Clustering away from stability using quasifree knockout reactions

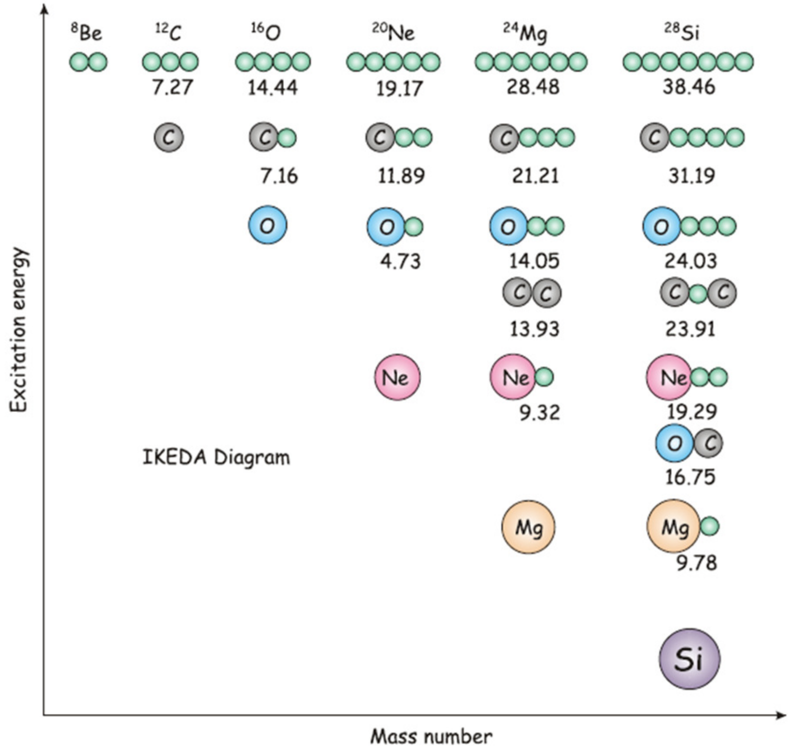
D.Beaumel
IJCLab, Orsay

- Introduction
  - Ikeda and beyond
  - Clustering in neutron rich nuclei towards the dripline
  - Beyond alpha clustering
- Cluster Knockout reactions
- First results on neutron-rich Be isotopes
  alpha clustering vs triton clustering
- Neutral clusters : recent results on tetraneutron and outlooks

2nd rencontre PhyNuBE : Clustering and Symmetries in nuclear physics
Aussois, March 27-31, 2023

Clustering in light nuclei

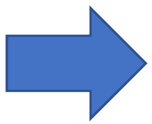
The Ikeda diagram
For N=Z=2n "alpha-conjugate" nuclei



K.Ikeda, N.Takigawa, H.Horiuchi, **PTP (1968)**

- **Cluster structure typically occurs close to cluster decay thresholds**

- **Based on properties of some near threshold states**
  - ✓ **Rotational bands with molecule-like structure**
    Very large moment of inertia
  - ✓ **Large alpha-decay widths**



Unified picture of clustering

Clustering in light nuclei

The Ikeda diagram

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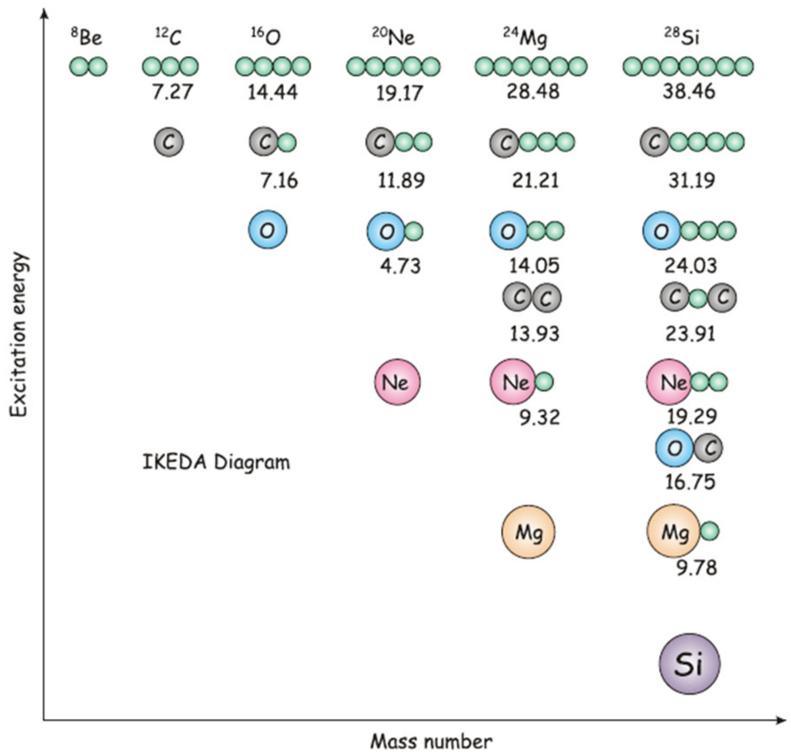


K.Ikeda, N.Takigawa, H.Horiuchi, **PTP (1968)**

Case of ^{8}Be

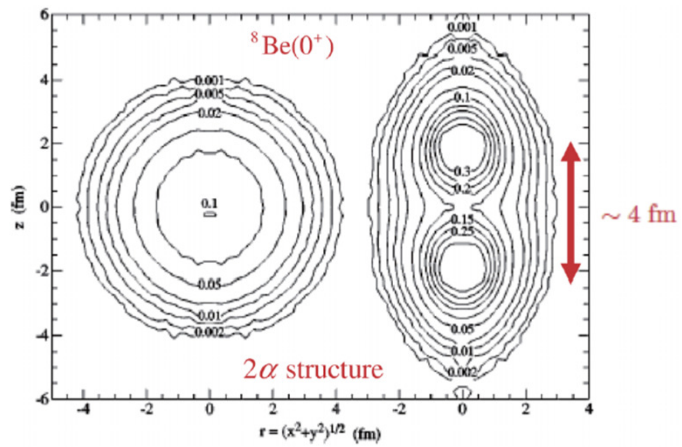
- **Cluster state is the ground-state (specific case)**
- **Recognized as alpha-cluster state in the late 50's**
  - **Rotational levels , large moment of inertia**

ab initio calculations for ^{8}Be

R.B. Wiringa, S.C.Pieper, J.Carlsson, V.R. Pandharipande, ***PRC 62 (2000)***

Green's function Monte-Carlo

nucleon-nucleon interaction: 2-body (AV18) + 3-body (Urbana IX)

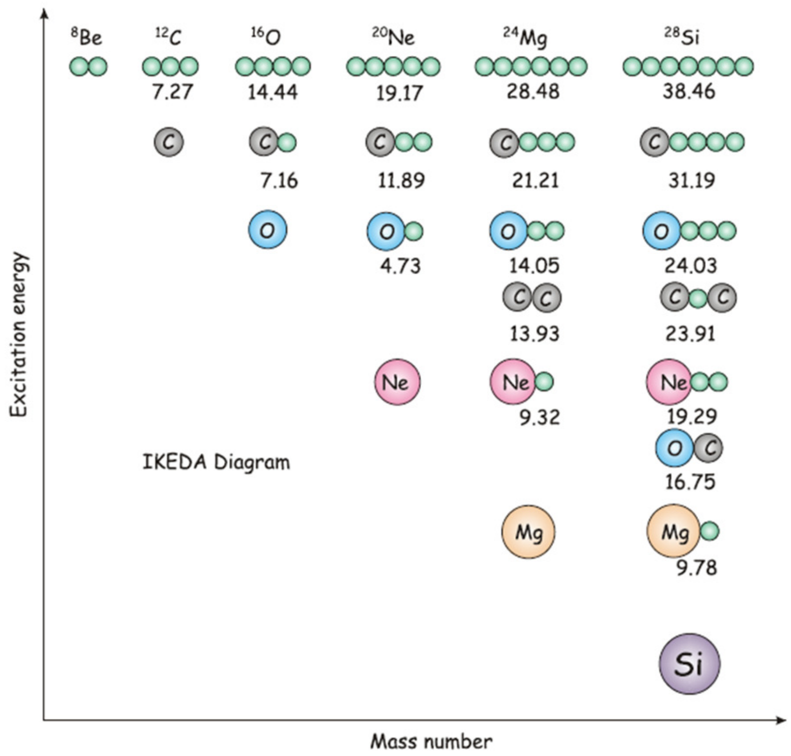


- 0+,2+,4+ sequence in ^{8}Be well-reproduced by calc.
- For precise properties, need take into account continuum coupling

Clustering in light nuclei

The Ikeda diagram

For N=Z=2n "alpha-conjugate" nuclei



K.Ikeda, N.Takigawa, H.Horiuchi, **PTP (1968)**

The Hoyle state in ^{12}C

Synthesis of elements heavier in ^{4}He (no stable isotopes A=5,8)

Fusion of 3α in ^{12}C in 2 steps:

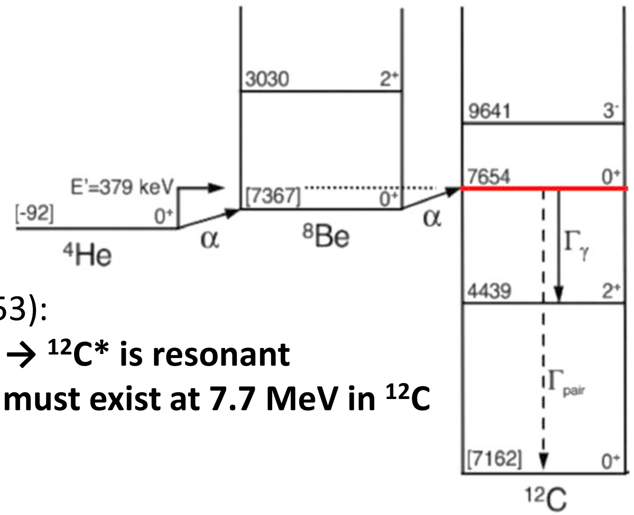
- $\alpha + \alpha \leftrightarrow {}^{8}\mathrm{Be}$

  $\tau({}^{8}\mathrm{Be}) = 9.7 \times 10^{-17}$ s
- $\alpha + {}^{8}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*}$

Fred Hoyle (1915 – 2001)

F.Hoyle (1953):

- ✓ **$\alpha + {}^{8}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*}$ is resonant**
- ✓ **a $J^{\pi}=0^{+}$ must exist at 7.7 MeV in ^{12}C**



Cluster Structure of the Hoyle state

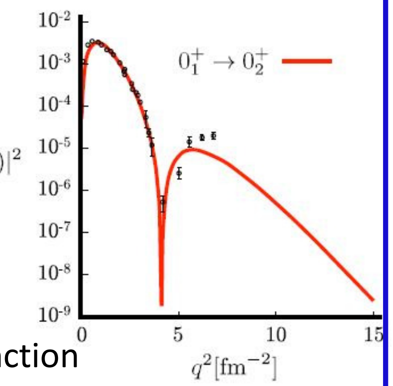
- Large radius needed to reproduce its width (Barker and Treacy, NP1962)

  → Large degree of alpha clustering
- Suggested as linear alpha chain (Morinaga, PL1966)
- Recently: Study of decay modes
- Description as an alpha condensate (Funaki et al., PRC2009)

  Tohsaki, Horiuchi, Schuck, Roepke (THSR) wave function

  Volume [Hoyle state] = 3~4 times x Vol [GS]

  Also: FMD calculations

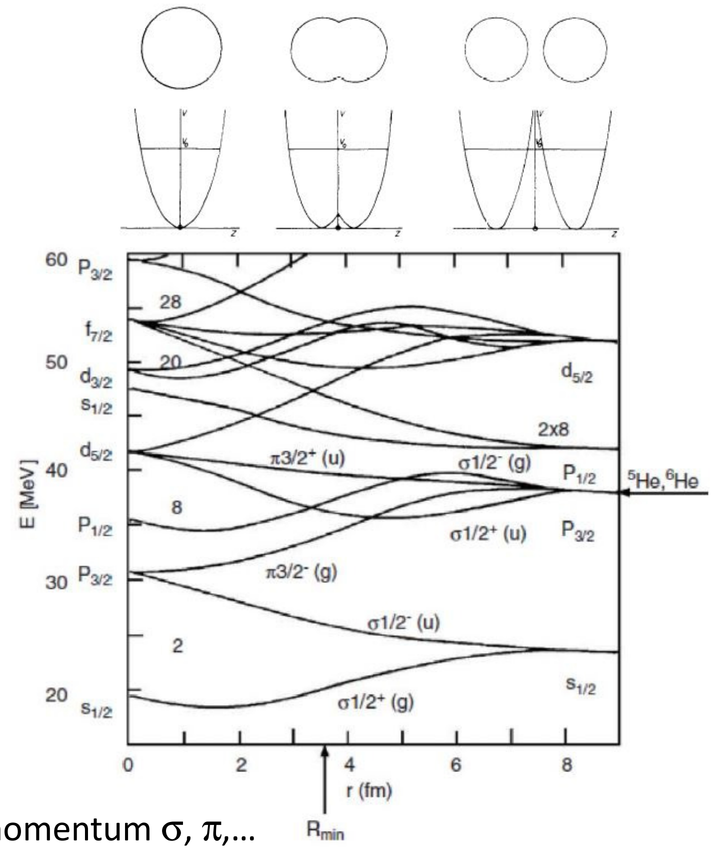


Adding neutrons to N=Z core

Two-center Shell Model

Scharnweber, Greiner, Mosel, Nucl.Phys. A164(1971)
Von Oertzen, Z.Phys. A357, 355 (1997)

dimer



Angular momentum σ, π,…
Spin projection, parity

Generalization : dimers → polymers

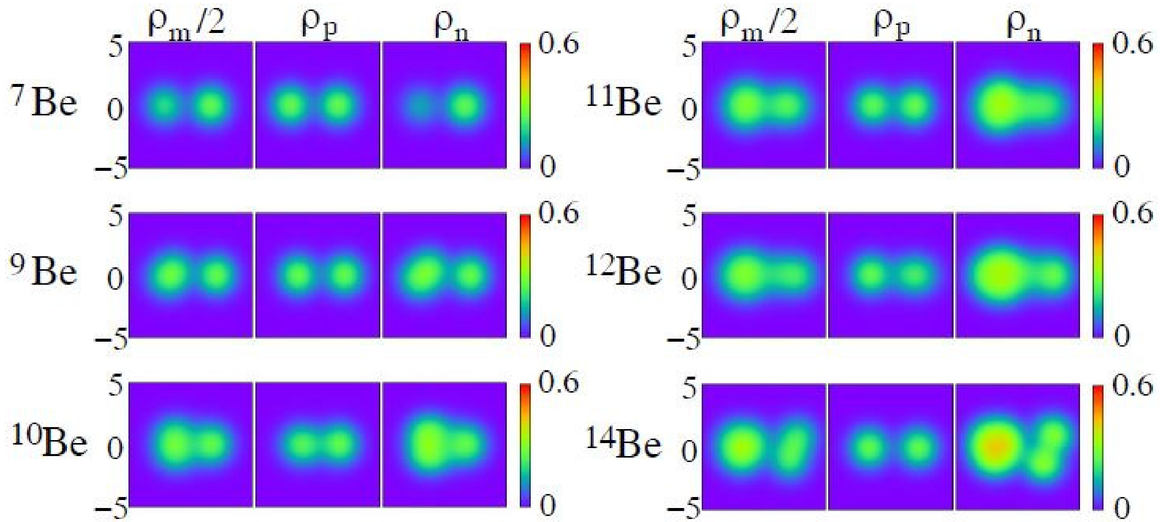
Antisymmetrized Molecular Dynamics

No assumption of preformed clusters

Early calculations for Be and B cases

Kanada-En'yo, Horiuchi, Ono , PRC 52, 628 (1995)
Kanada-En'yo, Horiuchi, PTP 142, 205(2001)

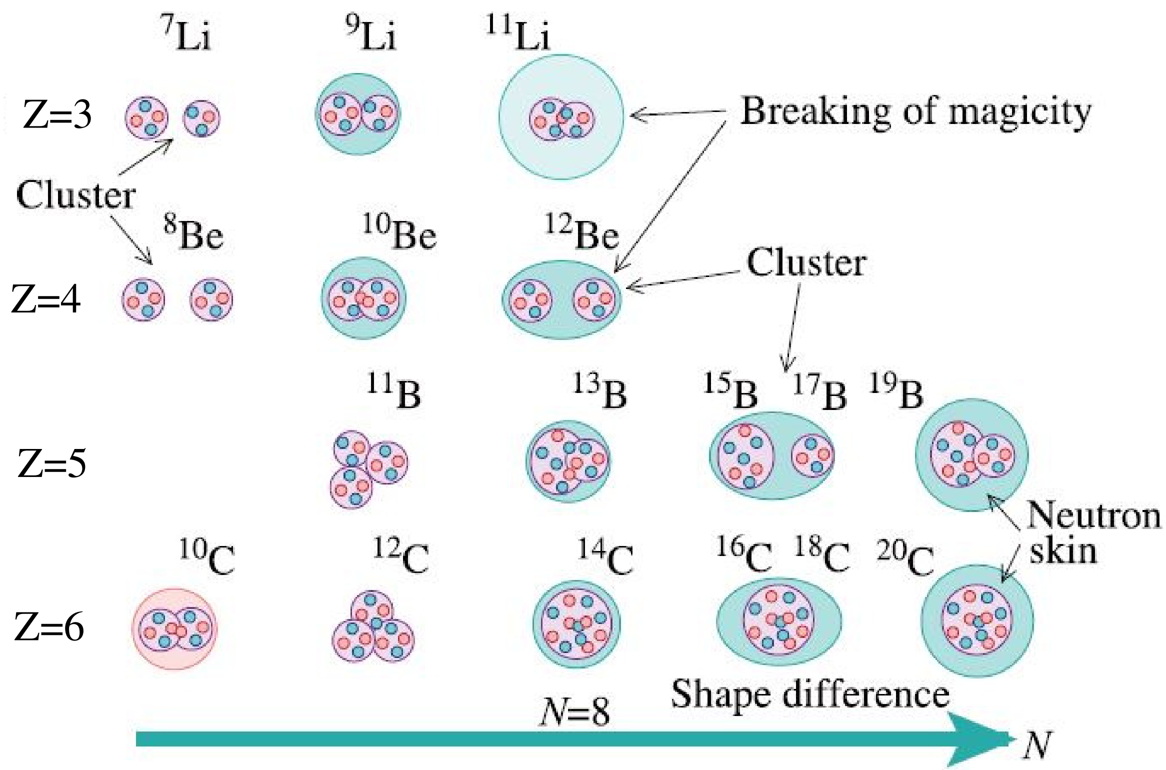
Recent calculations for Be ground-states



Kanada-Enyo, PRC91, 014315(2015)

Clustering in light neutron-rich nuclei

GROUND-STATES !



Antisymmetrized Molecular Dynamics (AMD)

Y.Kanada-En'yo, H.Horiuchi, Front. Phys. 13 (2018)

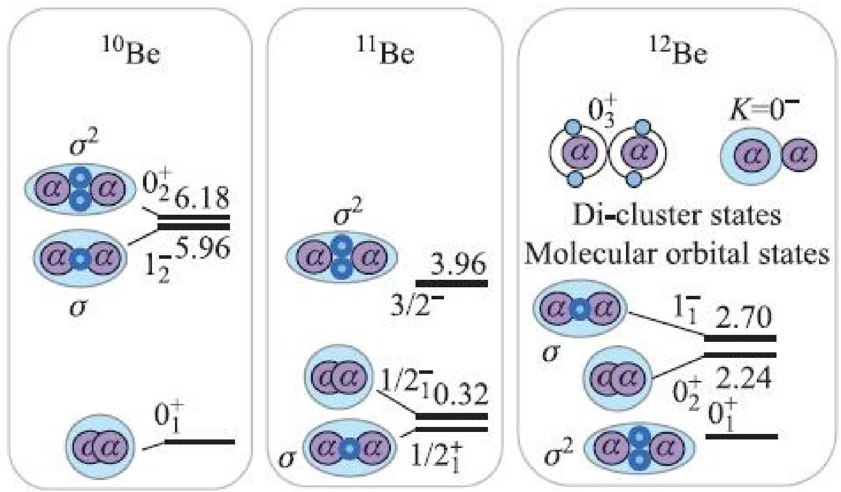
When Adding neutrons to N=Z nuclei:

Various Molecular structures

Neutron orbiting around the core of clusters

for low-lying states <u>including the ground-state</u>

Case of neutron rich Be



π orbit ↔ p-orbit in SM limit – reduce clustering

σ orbit ↔ sd intruder configuration –enhance clustering

Calls for direct evidence of Molecular structure !

