# ノックアウト反応を用いた中性子過剰核における2中性子相関の実験研究

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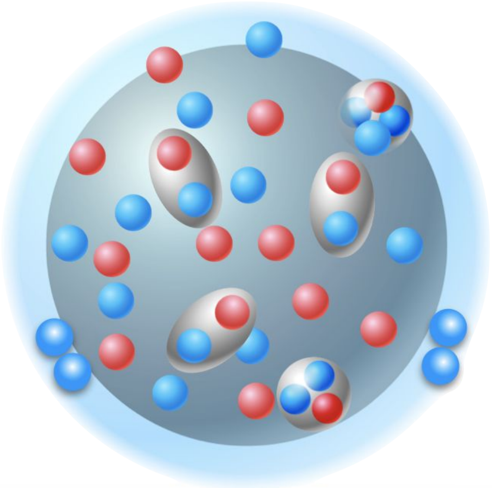


2025-06-05/06　量子もつれと原子核物理学

# Dineutron correlation

Common feature of Fermionic many-body systems: BCS mechanism for stabilization

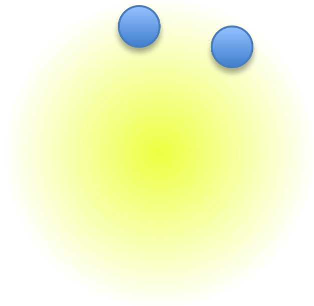
Unique feature of atomic nuclei: possible appearance of *dineutron correlation*

Dineutron = Hypothetical bound state of two neutrons

A. B. Migdal, Soviet J. of Nucl. Phys. **16**, 238 (1973).

Two neutrons in vacuum

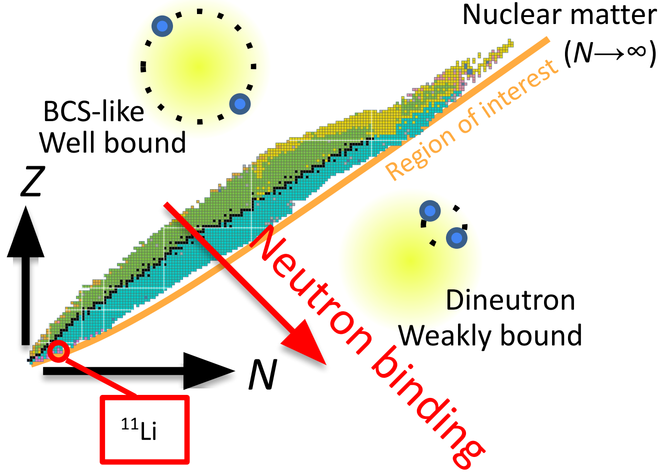
➔ No bound state



In a certain potential, two neutrons have a resonance with almost zero energy

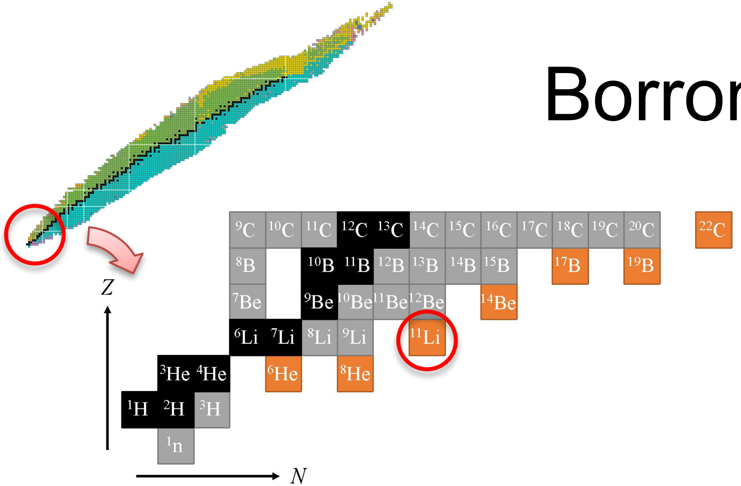
➔ Additional bound state

➔ This circumstance is realized on the surface of neutron drip-line nuclei



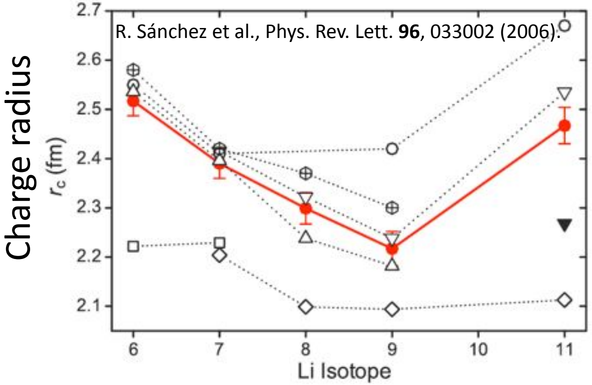

How does it evolve in response to a change of the system?

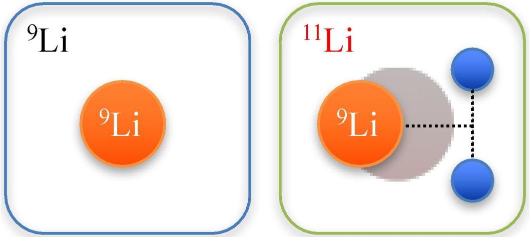
# Borromean nucleus $^{11}$Li




- Borromean nature.
  - ⟶ Binding mechanism.
- Large matter radius. (A~20)
  - ⟶ Neutron halo structure.
- Small two-neutron separation energy.
  - ⟶ Loosely-bound three-body system.
- Comparable contribution of *s*- and *p*-orbits.
  - ⟶ Large admixture of different parity states.
- Rapid increase of charge radius.
  - ⟶ Recoil of the $^{9}$Li core.

