利用直接核反应研究原子核体系的集团结构

- ✓ Introduction for cluster studies
  - ✓ Generally used methods to study clusters
- ✓ Formation of α cluster in heavy nuclei probed with ($p,p\alpha$)
- ✓ Future experiments at RCNP/RIBF/RIBLL1

杨再宏

RCNP, Oscaka University

Coexistence: clustering and mean-field

Duality of nuclear WF

Slide from T. Yamada

Bayman-Bohr theorem Nucl. Phys. 9, 596 (1958/1959)

c.o.m. w.f. of ^{16}O

$$\phi_{\rm cm}(\mathbf{R}_{\rm cm}) = \left(\frac{32\nu}{\pi}\right)^{3/4} \exp(-16\nu \mathbf{R}_{\rm cm}^2)$$

$$\frac{1}{\sqrt{16!}} \det\left|(0s)^4(0p)^{12}\right| \times [\phi_{\rm cm}(\mathbf{R}_{\rm cm})]^{-1}$$: closed shell

$$= N_0 \sqrt{\frac{12!4!}{16!}} \mathcal{A}\left\{\left[u_{40}(\xi_3, 3\nu)\phi_{L=0}(^{12}\mathrm{C})\right]_{J=0} \phi(\alpha)\right\}$$

relative wf (S-wave)

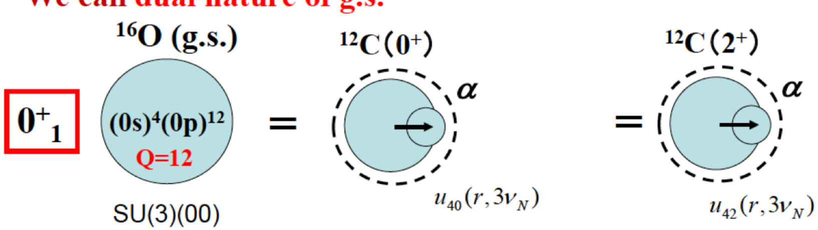
$$= N_2 \sqrt{\frac{12!4!}{16!}} \mathcal{A}\left\{\left[u_{42}(\xi_3, 3\nu)\phi_{L=2}(^{12}\mathrm{C})\right]_{J=0} \phi(\alpha)\right\}$$

relative wf (D-wave)

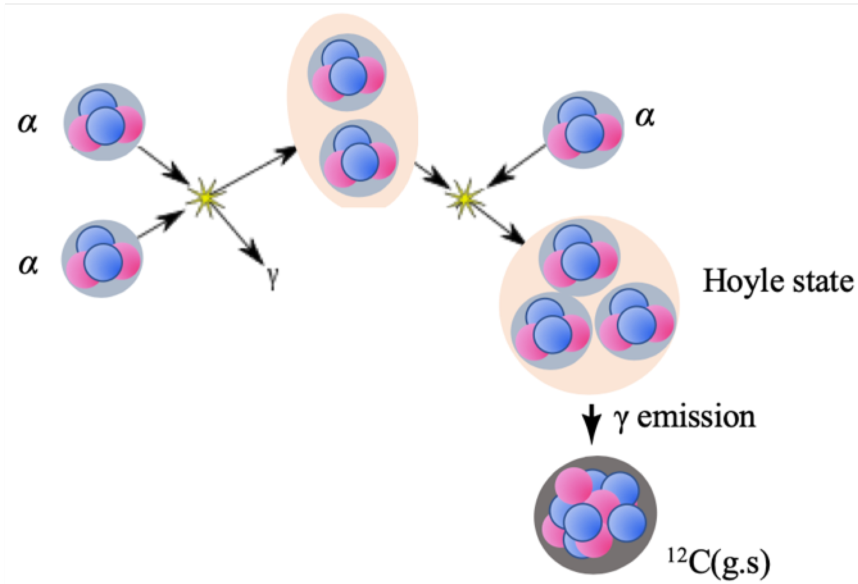
} α-degree of freedom

→G.S. has mean-field-type and α-cluster degrees of freedom.

We call dual nature of g.s.

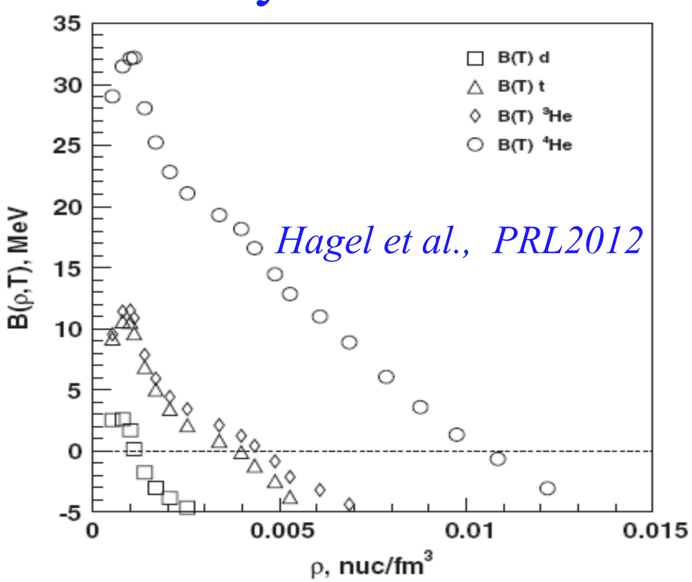


The Hoyle state

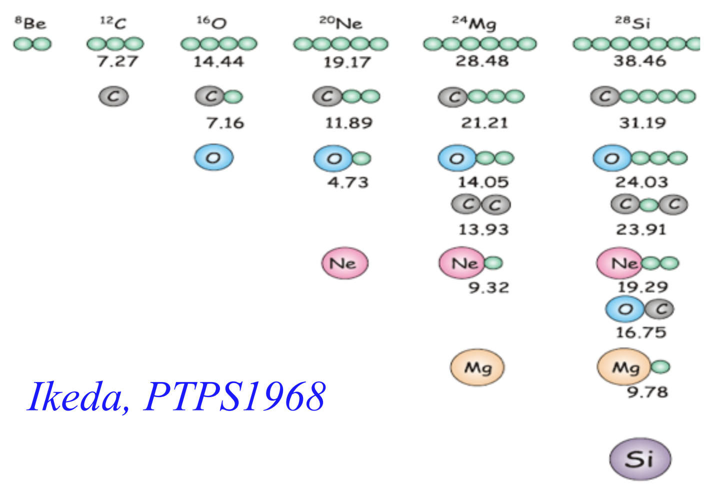


“Effective binding” or “Scale-saparation”

heavy-ion collions

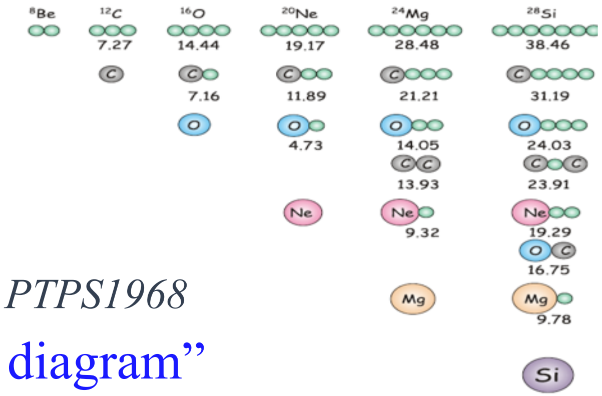


“Ikeda diagram”



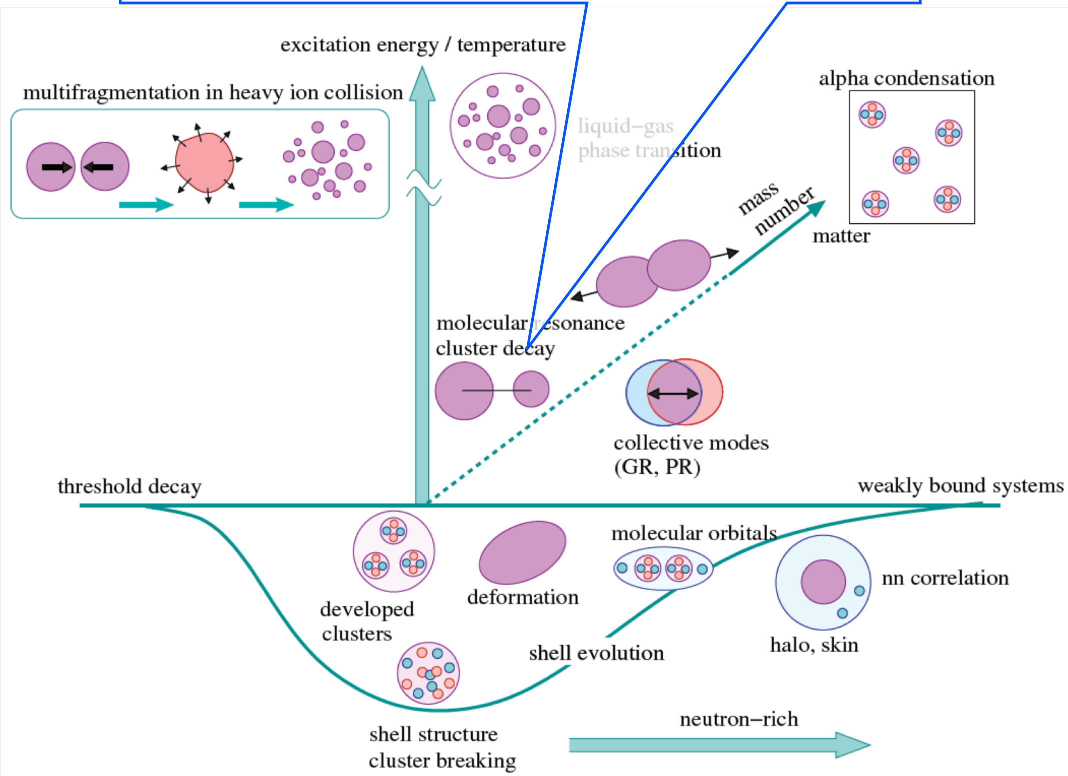
Ikeda, PTPS1968

Rich Cluster structures in light nuclei



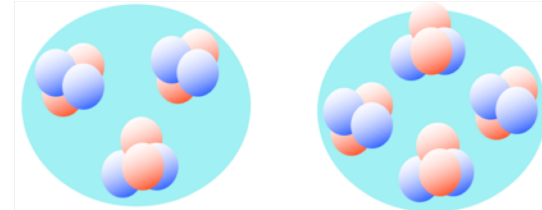
Ikeda, PTPS1968

"Ikeda diagram"

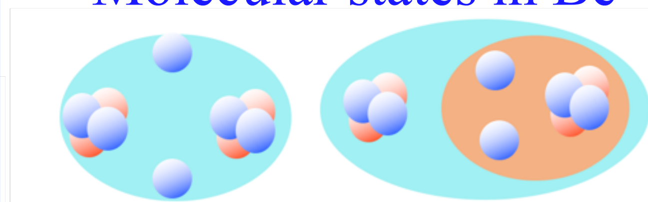


Kanada-Enyo, PTEP1(12)01A202

Gas-like (α-condensate) states



Molecular states in Be



PRL **112**, 162501 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Observation of Enhanced Monopole Strength and Clustering in ^{12}Be

Z. H. Yang (杨再宏),[1] Y. L. Ye (叶沿林),[1,*] Z. H. Li (李智焕),[1] J. L. Lou (楼建玲),[1] J. S. Wang (王建松),[2] D. X. Jiang (江栋兴),[1] Y. C. Ge (葛愉成),[1] Q. T. Li (李奇特),[1] H. Hua (华辉),[1] X. Q. Li (李湘庆),[1] F. R. Xu (许甫荣),[1] J. C. Pei (裴俊琛),[1] R. Qiao (乔锐),[1] H. B. You (游海波),[1] H. Wang (王赫),[1,3] Z. Y. Tian (田正阳),[1] K. A. Li (李阔昂),[1] Y. L. Sun (孙叶磊),[1] H. N. Liu (刘红娜),[1,3] J. Chen (陈洁),[1] J. Wu (吴锦),[1,3] J. Li (李晶),[1] W. Jiang (蒋伟),[1] C. Wen (文超),[1,3] B. Yang (杨彪),[1] Y. Y. Yang (杨彦云),[2] P. Ma (马朋),[2] J. B. Ma (马军兵),[2] S. L. Jin (金仕纶),[2] J. L. Han (韩建龙),[2] and J. Lee (李晓菁)[3]

Linear-Chain states in C

PHYSICAL REVIEW LETTERS **124**, 192501 (2020)

Positive-Parity Linear-Chain Molecular Band in ^{16}C

Y. Liu,[1] Y. L. Ye,[1,*] J. L. Lou,[1] X. F. Yang,[1] T. Baba,[2] M. Kimura,[3] B. Yang,[1] Z. H. Li,[1] Q. T. Li,[1] J. Y. Xu,[1] Y. C. Ge,[1] H. Hua,[1] J. S. Wang,[4,5] Y. Y. Yang,[5] P. Ma,[5] Z. Bai,[5] Q. Hu,[5] W. Liu,[1] K. Ma,[1] L. C. Tao,[1] Y. Jiang,[1] L. Y. Hu,[6] H. L. Zang,[1] J. Feng,[1] H. Y. Wu,[1] J. X. Han,[1] S. W. Bai,[1] G. Li,[1] H. Z. Yu,[1] S. W. Huang,[1] Z. Q. Chen,[1] X. H. Sun,[1] J. J. Li,[1] Z. W. Tan,[1] Z. H. Gao,[5] F. F. Duan,[5] J. H. Tan,[6] S. Q. Sun,[6] and Y. S. Song[6]

Exp. challenges: population + identication

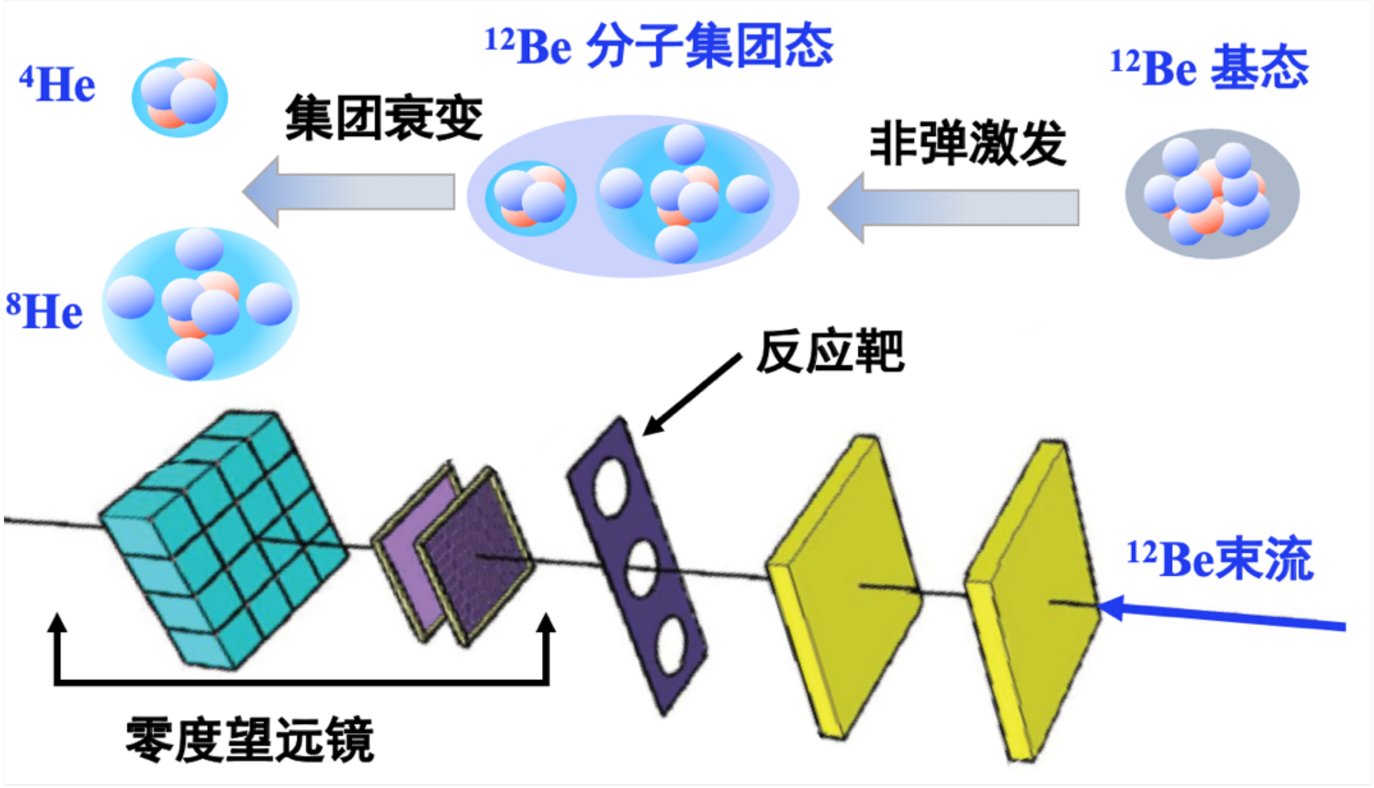
◆ **How to populate Cluster structure in the excited states:**

