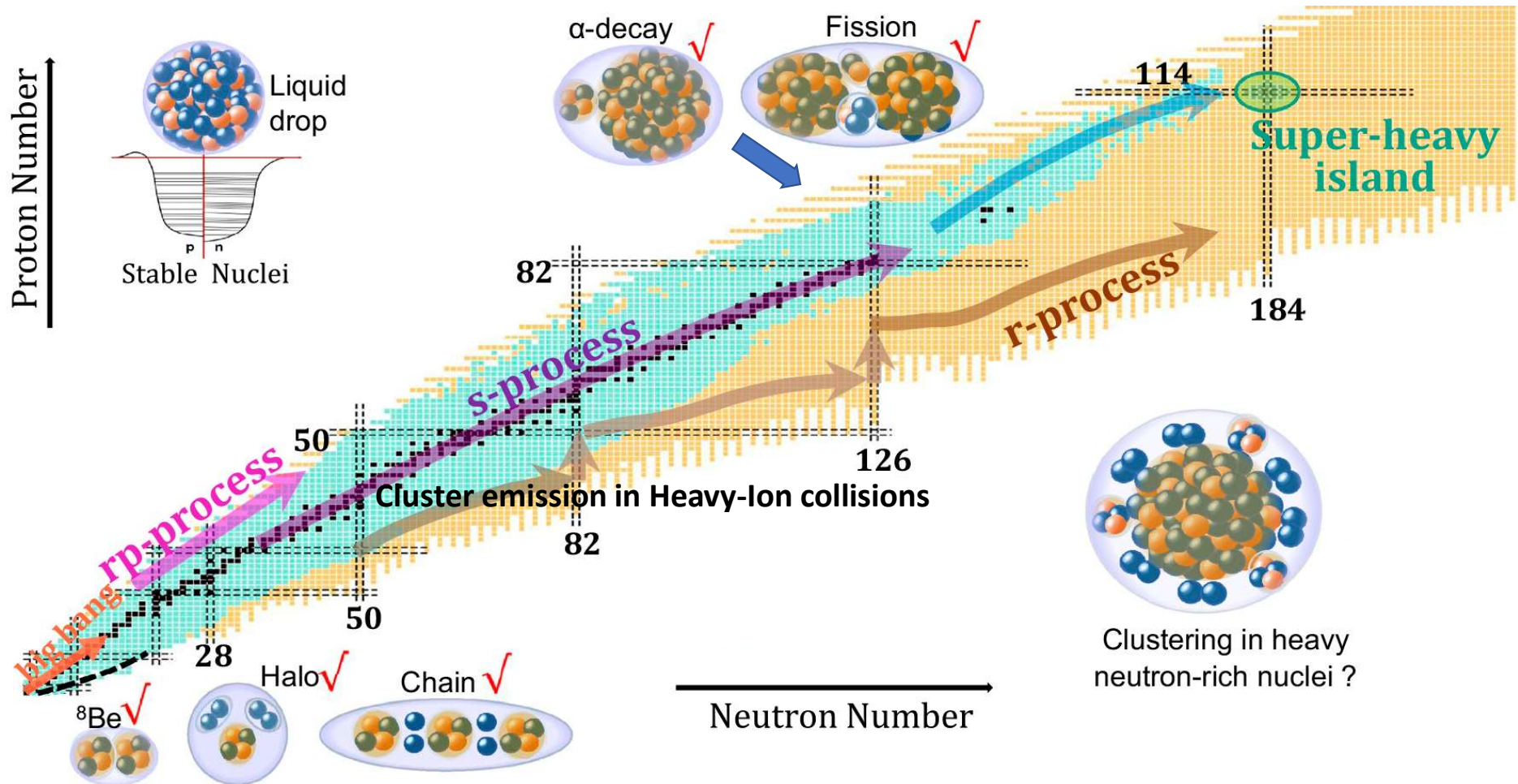


Nuclear clustering in the ground-state of neutron-rich nuclei via direct reactions

first studies in inverse kinematics at RIKEN and GANIL

D.Beaumel
IJCLab, Orsay, France

Clustering in nuclei

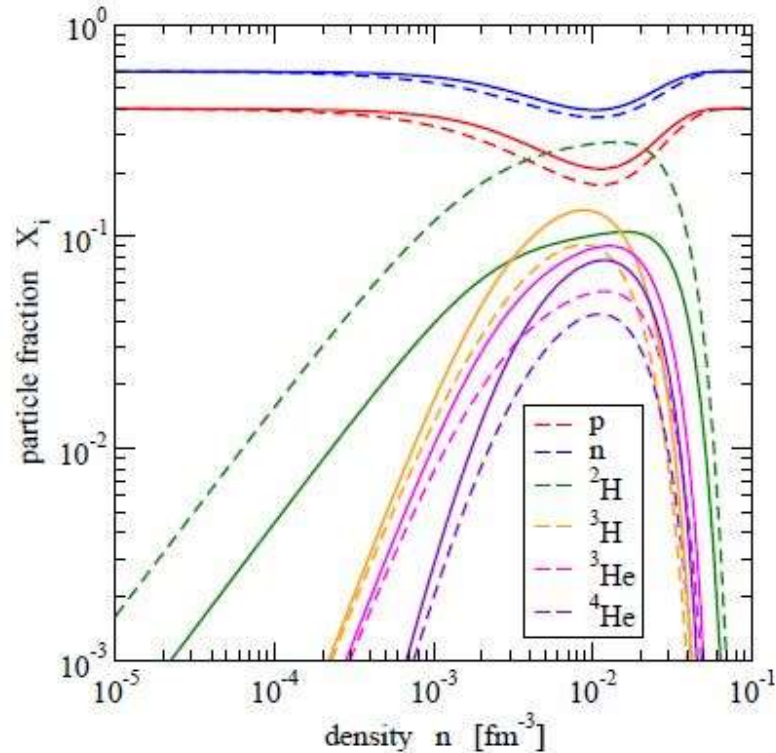


Adapted from K.Wei et al, Nucl.Sci.Tech (2024)

Formation of clusters in infinite nuclear matter

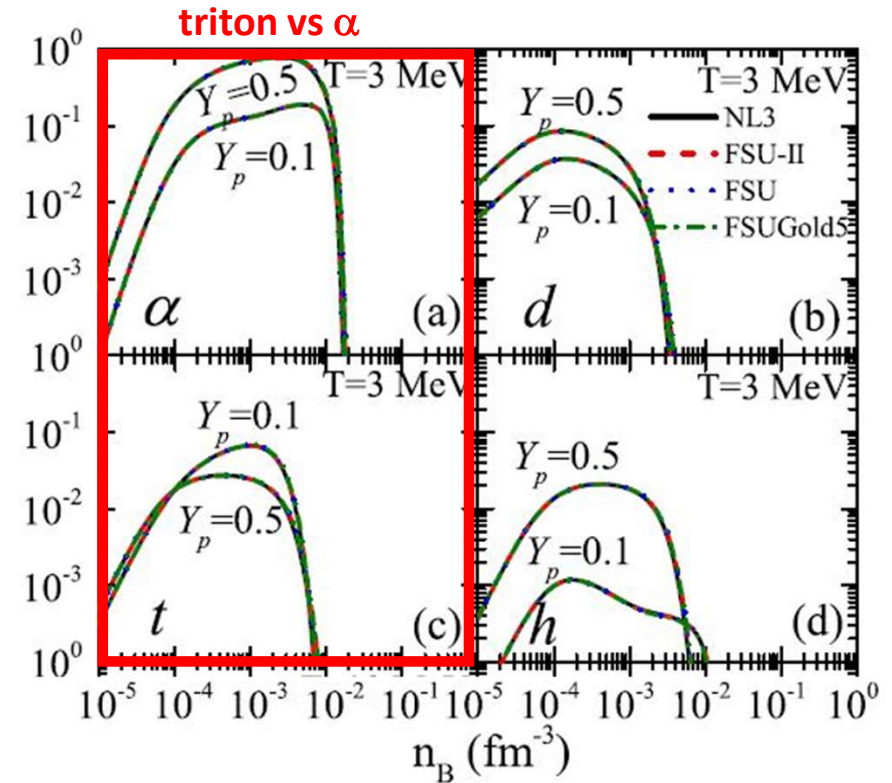
Generalized DFT calculations: include explicitly the cluster D.O.F

All kind of clusters should be formed at low density



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

Triton fraction increase clusters in neutron-rich matter



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

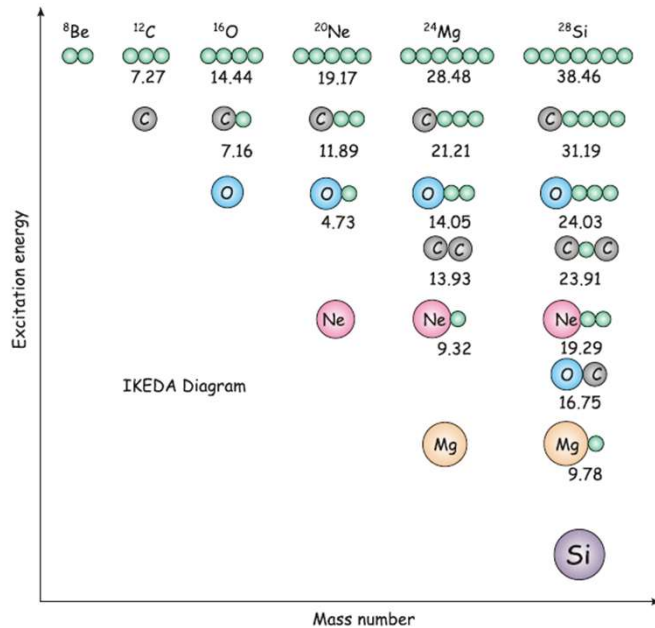
Cluster formation at the surface of nuclei



Study by means of DIRECT REACTIONS

Clustering in light exotic nuclei

**The Ikeda diagram
(alpha-conjugate nuclei)**

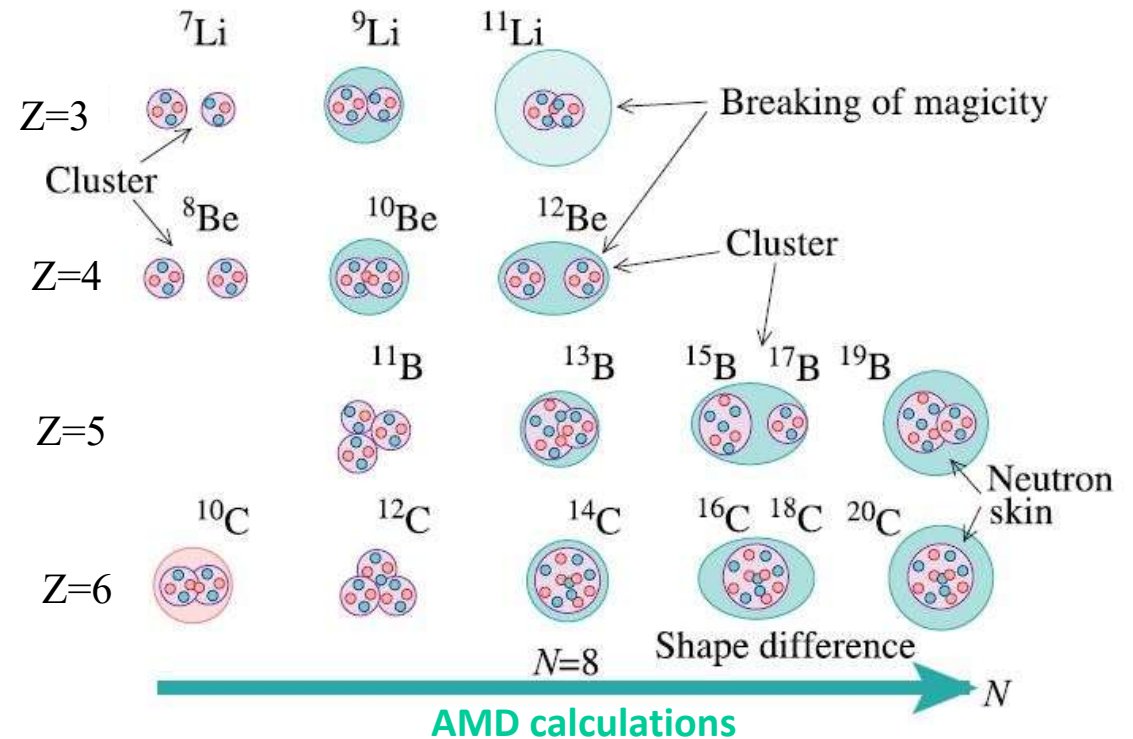


K.Ikeda, N.Takigawa, H.Horiuchi, PTP (1968)

**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

GROUND-STATES !



Adding neutrons to $N=Z$:

Molecular structure for ground and low lying states

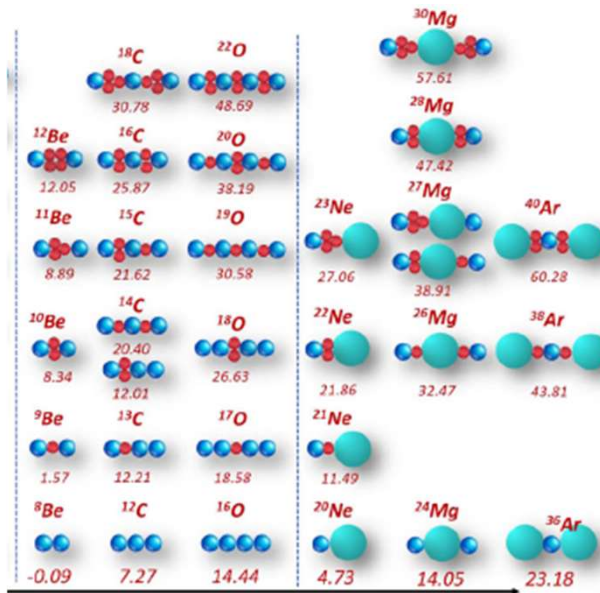
Towards the neutron dripline

Role of excess neutrons ?

Enhancement of n-rich clusters formation ?

Clustering in light exotic nuclei

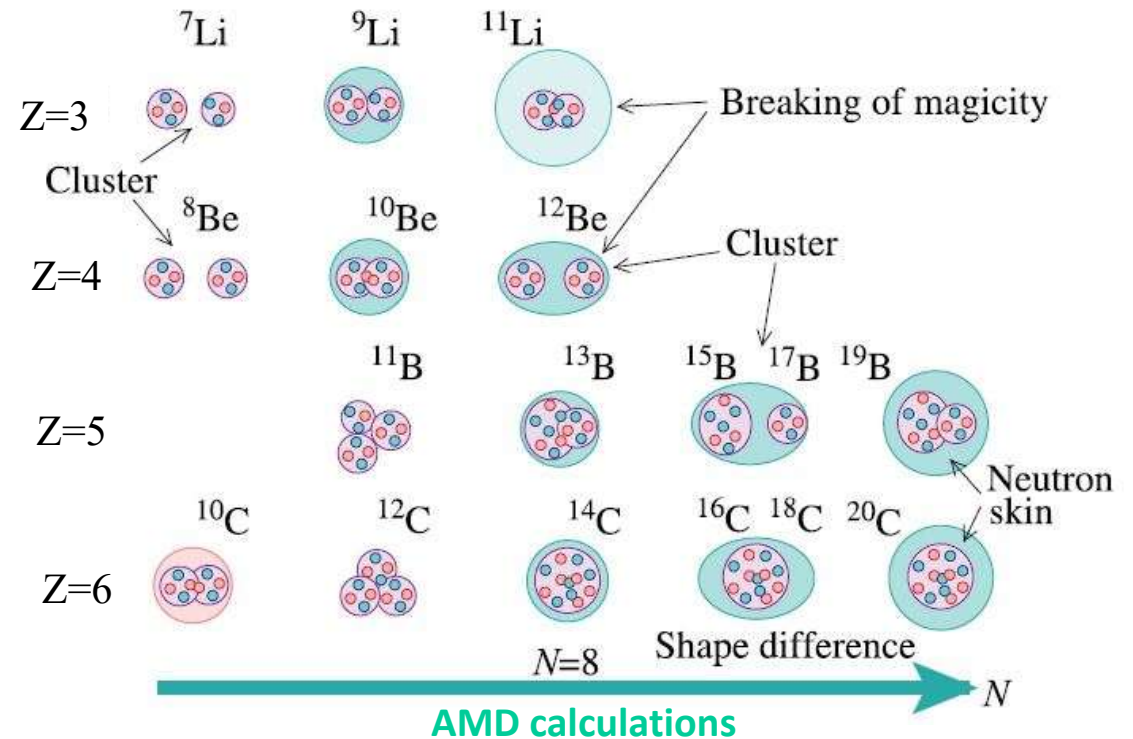
The **extended** Ikeda diagram



W. Von Oertzen Phys. Rev. 432 (2006)

Cluster structure typically occurs
close to cluster + Xn thresholds

GROUND-STATES !