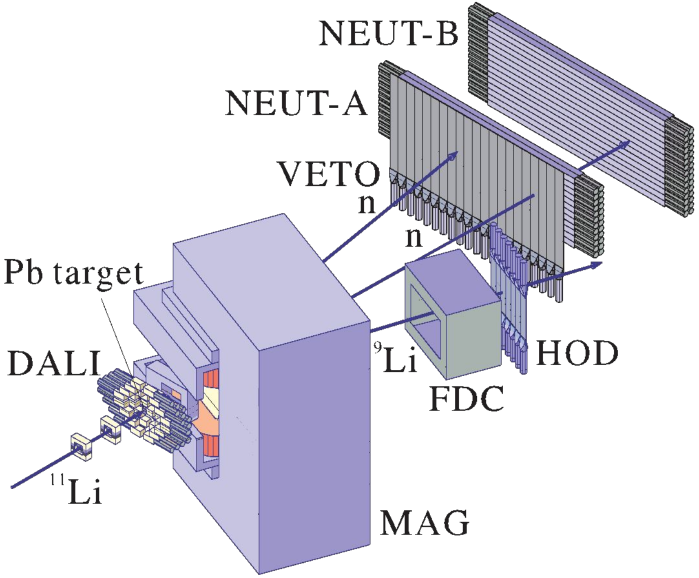
## $^{11}$Li is a benchmarking system

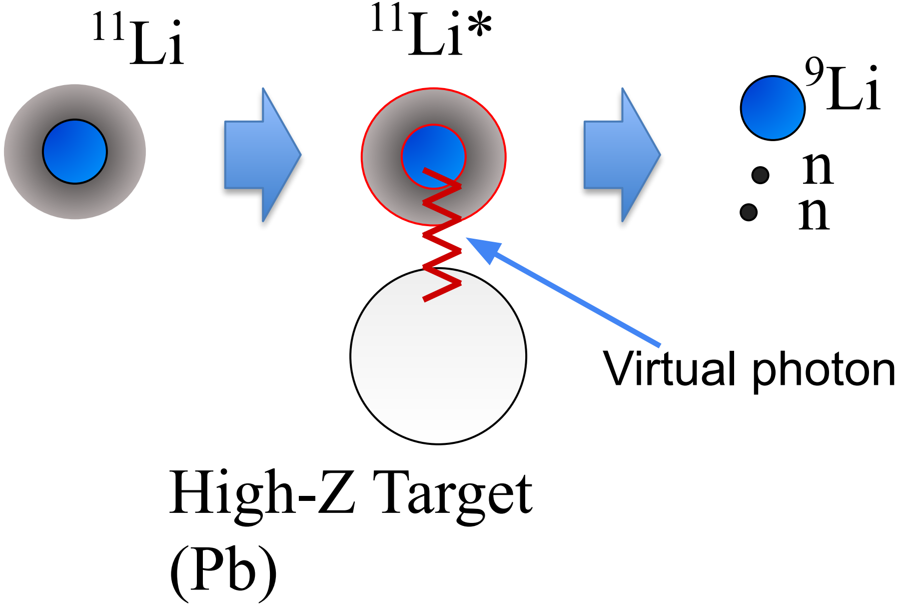



# Studies on $^{11}$Li using nuclear reactions
# 1) $B(E1)$ measurement

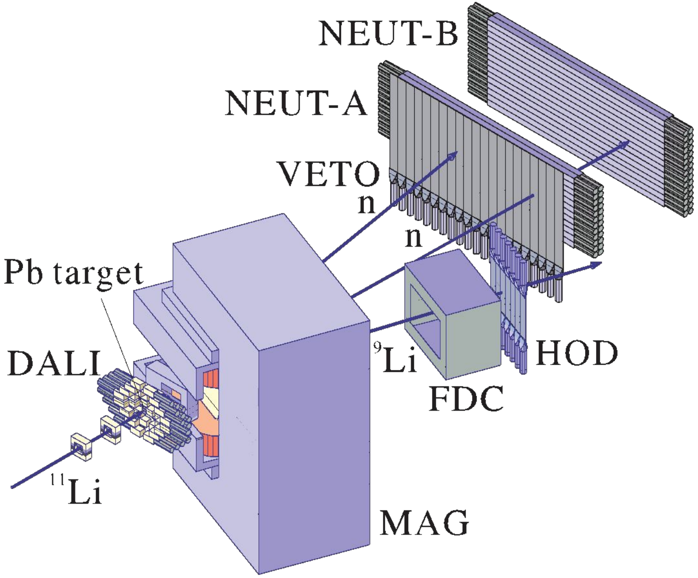
Coulomb dissociation at 70 MeV/u

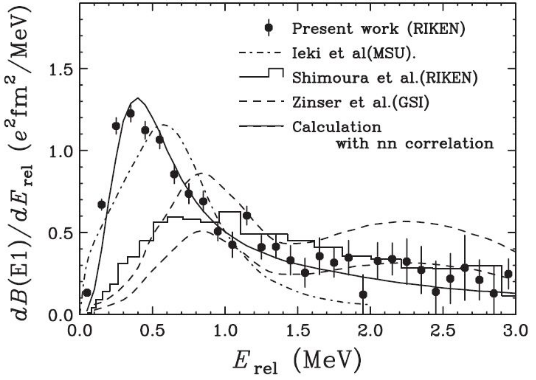


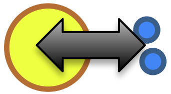
# Studies on $^{11}$Li using nuclear reactions
# 1) *B*(*E*1) measurement

Coulomb dissociation at 70 MeV/u




T. Nakamura et al., Phys. Rev. Lett. **96**, 252502 (2006).

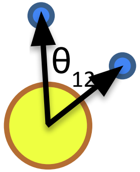


*E*1 cluster sum rule (based on 3-body model)

$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r_1^2 + r_2^2 + 2\boldsymbol{r_1}\cdot\boldsymbol{r_2}\rangle = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \langle r_{c,2n}^2\rangle,$$

$$\rightarrow \langle\theta_{12}\rangle = 48^{+14}_{-18} \text{ degrees}$$

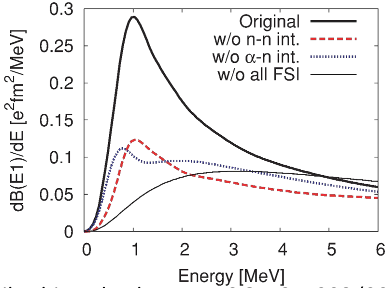
c.f. No correlation □ $\theta_{12}$ = 90 deg.



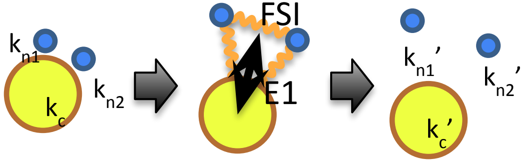

Strong dineutron correlation is suggested.

# Studies on $^{11}$Li using nuclear reactions
# 1) $B(E1)$ measurement

## Argument 1: Final-state interactions (FSIs)




Y. Kikuchi et al., Phys. Rev. C **81**, 044308 (2010).



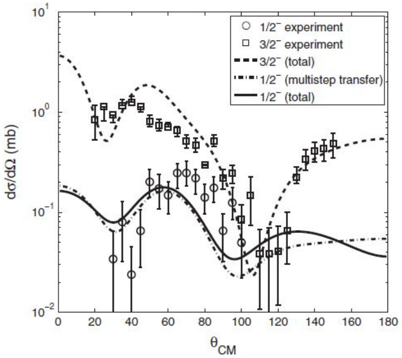

Initial　　Transient region　　Asymptotic

Spectrum is largely distorted by the FSI.

➔ Possible uncertainty in the derivation of the $B(E1)$ value.

Observation = Structure × Reaction (probe)

## Argument 2: Core excitation




G. Potel et al., Phys. Rev. Lett. **105** (2010).

$^{9}$Li core in $^{11}$Li ground state is not inert.

– c.f. α core in $^{6}$He.

*E*1 sum rule value is reduced by ~15%.

T. Myo et al., Prog. Theor. Phys. **119**, 561 (2008).
Y. Kikuchi et al., Phys. Rev. C **87**, 034606 (2013).

$$\langle\theta_{12}\rangle = 48^{+14}_{-18}\ \text{degrees}$$

→ ~ 65±11 degrees

→ Large model dependence

## Argument 3: Derivation of <$r_n$>

$$B(E1) = \frac{3}{4\pi}\left(\frac{Z_c}{A}\right)^2 e^2\langle r_n^2 + r_{n'}^2 + 2r_n r_{n'}\cos\theta_{nn'}\rangle,$$
$$\simeq \frac{3}{2\pi}\left(\frac{Z_c}{A}\right)^2 e^2\langle r_n^2\rangle[1+\langle\cos\theta_{nn}\rangle],$$

- Both <$r_n$> and <$\theta_{nn}$> were determined from a single meas.
- Simplified model.

→ Use of different data

- Matter radius
  → $\theta = 56.2^{+17.8}_{-21.3}$ degrees

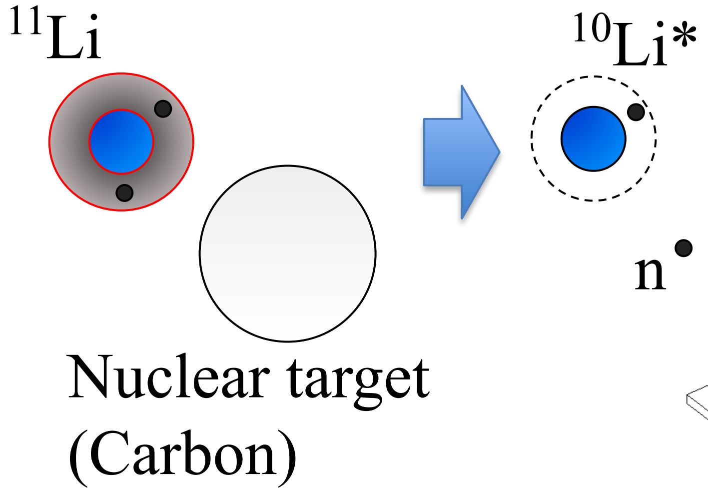
K. Hagino et al., Few-body Syst. **57**, 185 (2016).

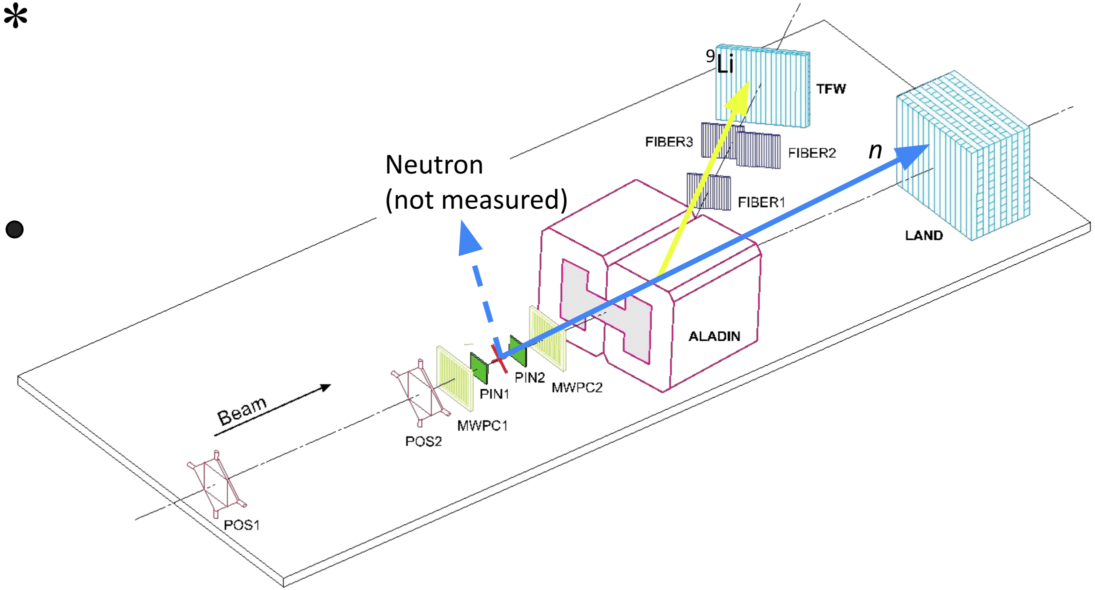
- Two-*n*. correlation function
  → $\theta = 66^{+22}_{-18}$ degrees

C.A. Bertulani et al., Phys. Rev. C **76**, 051602(R) (2007).