✓ Inelastic scattering: e.g. $^{12}C(\alpha, \alpha')$

✓ Cluster (multi-N) transfer: e.g $^{12}C(^{6}Li,d)^{16}O$, $^{9}Be(^{13}C, ^{18}O)^{4}He$

✓ Resonant scattering (active target): e.g $^{10}Be + \alpha$, $^{6}He + \alpha$

^{12}Be 实验@RIBLL1 [Z. H. Yang, Y. L. Ye et al. PRL 112, 162501 (2014)]



(实验识别-1) Cluster rotational band

- ✓ Invarimant-mass measurement by detecting the decay fragments
- ✓ Spin-parity assignment via **angular correlation analysis**
- ✓ E.g, ^{12}Be PRC82(99)1383, *PRL112(14)162501;* ^{10}*Be, PRL96(06)042501*

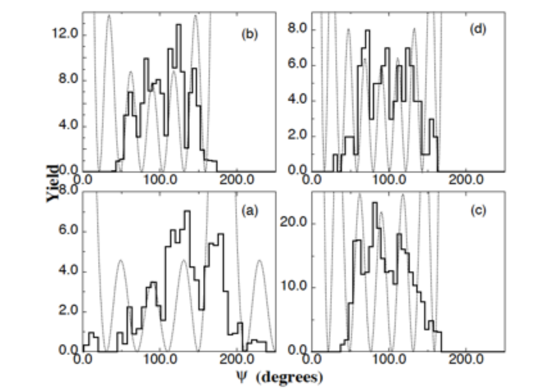
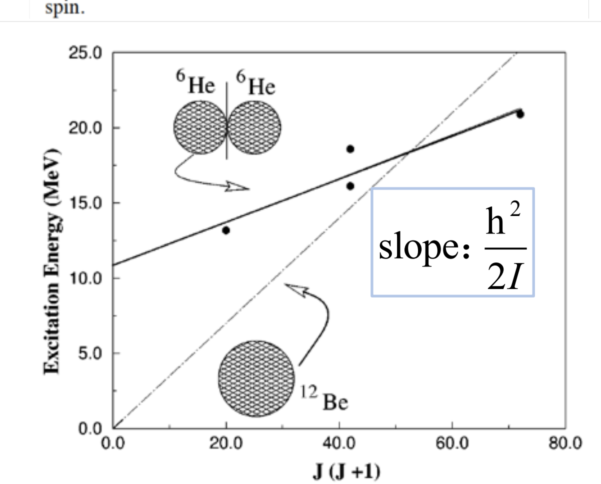


FIG. 3. Projected angular correlations (see text) for the states at (a) 13.2 MeV ($J = 4$), (b) 16.1 MeV ($J = 6$), (c) triplet centered at 18.6 MeV ($J = 6$), and (d) 20.9 MeV ($J = 8$). The dotted lines correspond to the $|P_J|^2$, where J is the assigned spin.



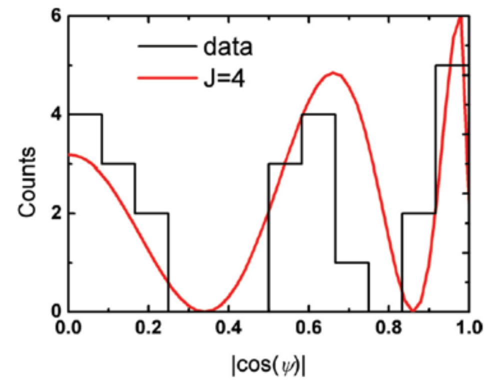
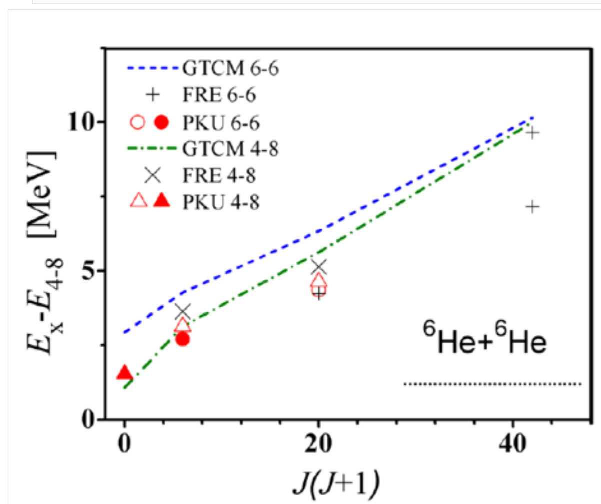


FIG. 6. (Color online) Angular correlation distribution for th 13.6-MeV state decaying into the ^{4}He + ^{8}He channel, compare with the simulation assuming $J = 4$ (red [gray] solid line).



(实验识别-2) Large Cluster SF

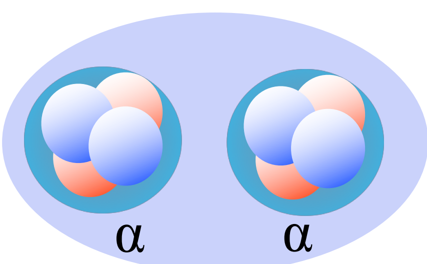
$\Gamma_\alpha(\mathrm{E}) = 2\gamma_\alpha{}^2 P_l(\mathrm{E})$ $\gamma_\alpha{}^2$-reduced width $P_l(\mathrm{E})$ – penetrability

Non-dimentional reduced width (Cluster spectroscopic factor)

$\theta^2 = \dfrac{\gamma_\alpha{}^2}{\gamma_W{}^2}\ (0 \le \theta^2 \le 1)$ $\gamma_W{}^2 = \dfrac{3\mathrm{h}^2}{2\mu a^2}$: *wigner* limit

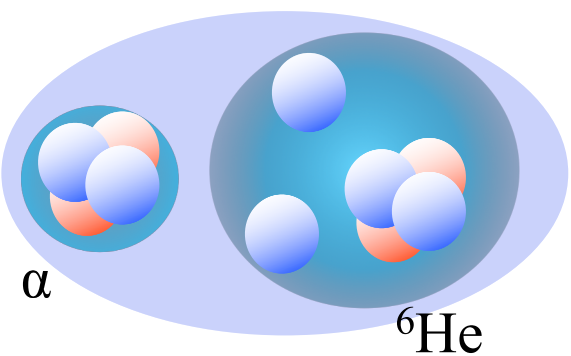
^{8}Be(g.s)

$\theta^2(\alpha)=0.45$



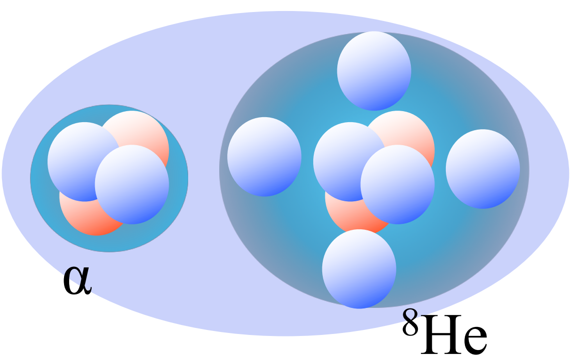
^{10}Be (4^+, 9.6MeV)

$\theta^2(\alpha)\sim0.5$



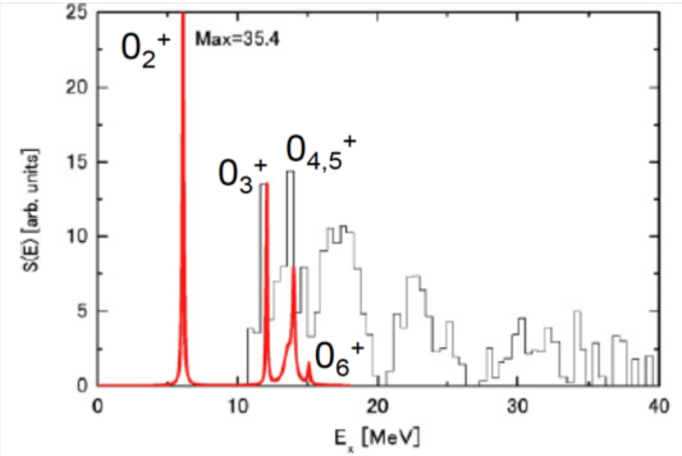
^{12}Be($0_3{}^+$, 10.3MeV)

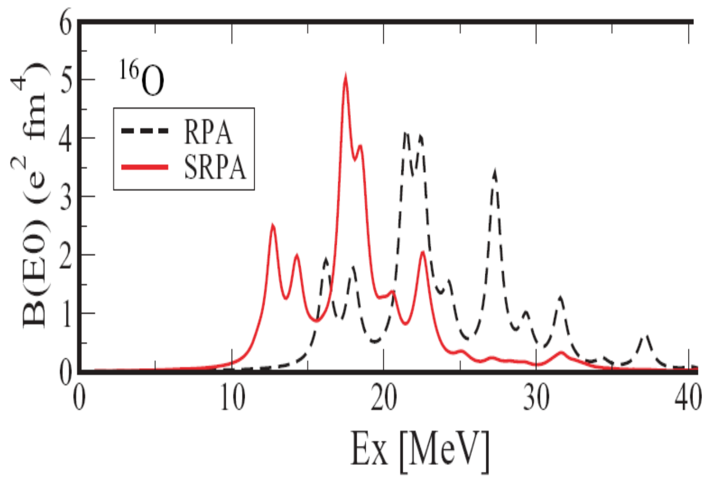
$\theta^2(\alpha)\sim0.5$



(实验识别-3) Isoscalar Monopole transtion

T. Yamada,, PRC85(12)034315, PTP120(12)1139; Ito, PRC 83(11)044319; Kimura, EPJA52(16)373

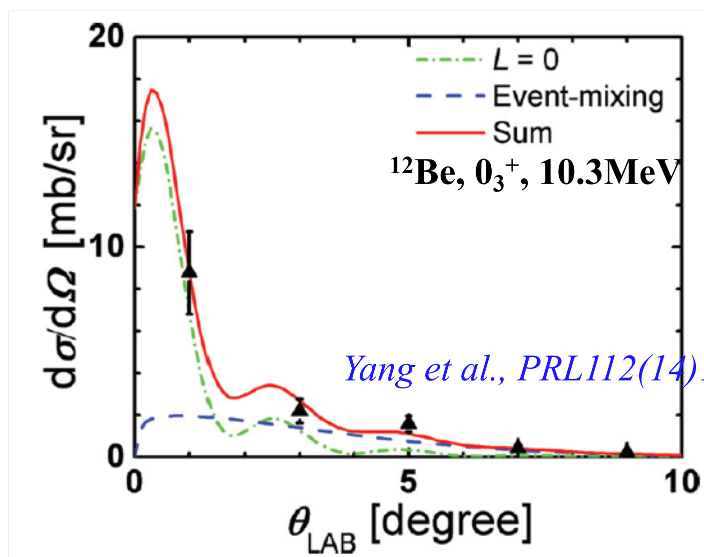




"imprint"

- ✓ Inelastic scattering on d/α/^{12}C
- ✓ Multiple decomposition analysis (MDA) of angular distribution

$$\left(\frac{d\sigma}{d\Omega}\right)^{\exp} = \sum_L a_L \left(\frac{d\sigma}{d\Omega}\right)_L^{DWBA}$$

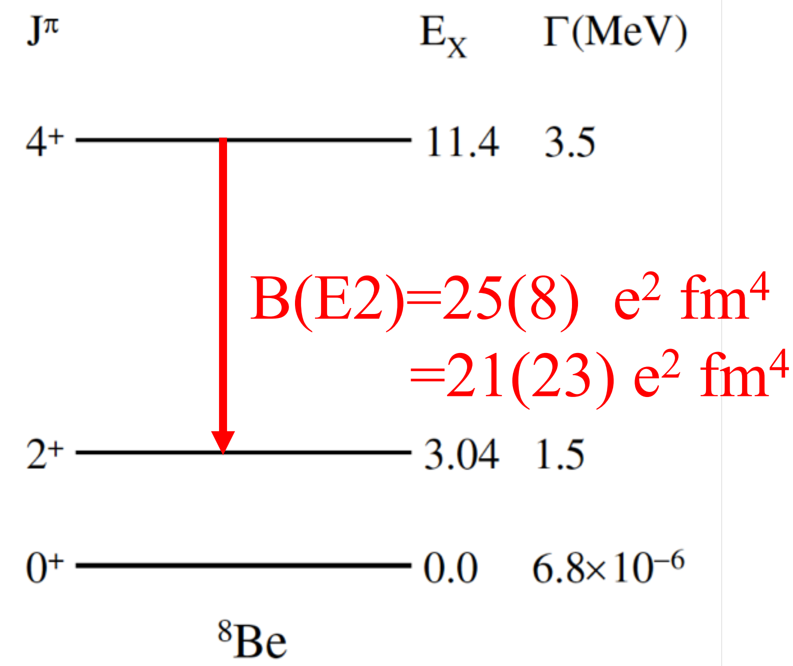


Yang et al., PRL112(14)162501

(实验识别-4) Characteristic EM transitions

^{8}Be: In-band B(E2)