Calculations from first principles for Be isotopes

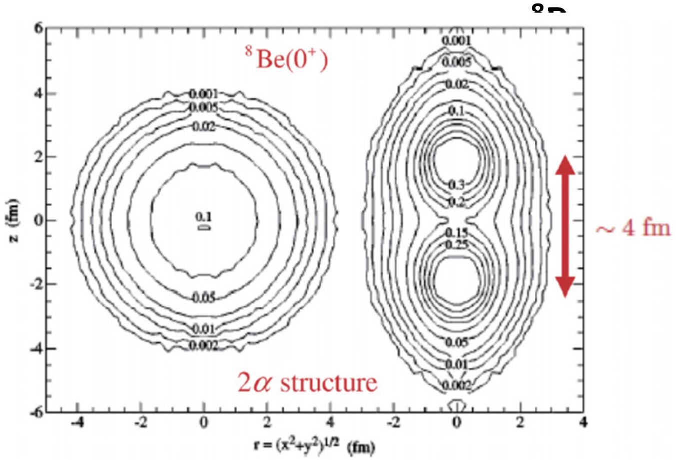
QMC calculation for ^{8}Be

R.B. Wiringa, S.C.Pieper, J.Carlsson, V.R. Pandharipande

Phys. Rev. C 62 (2000)

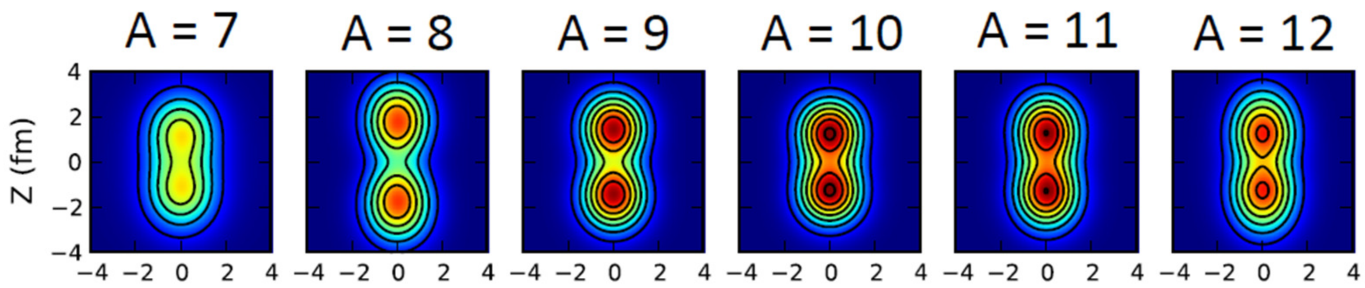
Quantum Monte-Carlo

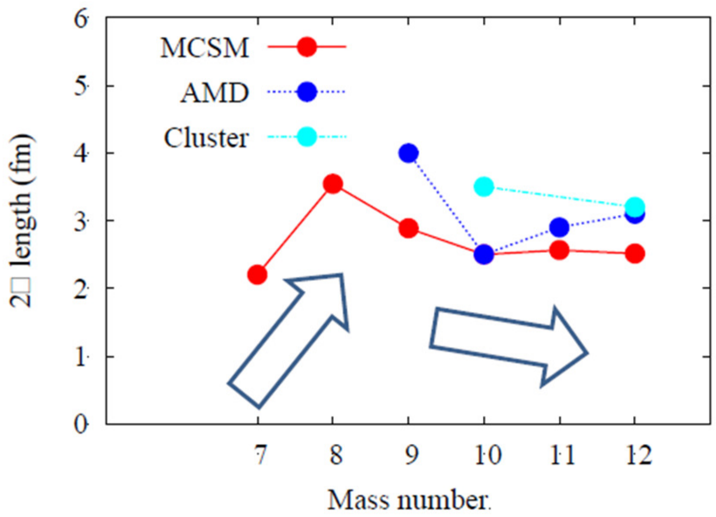
AV18 + Urbana IX



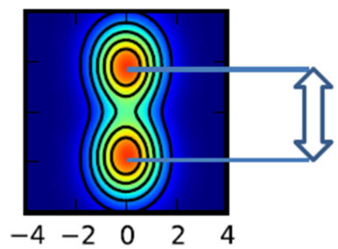
Rotational band well reproduced

Be isotopes in no-core Monte-Carlo Shell Model





Definition:
Distance btw the positions of each highest proton density



Courtesy T.Abe (2019)

AMD: Y. Kanada-En'yo, Phys. Rev C68, 014319 (2003)
Cluster: M. Ito & K. Ikeda, Rep. Prog. Phys. 77, 096301 (2014)

Calculations from first principles for Be isotopes

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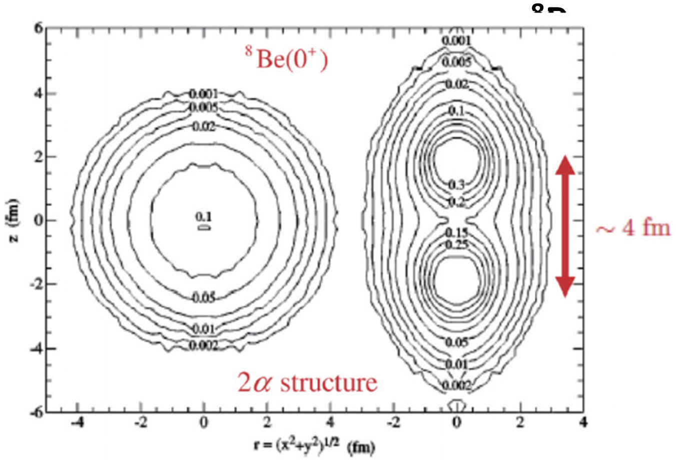

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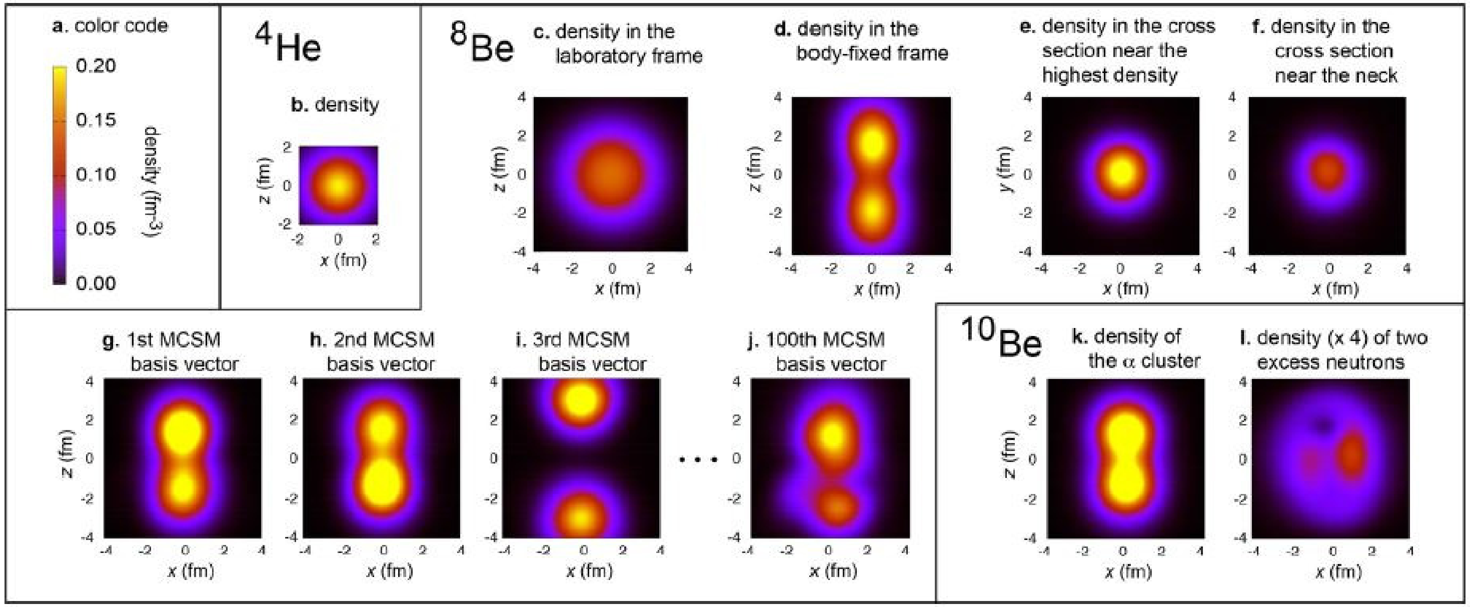


T.Otsuka, T.Abe et al., Nature comm. 2022

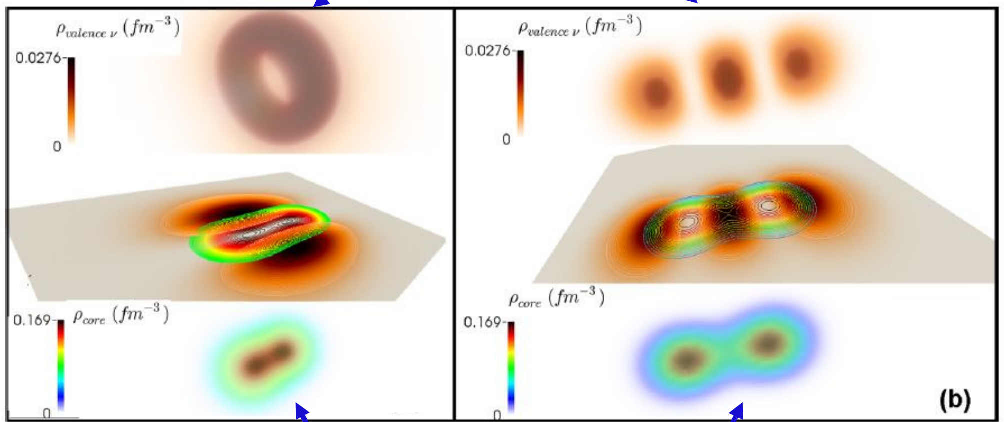
Density Functional Theory studies for clustering in light nuclei

DDME2 relativistic functional in rel. HB calculations

J.P.Ebran, E.Khan,T.Niksic, D.Vretenar, PRC90 (2014)

Neutron orbits

$^{10}Be^{GS}$ $^{10}Be^{*}$



Density of α+α core

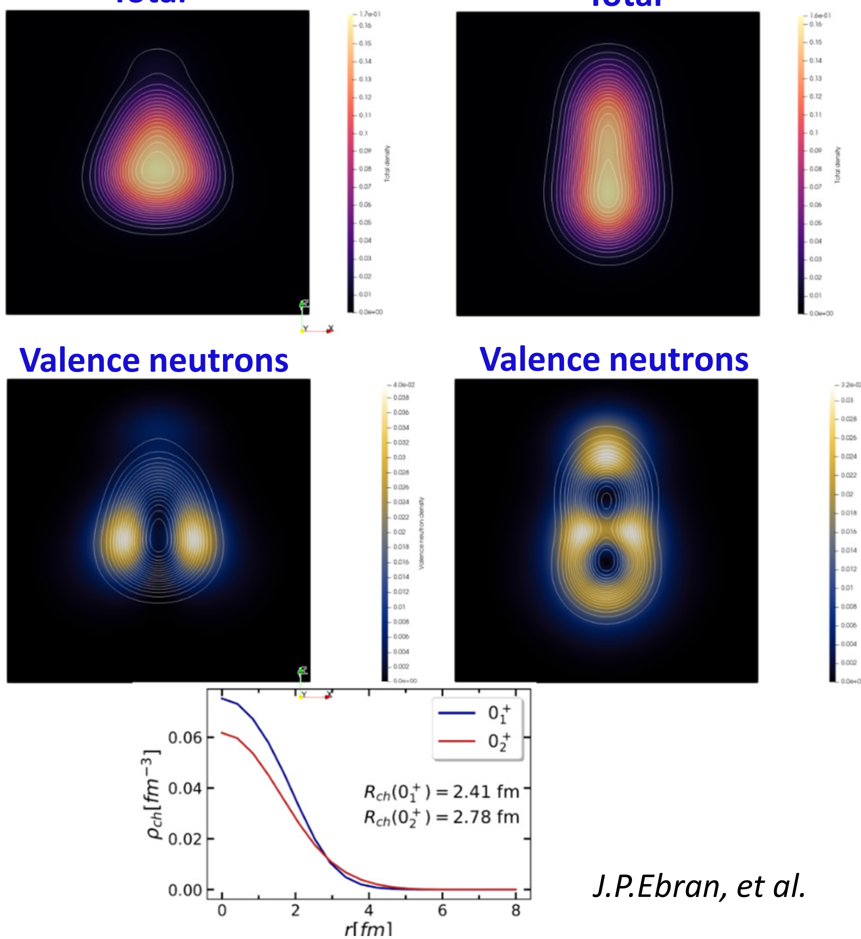
Recent calculations for ^{12}**Be**

Rel. HB with DD-PC1 + projected GCM

^{12}Be GS **^{12}Be G(0^+_2)**

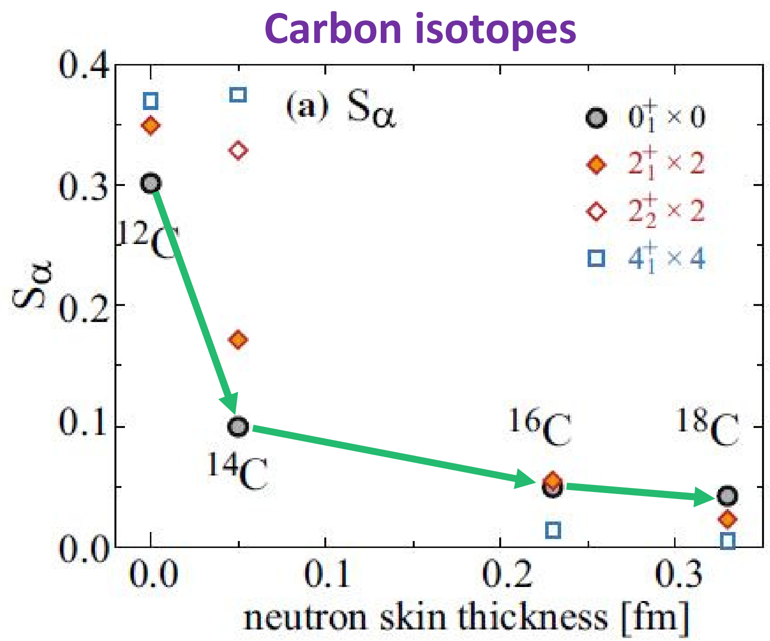
Total

Valence neutrons



J.P.Ebran, et al.

Clustering evolution towards the dripline



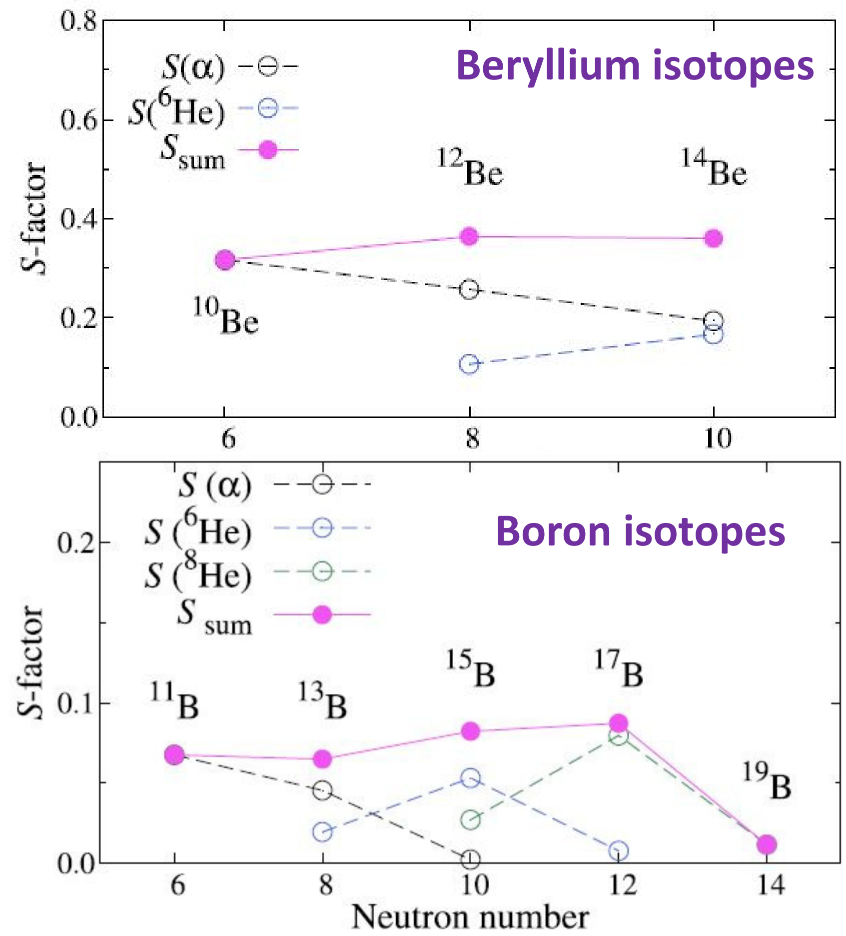
Q. Zhao, Y. Suzuki, J. He, B. Zhou, M. Kimura, EPJA 157 **(2021)**

AMD calculations using Gogny D1S functional

Hindrance effect due to neutron skin ?