# Studies on $^{11}$Li using nuclear reactions
# 2) Momentum distribution

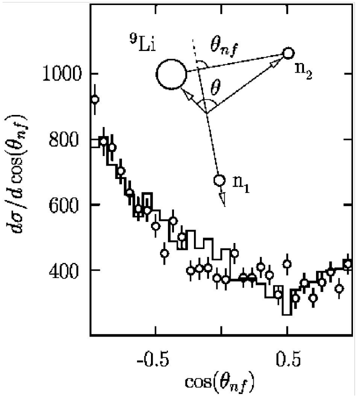
Neutron removal at 264 MeV/u w/ nuclear target



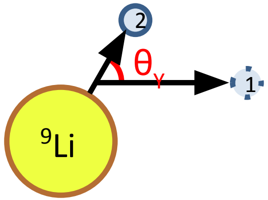
# Studies on $^{11}$Li using nuclear reactions
# 2) Momentum distribution

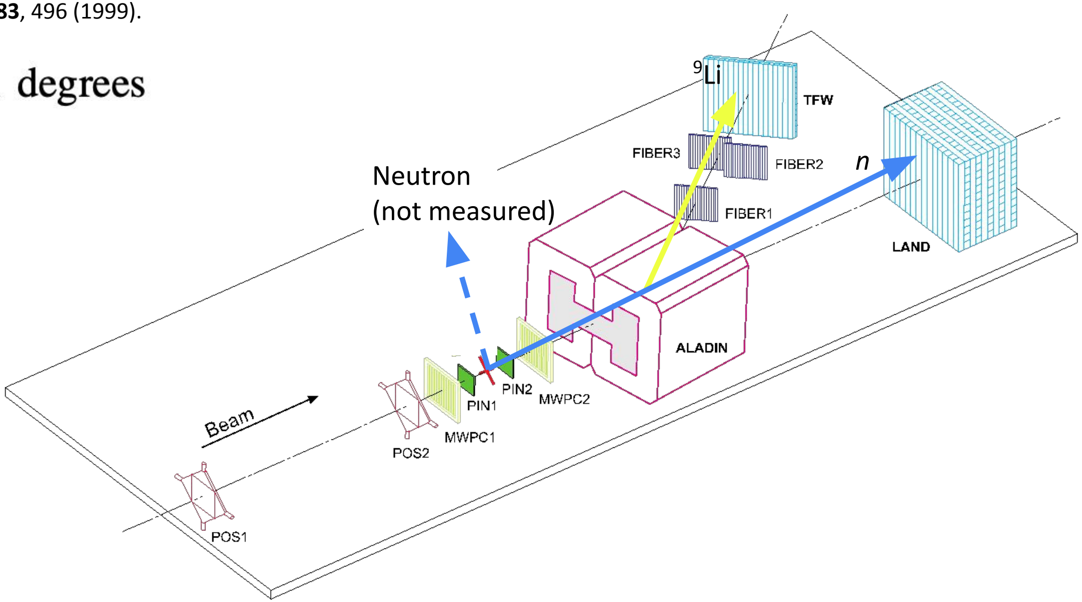
Neutron removal at 264 MeV/u w/ nuclear target




H. Simon et al., Phys. Rev. Lett. **83**, 496 (1999).

$$\langle \theta_Y^x \rangle = 76.6 \pm 2.1 \text{ degrees}$$



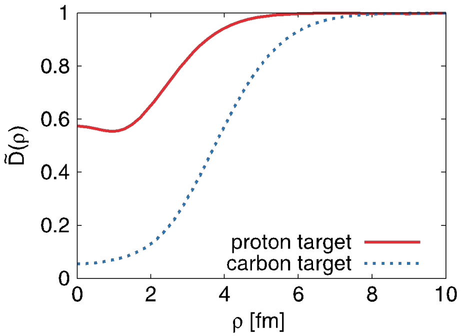




- $(s_{1/2})^2 : (p_{1/2})^2 = 45{\pm}10 : 55{\pm}10$
- Asymmetric angular distribution
  
  → Dineutron enhancement

# Studies on $^{11}$Li using nuclear reactions
# 2) Momentum distribution

**Argument 1: Peripherality**

Distortion effect in the neutron removal reaction from $^{6}$He

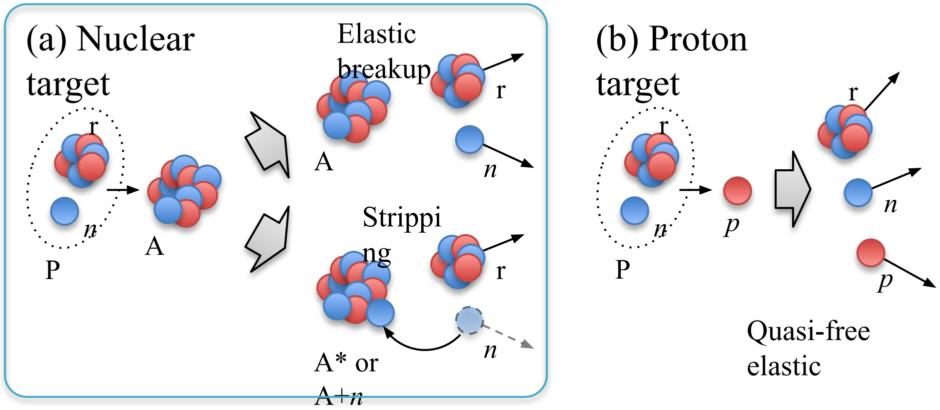



Y. Kikuchi et al., Prog. Theor. Exp. Phys. **2016** 103D03 (2016).

Strong distortion from the target

➔ Nuclear-target-induced knockout is only sensitive to the nuclear surface.

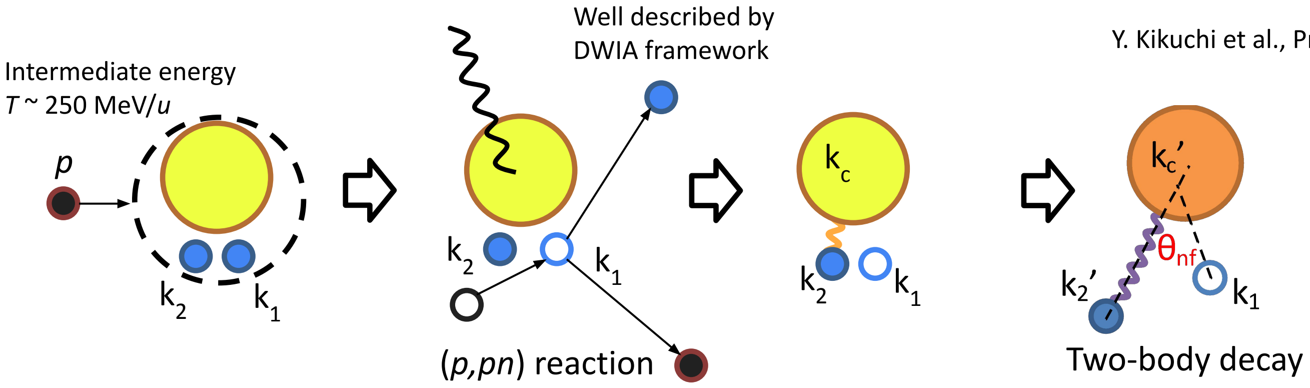
**Argument 2: Complicated reaction mechanism**



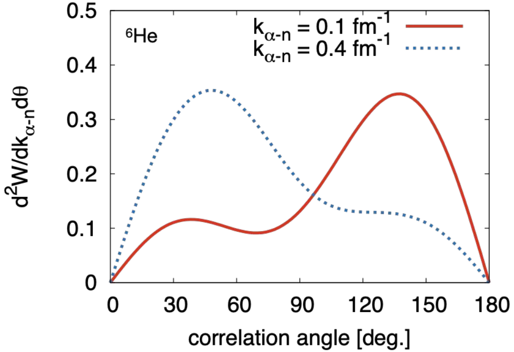

Two competitive processes having complicated formalisms.