Datar, PRL94(05)122502, PRL111(13)062502

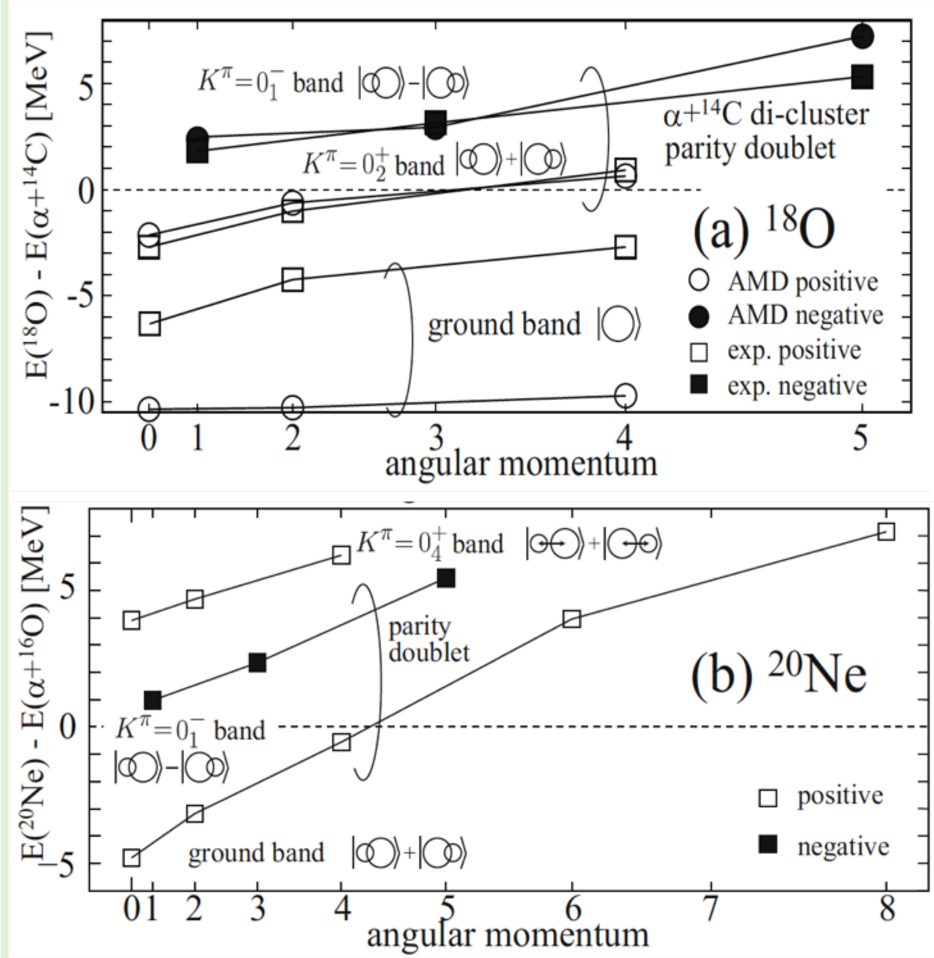


QMC: 18.2(4) $e^2\ fm^4$

GFMC: 27.2(15) $e^2\ fm^4$

Inter-band E1 between cluster parity doublet bands

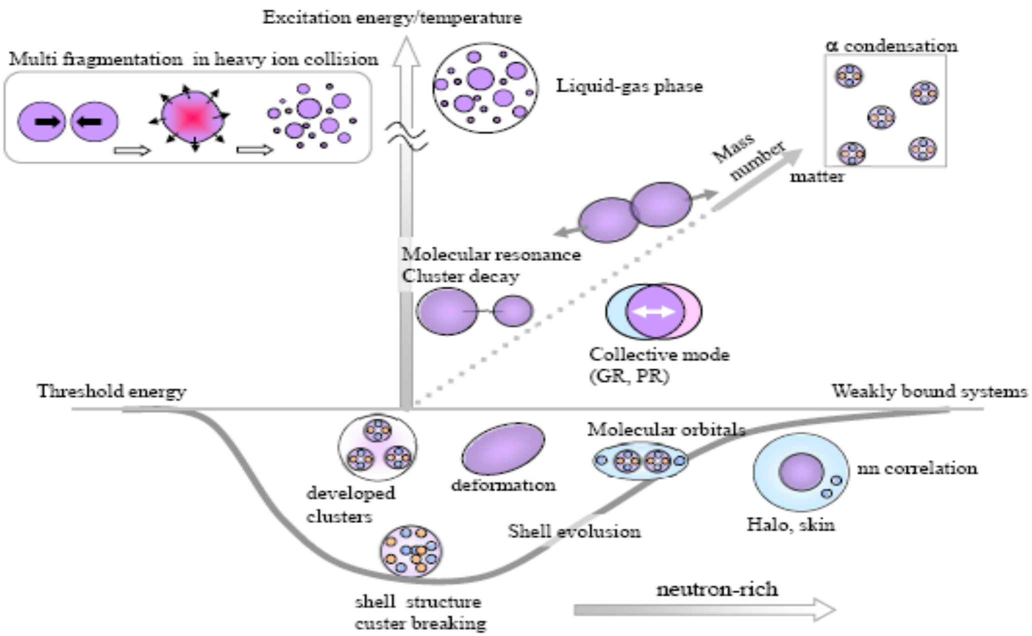
Kimura, EPJA52(16)373

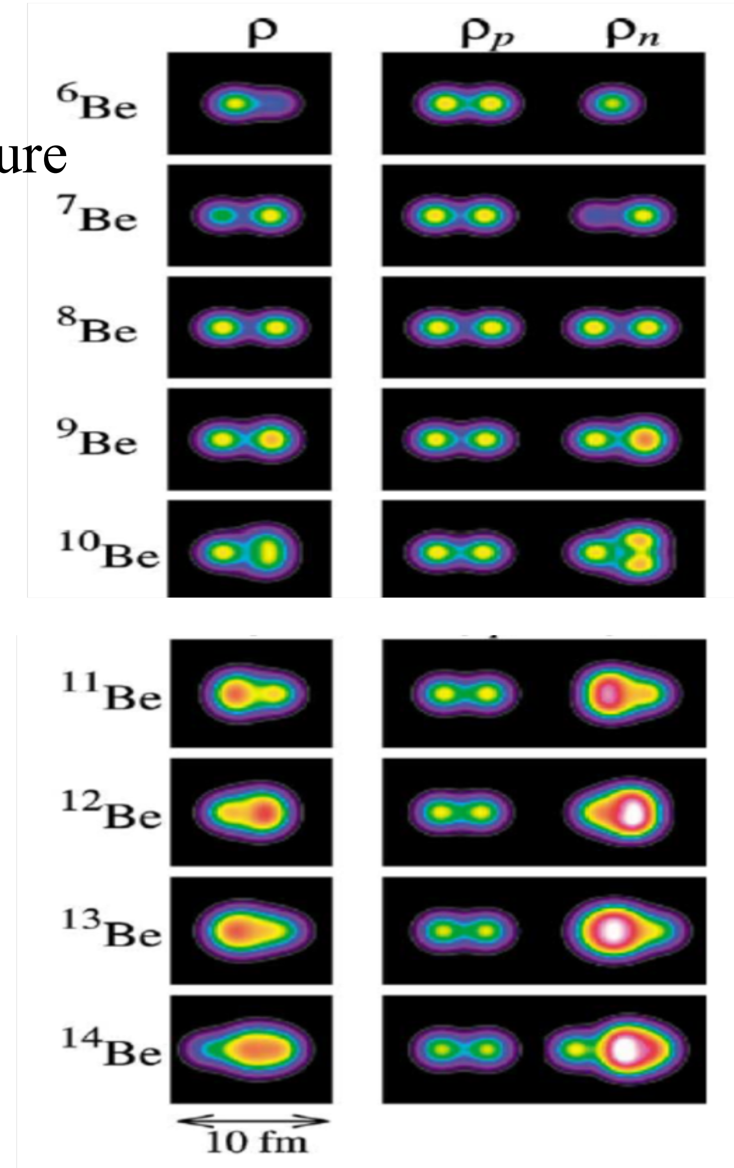


Nuclear Clusters in the ground state

✓ Rich Cluster structures in neutron-rich nuclei

➤ e.g. Be isotopes with two-centered structure



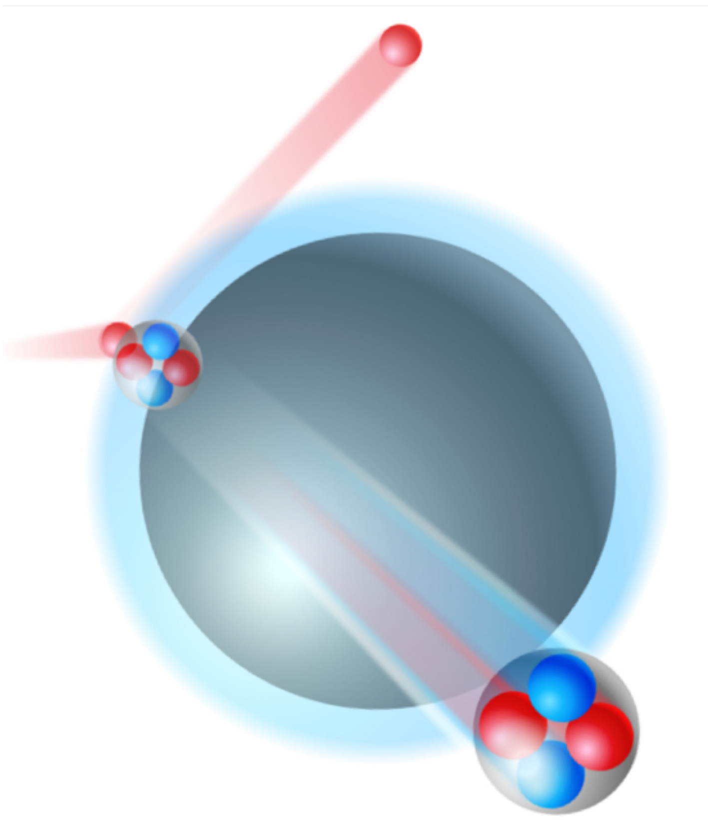


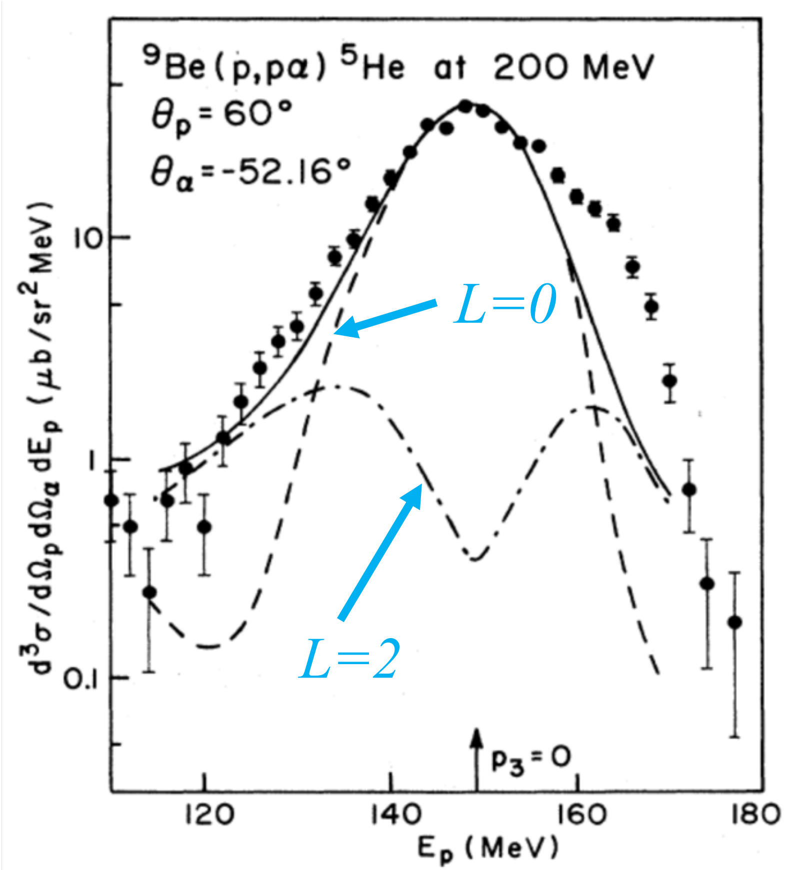
Y. Kanada-Enyo, et al., PTEP1, 01A202(2012), C. R. Physique 4 (2003) 497–520

Quasi-free ($p,p\alpha$) to probe α clusters

✓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.)*

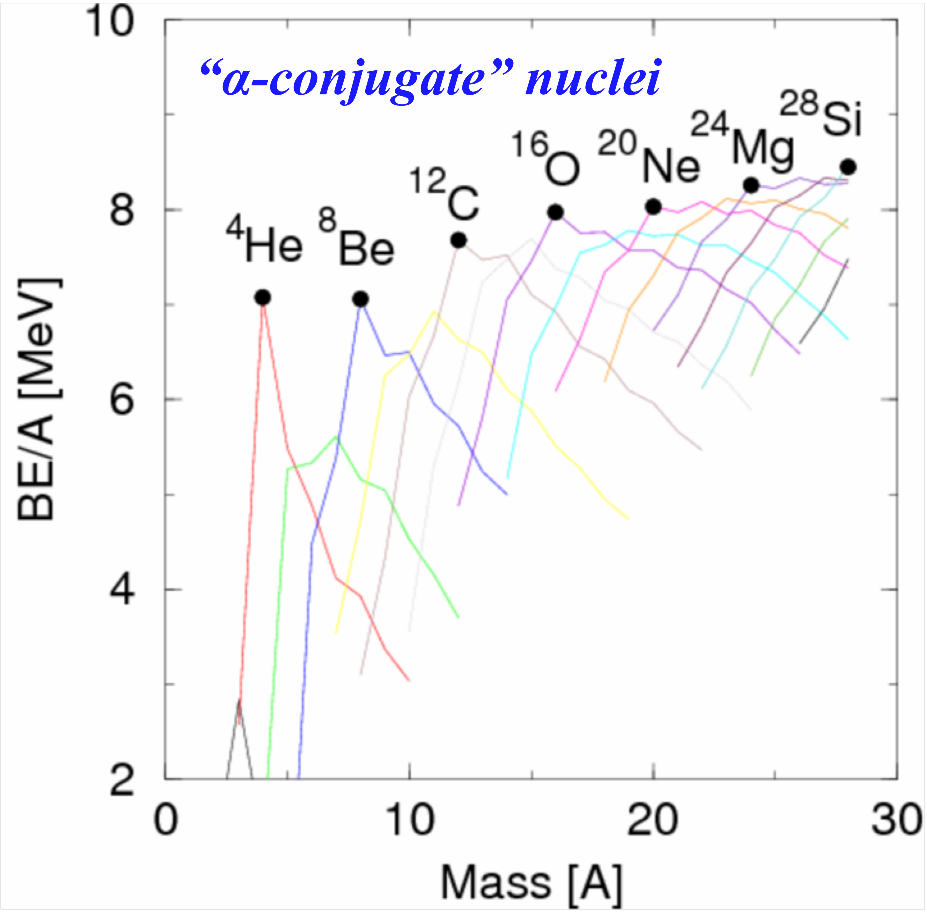


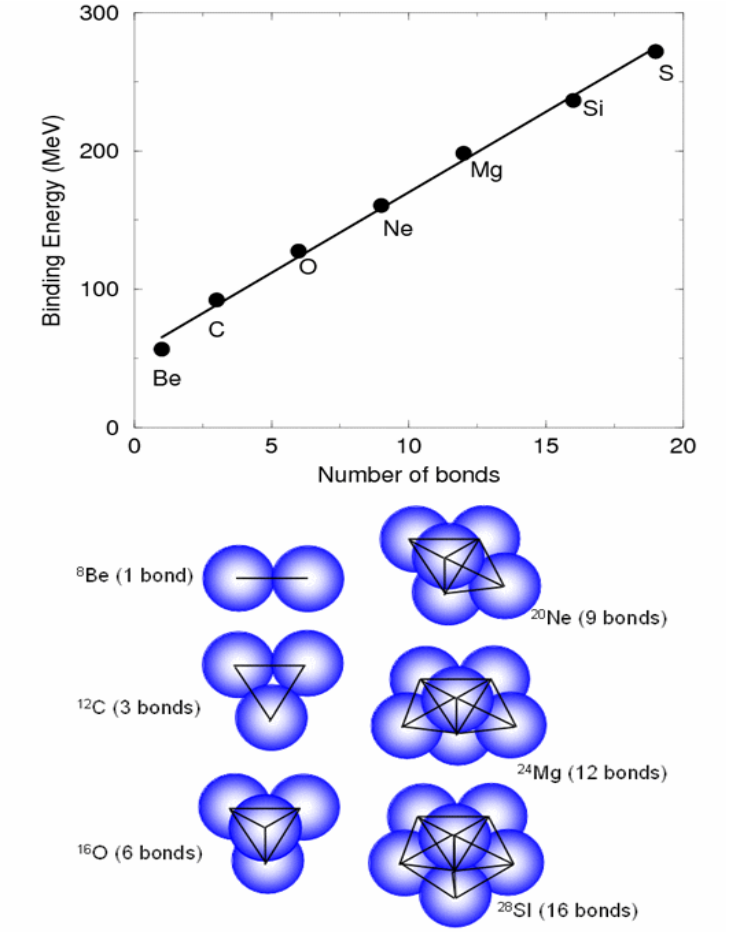


Nadasen, PRC40(1989) 1130.

