

# A wonderworld of atomic nuclei: from tiny to infinity

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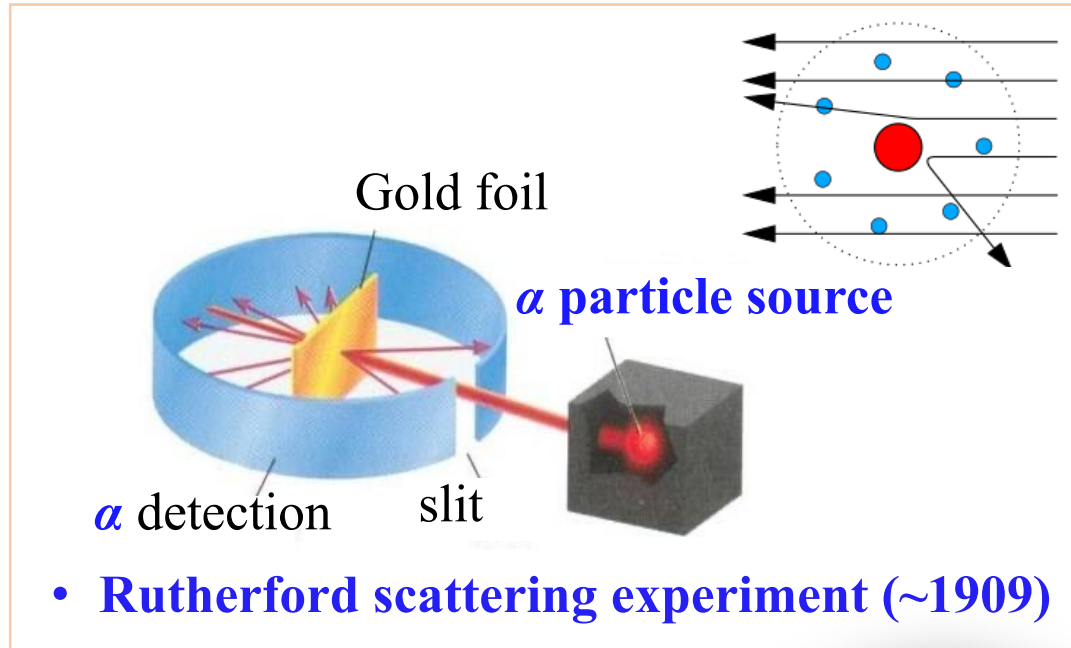
# Outline

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- ✓ **Introduction: basics about the structure of nucleus**
- ✓ **Clustering in nuclear systems**
- ✓ **Halo and neutron correlations**
- ✓ **Summary and Perspective**



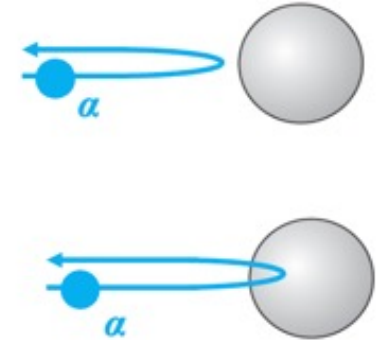
# The heart of atom: Atomic Nucleus



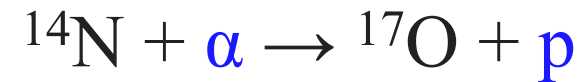
“Measure” the size of nucleus

Head-on collision  
→ closest distance  $r_d$

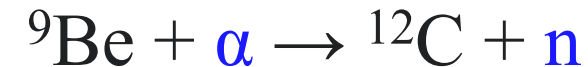
$$E_k = \frac{1}{2} m_\alpha v^2 = \frac{e^2}{4\pi\epsilon_0} \frac{Z_\alpha Z}{r_d}$$



