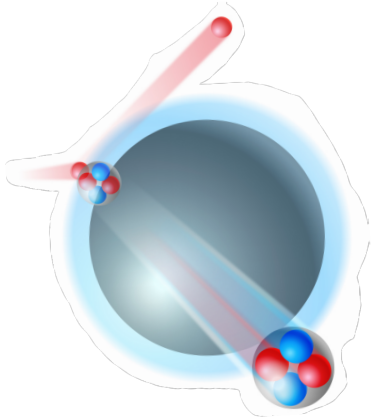
" COMEX7 ", Catania, Italy,June 11-16, 2023

Clustering in nuclear systems: from finite to infinite

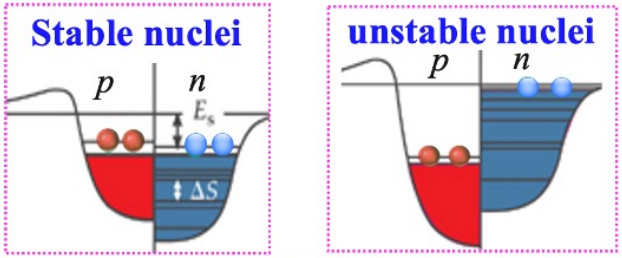
- ✓ Introduction
- ✓ α cluster in heavy nuclei: Sn as an example
- ✓ Prospect

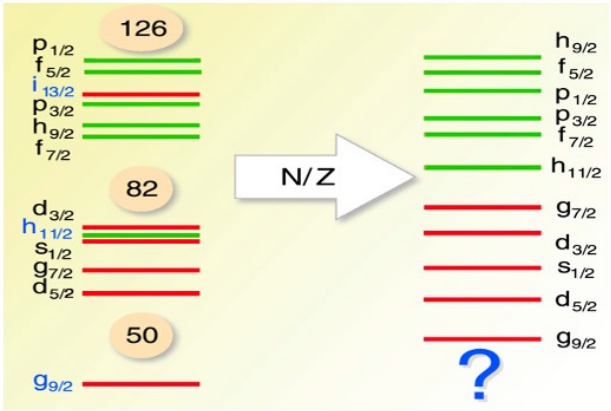


Zaihong YANG

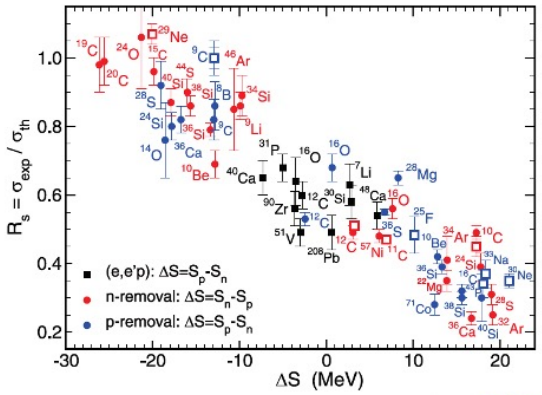
School of Physics, Peking university

What is the structure of the (unstable) nucleus?





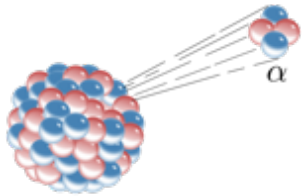
Change of shell structure



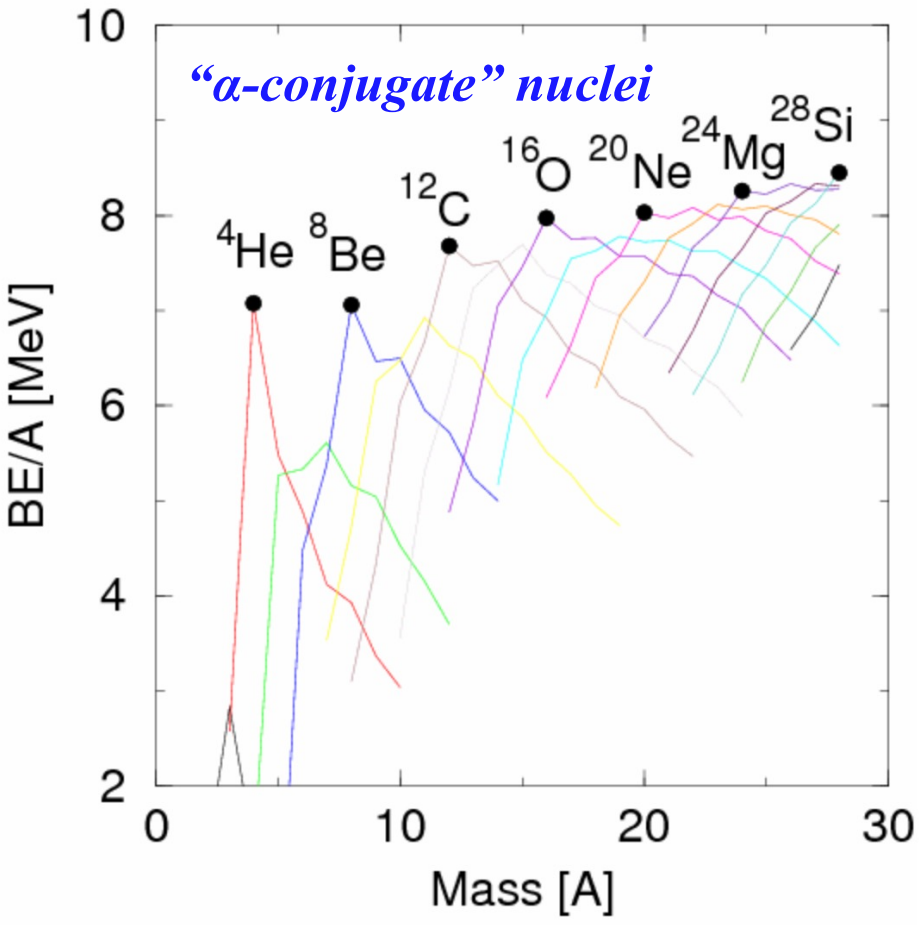
Tostevin/Gade PRC2021
Aumann et al. PPNP 2021

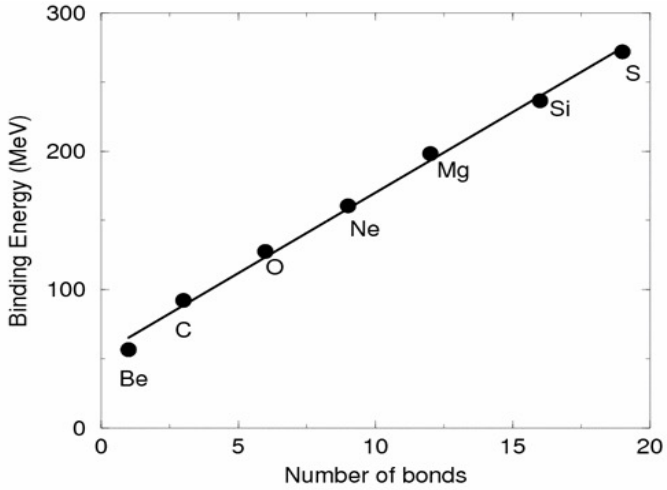
"α particle" nuclei in 1930s

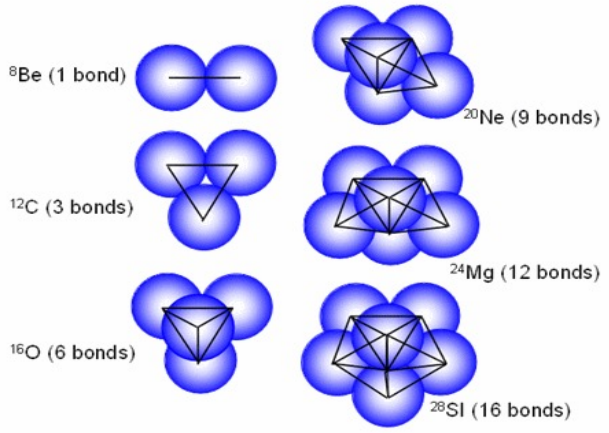
- ✓ Alpha radioactivity: 1890s
- ✓ Alpha decay model (quantum tunneling): Gamow, 1928
- ✓ Discovery of the neutron: 1932, Chadwick



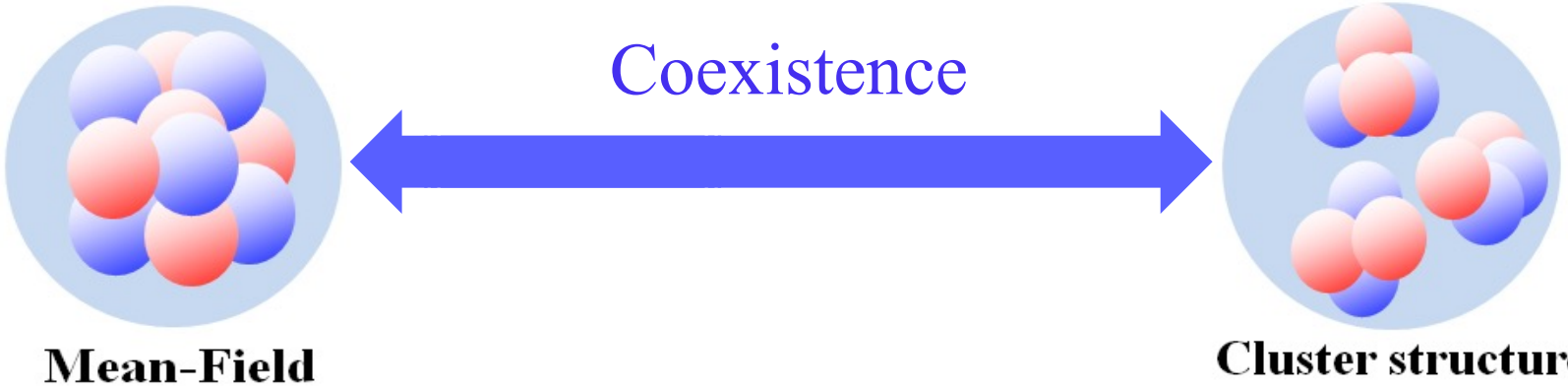
Hafstad and Teller, PR 1938







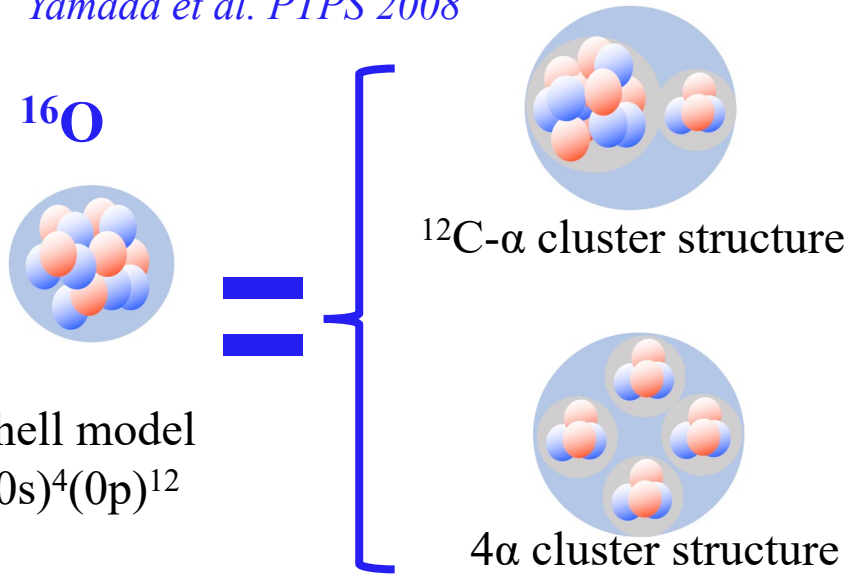
Coexistence of clustering and non-clustering