"α particle" nuclei [~1930s by *Hafstad and Teller*]

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





α cluster in medium-mass region (A~50)

Taniguchi, Yoshida, et al. PRC103, L031305 (2021)

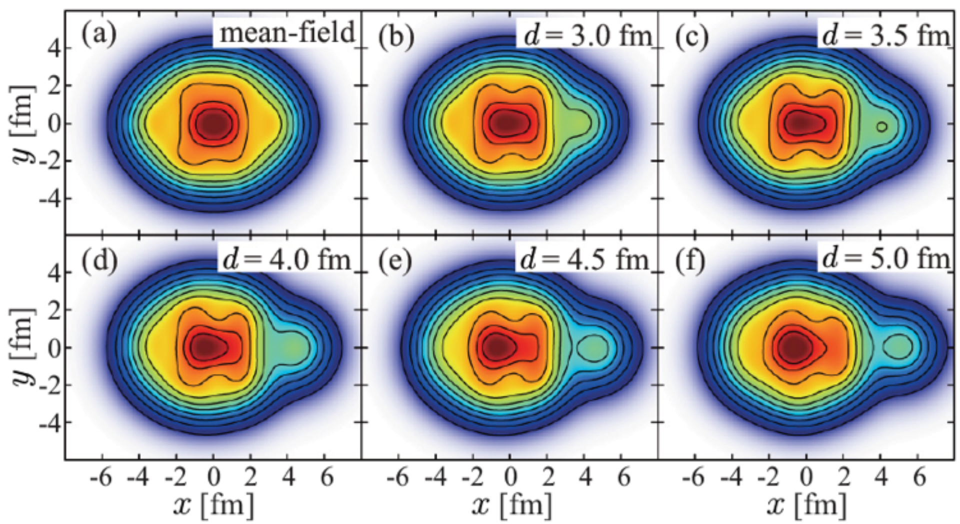


FIG. 1. Wave-function density distributions for RWA calculation—(a) mean-field solution; (b)–(f) $\alpha + {}^{44}\mathrm{Ca}$ system with different internuclear distances d.

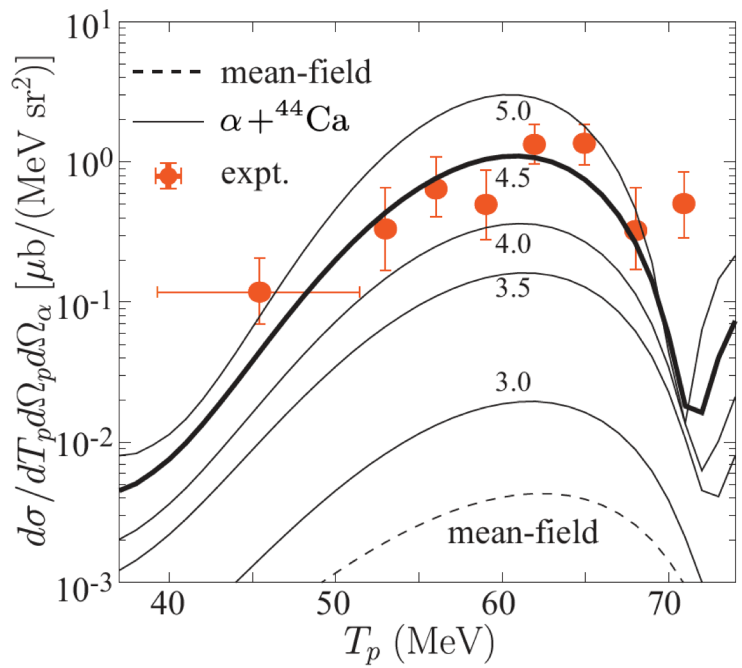
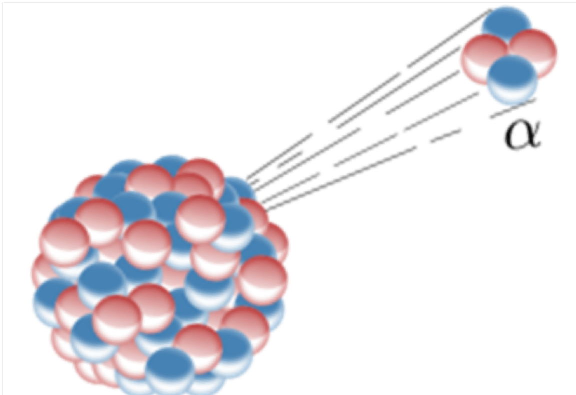
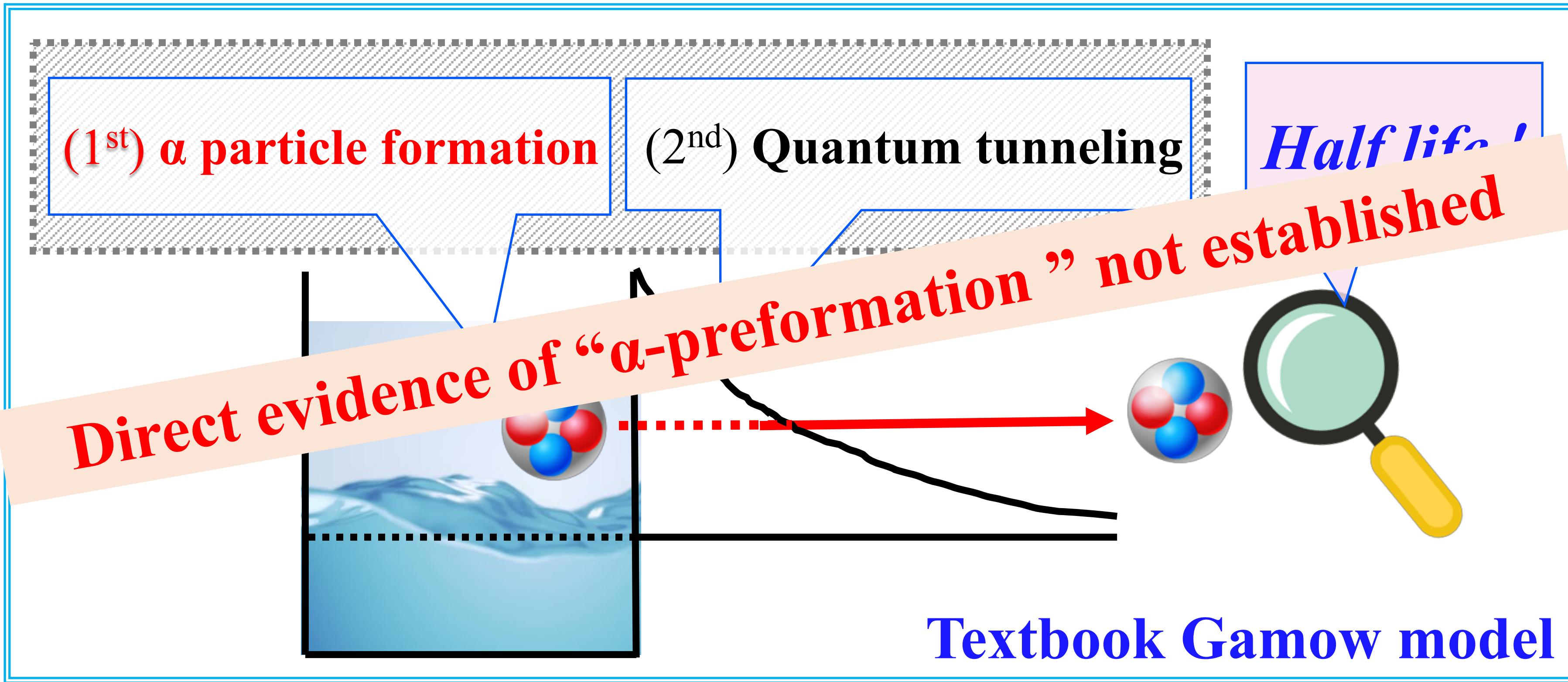


FIG. 3. Triple-differential cross section of ${}^{48}\mathrm{Ti}(p, p\alpha){}^{44}\mathrm{Ca}$ reaction via DWIA calculations using RWAs of the $\alpha + {}^{44}\mathrm{Ca}$ ($d =$ 3.0–5.0 fm) and mean-field wave functions shown in Fig. 2(a) and their comparison against experimental results reported by [20]. The

α decay of heavy nuclei: origin of α ?



Where I came from?
How I came here?



EoS and symmetry energy

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

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,0) + S(\rho)\,\delta^2 + \;\ldots$$

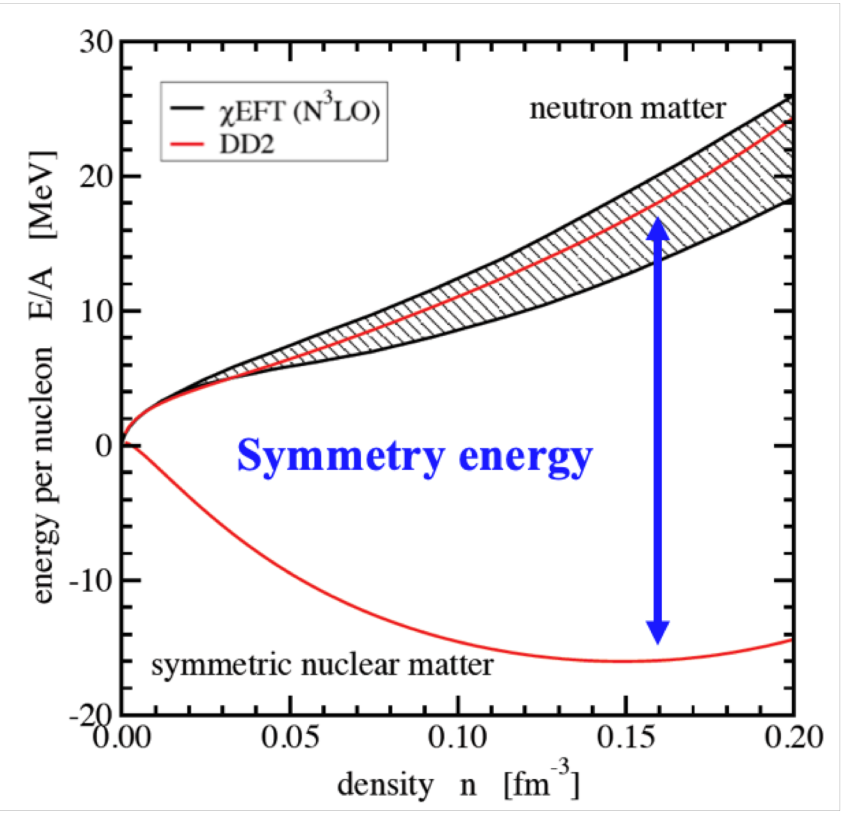
$$\rho(r) = \rho_n(r) + \rho_p(r)$$

$$\delta(r) = \frac{\rho_n(r) - \rho_p(r)}{\rho_n(r) + \rho_p(r)}$$

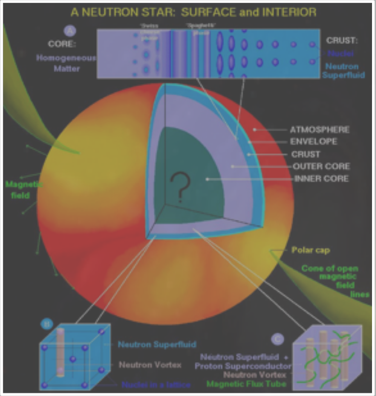
✓ **Symmetry energy**

Slope parameter (neutron pressure)

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



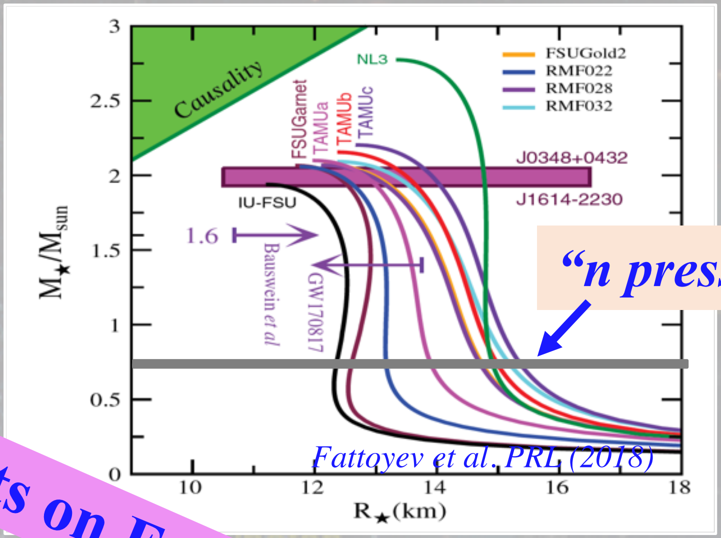
EoS: from nucleus to neutron stars



In Heaven

Neutron star
- ✓ Structure
- ✓ Cooling
- ✓ Merger

Mass-radius relation

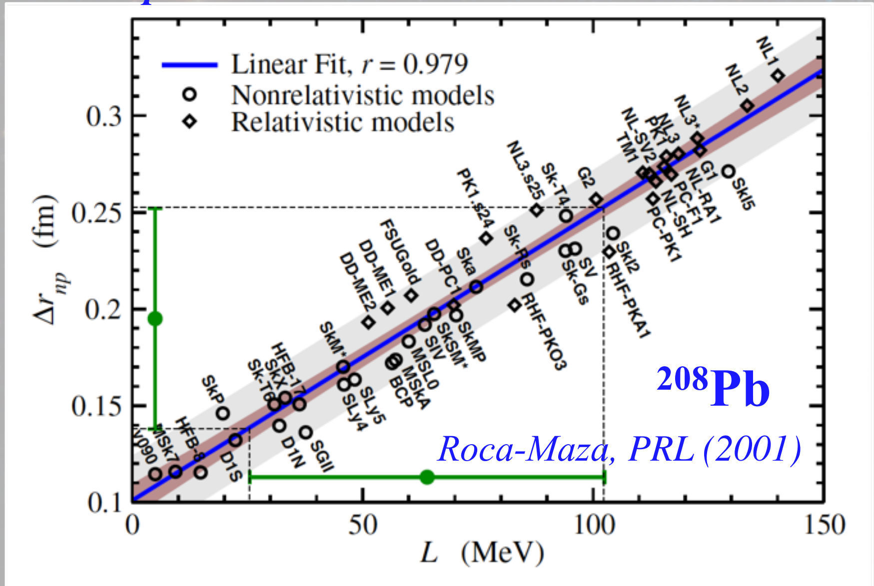


"n pressure"

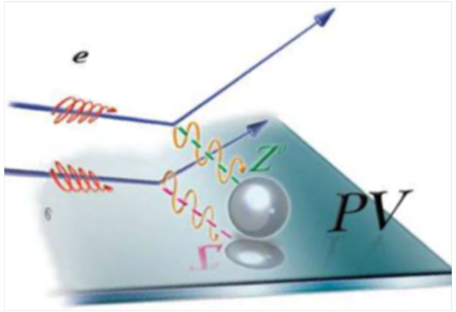
Constraints on EoS

EoS predictions

Δ_{np} ~L (slope parameter)



