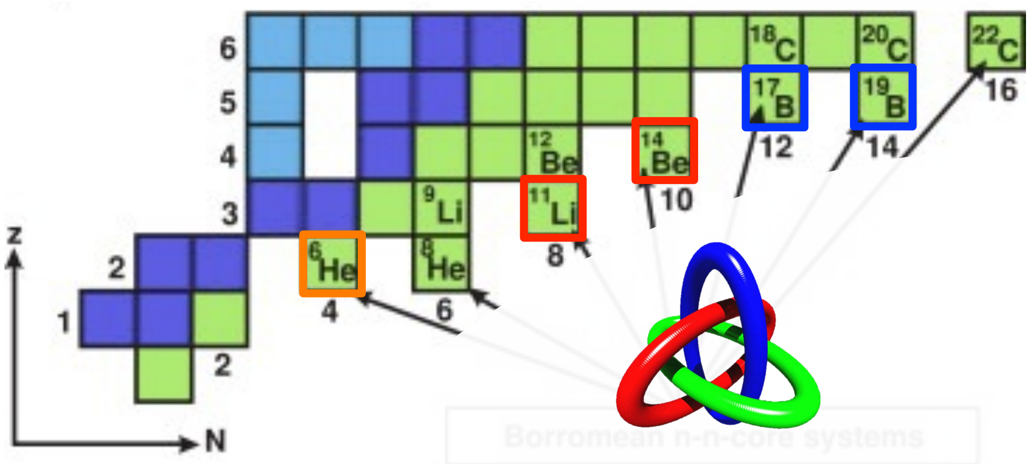
Spectra can be largely distorted by FSI

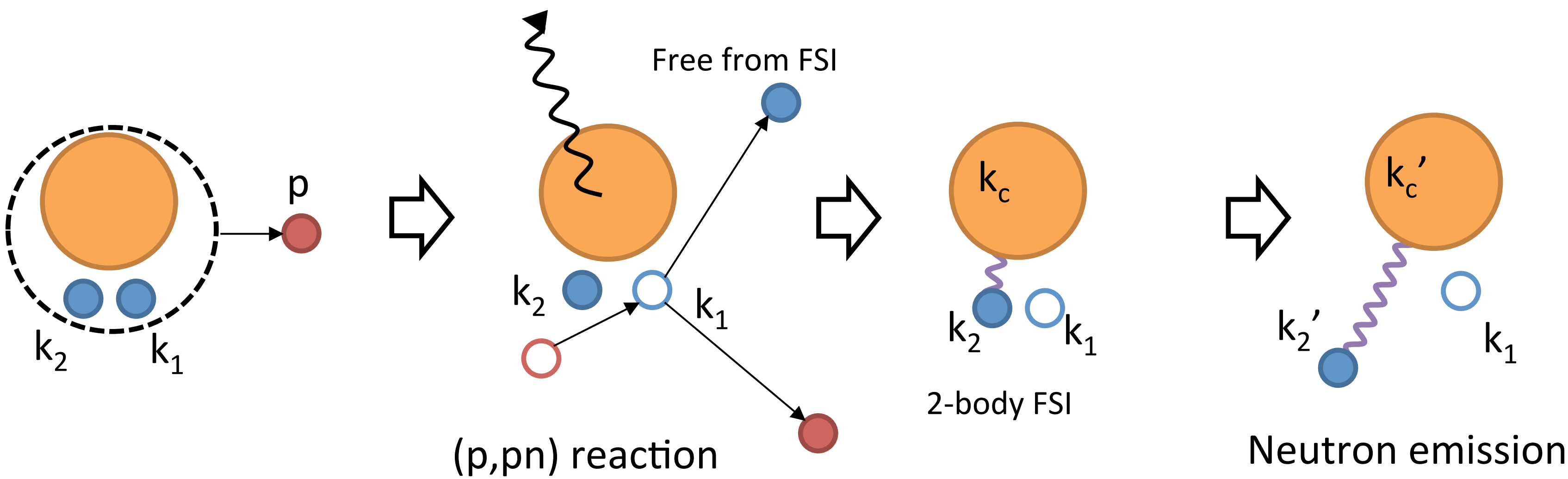
Steps to SEE clustering

1. Break
   – Nuclear reaction → break the nucleus into clustering ingredients
2. Measure
   – Momenta of all the ingredients after the reaction
3. **Connect → suffers from FSI**
   – **Measured (asymptotic) momenta → initial momenta in nucleus**
4. Represent
   – Appropriate coordinate

A solution with <u>the quasi-free knockout reaction</u> on <u>Borromean nuclei</u>

