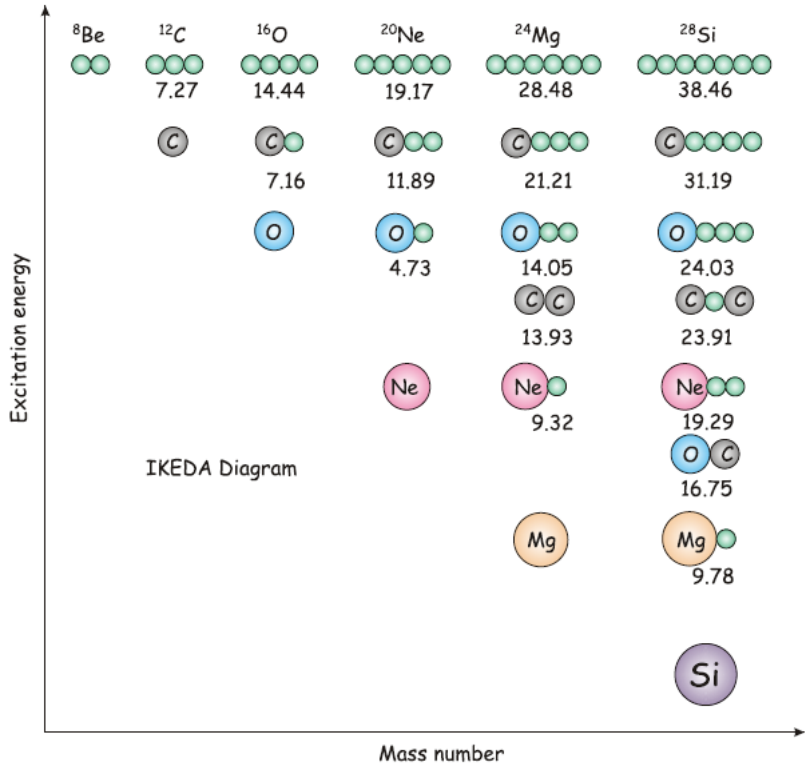
Cluster formation in neutron-rich unstable isotopes investigated by means of quasi-free scattering reaction

D.Beaumel
IJCLab, Orsay, France

- ***Introduction: clustering in light nuclei***
- ***Quasi-free scattering reactions***
- ***RIKEN experiment on n-rich beryllium isotopes***
  - ✓ ***Results Alpha-cluster structure***
  - ✓ ***Beyond alpha clustering***
- ***Conclusions and outlooks***

Clustering in light nuclei

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

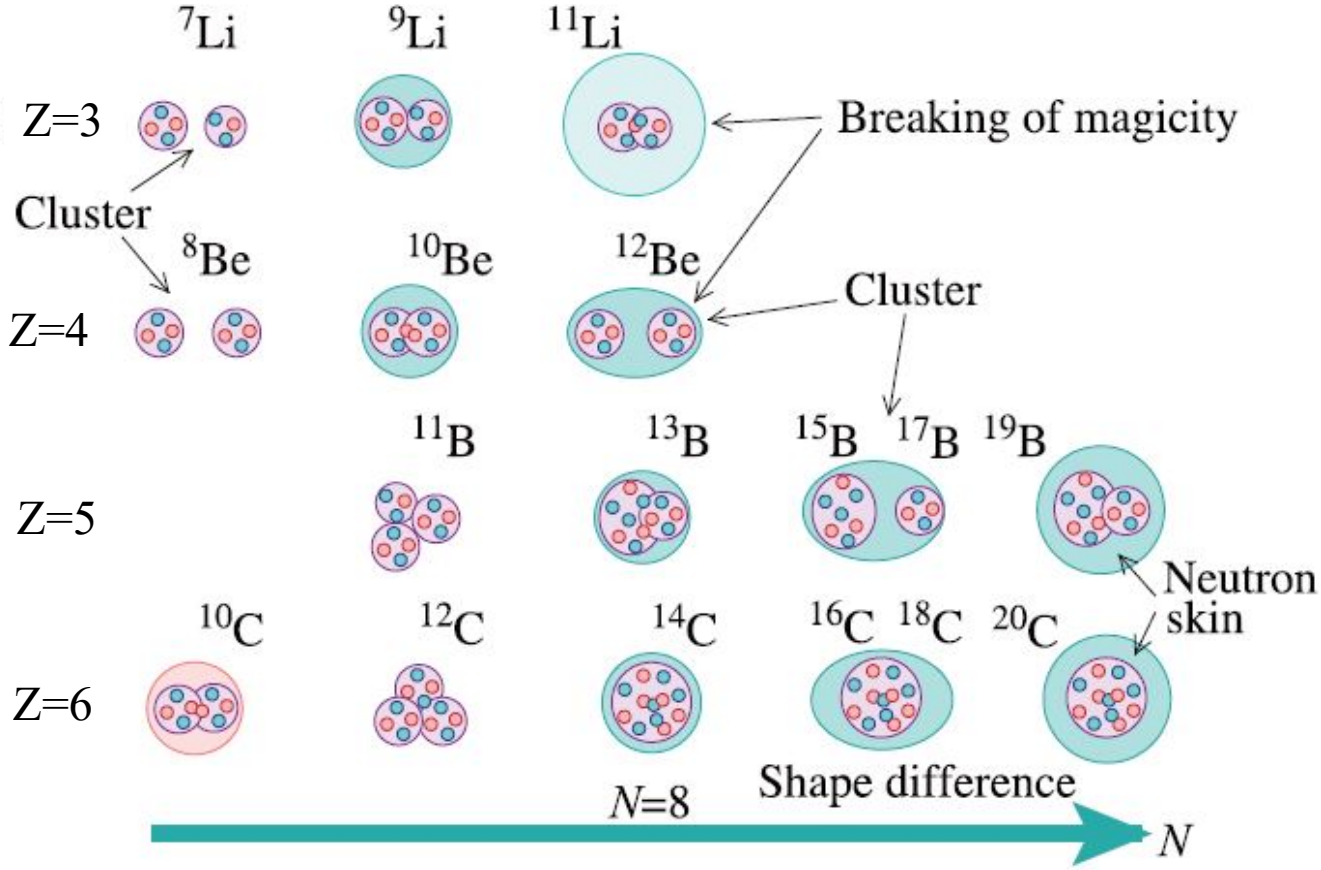


K.Ikeda, N.Takigawa, H.Horiuchi, **PTP (1968)**

- **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**

Light neutron-rich nuclei

GROUND-STATES !

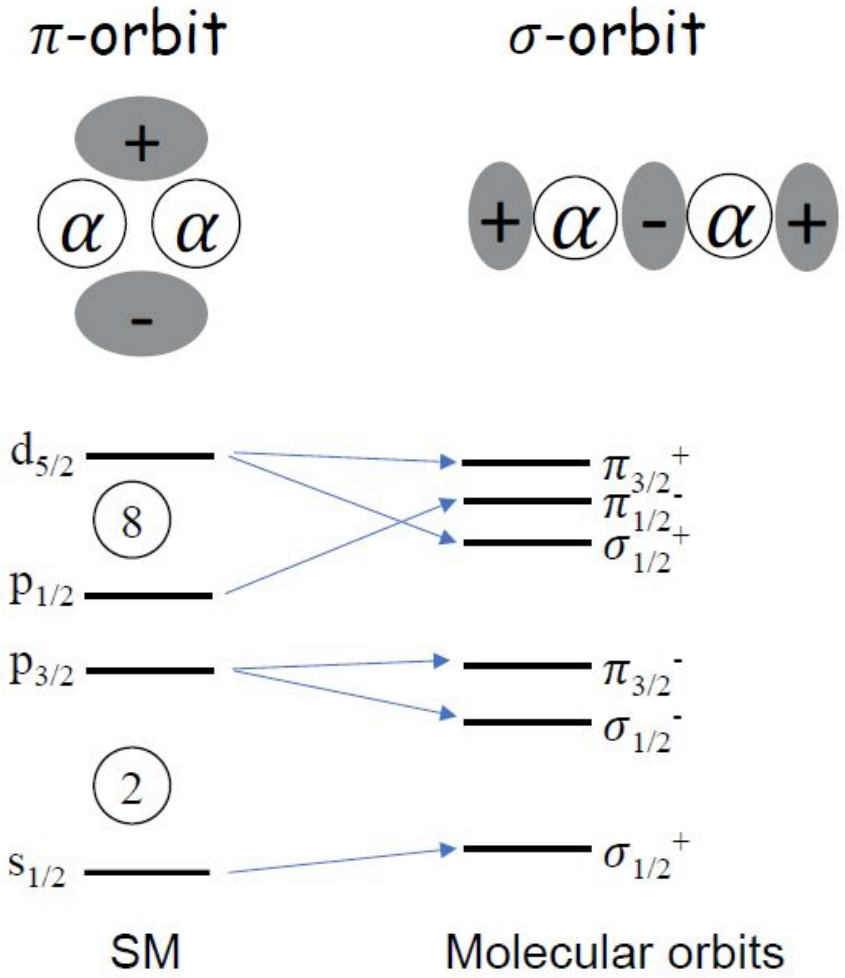


Antisymmetrized Molecular Dynamics (AMD)
Y.Kanada-En'yo, H.Horiuchi, Front. Phys. 13 (2018)

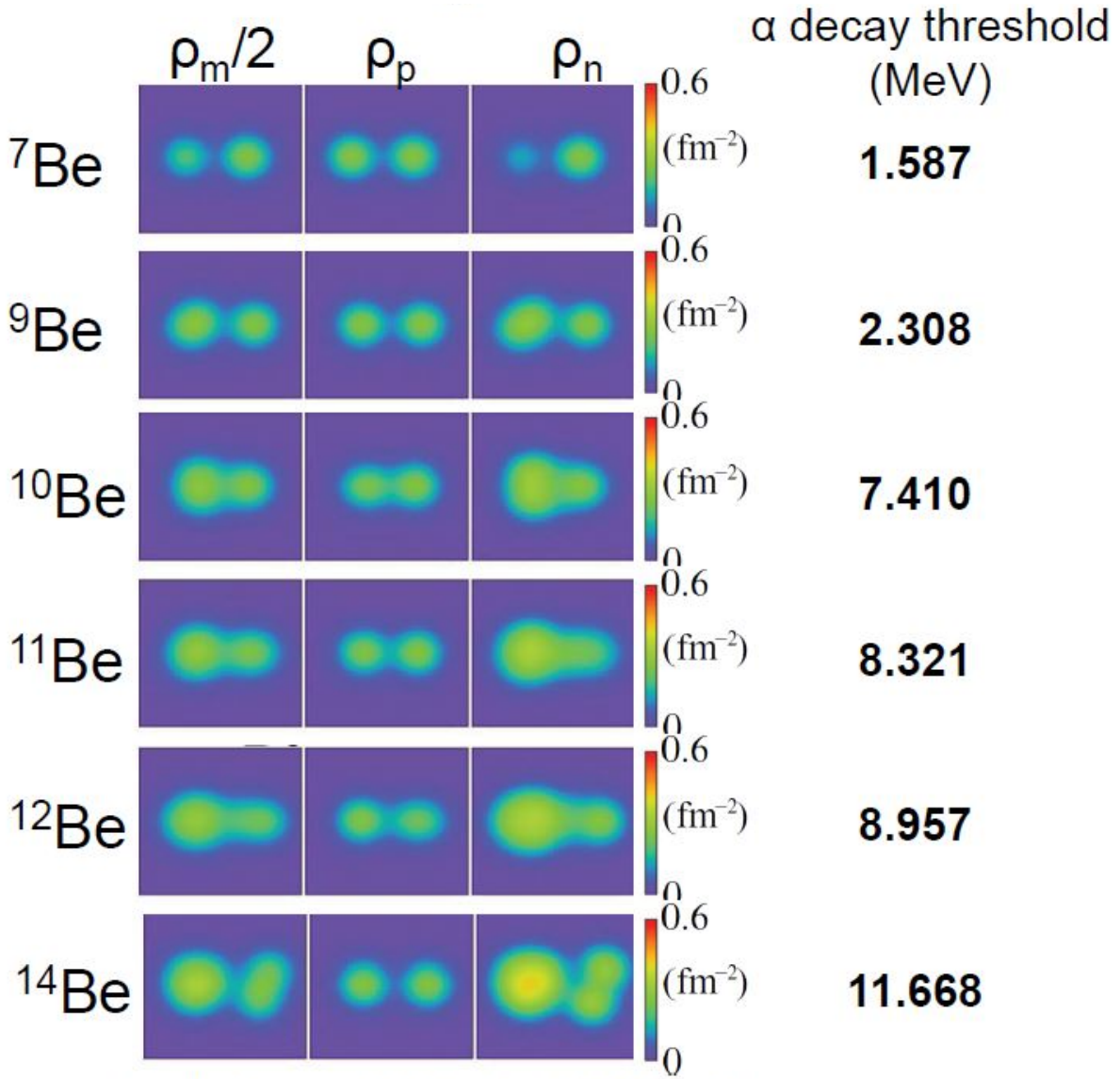
Clustering in beryllium isotopes – AMD calculation