PREX at JLAB

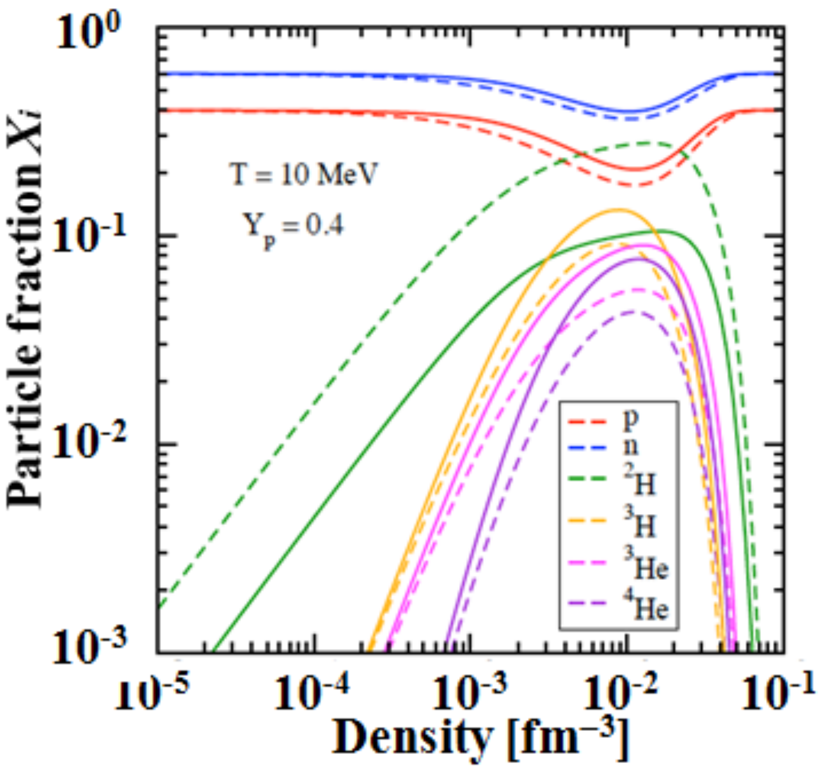


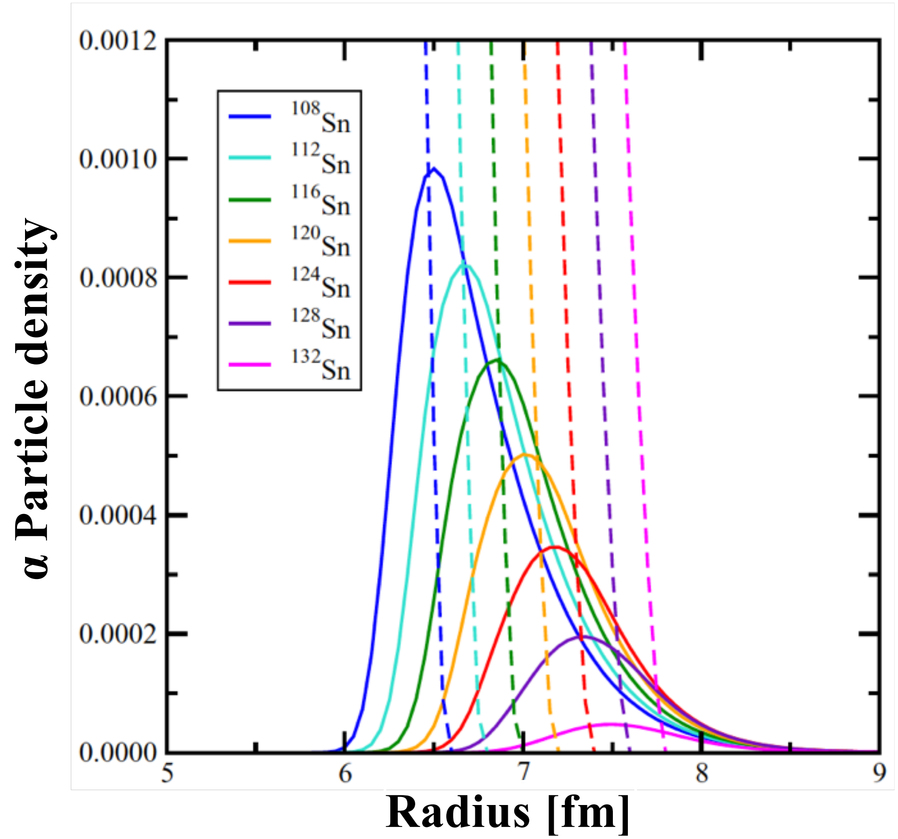
On Earth

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

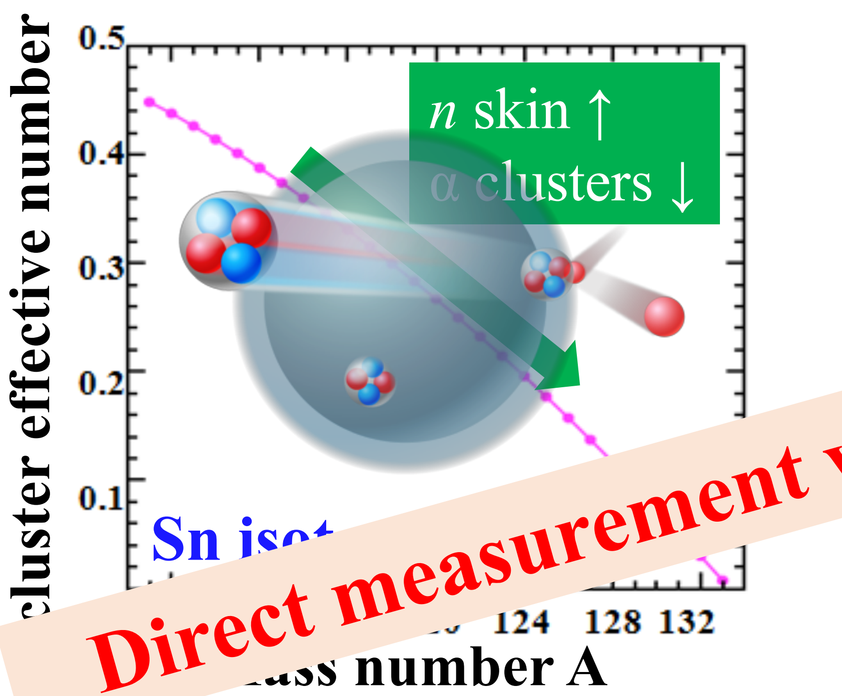
Typel, PRC89(2014) 064321,PRC 81(2010) 015803

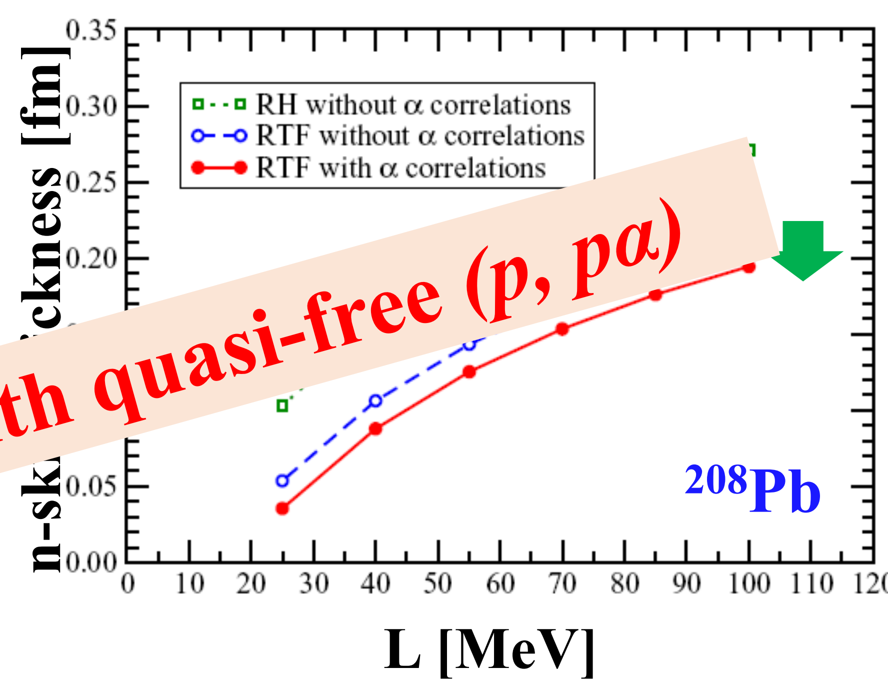
- ✓ Generalized relativistic density functional (gRDF) predictions: α clusters in low-ρ environments like the surface of heavy nuclei:

Tight interplay

α cluster ⟷ **neutron skin**

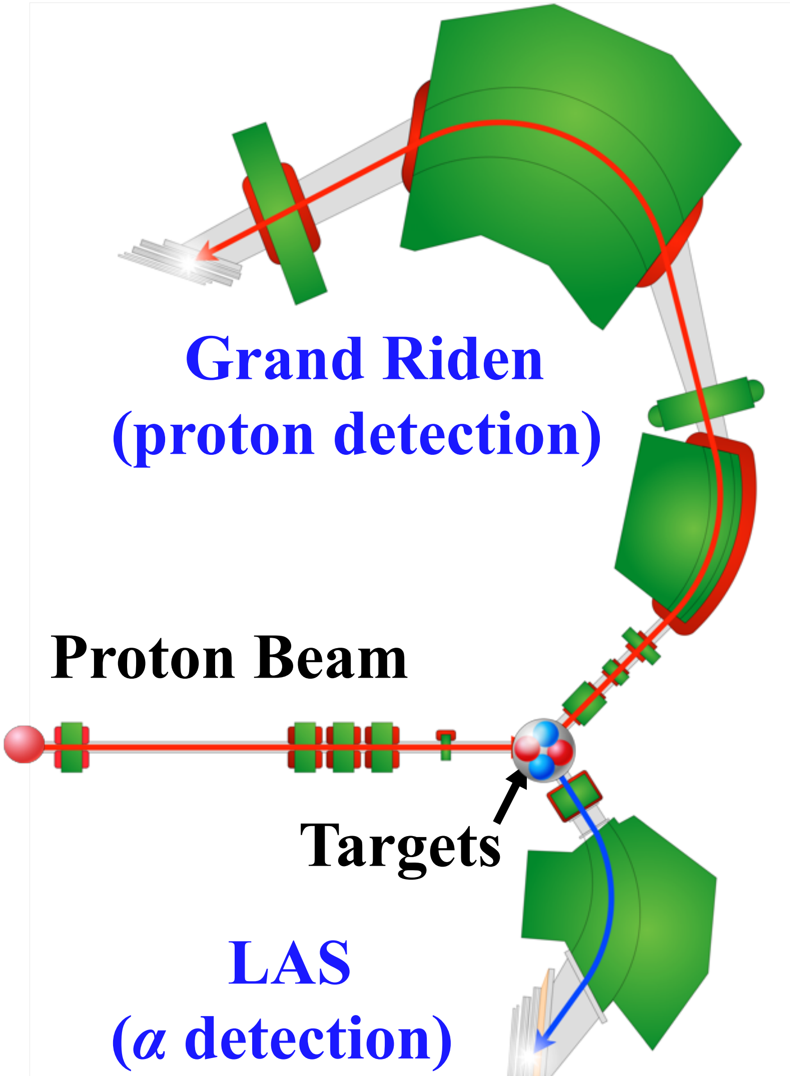
n-skin suppress α-cluster | **α cluster suppress n skin**

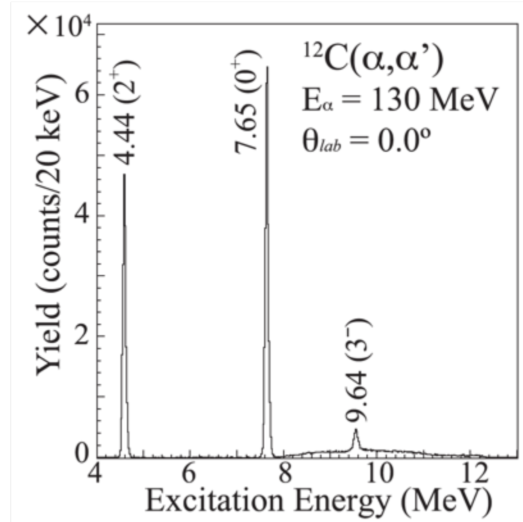




Direct measurement with quasi-free (p, pα)

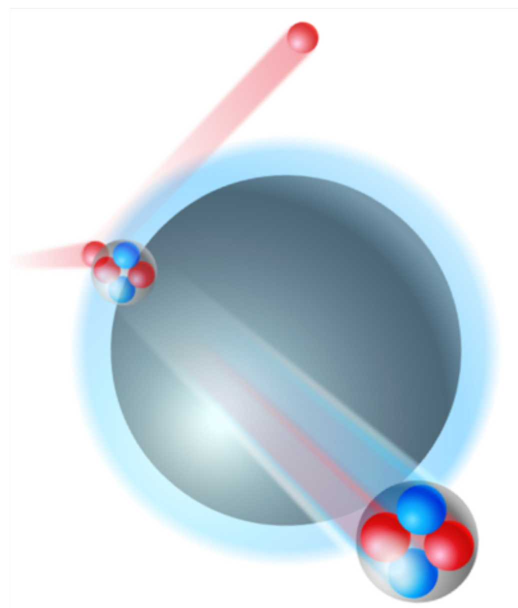
Quasi-free ($p,p\alpha$) at RCNP





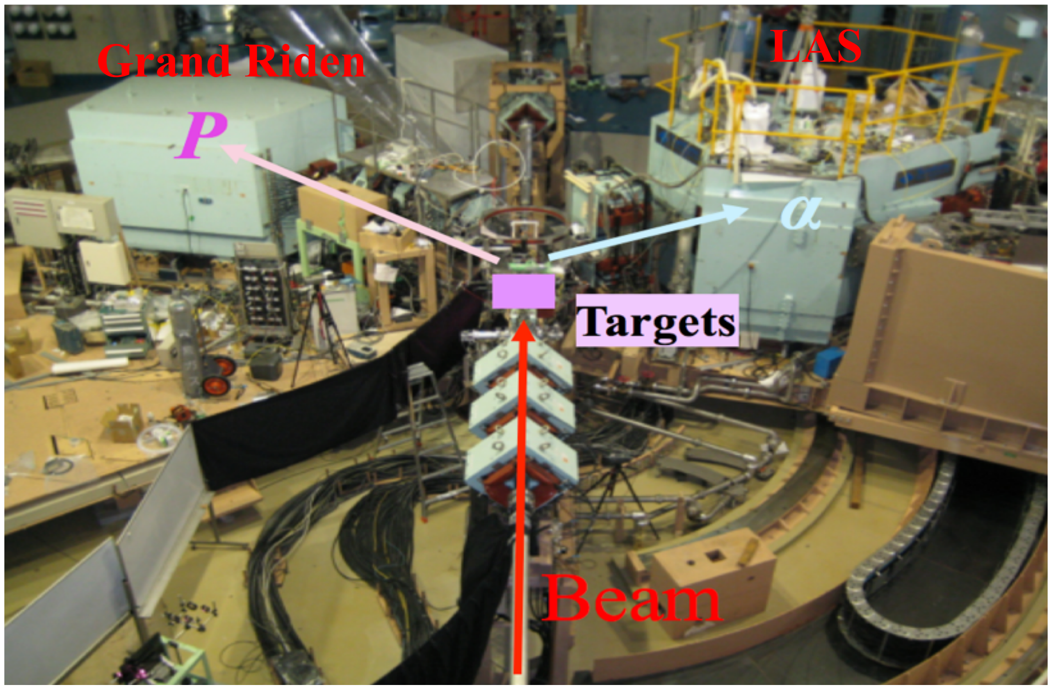
Adachi, PRC97(08)014601

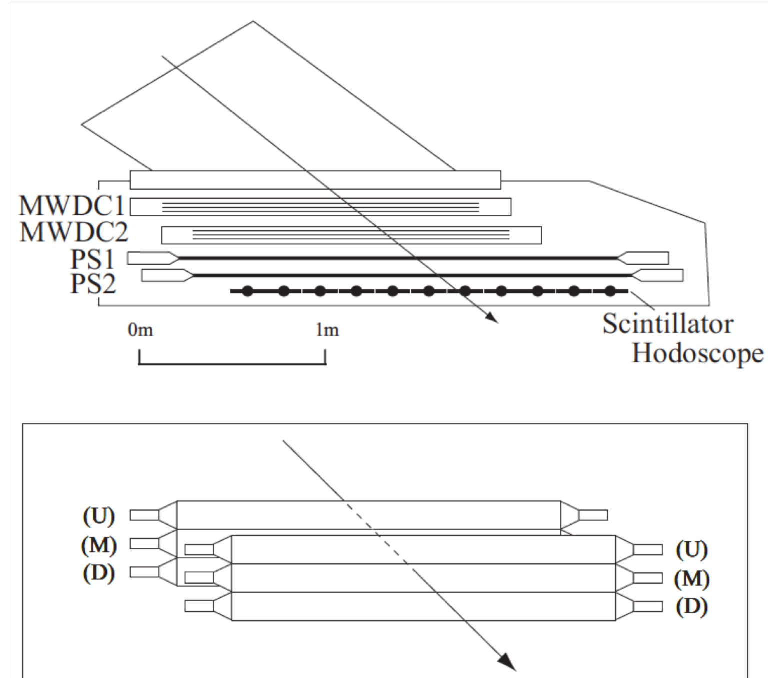
ΔE ~20 keV



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

- ✓ **Beam:** 392 MeV proton, ~100 pnA (halo-free)
- ✓ **Targets:** ^{112,116,120,124}Sn (~40 mg/cm^2)
- ✓ **Detectors:** Grand Riden (60°) + LAS (45.3°)





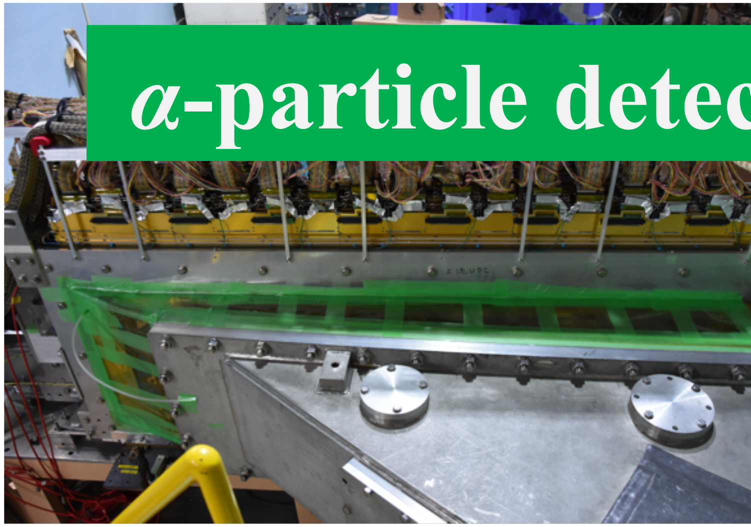
Sideview of the trigger scintillators .