- Elastic breakup
    - CDCC, ADS, Faddeev—AGS
- Stripping
    - Glauber model based on Eikonal reaction theory

# Key idea: quasi-free (*p,pn*) on Borromean nuclei




Y. Kikuchi et al., Prog. Theor. Exp. Phys. **2016** 103D03 (2016).




- ☺ Ground state correlation.
  - Minimization of the FSIs.
- ☺ Kinematically complete measurement.
  - Missing momentum $k_1$
  (measure of the radial position of the dineutron)
- ☺ Transparent probe.
- ☹ High luminosity is needed.

- Pioneering experiment at GSI.
  - Yu. Aksyutina et al., Phys. Rev. B **666**, 430 (2008).
  - Angular correlation is not shown.
    - Probably due to a low luminosity.

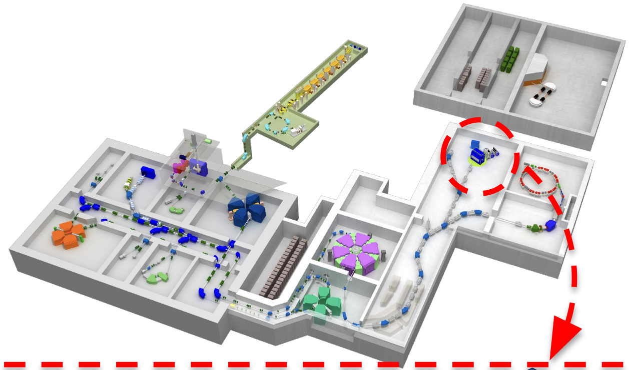
Table 2.1: Integrated cross sections of different reactions on $^{11}$Li.

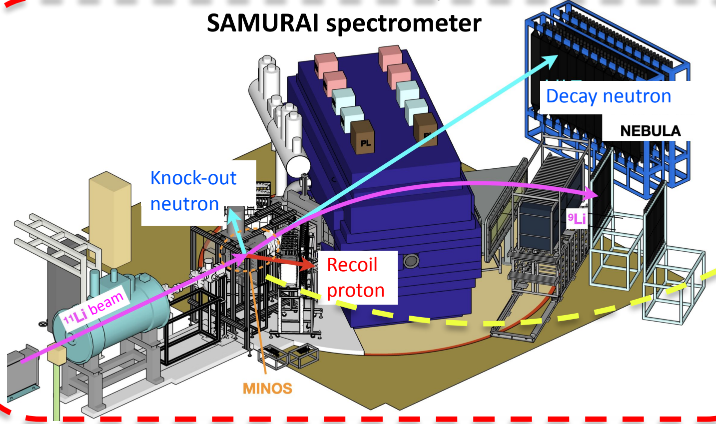
| Reaction | Energy [MeV/nucleon] | Integrated cross section $\sigma$ [b] for $E_{rel} \leq 3$ MeV | for $E_{rel} \leq 6$ MeV |
|---|---|---|---|
| Coulomb breakup [40] | 70 | $2.34 \pm 0.05$(stat) $\pm 0.28$(syst) | (not given) |
| Neutron removal [61] | 264 | $0.15^a$ | (not given) |
| Quasi-free $(p, pn)$ [64] | 280 | $0.035^a$ | $0.041^a$ |

x 1/10 (Coulomb breakup → Neutron removal)
x 1/10 (Neutron removal → Quasi-free $(p, pn)$)

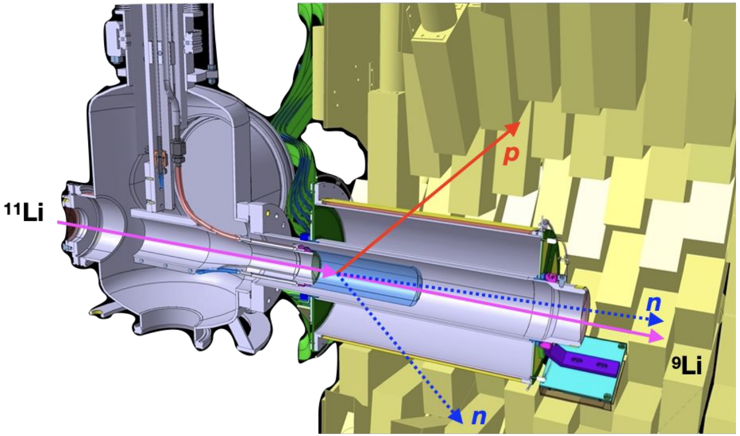
# RIBF×MINOS: highest luminosity in RIB experiments

RIBF: most intense $^{11}$Li beam





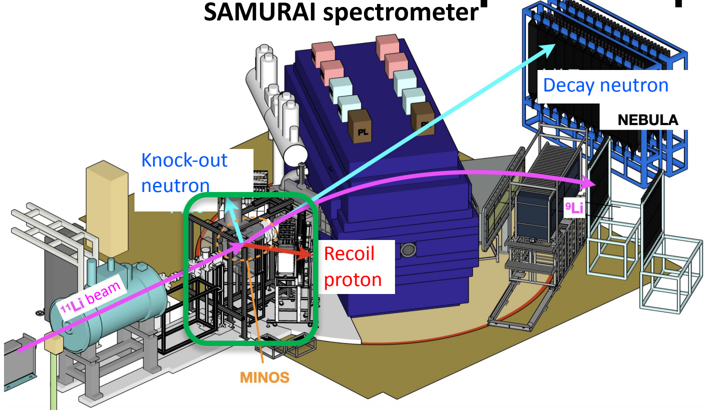

MINOS: mean-free path proton target




- 15-cm-thick liquid hydrogen target
- Tracking ⟶ vertex reconstruction

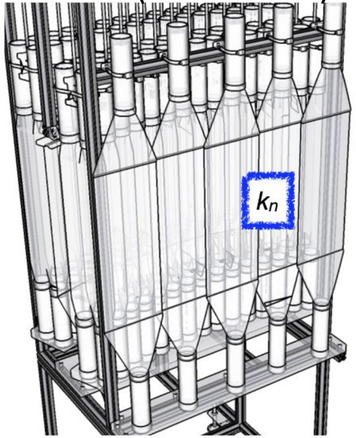
Highest luminosity in RIB experiments: $10^{29}$ cm$^{-2}$ s$^{-1}$

# Dedicated setup for quasi-free (*p*,*pn*) measurement

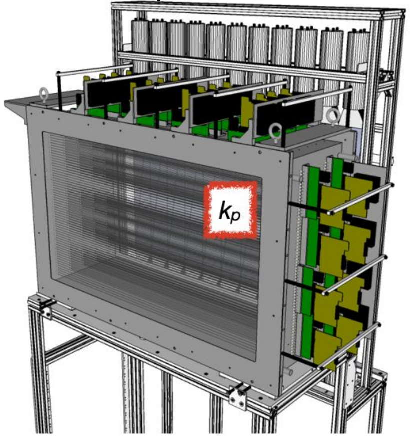


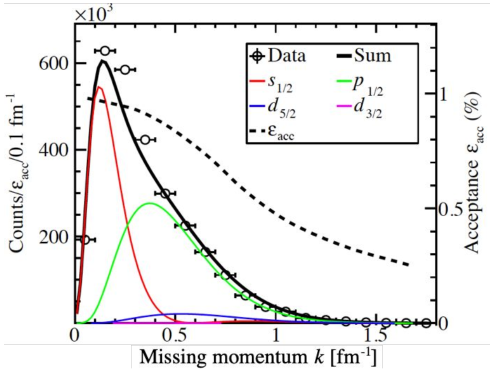

- Kinematically "too" complete measurement
  - $k = k_n + k_p - k_{\text{beam}}/A$
  - Quasi-free condition

WINDS (KO neutron)