AMD: no preformed cluster

Be isotopes: **α–Xn–α**



Density distributions of Be

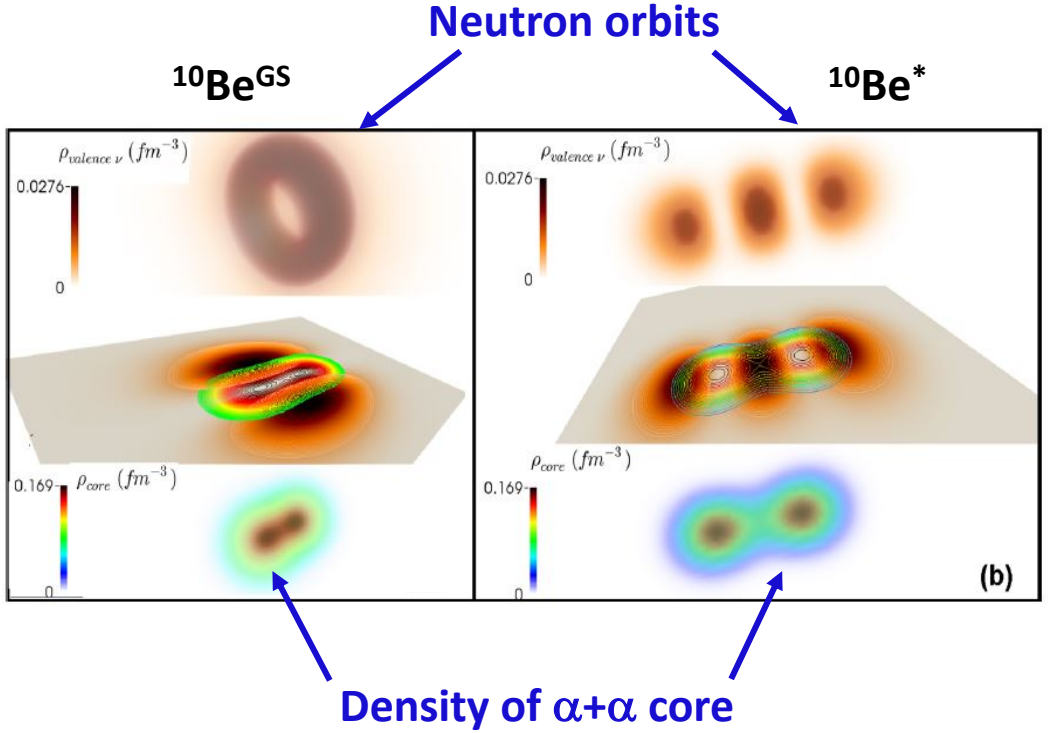


Kanada-Enyo, PRC91, 014315(2015)

Calculations of density distributions for Be isotopes

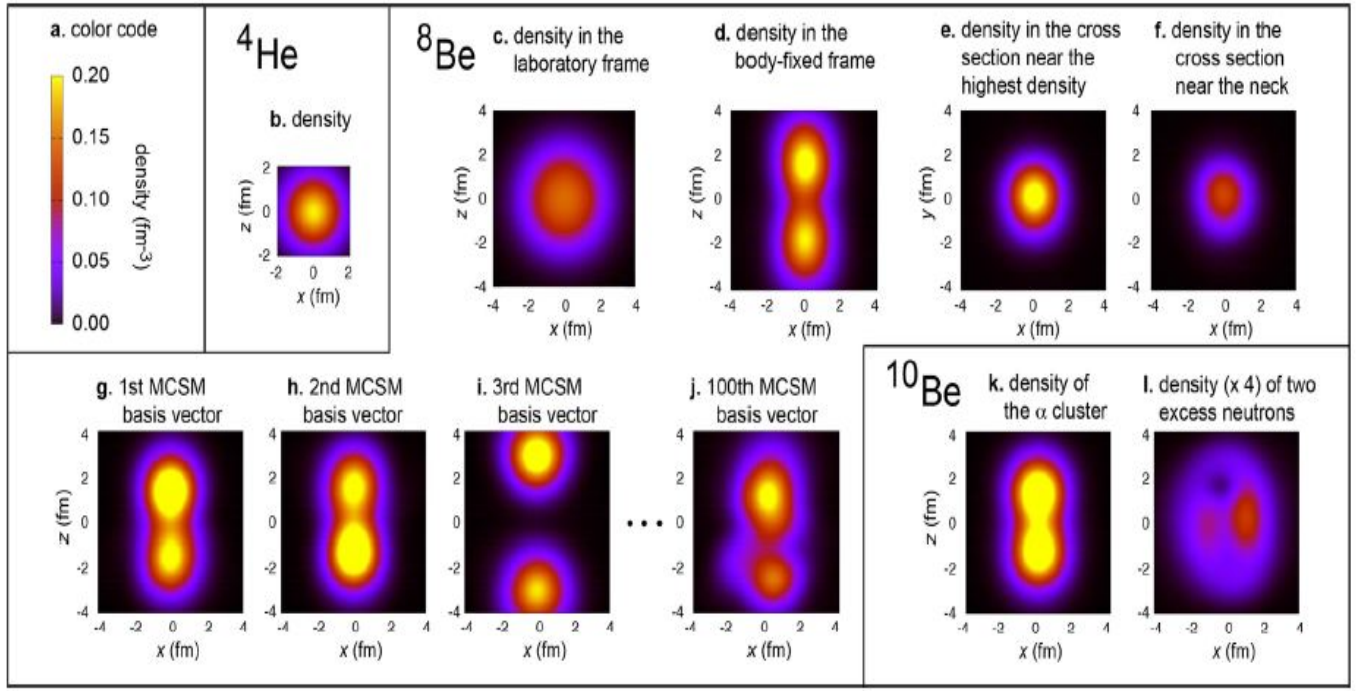
DDME2 relativistic functional in rel. HB calculations

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

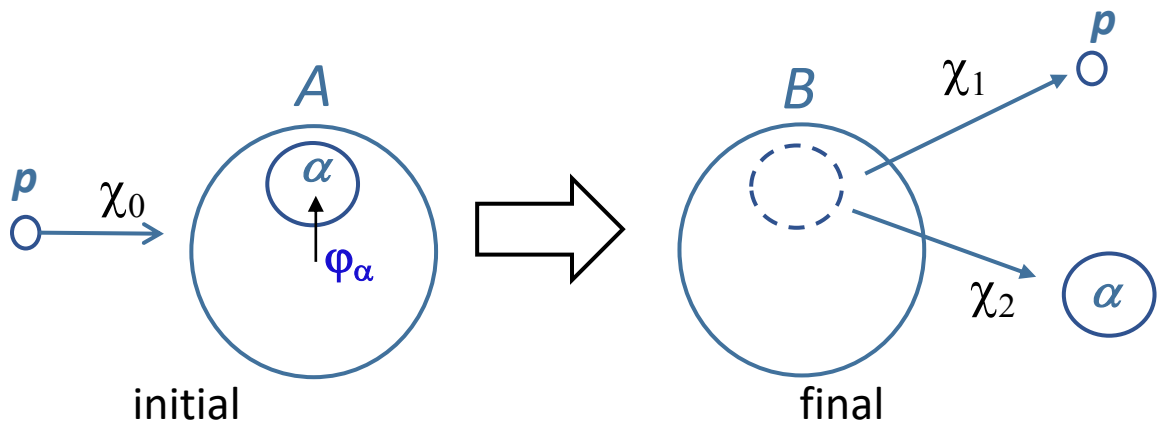


^{8,10}Be isotopes in no-core Monte-Carlo Shell Model

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



A(p,pα)B in the Distorted Wave Impulse Approximation (DWIA)



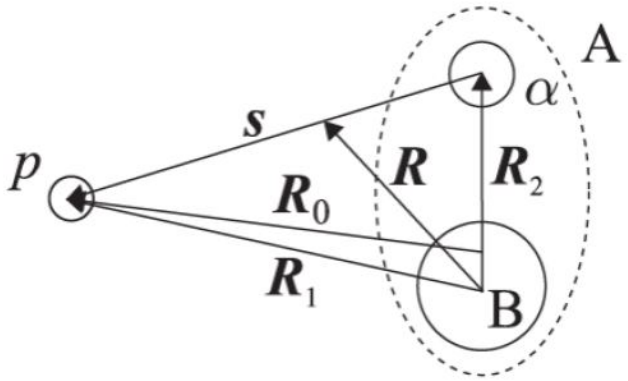
$$\frac{d^3\sigma}{dE_1^L d\Omega_1^L d\Omega_2^L}^{DWIA} = F_{\text{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) \left|\bar{T}_{P_0P_1P_2}\right|^2$$

