

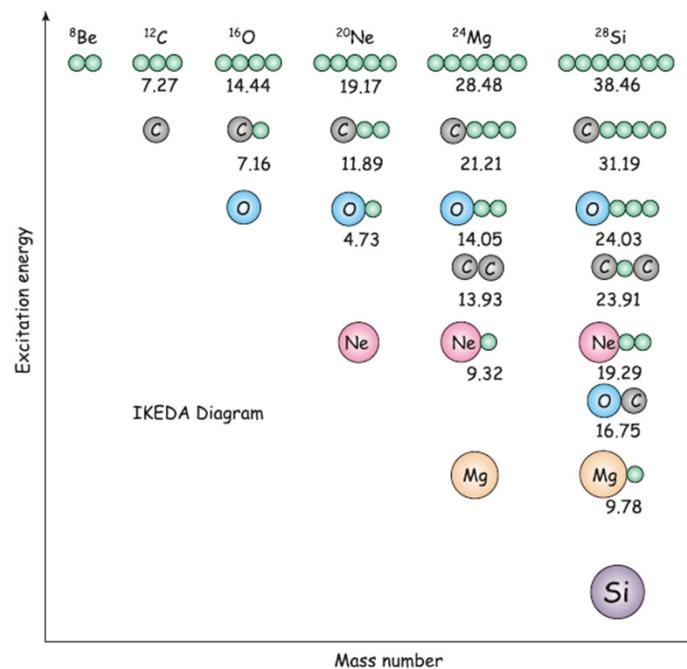
Studies of alpha clustering using cluster knockout reactions

D.Beaumel
IJCLab, Orsay

- **Introduction**
- **Experimental approaches to clustering**
- **Cluster knockout (Cluster quasifree scattering) reactions**
- **Study of clustering in the GS of neutron-rich Be**
- **Study of clustering in the GS of stable Sn isotopes**
- **Prospects**

Clustering in neutron-rich isotopes

The Ikeda diagram
(alpha-conjugate nuclei)



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

Cluster structure typically occurs
close to cluster decay thresholds

Adding neutrons :

New Cluster structure !
Orbital motion around core clusters
Molecular structure evidenced
for ground and low lying states

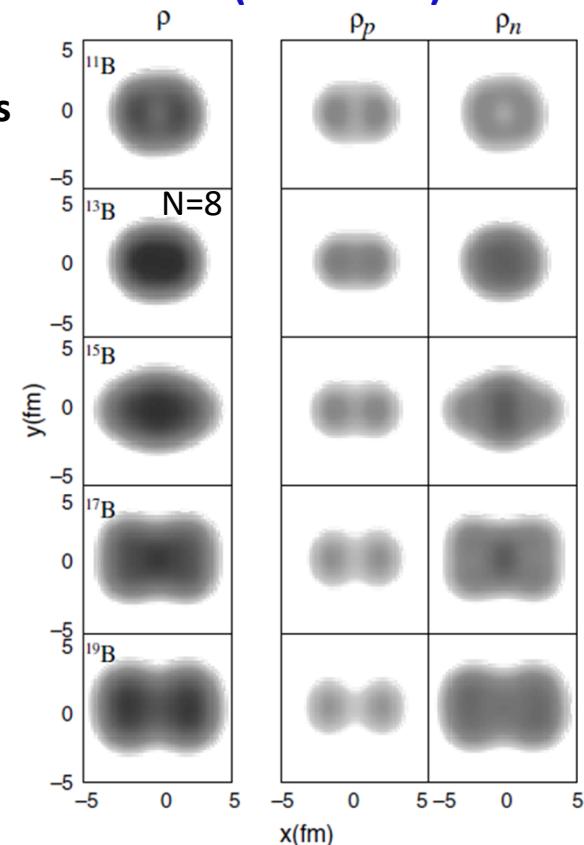
Close to dripline

Clustering vanishes?
role of excess neutrons
neutron skin vs surface clustering

Near $\text{N}\alpha + xn$ threshold

Neutron clusters e.g dineutron
Favourable to observe
neutron clusters ?

Boron isotopes GS
(AMD calc)



He-decay
Threshold
(MeV)

8.663

10.816

13.576

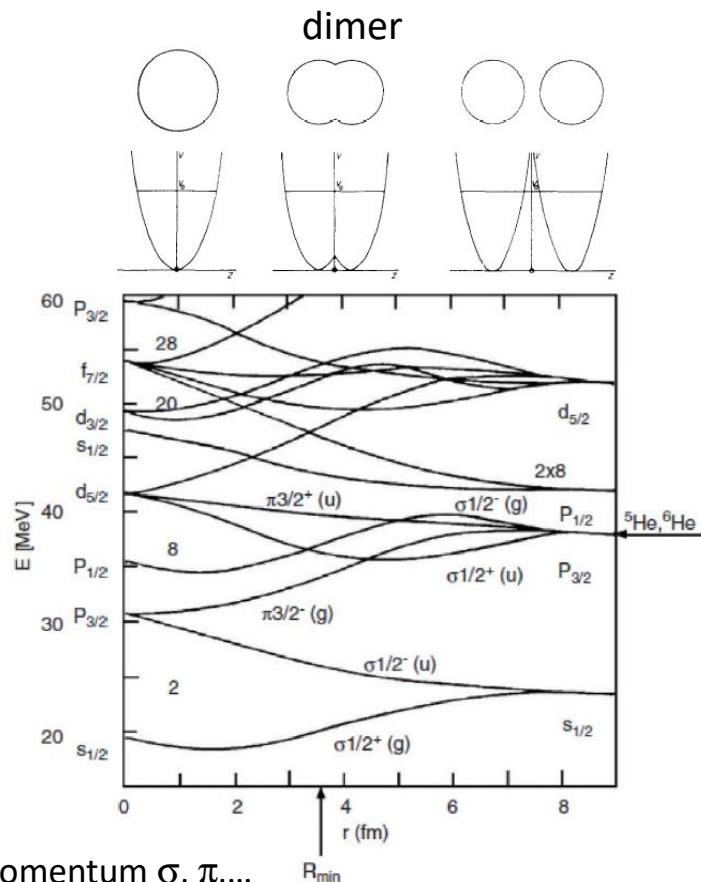
13.242

13.138

Antisymmetrized Molecular Dynamics calc.
Y.Kanada-En'yo, H.Horiuchi 2001

Two-center Shell Model

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

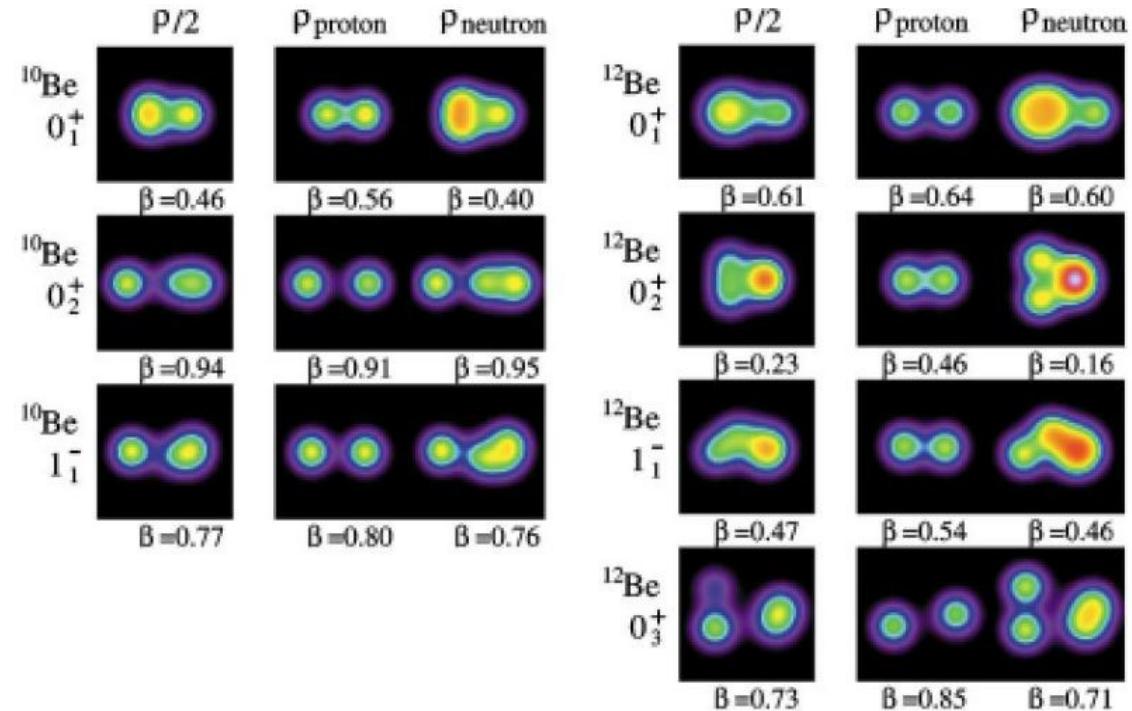


Generalization : dimers \rightarrow polymers

Antisymmetrized Molecular Dynamics

Y.Kanada-En'yo, M.Kimura, H.Horiuchi, CR Physique 4(2003)

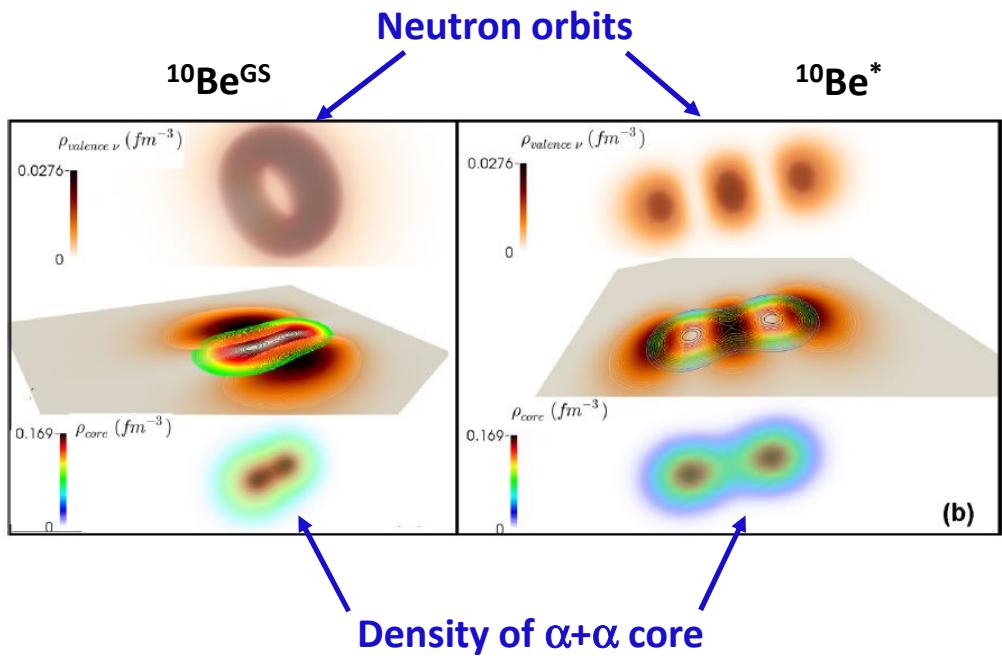
Intrinsic densities for Be isotopes



Density Functional Theory studies for clustering in light nuclei

DDME2 relativistic functional in rel. HB calculations

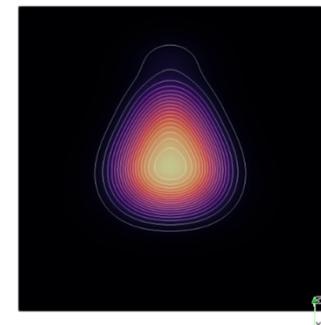
J.P.Ebran, E.Khan, T.Niksic, D.Vretenar, PRC90 (2014)