Alternative interpretations

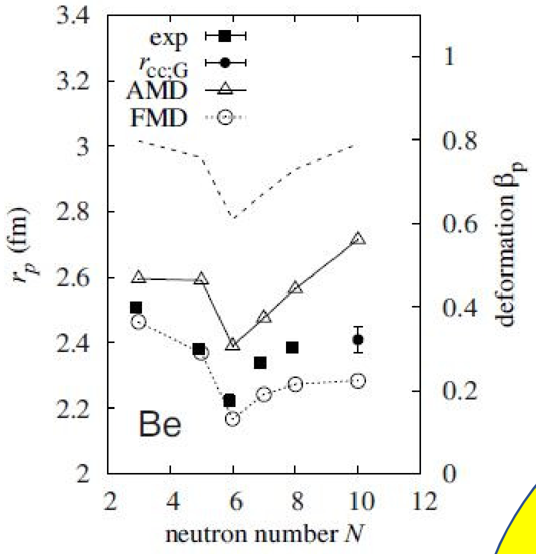
- Neutron single-particle configurations
- Relationship between α-clustering and α-threshold

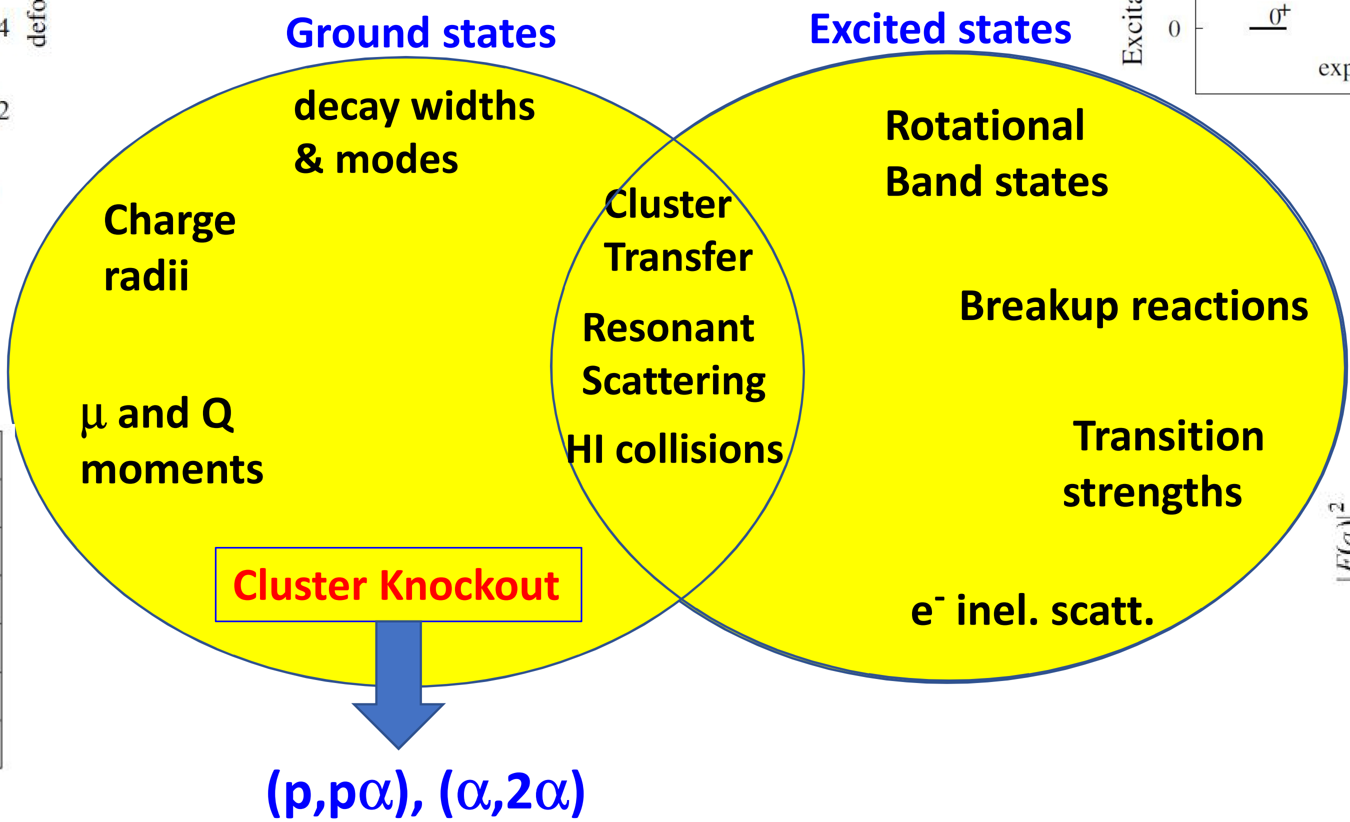


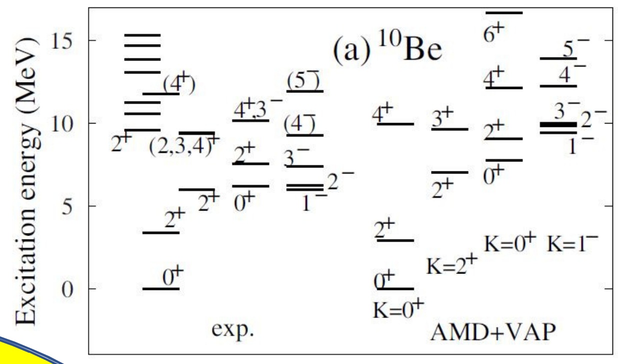
H.Motoki, et al, PTEP **(2022)**113D01 - AMD calculations using Gogny D1S

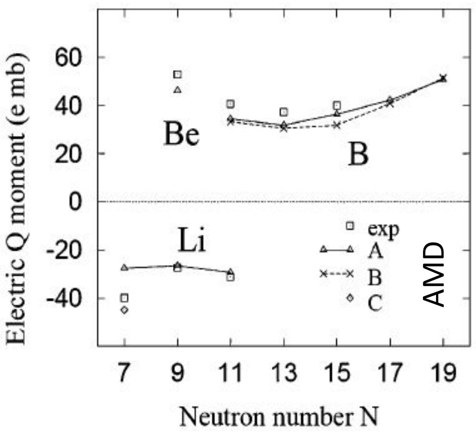
- **Hindrance of α clustering**
- **Development of ^{6}He clutering**

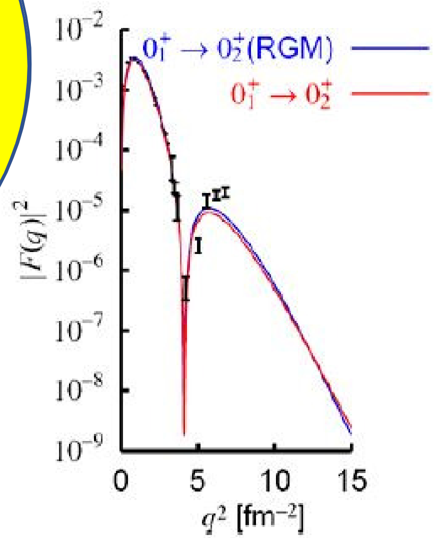
Experimental investigations of clustering







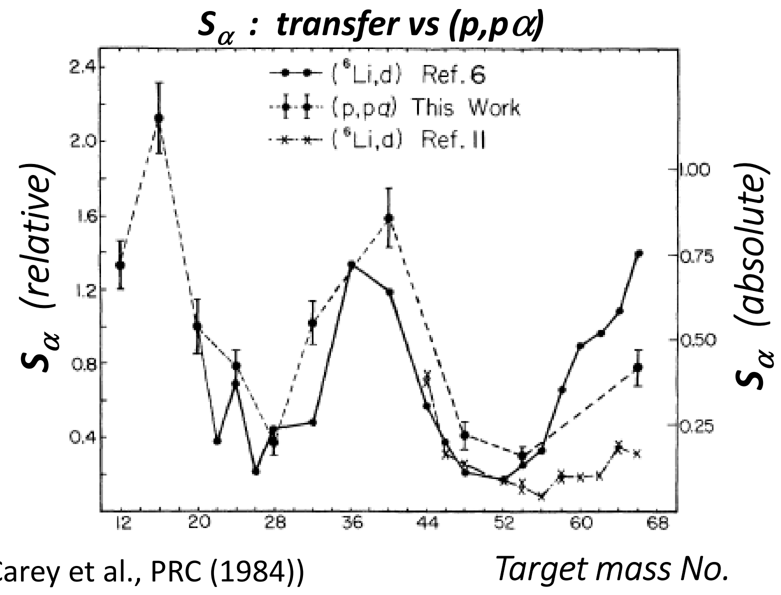




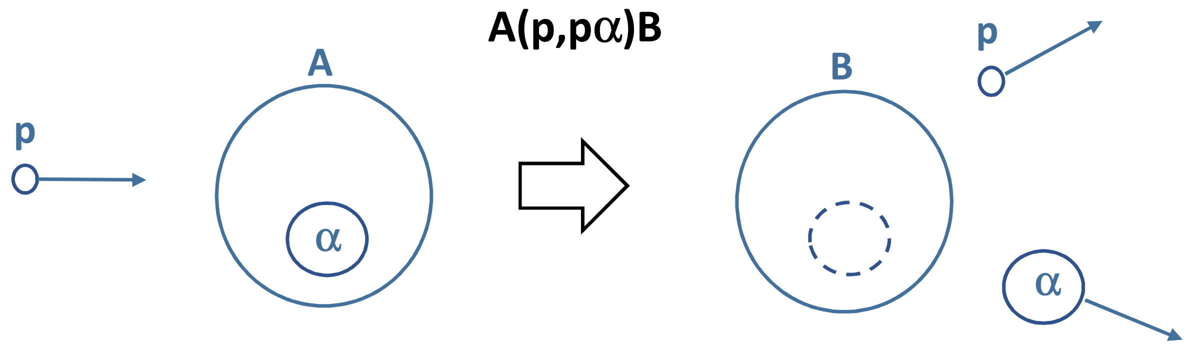
Cluster knockout reactions

- Direct reaction
  - ✓ short reaction time (~10^{-22}s)
  - ✓ one-step dominant
- (e,e'p), (p,2p) and (p,pn) for nucleons
  (p,pα), (α,2α) for alpha cluster
- Well-studied since the 70's with proton and alpha beams on stable targets
- Incident p energy : 100~400 MeV
  (λ ~ 0.5-0.25fm)
- *Peripheral* reaction
- Extraction of spectroscopic factors S_α

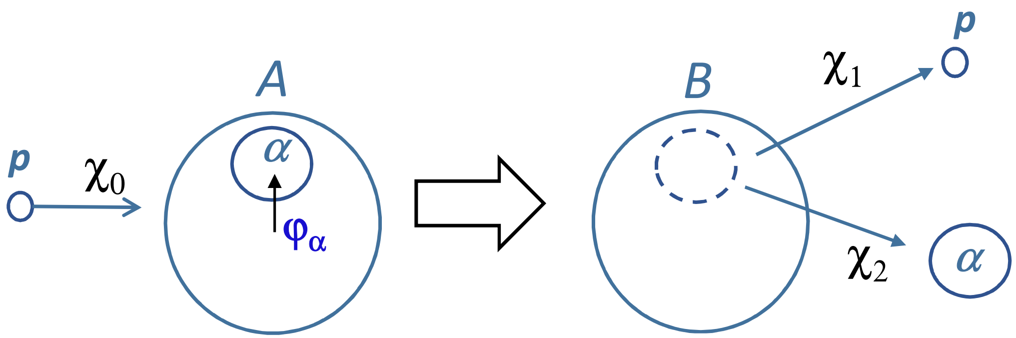
- **Recently: new analysis procedure**



(T. Carey et al., PRC (1984))



Measurement of (p,pα) reactions



- **Excitation energy spectrum of the residue**

  conservation laws -> 6 degrees of freedom (e.g. ($\overrightarrow{p_1}, \overrightarrow{p_2}$))

$$E_B = E_A + E_0 - E_1 - E_2$$

$$p_B = (p_A^2 + p_1^2 + p_2^2 - 2p_A p_1 \cos\theta_1 - 2p_A p_2 \cos\theta_2 + 2p_1 p_2 \cos\theta_{1-2})^{1/2}$$

$$m_B^* = \sqrt{E_B^2 - p_B^2}$$

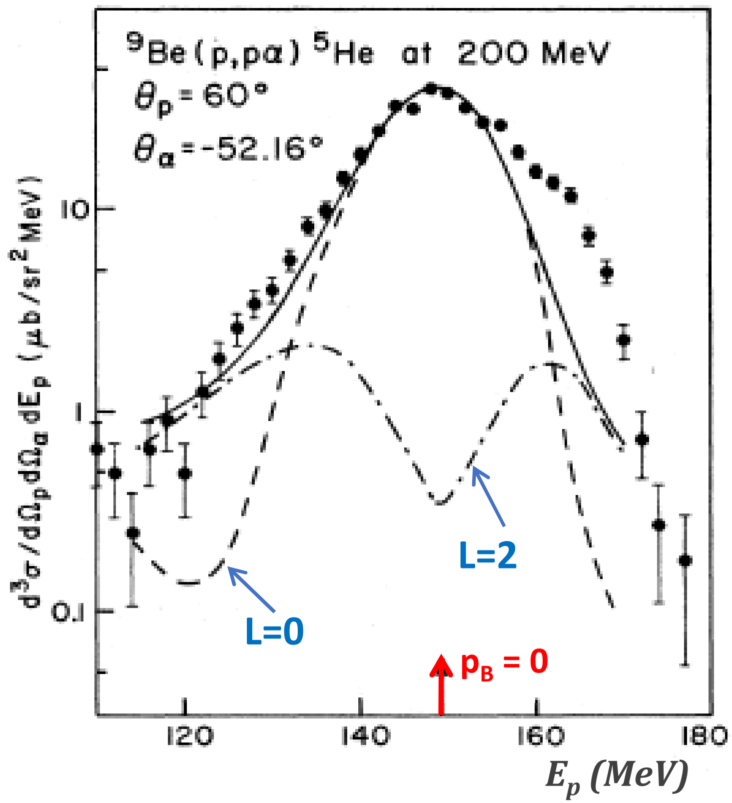
- **Triple differential cross-section**

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2}$$

Energy and solid angle of particle 1 — solid angle of particle 2

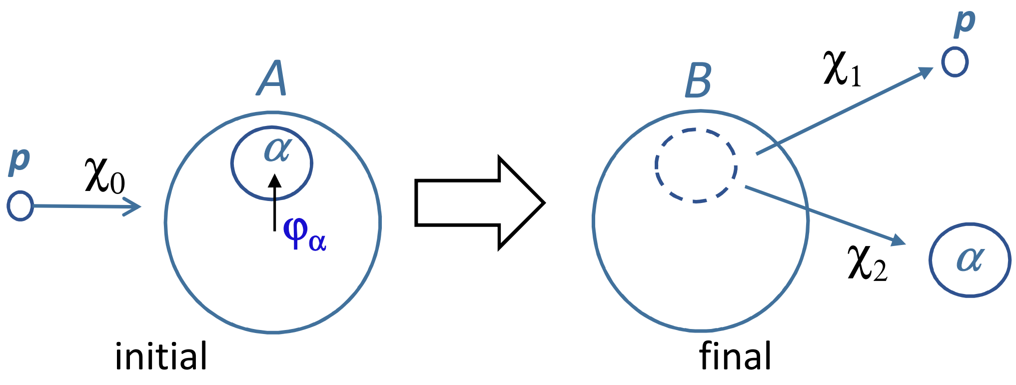
Measured around recoil-less conditions $\overrightarrow{p_B} = \vec{0}$ (quasifree)

^{9}Be(p,pα) at 200 MeV



Nadasen *et al.*, PRC(1989)

Amplitude and cross-section in Distorted Wave Impulse Approximation (DWIA)



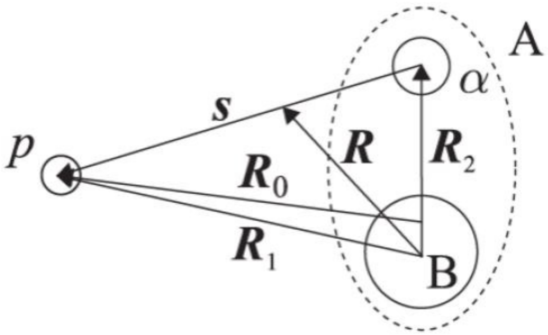
$$\frac{d^3\sigma^{DWIA}}{dE_1^L d\Omega_1^L d\Omega_2^L} = F_{\mathrm{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) \left|\bar{T}_{P_0P_1P_2}\right|^2$$

Kinematical factor

Constant

2-body p–α Xsection

Transition amplitude



$$T_{P_0P_1P_2} = \left\langle \chi_{1,P_1}^{(-)}(R_1)\,\chi_{2,P_2}^{(-)}(R_2) \left| t_{p\alpha}(s) \right| \chi_{0,P_0}^{(+)}(R_0)\,\varphi_\alpha(R_2) \right\rangle$$

$\chi_{0,P_0}^{(+)}(R_0)$ $\chi_{1,P_1}^{(-)}(R_1)$ $\chi_{2,P_2}^{(-)}(R_2)$ distorted waves for p-A, p-B and α-B
Obtained from elastic scattering data

$t_{p\alpha}(s)$ Transition interaction

$\varphi_\alpha(R_2)$ **Cluster Wave function**

- Phenomenological
- **Microscopic (AMD, ab initio …)**

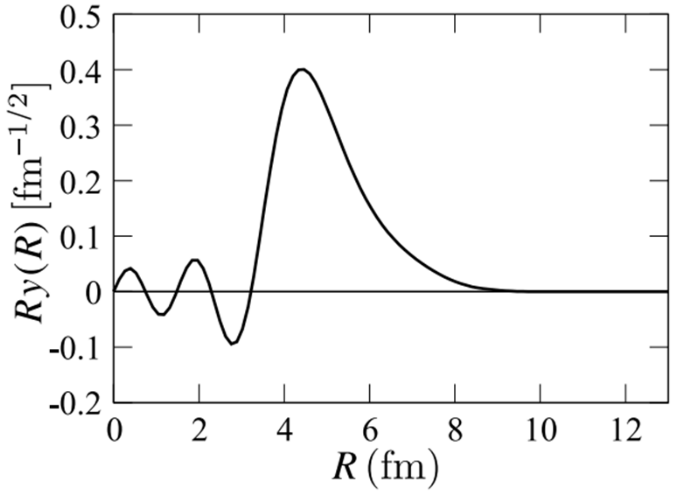
Analysis using microscopic cluster WF

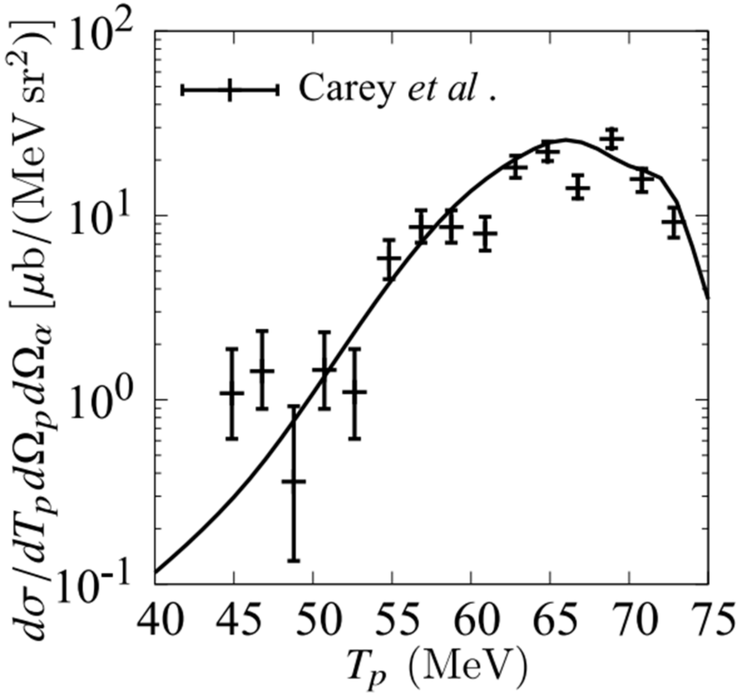
"Test" case : reanalysis of $^{20}Ne(p,p\alpha)^{16}O$ data at 101.5 MeV/u

*K.Yoshida et al., PRC 99, 064610 (**2019**)*

- AMD cluster WF
- Reliable $\alpha+^{16}O$ optical potential

AMD $\alpha+^{16}O$ cluster WF





Data reproduced without any normalization

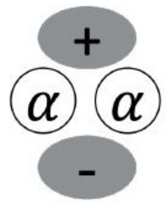
(p,pα) represents a quantitative probe for a-clustering

THSR-based calculations for ^{10}Be(p,pα) ^{6}He$^{(GS)}$ at 250 MeV/u

M.Lyu et al., PRC 97 (2018)

Tohsaki, Horiuchi, Schuck, Röpke (THSR) wave-function
Well adapted to discuss cluster states in light nuclei
→ Cluster wave-function
overlap of ^{10}Be and ^{6}He
→ Optical potentials
folding of calculated density

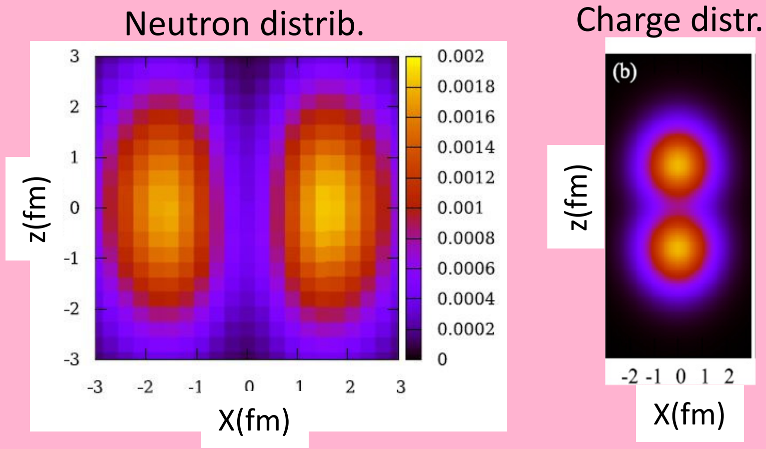
^{10}Be: 2α + 2n(π)