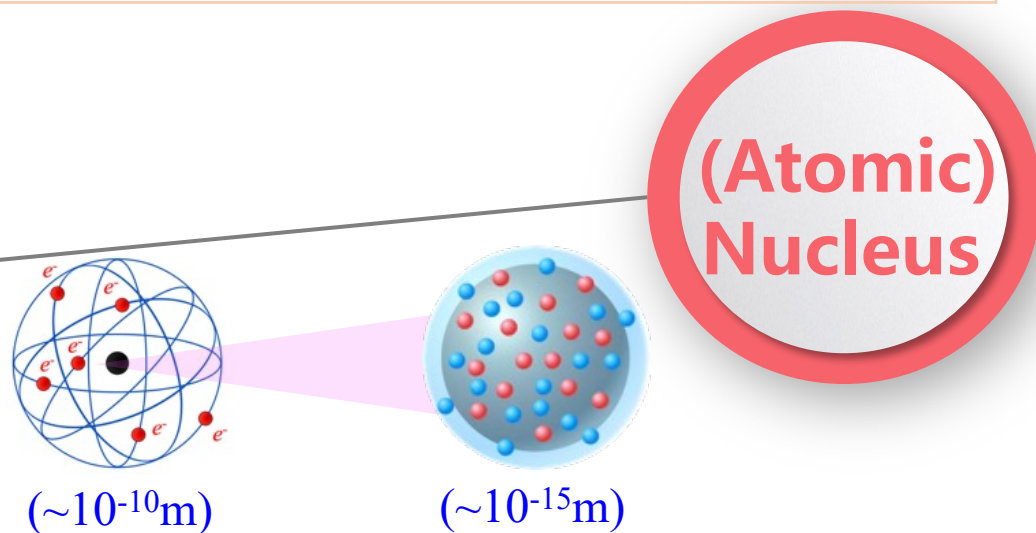
Discovery of proton (Rutherford, 1914)



Discovery of neutron (Chadwick, 1932)