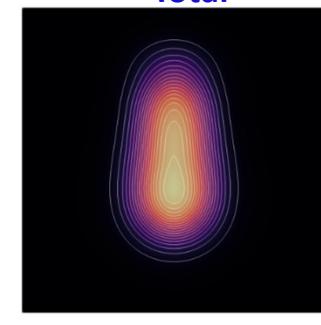
Recent calculations for ^{12}Be

Rel. HB with DD-PC1 + projected GCM

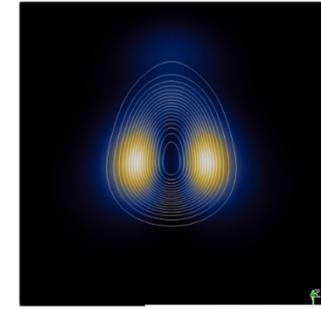
$^{12}\text{Be GS}$
Total



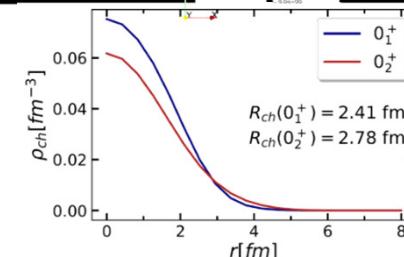
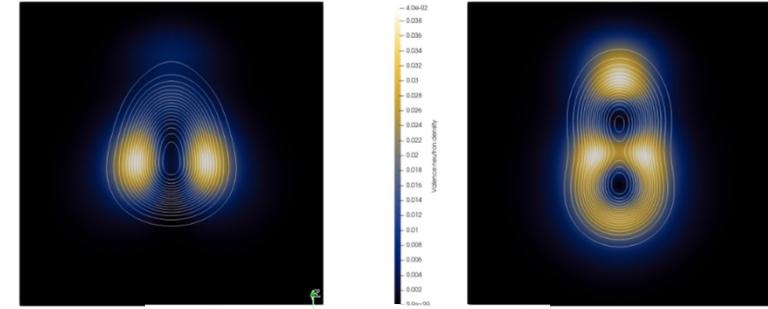
$^{12}\text{Be } \text{G}(0^+_2)$
Total



Valence neutrons



Valence neutrons

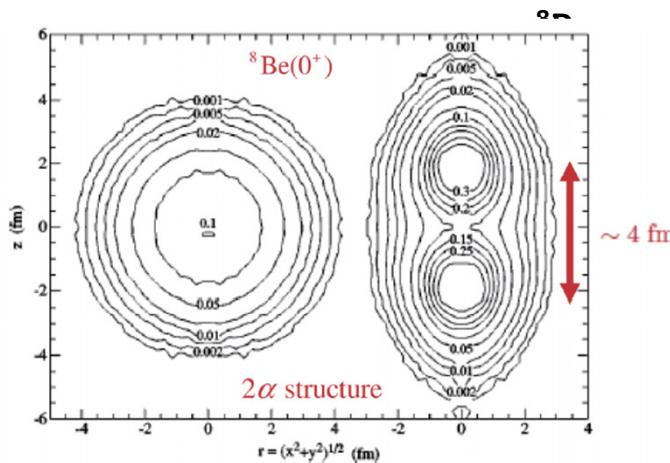


J.P.Ebran, et al.

ab initio calculations for Be isotopes

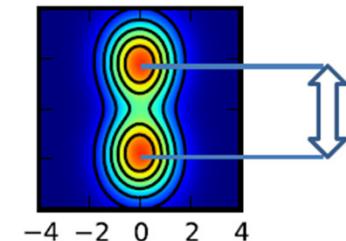
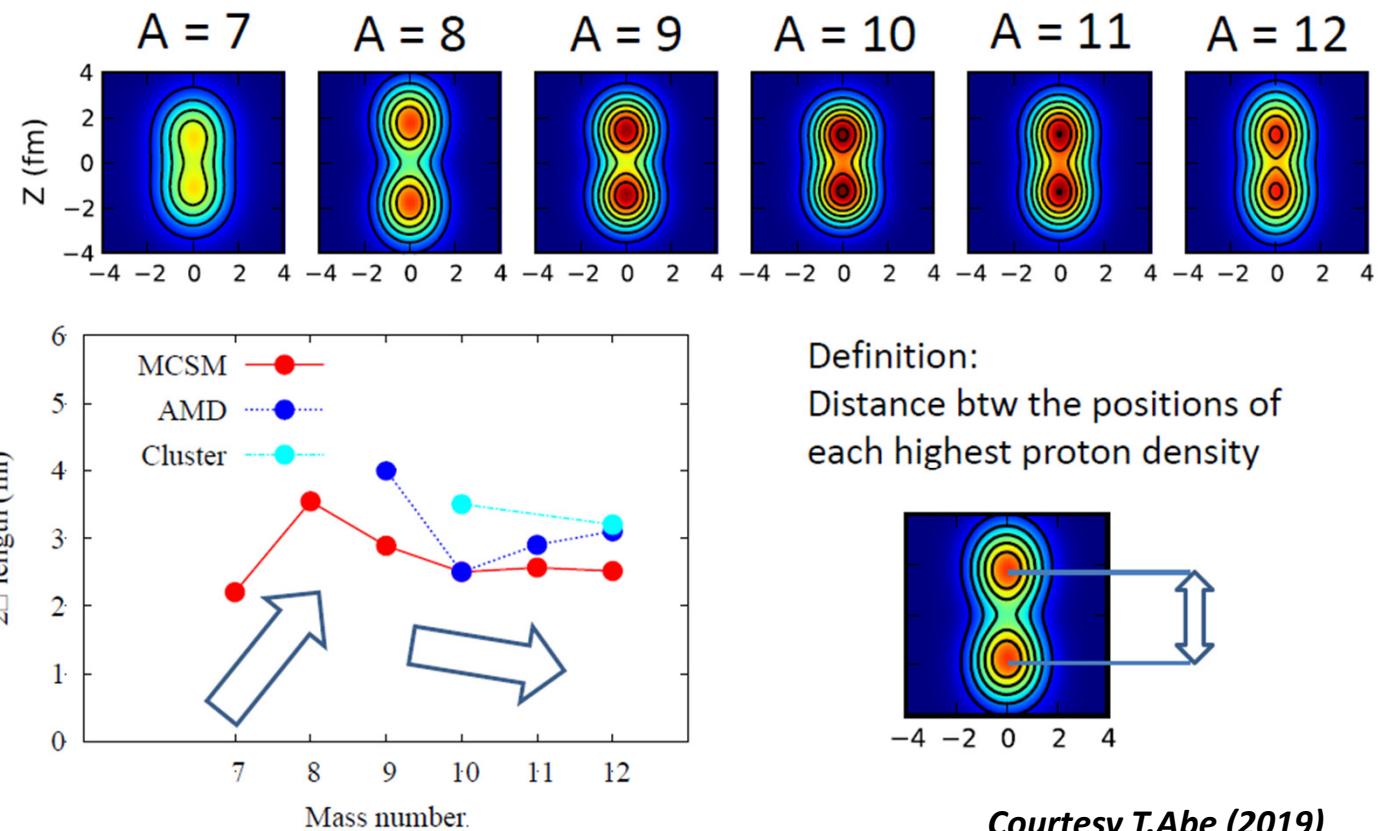
QMC calculation for ${}^8\text{Be}$

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

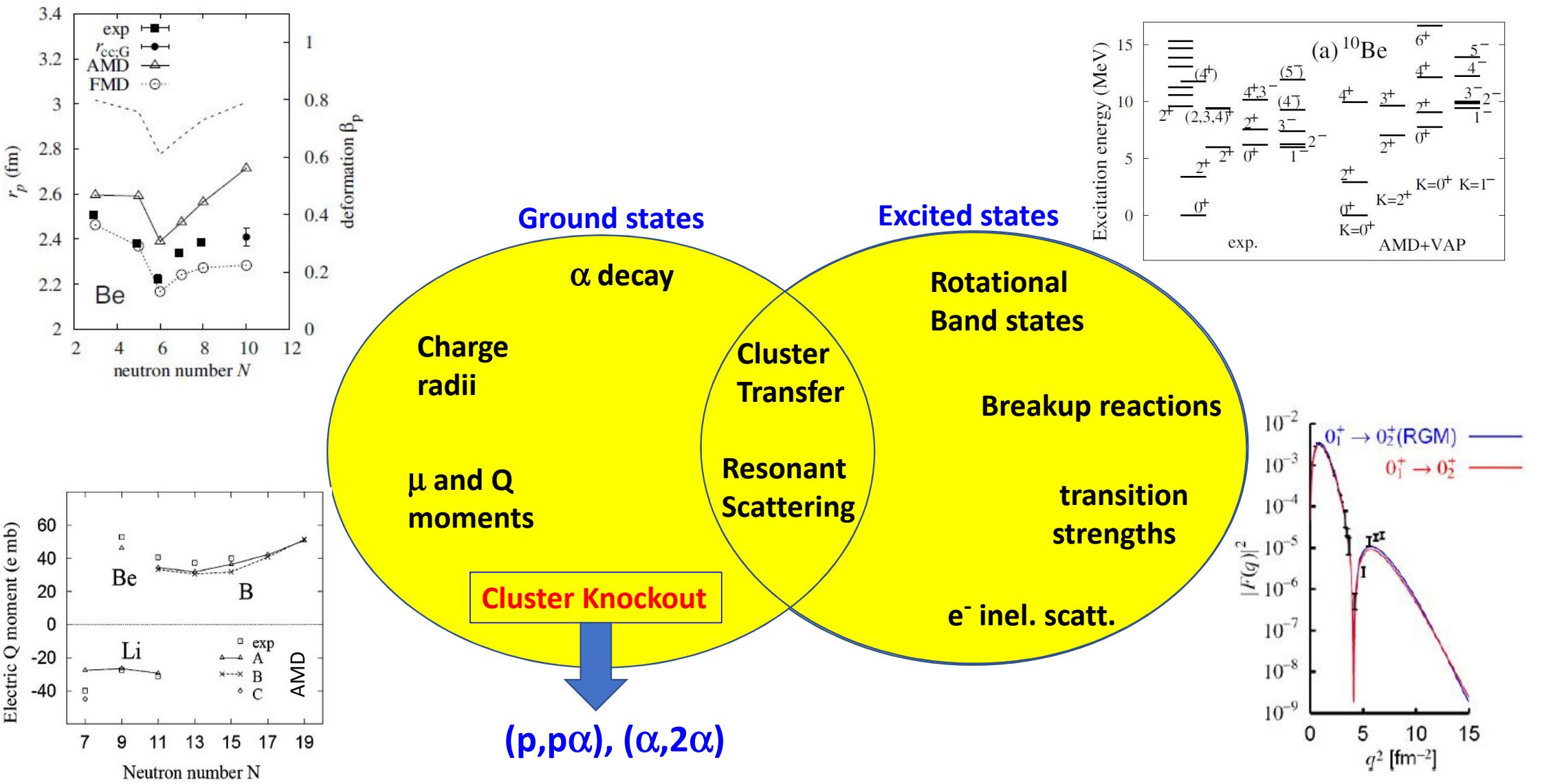


Courtesy T.Abe (2019)

AMD: Y. Kanada-En'yo, Phys. Rev C68, 014319 (2003)