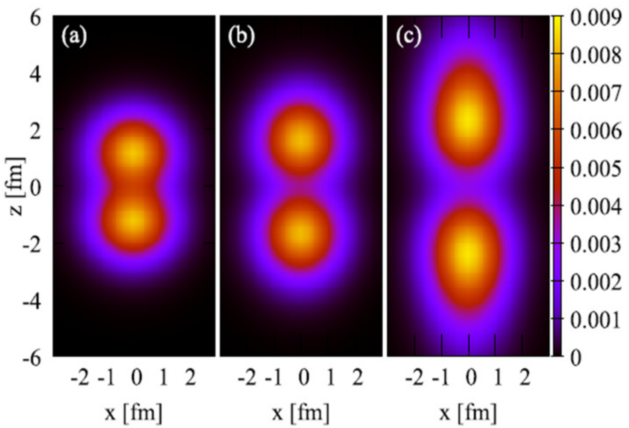
π-orbit

Good reproduction of :
- ^{10}Be GS energy
- Charge radius 2.31fm (exp=2.36fm)

^{10}Be ground state



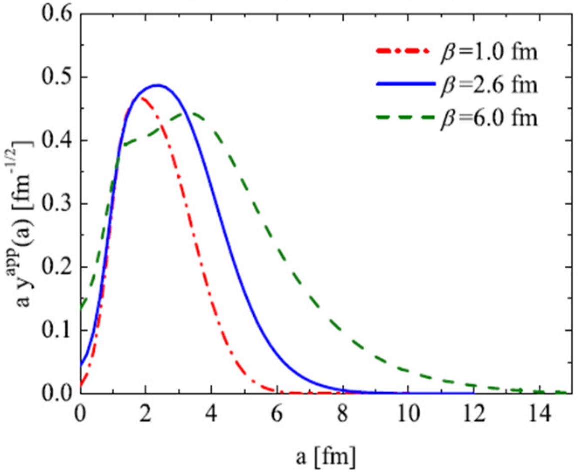
^{10}Be charge distribution



↑ **Variational result**

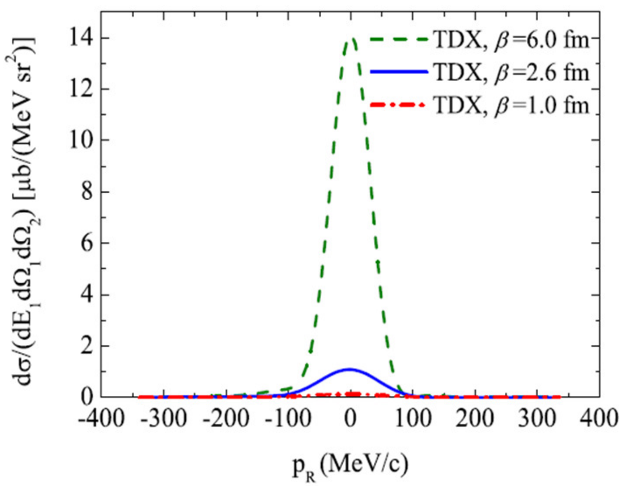
RWA

Cluster wave-function



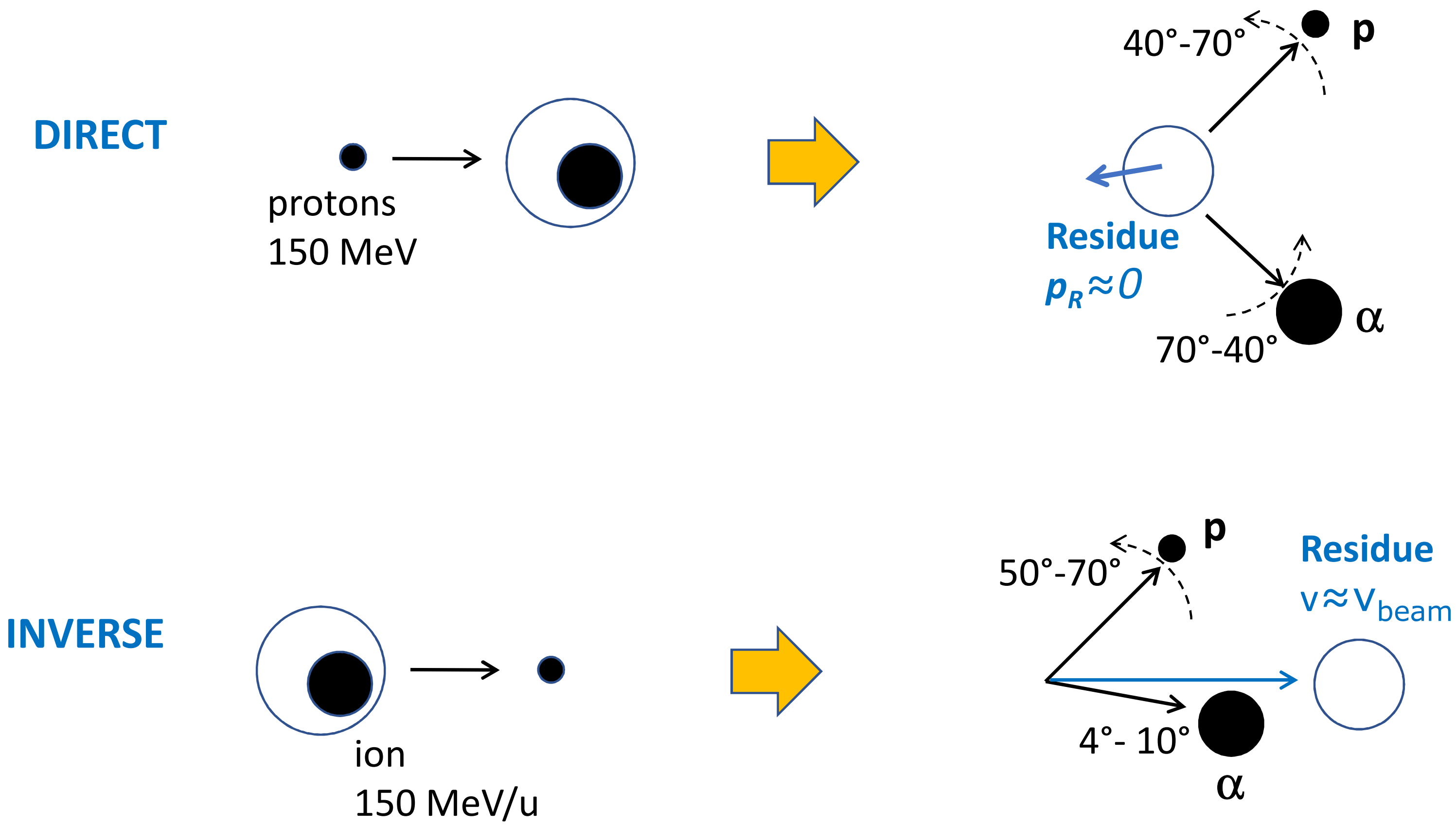
DWIA calc.

^{10}Be(p,pα) cross-section



Kinematics for alpha quasifree knockout reactions

Direct vs inverse kinematics



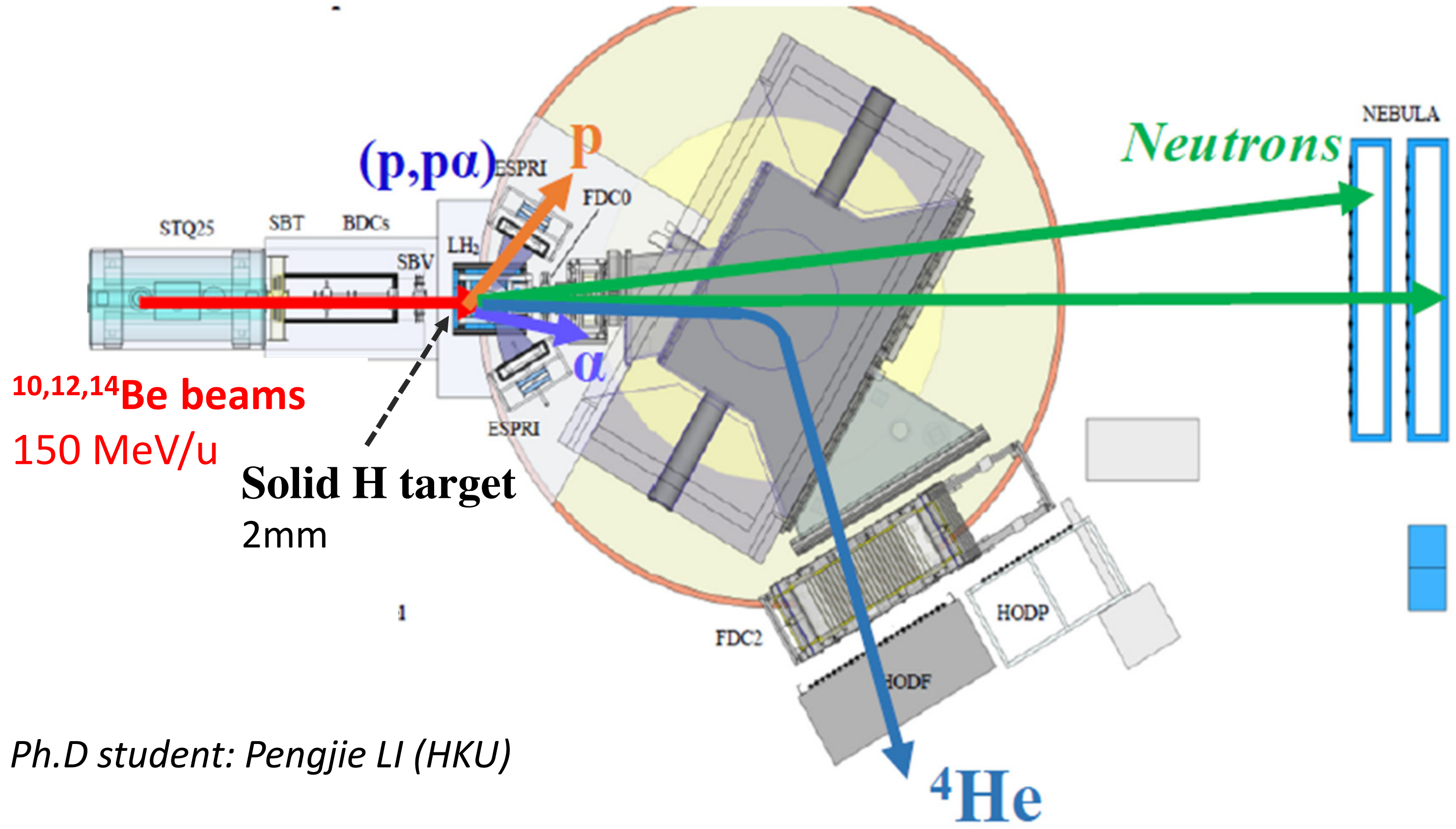
Proton
- 50°-70°
- 20~150MeV

Alpha
- 4-10°
- $v \approx v_{beam}$

Study ^{10,12,14}Be(p,pα) at 150 MeV/u

- **Clustering in n-rich Be**
- **First spectrum for the 6n system**

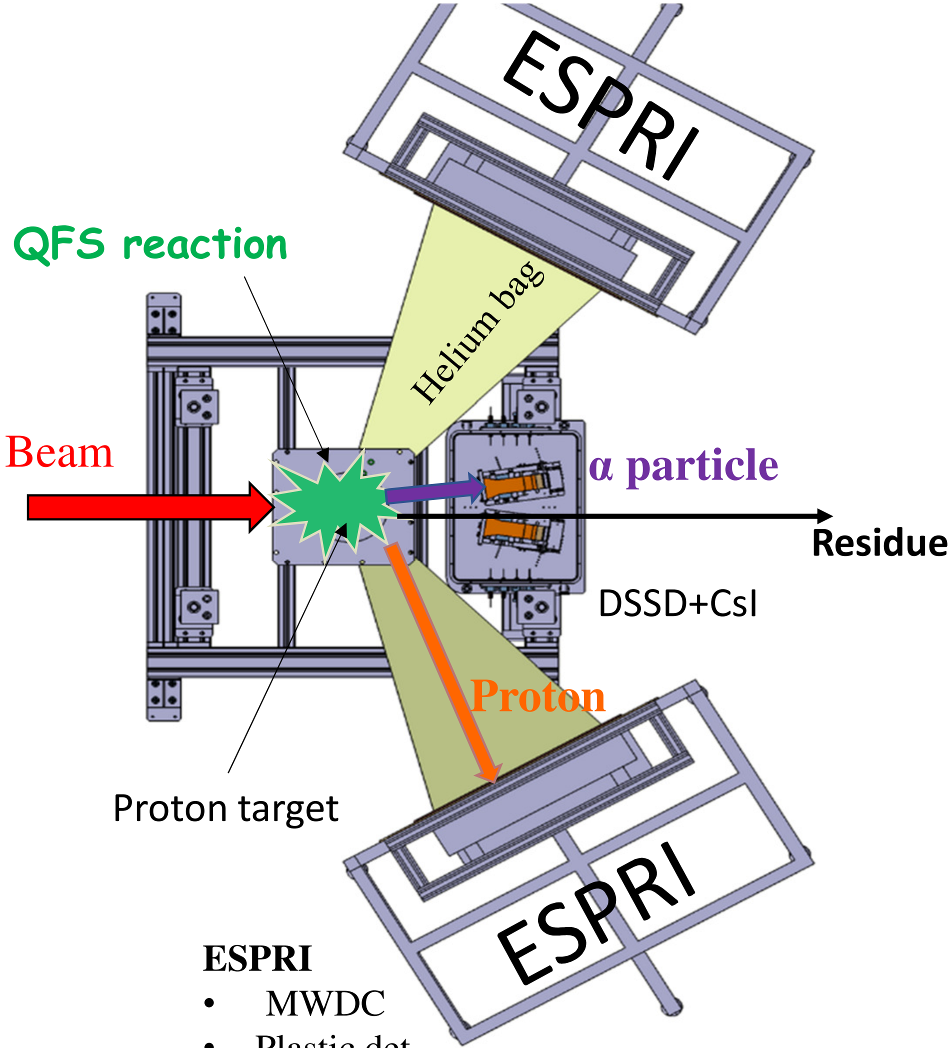
- Missing-mass measurement
- measure: GS → GS and GS → 2^+ transitions



Ph.D student: Pengjie LI (HKU)

Collaboration: **IJCLab, Hong Kong U., RIKEN**, TI Tech, LPC Caen, Tohoku U., RCNP Osaka, CEA Saclay, Kyoto U., TU Darmstadt, NIPNE Bucharest, Kyushu U.

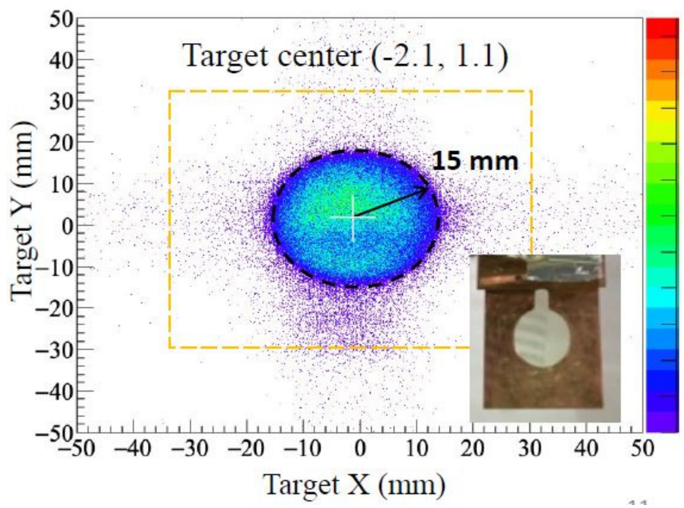
Setup around target



ESPRI
- MWDC
- Plastic det.
- NaI rods

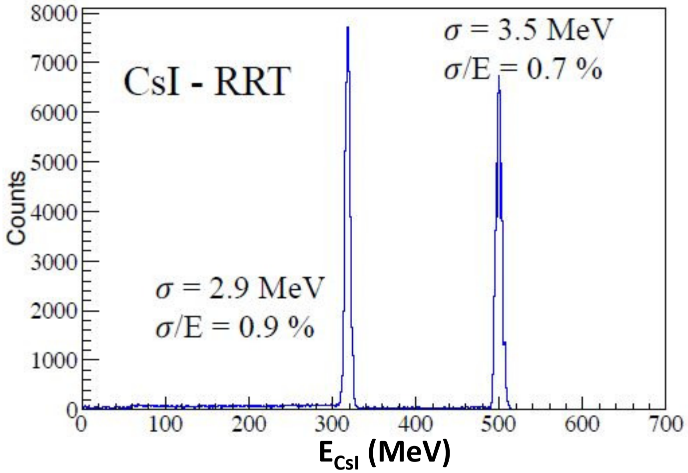
Target : 2mm-thick solid H

Y.Matsuda et al., NIMA 643 (2011)