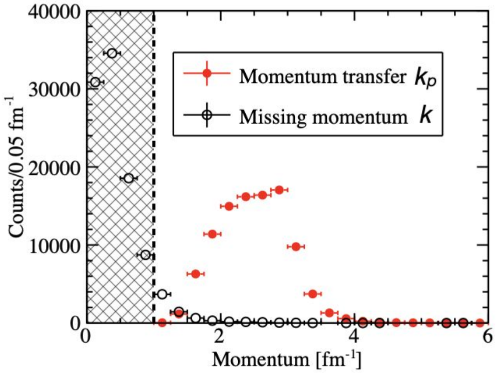



Recoil proton detector



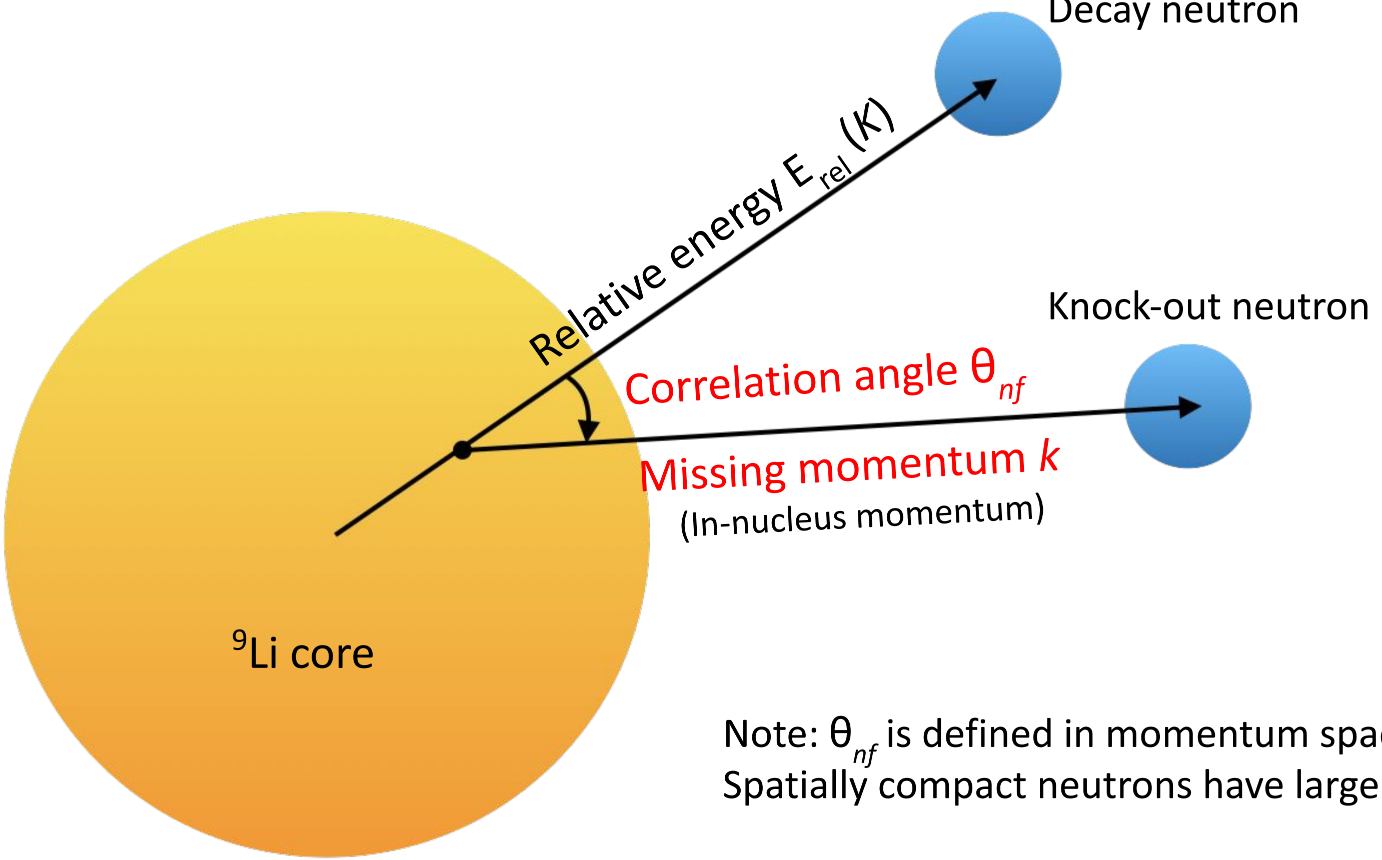




→ Reliable determination of ℓ, radial position of dineutron

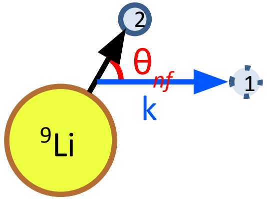



→ Verification of quasi-free picture

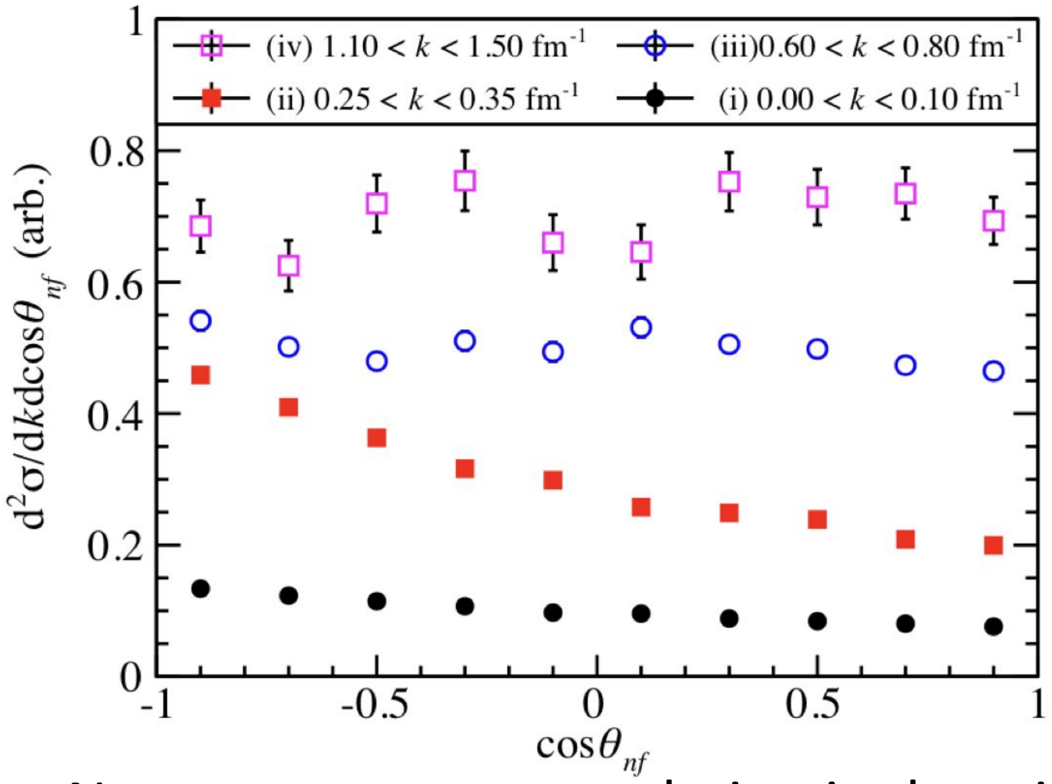
# Correlation angle: measure of the dineutron strength

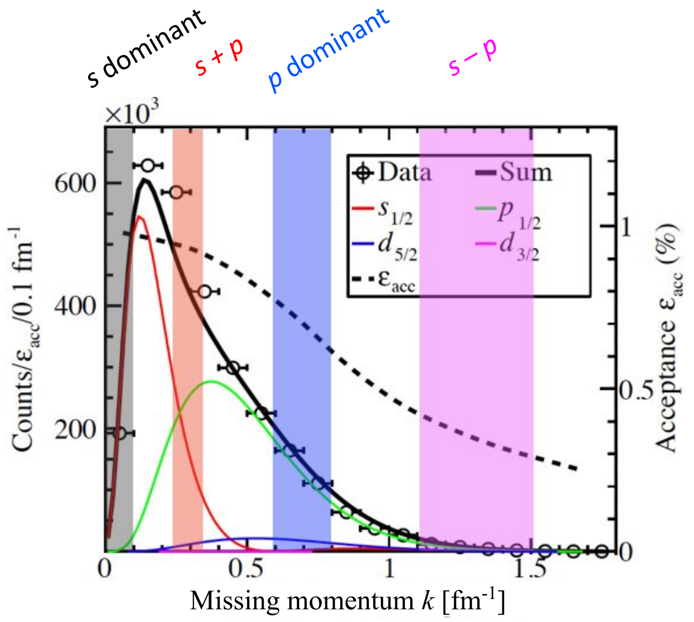



Note: $\theta_{nf}$ is defined in momentum space:
Spatially compact neutrons have large correlation angle.