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 …)**

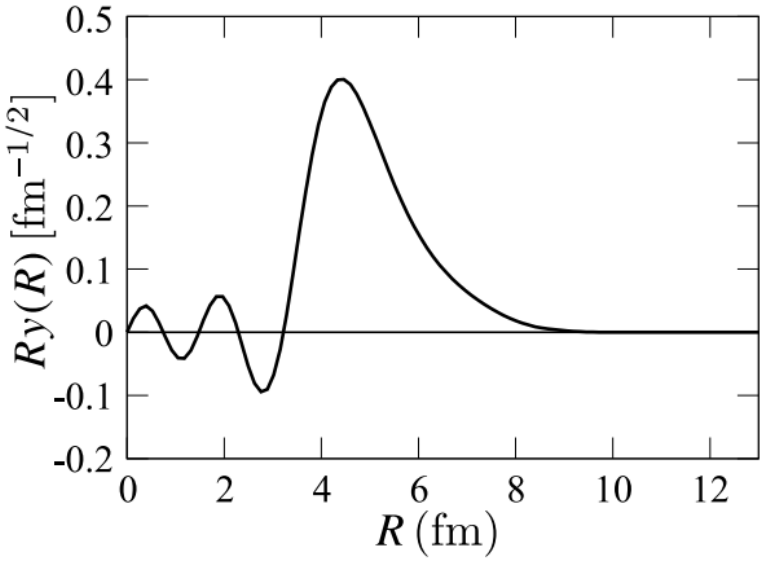
Analysis using microscopic cluster WF

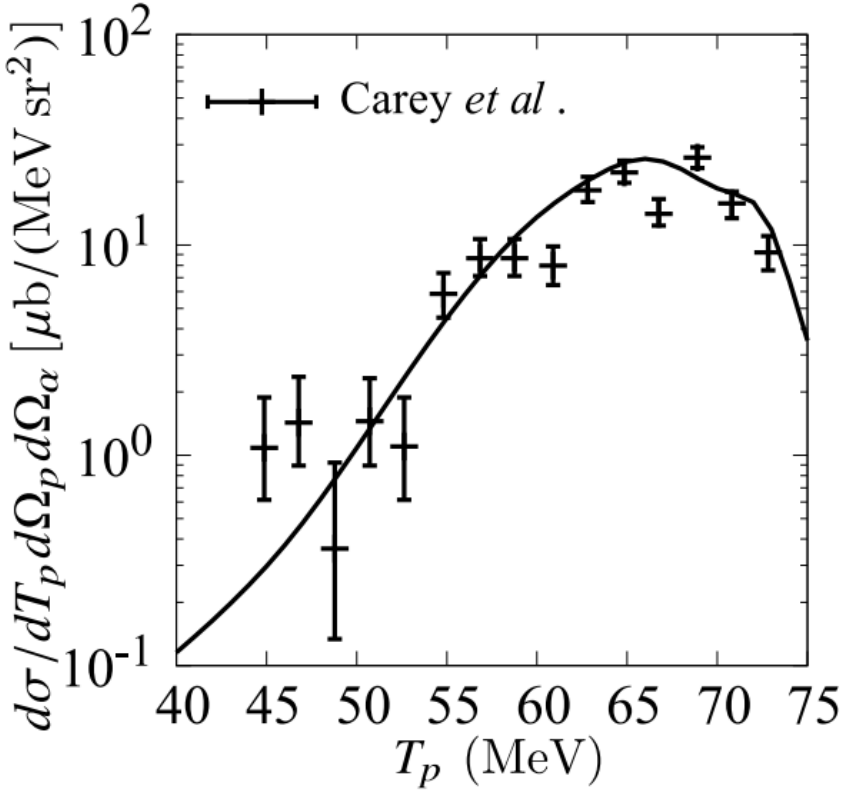
"Test" case : reanalysis of ^{20}Ne(p,pα)^{16}O data at 101.5 MeV/u

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

- AMD cluster WF
- Reliable α+^{16}O optical potential

AMD α+^{16}O cluster WF

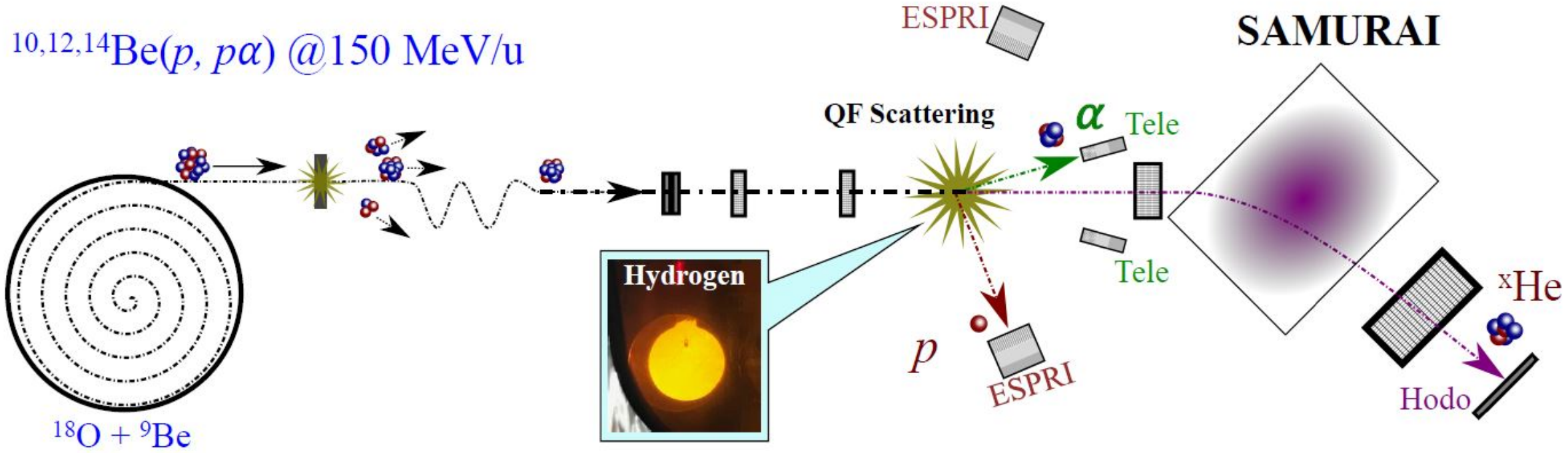


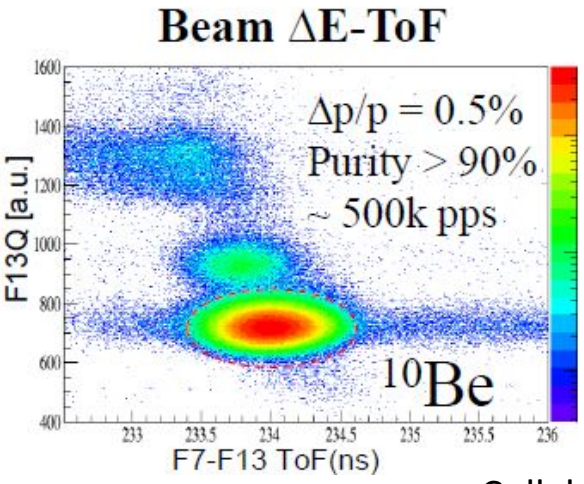


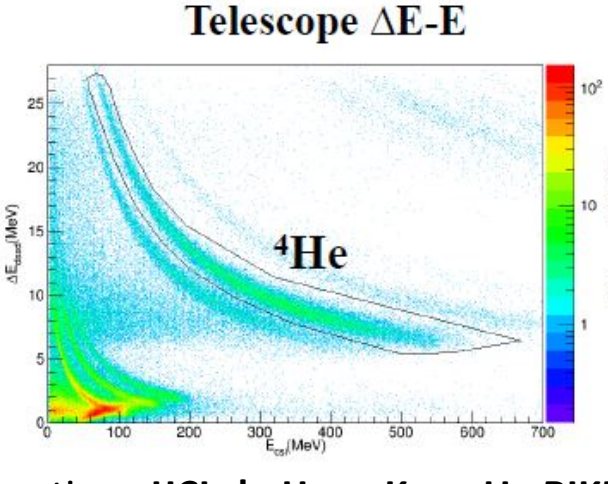
Data reproduced without any normalization

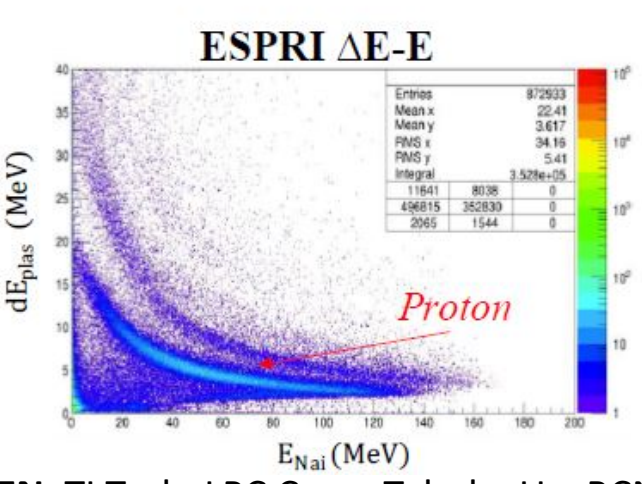
(p,pα) represents a quantitative probe for a-clustering in light nuclei

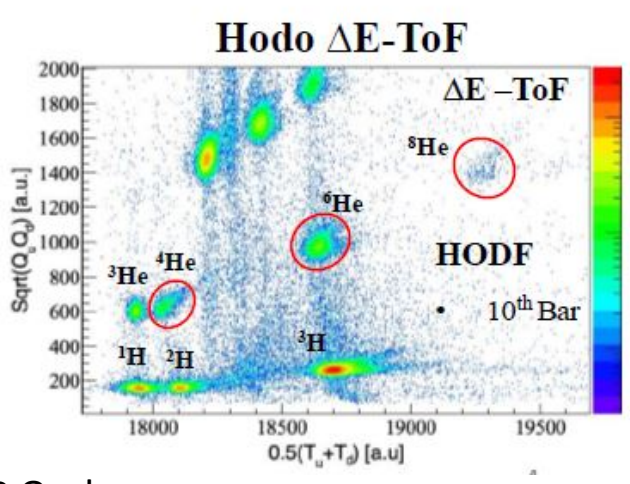
SAMURAI12 experiment: Study of ^{10,12,14}Be(p,pα) at 150 MeV/u