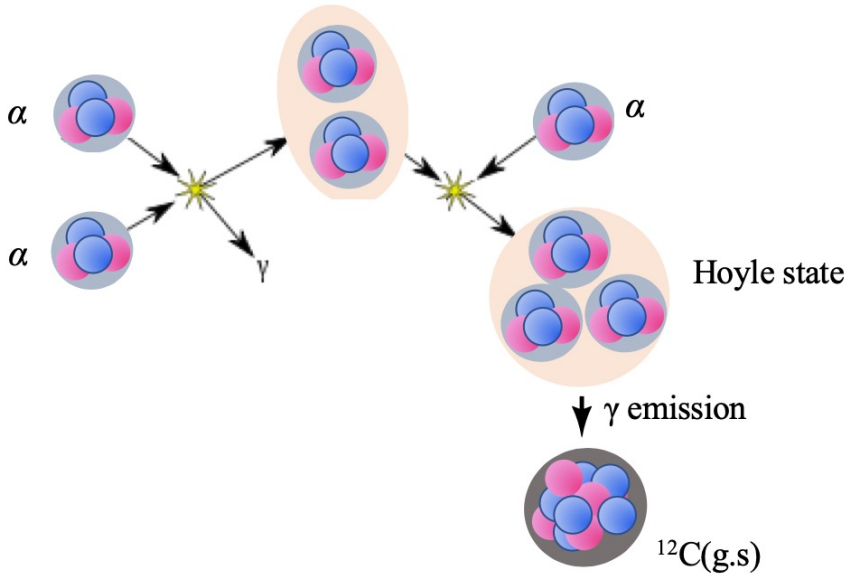
Duality of nuclear WF

✓ Bayman-Bohr theorem *Nucl. Phys. 1958*

Yamada et al. PTPS 2008

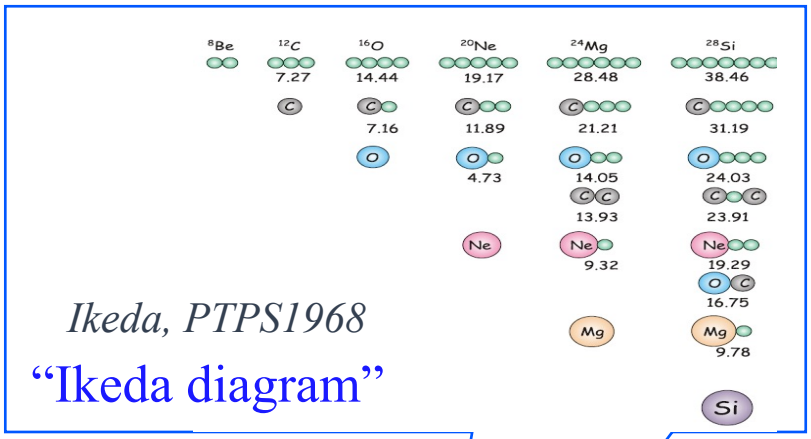


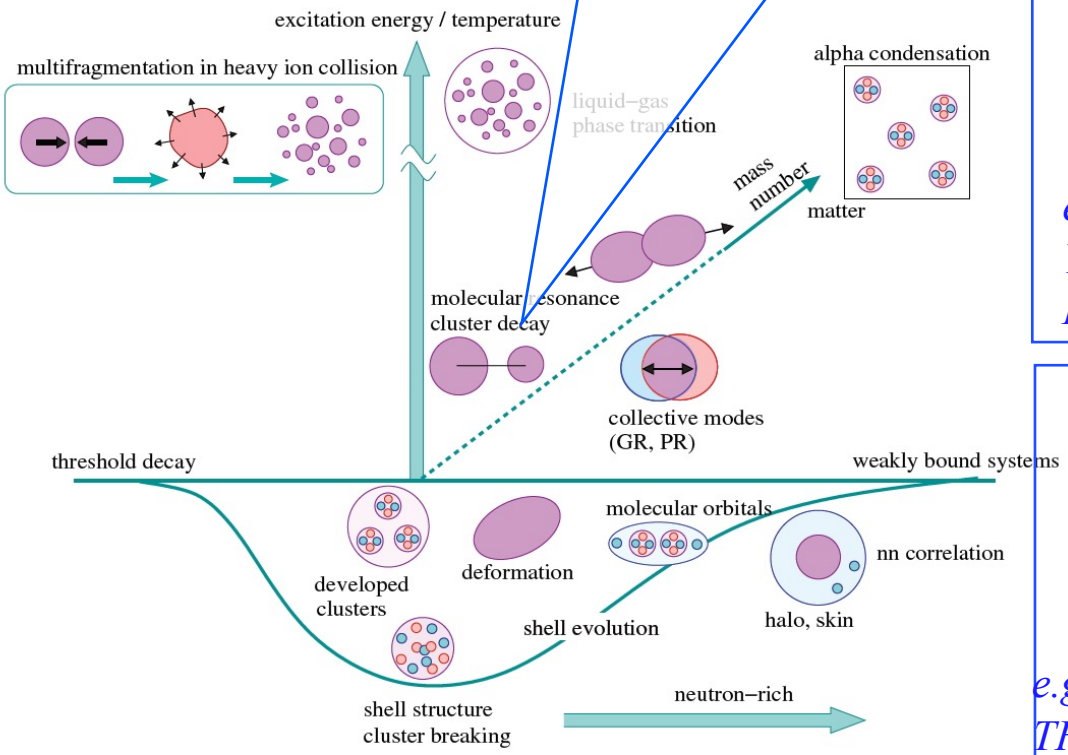
The Hoyle state



Otsuka et al. Nat.Comm.13(2022)2234

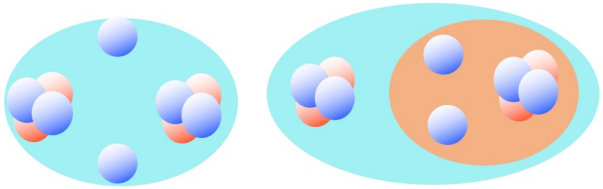
Cluster structures in excited states of light nuclei





Kanada-Enyo, PTEP 2012

Molecular states in Be

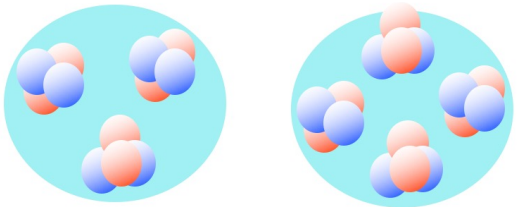


e.g., ZY et al., PRL2014; Suzuki PRC2013
Freer et al. PRL2006, PRL1999
Ito et al. PRL2008, RPP2014

Linear-Chain states in C

e.g., Liu et al. PRL 2020, Li et al. PRC2017
Yamaguchi PLB2017,Fritsch et al.PRC2016
Baba/Kimura PRC2018

Gas-like (α-condensate) states



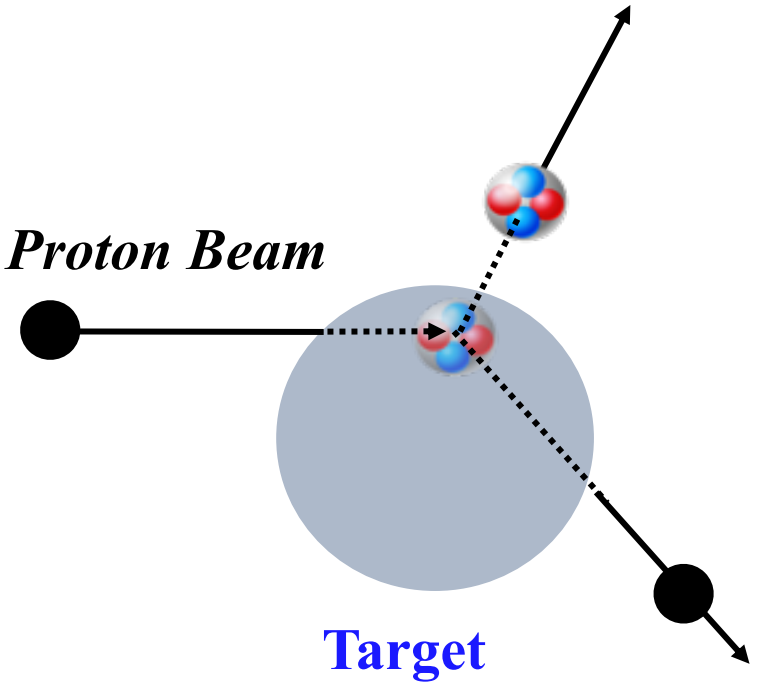
e.g., Chen et al. SC2023; Adachi et al. PLB2021;
THSR, PRL2001;Funaki et al. PPNP2015

(p,$p\alpha$): probe clusters in the ground state

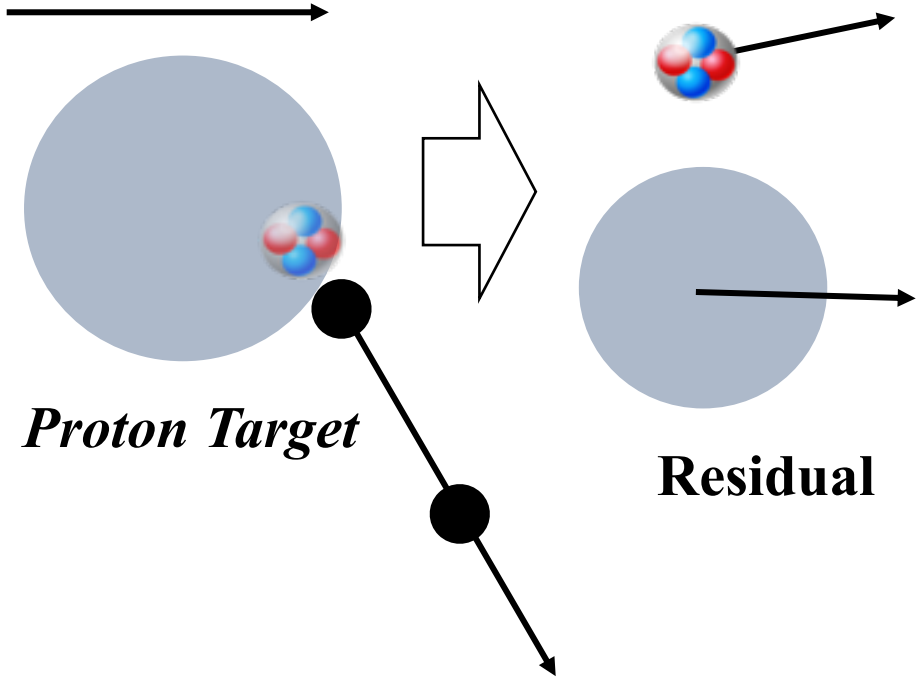
- ✓ Cluster structure in excited states: one may measure cluster fragments
- ✓ Clusters in *g.s*: quasi-free (p,$p\alpha$) [~ several hundred MeV/u]