Adding neutrons to $N=Z$:

Molecular structure for ground and low lying states

Towards the neutron dripline

Role of excess neutrons ?

Enhancement of n-rich clusters formation ?

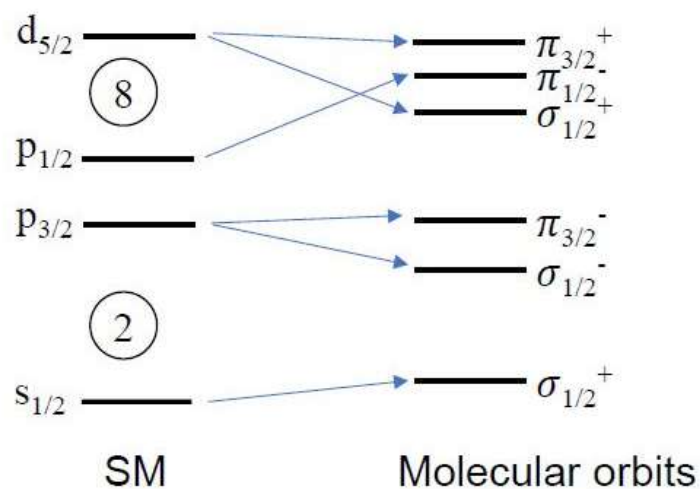
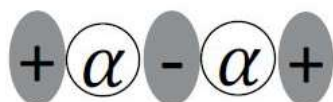
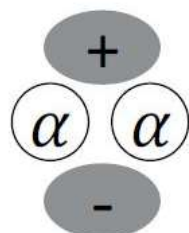
Clustering in beryllium isotopes – AMD calculation

AMD: no preformed cluster

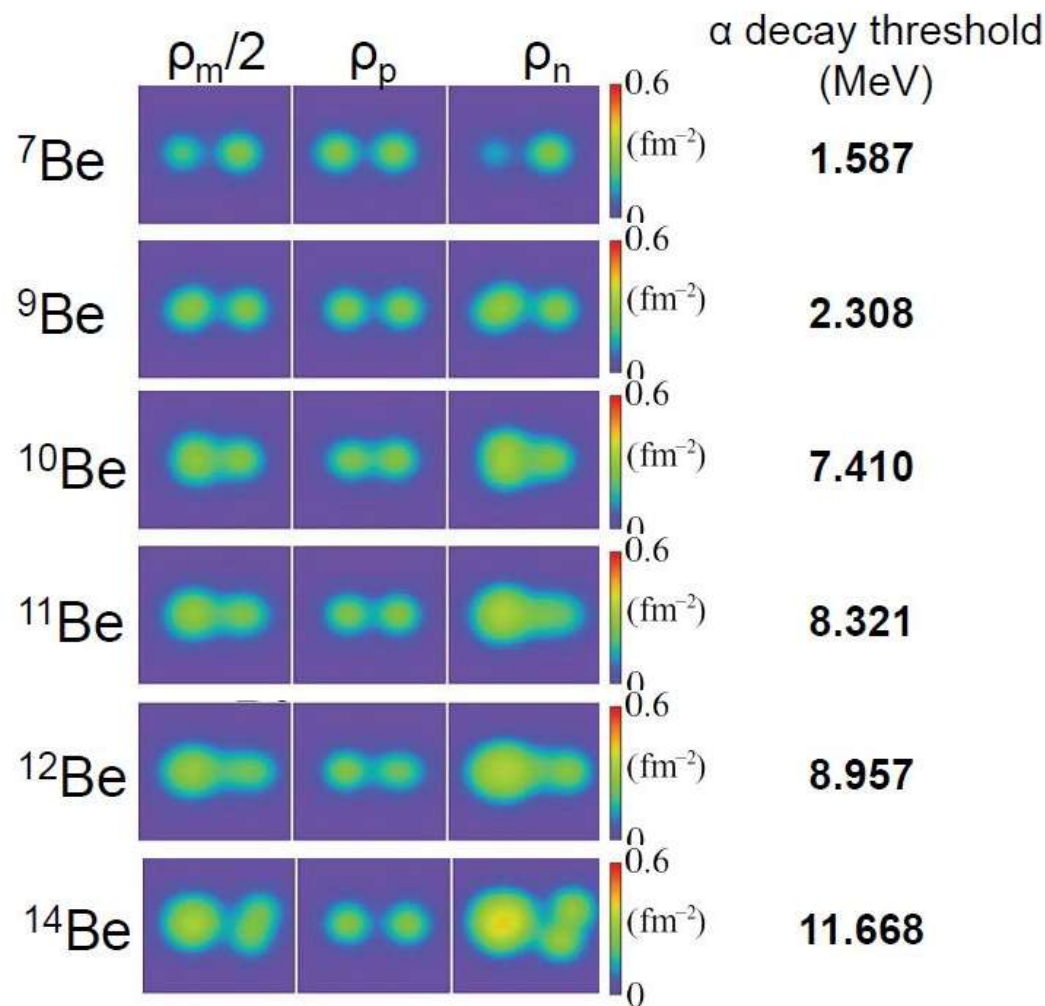
Be isotopes: α -Xn- α

π -orbit

σ -orbit



Density distributions of Be

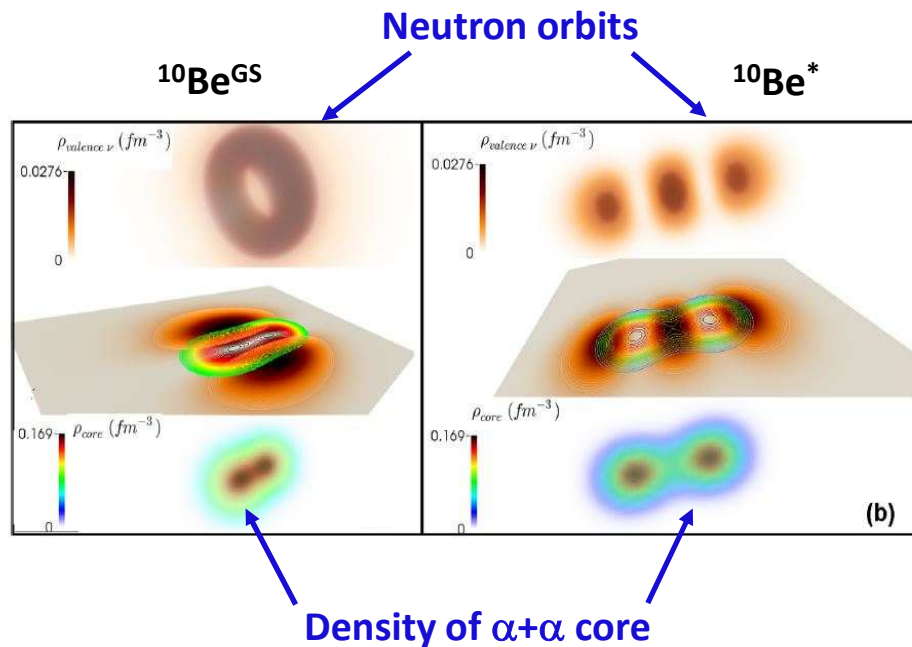


Kanada-Enyo, PRC91, 014315(2015)

Calculations of density distributions for Be isotopes

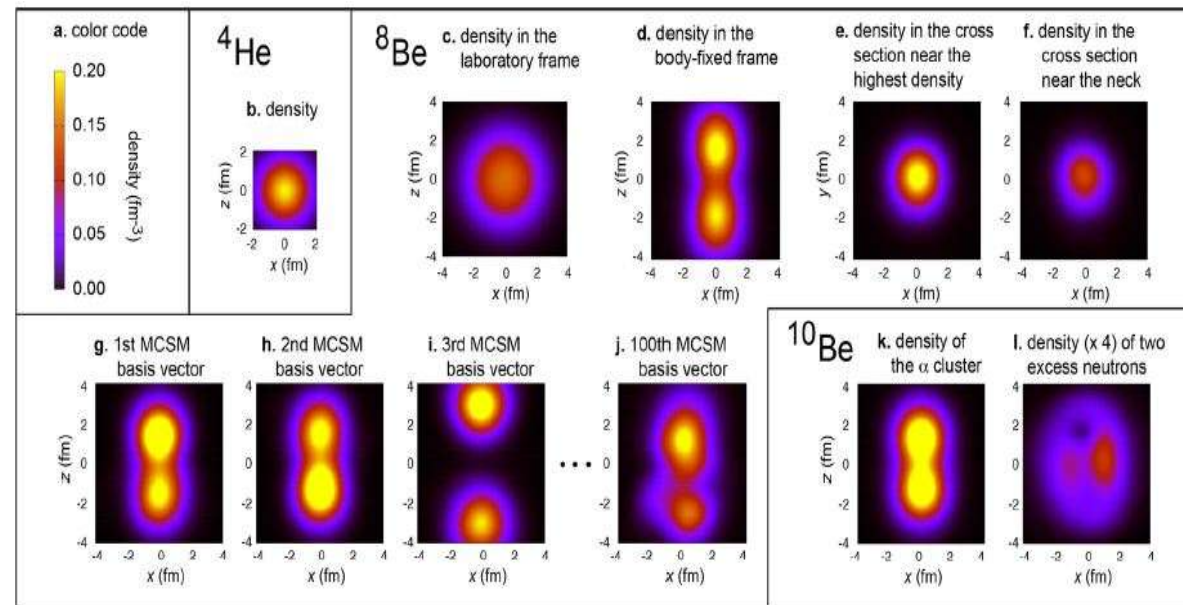
DDME2 relativistic functional in rel. HB calculations

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



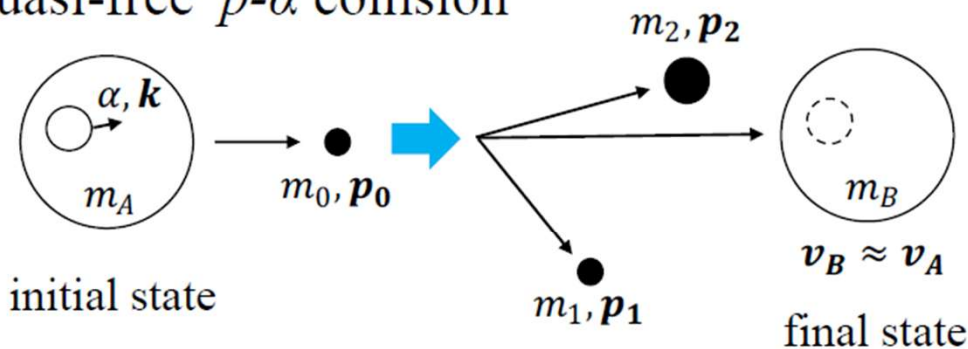
$^{8,10}\text{Be}$ isotopes in no-core Monte-Carlo Shell Model

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



Approach using cluster quasi-free scattering

Quasi-free p - α collision



- Single-step direct reaction
- Incident beam energy: 150 MeV/u ($\lambda_p \sim 0.4$ fm)
- **Peripherality**: α -particle on the nuclear surface is selectively probed

Distorted Wave Impulse Approximation (DWIA)

$$\frac{d^3\sigma}{dE_1^L d\Omega_1^L d\Omega_2^L} = F_{\text{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) \left| \bar{T}_{P_0 P_1 P_2} \right|^2$$

Transition amplitude χ_i : scattering wave of particle i

$$T = \langle \chi_1 \chi_2 | t_{p\alpha} | \chi_1 \chi_2 \rangle$$

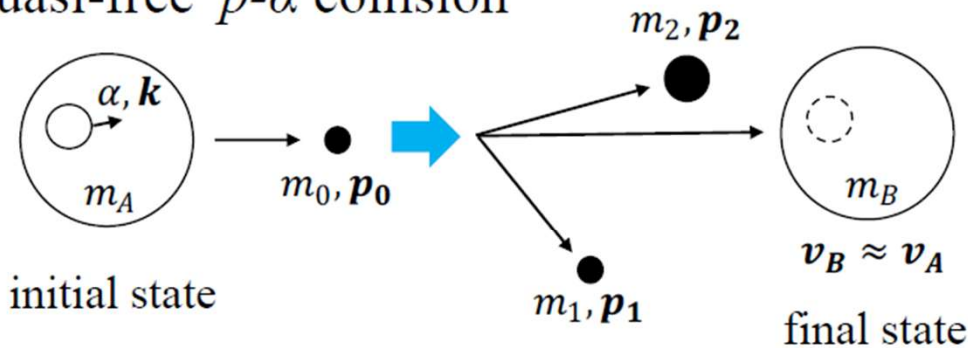
$t_{p\alpha}$: free p - α t -matrix

α -cluster wave function φ_α

- Phenomenological $S_\alpha = \text{TDX}_{\text{exp}} / \text{TDX}_{\text{calc}}$
- Microscopic (*ab initio*, AMD, THSR...)

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Distorted Wave Impulse Approximation (DWIA)

Triple differential cross section (TDX)

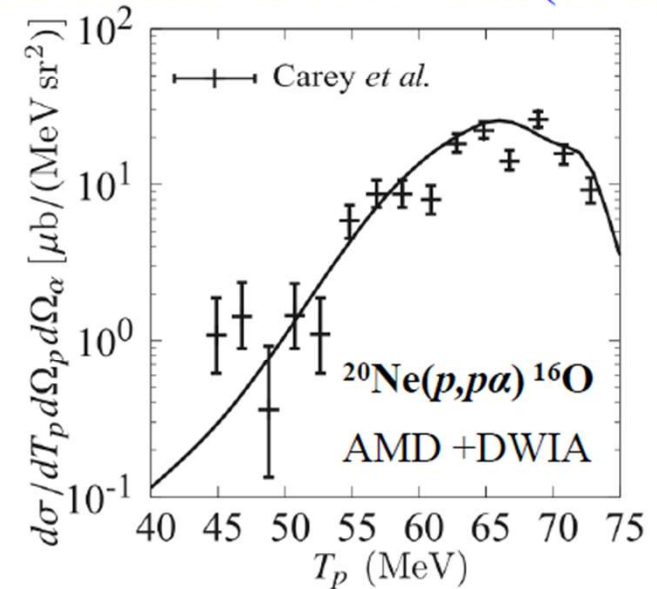
$$\frac{d^3\sigma}{dE_1^L d\Omega_1^L d\Omega_2^L} = F_{\text{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}} (\theta_{p\alpha}, E_{p\alpha}) |\bar{T}_{P_0 P_1 P_2}|^2$$

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- Microscopic (*ab initio*, AMD, THSR...)