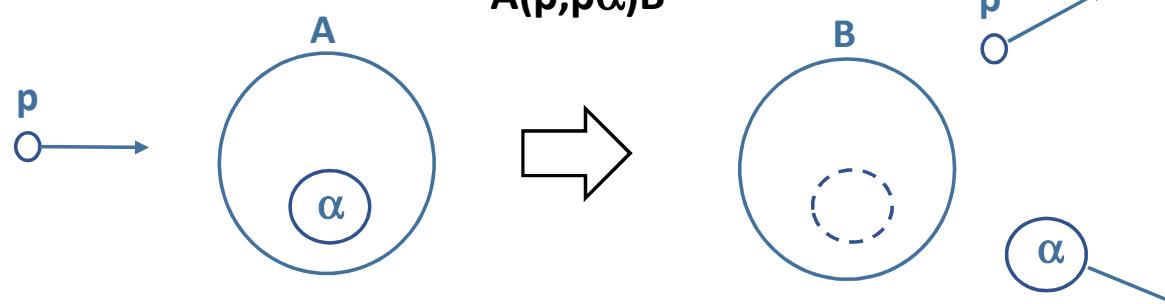
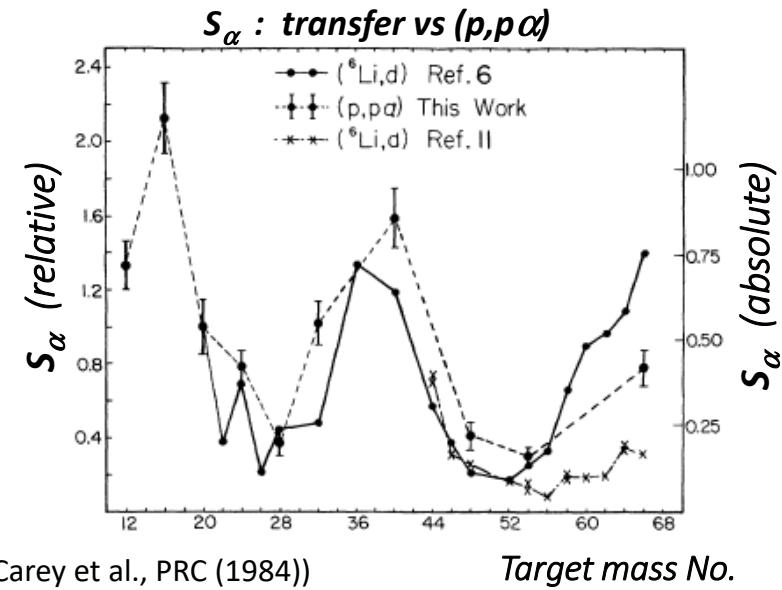
Cluster: M. Ito & K. Ikeda, Rep. Prog. Phys. 77, 096301 (2014)

Experimental investigations of clustering

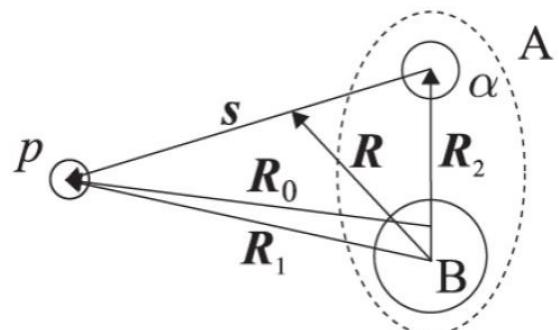
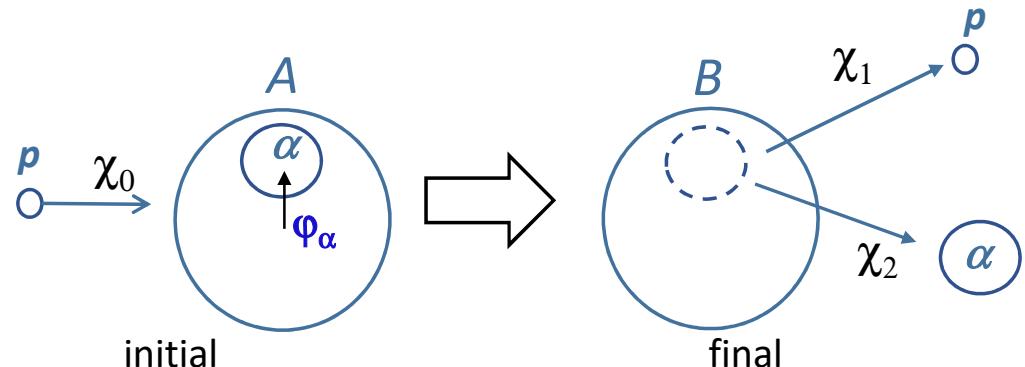


Cluster knockout reactions

- Direct reaction
 - ✓ short reaction time ($\sim 10^{-22}$ s)
 - ✓ one-step dominant
- $(e,e'p)$, $(p,2p)$ and (p,pn) for nucleons
- Well-studied since the 70's with proton (and alpha) beams on stable targets
- Incident p energy : $100\sim400$ MeV
 $(\lambda \sim 0.5\text{-}0.25\text{fm})$
- *Peripheral* reaction
- Extraction of spectroscopic factors S_α
- Very few studies with RIB's
- Recently: new analysis



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



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

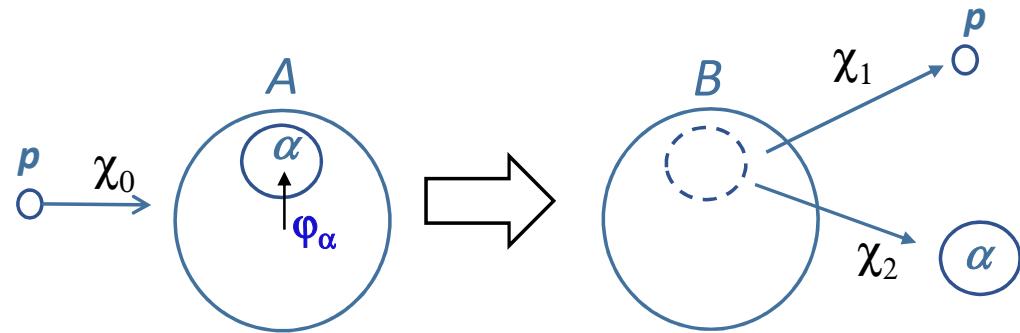
$\chi_{0,P_0}^{(+)}(R_0) \quad \chi_{1,P_1}^{(-)}(R_1) \quad \chi_{2,P_2}^{(-)}(R_2)$ distorted waves for p-A, p-B and α -B
Obtained from elastic scattering data

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

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

- Phenomenological
 - **Microscopic (MF, AMD, ...)**

Measurement of $(p, p\alpha)$ reactions



➤ Excitation energy spectrum of the residue

conservation laws \rightarrow 6 degrees of freedom (e.g. (\vec{p}_1, \vec{p}_2))

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

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

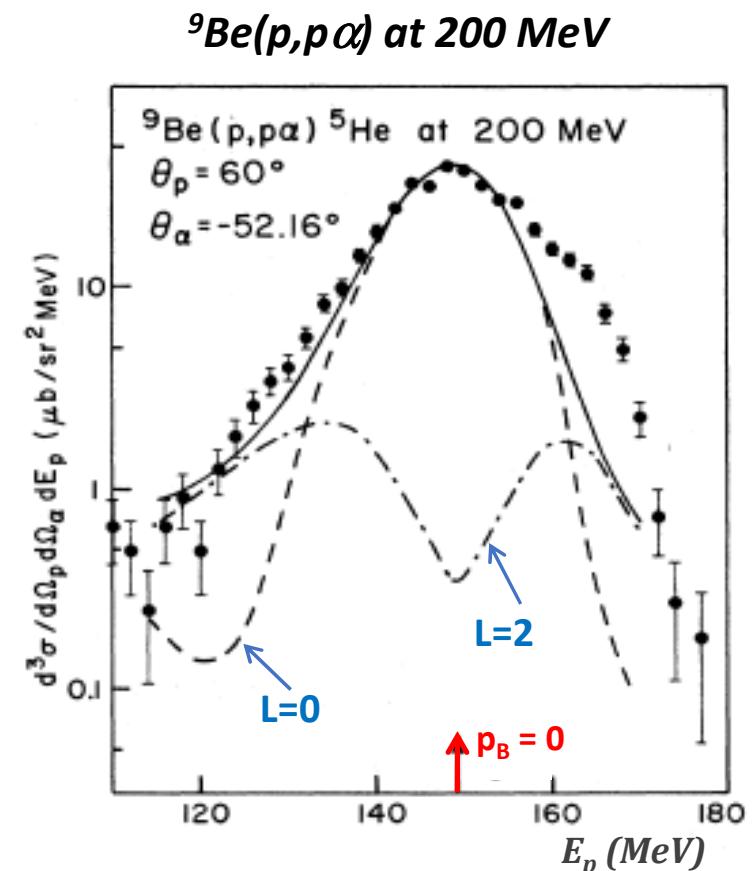
$$m_B^* = \sqrt{E_B^2 - p_B^2}$$

➤ 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 $\vec{p}_B = \vec{0}$ (quasifree)



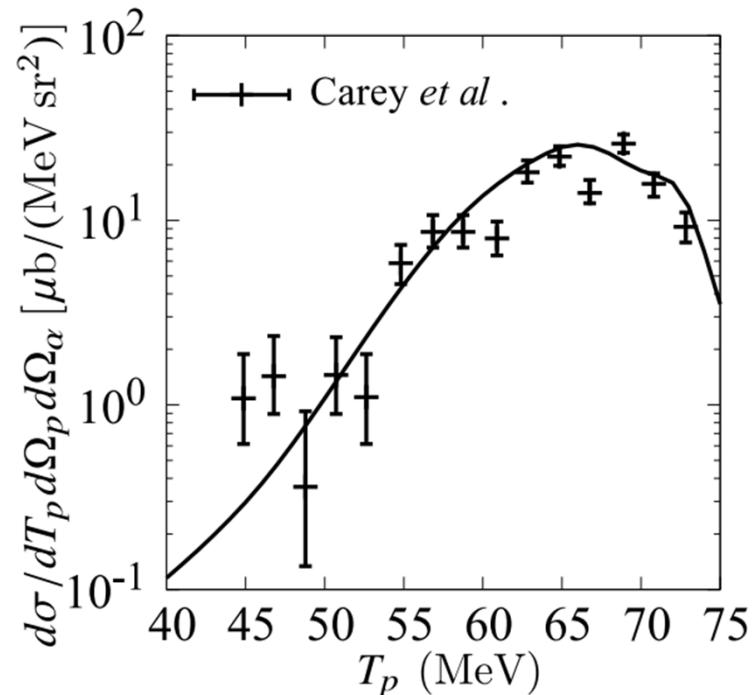
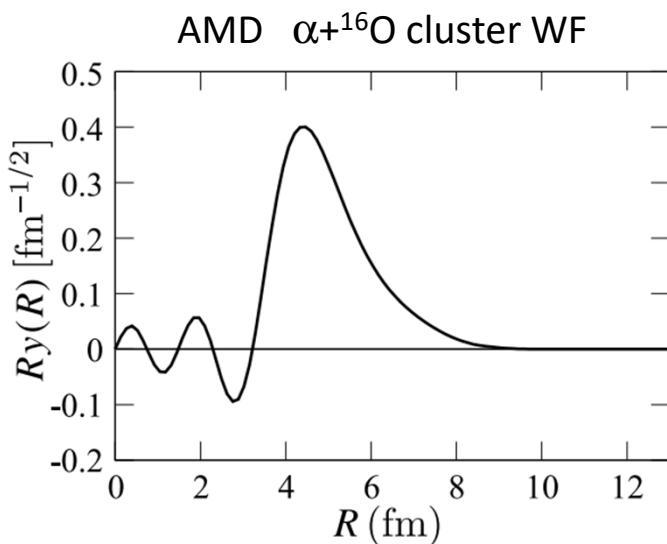
Nadasen *et al.*, PRC(1989)