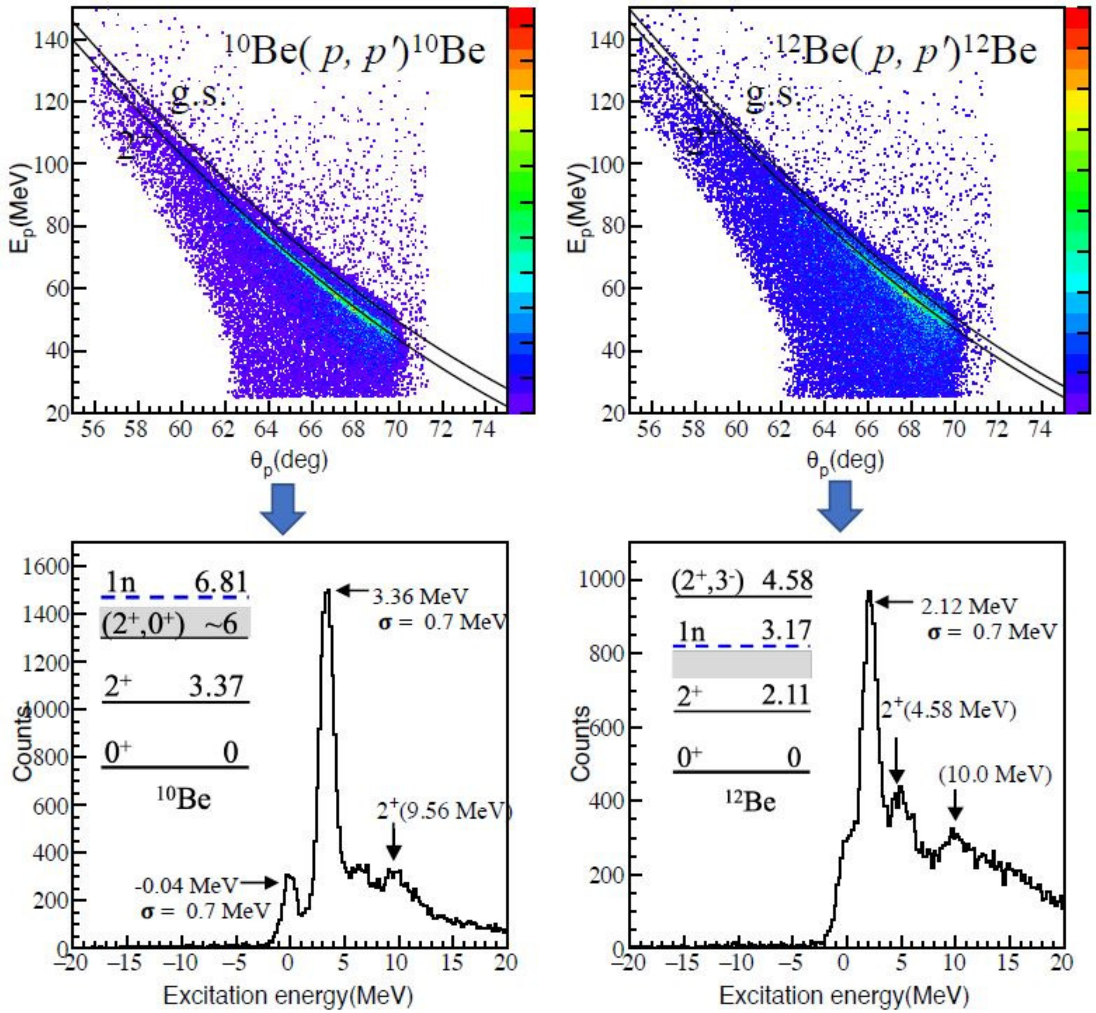


Energy calibrations of Telescopes

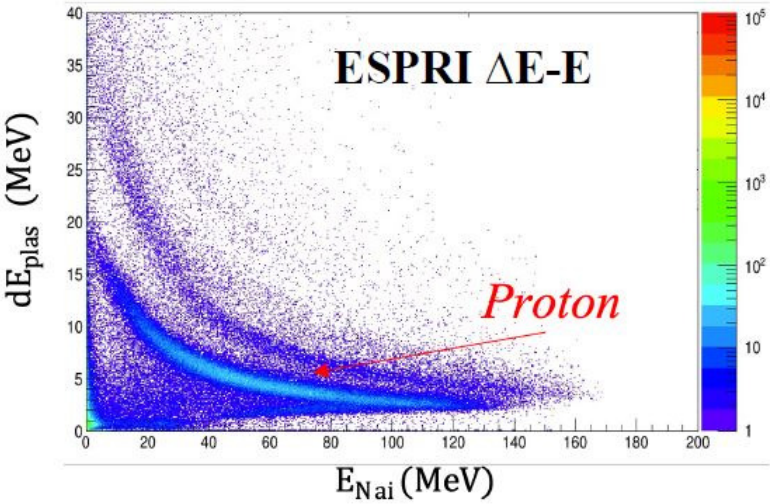
α beams at 120 and 150 MeV/u

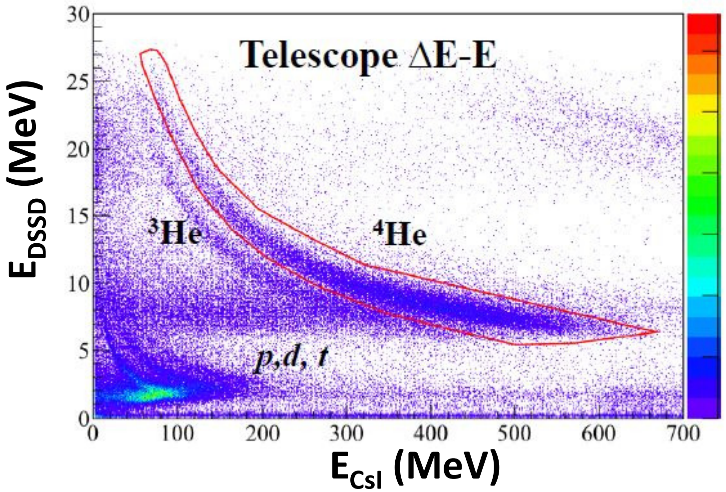


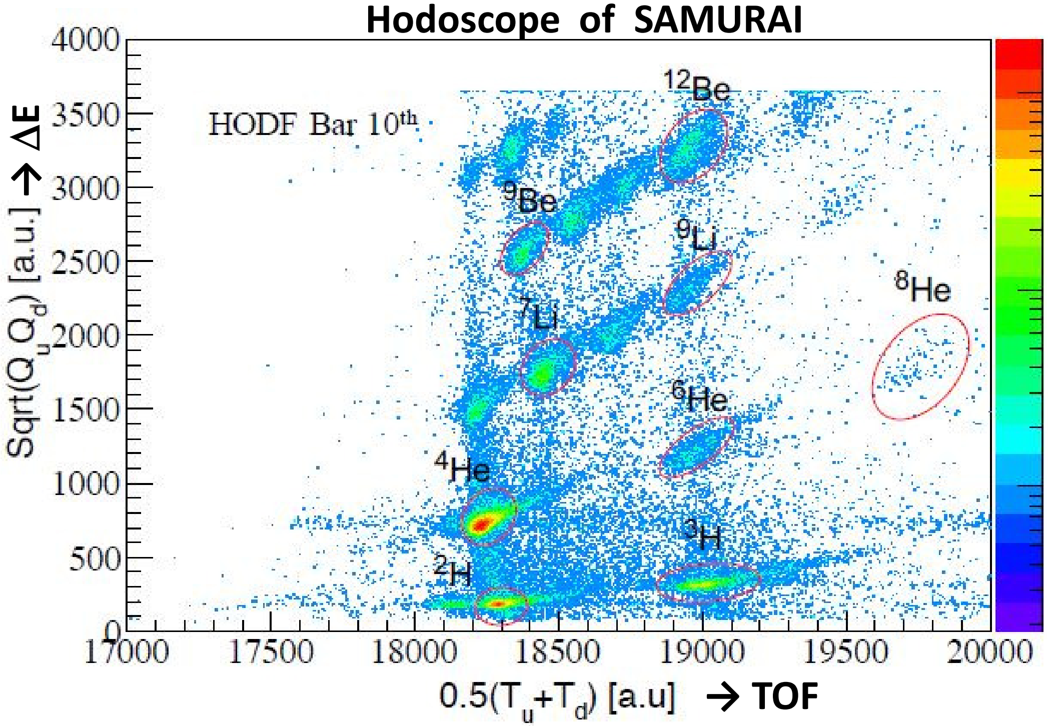
Energy calibrations of ESPRI



Particle identification – channel selection

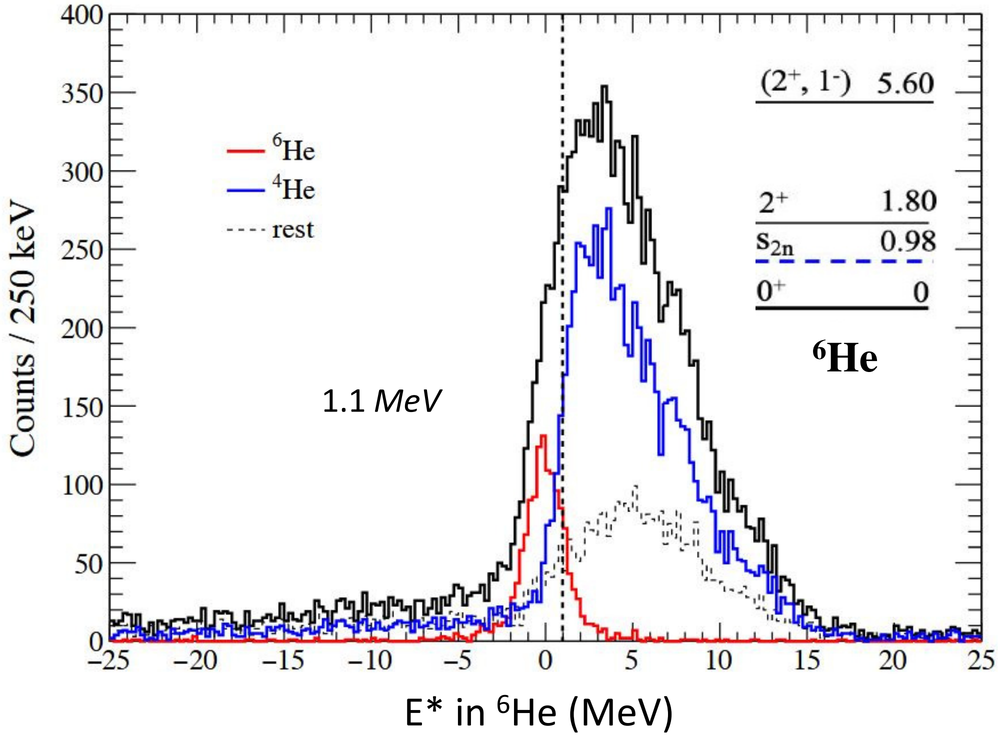






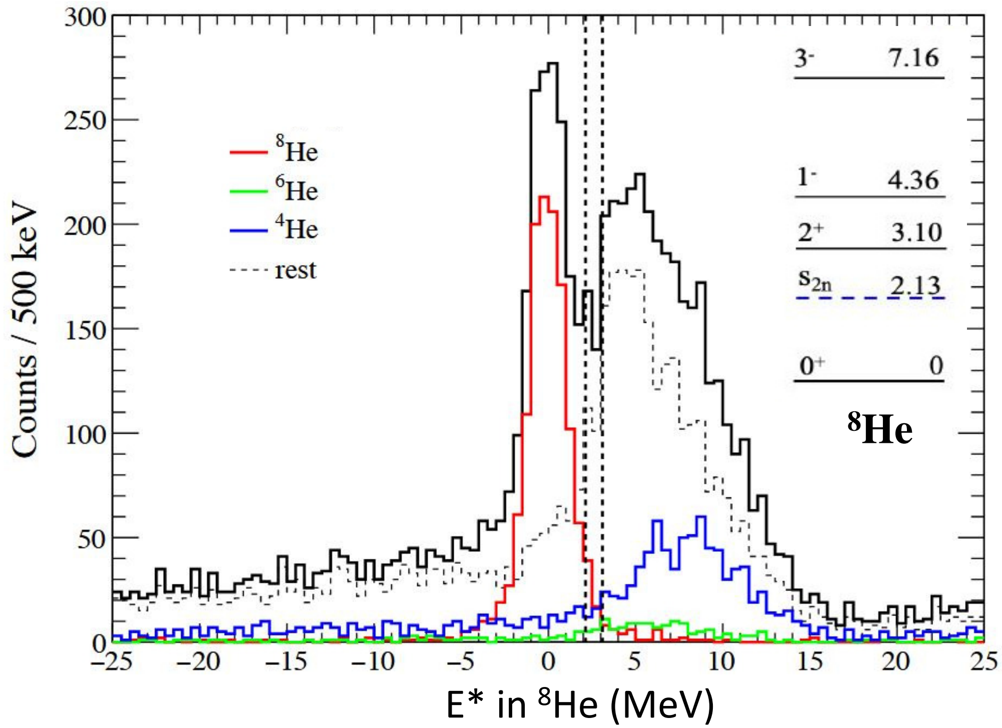
Excitation energy spectra

$^{10}Be(p,p\alpha)$



σ ($^6He^{GS}$) = 1.1 MeV

$^{12}Be(p,p\alpha)$



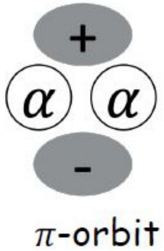
σ ($^8He^{GS}$) = 1.1 MeV

Calculations for ^{10}Be(p,pα) ^{6}He$^{(GS)}$ at 150 MeV/u

- Tohsaki, Horiuchi, Schuck, Röpke (THSR) wave-function

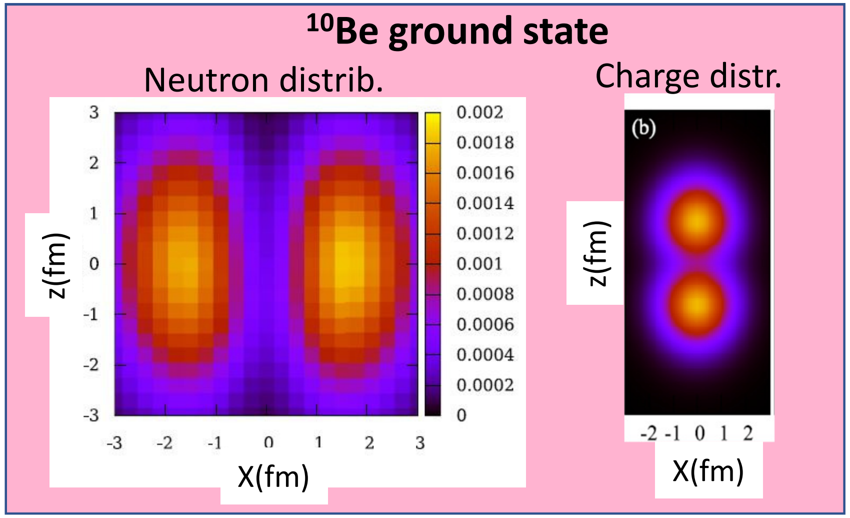
Well adapted to discuss cluster states in light nuclei

^{10}Be: 2α + 2n(π)



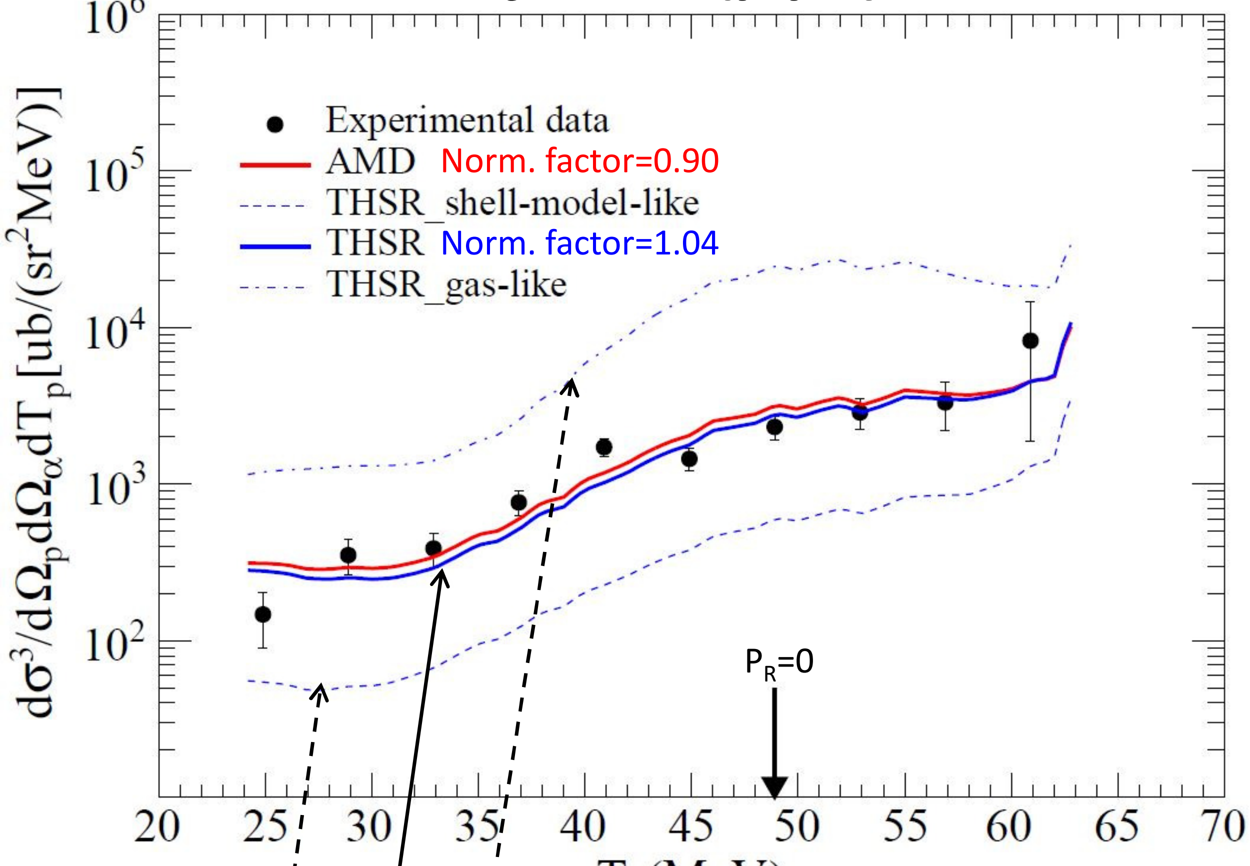
Good reproduction of :

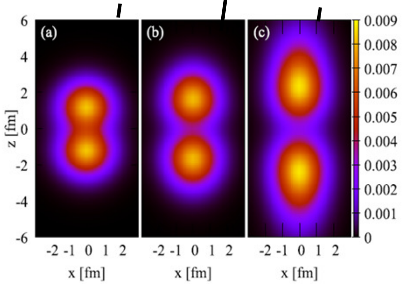
- ^{10}Be GS energy
- Charge radius 2.31fm (exp=2.36fm)