Yoshida, PRC2016/PRC2018/PRC2019

Normal kinematics

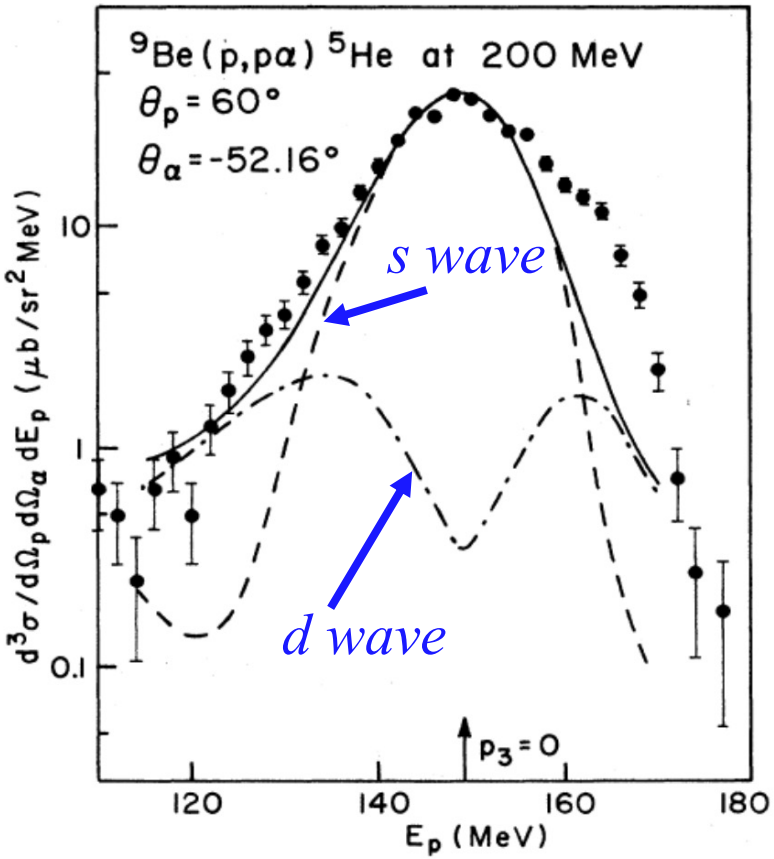


Inverse kinematics

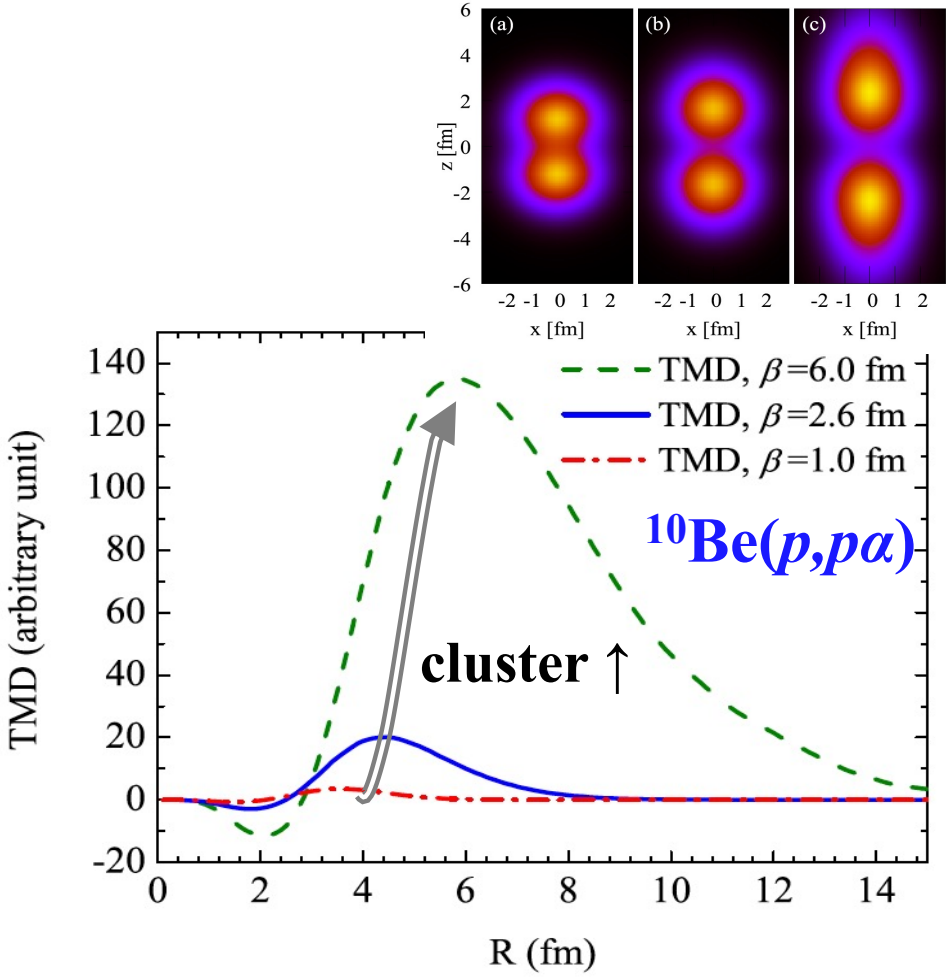


(p,$p\alpha$): probe α clusters in light nuclei

- ✓In1970s and 1980s: with light stable nuclei like ^{7}Li/^{9}Be/^{12}C.
- ✓Recent theoretical development for (p,$p\alpha$) (*Yoshida, Ogata et al.)*



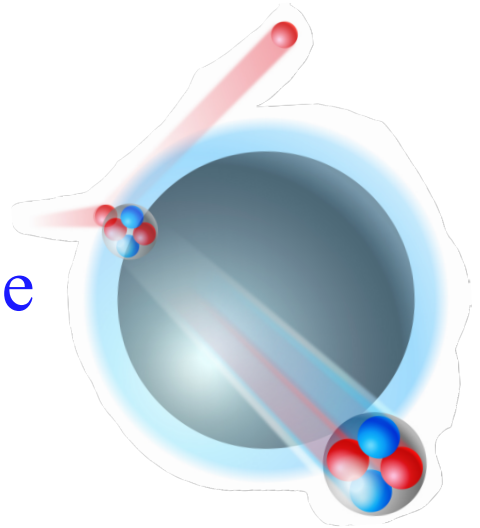
Nadasen et al. PRC1989
Chan and Roos PRC1977;Carey et al. PRC1981



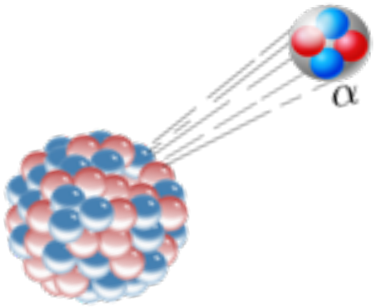
Lyu, et al., PRC2018; Yoshida et al. PRC2019; Taniguchi et al. PRC2021

Clustering in nuclear systems: from finite to infinite

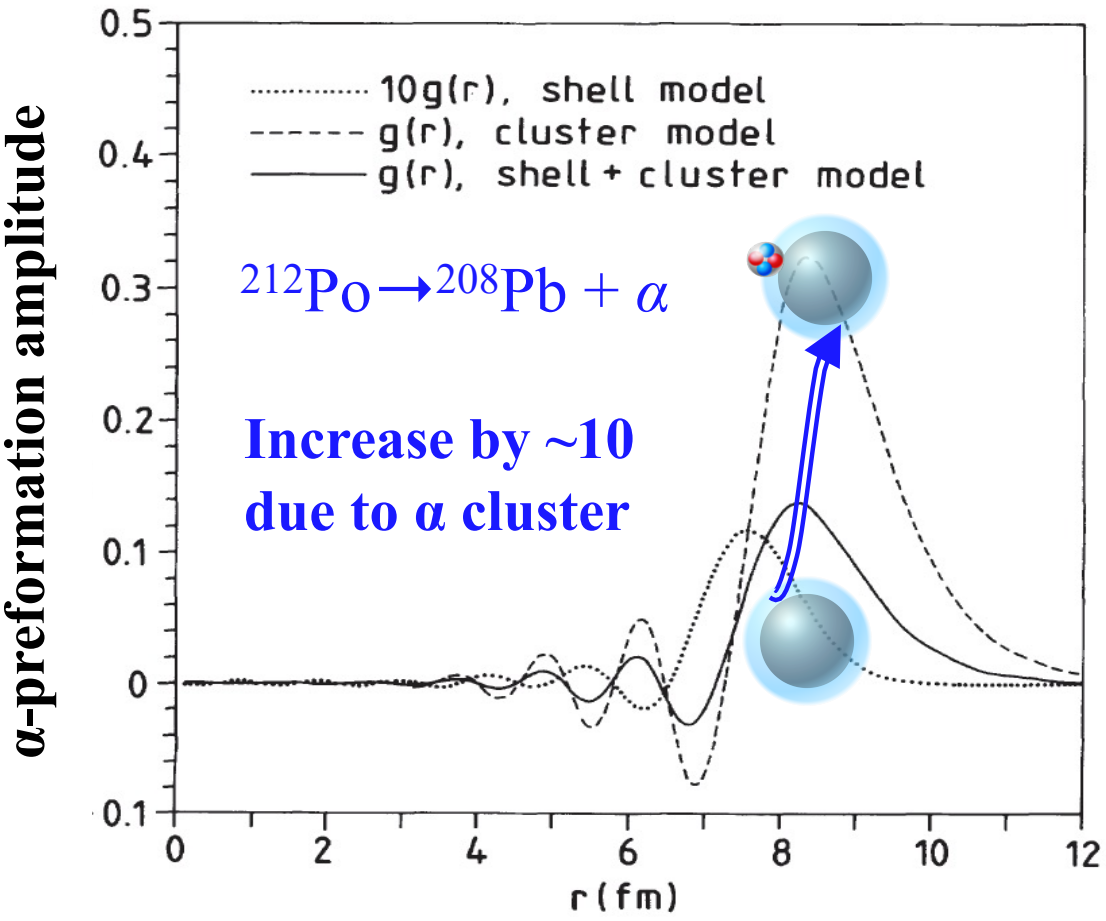
- ✓ Introduction
- ✓ α cluster in heavy nuclei: Sn as an example
- ✓ Prospect



Are there α clusters in heavy nuclei?