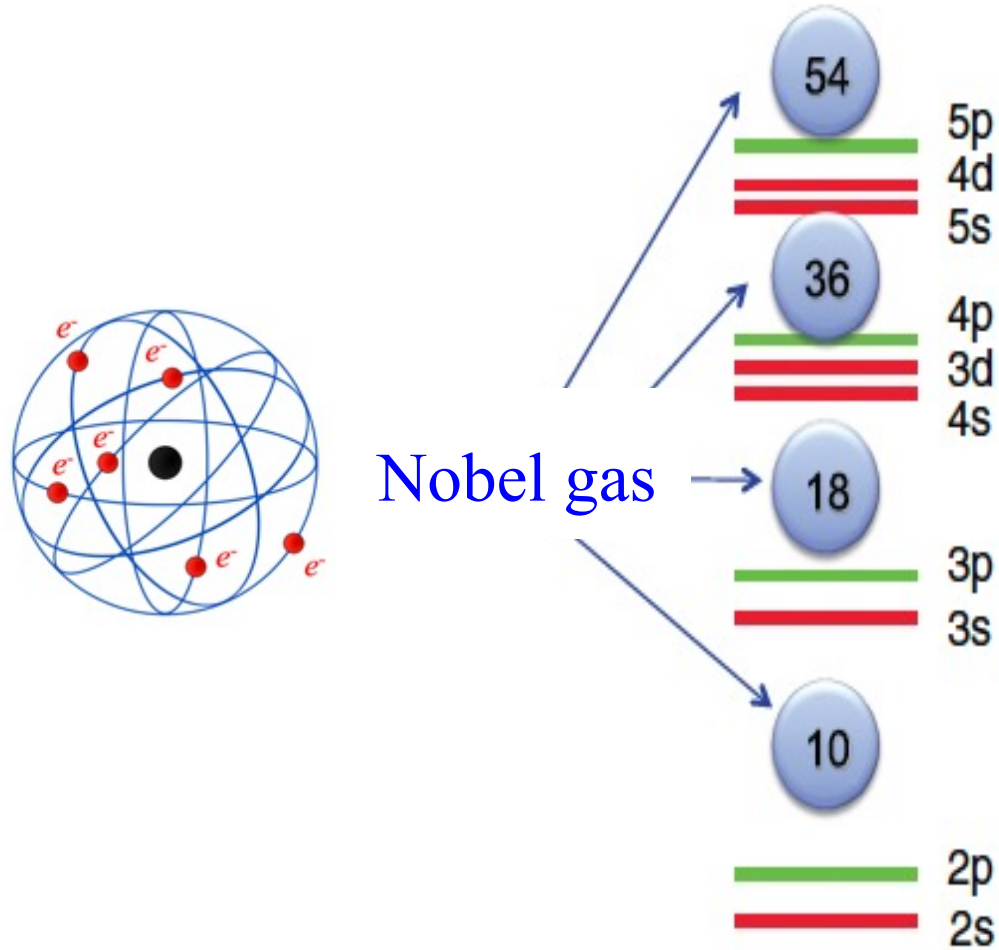


Nuclear reaction as a probe for nuclear structure

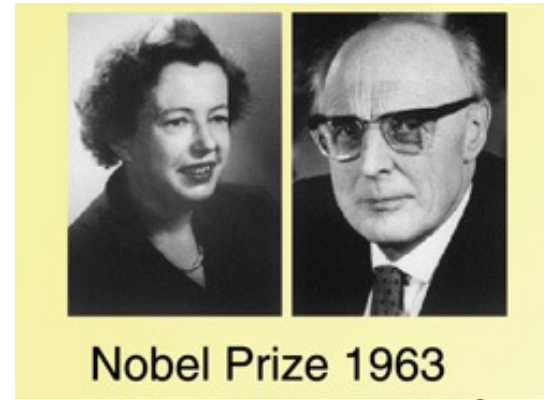


# What is the structure of the nucleus?

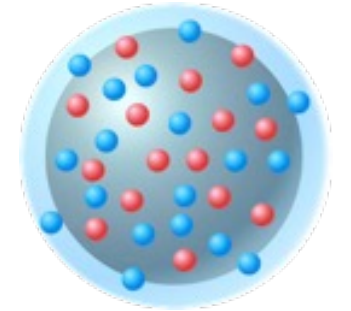
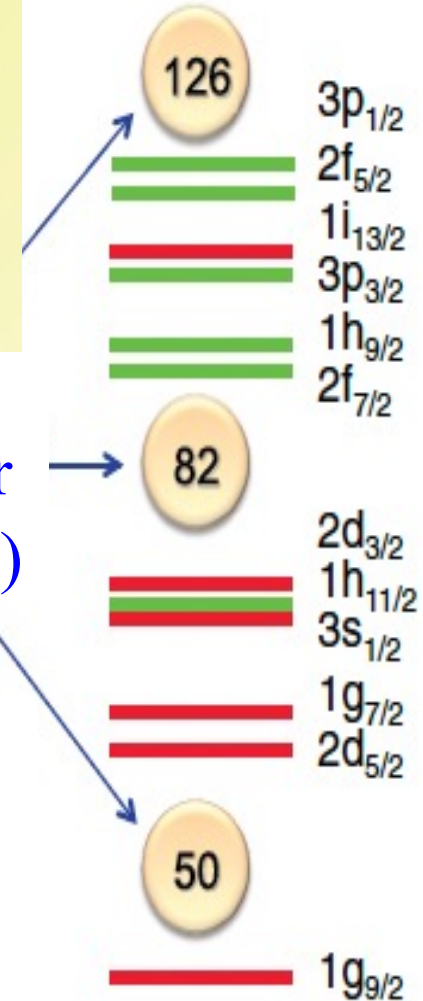
## Shell structure of atom