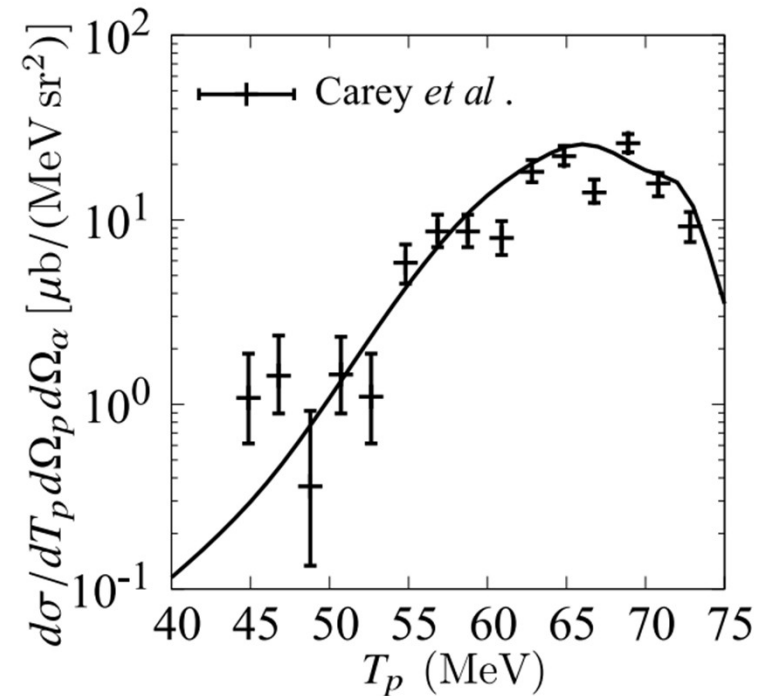
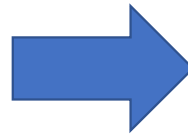
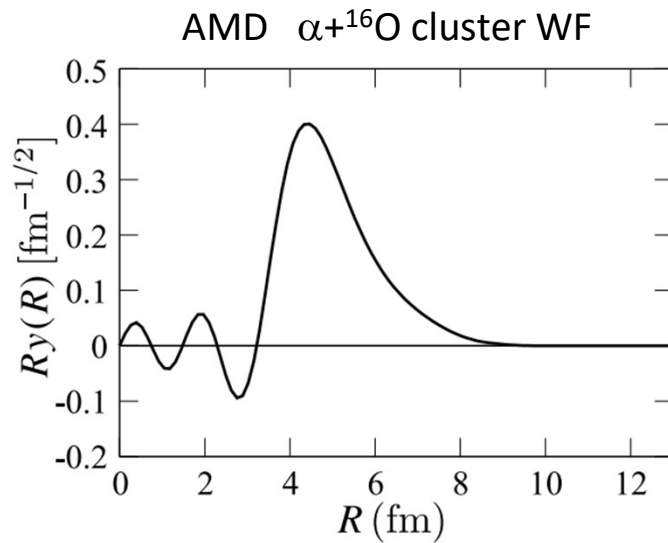
K. Yoshida et al., PRC 100, 044601 (2019)

Test case of cluster K.O. study within a microscopic framework

Reanalysis of $^{20}\text{Ne}(p,p\alpha)^{16}\text{O}$ 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

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

New DWIA code: PIKOE [Ogata, Yoshida, Chazono, Computer Physics Comm. 297 (2024) 109058]



Letter

Ab initio informed $^{20}\text{Ne}(p, p\alpha)^{16}\text{O}$ reaction elucidates the emergence of alpha clustering from chiral potentials

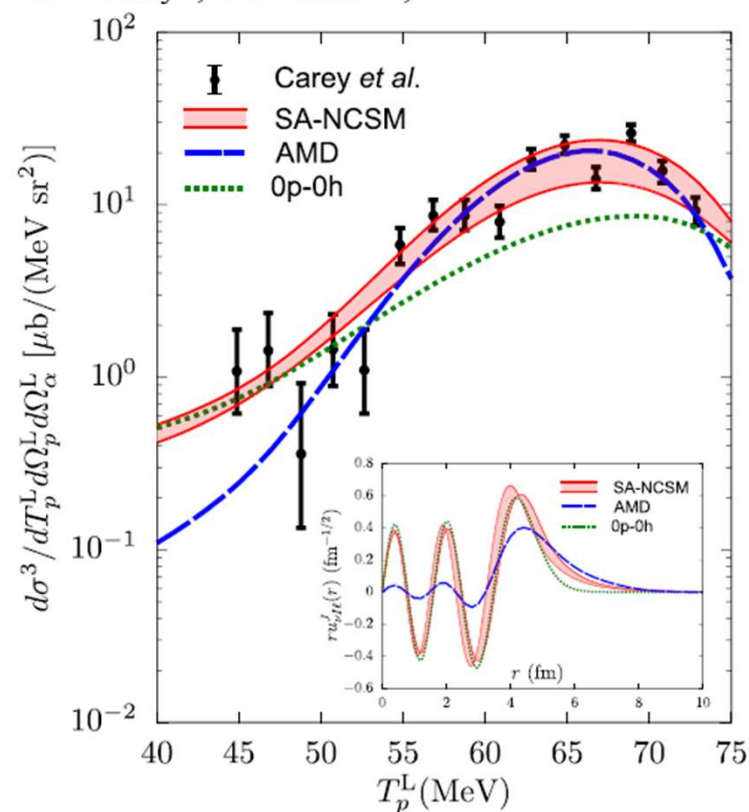
G.H. Sargsyan^{a, b, *}, Kazuki Yoshida^b, Kazuyuki Ogata^{c, d}, K.D. Launey^e, J.E. Escher^f,
D. Langr^g, T. Dytrych^{h, e}



ab initio symmetry-adapted no-core shell model
NNLO_{opt} NN chiral potential in 13 HO shells

Charge radius of ^{20}Ne

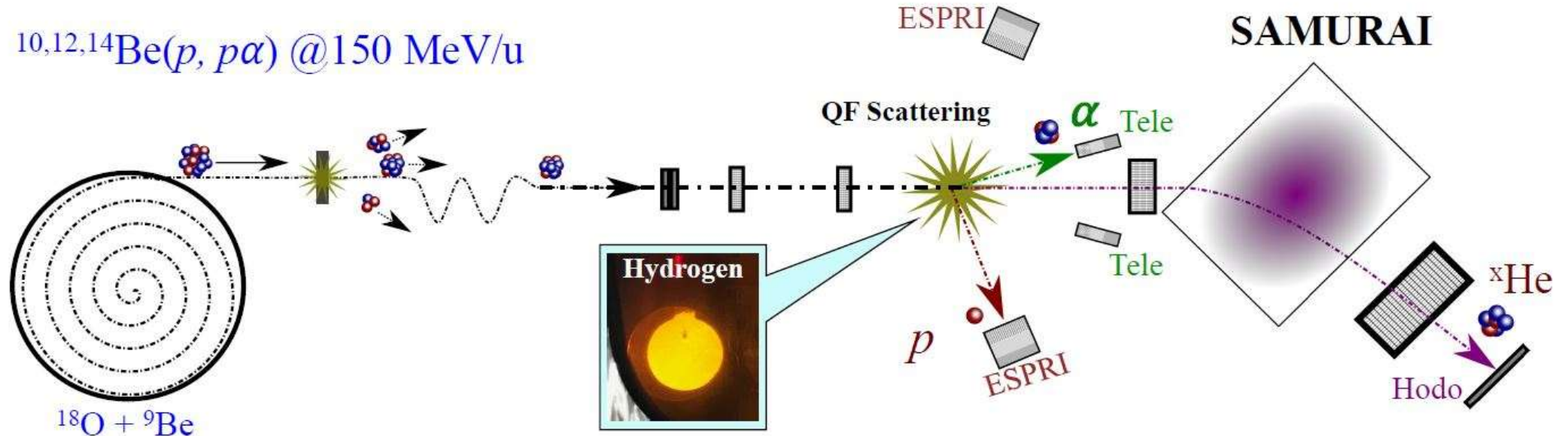
SA-NCSM	2.94(9) fm
EXP	3.0055(21) fm



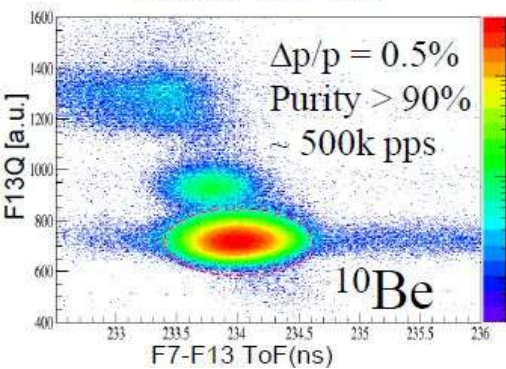
Study of $^{10,12,14}\text{Be}(p, p\alpha)$ at 150 MeV/u

First study in Inverse Kinematics with proper kinematics condition

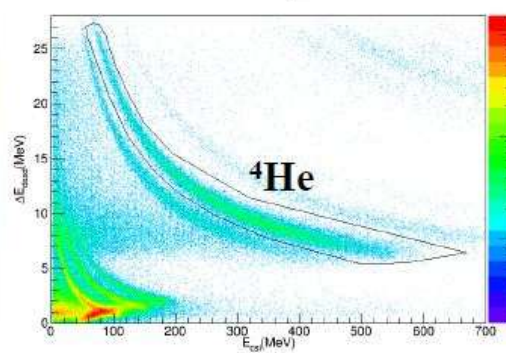
$^{10,12,14}\text{Be}(p, p\alpha)$ @150 MeV/u



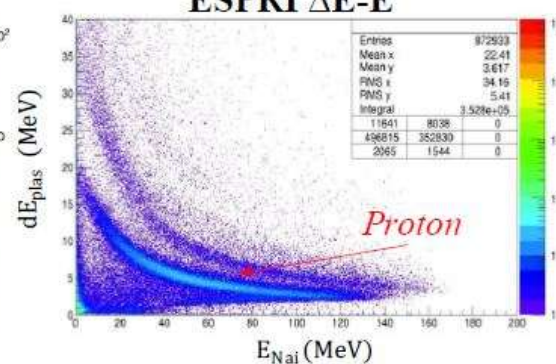
Beam ΔE -ToF



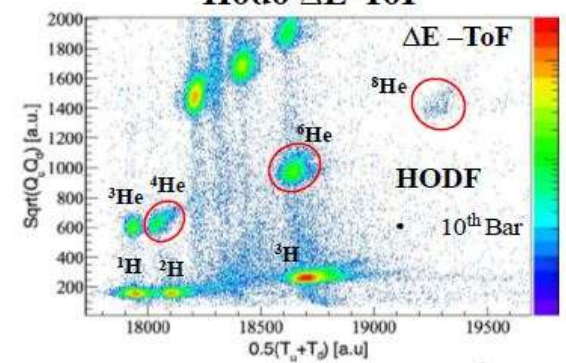
Telescope ΔE -E



ESPRI ΔE -E



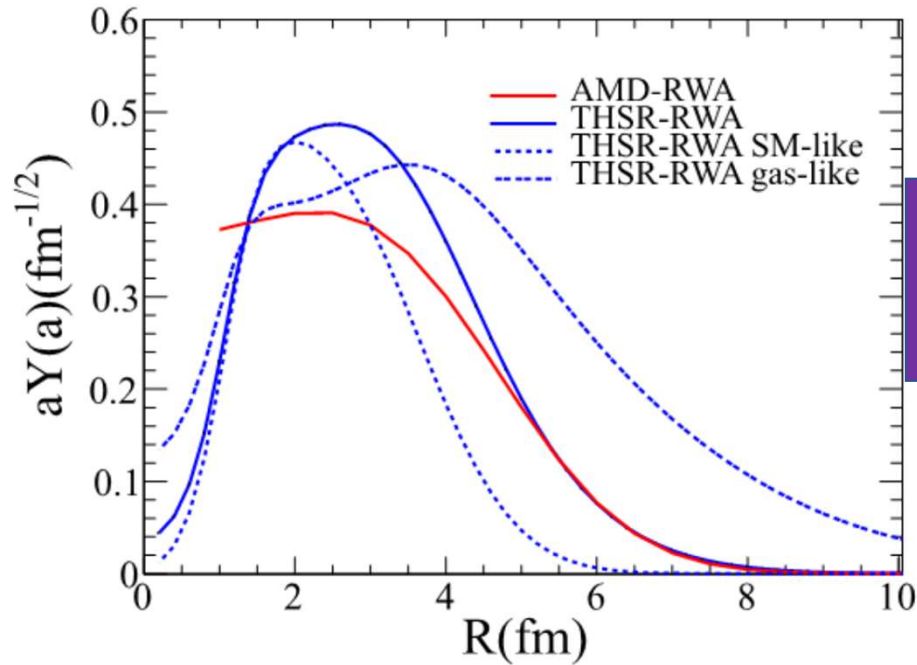
Hodo ΔE -ToF



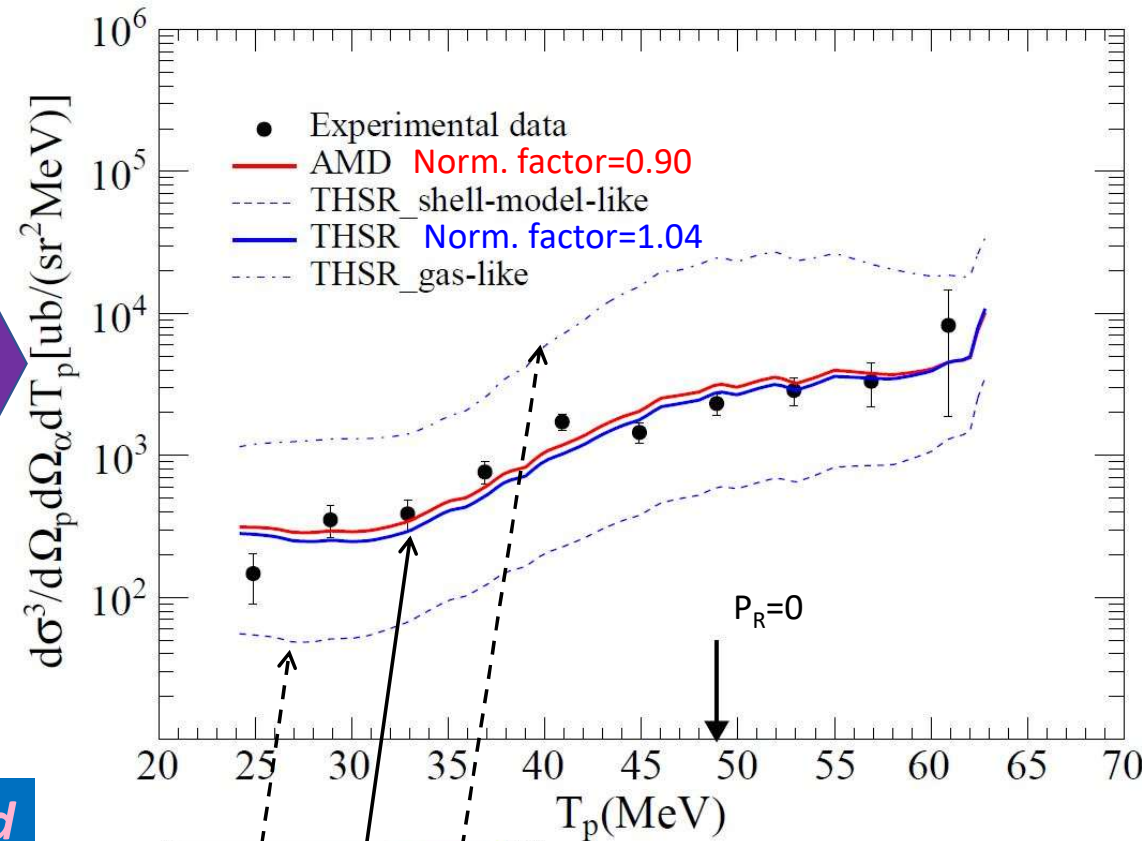
Collaboration: **IJCLab, Hong Kong U., RIKEN, TI Tech, LPC Caen, Tohoku U., RCNP Osaka, CEA Saclay, Kyoto U., TU Darmstadt, NIPNE Bucharest, Kyushu U.**

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

Microscopic cluster WF used in DWIA calc.

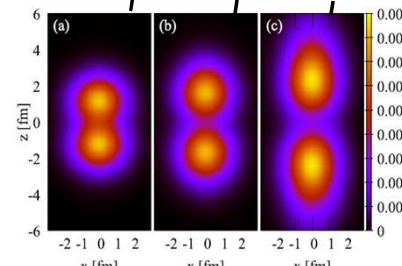
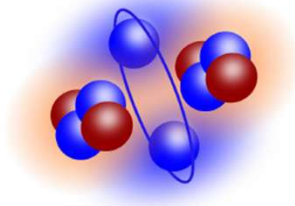