(p,pn) on Borromean nuclei





Steps to SEE clustering

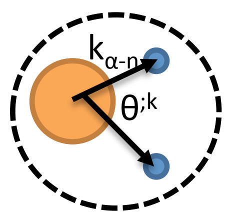
1. Break
   - Nuclear reaction → break the nucleus into clustering ingredients

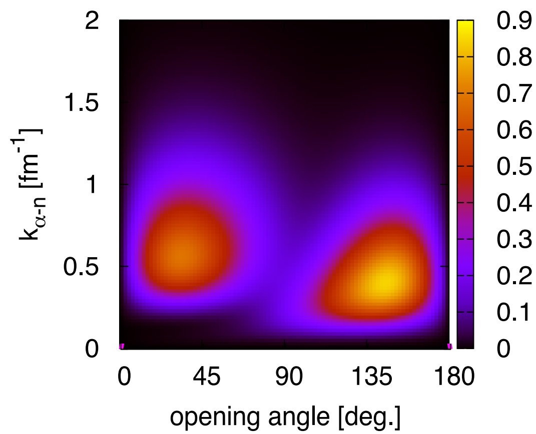
   → All the cluster ingredients go apart through the reaction (and decay)
2. Measure
   - Momenta of all the ingredients after the reaction

   → Complete measurement
3. **Connect**
   - **Measured (asymptotic) momenta → initial momenta in nucleus**

   → FSI is minimized
   - One FSI remaining → can be handled
4. Represent
   - Appropriate coordinate

How?

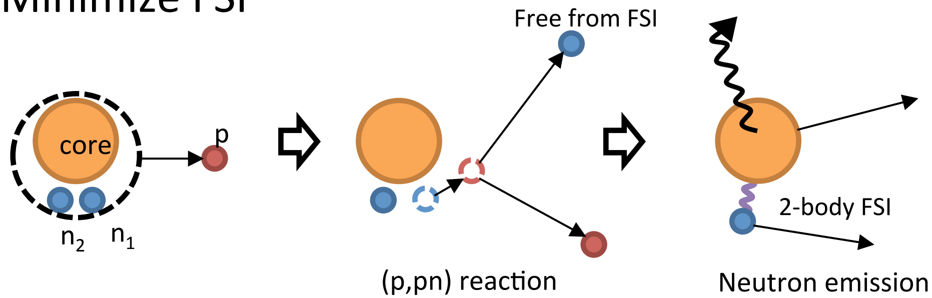




In the courtesy of Y. Kikuchi

RIBF x SAMURAI x MINOS

1. Simple mechanism of the quasi-free (p,pn) reaction at intermediate energies
   - ✓ Determine the single particle nature most reliably
   - ✓ Minimize FSI



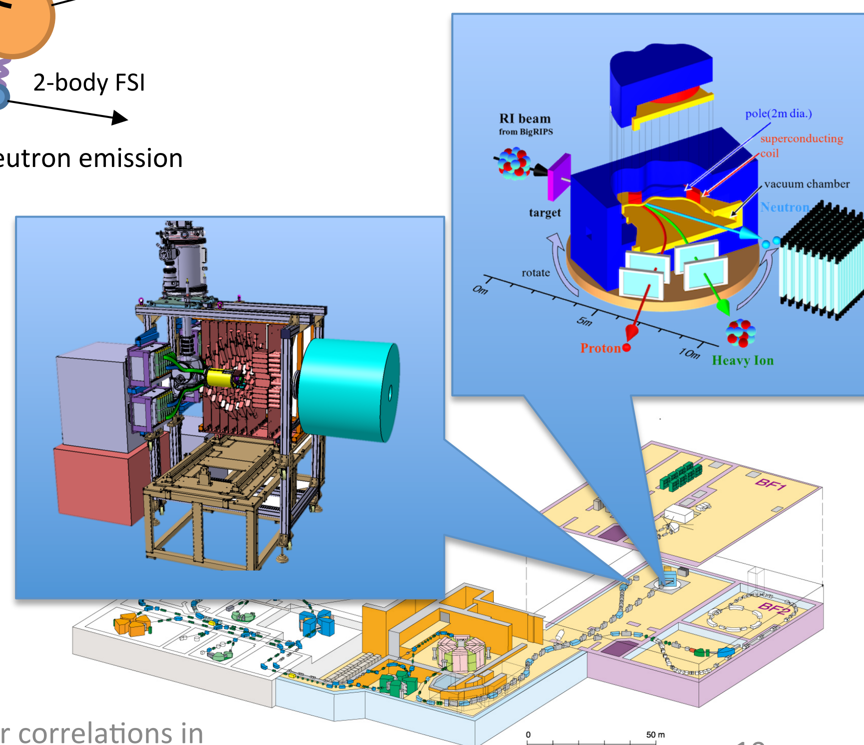
2. γ-ray detection
   - ✓ Core excitation