- AMD cluster WF

TDX for $^{10}Be(p,p\alpha)^{6}He^{(GS)}$





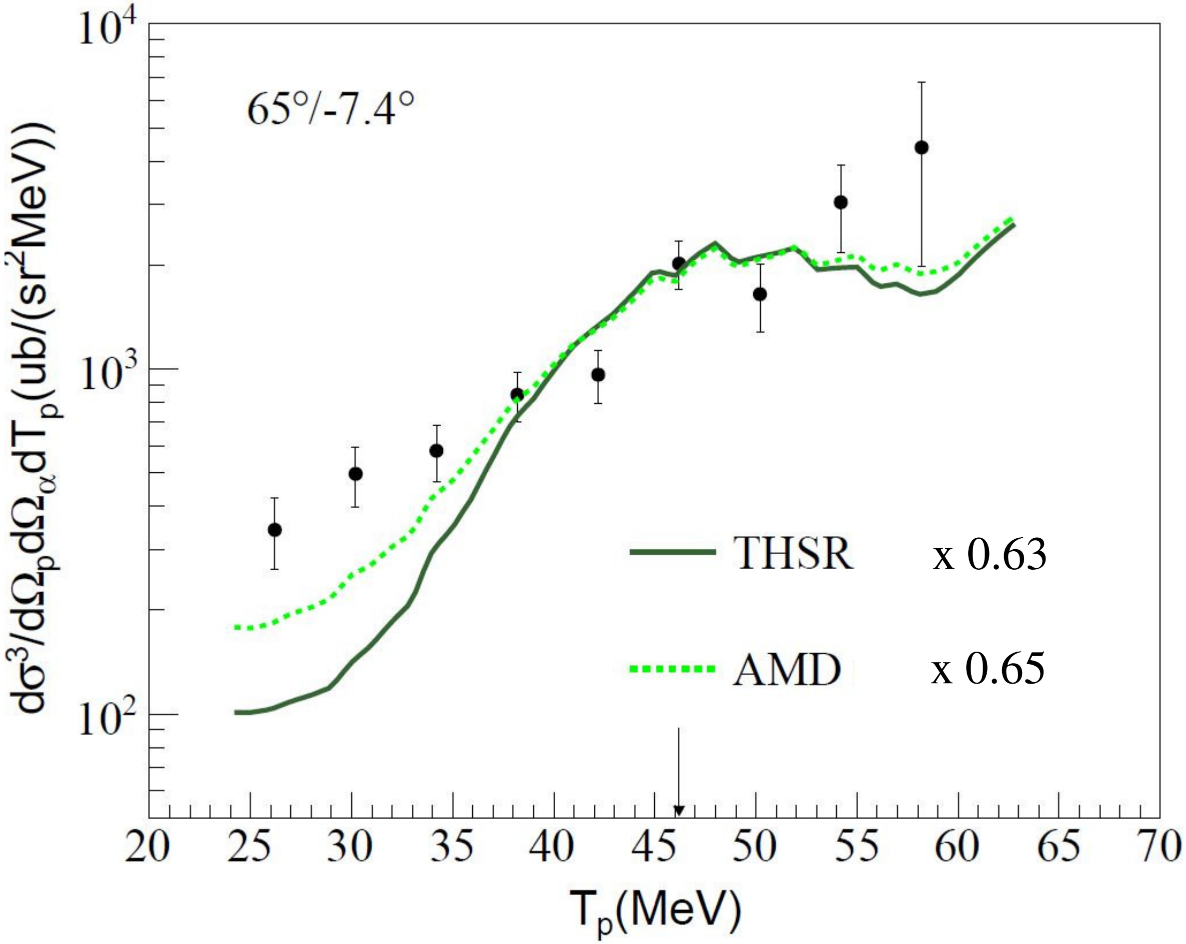
Error bars: statistical + error on PV

Optical potentials : from Dirac phenomenology

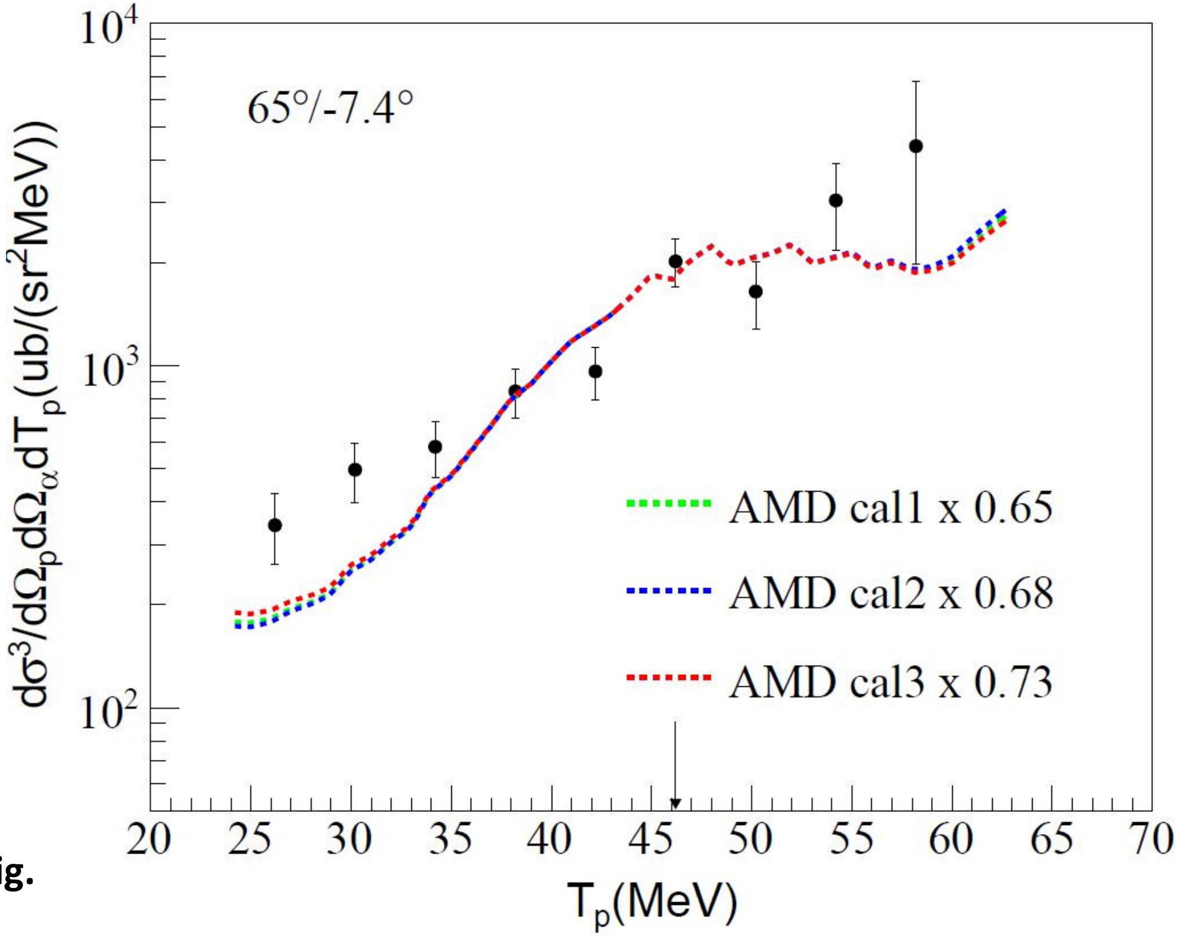
Molecular structure of the ^{10}Be GS is validated

Submitted for publication

TDX for $^{12}Be(p,p\alpha)^8He^{(GS)}$



TDX for $^{12}Be(p,p\alpha)^8He^{(GS)}$

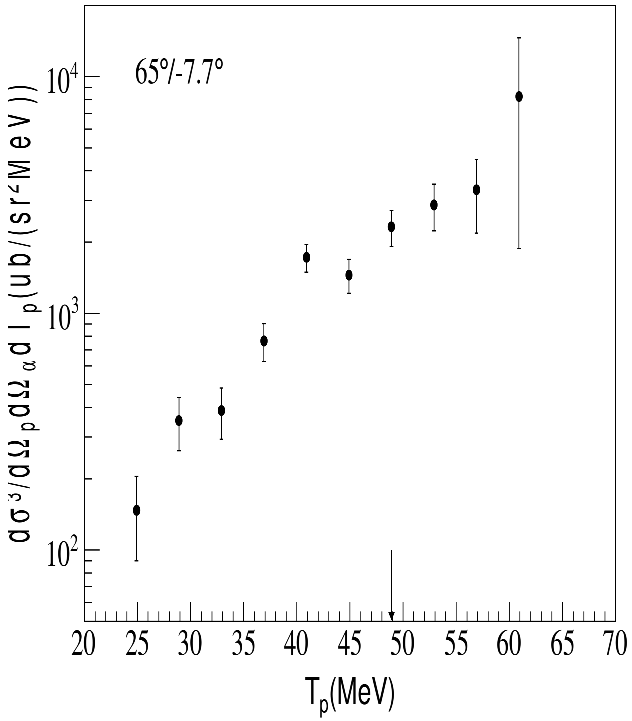


Sensitivity to intruder config.

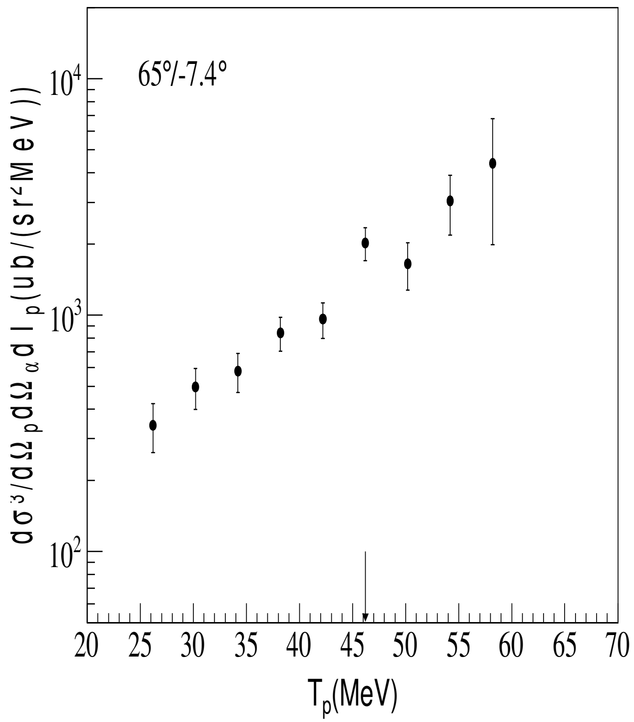
- CAL1: default LS parameter
- CAL2 : weaker LS parameter
- CAL3: pure 2hω

Experimental TDX for $^{10\sim14}$Be(p,pα)

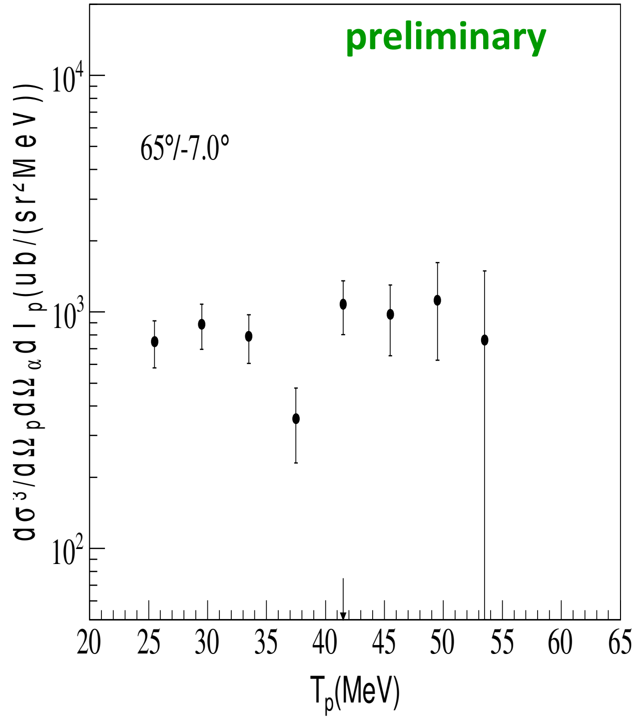
^{10}Be(p,pα)^{6}He



^{12}Be(p,pα)^{8}He



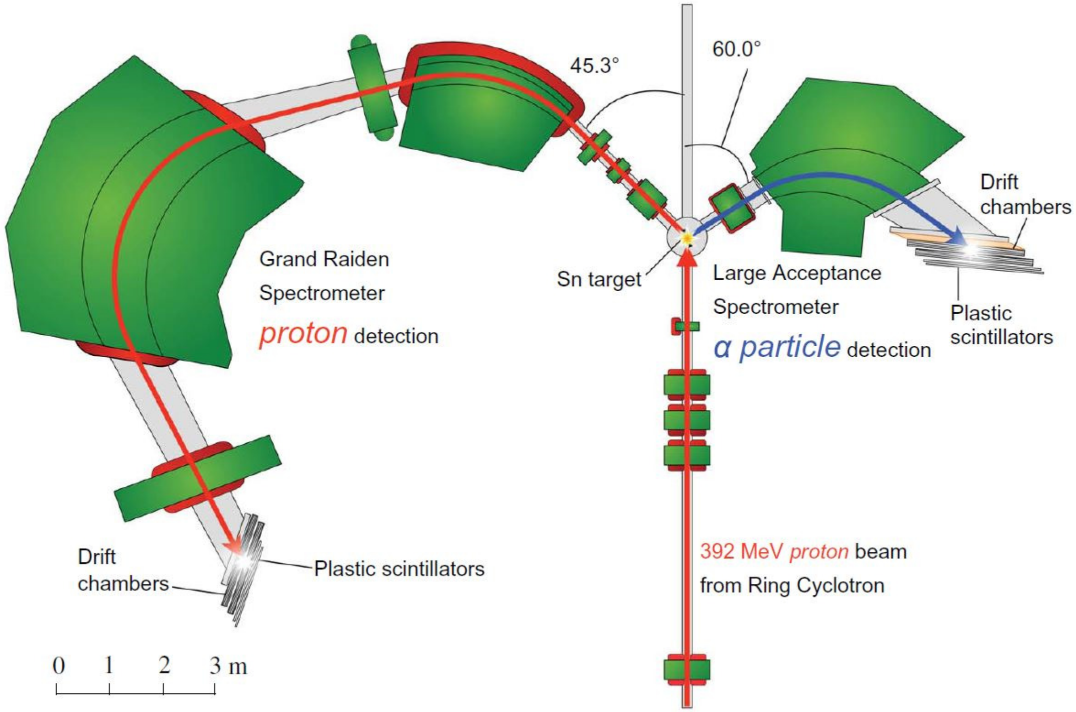
^{14}Be(p,pα)^{8}He

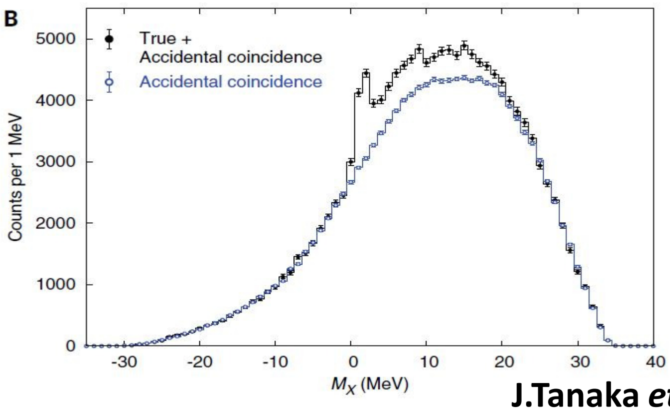


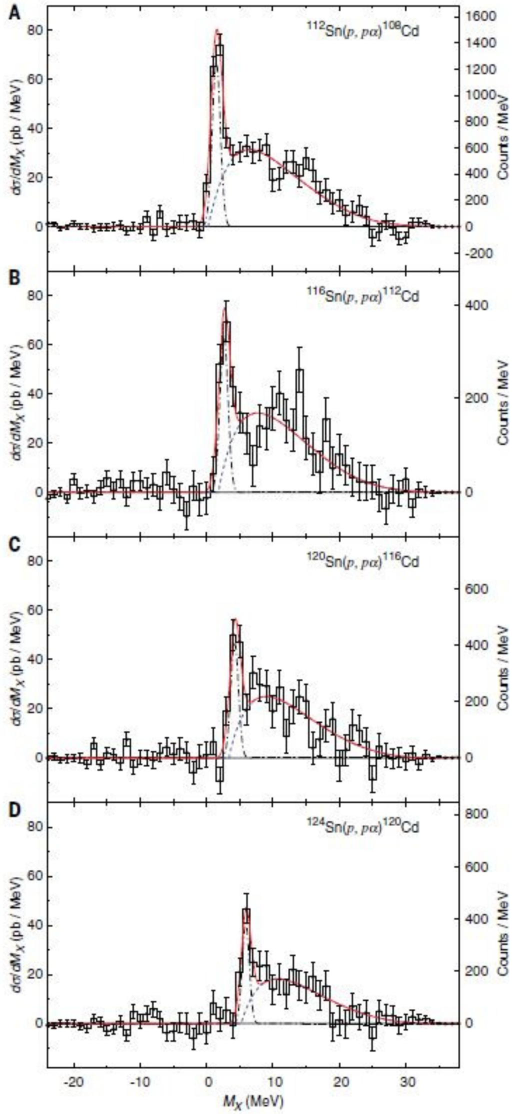
Gated by ^{8}He residue

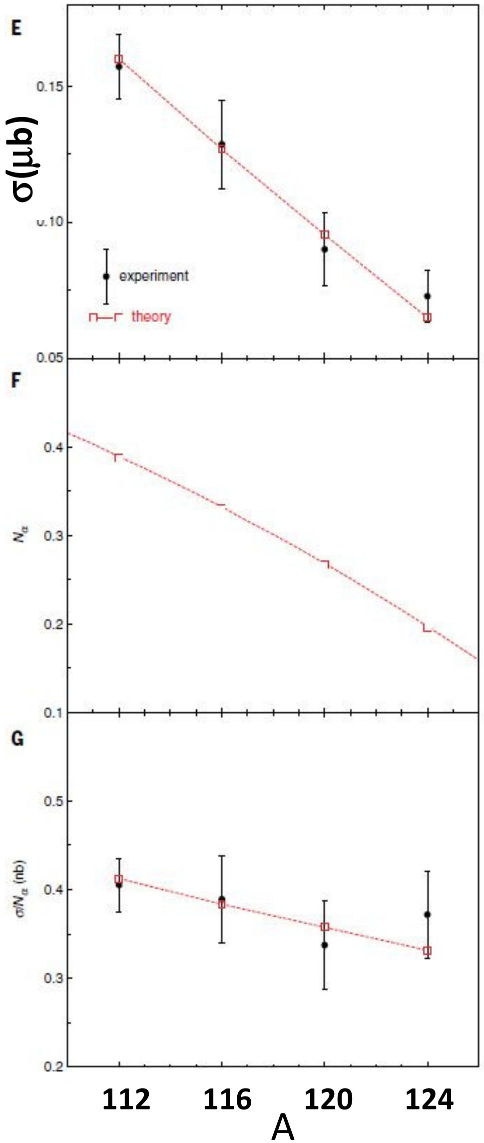
Clustering evolution with N

Study of surface α-clustering in $^{112,116,120,124}Sn(p,p\alpha)$





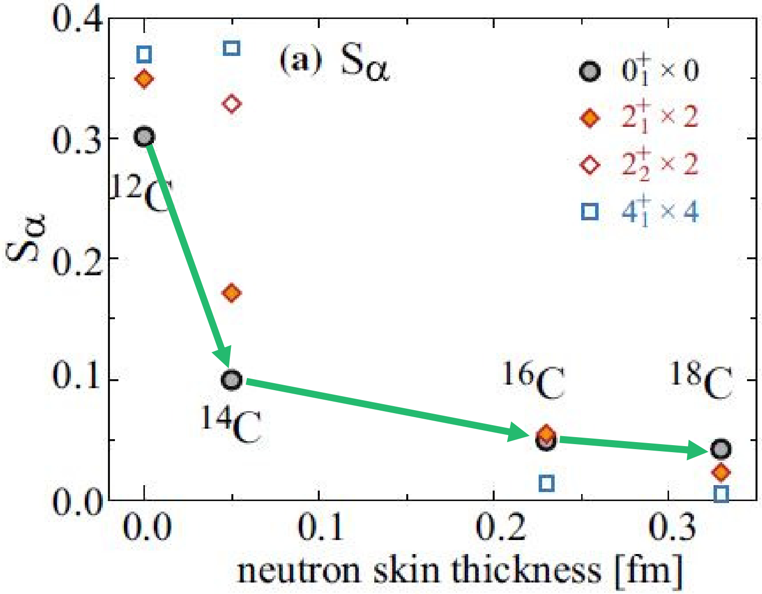




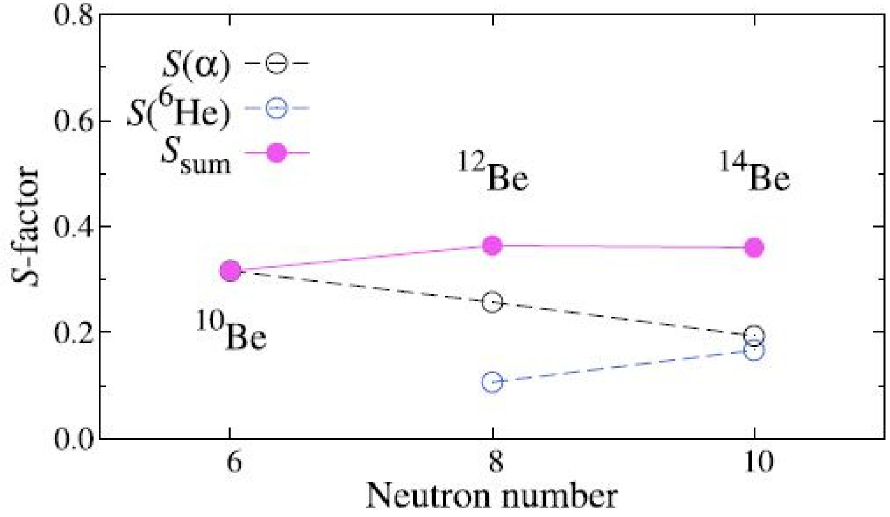
J.Tanaka *et al.,* Science 371, 260 (2021)

Clustering evolution towards the dripline

Carbon isotopes



Beryllium isotopes



Q. Zhao, Y. Suzuki, J. He, B. Zhou, M. Kimura, EPJA 157 (2021)
AMD calculations using Gogny D1S functional

H.Motoki, Y.Suzuki, T.Kawai. M. Kimura, PTEP (2022)113D01
AMD calculations using Gogny D1S

Hindrance effect due to neutron skin ?