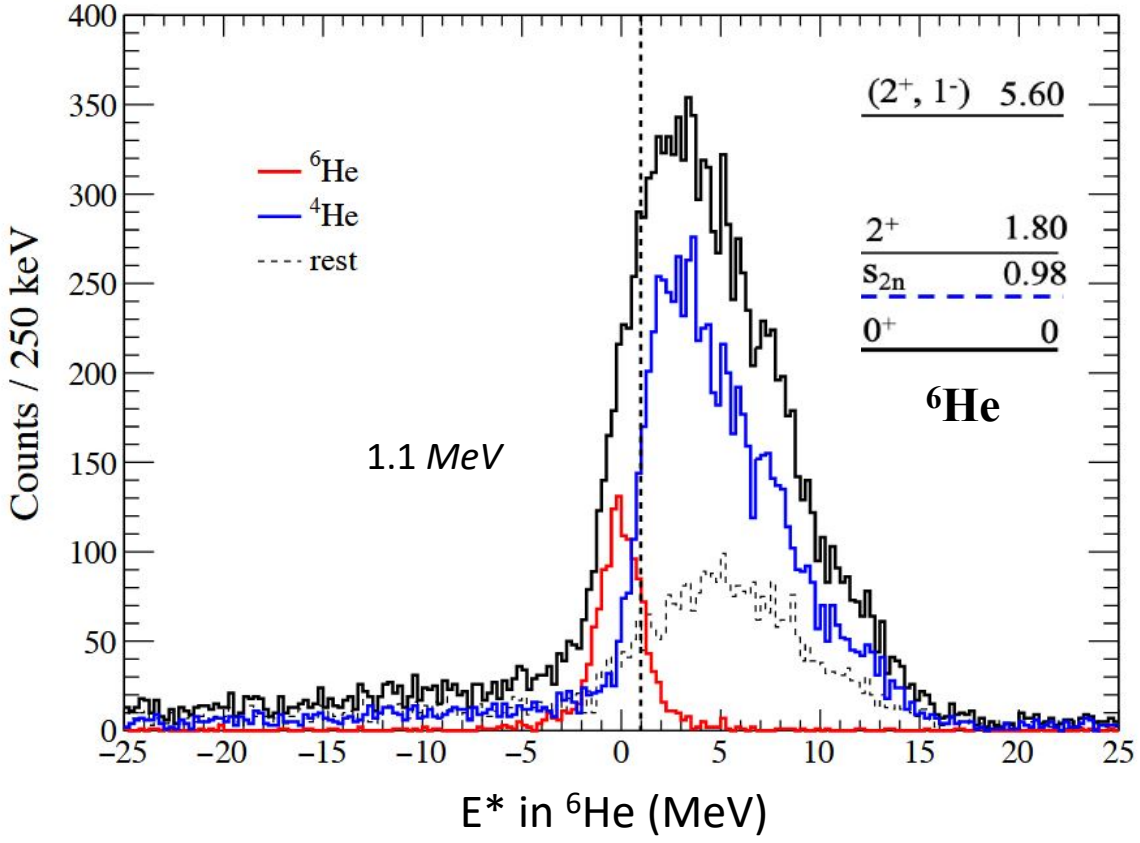




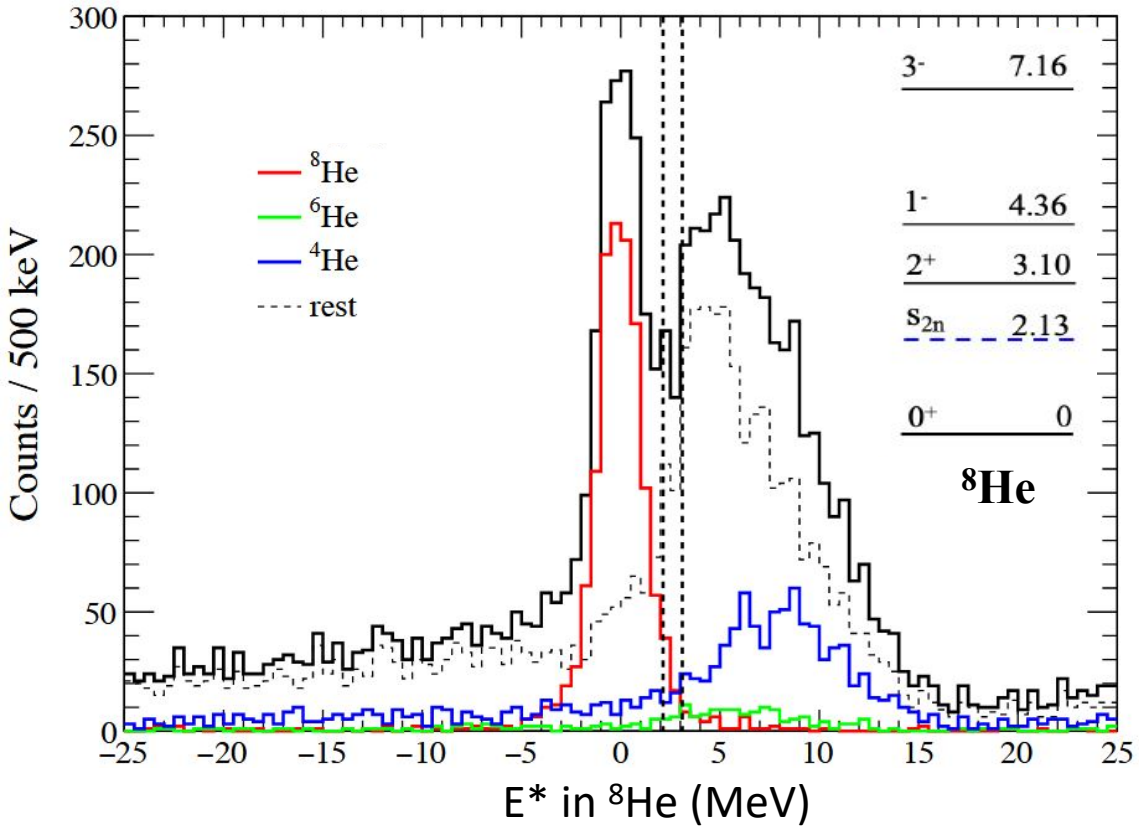
Collaboration: **IJCLab, Hong Kong U., RIKEN**, TI Tech, LPC Caen, Tohoku U., RCNP Osaka, CEA Saclay, Kyoto U., TU Darmstadt, NIPNE Bucharest, Kyushu U.

Excitation energy spectra

^{10}Be(p,pα)



^{12}Be(p,pα)



σ (^{6}He^{GS}) = 1.1 MeV

σ (^{8}He^{GS}) = 1.1 MeV

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

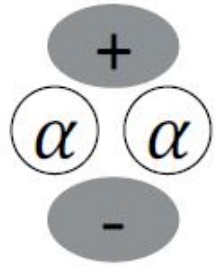
M.Lyu et al., PRC 97 (2018)

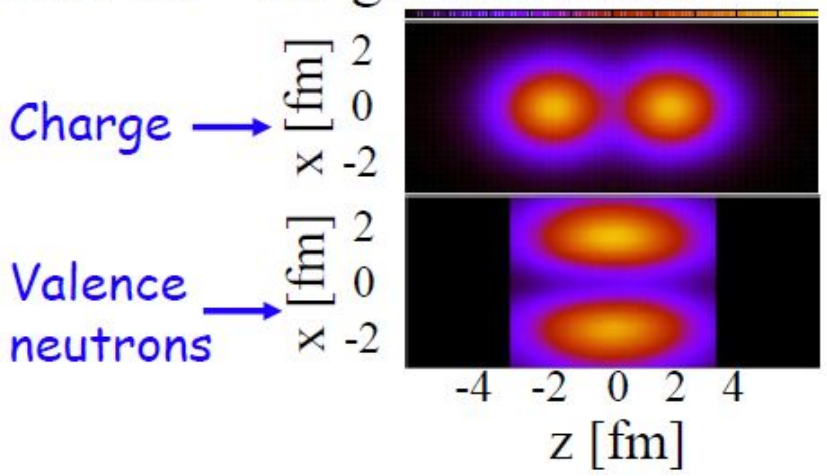
Tohsaki, Horiuchi, Schuck, Röpke (THSR) Wave-Function
Well adapted to discuss cluster states in light nuclei

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

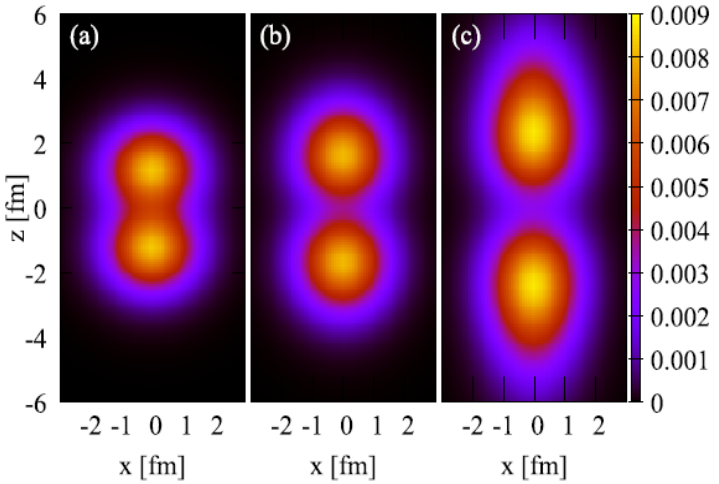
Extended THSR for ^{10}Be ground-state:

$2\alpha + 2n(\pi)$





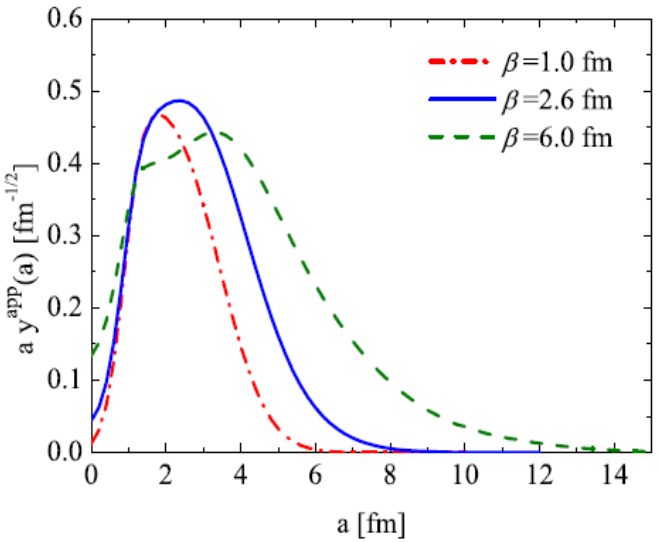
^{10}Be charge distribution



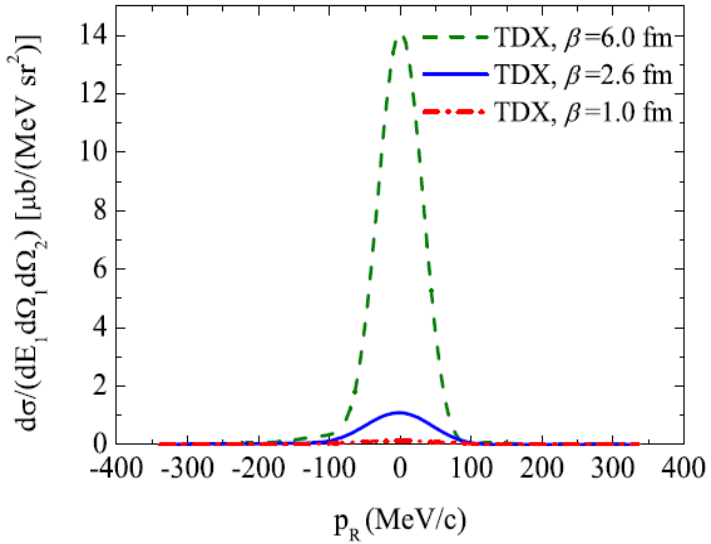
Variational result

RWA

Cluster wave-function



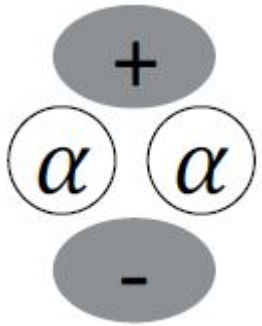
DWIA calc.