     Y. Kikuchi *et al.*, PRC **87**, 034606 (2013)
     G. Potel *et al.*, PRL **105**, 172502 (2010)

3. High statistics
   - ✓ Higher multipole
   - ✓ 100—1000 times larger luminosity
     by combination of RIBF with MINOS

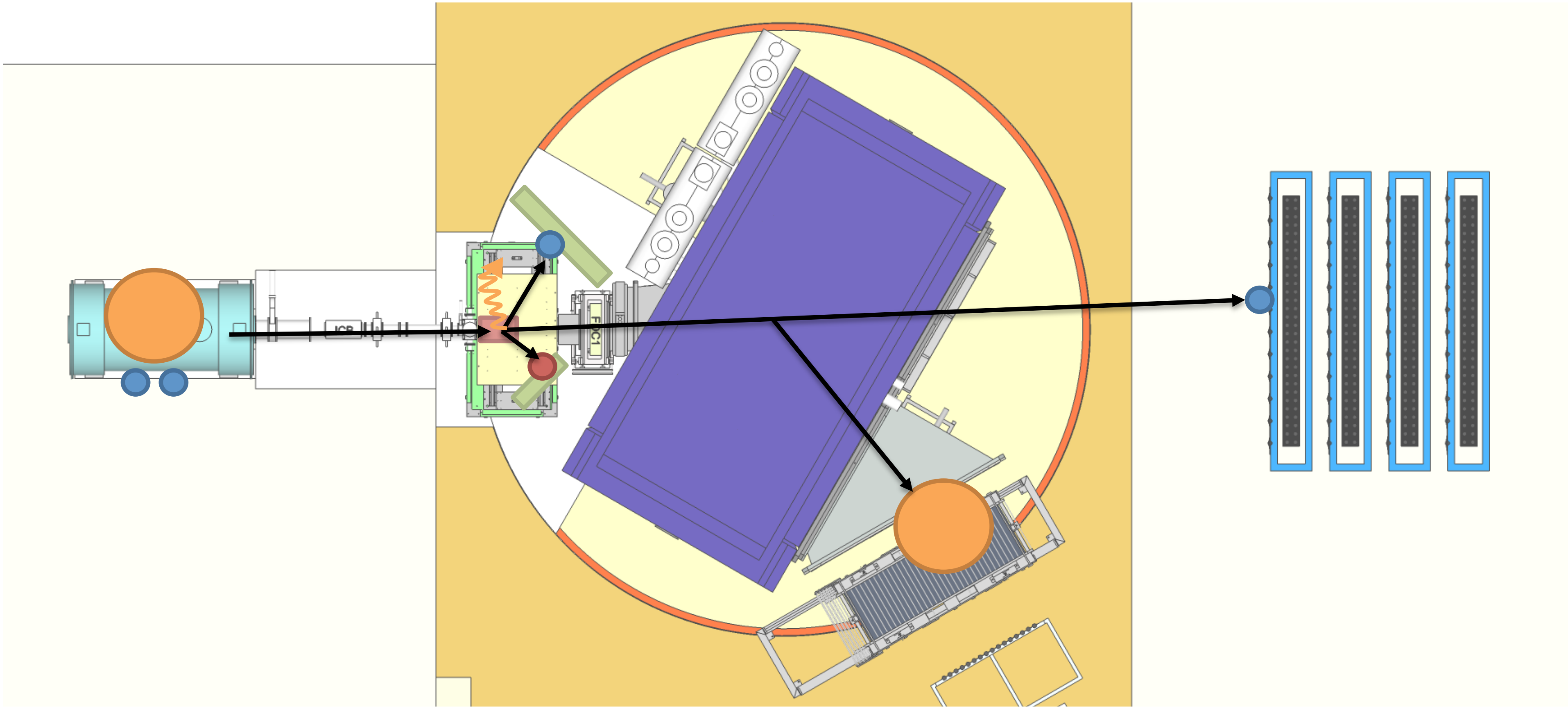
SAMURAI

MINOS
+ DALI2



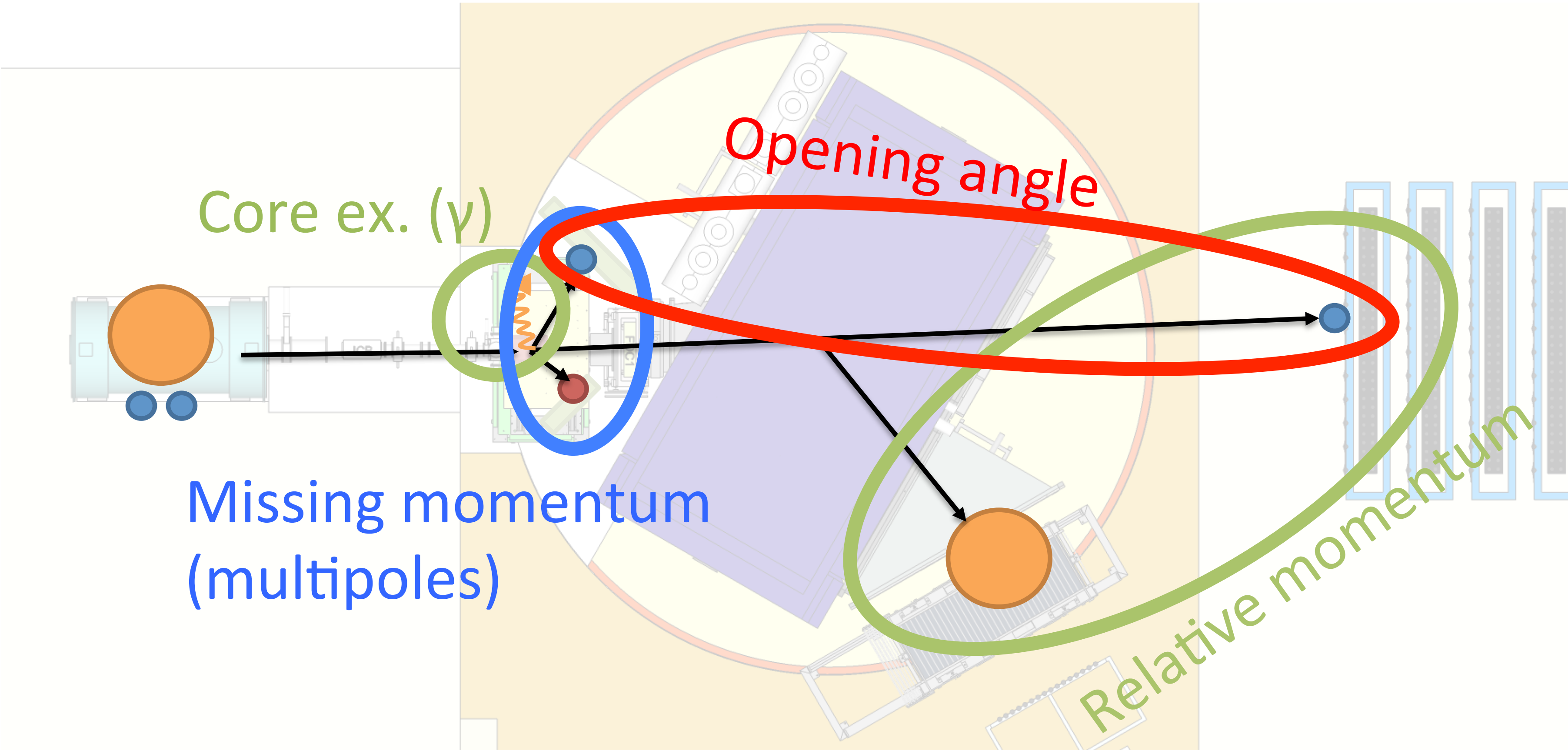
RIBF facility

Experimental setup



Kinematically complete measurement!