DWIA

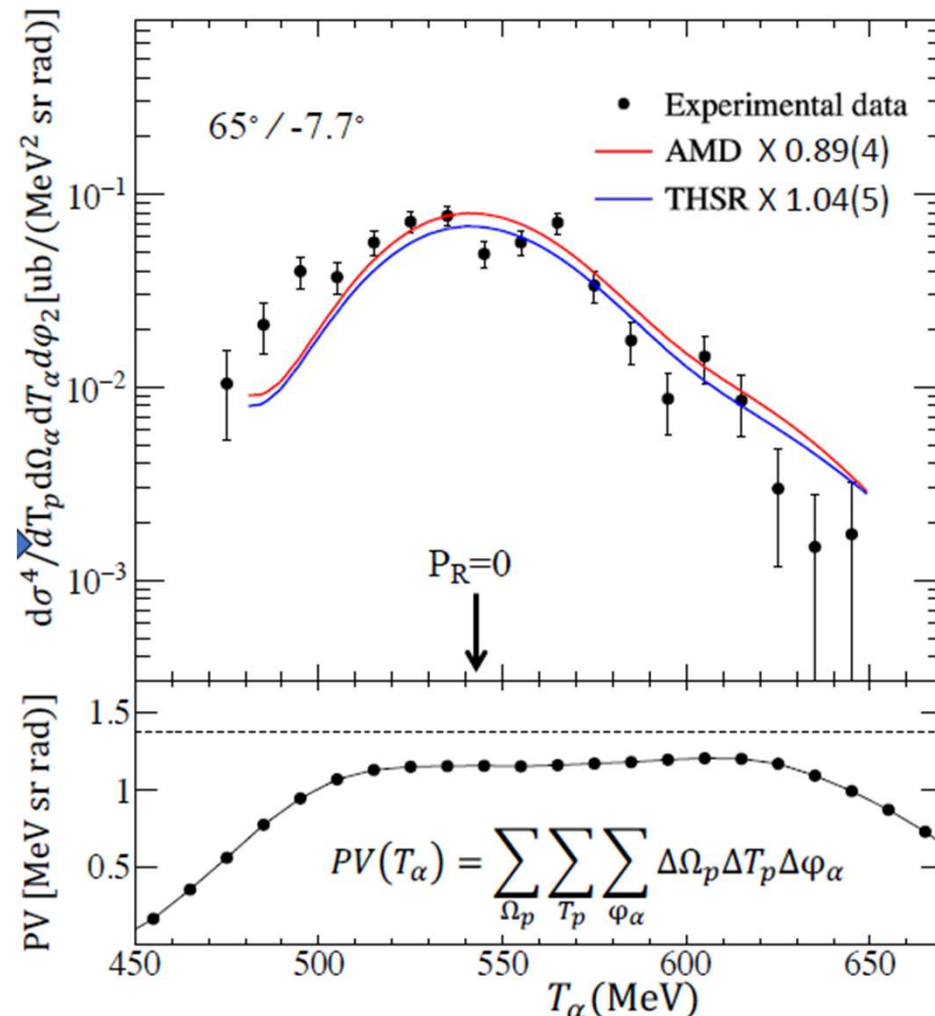
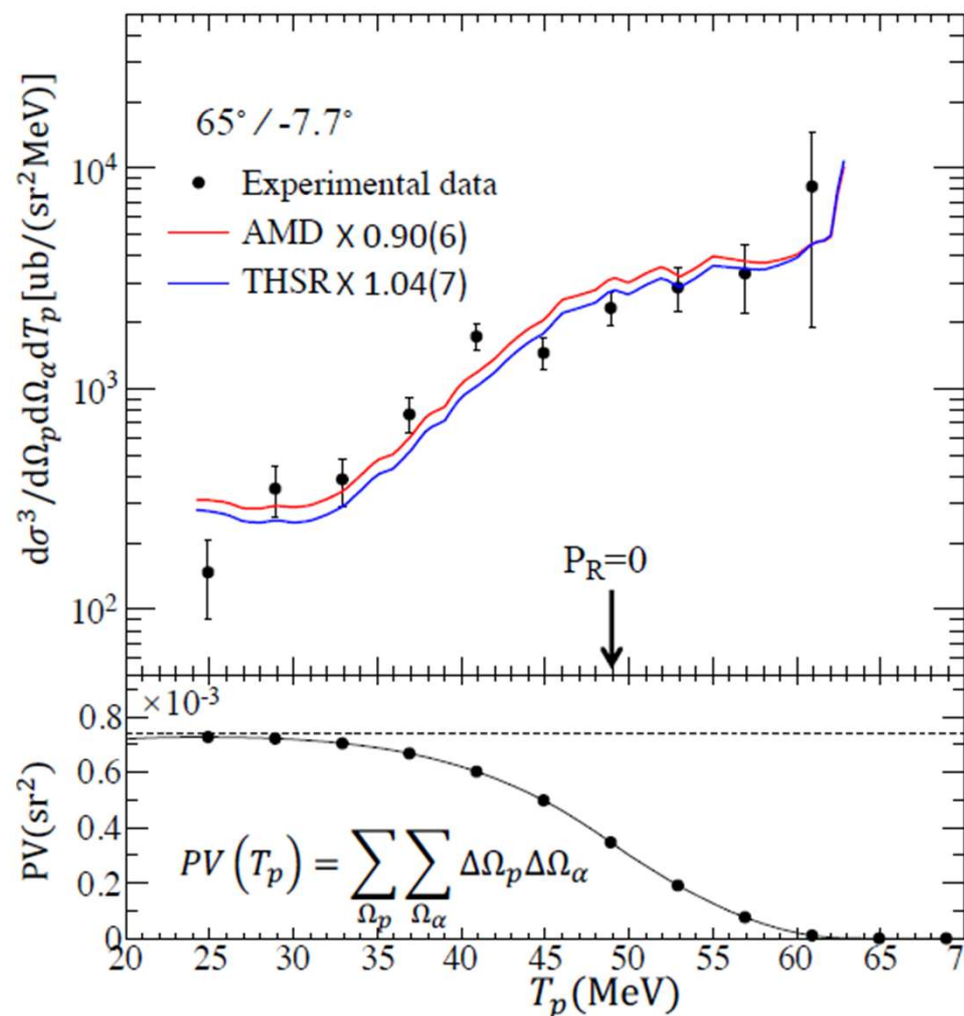


Molecular structure of the ^{10}Be GS is validated

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



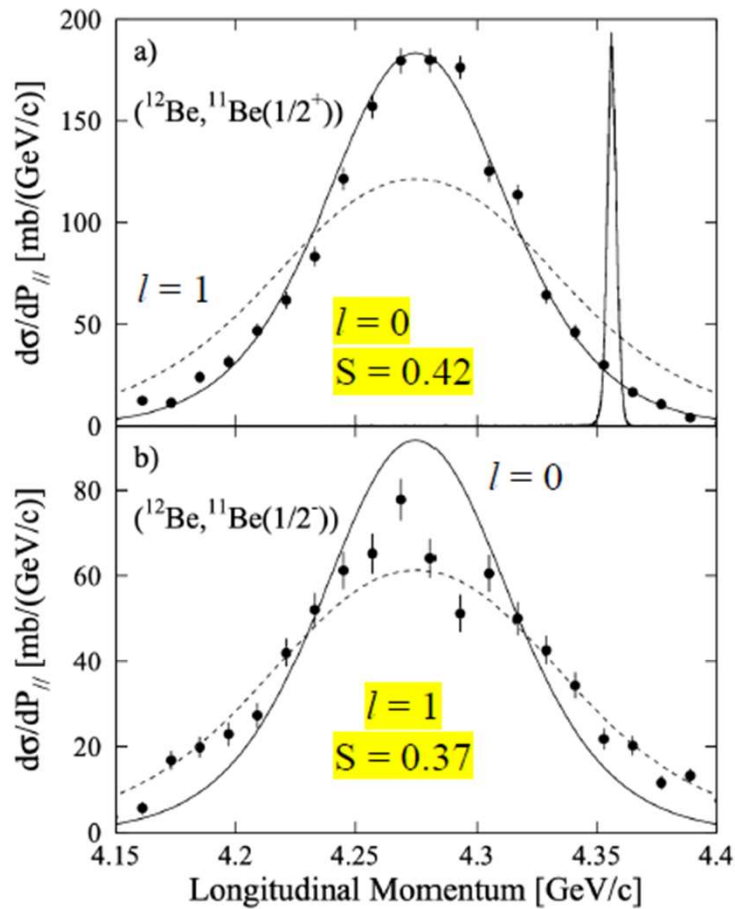
From TDX to QDX (quadruple diff Xsection)



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

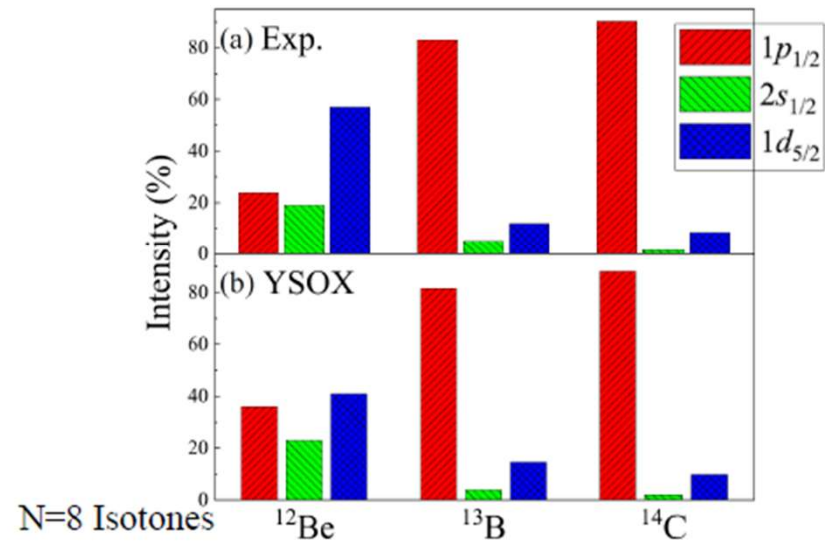
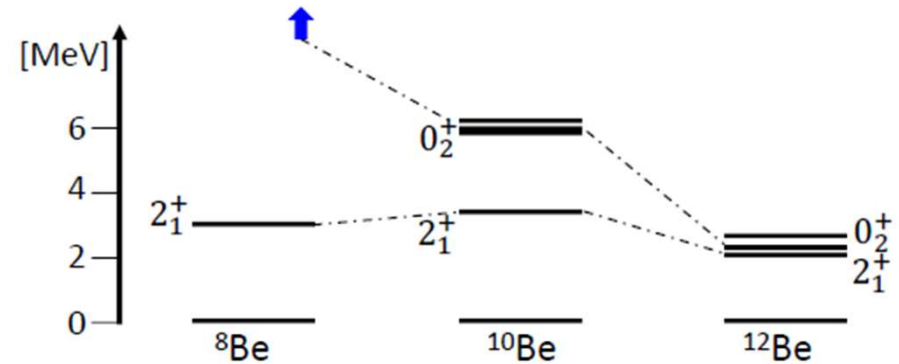
N=8 shell quenching in ^{12}Be

Direct Evidence for breakdown of N = 8 shell



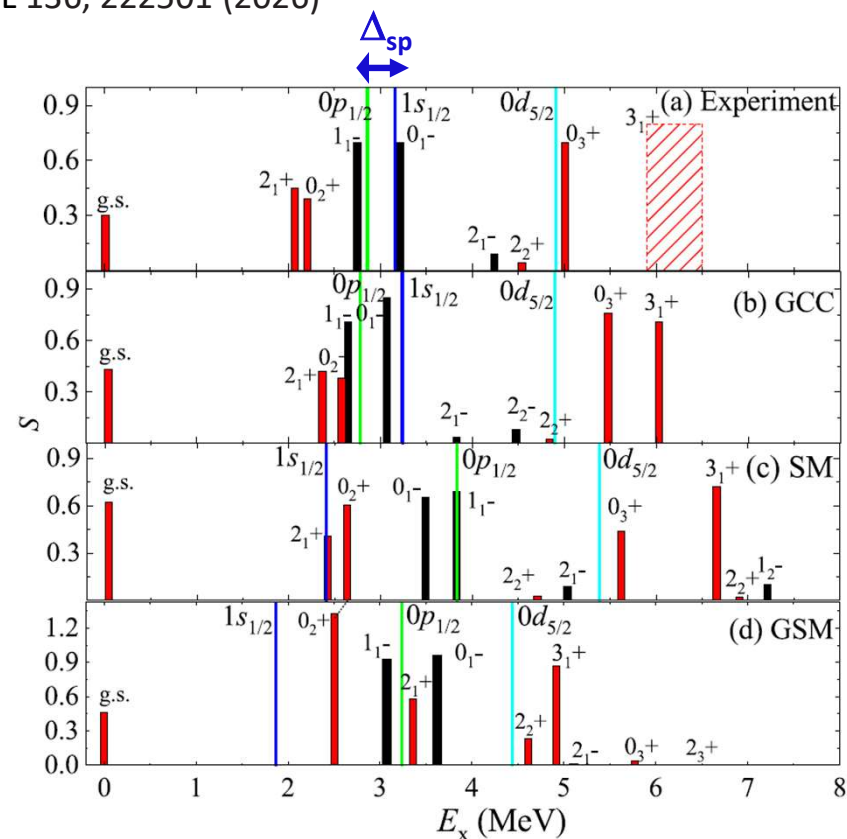
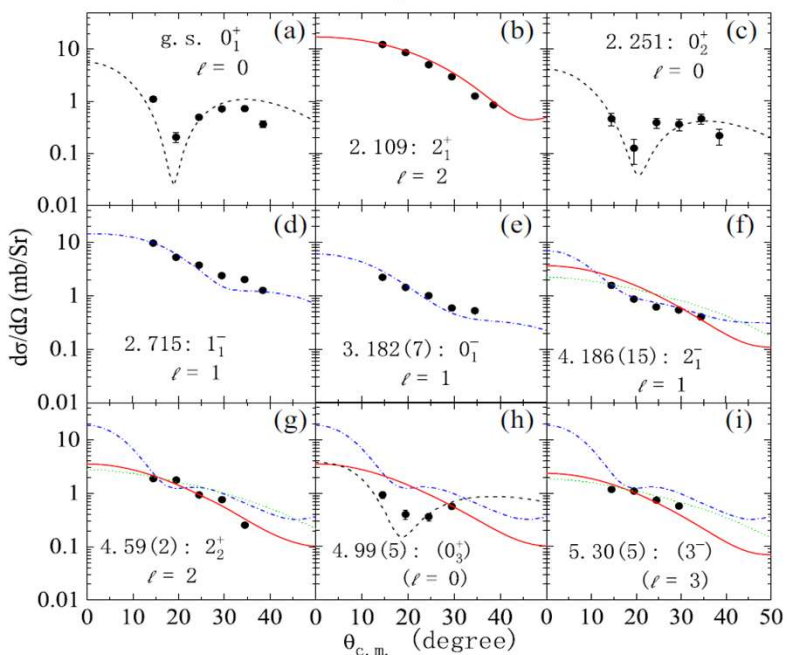
A. Navin et al., Phys. Rev. Lett. 85, 266 (2000)

0_2^+ and 2_1^+ systematics in Be



W. Liu, J. L. Lou, Y. L. Ye, Z. H. Li et al., Phys. Rev. C 104, 064605 (2021).

$^{11}\text{Be}(d,p)^{12}\text{Be}$ in IK

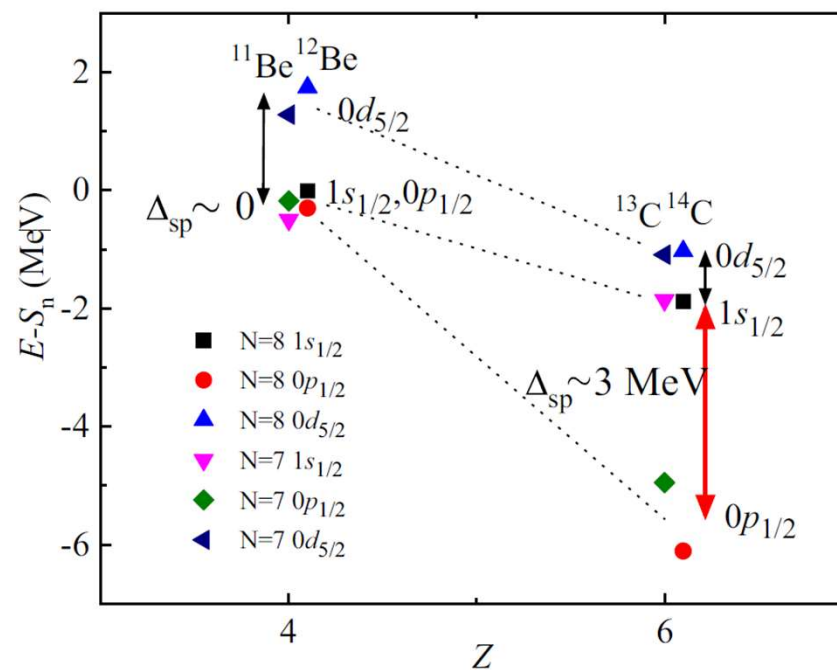
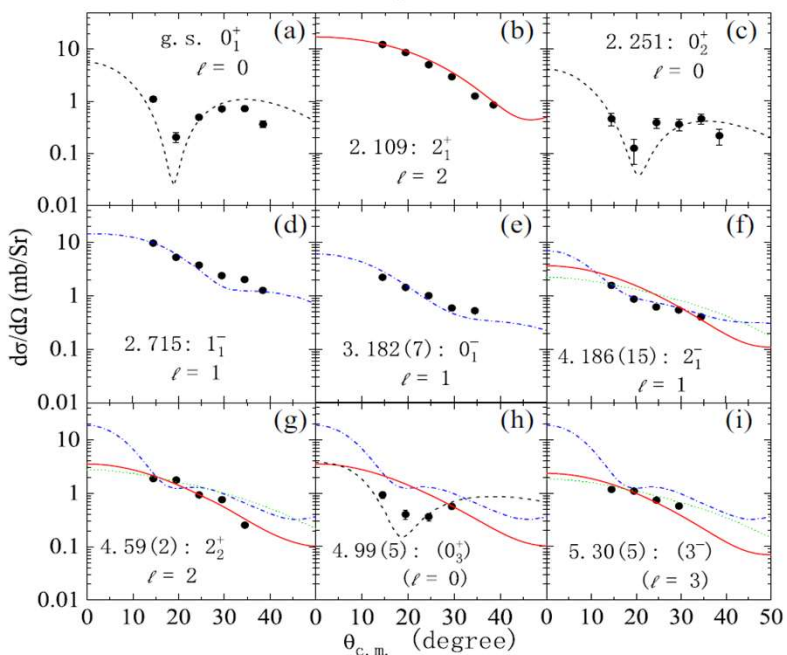
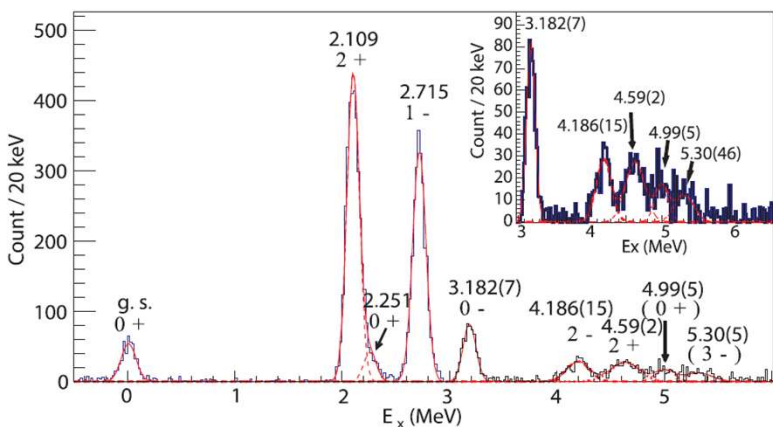


$$\Delta_{\text{sp}} [1s_{1/2} - 0p_{1/2}] \cong 300 \text{ keV}$$

Recent results on the s.p. structure of ^{12}Be

$^{11}\text{Be}(d,p)^{12}\text{Be}$ in IK

J.Chen et al., PRL 136, 222501 (2026)