Analysis using microscopic cluster WF

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

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

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



Data reproduced without any normalization

$(\text{p},\text{p}\alpha)$ represents a quantitative probe for α -clustering

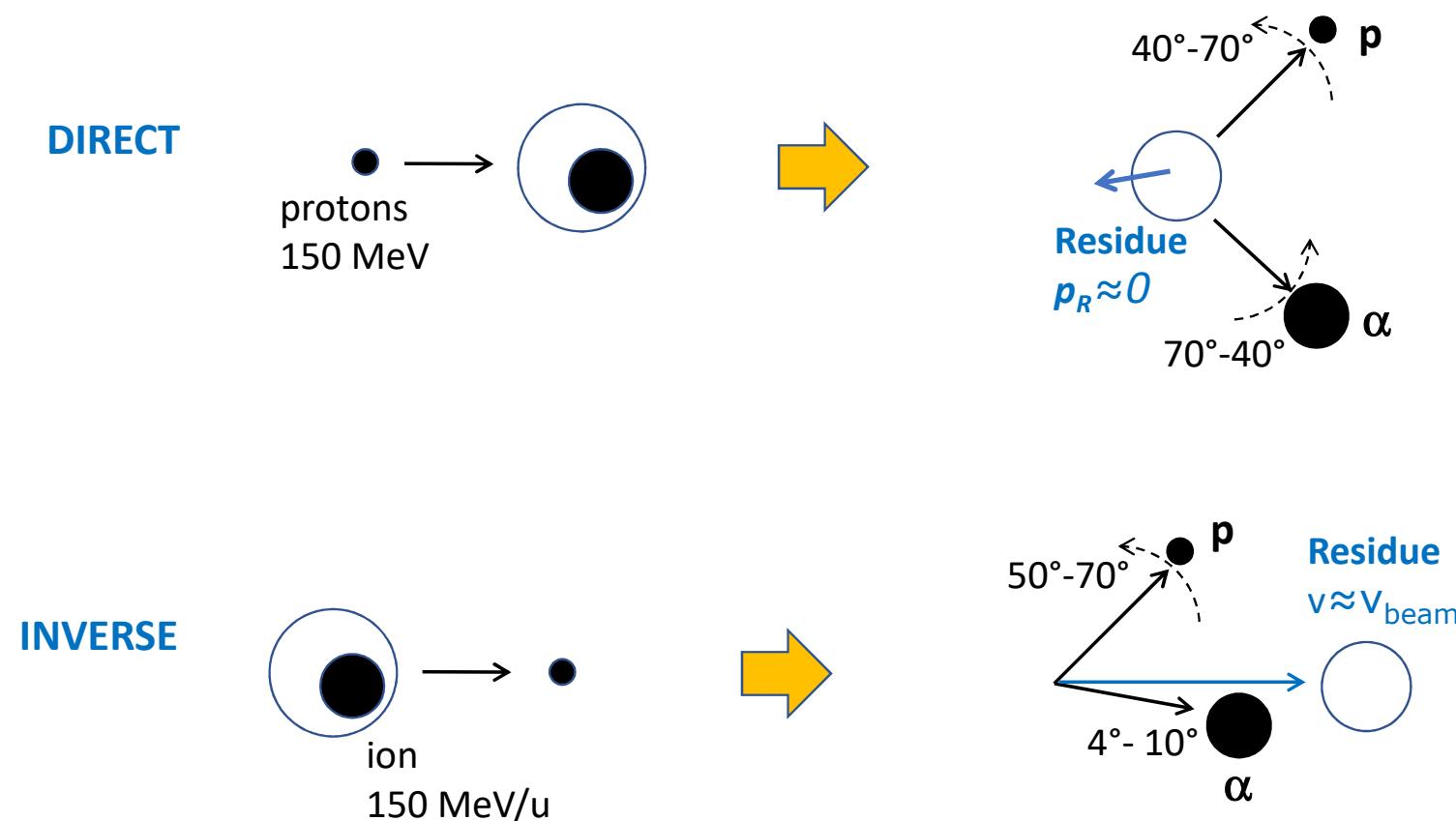
Experimental studies of cluster knockout reactions

- In inverse kinematics (RIB – proton target)
clustering in n-rich Be

- In forward kinematics (proton beam – stable target)
clustering in stable Sn

Kinematics for alpha quasifree knockout reactions

Direct vs inverse kinematics



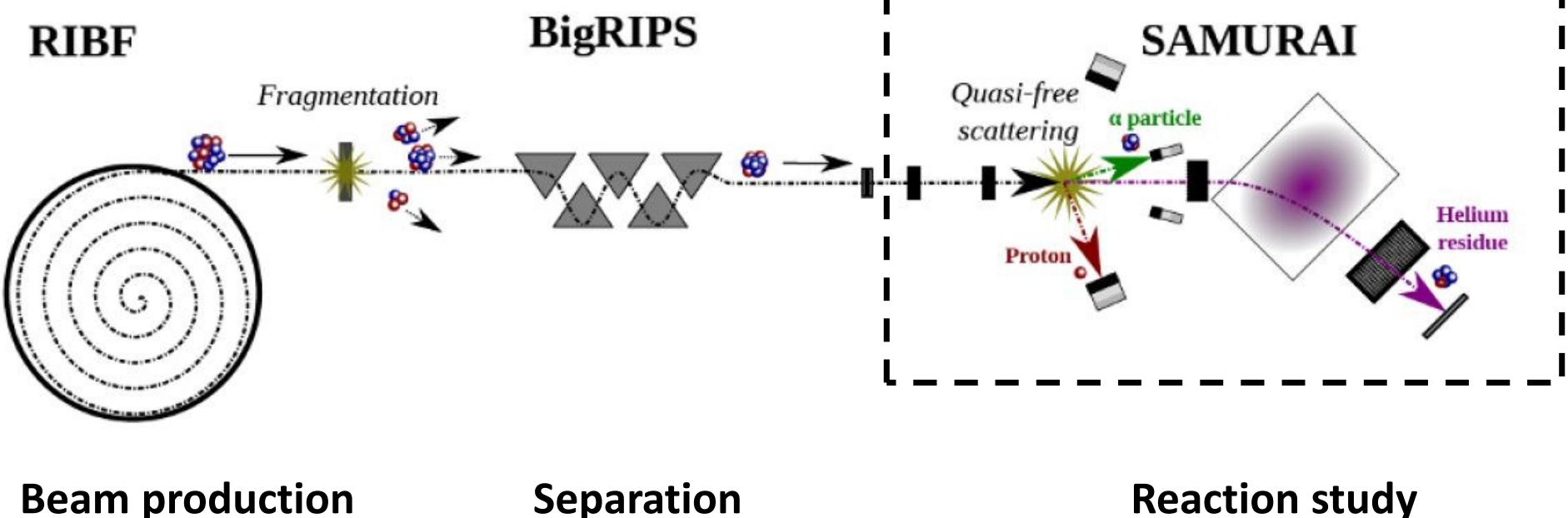
- Proton
- $50^\circ - 70^\circ$
 - $20 \sim 150 \text{ MeV}$
- Alpha
- $4^\circ - 10^\circ$
 - $v \approx v_{\text{beam}}$

Cluster KO reaction study at RIKEN/RIBF

Inverse kinematics

SAMURAI12 experiment: $^{10,12,14}\text{Be}(\text{p},\text{p}\alpha)$ at 150 MeV/u

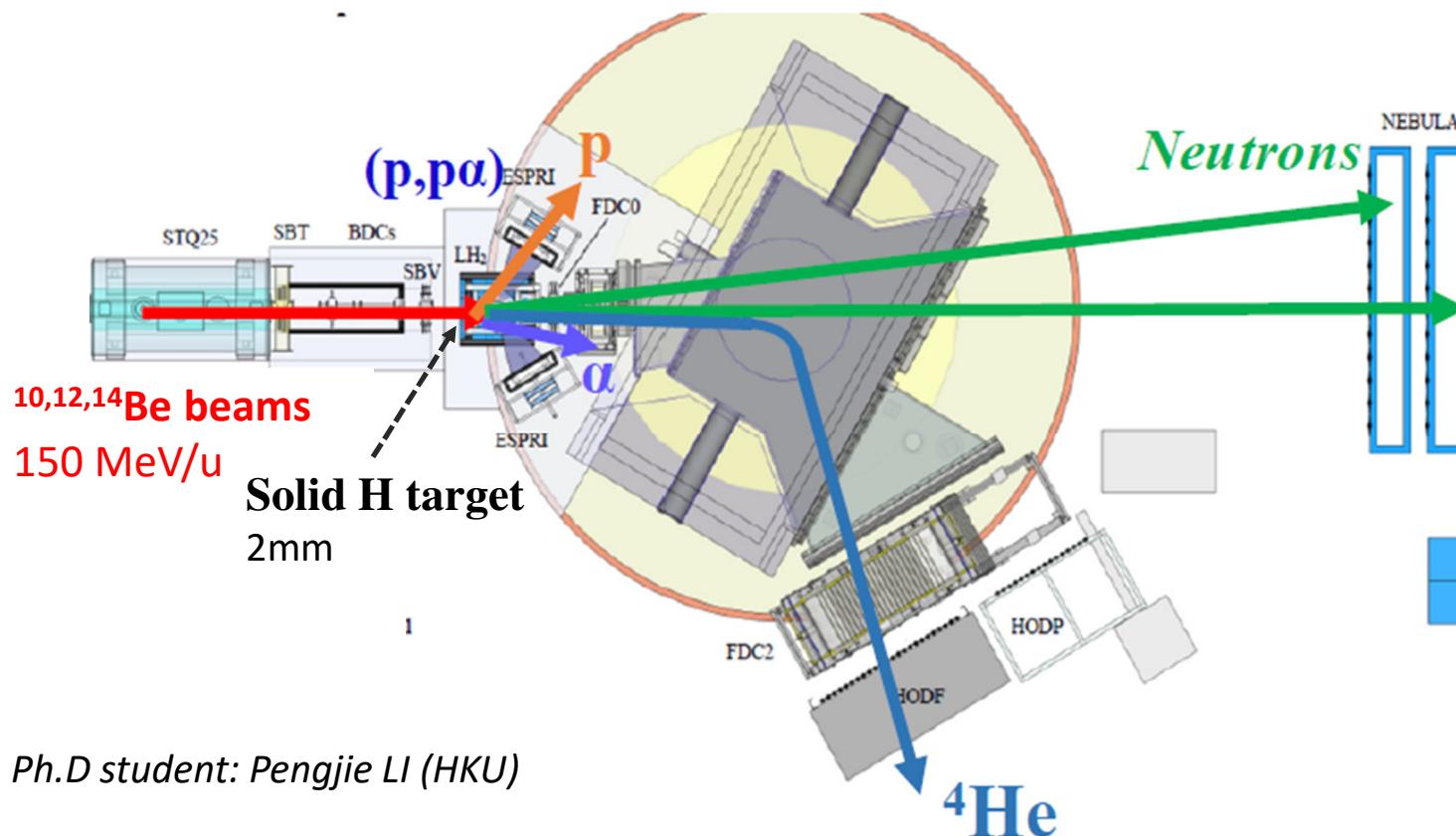
- Clustering in n-rich Be
- First spectrum for the 6n system