α decay half life: $T_{1/2} = \frac{\hbar \ln 2}{\Gamma_\alpha}, \Gamma_\alpha \propto |g(r)|^2$



Varga et al. PRL 1992
Delion et al. PRC 2012
Qi et al. PPNP2019

EoS and symmetry energy

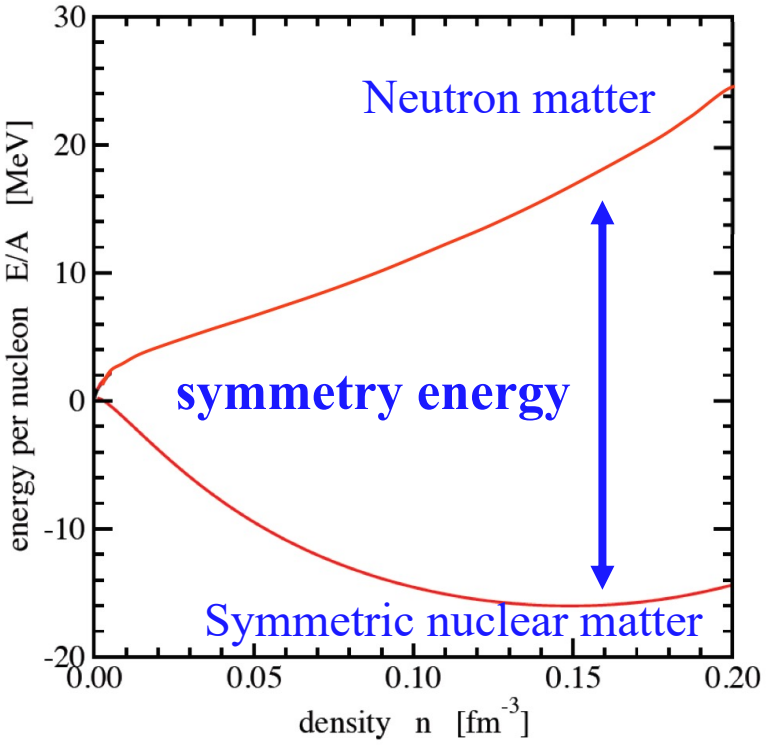
✓ **Nuclear matter equation of state (EoS)**

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,0) + S(\rho)\delta^2 + \ \ldots \qquad \rho(r) = \rho_n(r) + \rho_p(r) \qquad \delta(r) = \frac{\rho_n(r) - \rho_p(r)}{\rho_n(r) + \rho_p(r)}$$

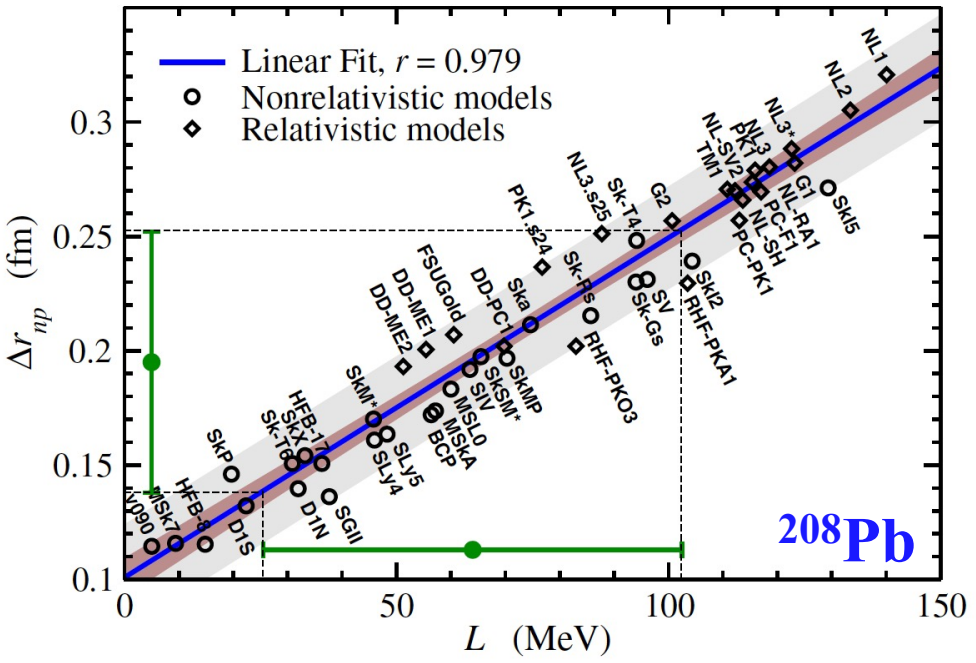
✓ **Symmetry energy**

Slope parameter

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0}(\rho - \rho_0)^2 + \ \ldots$$



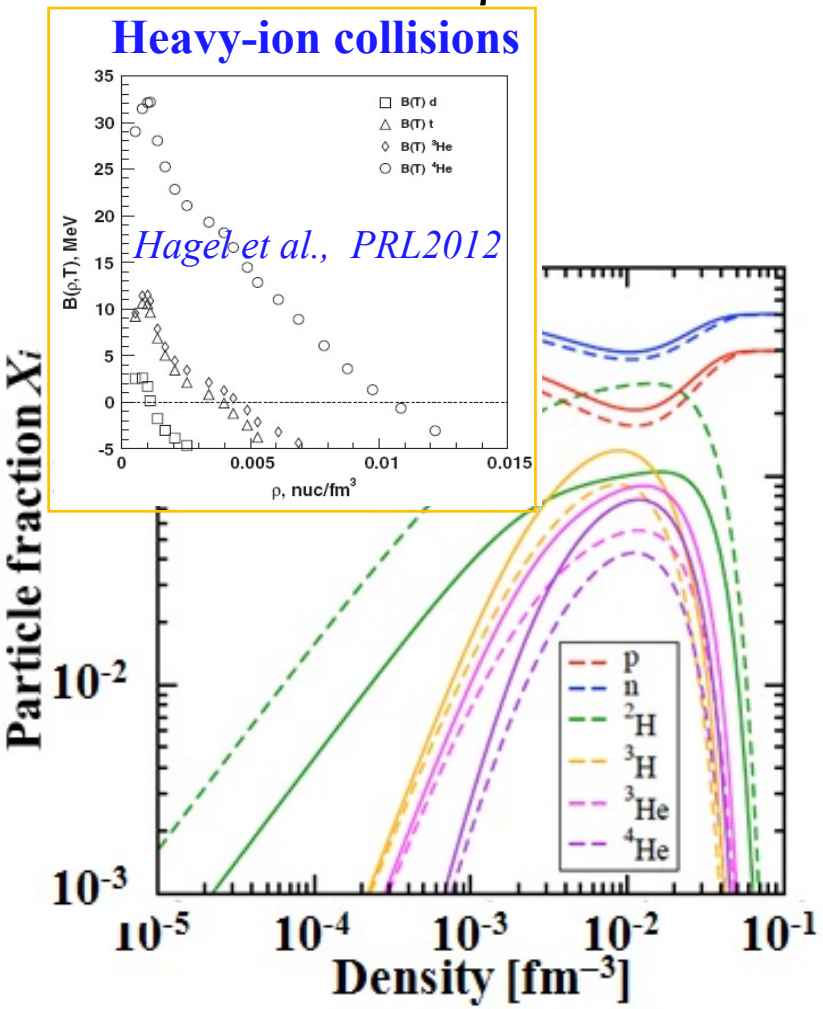
$\Delta_{np} \sim L$ *Roca-Maza, PRL (2001)*

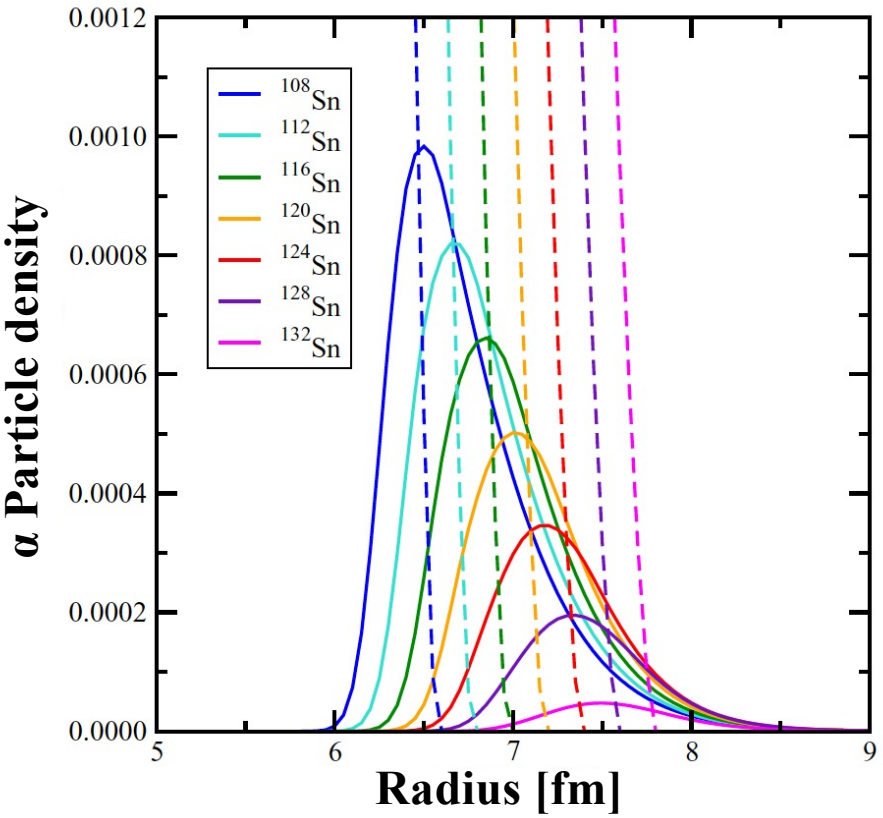


Impact of clustering on EoS

Typel, PRC89(2014) 064321,PRC 81(2010) 015803

✓ Generalized relativistic density functional (gRDF) predictions: α clusters in low-ρ environments like the surface of heavy nuclei:





Impact of clustering on EoS

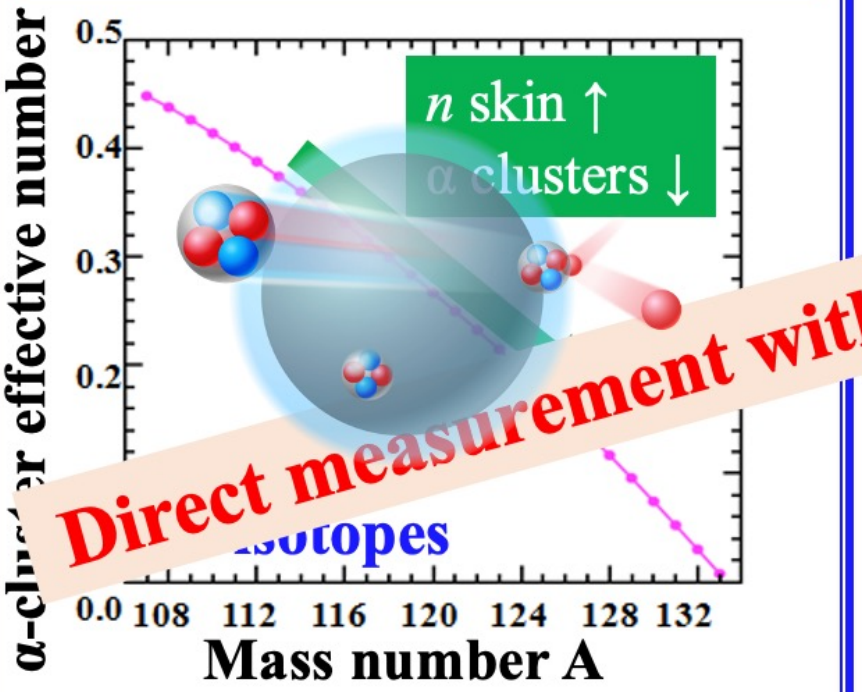
Typel, PRC89(2014) 064321,PRC 81(2010) 015803

✓ Generalized relativistic density functional (gRDF) predictions: α clusters in low-ρ environments like the surface of heavy nuclei:

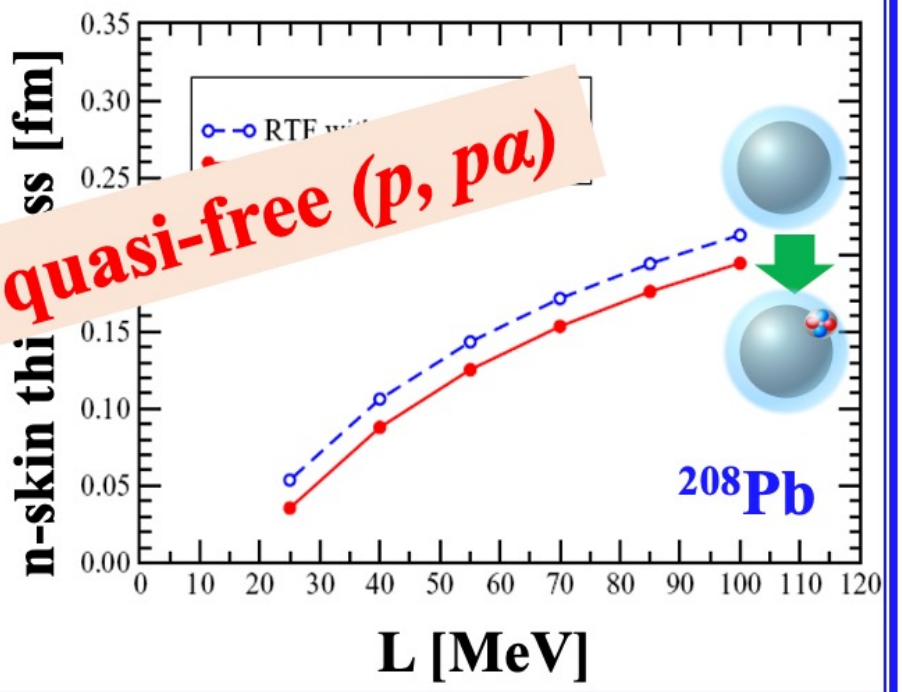
Tight interplay

α cluster ⟷ **neutron skin**

n-skin suppress α-cluster

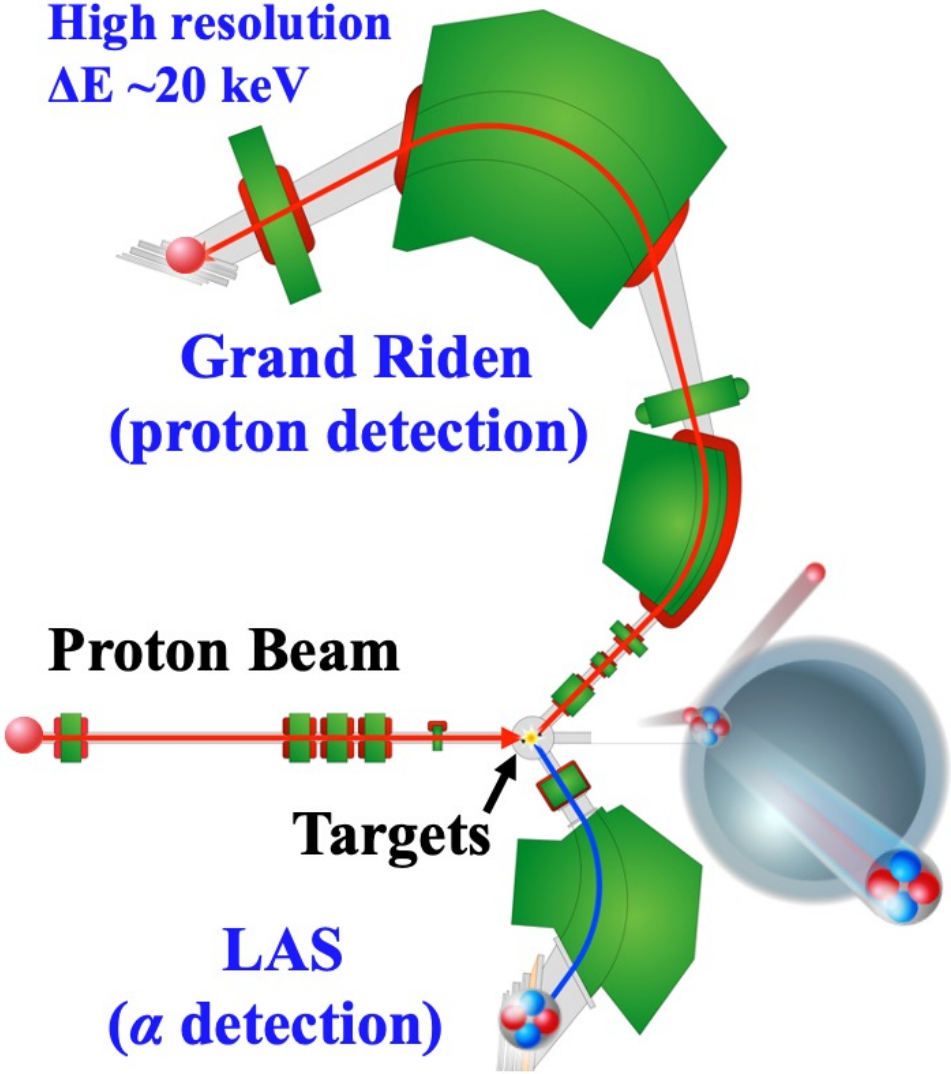


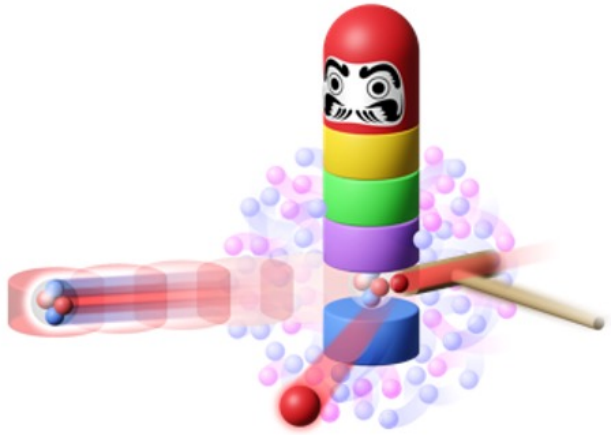
α cluster suppress n skin



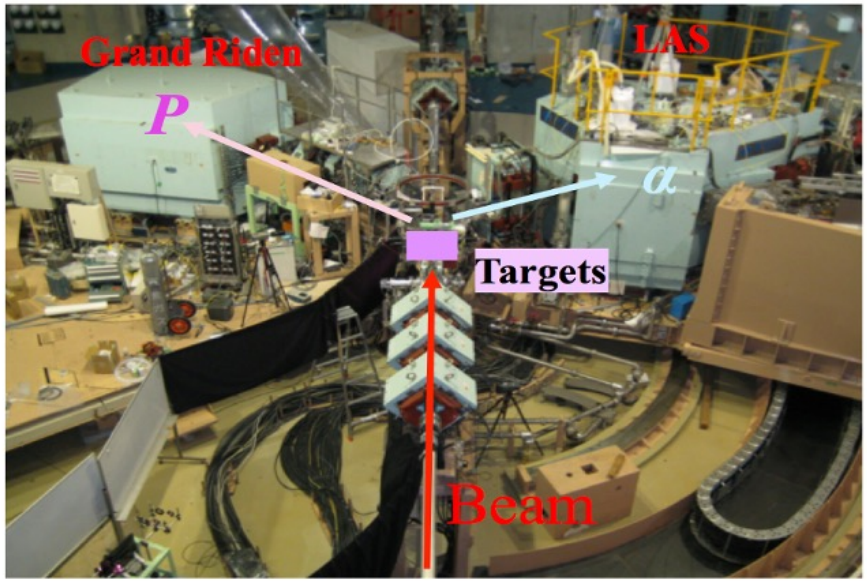
Direct measurement with quasi-free (p, pα)

Quasi-free ($p,p\alpha$) at RCNP (Osaka/Japan)