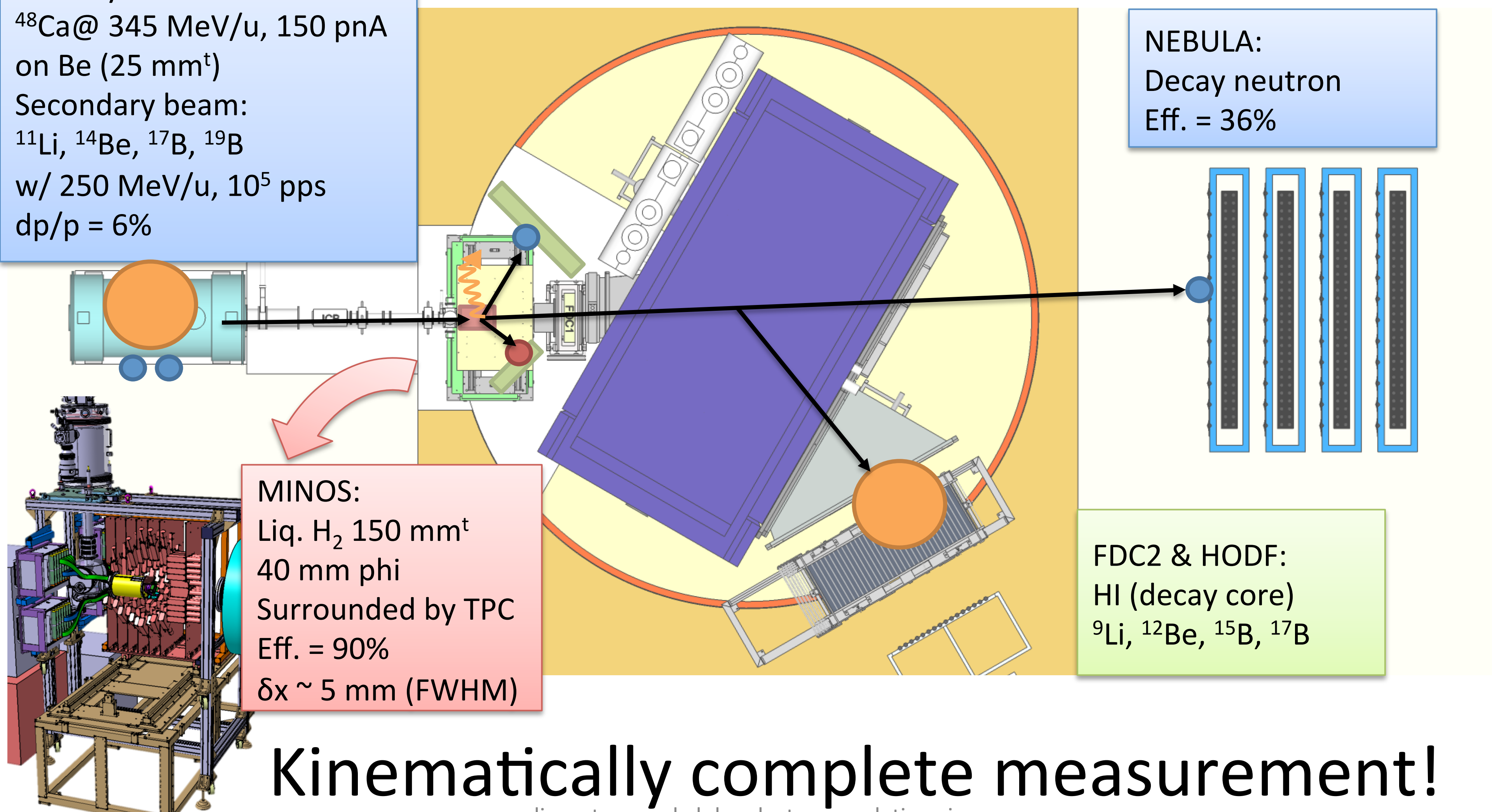
Experimental setup



Kinematically complete measurement!

Experimental setup

Primary beam:
^{48}Ca@ 345 MeV/u, 150 pnA
on Be (25 mm^t)
Secondary beam:
^{11}Li, ^{14}Be, ^{17}B, ^{19}B
w/ 250 MeV/u, 10^5 pps
dp/p = 6%