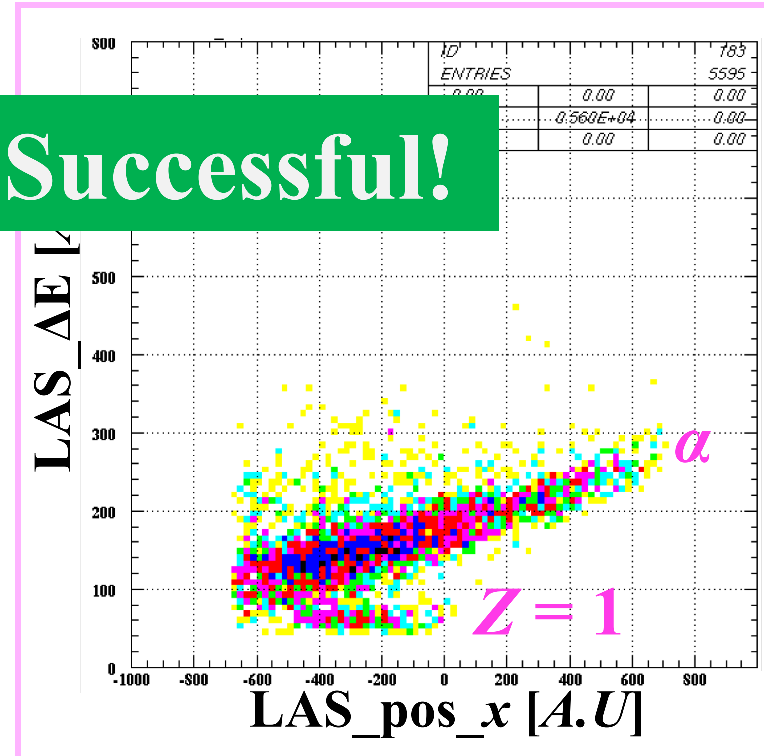
Main challenges:

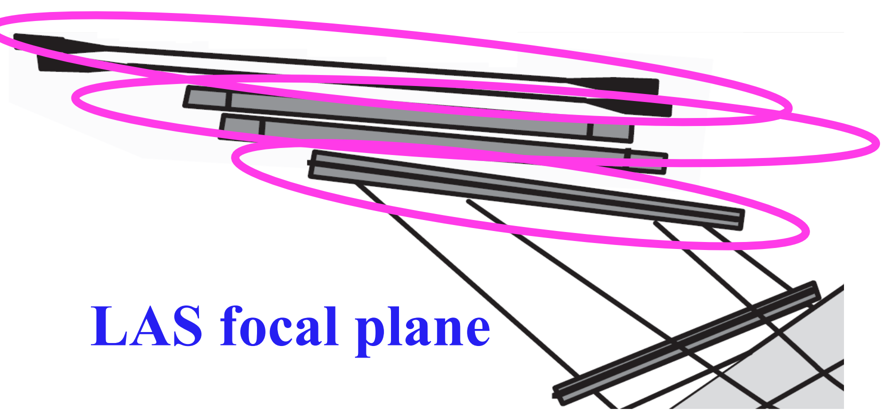
- ✷ **Small σ (~ pb).**
- ✷ **Detection of low-energy alpha particles (~ 50MeV).**

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

α-particle detection : Successful!







LAS focal plane

Physics run in 2018

"Window-less" helium-gas bag

Drift chambers (gas, HV)