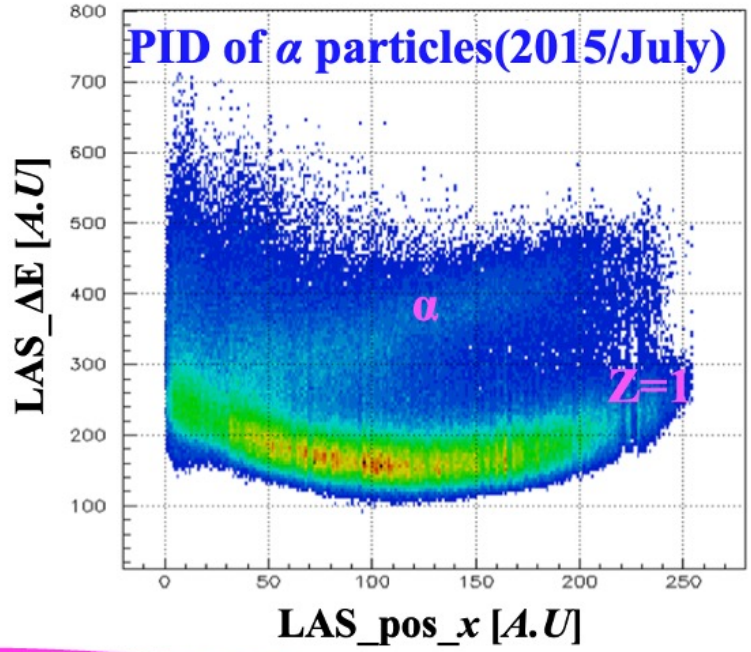


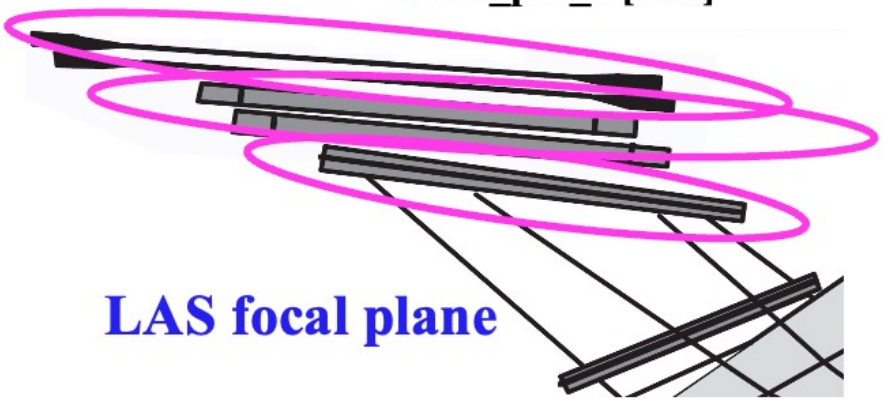


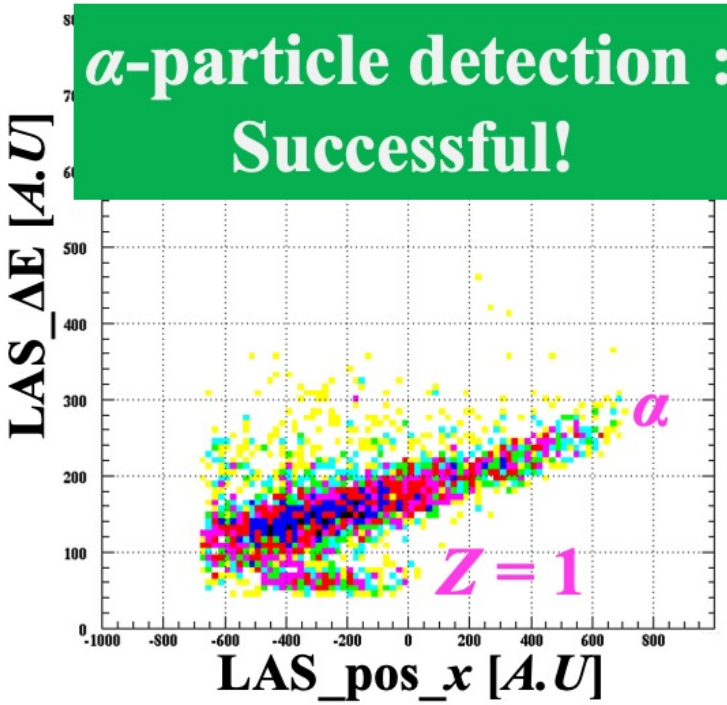
- ✓ **Beam:** 392 MeV proton, ~100 pnA
- ✓ **Targets:** ^{112,116,120,124}Sn (~40 mg/cm^2)



Development of (p,$p\alpha$) setup (2015~2018)







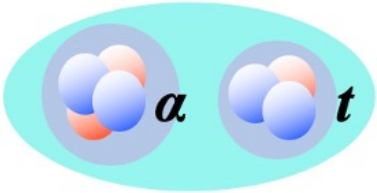
Physics run in 2018

- "Window-less" helium-gas bag
- Optimization of drift chambers
- Trigger scintillators
- The exit flange

Project started in 2015

Proof-of-principle: ^{7}Li$(p,p\alpha)$

✓Measurement with ^{7}Li$(p,p\alpha)t$



Timing correlation

Momentum correlation

Separation energy

True coincidence

True coincidence

^{7}Li$(p,p\alpha)t$

$(p,p\alpha)$ setup well developed!

Accidental

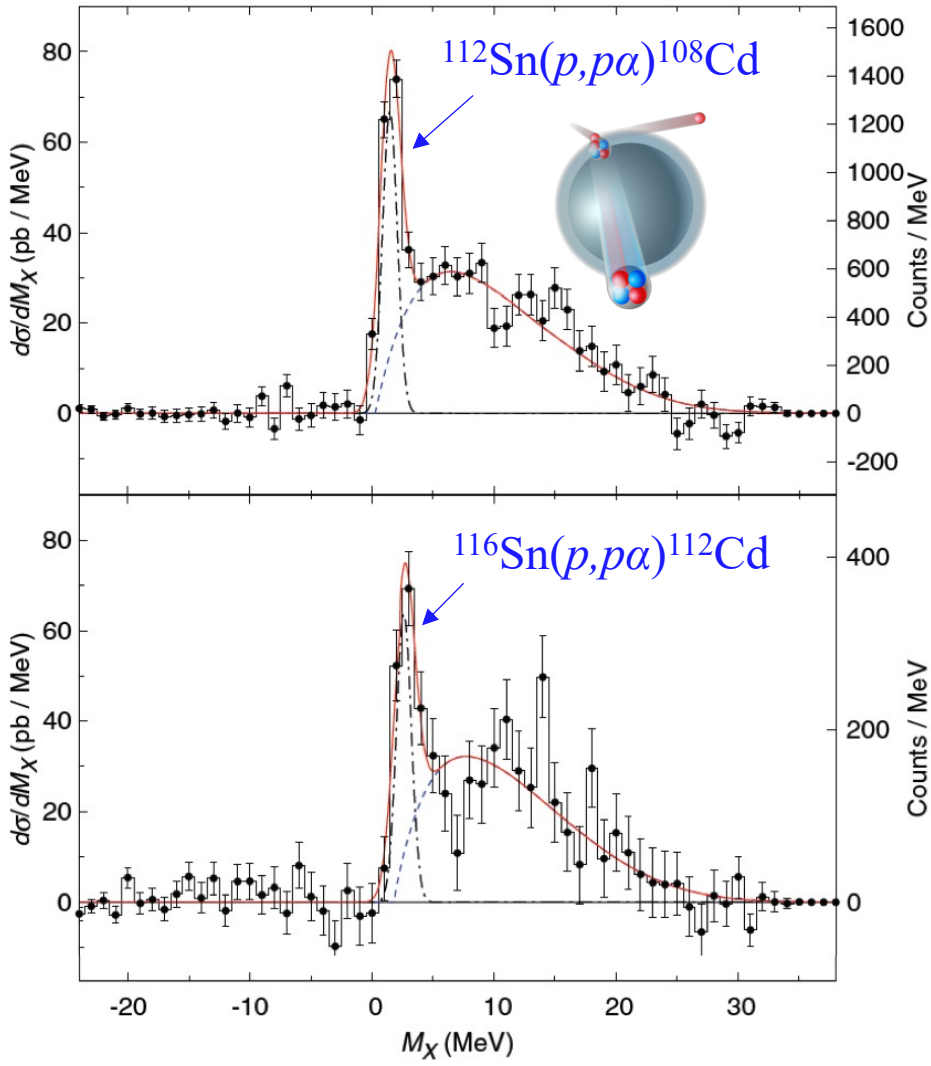
Accidental *10

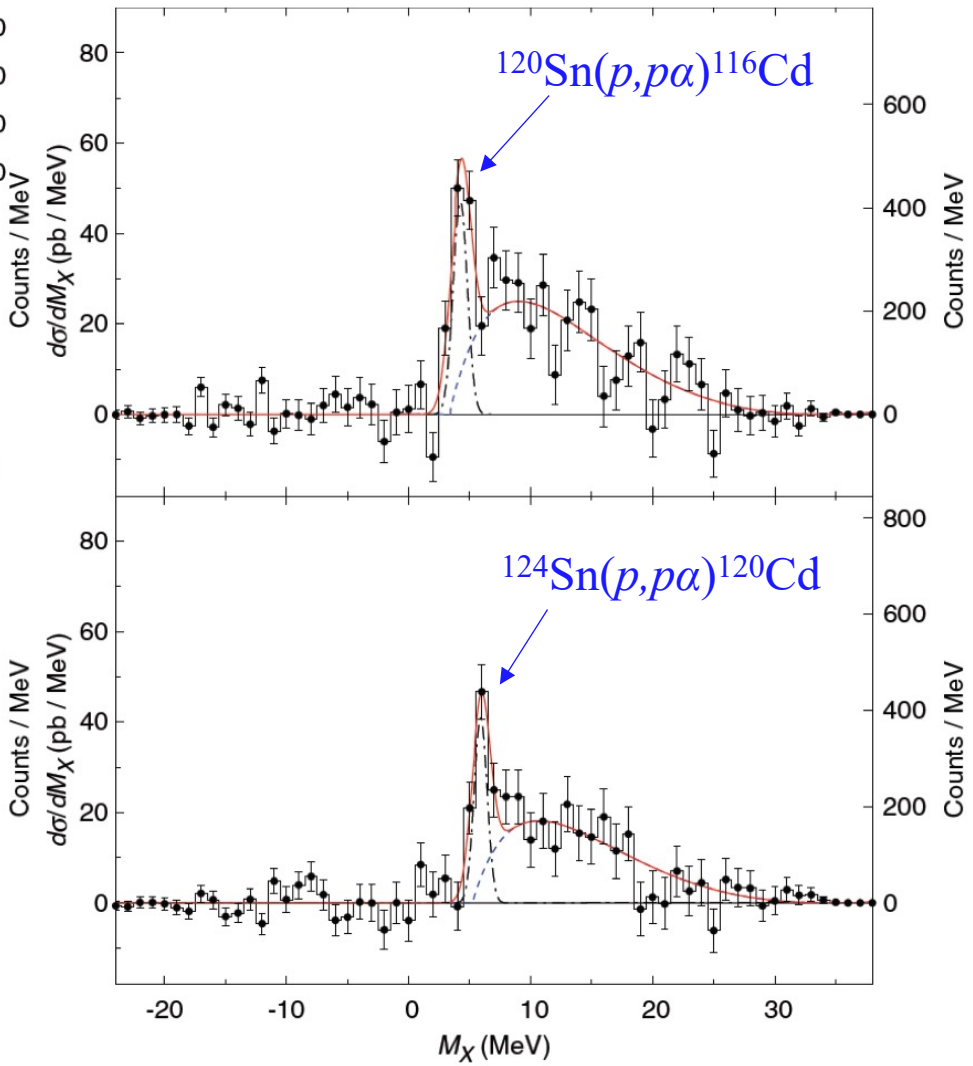
$T_\alpha - T_p$ [ns]

E_{sep} [MeV]

proton_momentum [A.U]