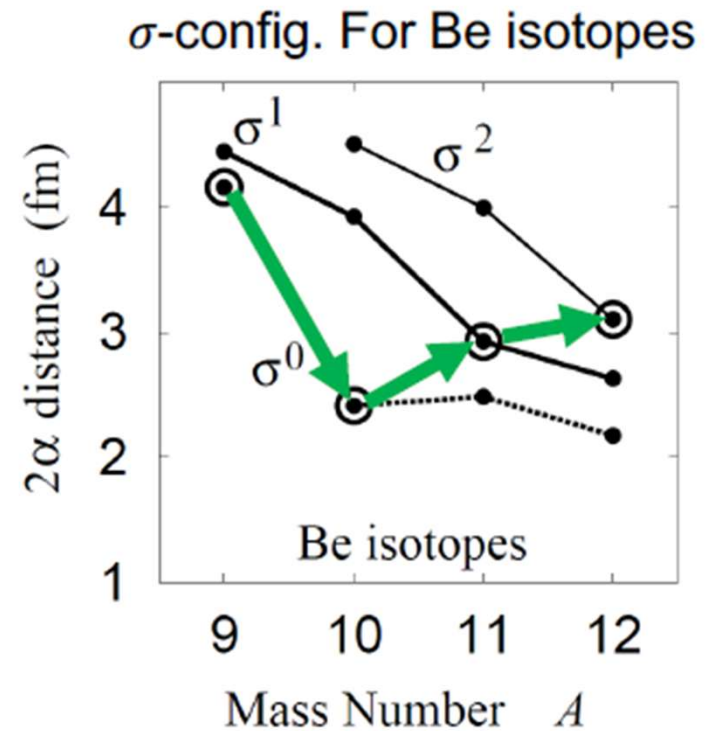
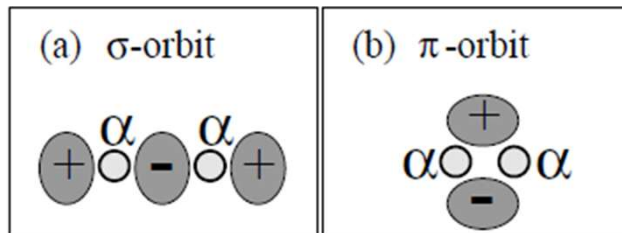
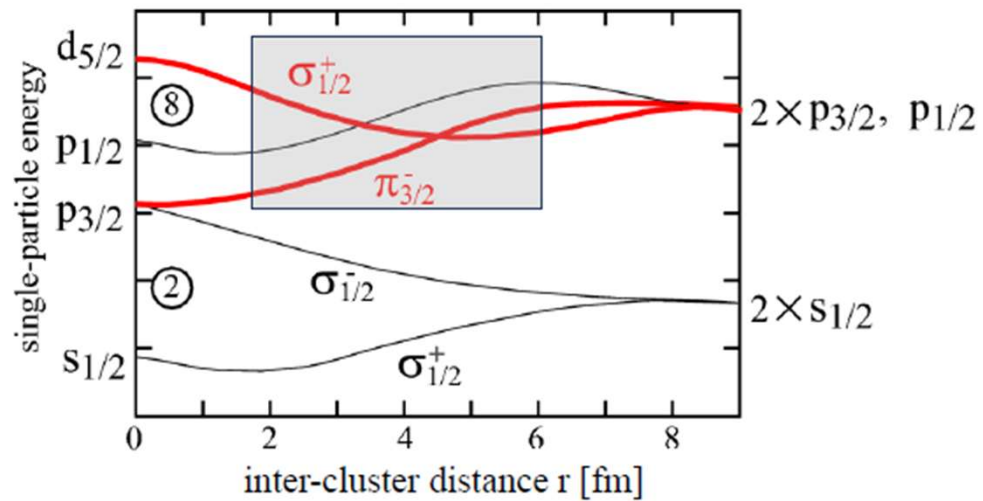


$\Delta_{sp} [1s_{1/2} - 0p_{1/2}]$ reduces by $\sim 3\text{MeV}$
reproduced by deformed WS pot. calculation

Predicted cluster structure of ^{12}Be in AMD

Molecular Orbital Description of ^{12}Be

- Mixture of $(0p)^6$ and $(0p)^4 + (sd)^2$
- ^{10}Be : $2\alpha + 2n(\pi)$
- ^{12}Be : $2\alpha + 2n(\pi) + 2n(\sigma)$

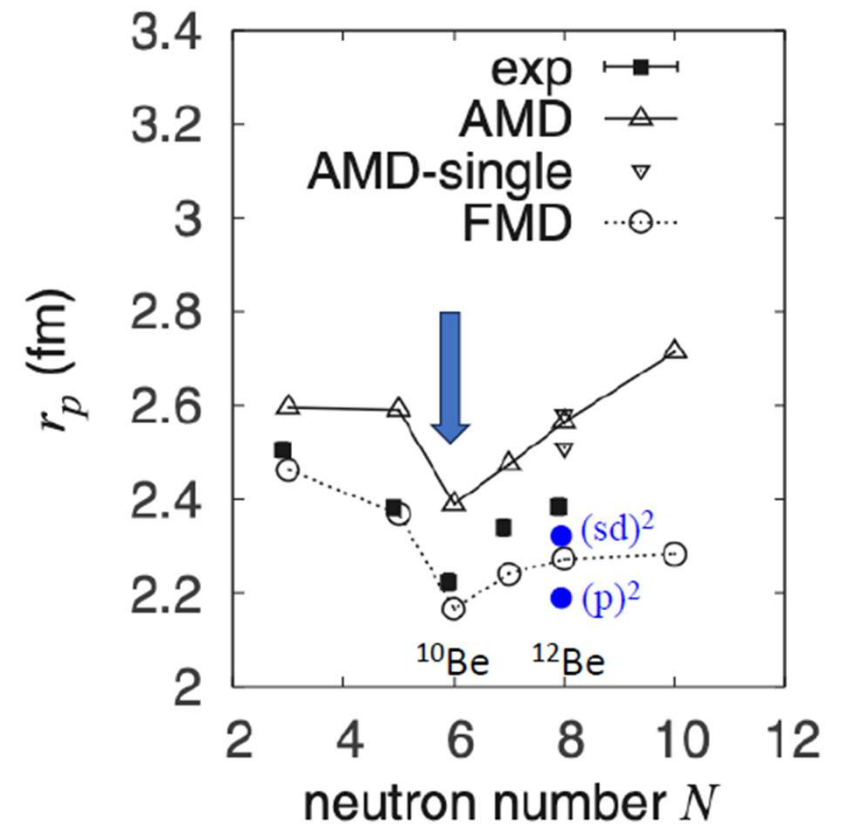
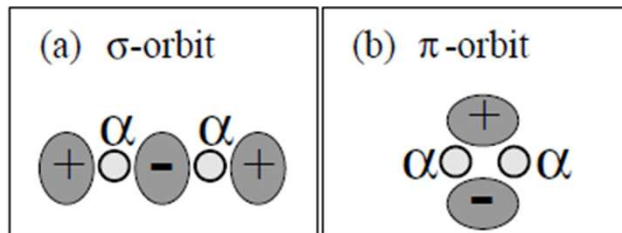
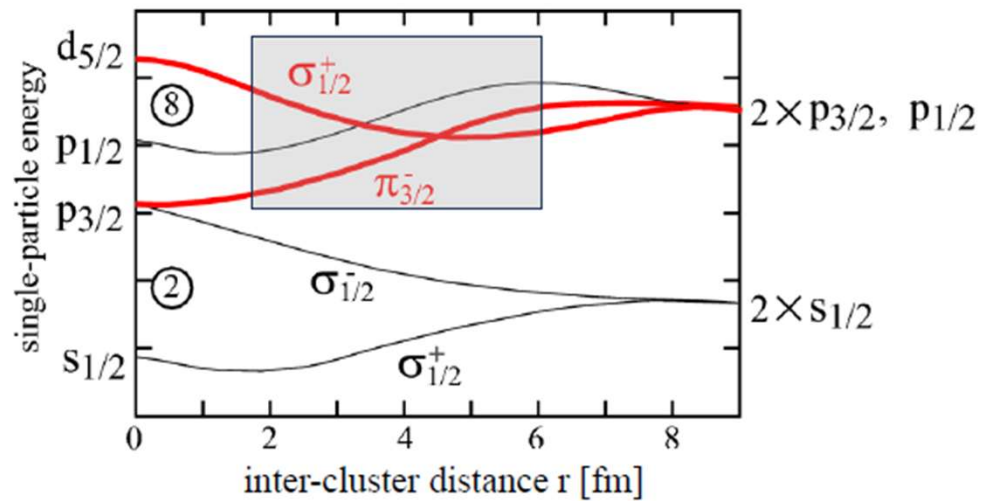


Y.Kanada-En'yo and H.Horiuchi, PRC 68, 014319 (2003)

Predicted cluster structure of ^{12}Be in AMD

Molecular Orbital Description of ^{12}Be

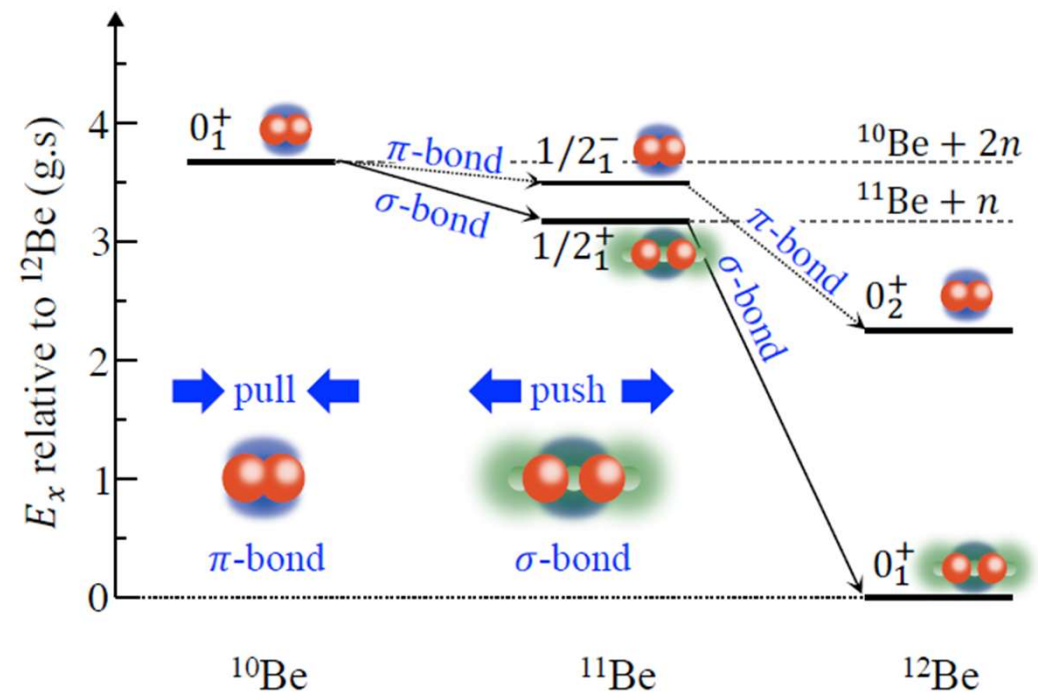
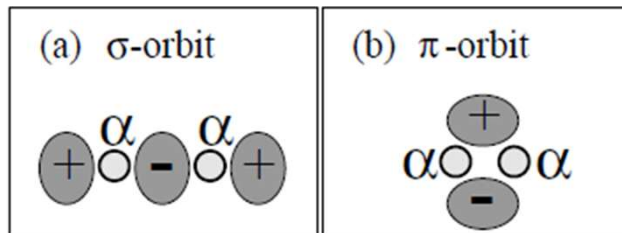
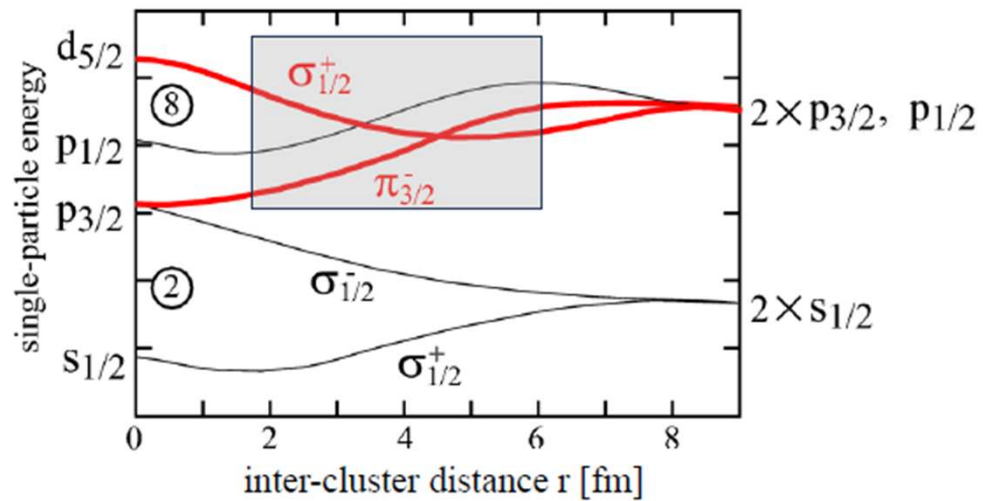
- Mixture of $(0p)^6$ and $(0p)^4 + (sd)^2$
- ^{10}Be : $2\alpha + 2n(\pi)$
- ^{12}Be : $2\alpha + 2n(\pi) + 2n(\sigma)$



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Molecular Orbital Description of ^{12}Be

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- ^{12}Be : $2\alpha + 2n(\pi) + 2n(\sigma)$



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

- **AMD**
mixture of $(0p)^8$ and $(0p)^6+(1s,0d)^2$

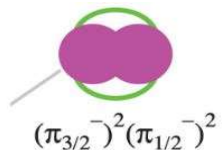


- **CtrlNN**
Phenomenological cluster WF based on Brink-Bloch WF
with a high-L cluster-pair component
Optimized to reproduce ^{12}Be properties (E, radii, E0 transition)
AI based Control Neural Network approach
Dominant $\pi^2\sigma^2$