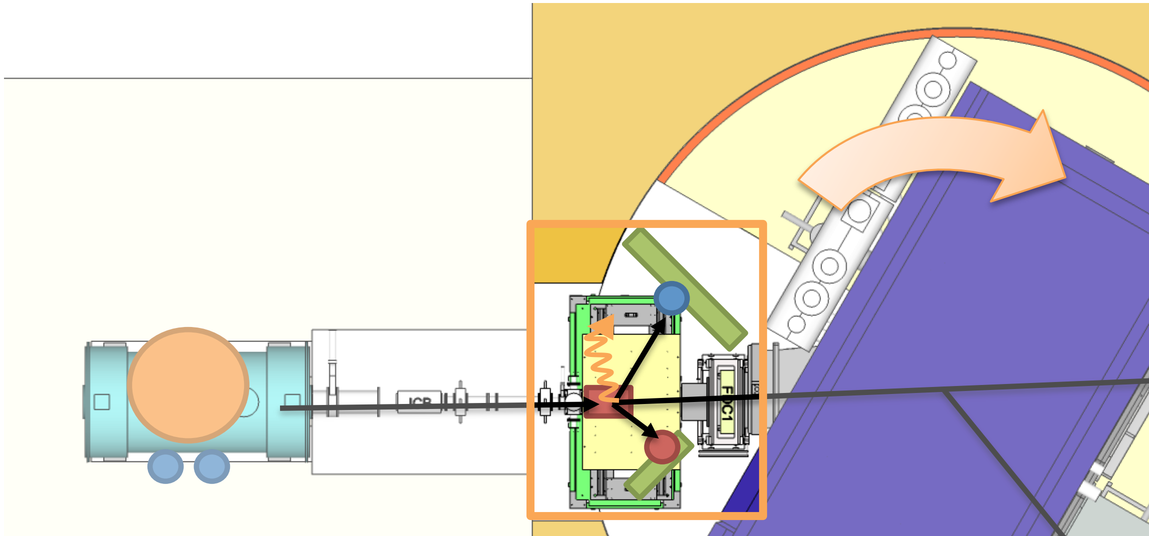
NEBULA:
Decay neutron
Eff. = 36%

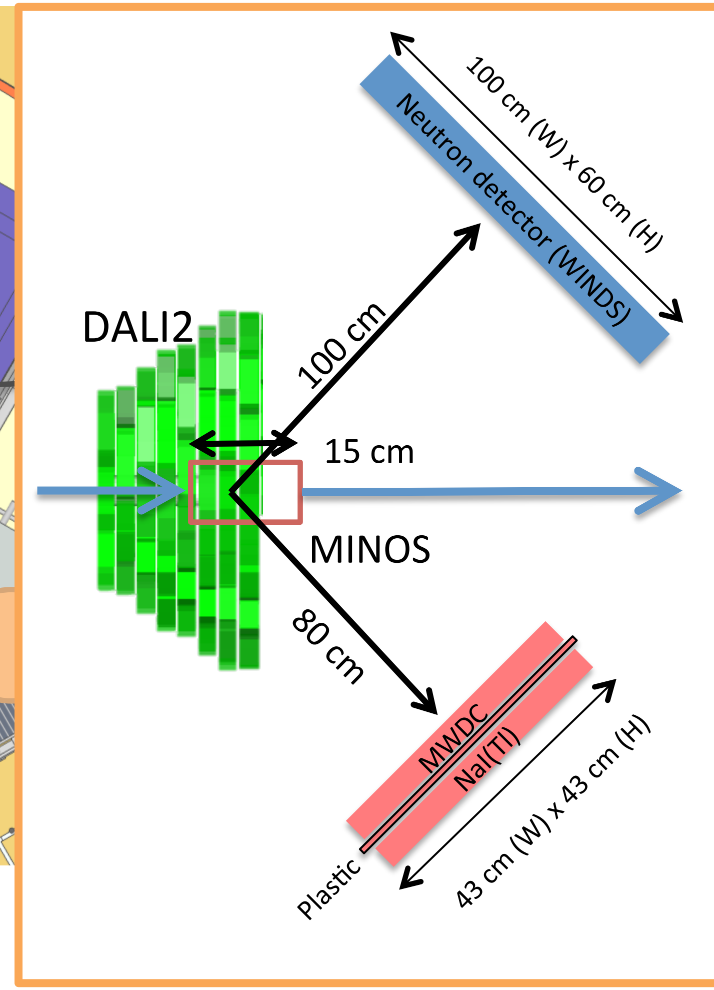
MINOS:
Liq. H_2 150 mm^t
40 mm phi
Surrounded by TPC
Eff. = 90%
δx ~ 5 mm (FWHM)

FDC2 & HODF:
HI (decay core)
^{9}Li, ^{12}Be, ^{15}B, ^{17}B

Kinematically complete measurement!