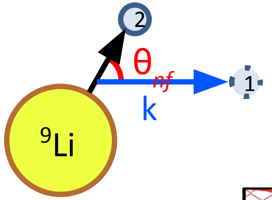

# Correlation angle $\theta_{nf}$ (dineutron strength) depends on missing momentum $k$ (radial position of dineutron)



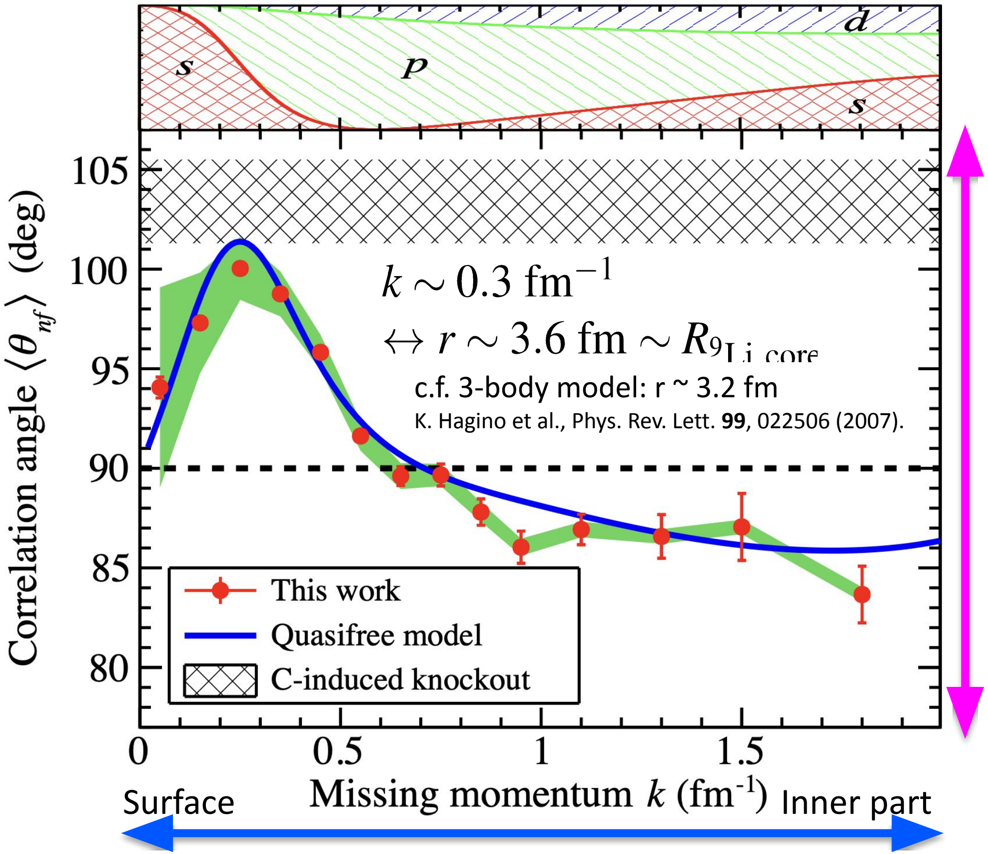



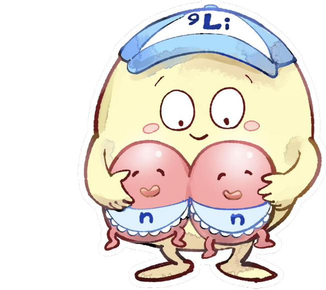

Neutron-neutron correlation is changing from region to to region!

YK et al., Phys. Rev. Lett. **125**, 252501 (2020).




# Surface localization of dineutron in $^{11}$Li

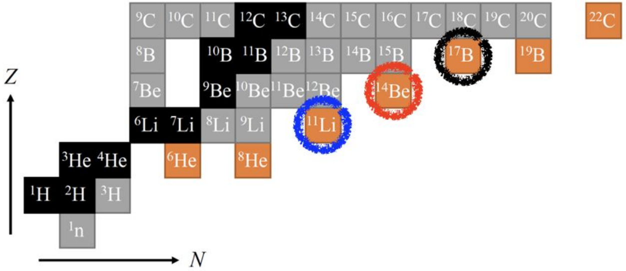



Dineutron formation

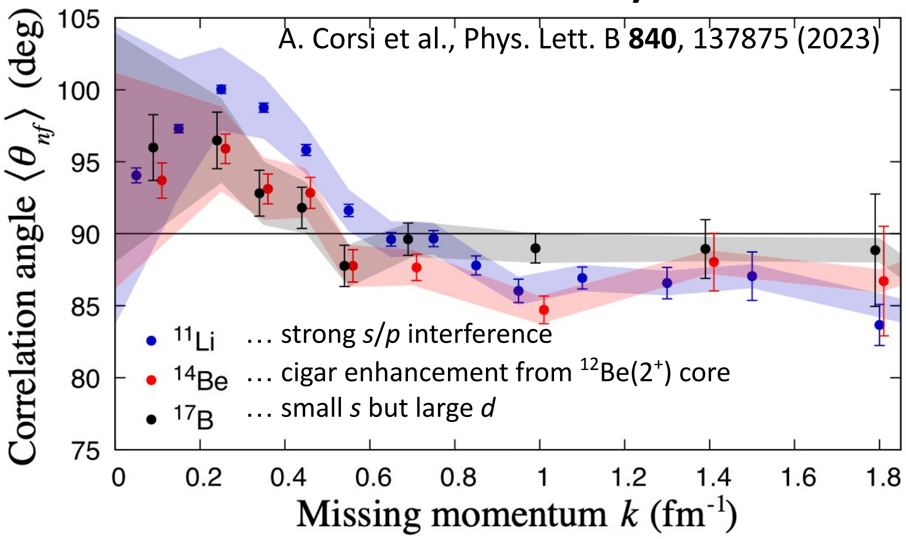
No correlation


Back-to-back (cigar-like)



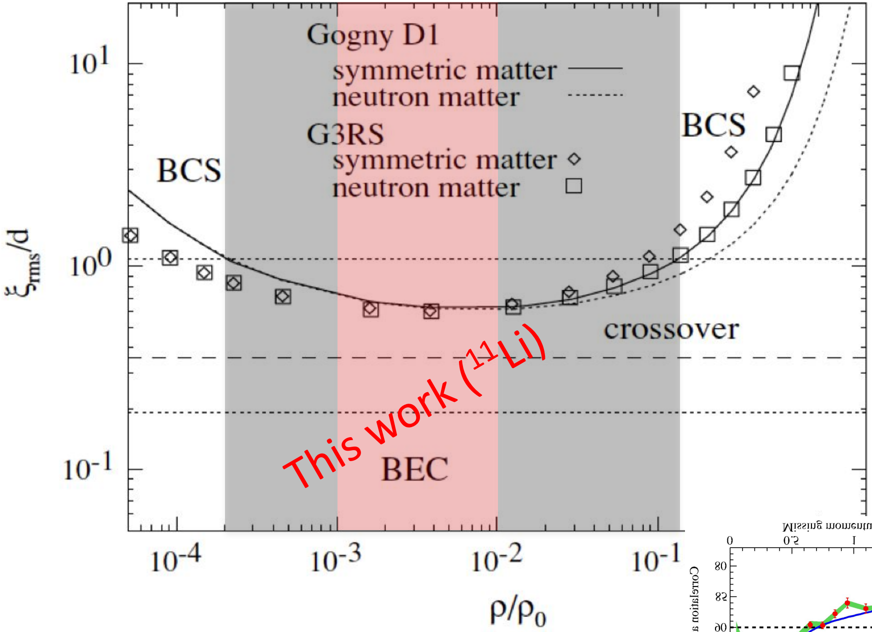

# Universality of the dineutron

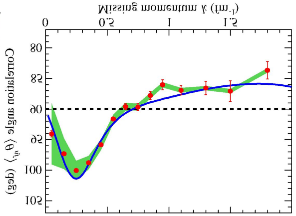
## In other finite systems




## Nuclear matter theory

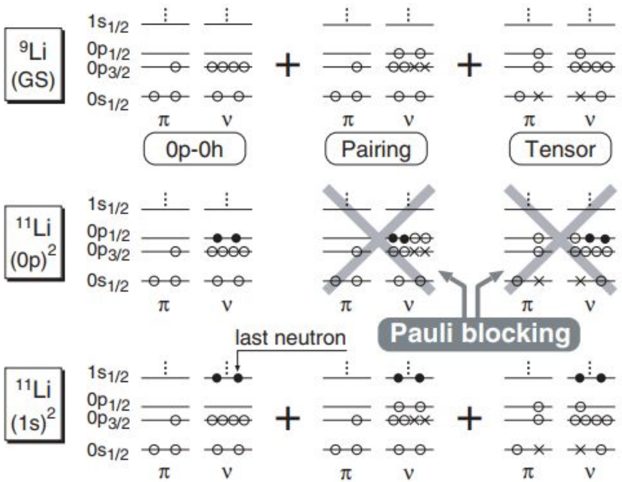
M. Matsuo, Phys. Rev. C **73**, 044309 (2006).