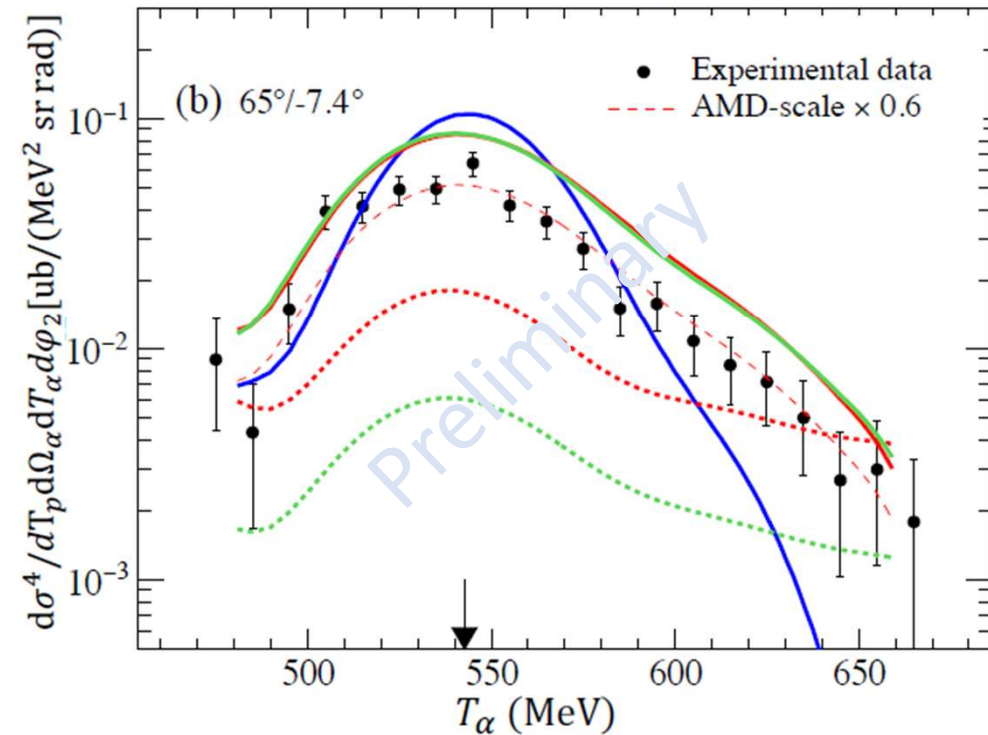
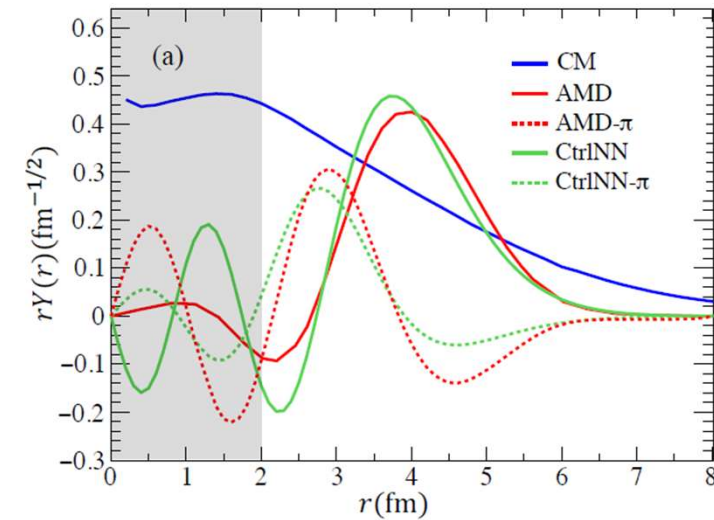
- **Cluster Model**

Model space

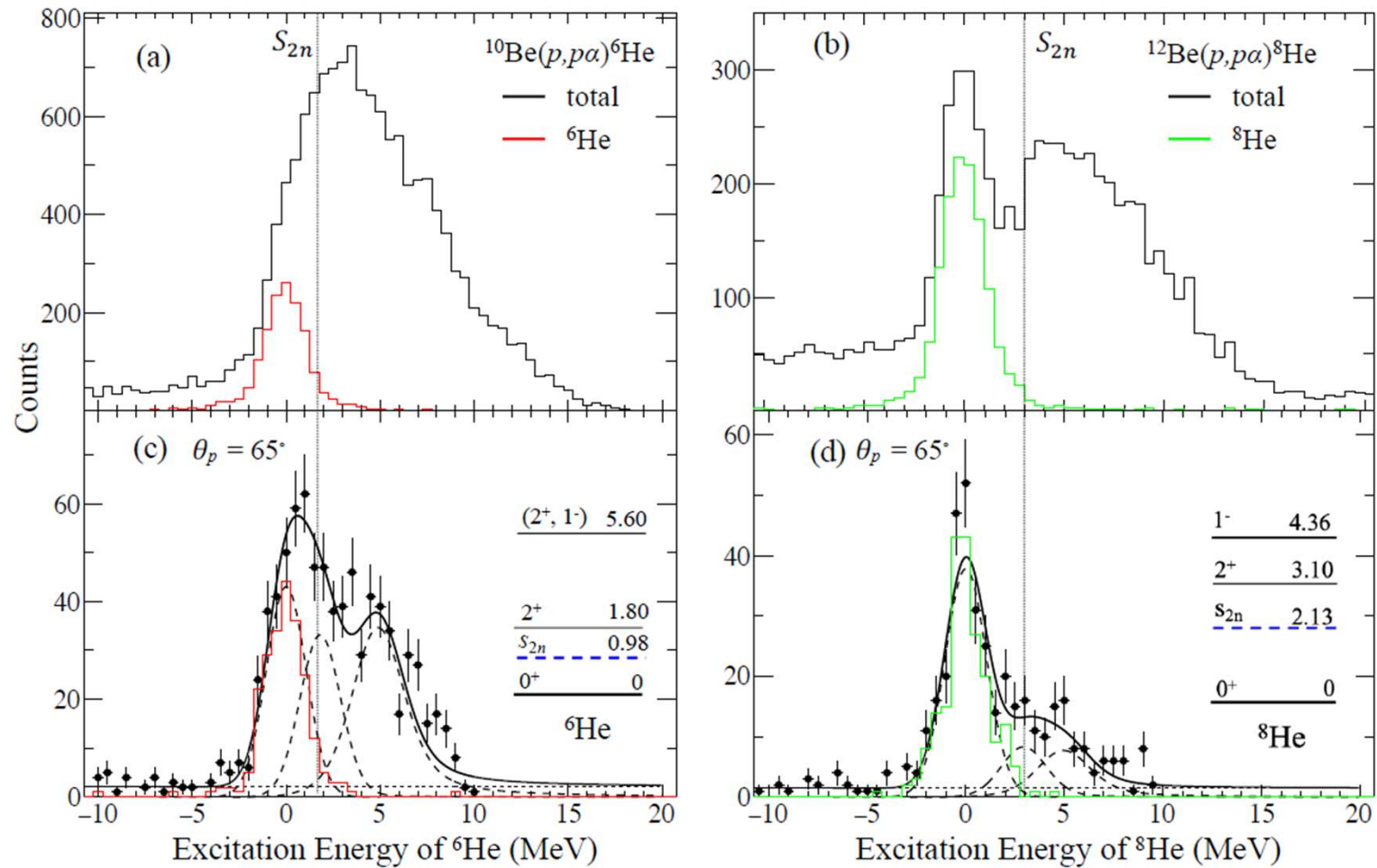
π orbits



dicluster

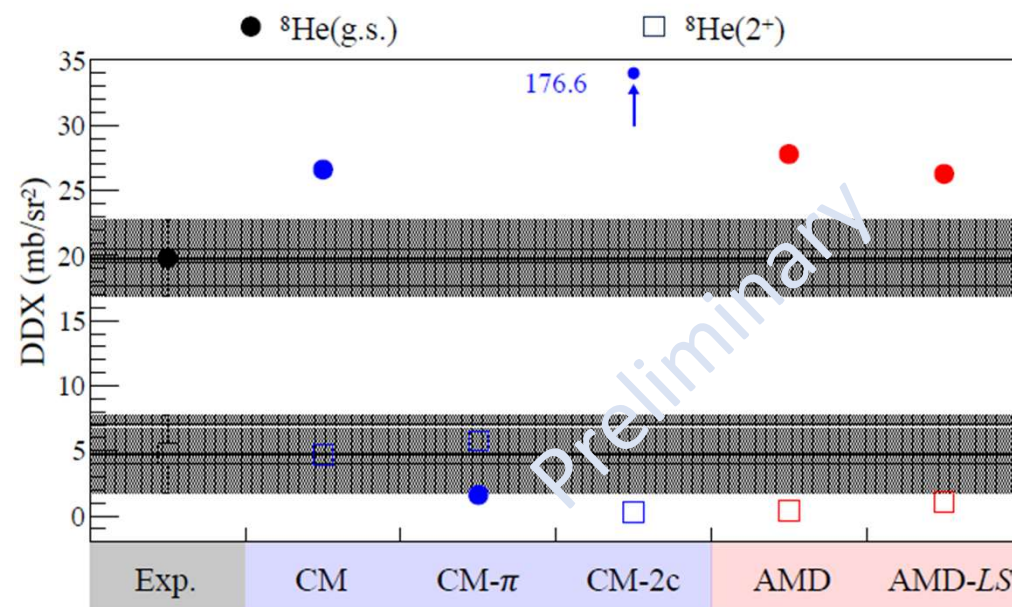
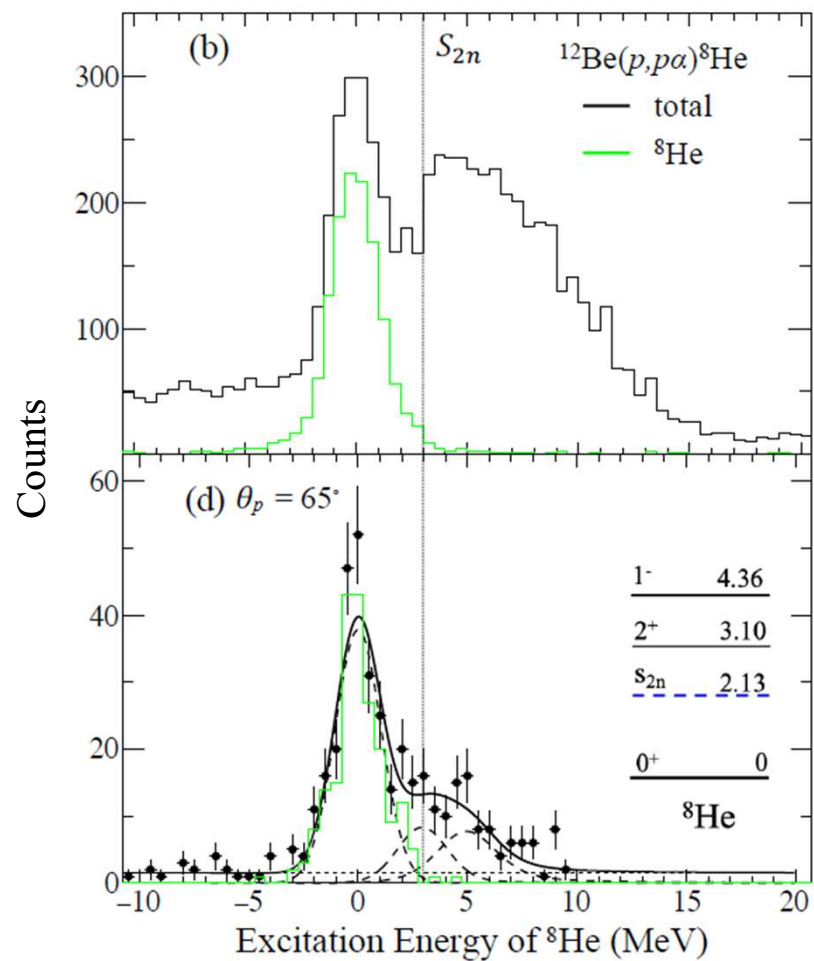


Core-excited components in ^{12}Be vs ^{10}Be



Direct evidence of a larger weight of C.E. components in the GS of ^{12}Be

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



Conclusions on ^{12}Be

The cluster structure of the ^{12}Be GS has been investigated using the sensitive probe (p,p α) in IK

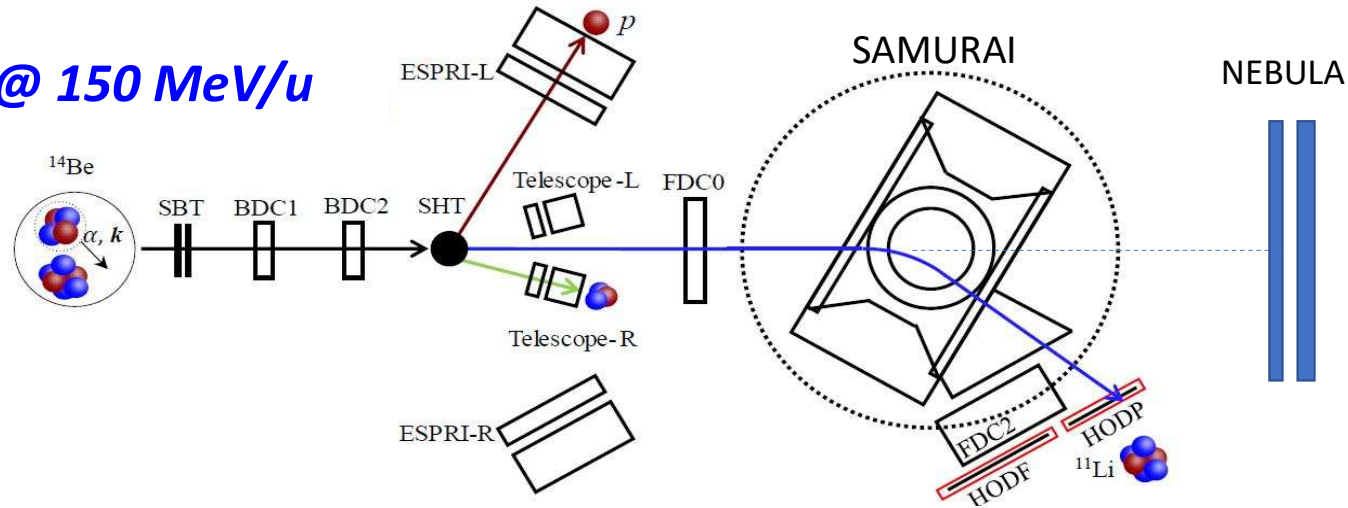
- $^{12}\text{Be}(\text{p},\text{p}\alpha)$ cross-section to the GS of the ^8He residue fairly reproduced by reaction calculation using microscopic cluster WF
- Dominance of the $\pi^2\sigma^2$ configuration is evidenced. Inclusion of an enhanced π^4 config. improves the reproduction of data
- Suppression of the core-excited components is clearly observed compared to ^{10}Be , broadly reproduced by microscopic calculations

Both observables confirm the crucial role of intruder configurations

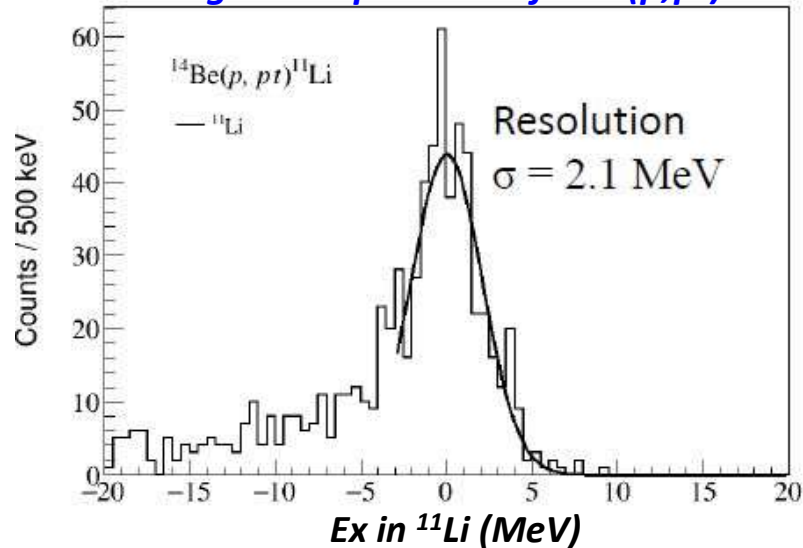
The corresponding deformation of the ^{12}Be GS provides a qualitative explanation of the magicity loss in ^{12}Be

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

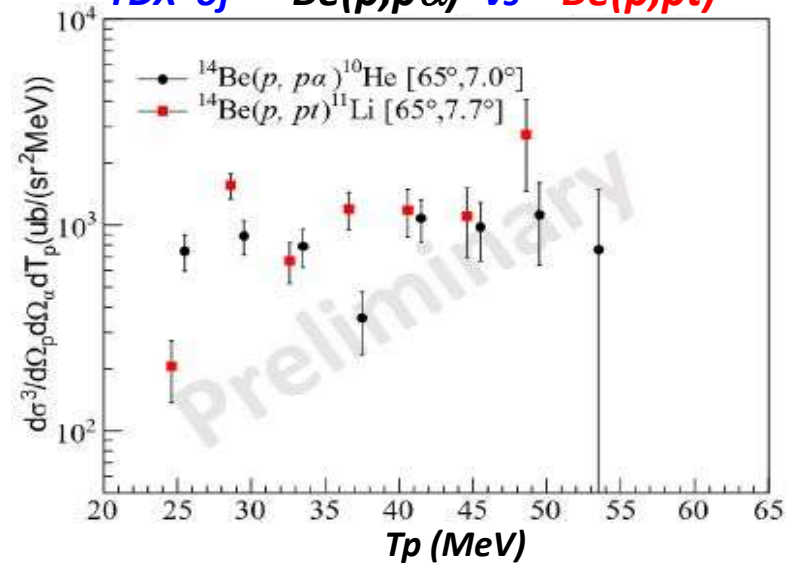
$^{14}\text{Be}(p,pt)^{11}\text{Li}$ @ 150 MeV/u