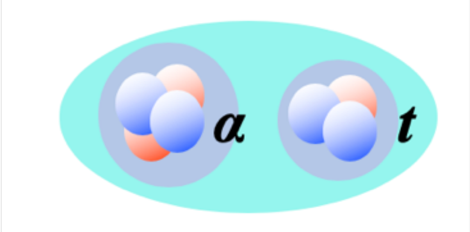
Trigger scintillators

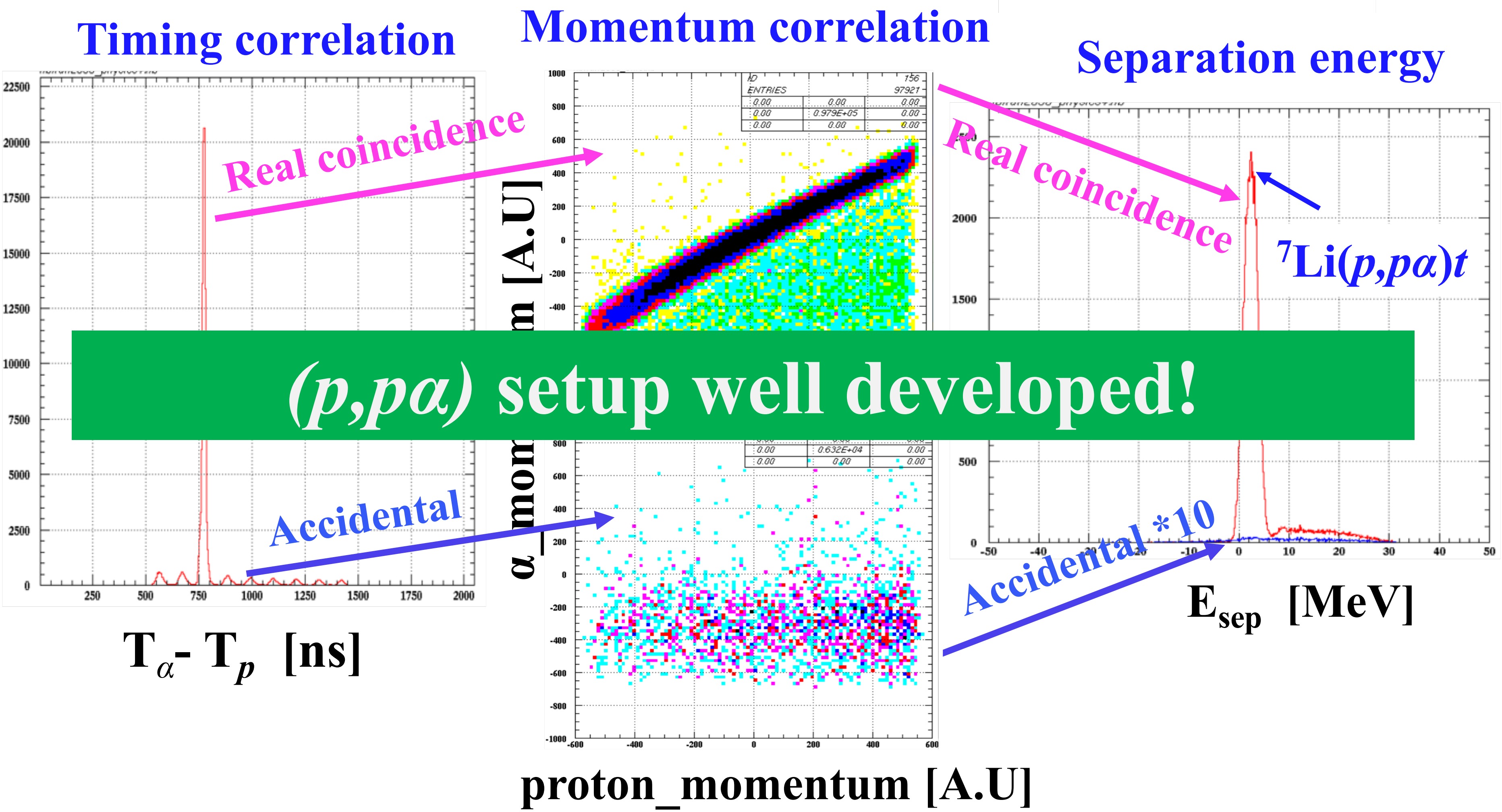
The exit flange

Project started in 2015

Proof-of-principle: ^{7}Li*(p,pα)*

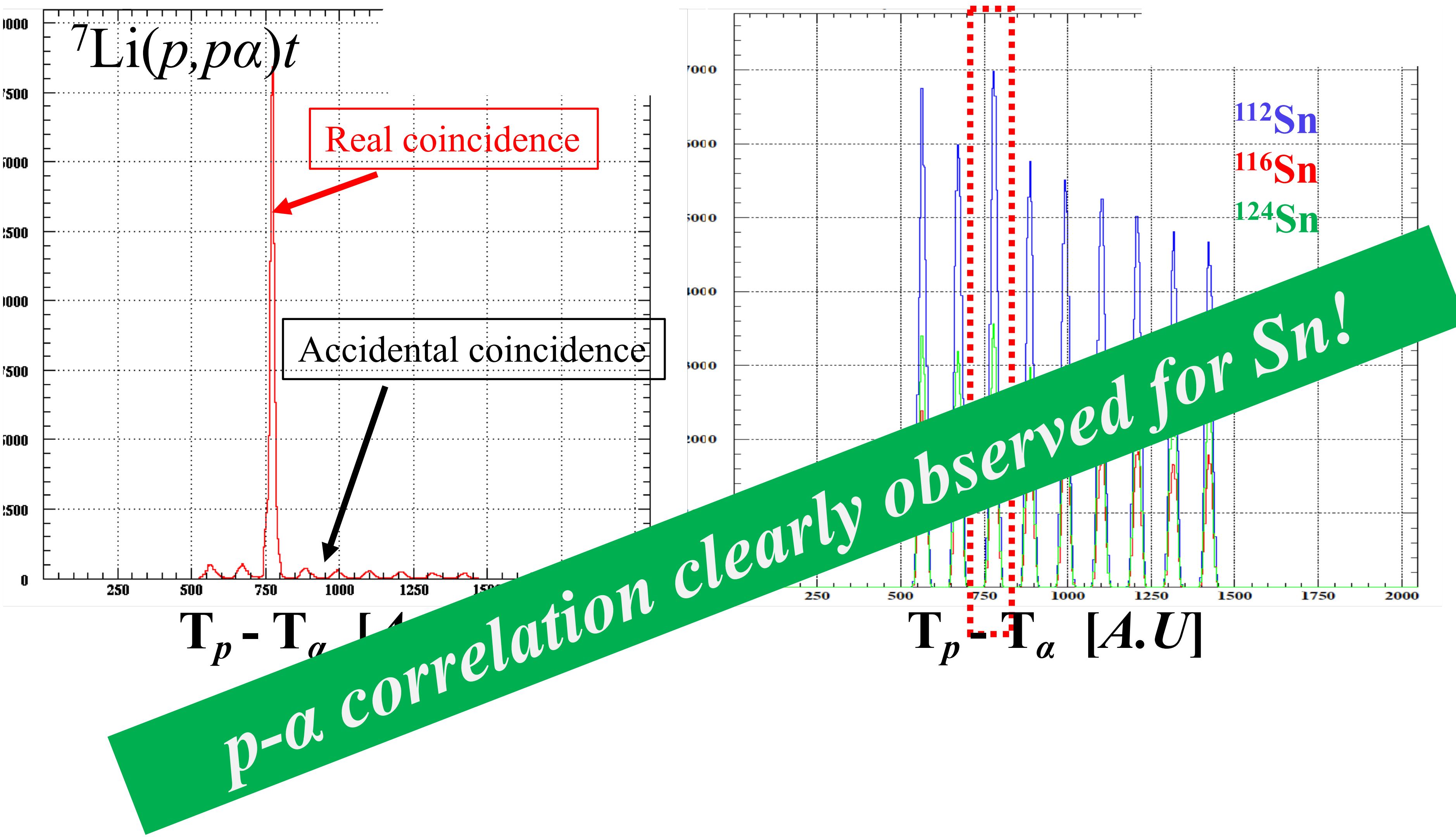
✓Measurement with ^{7}Li(*p,pα*)*t*





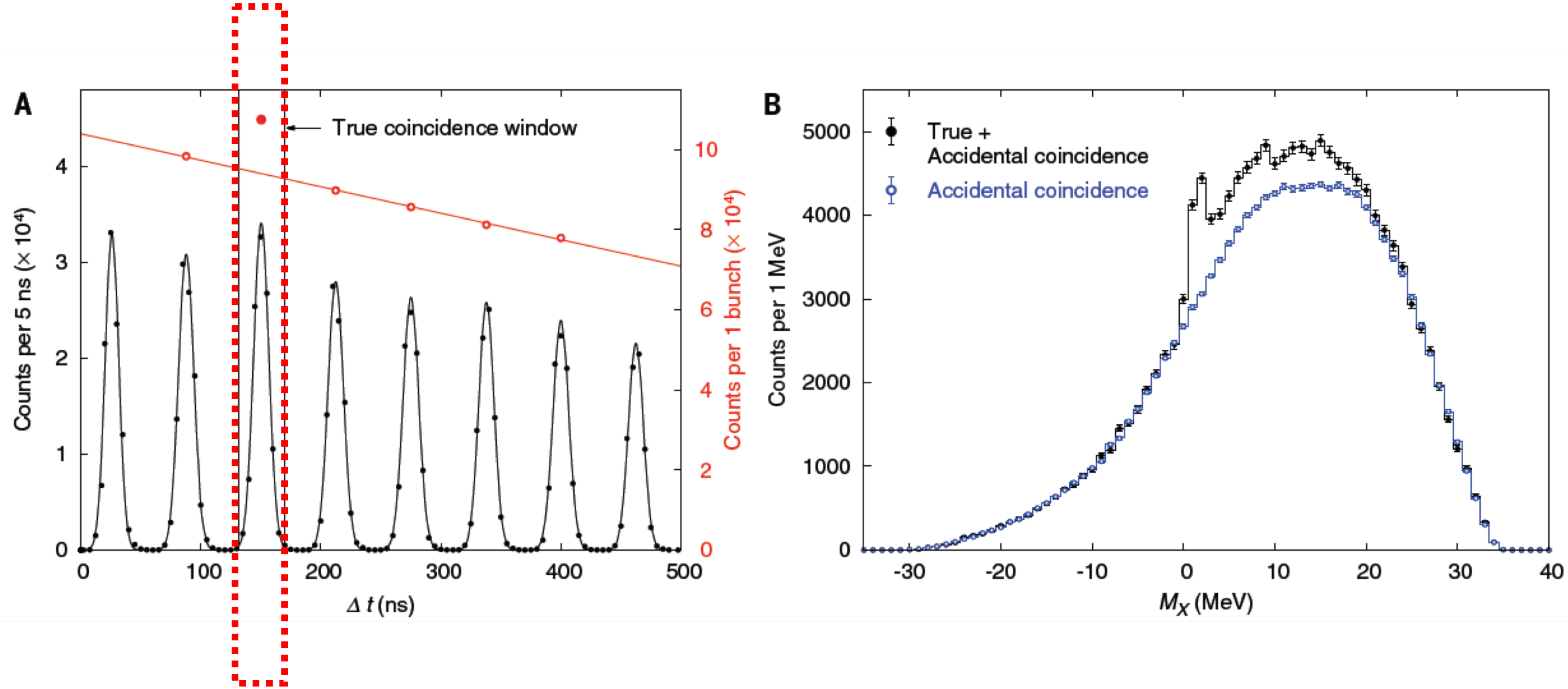
***(p,pα)* setup well developed!**

$(p,p\alpha)$ with $^{112,116,120,124}Sn$



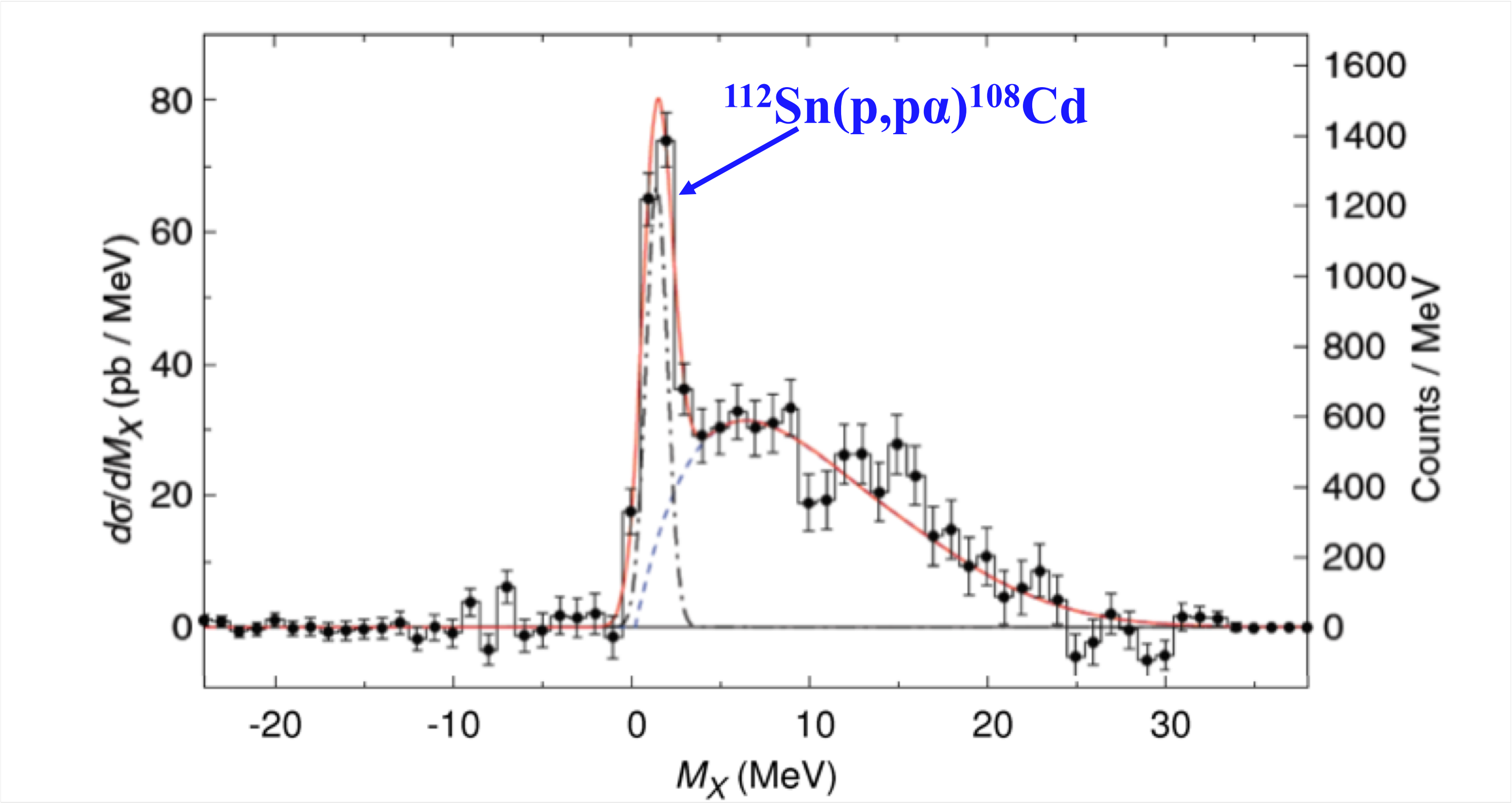
^{112}Sn(p,$p\alpha$) : Missing-mass spectrum

Missing-mass in (p,$p\alpha$): $M_X = E_{p0} - T_p - E_\alpha$



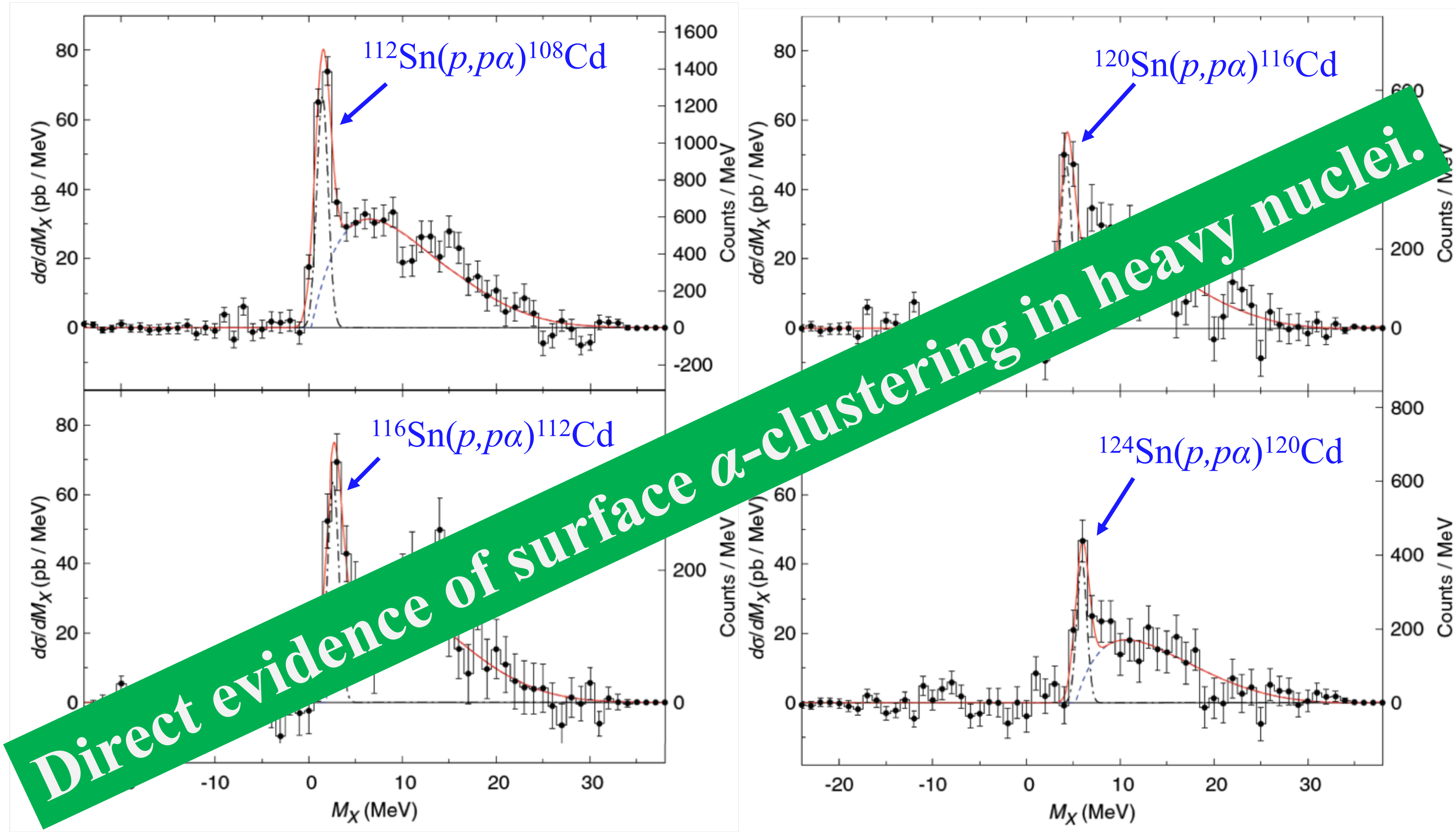
$^{112}Sn(p,p\alpha)$: Missing-mass spectrum

Missing-mass in $(p,p\alpha)$: $M_X = E_{p0} - T_p - E_\alpha$



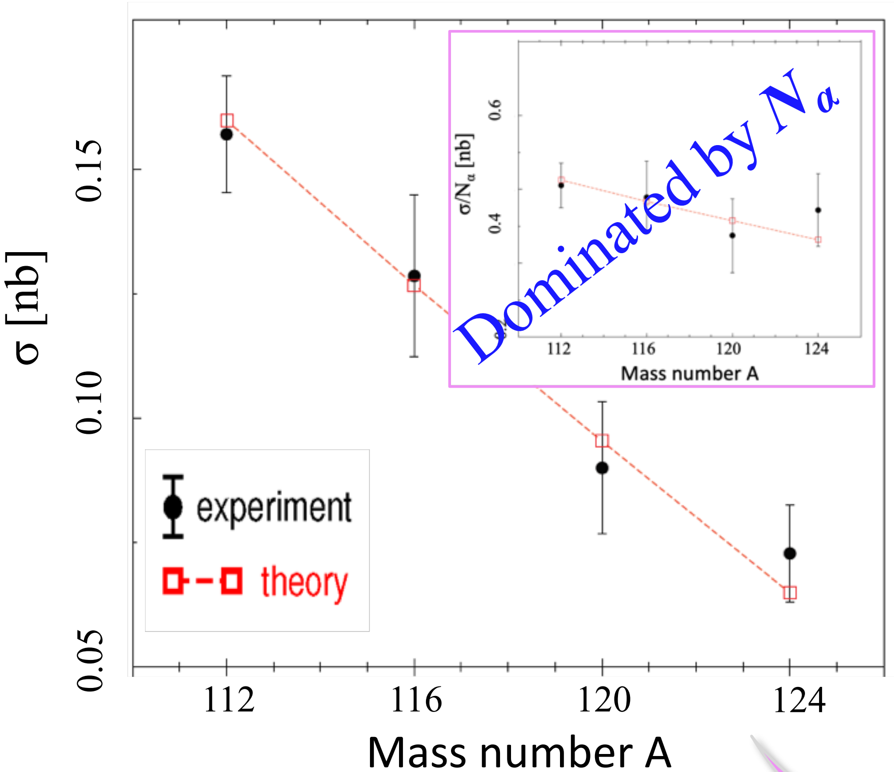
- ✓ "Accidental coincidence" subtracted.
- ✓ Fitted using a gaussian peak and the simulated continuum background

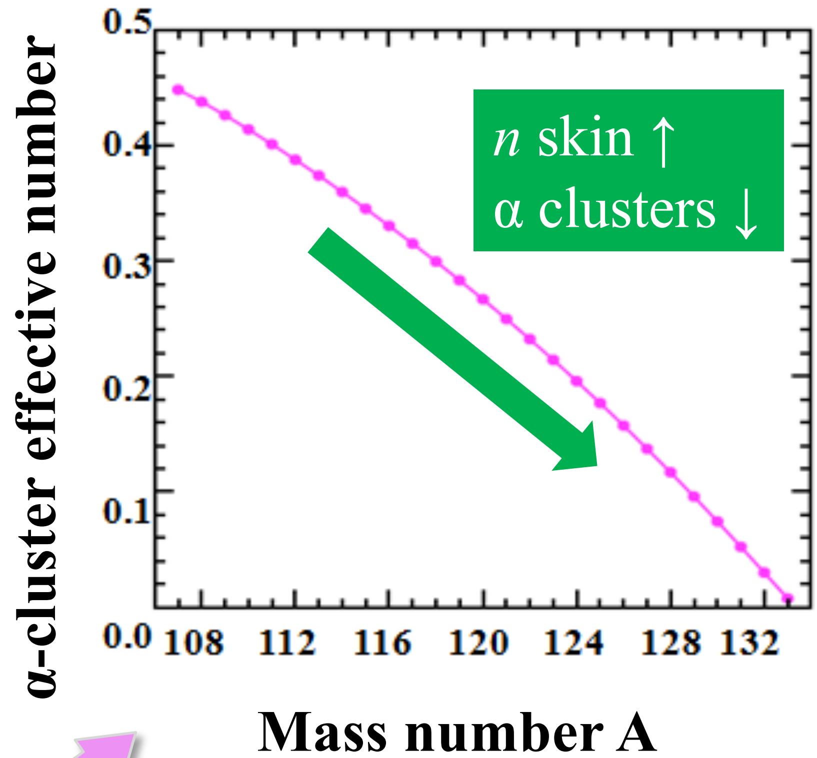
Result-1: α separation energy spectrum



✓ E_{sep} Peak clearly observed for each Sn isotope ^{112,116,120,124}Sn

Result-2: systematics of α-clustering

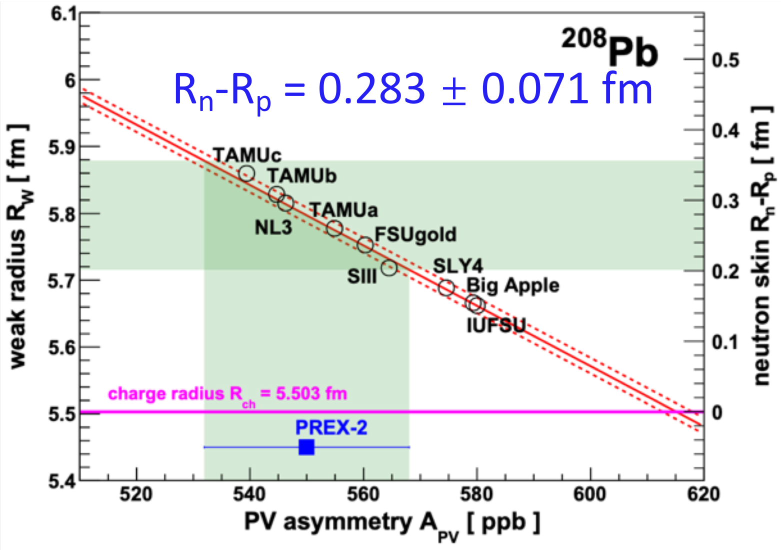


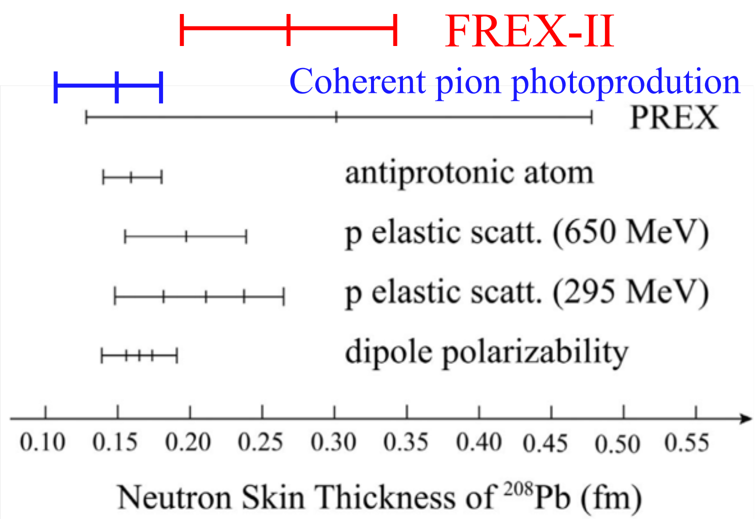


- ✓ Reaction Theory: Distorted-Wave Eikonal Approximation
  - ✓ α-cluster distribution from gRDF
  - ✓ Distortion effect considered
  - ✓ Realistic experimental conditions.

PREX-II: Where we are now?