Study $^{10,12,14}\text{Be}(\text{p},\text{p}\alpha)$ at 150 MeV/u

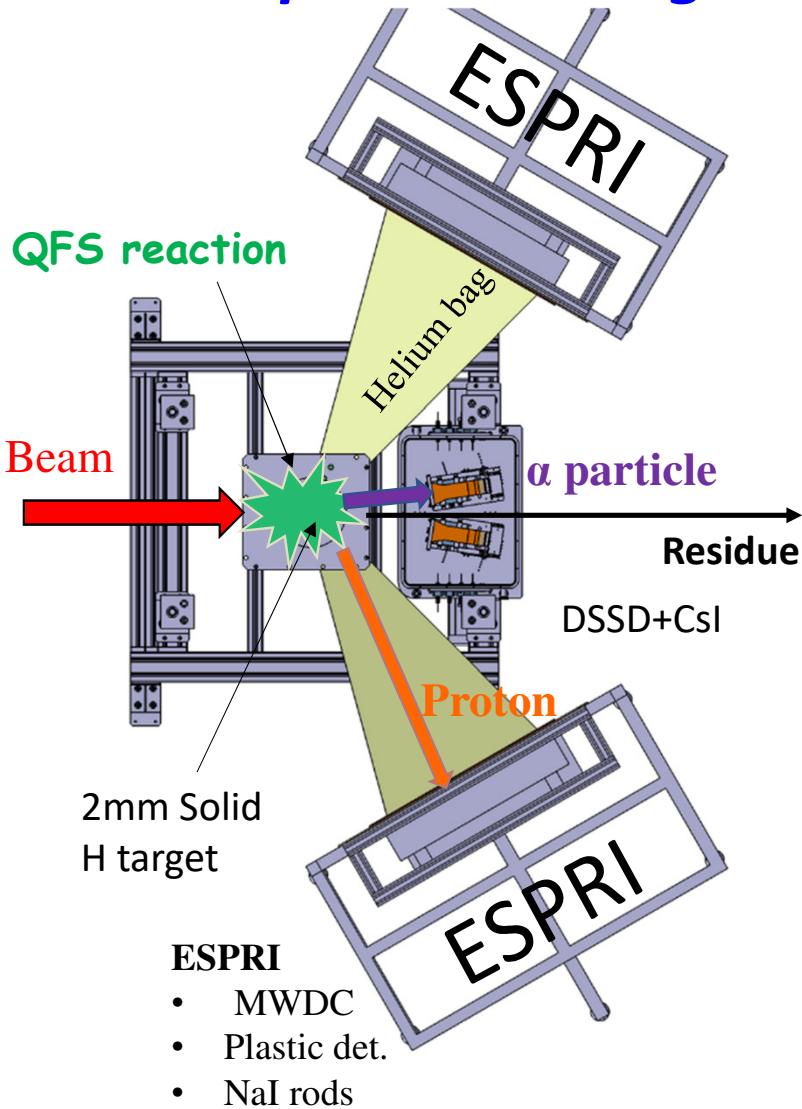
- Clustering in n-rich Be
- First spectrum for the 6n system

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

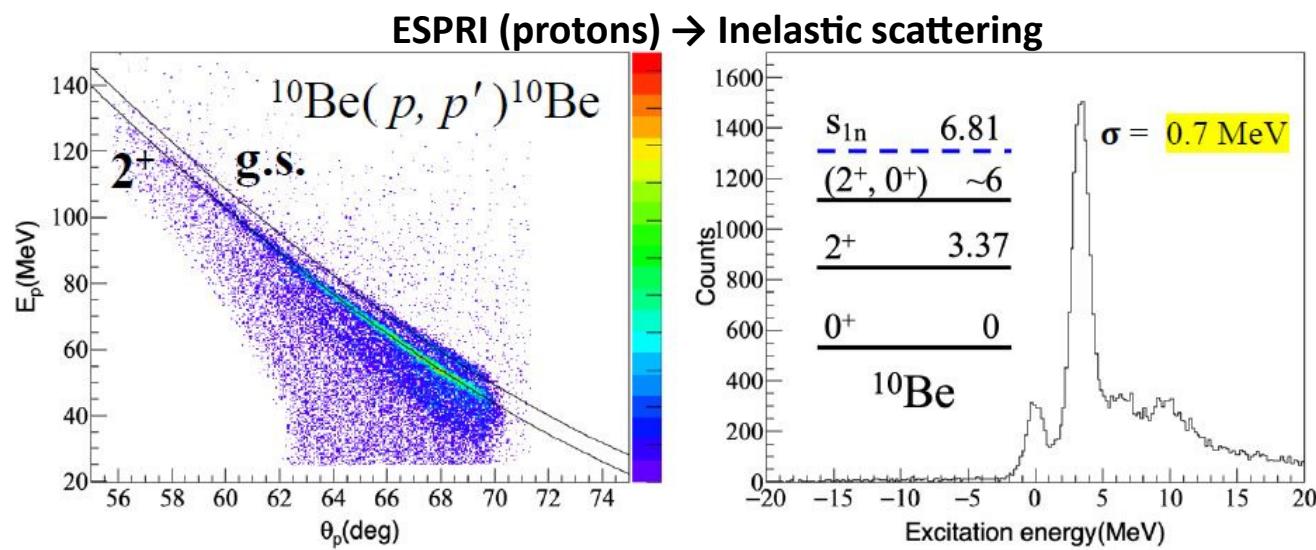


Collaboration: IJCLab, Hong Kong U., RIKEN, TI Tech, LPC Caen, Tohoku U., RCNP Osaka,
CEA Saclay, Kyoto U., TU Darmstadt, NIPNE Bucharest, Kyushu U.

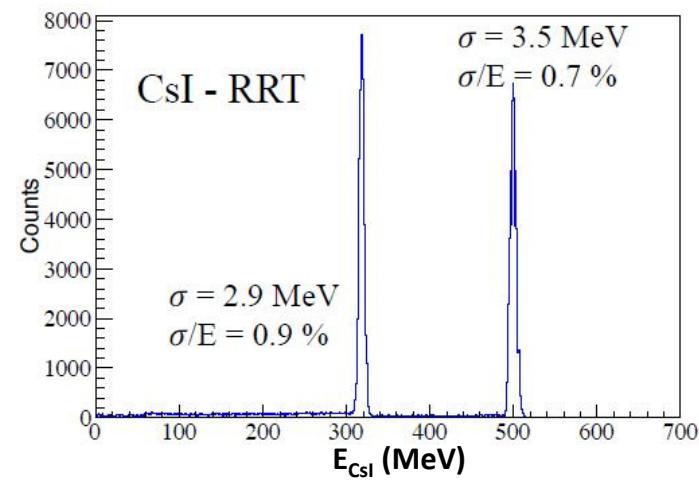
Setup around target



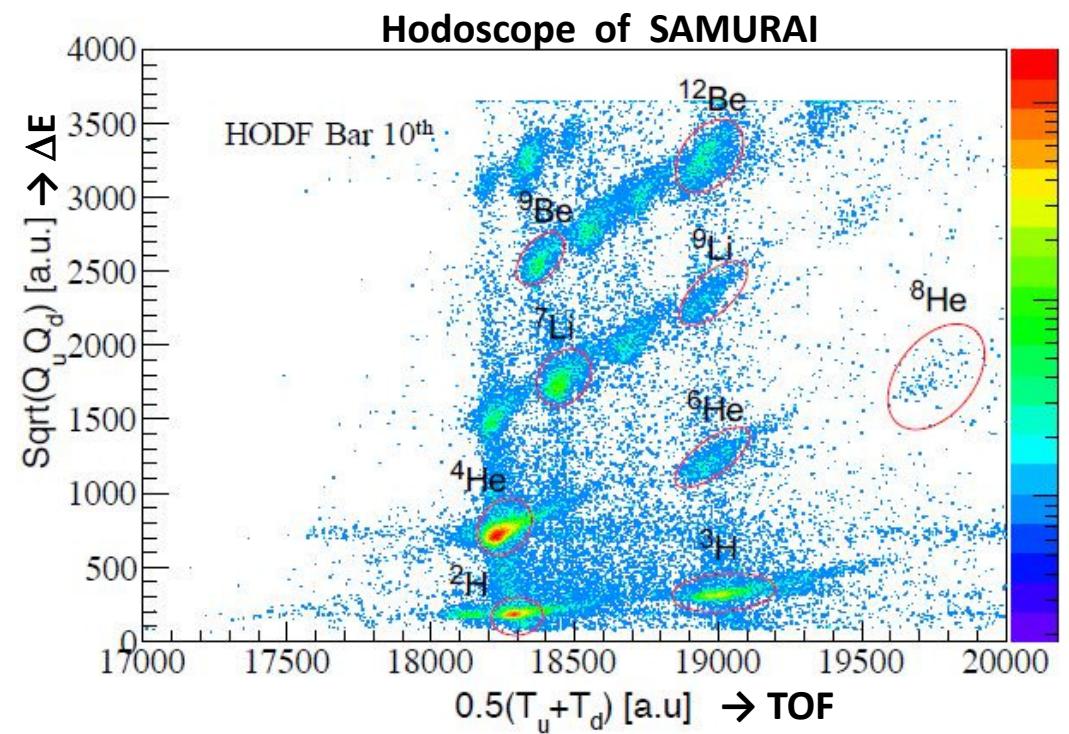
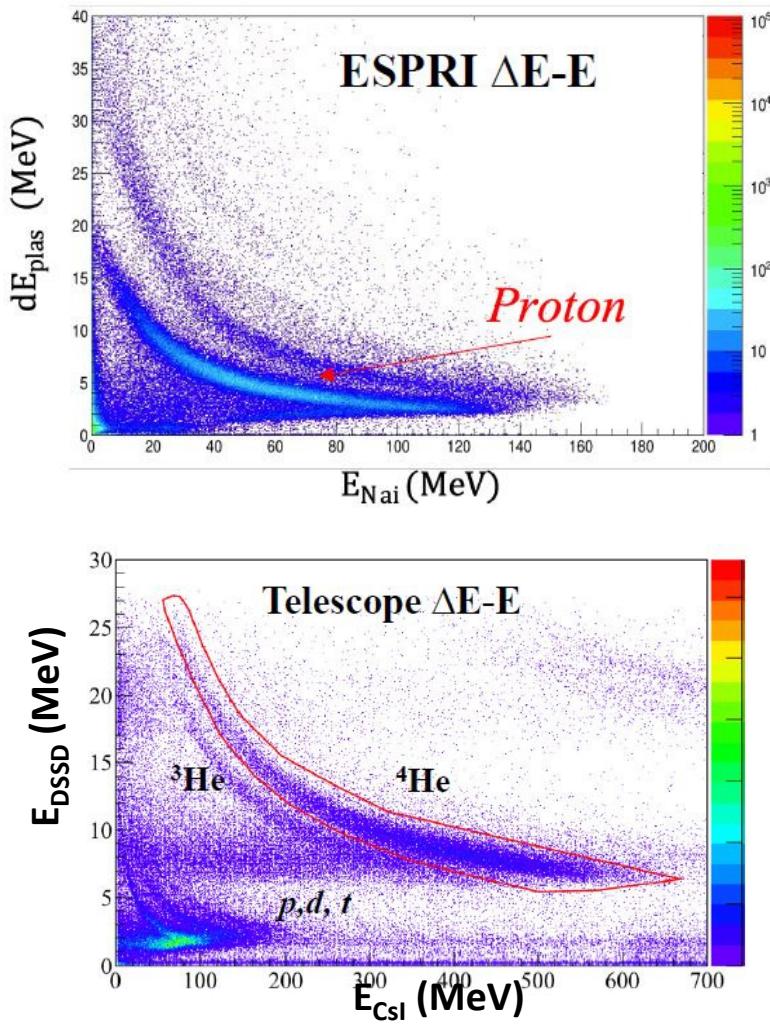
Energy calibrations