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

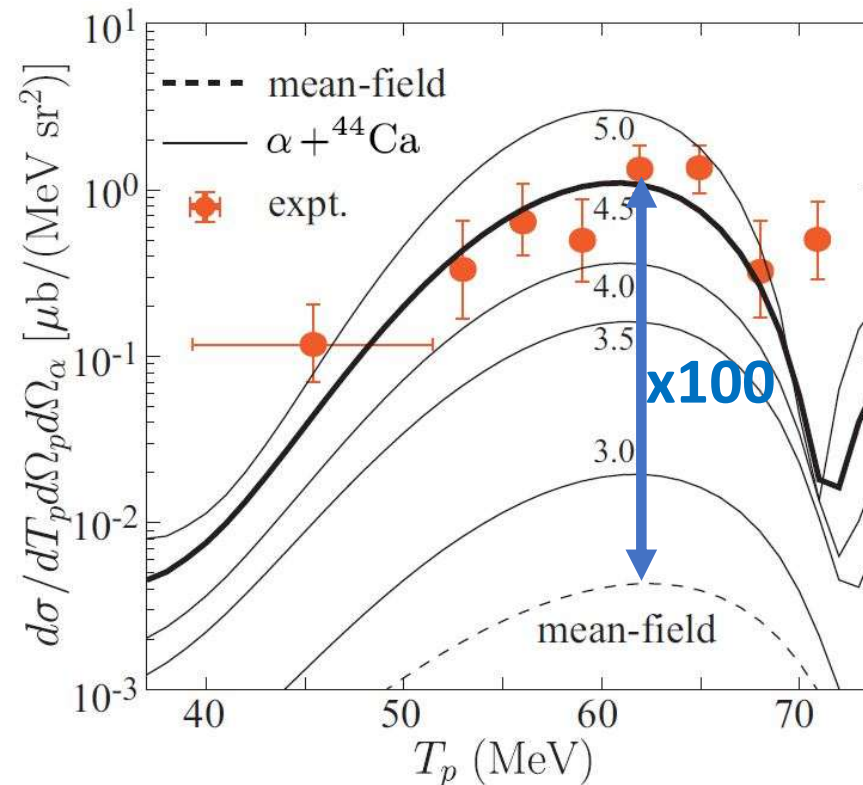
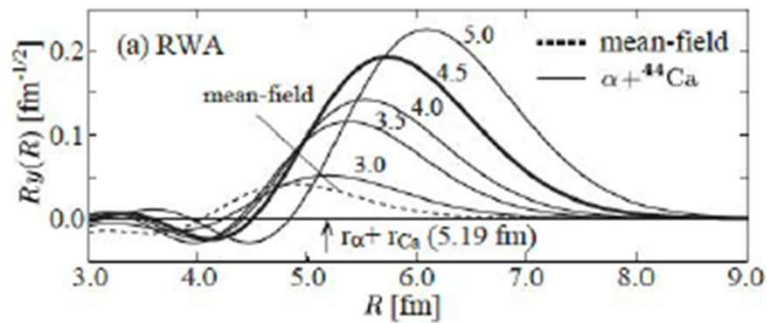


TDX of $^{14}\text{Be}(p,p\alpha)$ vs $^{14}\text{Be}(p,pt)$



How about in heavier nuclei ?

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

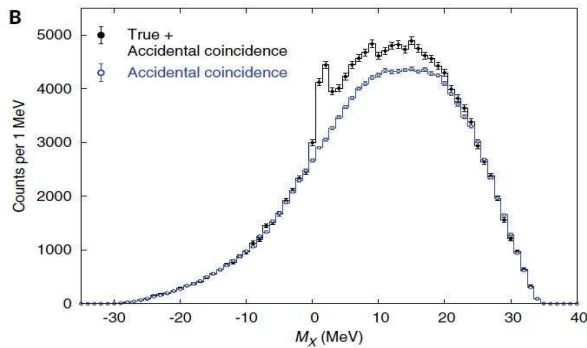
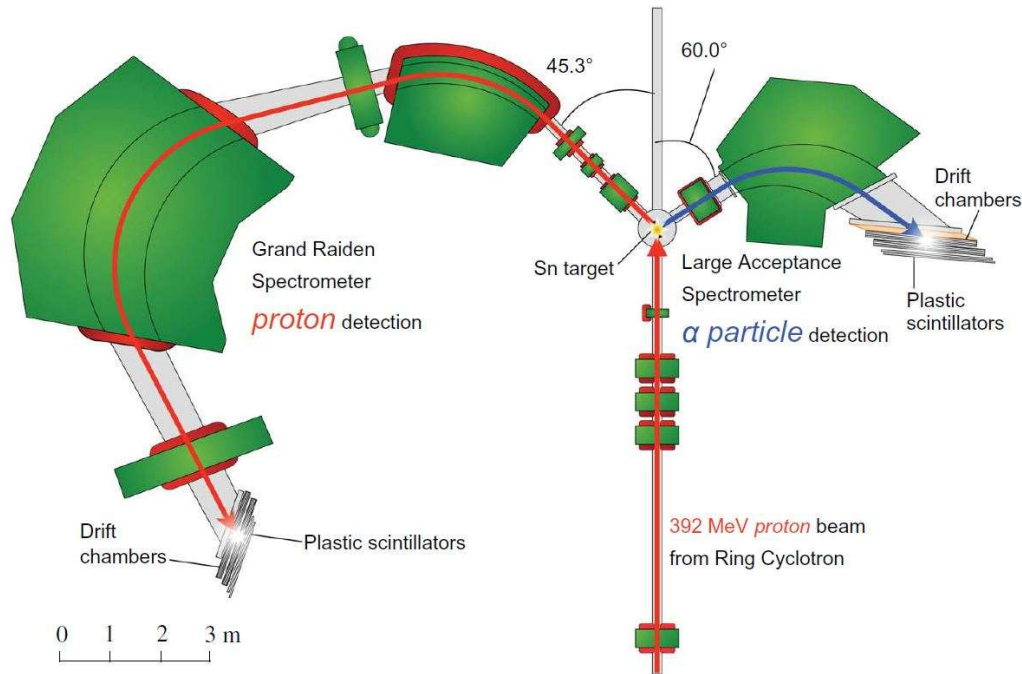


Failure of the DWIA+AMD framework

Due to strong S.O. contribution in AMD ?
Missing of the tensor term ?

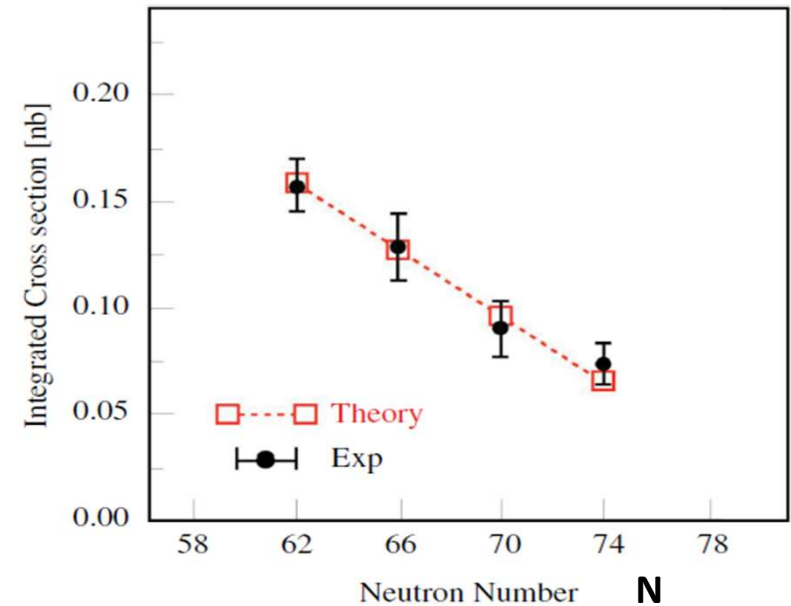
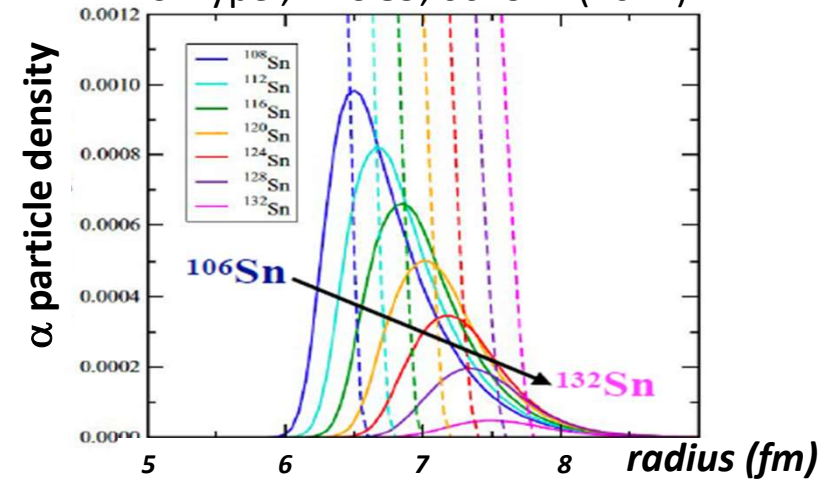
Y.Taniguchi et al., PRC 103, L031305 (2021)

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



- Alpha clusters develop in medium mass nuclei
- Alpha formation vs skin
- Cluster K.O. reactions are useful tool
- Isospin dependence is Key

S. Typel, PRC **89**, 064321 (2014).



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

ONOKORO project

科研費 特推 490M JPY
for FY 2021–2025
KAKENHI

PI: T.Uesaka, J.Zenihiro

Clustering in medium-heavy nuclei
via (p, pX) knockout reaction & elastic scattering

Wide mass region
 $A = 40-220$

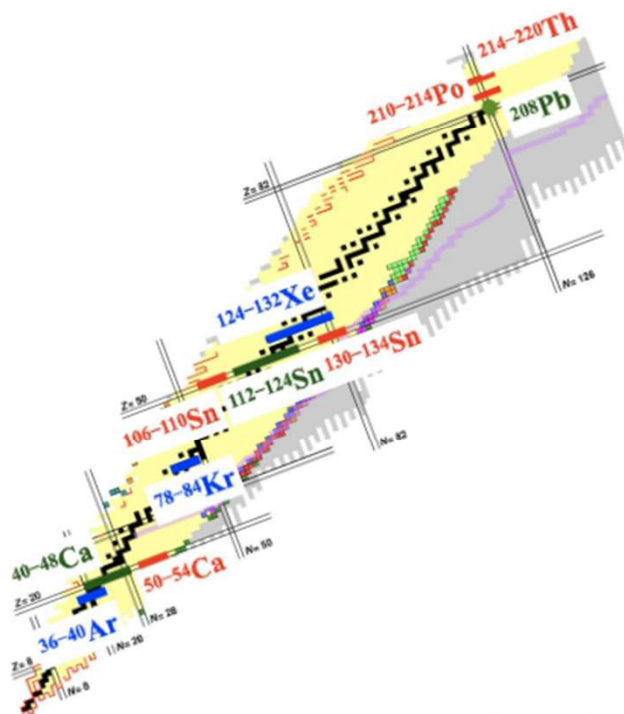
×

Stable and **unstable**
nuclei

RIBF, RIKEN

×

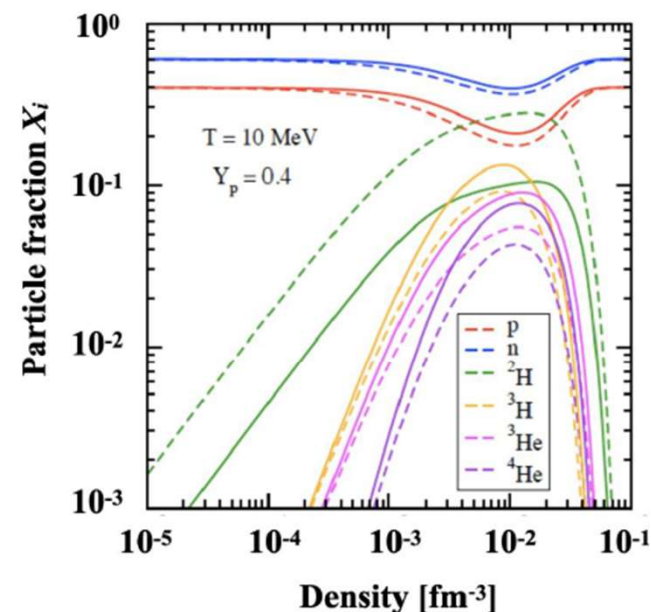
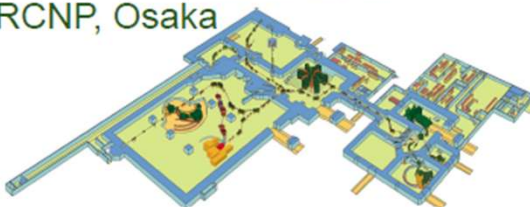
All the light clusters
 $d, t, {}^3\text{He}, \alpha \dots$



HIMAC, QST



RCNP, Osaka

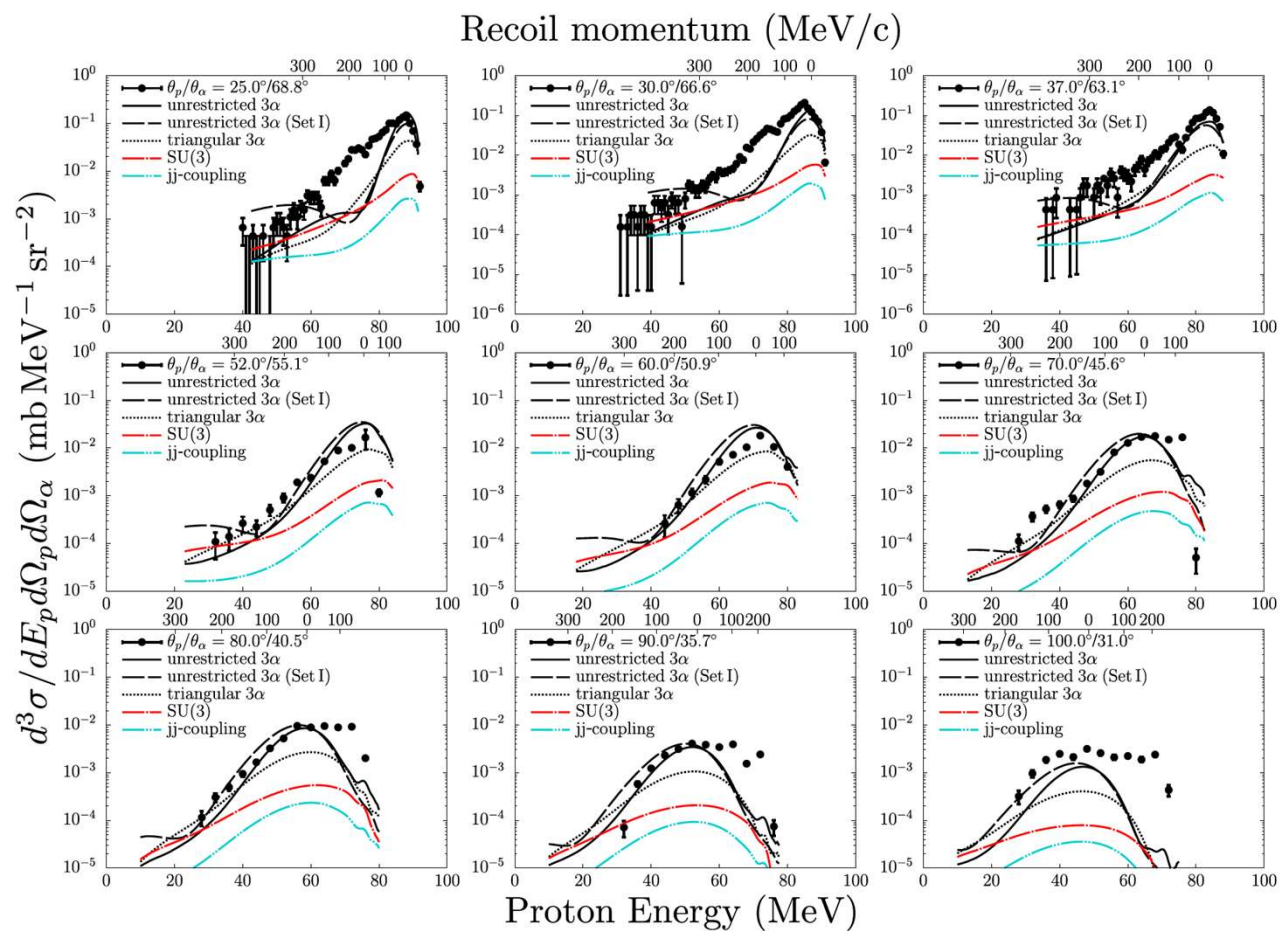
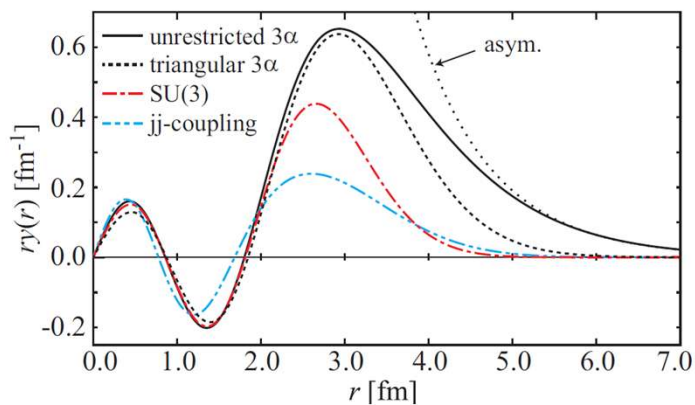
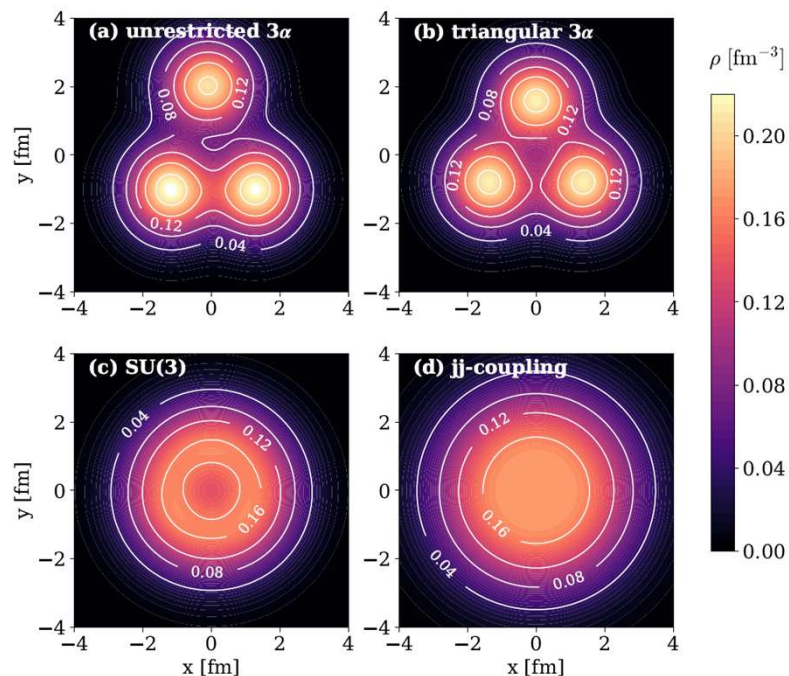