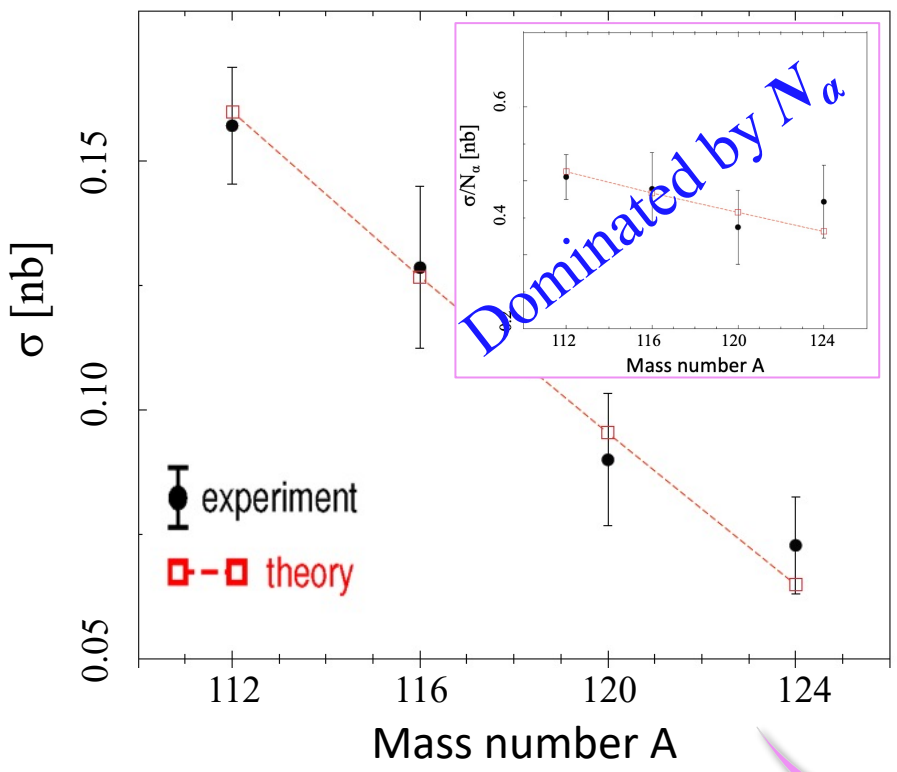
$^{112\text{-}124}$Sn(p,$p\alpha$): α separation energy spectrum

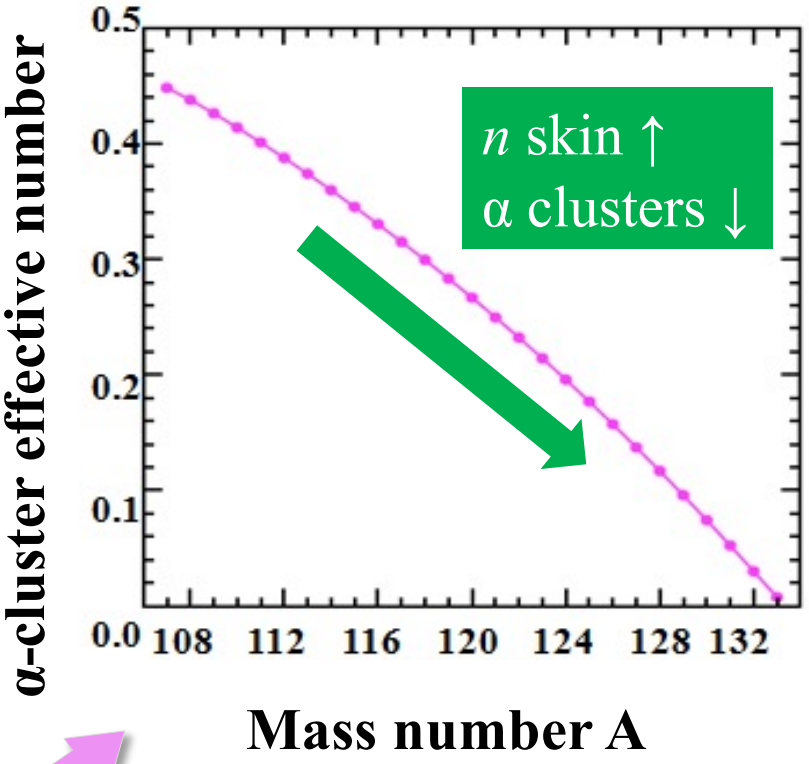




- ✓ E_{sep} Peak clearly observed for each Sn isotope ^{112,116,120,124}Sn
- ✓ Fitted using a gaussian peak and the continuum background

Systematics of α-clustering along Sn isotopic chain





- ✓ Reaction Theory: Distorted-Wave Eikonal Approximation
  - ✓ Structure input from gRDF
  - ✓ Distortion effect considered

Acknowledgement to collaborators of Sn(p,$p\alpha$)

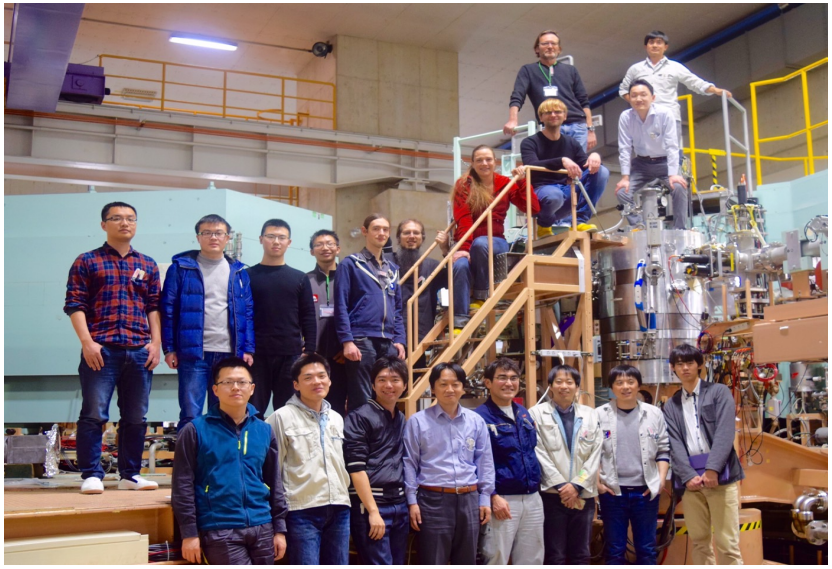
Science Contents News Careers Journals

REPORT

Formation of α clusters in dilute neutron-rich matter

Junki Tanaka[1,2,3,*], Zaihong Yang[3,4,*], Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]

Science 371, 260–264 (2021) 【Highlited】



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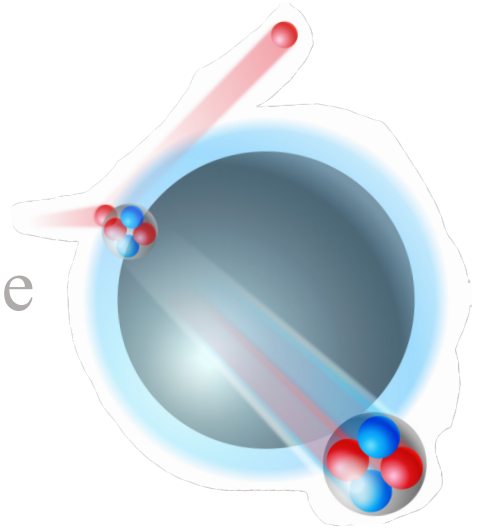
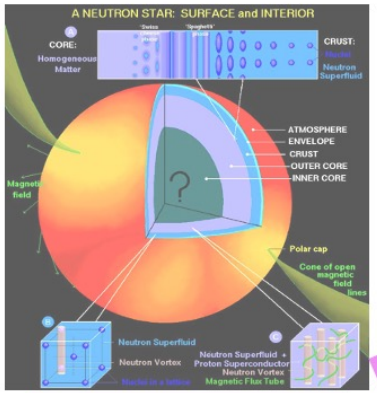


Clusters: from nucleus to neutron stars



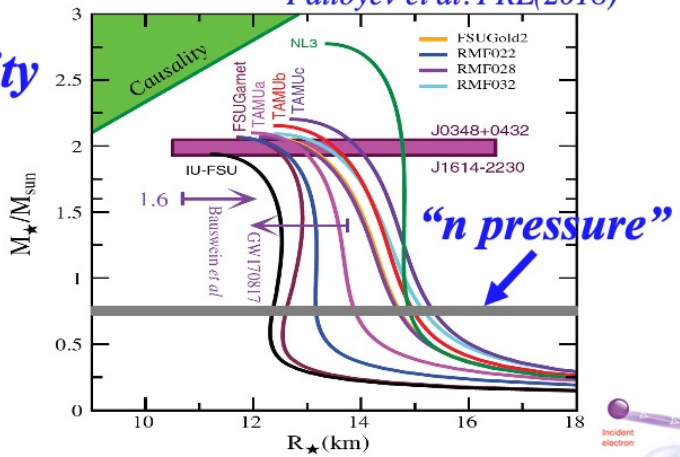
Neutron star

- ✓ *EoS + General relativity*
- ✓ *Merger*
- ✓ *Cold dense matter*

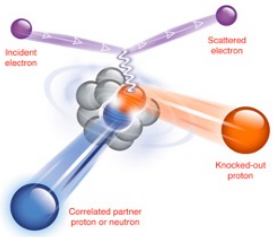
In Heaven

Mass-radius relation

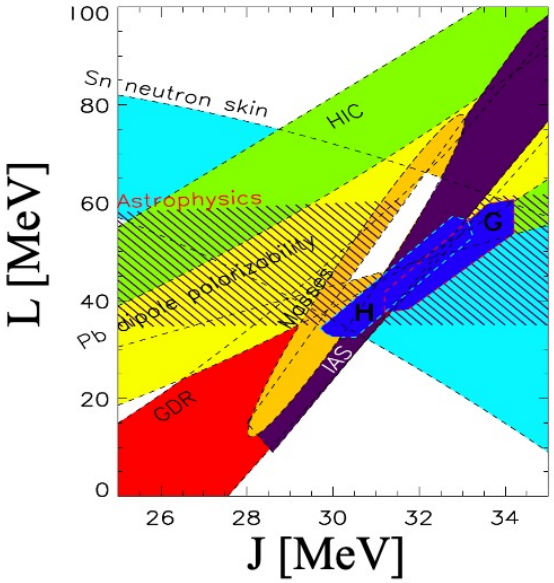
Fattoyev et al. PRL(2018)



Nuclar matter EoS

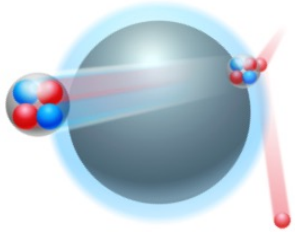


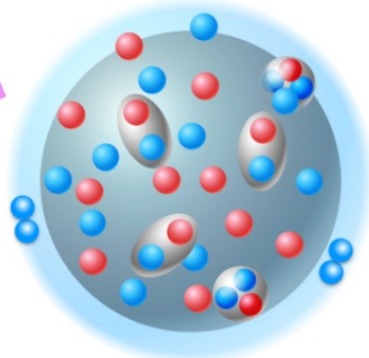
Roca-Maza, PPNP(2018)



Better constraints

- ✓ *More (accurate) data*
- ✓ *Nuclear interactions*
- ✓ *Correlations and clusters*