Alternative interpretations

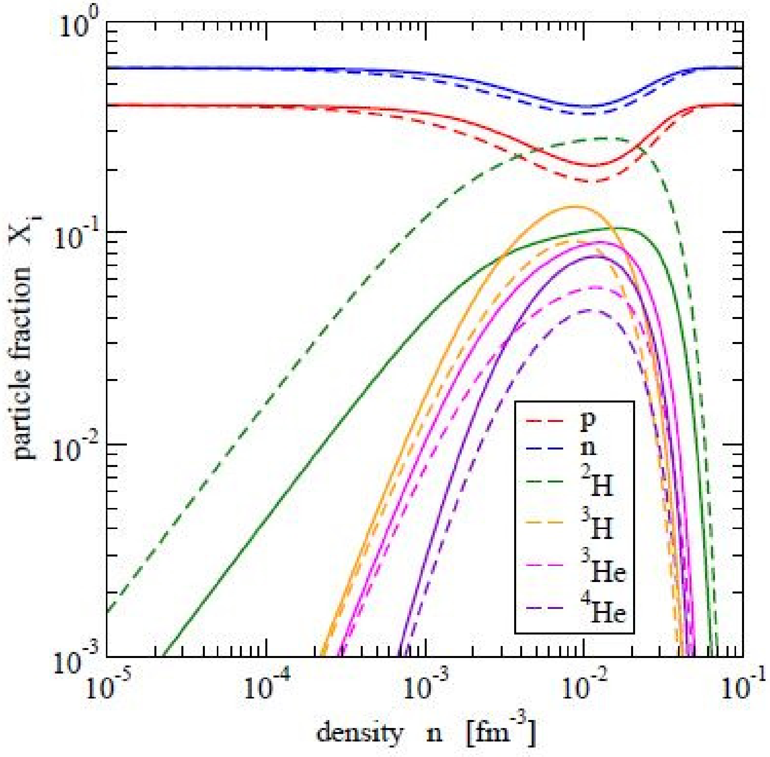
- Neutron single-particle configurations
- Relationship between α-clustering and α-threshold

- Hindrance of α clustering
- Development of ^{6}He clutering

Formation of clusters in infinite nuclear matter

Generalized DFT calculations

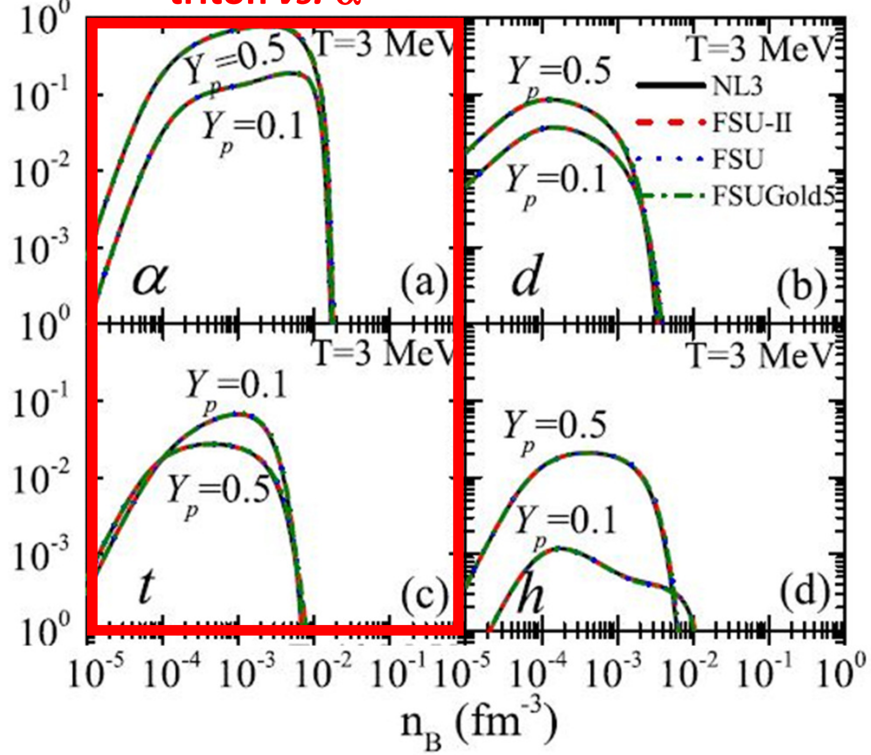
All kind of clusters should be formed at low density



S.Typel, J.Phys.Conf.Ser.420,012078(2013)

Neutron-rich clusters might well be predominant in neutron-rich nuclei

triton *vs.* α

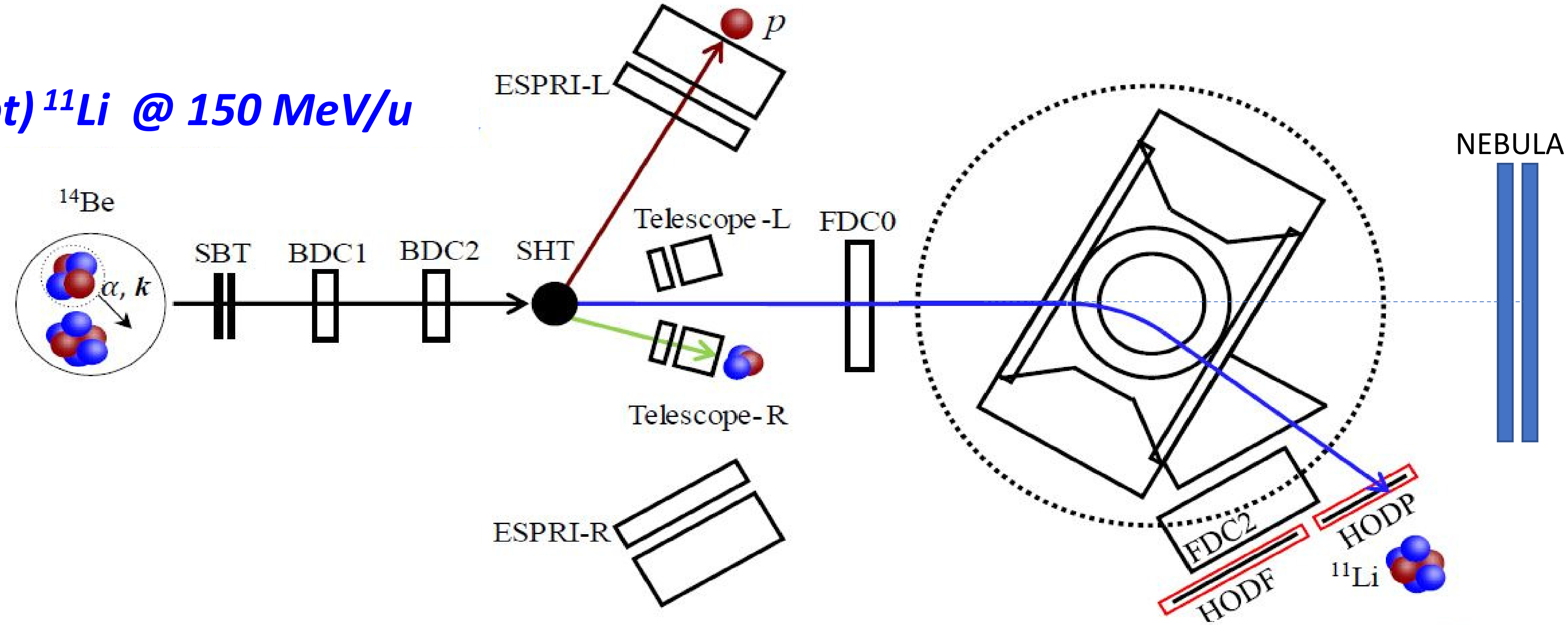


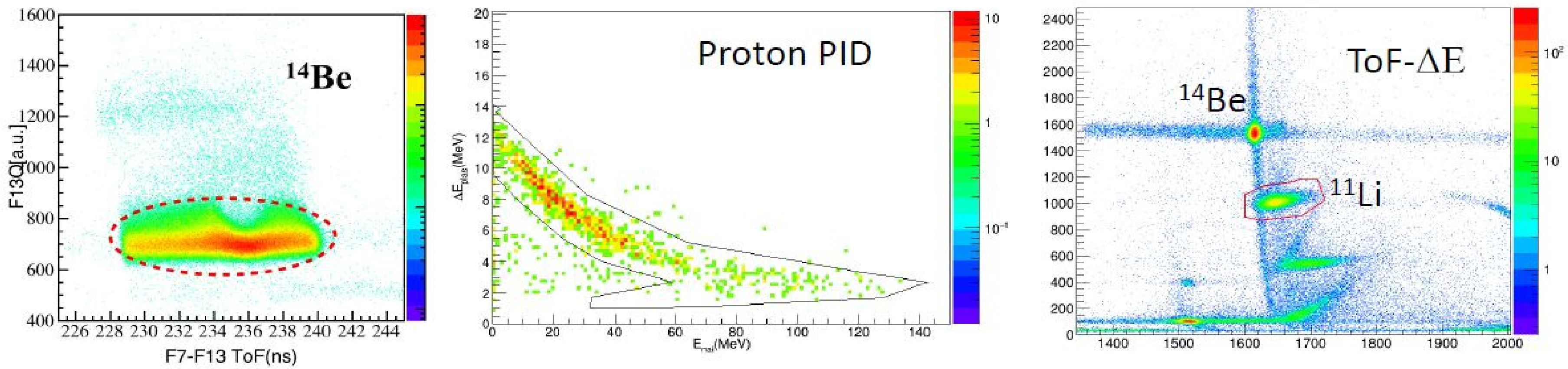
Z.-W. Zhang and L.-W Chen, Phys. Rev. C 95, 064330 (2017)

Seek for triton clustering in light n-rich isotopes

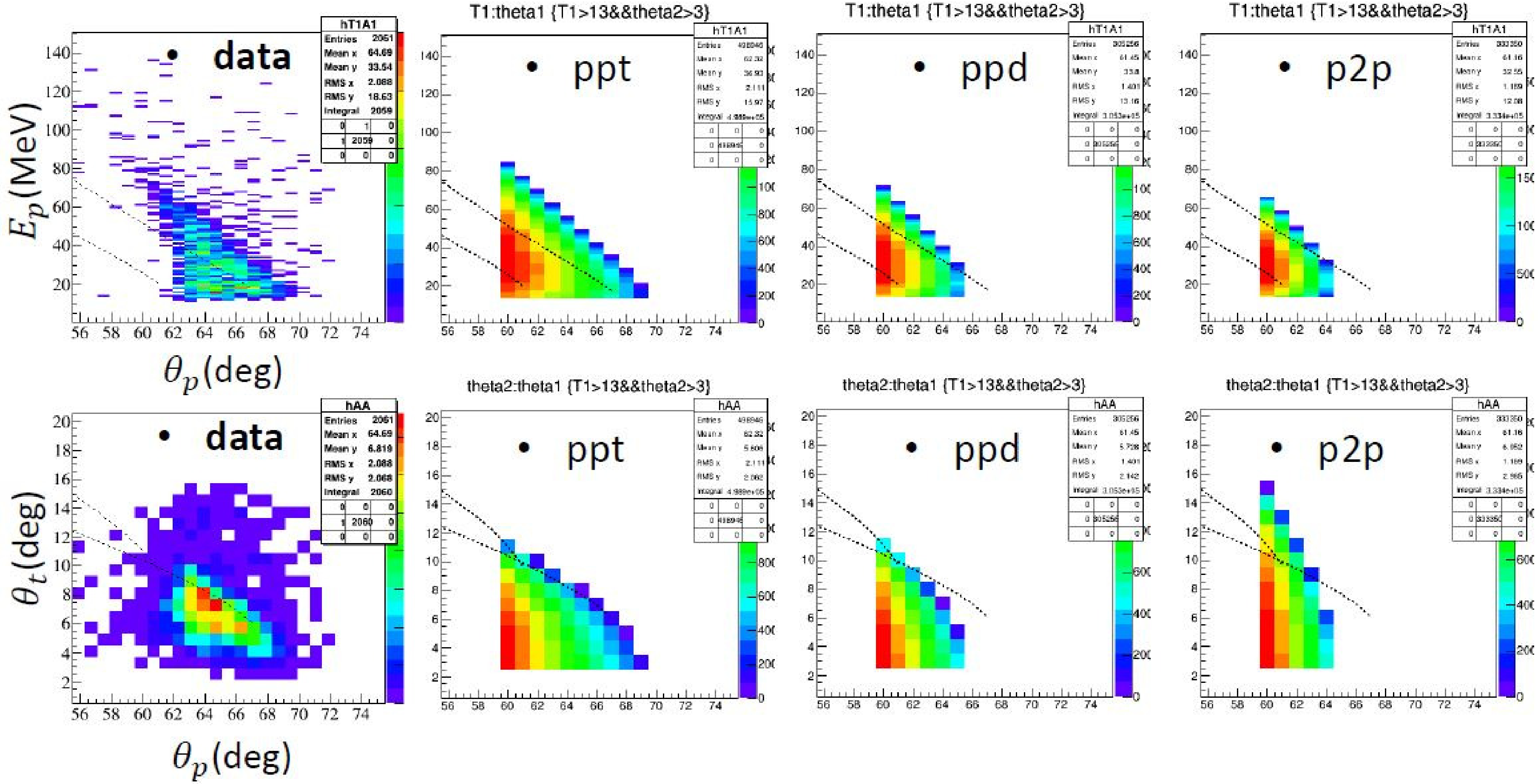
Search for triton formation at the surface of ^{14}Be

^{14}Be(p,pt) ^{11}Li @ 150 MeV/u



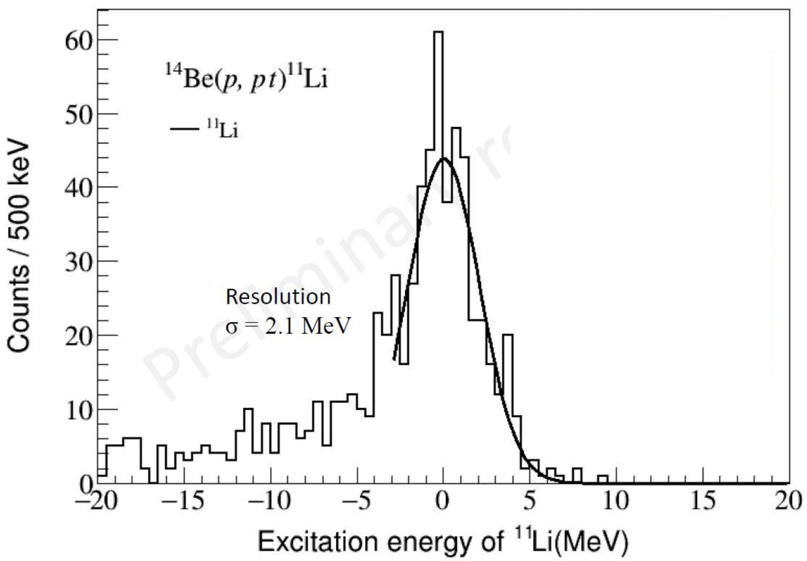


Kinematical correlations

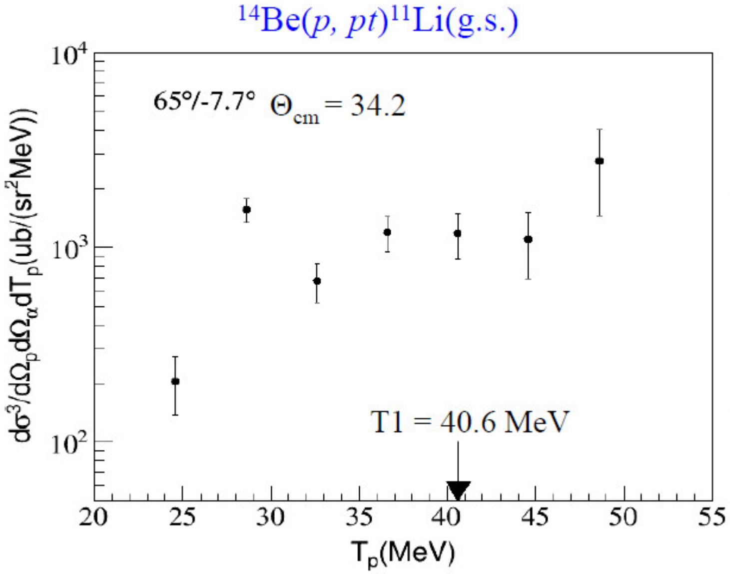


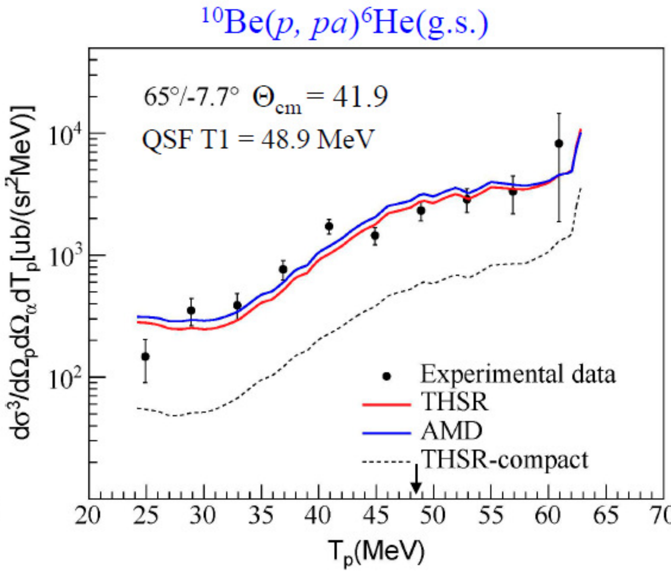
Preliminary results for triton knockout from ^{14}Be

E_x spectrum in ^{11}Li residue



Triple differential cross-section





Comparable magnitude !

Sizeable amount of triton clusters at the surface of the ^{14}Be halo nucleus

Conclusions/Prospects (clustering)

- First measurement of (p,pα) in inverse kinematics with RIB with proper kinematical conditions
  → direct evidence of the Molecular structure of the ^{10}Be GS

- First steps to quantitatively probe cluster evolution in GS towards the dripline
  Preliminary results show large amount of tritons at the surface of the halo nucleus ^{14}Be

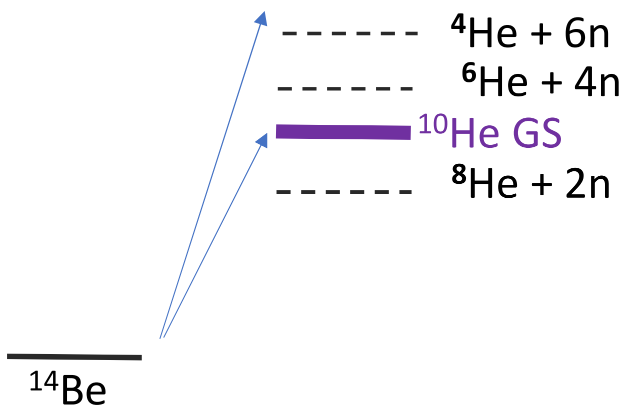
  Complementary program using transfer reaction at LISE/GANIL with the MUGAST array
  E870 experiment accepted at last GANIL PAC meeting
  (p,α) and (d,^{6}Li) pickup reactions in inverse kinematics

- Planned study of (p,pα) on n-rich Carbon isotopes at RIKEN/Samurai (accepted expt)
  (spokesperson: Zaihong Yang)

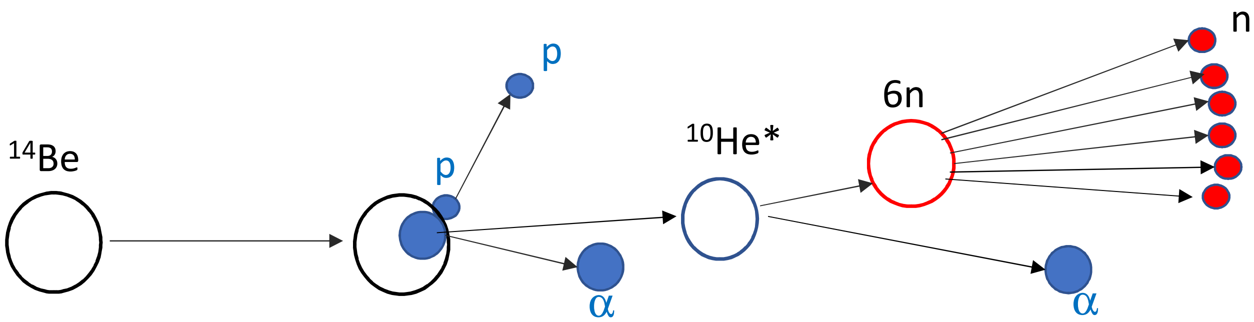
- The "ONOKORO" research project (T.Uesaka, J.Zenihiro)
  study of (p,pα), (p,pt), (p,^{3}He),(p,pd)… in stable and unstable medium-mass and heavy nuclei
  TOGAXSI device under construction