Experimental setup



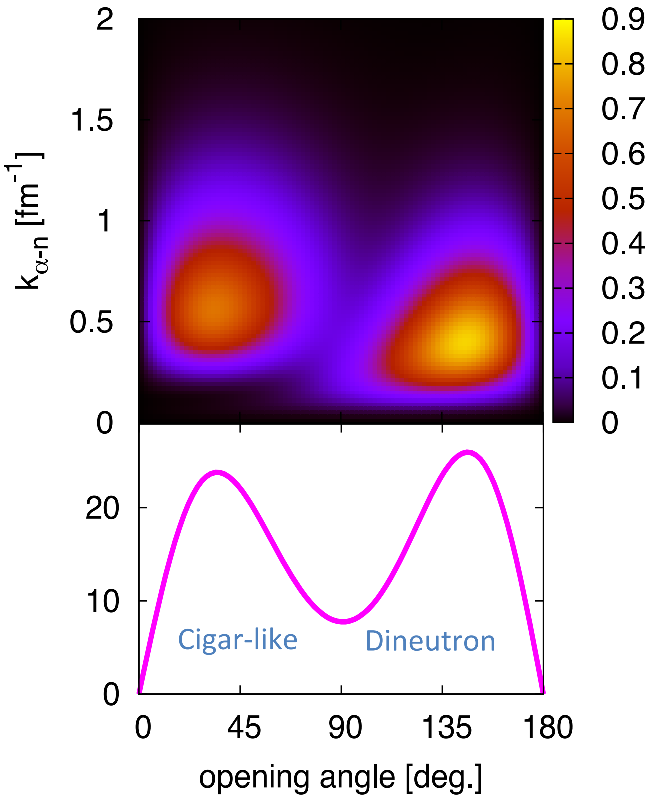


- ✓ Good kinematical region to minimize the FSI
  - θ_n = 25—65°
  - θ_p = 25—65°
- γ-ray detection for backward angle
  - ✓ No interference with p, n detection
  - ✓ Efficiency(2.7 MeV) * Acceptance = 7%
    (GEANT4 simulation)

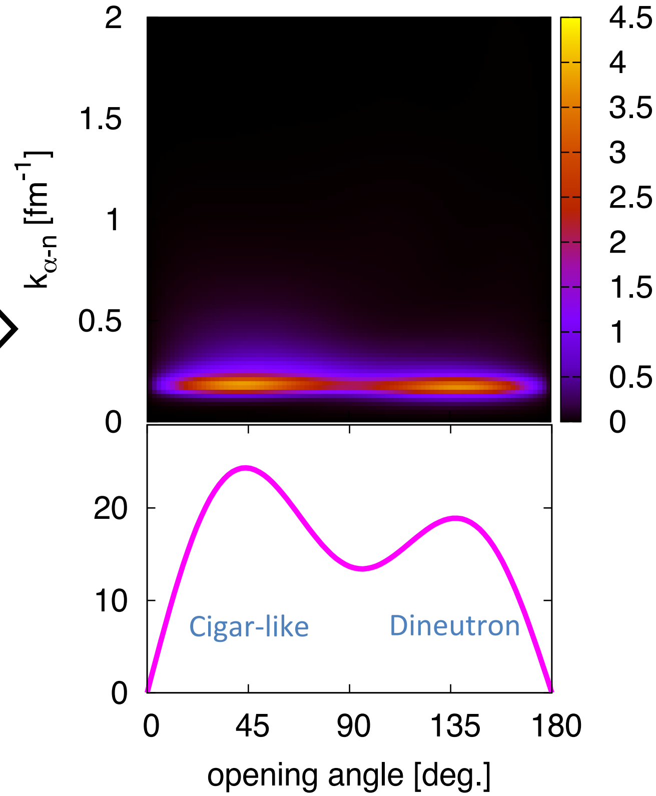
How can the dineutron be observed?

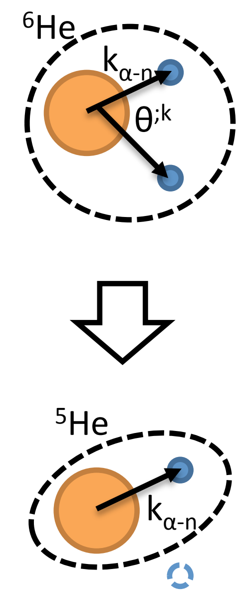
Work done by Y. Kikuchi and K. Ogata

Ground-state (non-observable)



After (p,pn) reaction (observable)