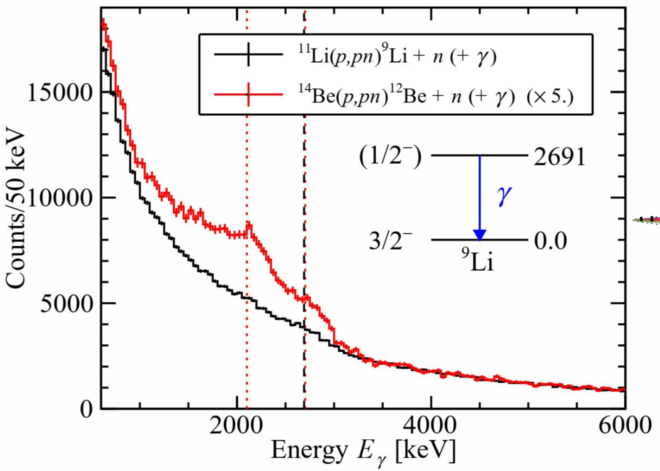
Surface localization is the common feature.

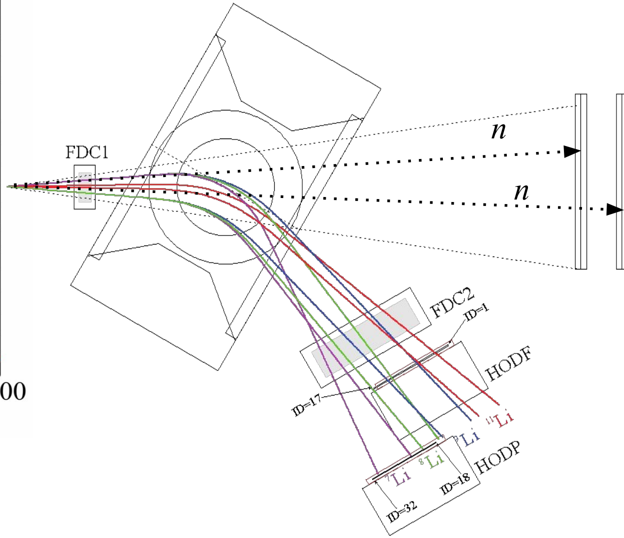
# Investigation of the $^{9}$Li core excitation




T. Myo et al., Phys. Rev. C **76**, 024305 (2007).

No signature in $^{9}$Li+$n$ channel




$^{11}$Li($p$,$pn$)$^{10}$Li ⟶ $^{9}$Li (+γ) + $n$

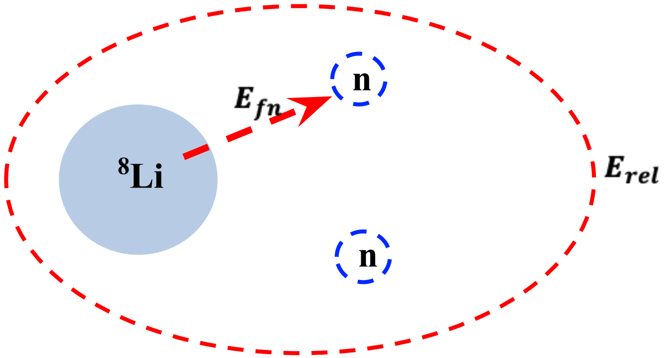
$^{8}$Li (+γ) + $n$ + $n$

$^{7}$Li (+γ) + $n$ + $n$ + $n$

…

Courtesy of Y. Li

# Direct decay or sequential decay?




Preliminary

counts

Preliminary

Preliminary

***Direct decay***

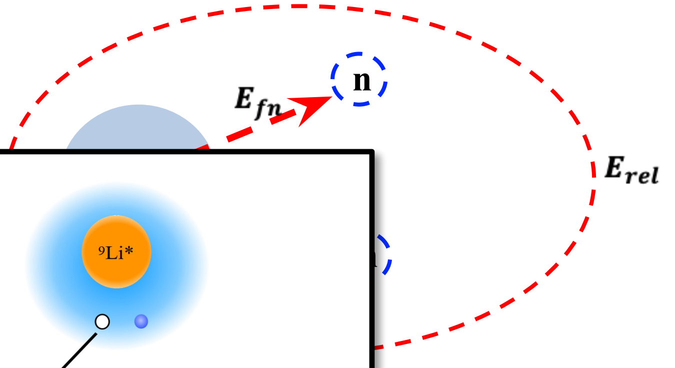
$\varepsilon_{fn} = E_{fn}/E_{rel}$

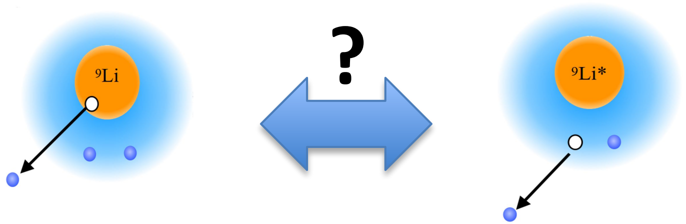
***Sequential decay***

$\varepsilon_{fn} = E_{fn}/E_{rel}$

Courtesy of Y. Li

# Direct decay or sequential decay?




Core knockout
+ 2*n* decay

Delayed *n* emission
from excited core

Interpretation has not yet finalized

Preliminary

Preliminary

*Direct decay*

$\varepsilon_{fn} = E_{fn}/E_{rel}$

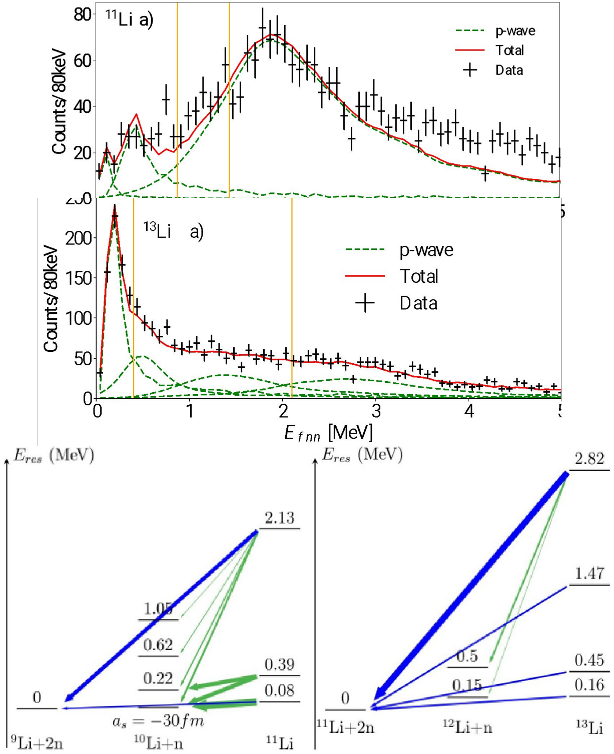
*Sequential decay*

$\varepsilon_{fn} = E_{fn}/E_{rel}$

# Neutron-neutron correlation **not** in g.s.

$^{12,14}$Be($p$,2$p$) → { $^{11}$Li*: sequential decay; $^{13}$Li*: direct decay

P. André et al., PLB **857**, 138977 (2024).

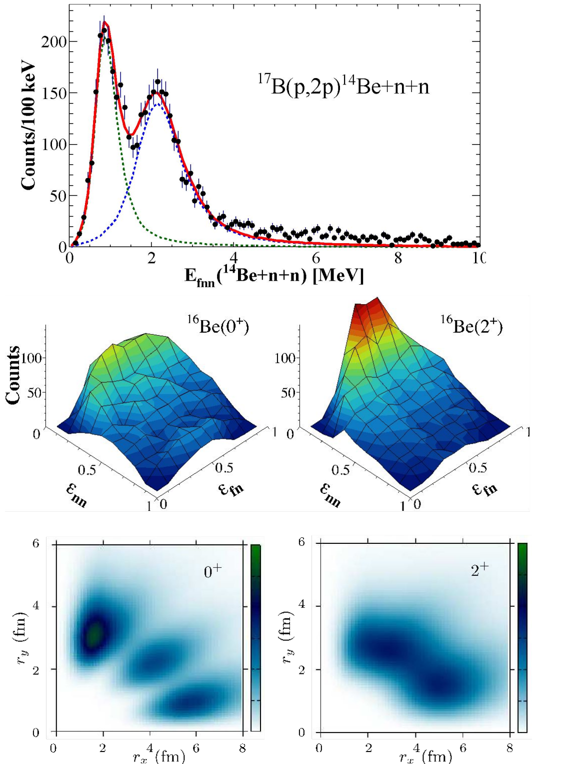



$^{11}$Li($p$,2$p$) → $^{10}$He*: three-body $s$-wave resonance?

Y.L. Sun et al., submitted.