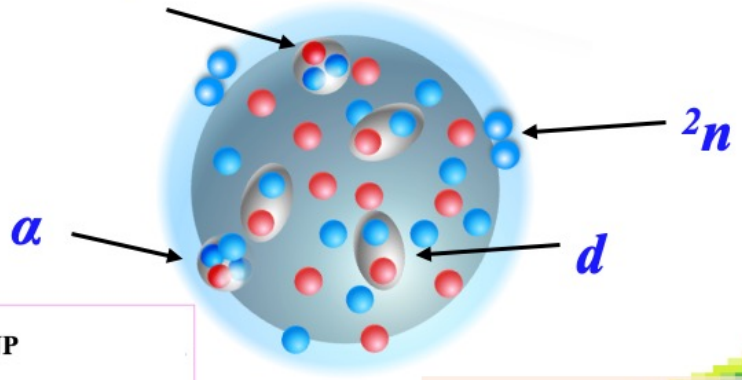


On Earth

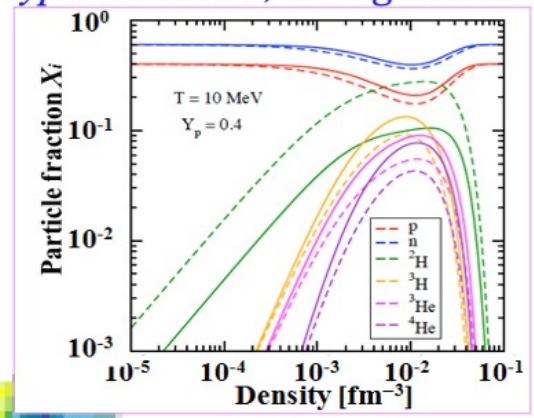
A new era of cluster knockout

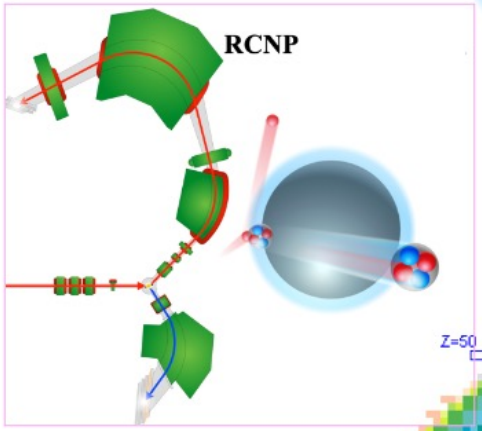
✓ More exotic nuclei at RIBF, **HIAF**, GSI/FAIR,FRIB …

t-^{3}He (mirror)



Typel PRC2010; Zhang/Chen PRC2017



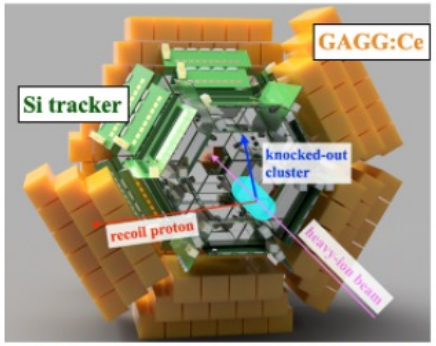


Radioactive nuclei: (p,$p\alpha$) at RIBF

Heavy nuclei: (p,$p\alpha$) with Nd and Sm at RCNP

Midium-mass: Ca(p,pX) at RCNP/RIBF

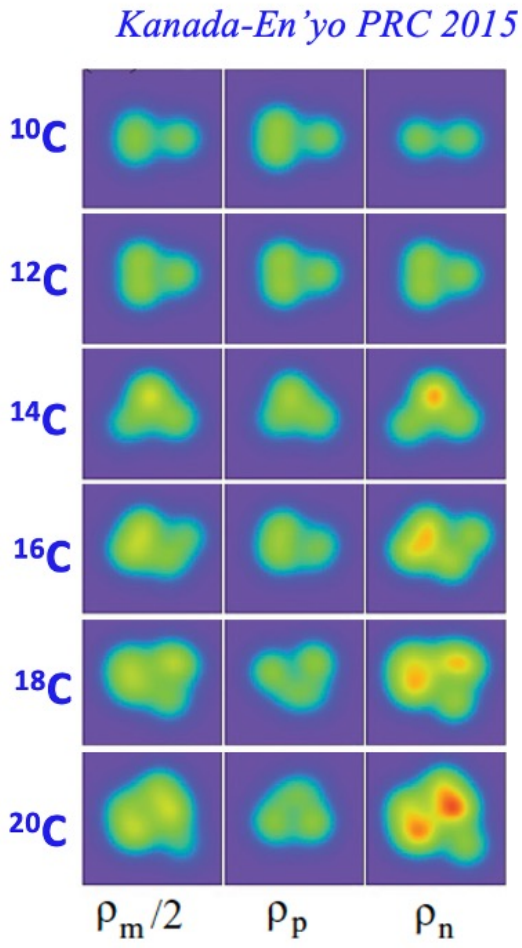
Light neutron-rich nuclei : (p,$p\alpha$) with C at RIBF

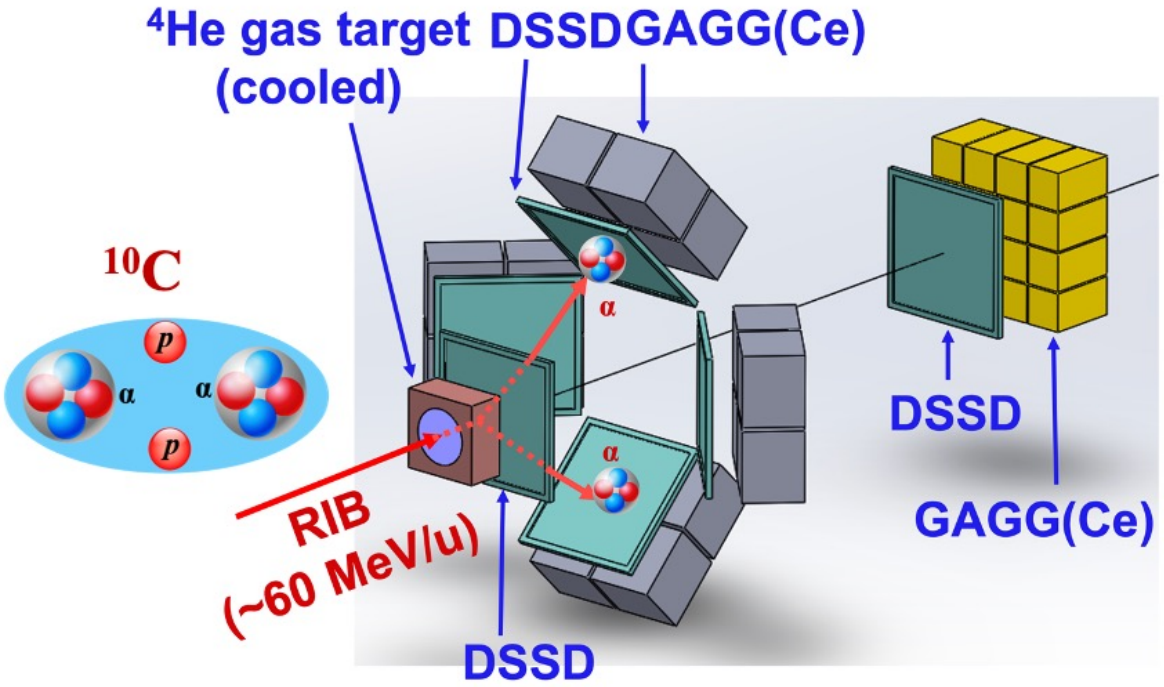


TOGAXSI@RIBF
(Uesaka et al.)

Cluster knockout in China (starting…)

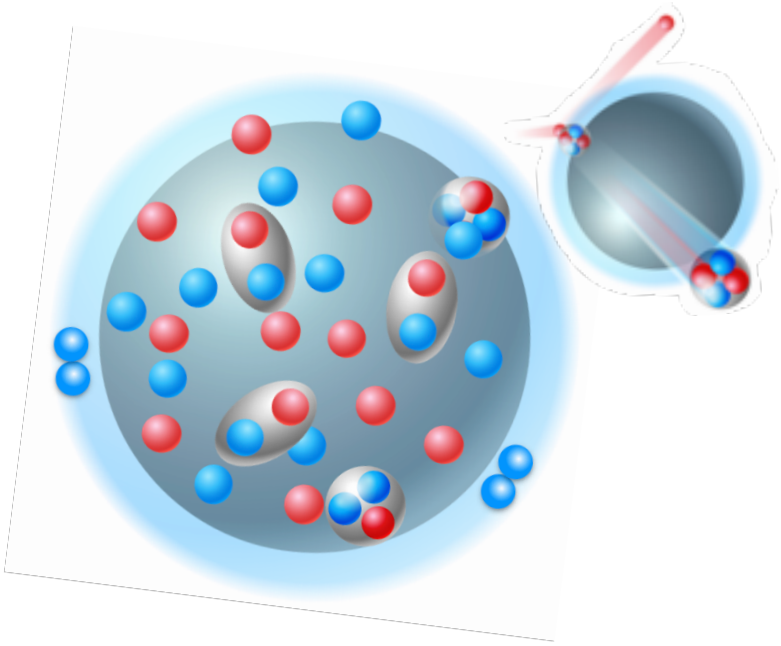
✓ Knockout of α cluster on ^{10,11}C and $^{10\text{-}11}$Be at RIBLL1 (IMP, lanzhou).

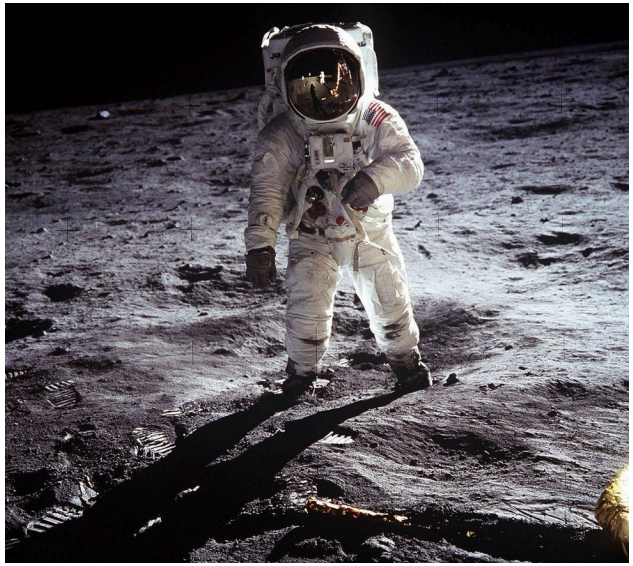




✓ More opportunities to be opened at the new facility HIAF (2025~)

Clustering in nuclear systems: from finite to infinite





"That's one small step for man. One giant leap for mankind."
-Neil Armstrong, July, 1969, Moon.

Thanks for your attention!