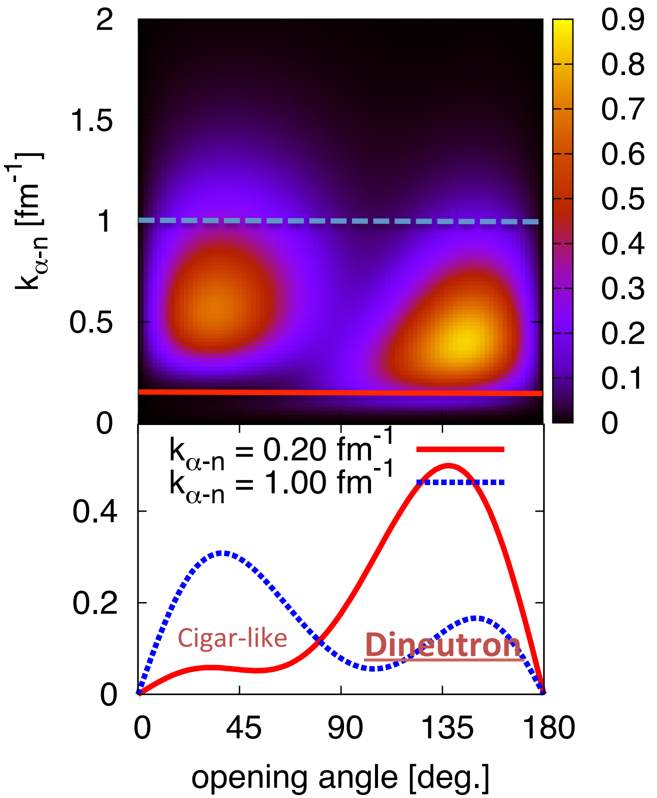


The remaining one FSI effect is large, but …

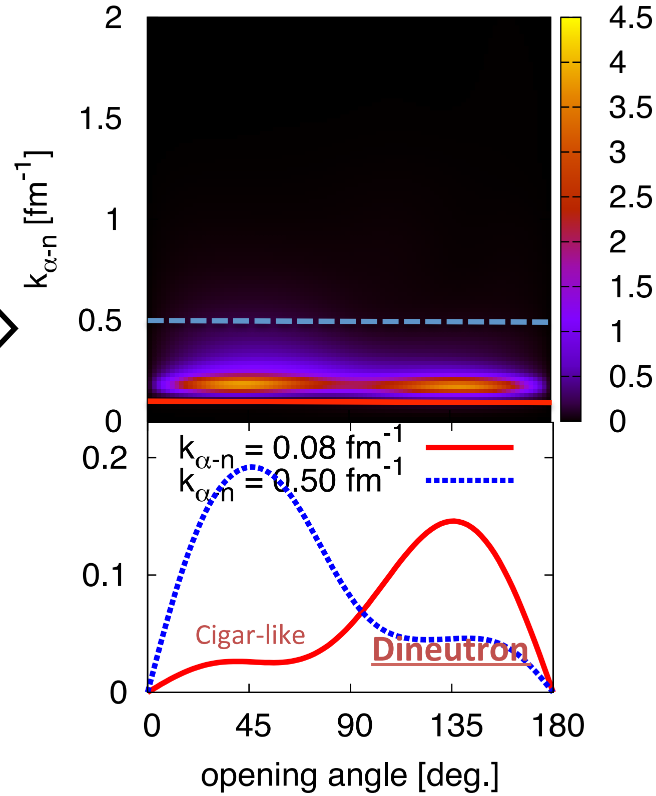
How can the dineutron be observed?

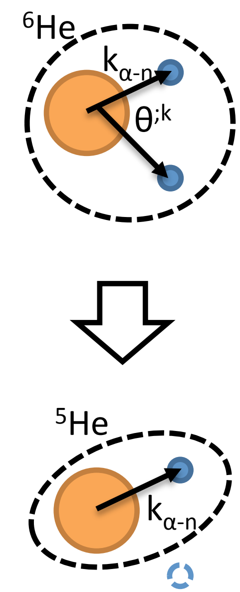
Work done by Y. Kikuchi and K. Ogata

Ground-state (non-observable)



After (p,pn) reaction (observable)





Dineutron component can be extracted.

- Dineutron ←→ Cigar-like
- Coherence is preserved.

Coherence of the wave function

Shell-model basis

$$|\Phi_{\text{g.s.}}\rangle = |\text{Core}\rangle \otimes \Big(\alpha|(s_{1/2})^2\rangle + \beta|(p_{3/2})^2\rangle + \gamma|(d_{5/2})^2\rangle + \cdots\Big) + |\text{Core}^*\rangle \otimes$$

$$\Downarrow$$

$|\alpha|, |\beta|, |\gamma|, \ldots$

Talmi-Moshinsky tr.

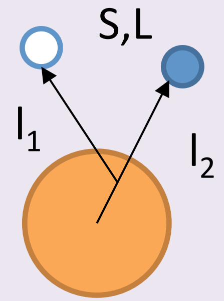
$$\Leftrightarrow$$

Jacobi coordinate

$$= \sum A^{SL}_{l_1 l_2} |SL l_1 l_2\rangle$$

$$\Downarrow$$

$$|A^{SL}_{l_1 l_2}|$$



Spectroscopic factor by (p,pn)

Complete measurement of three particles

"(p,pn)" + "Complete measurement" $\Rightarrow$ $\alpha, \beta, \gamma, \ldots$ $\Rightarrow$ $|\Phi_{\text{g.s.}}\rangle$

(including phase info.)

Summary

- One can see the clustering through
  1. Break
  2. Measure
  3. **Connect**
  4. Represent
- The first case will be demonstrated
  - With quasi-free knockout reaction
  - On Borromean nuclei
  - In combination with MINOS and SAMURAI @RIBF