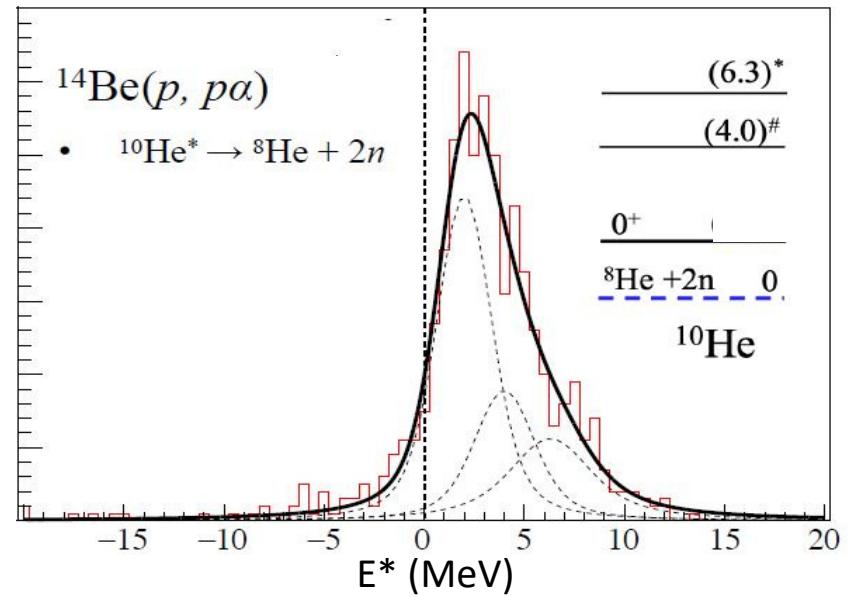
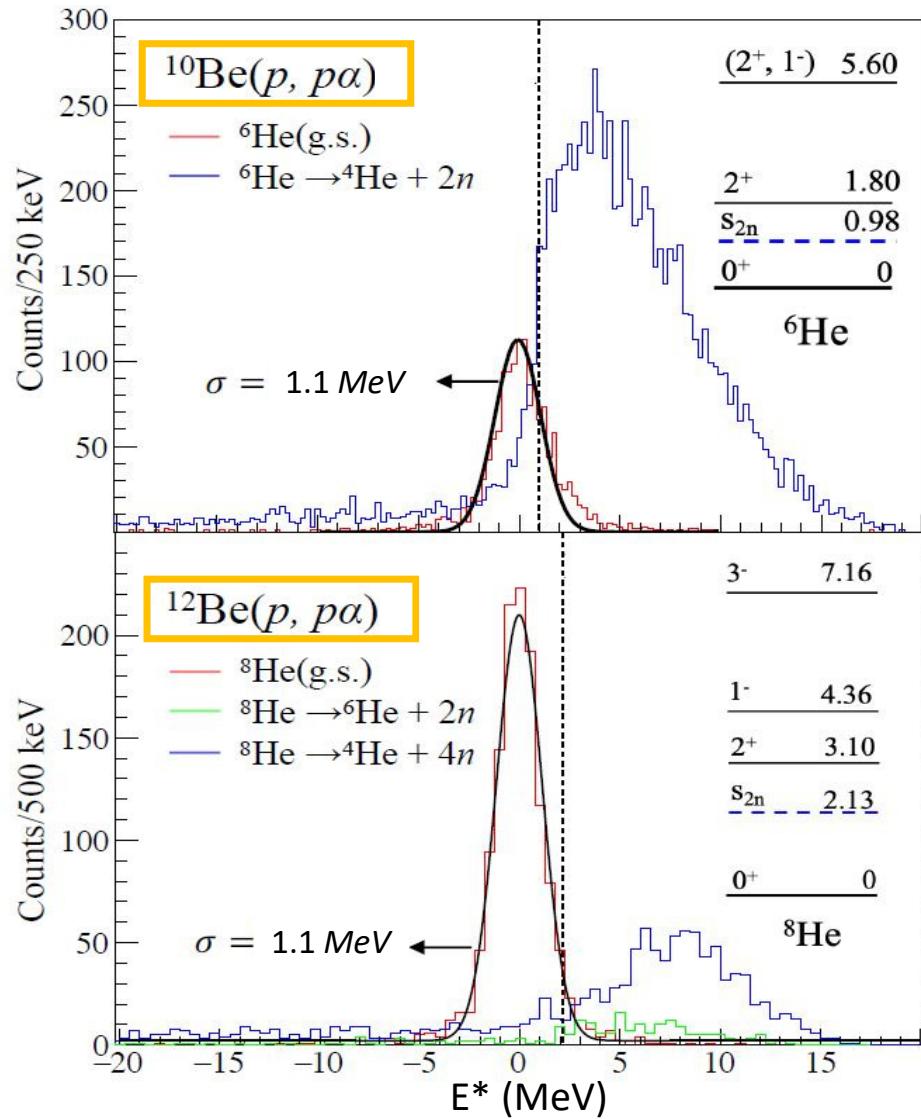
TELESCOPES (alphas) → α beam



Particle identification – channel selection



Excitation energy spectra



${}^{10}\text{He}$ (g. s.)	$E_{g.s.}$ (MeV)	Γ (MeV)
Johansson2010	1.6(2)	1.8(4)
Matta2015	1.4(3)	1.4(2)
Preliminary	2.0(1)	1.3(2)

[*] A. Matta et al. *Physical Review C* 92 (2015), 041302

[#] H. T. Johansson et al. *Nuclear Physics A* 842 (2010), 15

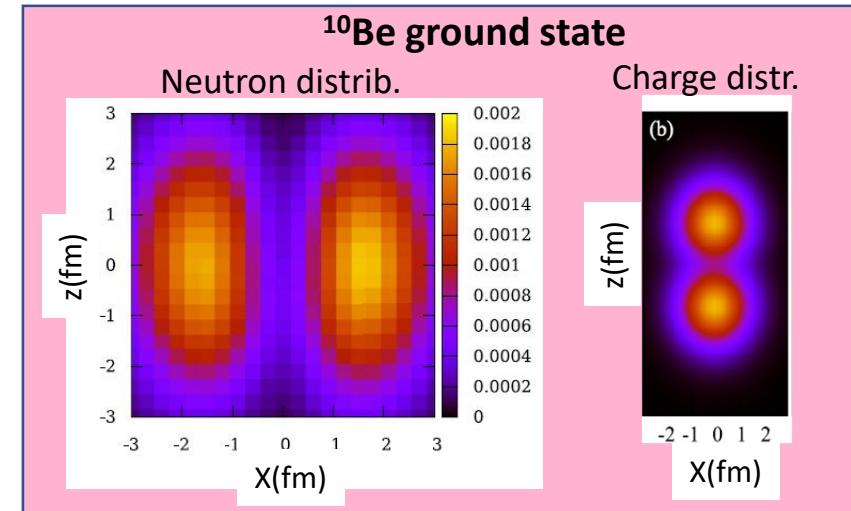
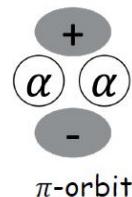
Calculations for $^{10}\text{Be}(p,p\alpha) {}^6\text{He}^{(\text{GS})}$ at 250 MeV/u

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

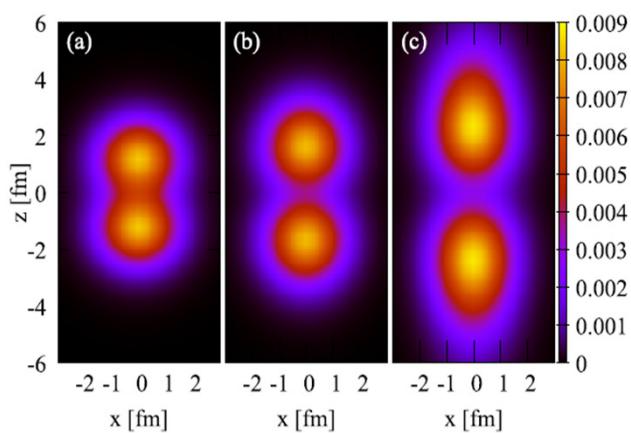
Tohsaki, Horiuchi, Schuck, Röpke (THSR) wave-function
Well adapted to discuss cluster states in light nuclei

- Cluster wave-function overlap of ^{10}Be and ${}^6\text{He}$
- Optical potentials folding of calculated density with interaction

$^{10}\text{Be}: 2\alpha + 2n(\pi)$

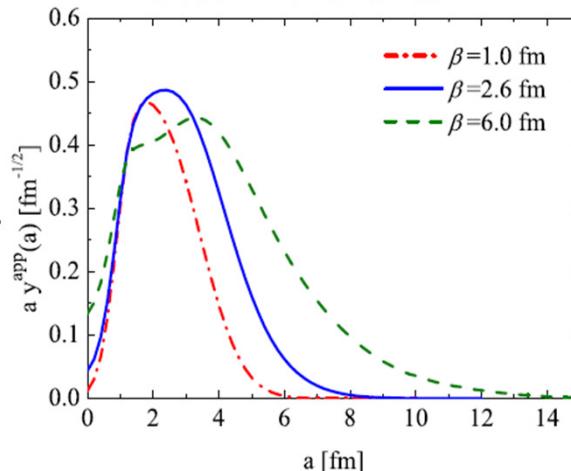


^{10}Be charge distribution

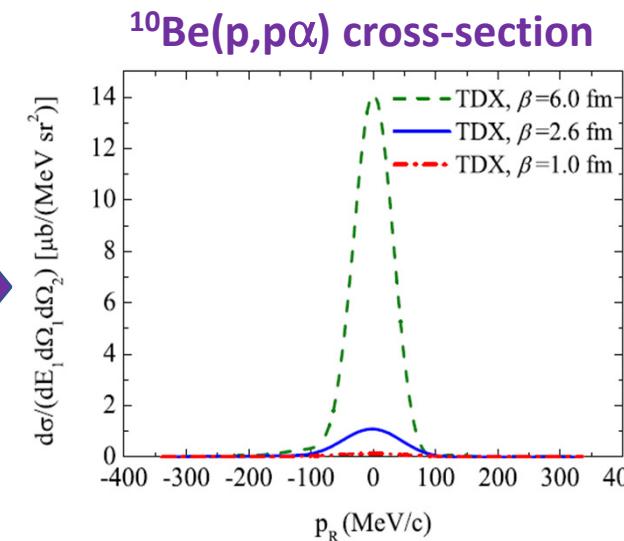


Variational result

Cluster wave-function



DWIA calc.

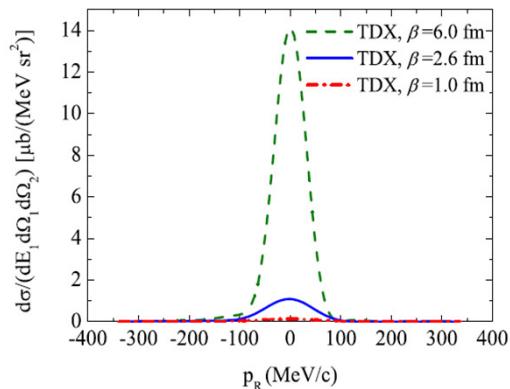
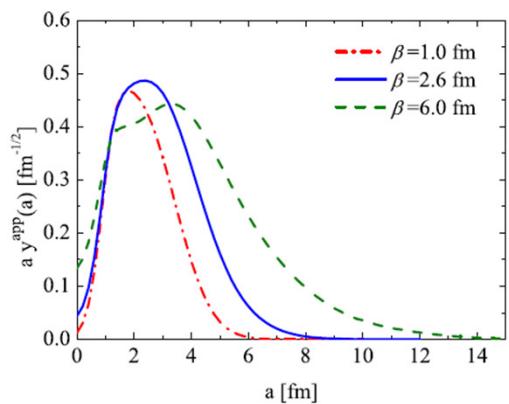
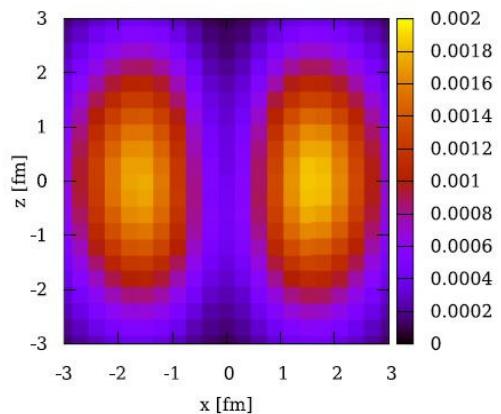
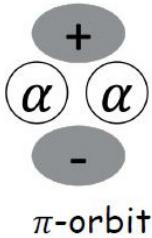