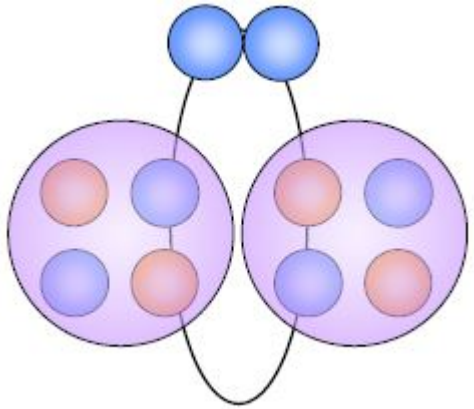
Triple differential cross-section for ^{10}Be(p,pα)^{6}He$^{(GS)}$

Microscopic cluster WF used in DWIA calc.

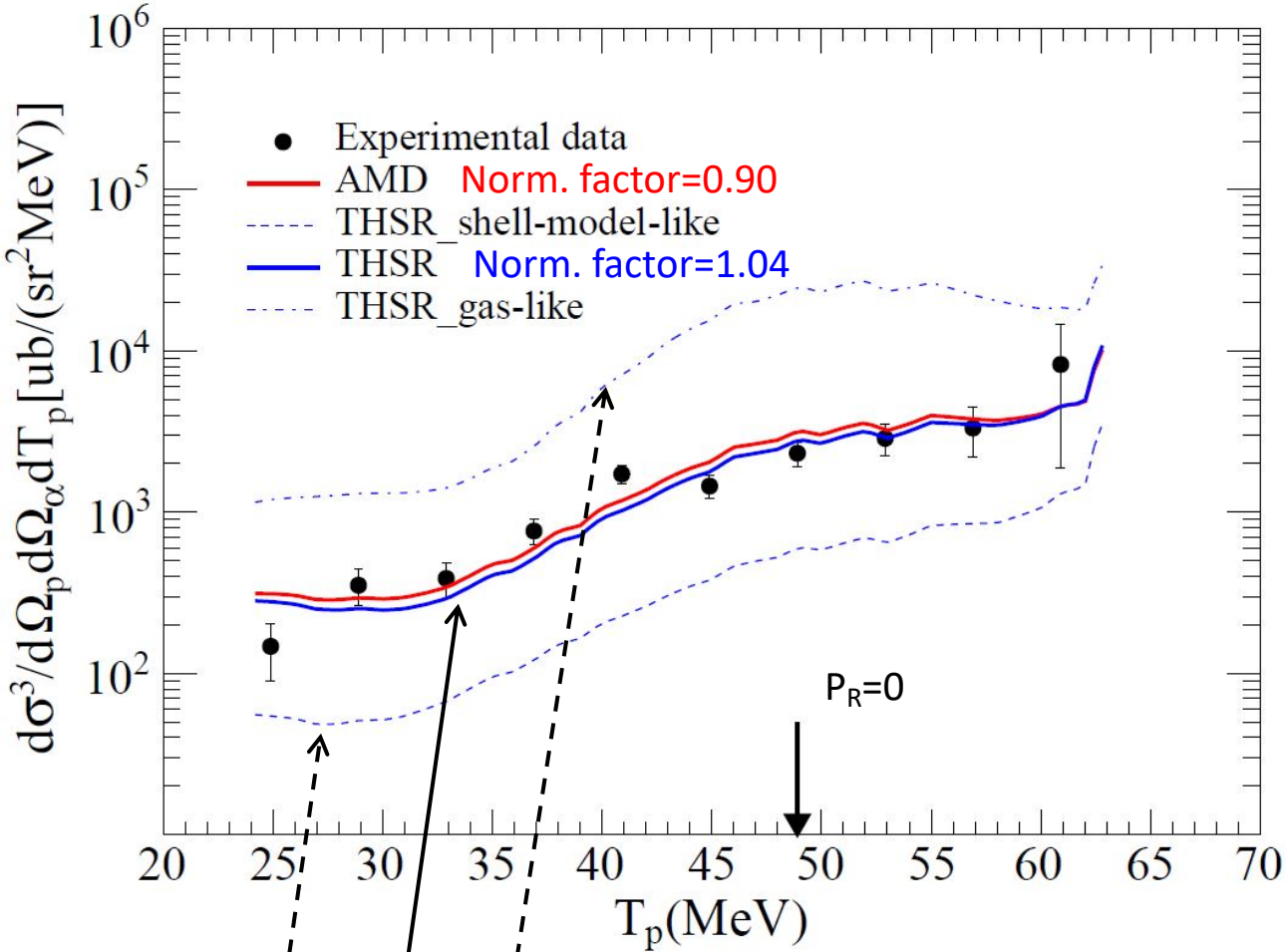
Extended THSR (M.Lyu)



AMD (Y.Kanada-En'yo)



DWIA



Predicted structure of ^{10}Be GS: 2α + 2n(π)

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

P.Li, D.B., et al, PRL 131, 212501 (2023)

Triple differential cross-section for $^{12}Be(p,p\alpha)^{8}He^{(GS)}$

THSR description of ^{12}Be(g.s)

main configurations for extra neutrons (revised) :

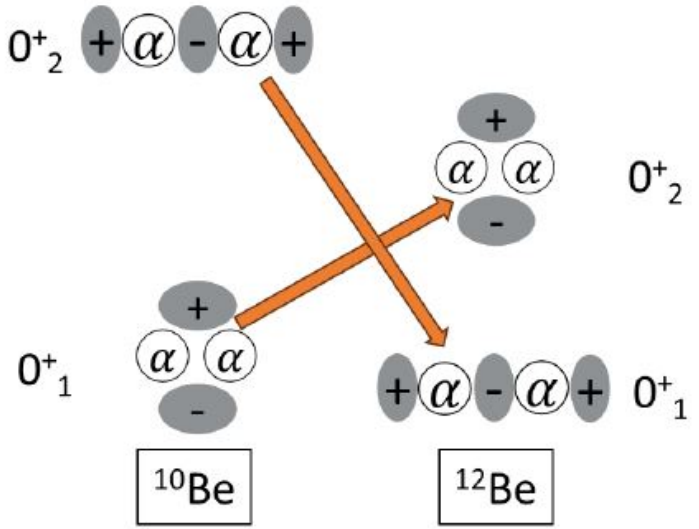
π orbits

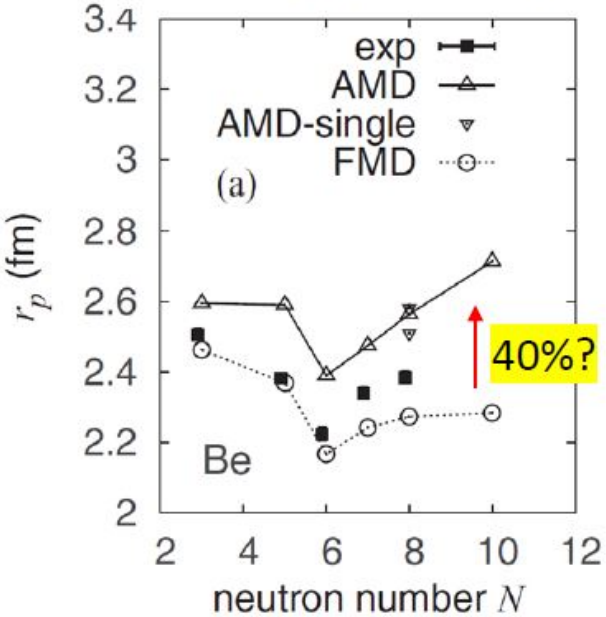
$(\pi_{3/2}^{-})^2(\pi_{1/2}^{-})^2$

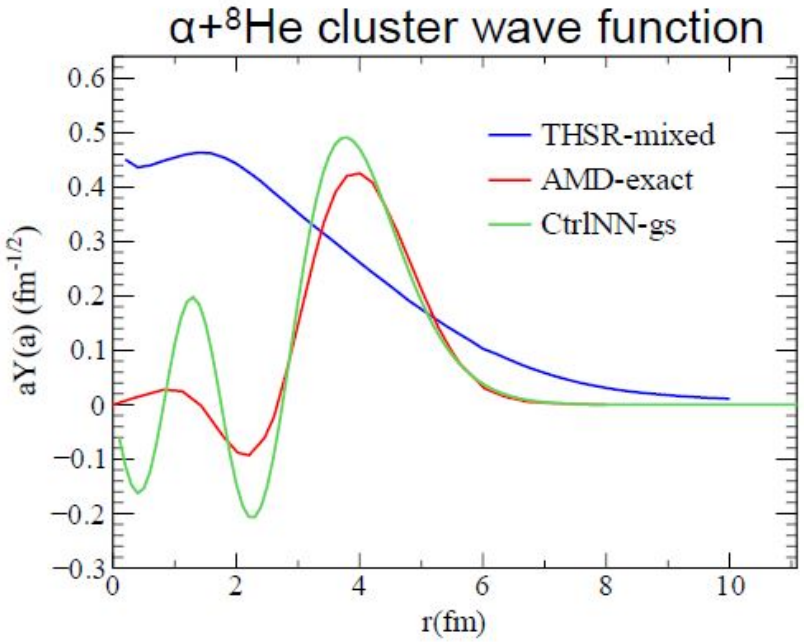
bicluster

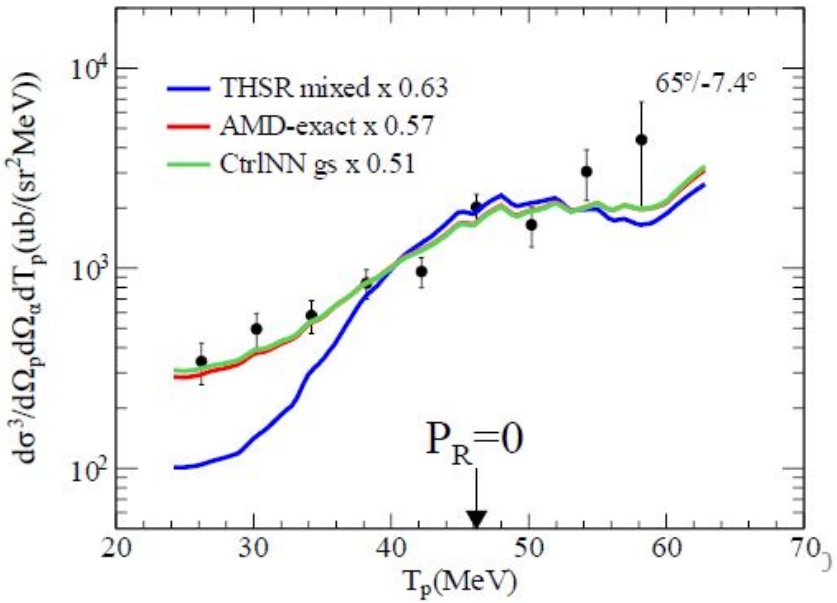
AMD description of ^{12}Be(g.s)