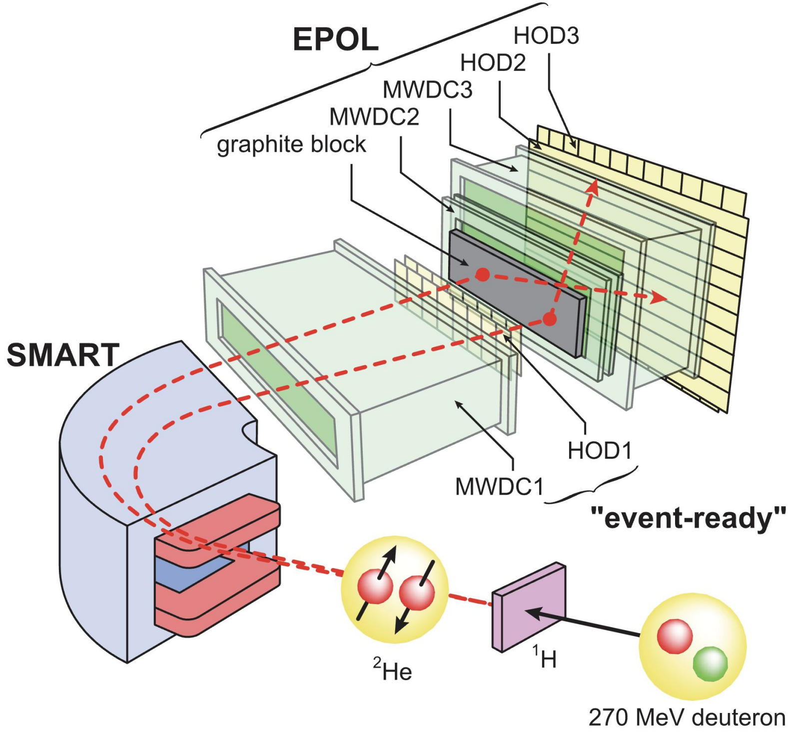
$^{17}$B($p$,2$p$) →$^{16}$Be* { $0^+$: compact dineutron; $2^+$: diffuse distribution

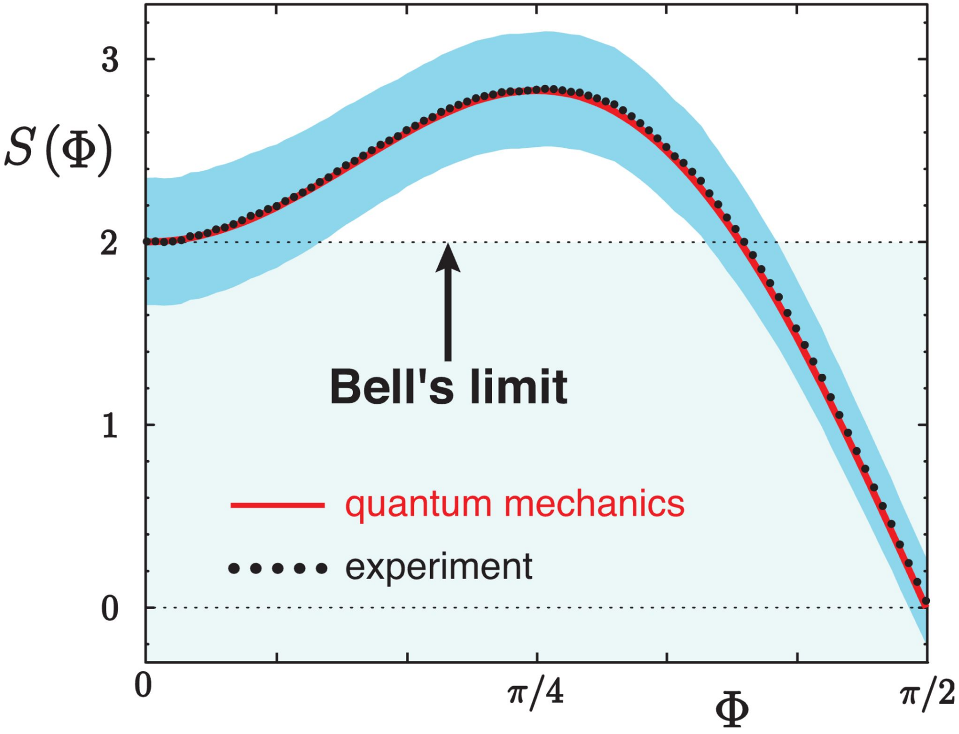
B. Monteagudo et al., PRL **132**, 082501 (2024).



# Can we measure neutron spins?

**“Spin Correlations of Strongly Interacting Massive Fermion Pairs as a Test of Bell's Inequality”**
H. Sakai et al., PLR **97**, 150405 (2006).



# Can we measure neutron spins? → Yes, but challenging

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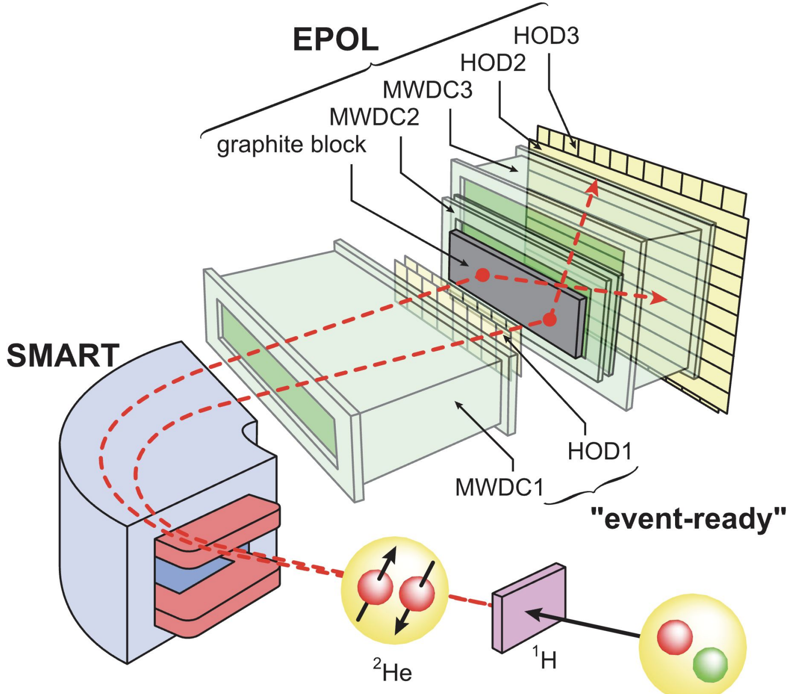
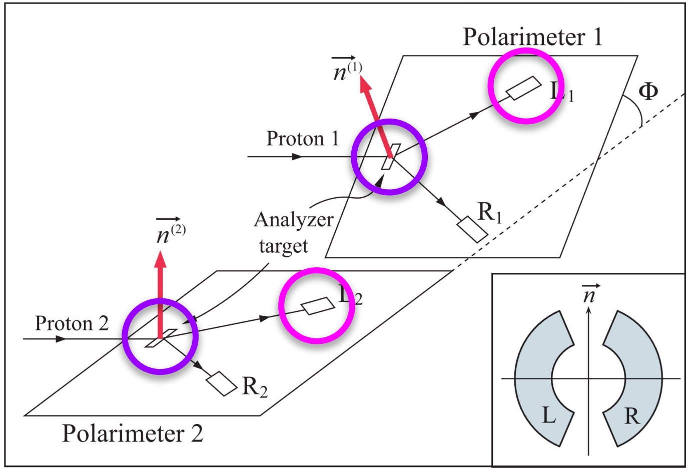
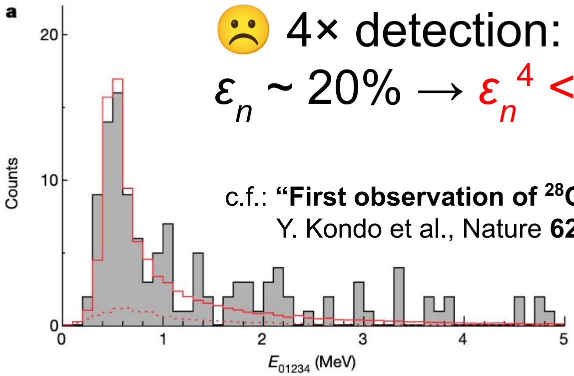



☹️ 4× detection:

$\varepsilon_n$ ~ 20% → $\varepsilon_n^4$ < 0.02%




c.f.: **“First observation of $^{28}$O”**
Y. Kondo et al., Nature **620**, 965 (2023).

# Summary

- Neutron-neutron correlation is investigated via the quasi-free knockout reactions.
- Dineutron universality in neutron-rich Borromean nuclei $^{11}$Li, $^{14}$Be, and $^{17}$B.
  - Localization of dineutron around the nuclear surface.
  - $^{10}$Li → $^{8}$Li + 2*n* channel is being analyzed for understanding $^{9}$Li core excitation in $^{11}$Li.
- Neutron-neutron correlation not in the ground states is being analyzed.
  - $^{11,13}$Li*: different decay scheme
  - $^{10}$He*: three-body *s*-wave resonance?
  - $^{16}$Be*: compact/diffuse dineutron
- Neutron spin measurement is possible, but challenging.