Predictions for TDX (at 250MeV/U)

M.Lyu et al., PRC 97 (2018)
 M.Lyu et al., PRC 99 (2019)

$^{10}\text{Be}(p,p\alpha)^6\text{He}$

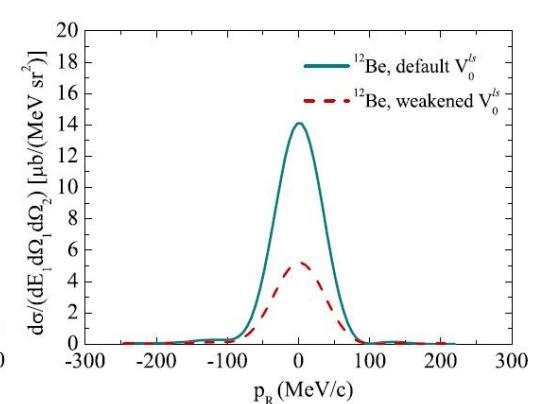
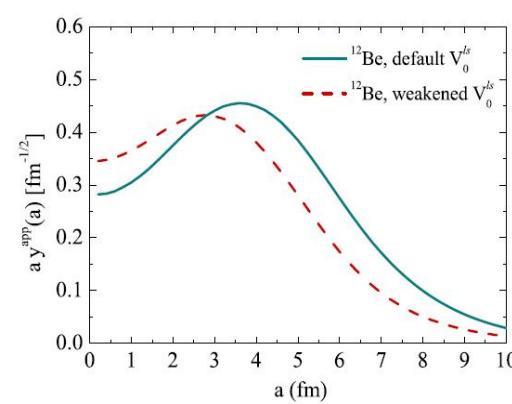
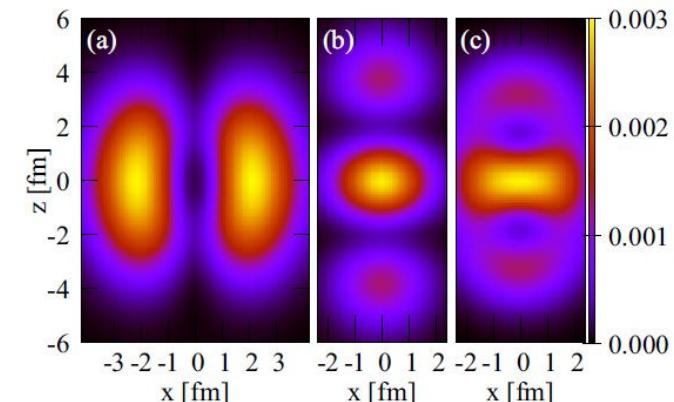
$^{10}\text{Be}: 2\alpha + 2n(\pi)$



$^{12}\text{Be}(p,p\alpha)^8\text{He}$

Cluster configuration

- $2\alpha + 2n(\pi) + 2n(\pi^*)$
- $2\alpha + 2n(\pi) + 2n(\sigma)$
- $\alpha + ^8\text{He}$

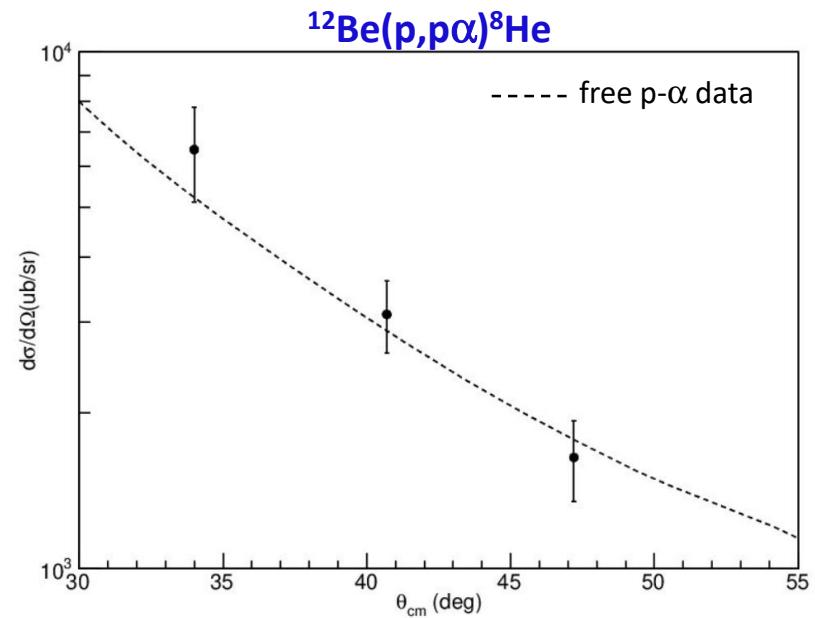
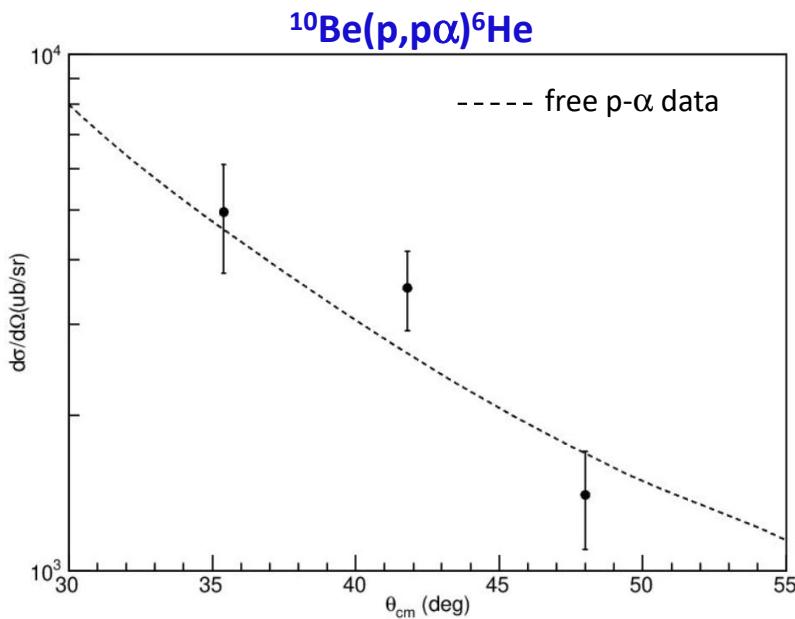


Fact ~15

Check of reaction mechanism

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_p} / F_k = S_\alpha \left(\sum_\lambda |T_{BA}^{\alpha L\lambda}|^2 \right) \frac{d\sigma}{d\Omega_{p-\alpha}} .$$

Compare TDX for ($p, p\alpha$) at QF conditions with free p-alpha exp^{al} cross-section (data)



TDX extraction from data

$$\frac{d^3\sigma^{\text{exp}}}{dT_1 d\Omega_1 d\Omega_2} = \frac{\Delta N(T_1)}{\varepsilon_{\text{det}} N_{\text{tgt}} N_{\text{beam}} \Delta T_1 \cdot \varepsilon_{\varphi_1} \varepsilon_{\varphi_{12}} PV(T_1)}$$

$$PV(T_1) = \sum_{\theta_1} \sum_{\theta_2} \sum_{\varphi_1} \sum_{\varphi_2} \Delta \cos \theta_1 \Delta \varphi_1 \Delta \cos \theta_2 \Delta \varphi_2$$