Mixture of $(0p)^8$ and $(0p)^6 + (1s, 0d)^2$



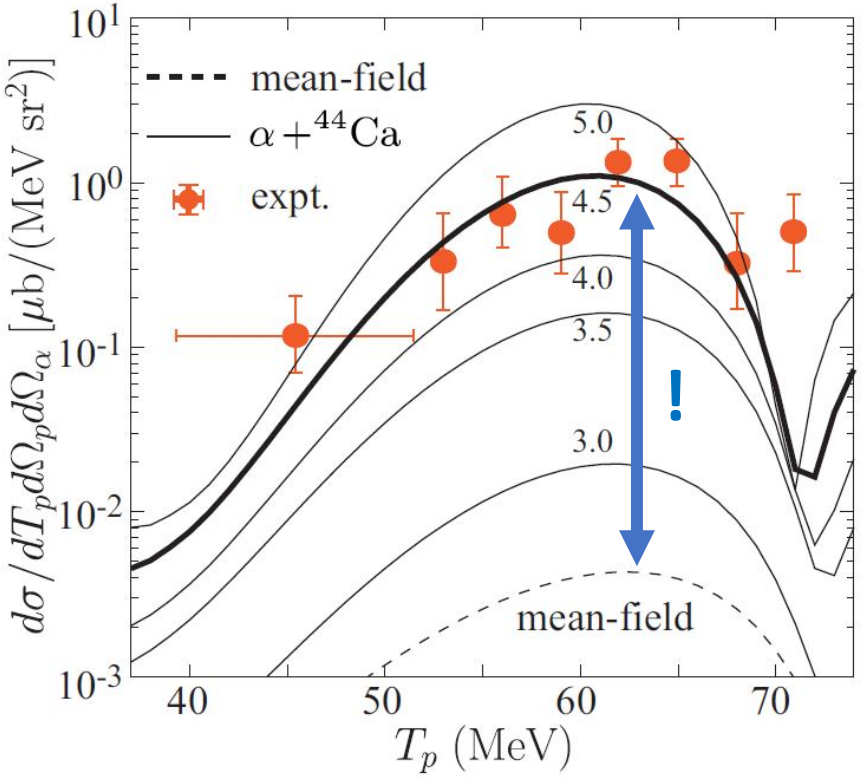






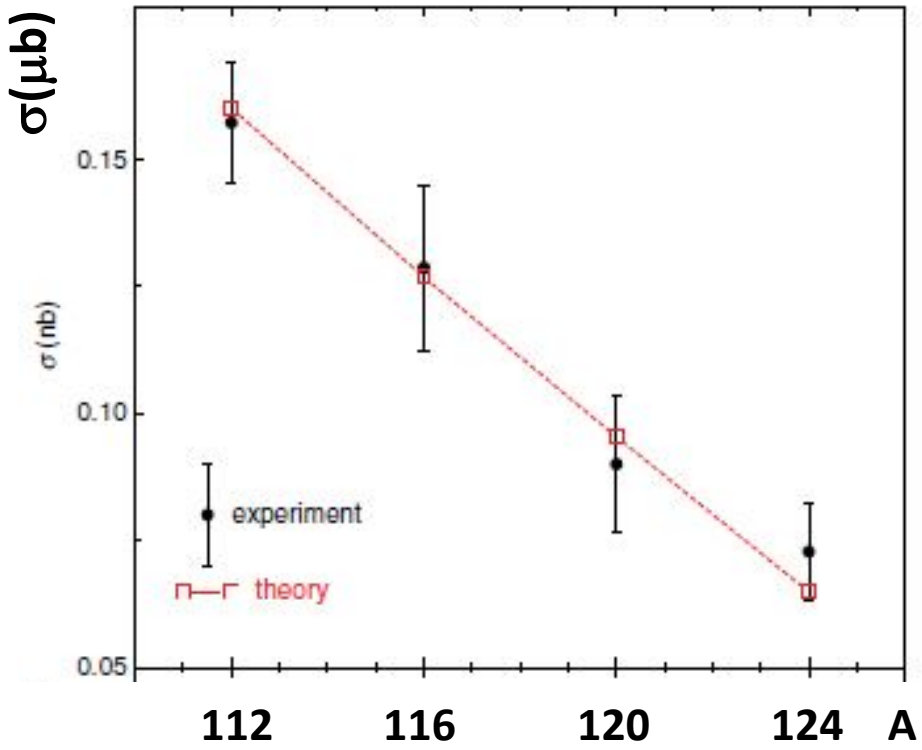
How about in heavier nuclei ?

$^{48}Ti\ (p,p\alpha)\ ^{44}Ca$



Y.Taniguchi et al., PRC 103, L031305 (2021)

$^{A}Sn\ (p,p\alpha)\ ^{A-4}Cd$



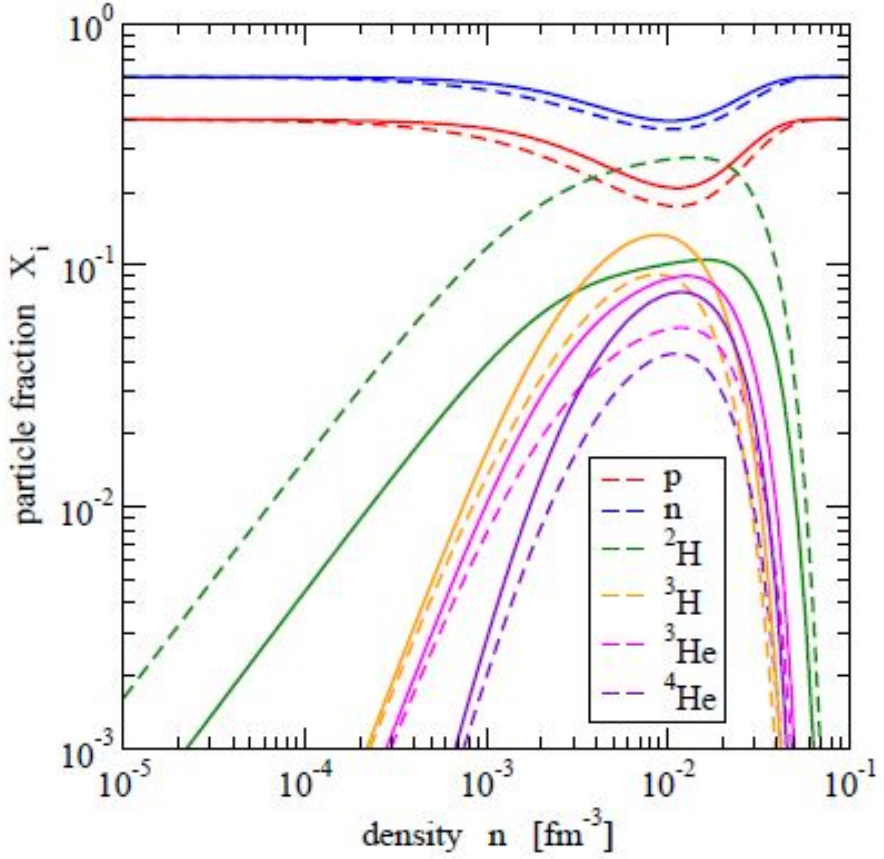
J.Tanaka *et al.*, Science 371, 260 (2021)

Need rescale imaginary potential depth in Xsection calculations

Formation of clusters in infinite nuclear matter

Generalized DFT calculations

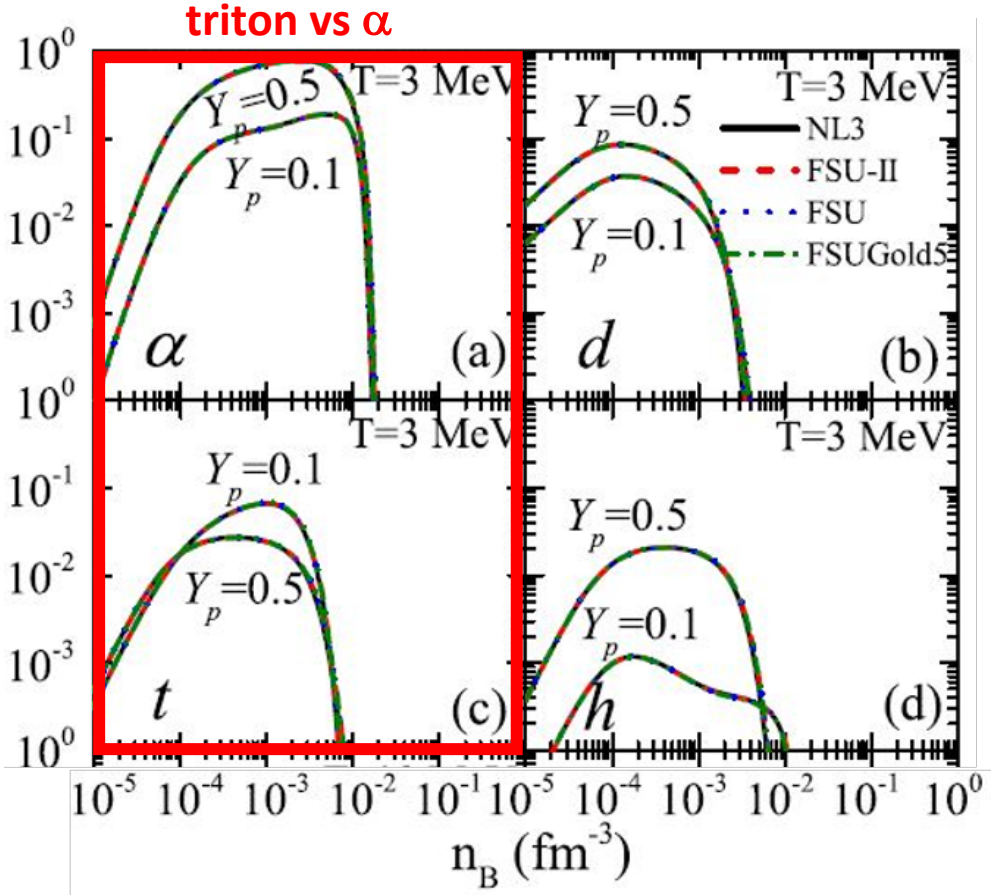
All kind of clusters should be formed at low density