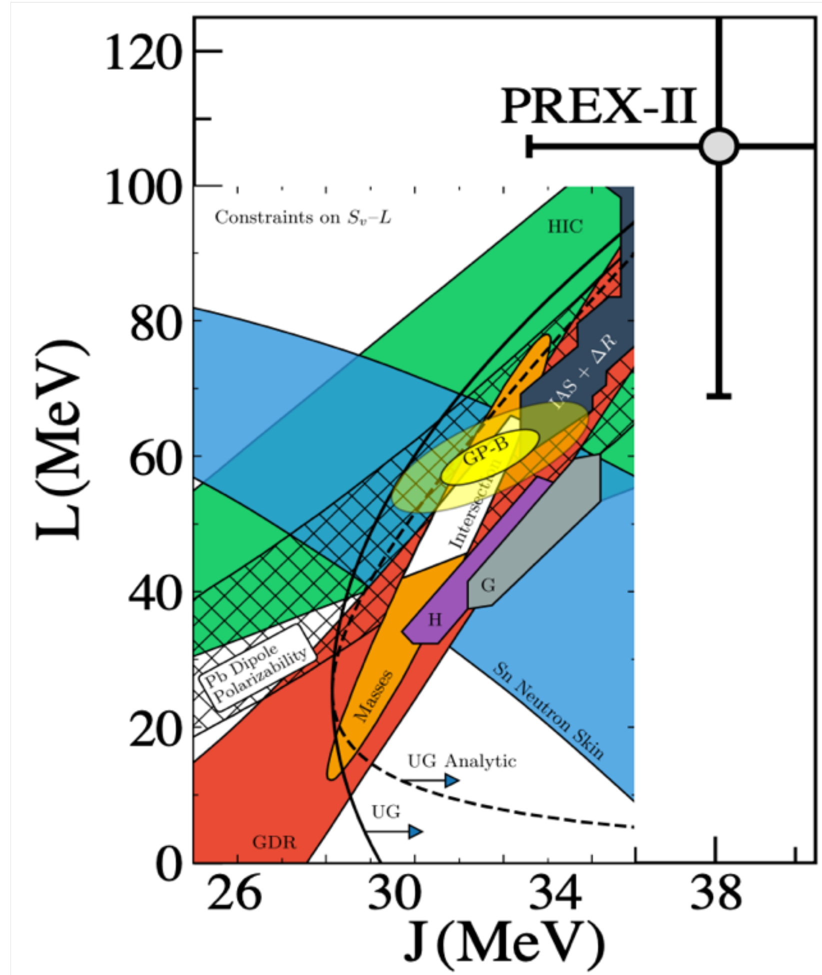
PREX collaboration PRL126,172502 (2021)





Tamii et al. EPJA 2014;Tarbert et al. PRL2014

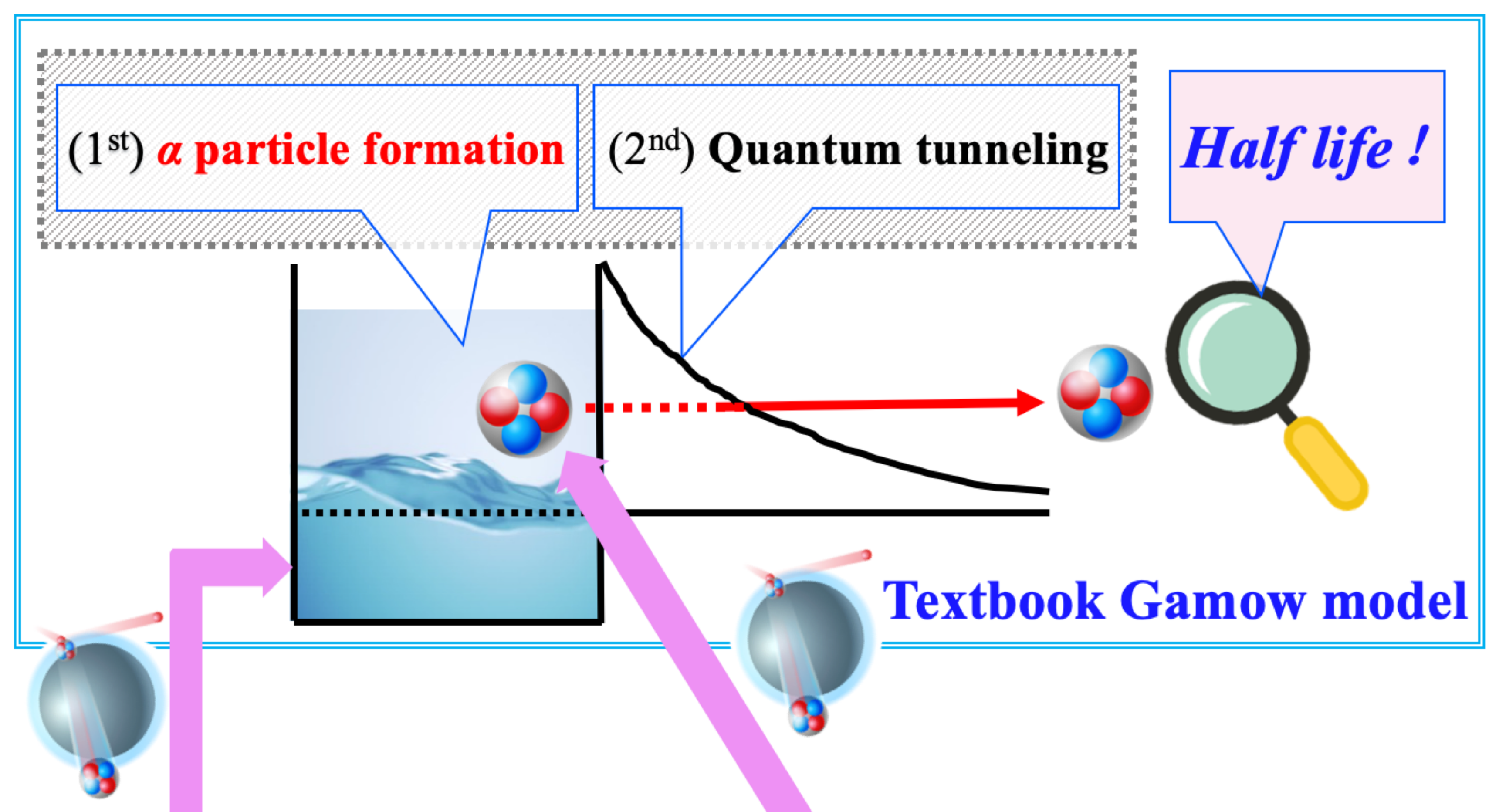
Reed,et al. arXiv:2101.03193v3



Estee et al. (SπRIT), PRL126,162701 (2021)

SπRIT: 42 < L <117 MeV

Nd/Sm(p,$p\alpha$)@RCNP: from α-clustering to α decay



Now: (p,$p\alpha$) with α-bound Sn

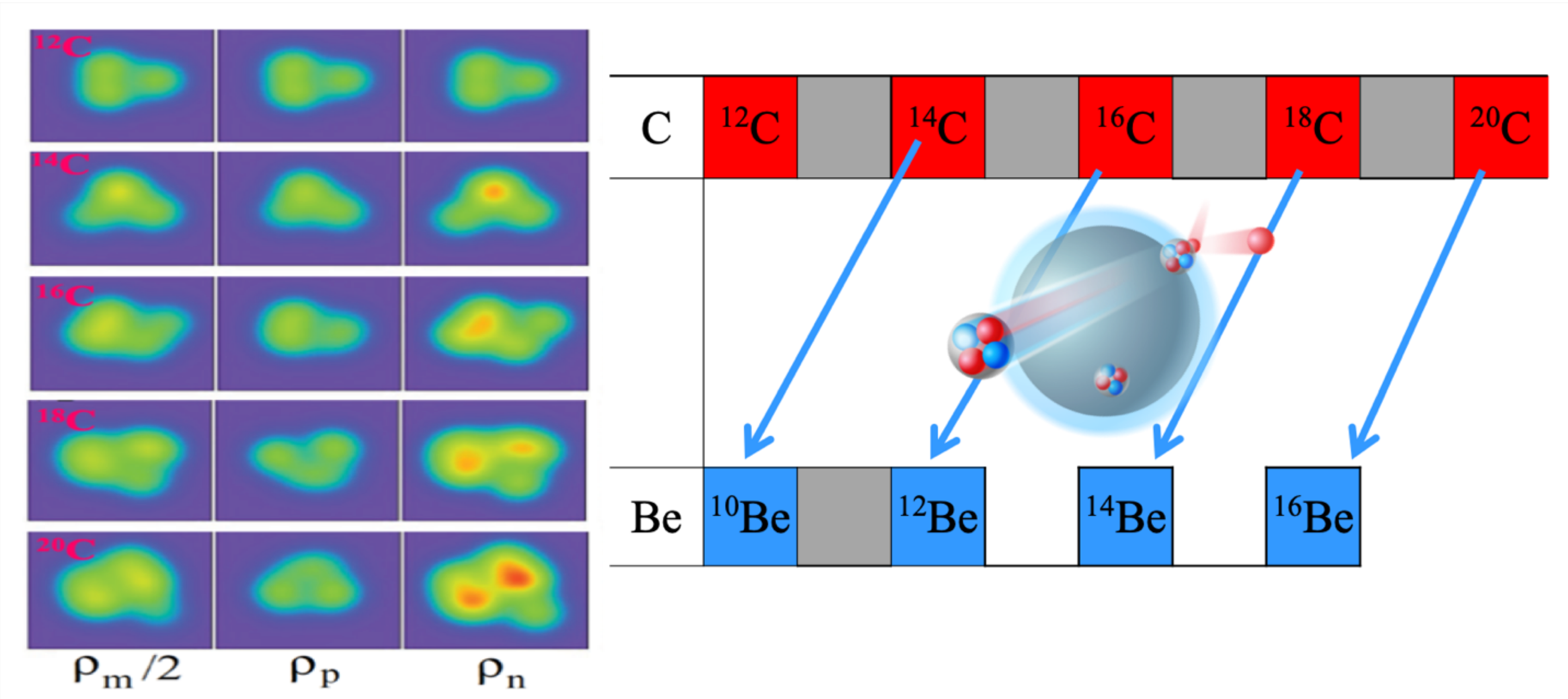
✓ **α-lcuster formation evidenced!**

Next: (p,$p\alpha$) with α-emitting nuclei

✓ Long lived (stable) Nd and Sm isotopes (Yang et al., already approved)

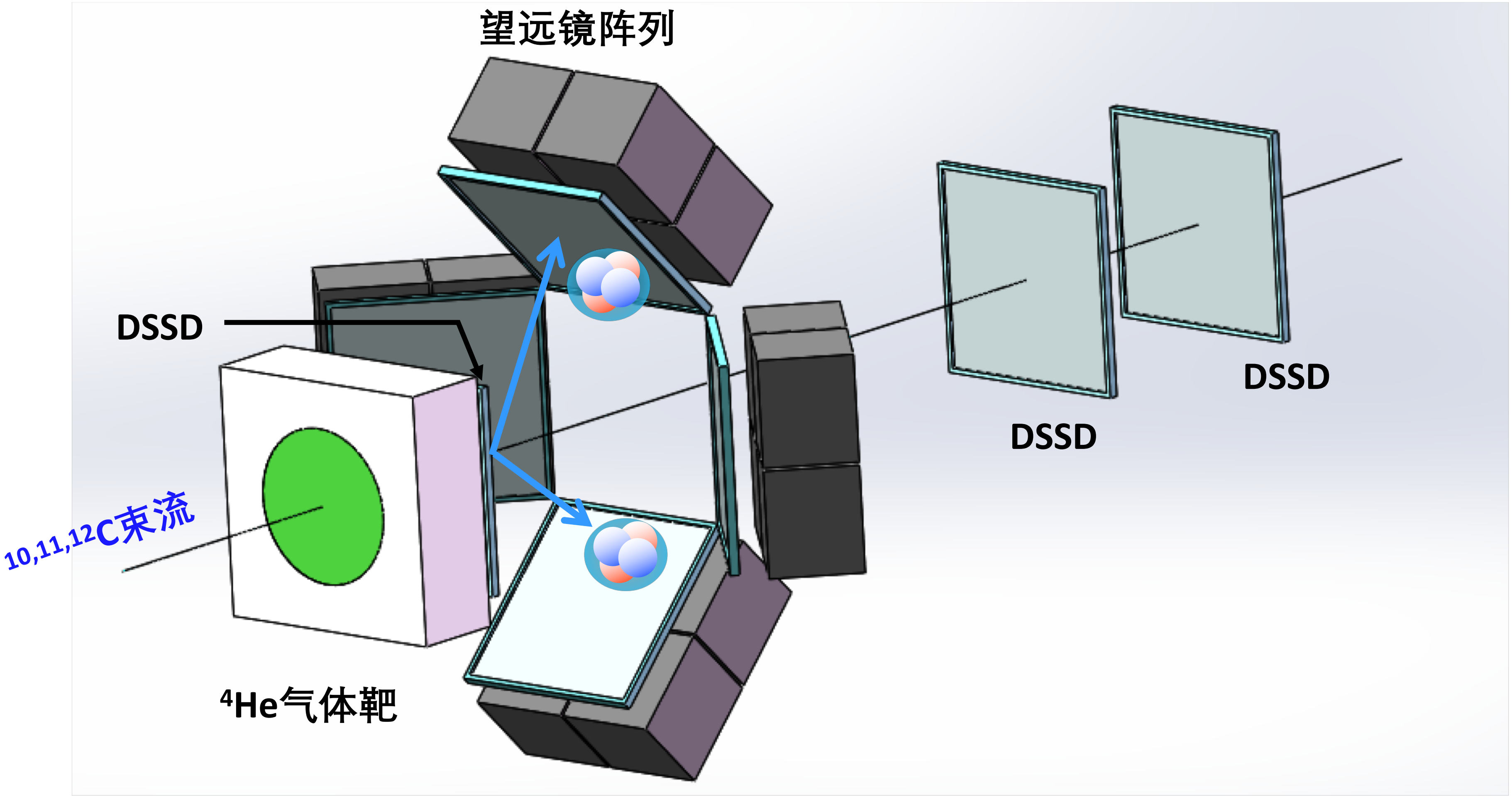
$^{12-20}$C(p,$p\alpha$) at RIBF (Yang *et al.*, approved)

- ✓ Rich cluster structures in C isotopes
- ✓ Measurement at RIBF in inverse kinematics



***α*-cluster formation in (extremely) neutron-rich systems.**

$^{10,11,12}C(\alpha,2\alpha)$ at RIBLL1(Yang, Ye, Ong *et al.*)



Acknowledgement to collaborators

Science Contents News Careers Journals

REPORT

Formation of α clusters in dilute neutron-rich matter

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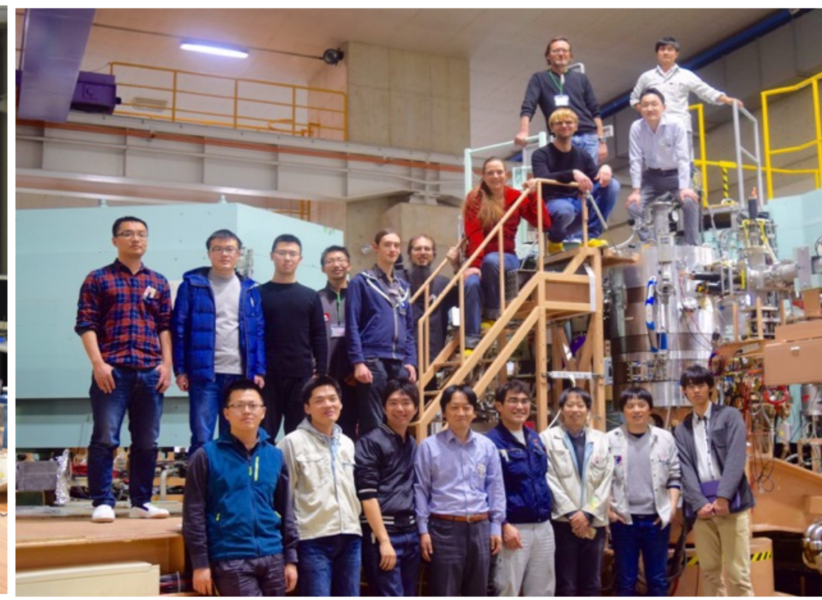

Thanks for your attention!