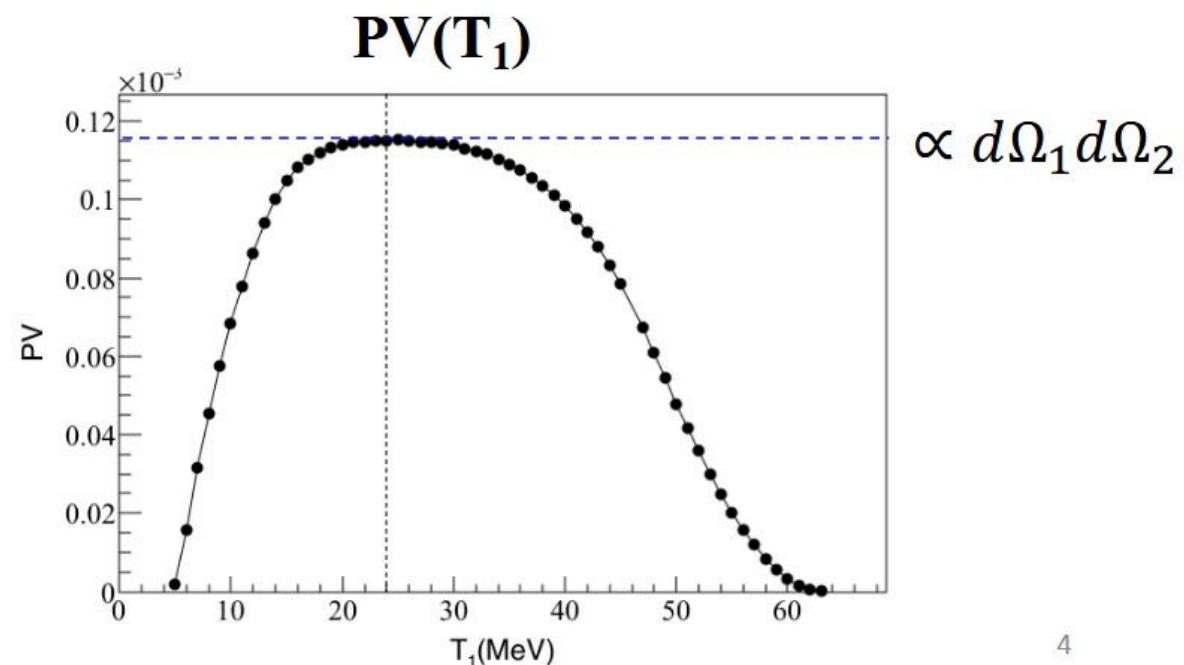
^{10}Be Beam

$\theta_1 \in [64, 66]$, $\Delta\theta_1 = 0.1^\circ$

$\theta_2 \in [6.7, 8.7]$, $\Delta\theta_2 = 0.1^\circ$

$\varphi_{12} \in [160, 200]$, $\Delta\varphi = 1^\circ$

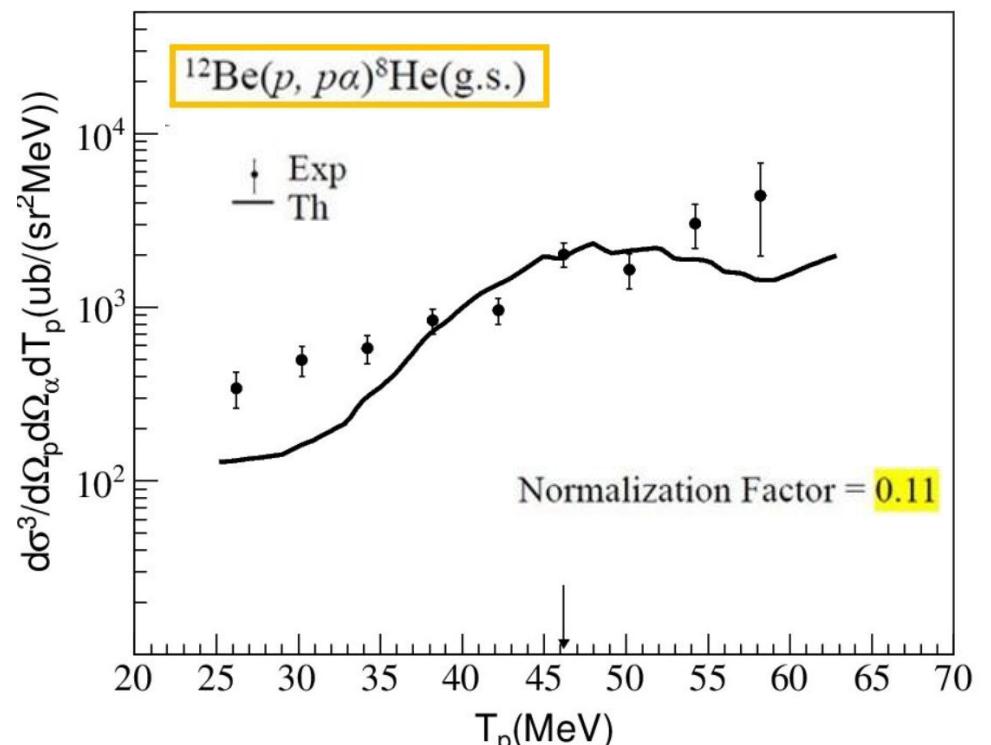
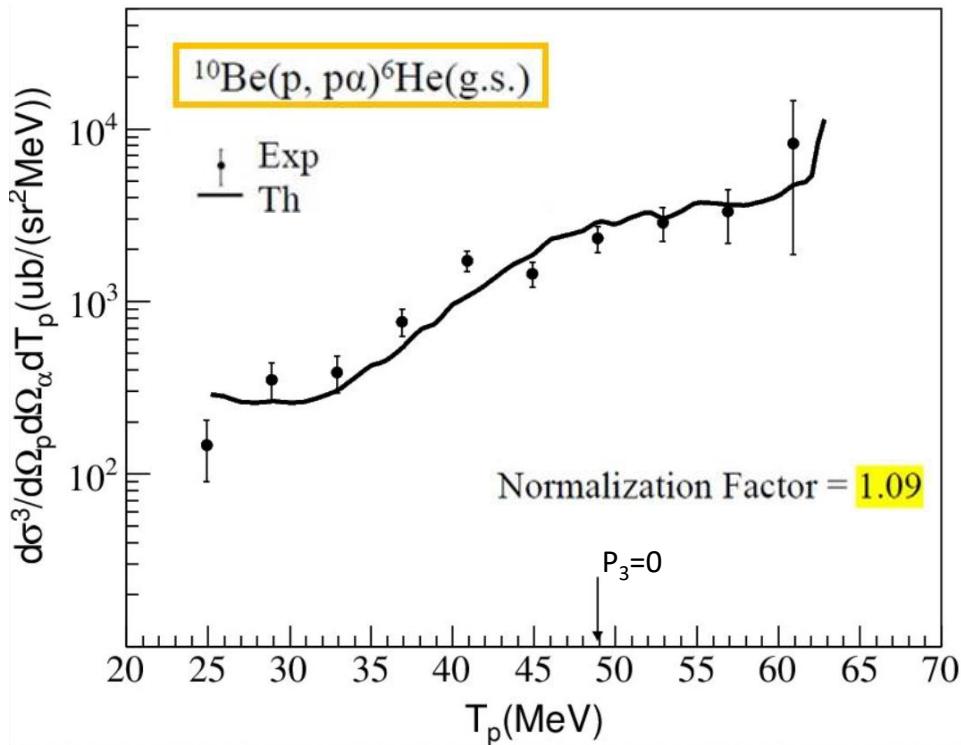
T1 threshold 24 MeV



TDX to the ground-states

DWIA Calculations using extended THSR

Preliminary



DWIA calculations by K.Ogata

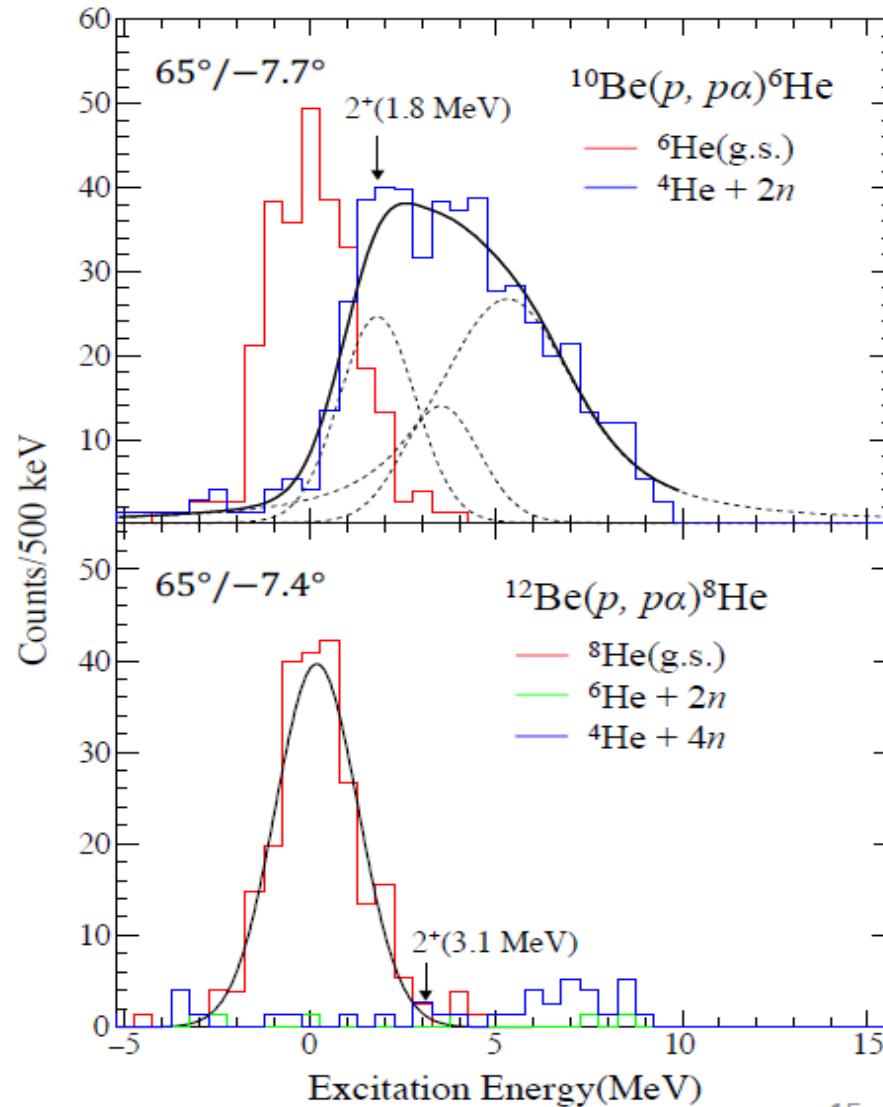
Ground-state vs excited states population

- Strong difference in the population of GS vs excited states of the residual nuclei
- Contribution of the 2+ of ${}^6\text{He}$ deduced from a fit
- 2+/GS ratio

${}^{10}\text{Be}$: 47%

${}^{12}\text{Be}$: <0.4%

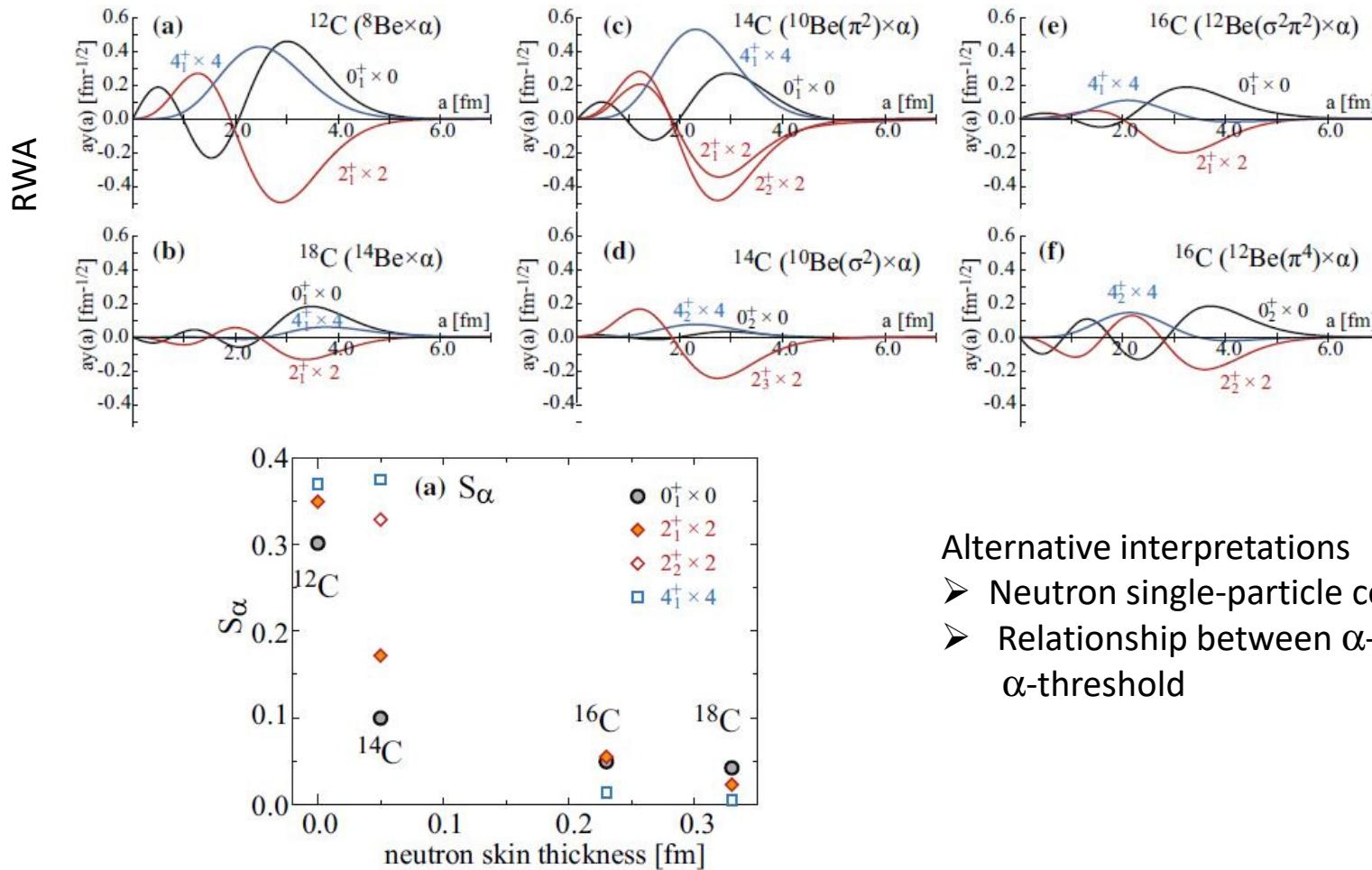
Core-excited states play very different role in the GS of ${}^{10}\text{Be}$ vs ${}^{12}\text{Be}$



Clustering and neutron skin in C isotopes

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

AMD calculations using Gogny D1S functional



Alternative interpretations

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

Prospects

- Planned study of $(p,p\alpha)$ on n-rich Carbon isotopes at RIKEN/Samurai
(spokesperson: Zaihong Yang)
- For our Be case
 - ❑ Analyze data with ^{14}Be beam
 - ❑ Investigate present TDX calculations with THSR
 - ❑ Call for calculations using AMD, NCMCSM
- The “ONOKORO” research project (T.Uesaka, J.Zenhiro)
Comprehensive study of clustering in medium-mass and heavy nuclei
with stable (RCNP) and unstable (RIBF) beams
Investigation of new type of clustering (^3He , t, d)
- Detector development : the TOGAXSI device (DSSD + Scintillator)
- Investigation of alpha-decay by $(p,p\alpha)$