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

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

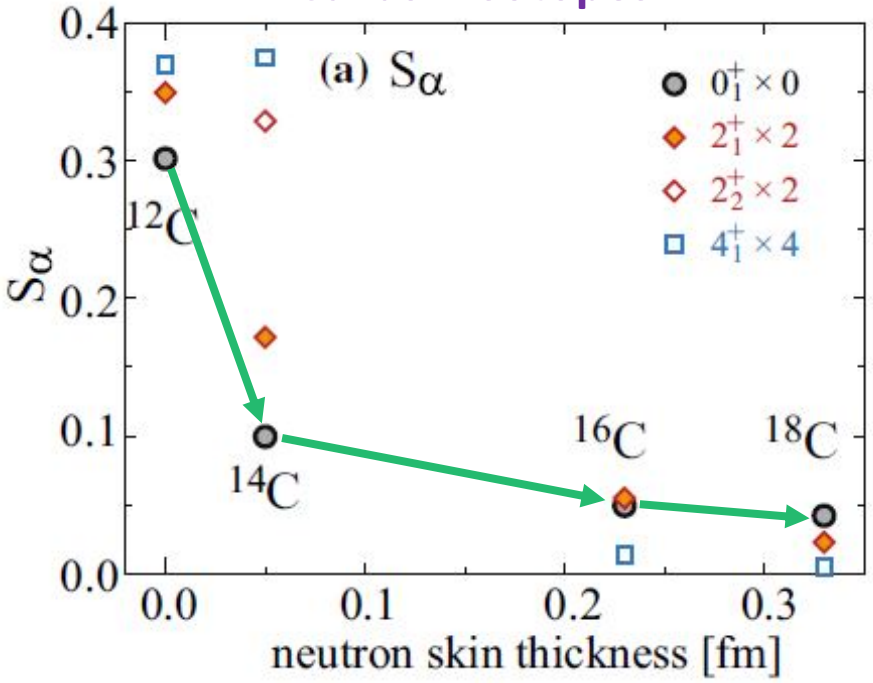
triton vs α



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

Clustering evolution towards the dripline

Carbon isotopes



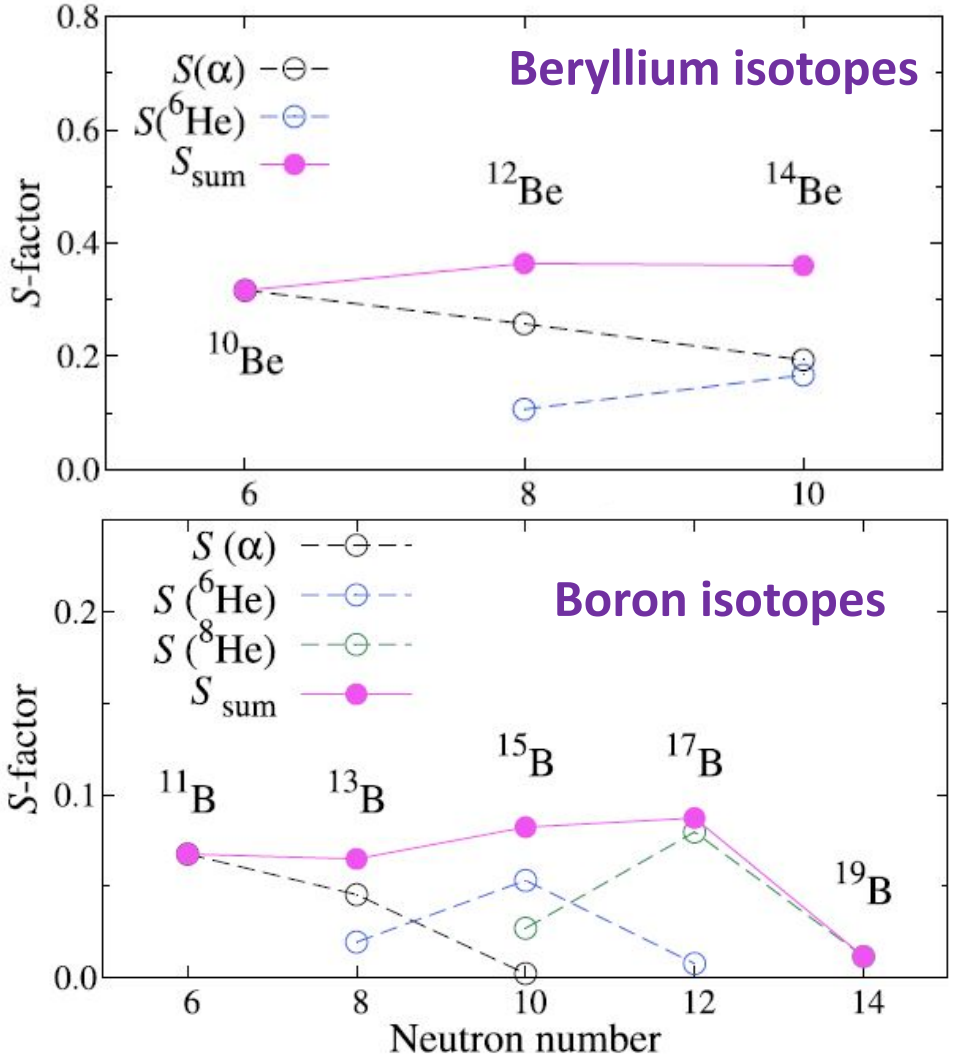
Q. Zhao, Y. Suzuki, J. He, B. Zhou, M. Kimura, EPJA 157 (2021)
AMD calculations using Gogny D1S functional

Hindrance effect due to neutron skin ?

Alternative interpretations

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

Beryllium isotopes



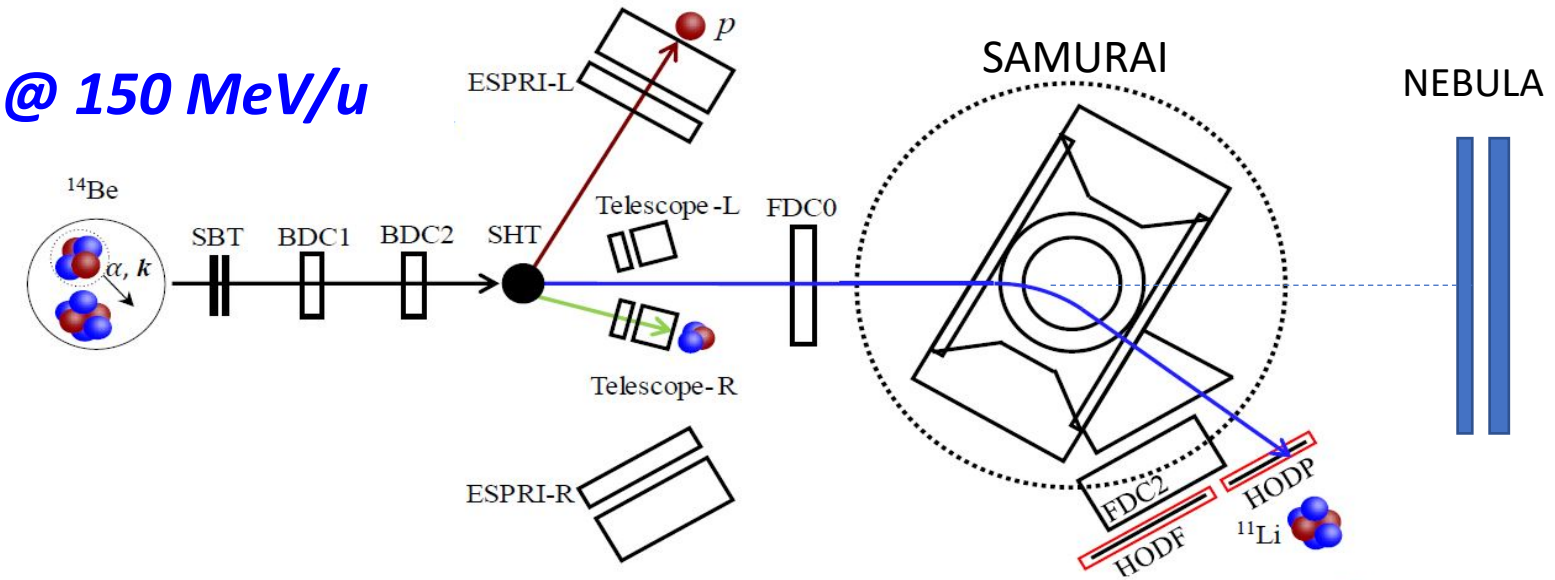
Boron isotopes

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

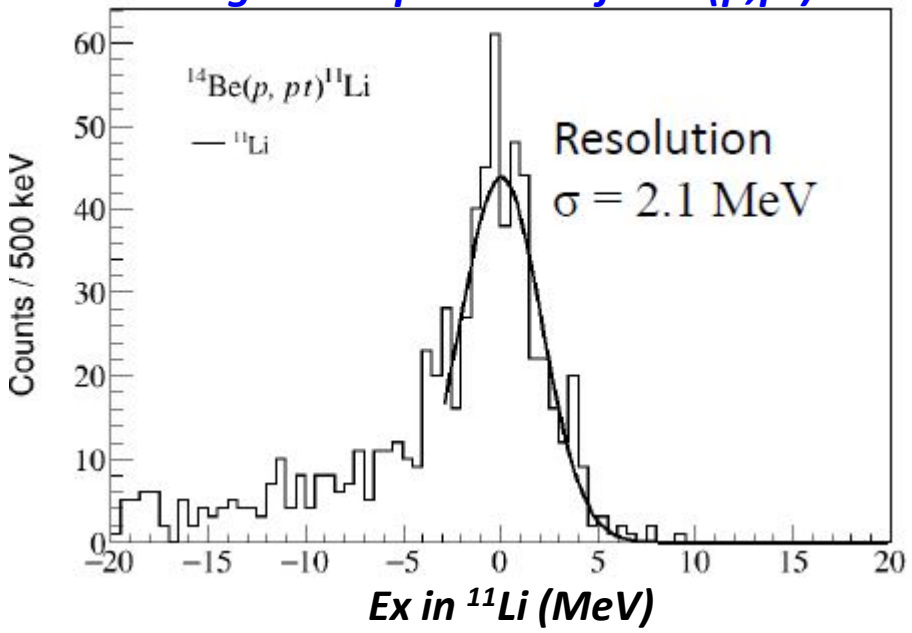
- **Hindrance of α clustering**
- **Development of ^{6}He clutering**

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

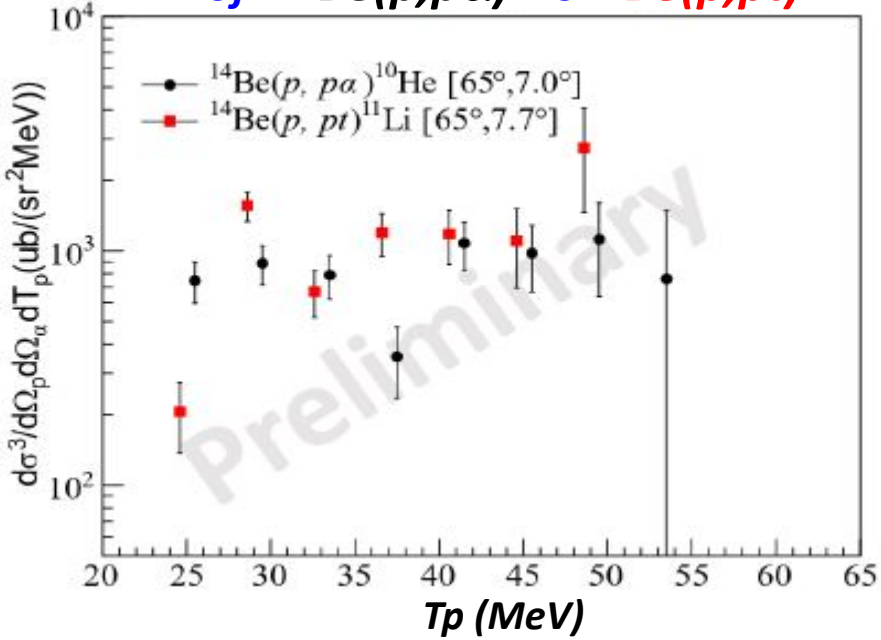
^{14}Be(p,pt)^{11}Li @ 150 MeV/u



Missing mass spectrum of ^{14}Be(p,pt)^{11}Li



TDX of ^{14}Be(p,pα) vs ^{14}Be(p,pt)



Conclusions/Prospects

- First measurement of ^{10,12,14}Be(p,pα) in inverse kinematics with RIB with proper kinematical conditions

- Shape and magnitude of the TDX for ^{10}Be(p,pα)^{6}He^{GS} are very well reproduced by DWIA calculations using microscopic α-cluster wave-functions, directly validating the 2α + 2n(π) molecular structure of ^{10}Be