From: Y.Kubota

Y.Kubota et al., Nucl. Phys. A 1060 (2025) 123123

Recent re-analysis of $^{12}\text{C}(p,p\alpha)$ data

T. Yoshida and M. Kimura, ArXiv 2026



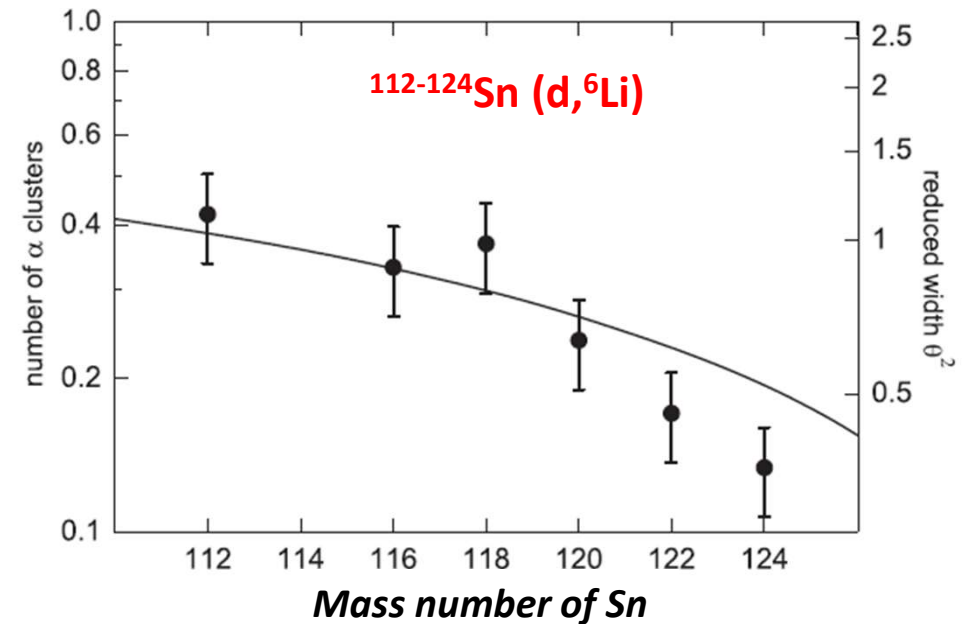
Approach using cluster transfer reactions

- Compare measured cross-sections with calculated ones making use of microscopic cluster WF
- Only few studies performed so far (stable nuclei)
- Cluster structure of ground-states
- Access to excited states using stripping
- Need collaboration with theorist structure AND reaction
 - AMD only suitable for light nuclei
 - Generalized DFT failed to reproduce the magnitude of $^{112-124}\text{Sn}(p,p\alpha)$ Xsection
- Need γ -ray detection to separate GS- $\rightarrow$ GS from other channels

$$T_{fi}^{\text{DWBA}} = \int d\mathbf{R} \chi_b^{(-)*}(\mathbf{R}) F(\mathbf{R}) \chi_a^{(+)}(\mathbf{R}).$$

$$\mathbf{x} = \mathbf{R} - \gamma \mathbf{r} \quad F(\mathbf{R}) \propto \varphi_c\left(\frac{\mathbf{R}}{\gamma}\right)$$

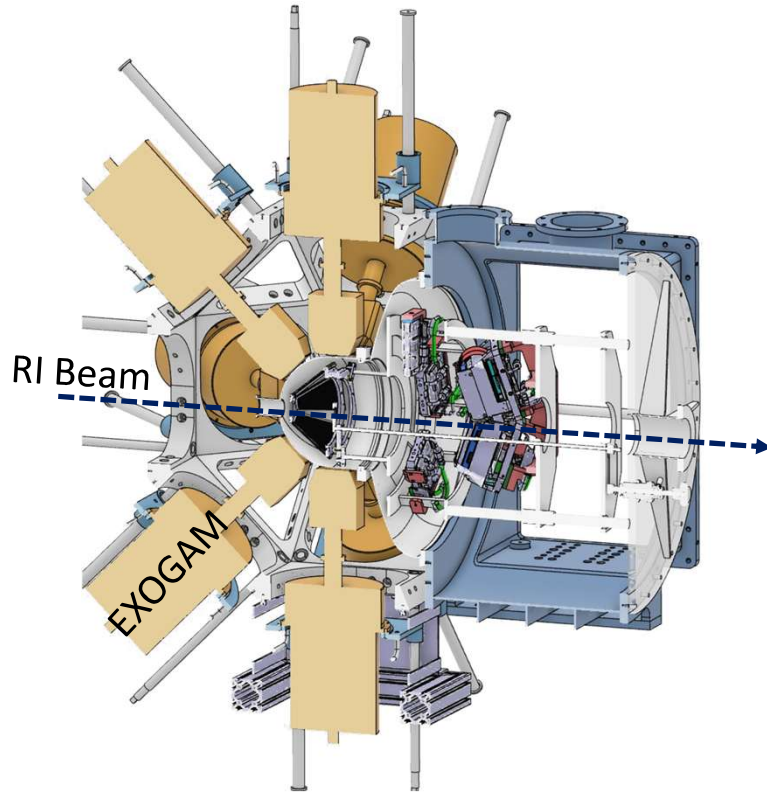
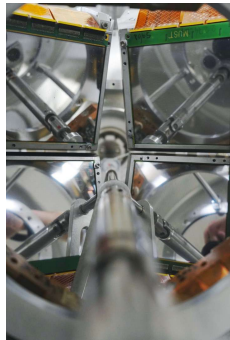
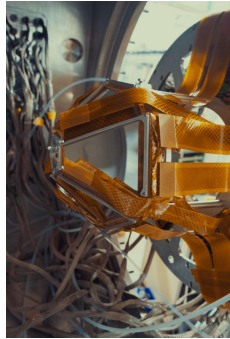
Same trend observed in transfer as in knockout !



A.A.Cowley, PRC 93 (2016)

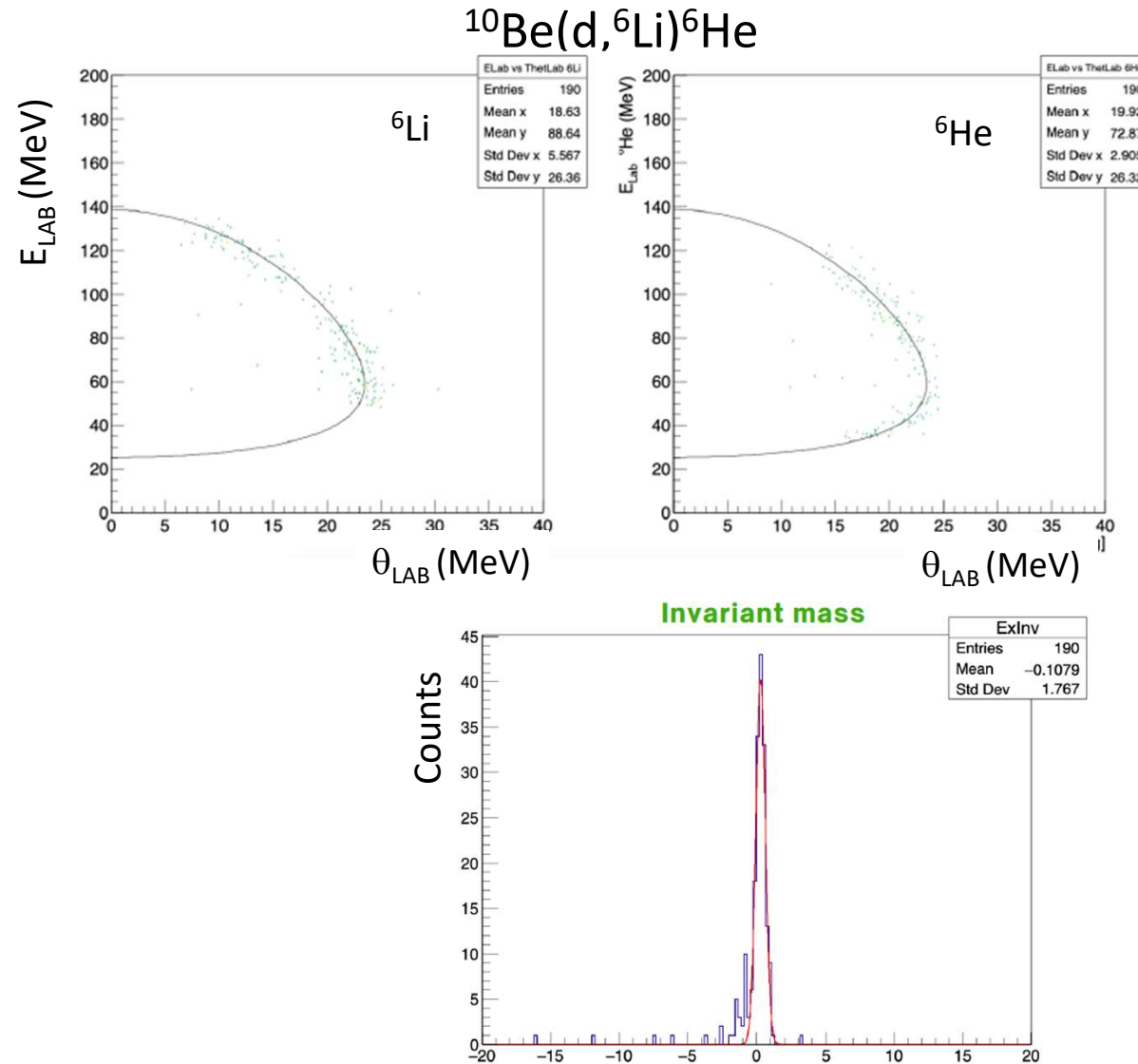
Clustering in light n-rich nuclei using transfer reactions

MUGAST@LISE-GANIL



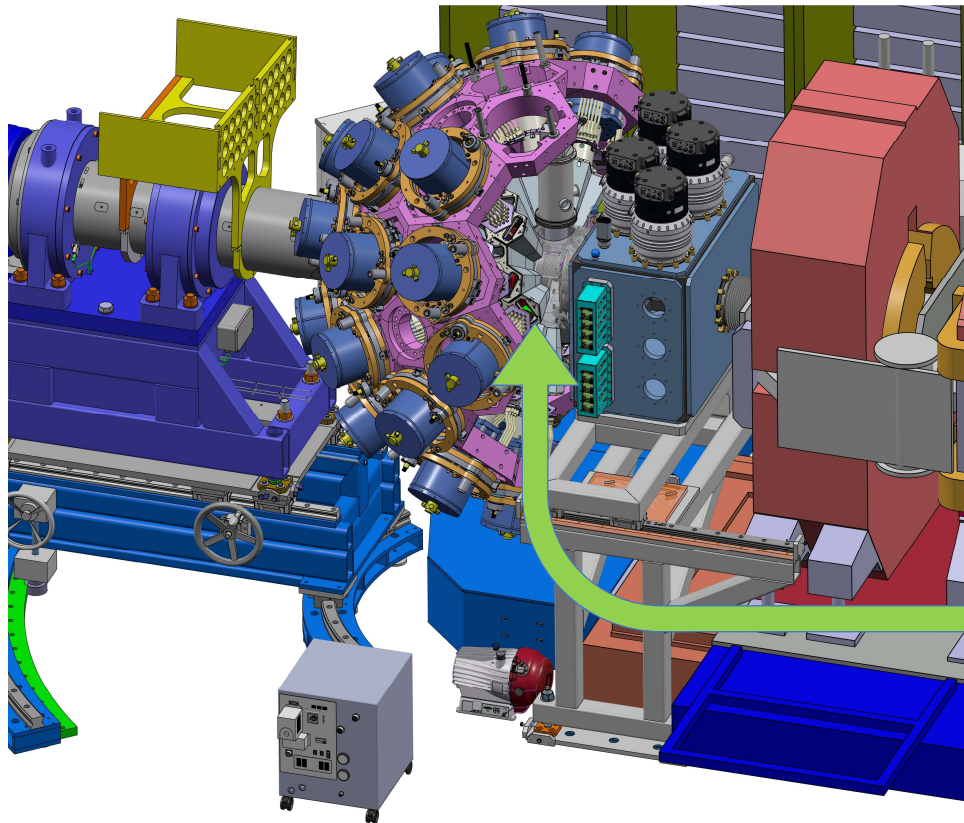
Study of $^{10,12}\text{Be}(p,\alpha)$ and $^{10}\text{Be}(d,^6\text{Li})$
 Spokesperson : V.Girard-Alcindor, DB
 Ph.D Student: T.Zanatta-Martinez

Performed in June 2024



AGATA – GRIT setup to be used at VAMOS

An AGATA-GRITPhase0-VAMOS campaign is now planned at GANIL starting 2029

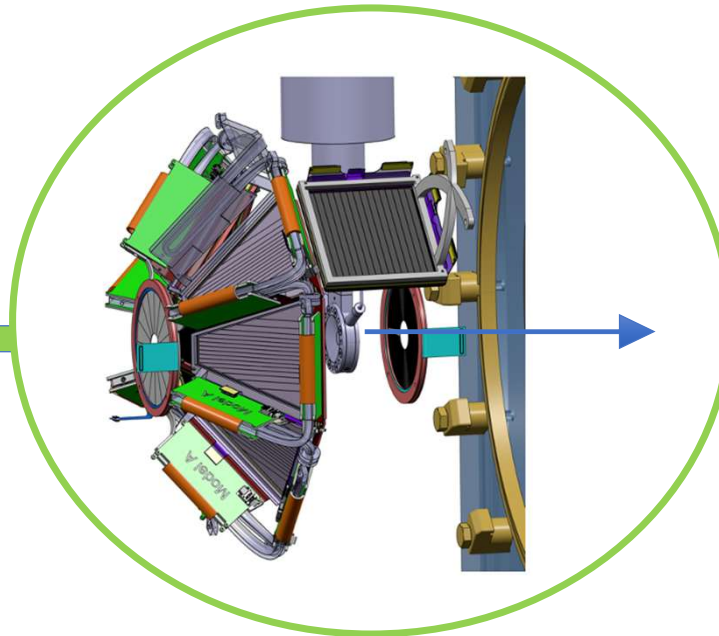


SPIRAL1 beams

Backward: 6 trapezoidal telescopes (2 stages)
read by **GRIT electronics**

+ Additional detectors readout by **Mesytec Electronics**

+ Helium cryo target



Lol on cluster transfer experiment presented