First exp^al^ determination of the 6-neutron spectrum

^{14}Be(p,pα) reaction



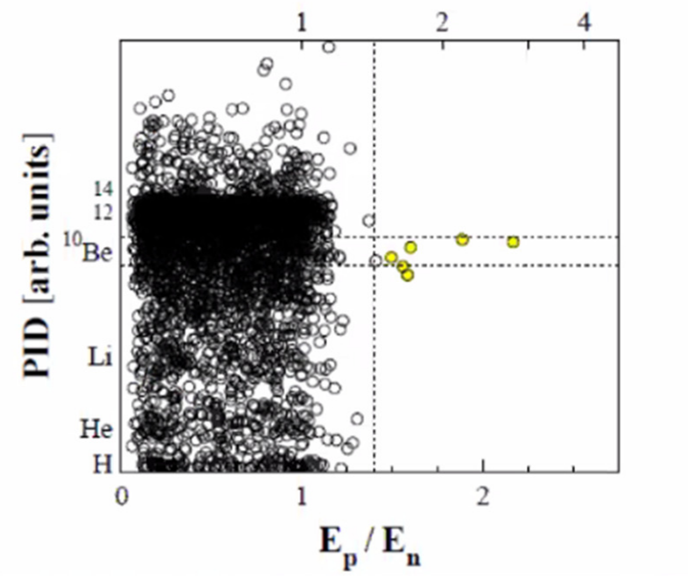
- ^{10}He* populated by **^{14}Be(p,pα)**
- High ^{14}Be rate at RIBF
- Decay channel : α + 6n
  α is detected by SAMURAI
- 6n spectrum reconstructed by missing mass
  - ✓ No need of neutron detection
  - ✓ No direct info on neutron correlations



Theory: no realistic calculation for the 6n system

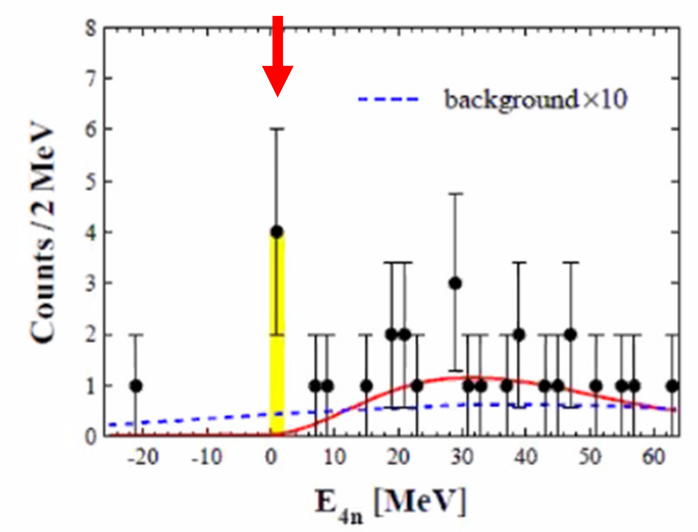
Recent (XXI century) signals on tetraneutron

$^{14}Be \rightarrow {}^{10}Be + 4n$



M.Marques et al., PRC65, 044006 **(2002)**

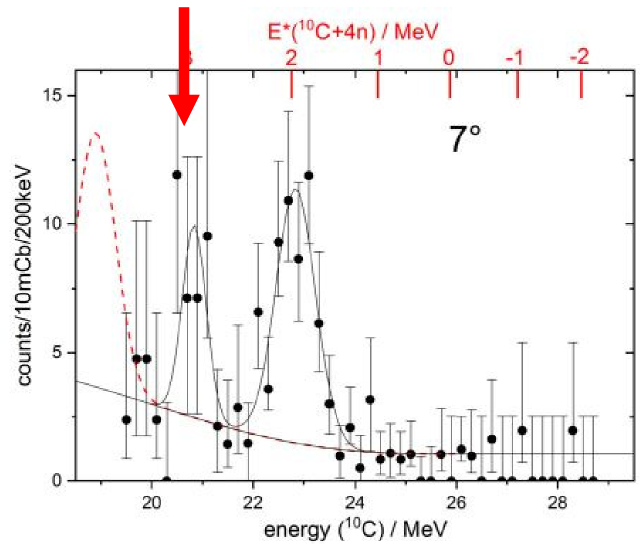
$^{4}He\ (^{8}He,\alpha\alpha)\ 4n$



K.Kisamori et al., PRL 116, 052501 **(2016)**

E = 0.83 ± 0.65 (stat) ± 1.25 (syst) MeV

$^{7}Li\ (^{7}Li,\ ^{10}C)\ 4n$



T.Faestermann et al. Phys.Lett. B 824 **(2022)**

E = 0.42 ± 0.16MeV

Theory : another hard & interesting quest

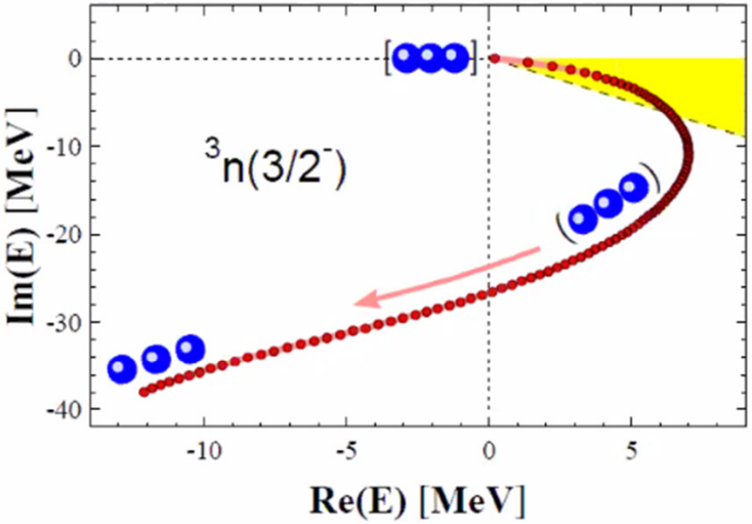
- 'Exact' calculations are categorical !

Glöckle, PRC 18 (1978) 564 : $V_{nn} \times 4.2$

Offermann, NPA 318 (1979) 138 : $V_{nn} \times 3.7$ (+P-waves)

Witała, PRC 60 (1999) 024002 : avoid ^{2}n with $V_{nn}(^1S_0) \times 1$

Hemmdan, PRC 66 (2002) 054001 :



"3n resonances close to the physical region will not exist"

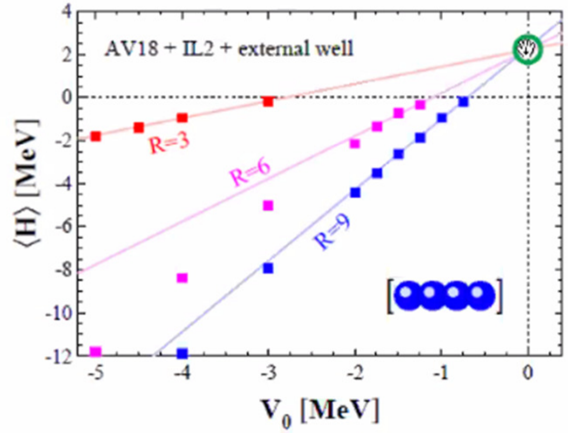
(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF ✗

(4n) Lazauskas, PRC 72 (2005) 034003 : 4NF ✗

(3,4n) Hiyama, PRC 93 (2016) 044004 : 3NF(T=3/2) ✗ !

- Many-body approximations, not so much ...

Pieper, PRL 90 (2003), 252501 :



"the resonance, if it exists at all, must be very broad"

Shirokov, PRL 117 (2016) 182502
Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501
Li, PRC 100 (2019) 054313

} 3n/4n ✔ ?

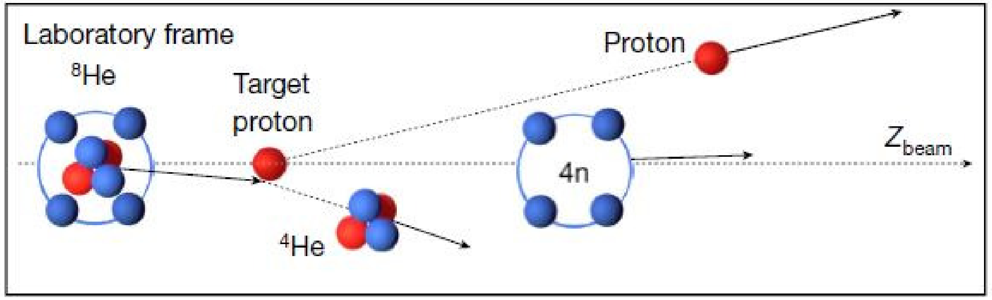
Courtesy from F.M.Marques

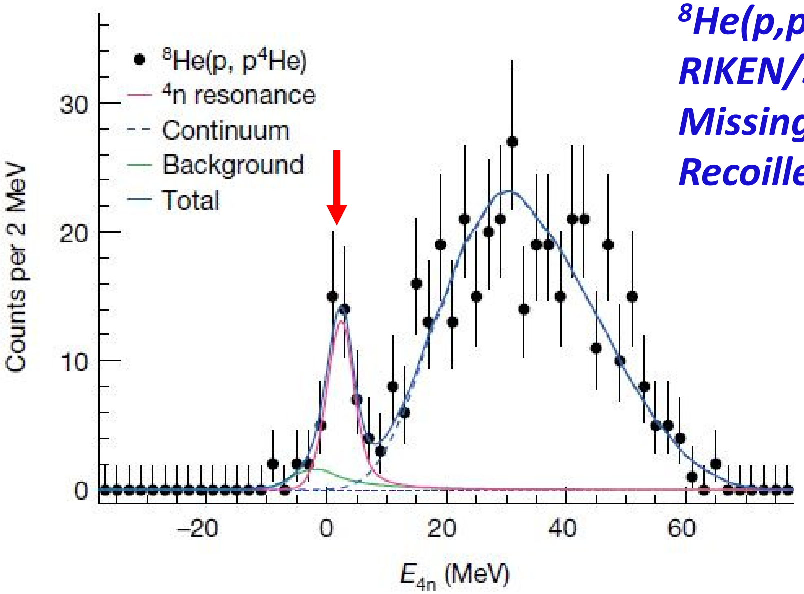
Article

Observation of a correlated free four-neutron system

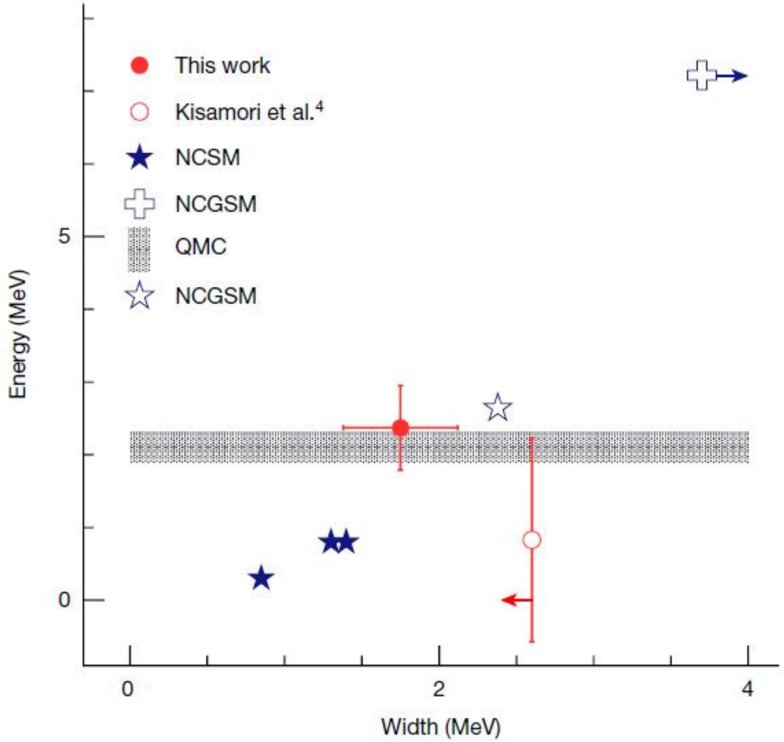
M. Duer et al., Nature (London) 606, 678 (2022)

https://doi.org/10.1038/s41586-022-04827-6 M. Duer[1], T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1],





^{8}He(p,pα) @ 156 MeV/u
RIKEN/Samurai
Missing mass
Recoilless condition



- ***Low energy peak***

  E = 2.37 ± 0.38(stat.) ± 0.44 (sys.) MeV

  Γ= 1.7 ± 0.22 (stat.) ± 0.30 (sys.) MeV

- ***Broad bump***

  well described by non-resonant continuum calculations

Interpretation by Lazauskas, Hiyama, Carbonell

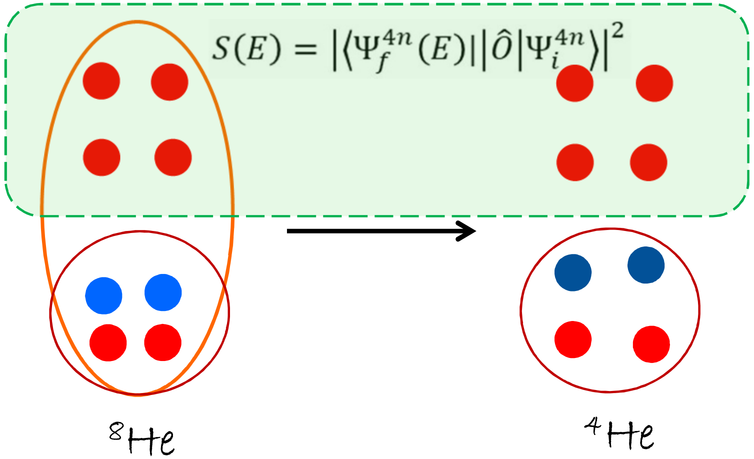
Phys. Rev. Lett. 130, 102501 (2023)

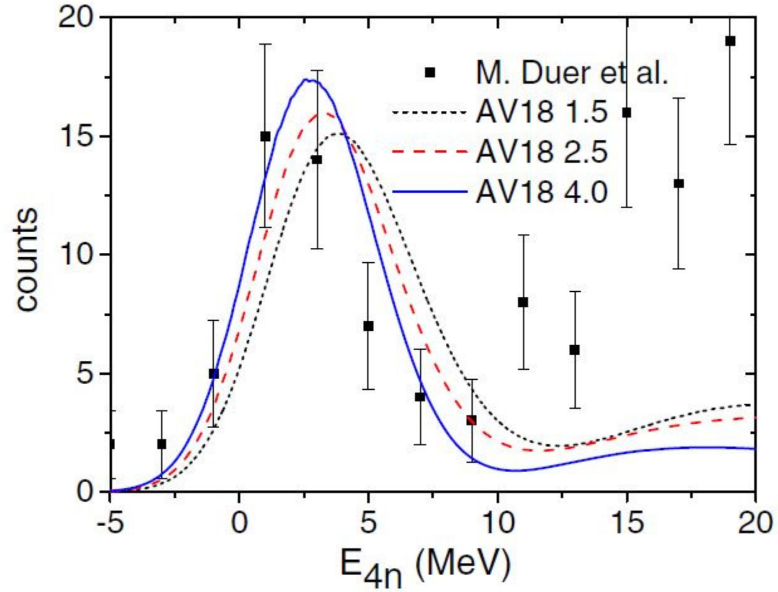
$$H_i = H_0 + \lambda \sum_{i=1}^{N} |\psi_\alpha(r_i)\rangle\langle\psi_\alpha(r_i)| + \sum_{i<j=1}^{N} V_{nn}(r_{ij})$$
$$+ \sum_{i=1}^{N} V(r_{iG}) + \sum_{i<j=1}^{N} W_{ij}(\rho, r_{ijG}),$$

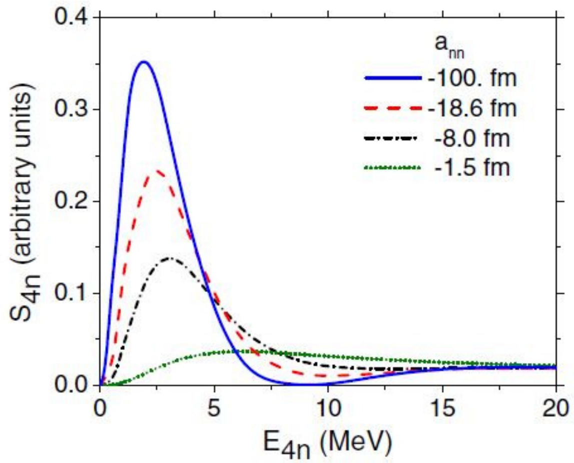
Action of the ^{4}He mean field on valence n's adjusted to ^{6}He and ^{8}He GS binding

$$H_f = H_0 + \sum_{i<j=1}^{4} V_{nn}(r_{ij}).$$

$$\begin{cases} H_i \mid \Psi_i\rangle = E_i \mid \Psi_i\rangle. \\ H_f|\Psi_f\rangle = E_{4n}|\Psi_f\rangle. \end{cases}$$







dineutron-dineutron correlations !

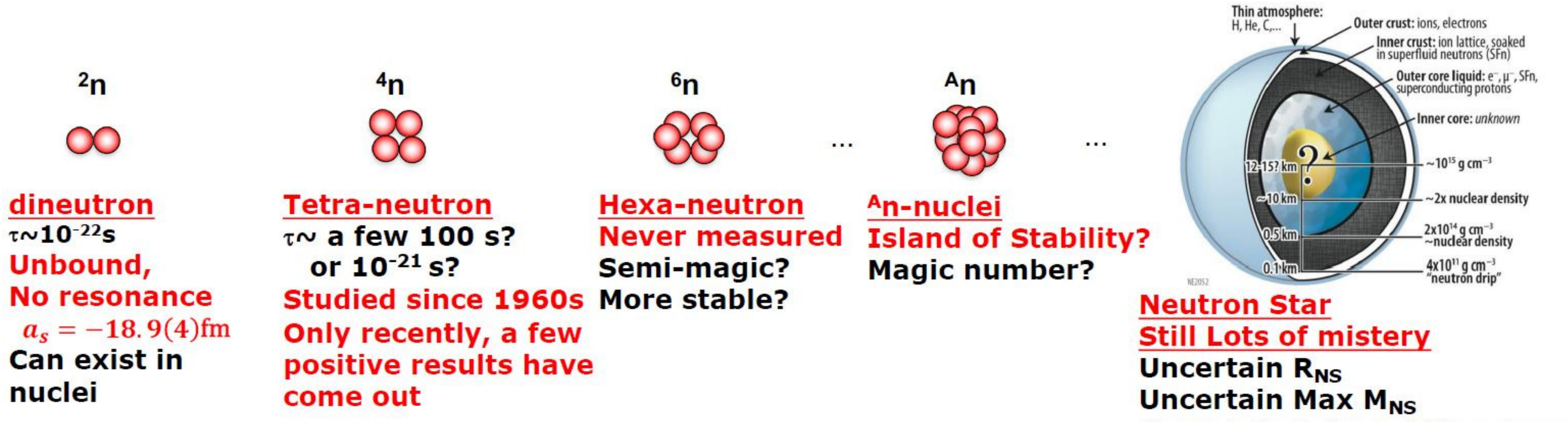
Conclusions/Prospects

3n and 4n system

- Data for ^{8}He (p,2p) {^{3}H+**4n**} (RIKEN/Samurai) under analysis (LPC Caen)
- t (t, ^{3}He)**3n** (RIKEN/SHARAQ) under analysis (T.Miki)

6n system

- $^{14}Be(p,pa)^{10}He^{*}$ -> **6n**+alpha - Data from SAMURAI12 under analysis (O.Nasr, IJCLab)
- $^{11}Li(p,2p)^{10}He^{*}$ -> **6n**+alpha - SAMURAI47 (Sp. T.Nakamura) to be run in June 2023
- $^{6,8}He(p,3p)$ accepted at RIKEN



Sketch from T.Nakamura