- For ^{12}Be(p,pα)^{8}He^{GS} TDX calculations slightly overestimate the measured distribution, indicating a more compact GS of ^{12}Be than predicted
  Next: with ^{14}Be data we'll quantitatively probe alpha-cluster evolution up to the dripline in berylliums

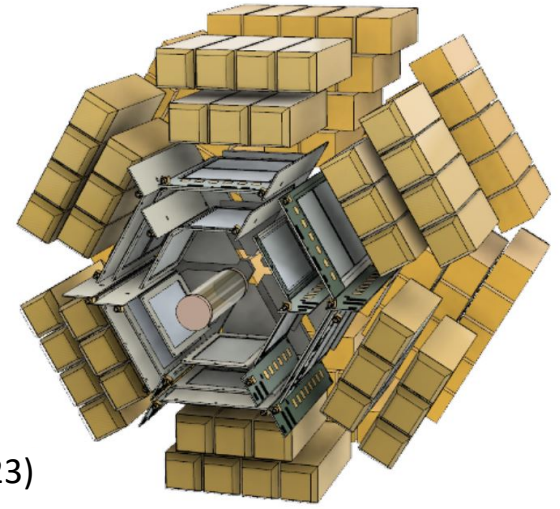
- We started to investigate other sort of clustering
  Preliminary results show sizeable formation of tritons at the surface of the halo nucleus ^{14}Be
  Complementary program using transfer reaction started at GANIL

- Planned study of (p,pα) on other light n-rich isotopes at RIKEN/Samurai
  The TOGAXSI device will allow measurements in excellent conditions

TOGAXSI

TOtal energy measurement by **GA**gg
and verte**X** reconstruction by **SI**licon

J.Tanaka et al., Nucl. Instrum. Meth. in Phys. Res. B 542, 4 (2023)



SAMURAI12 collaboration

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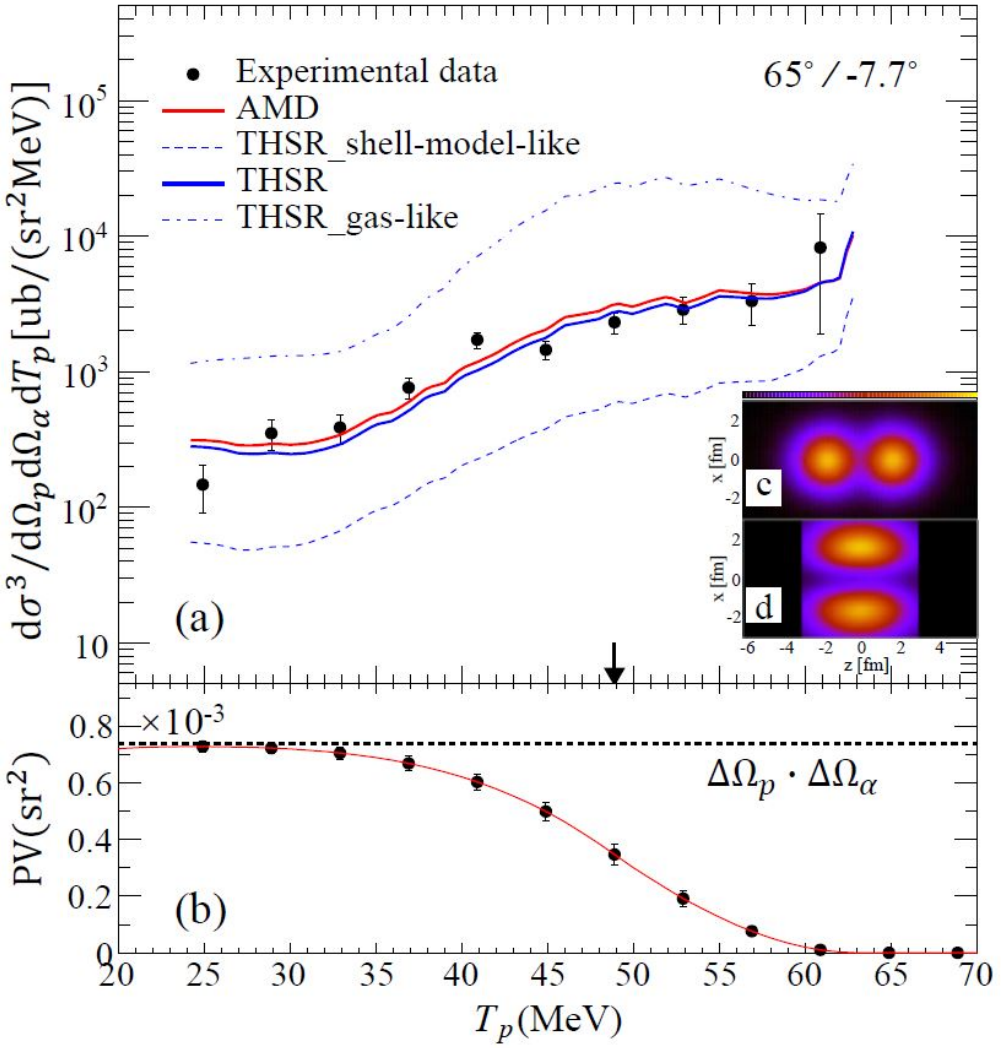
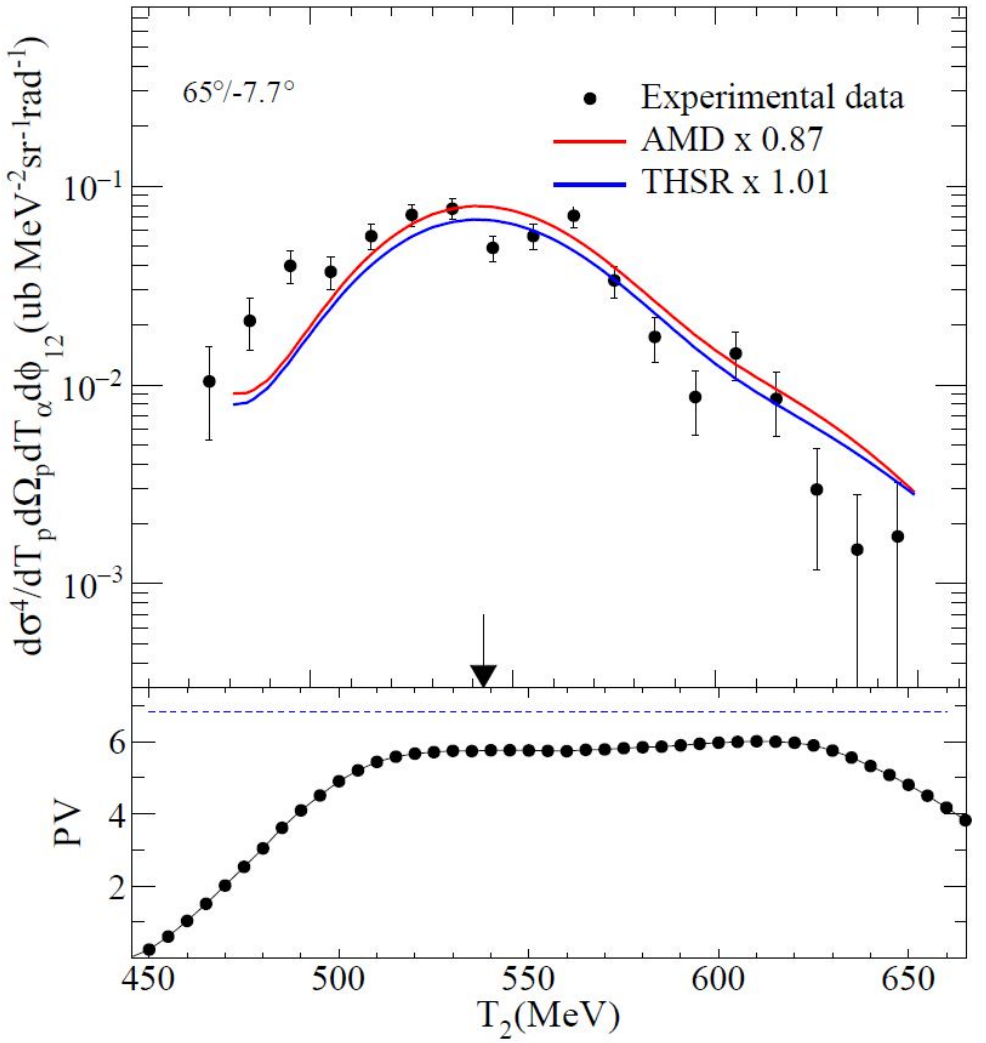
PKU: J. Gao, Z. H. Yang ; **CEA Saclay:** A. Corsi, A. Gillibert
Rikkyo Univ: Y.Togano; **INFN:** G. Cardella

BACKUP SLIDES

From TDX to QDX (quadruple diff Xsection)





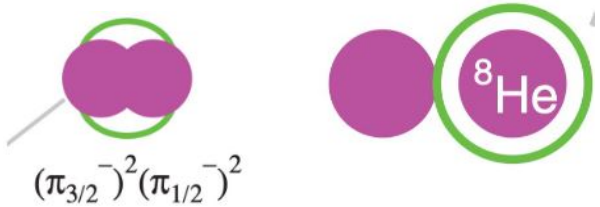
- Shape strongly governed by PV
- Divergence issues in inverse kinematics

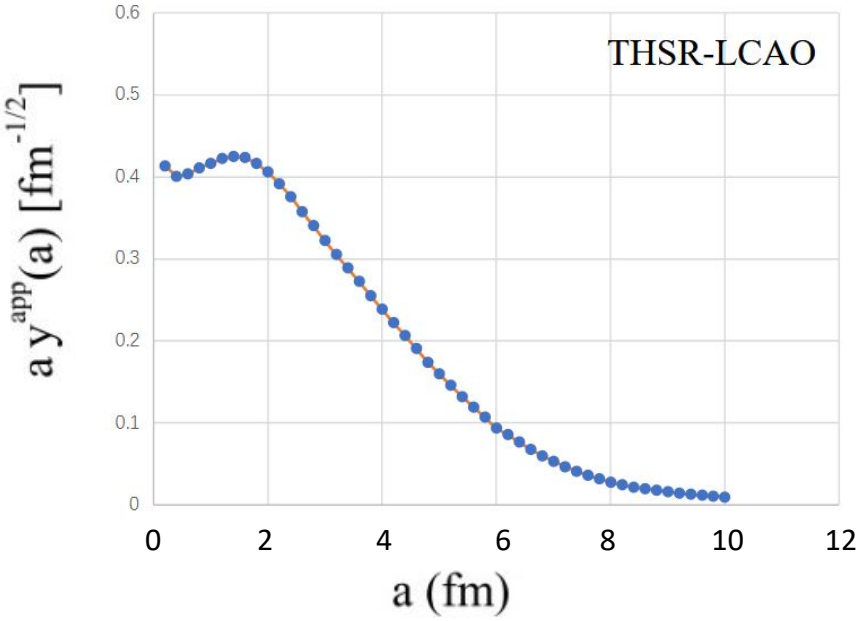
QDX for $^{12}Be(p,p\alpha)^{8}He^{(GS)}$

More complex WF than ^{10}Be

THSR main configurations for neutrons (revised) :

π orbits two-cluster





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