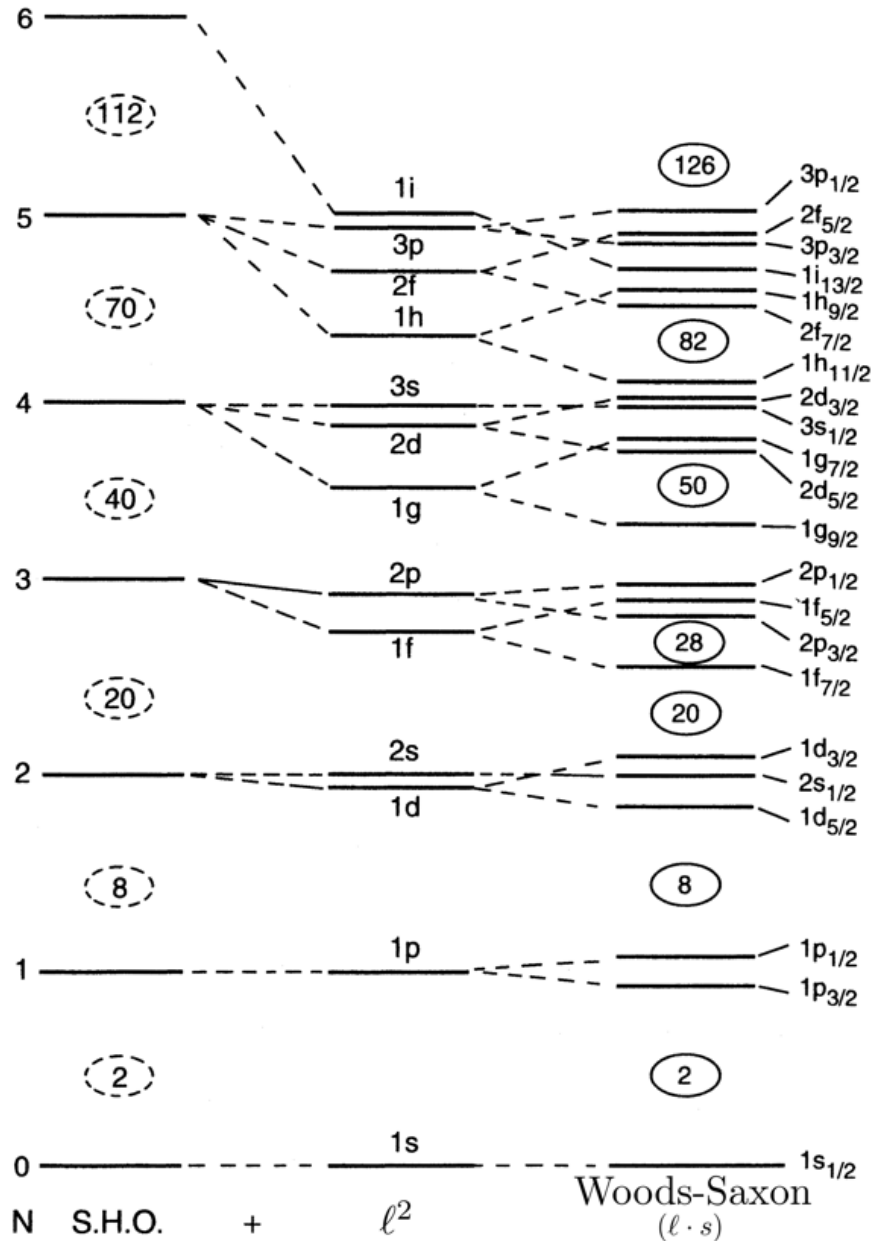
## Shell structure of nucleus



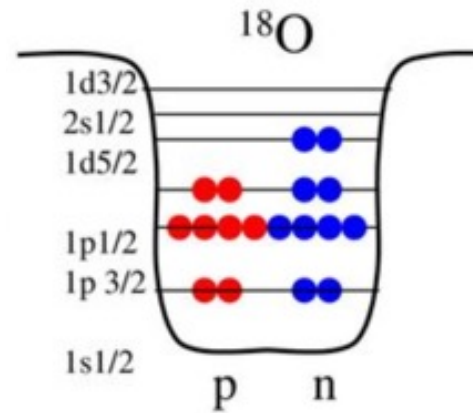
Magic number  
(幻数/魔法数)



# Single-particle levels and shell structure

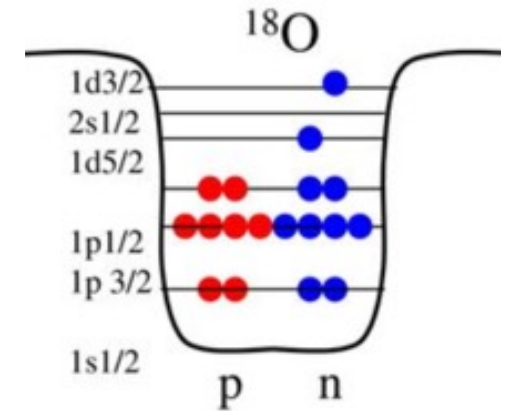


Ground state

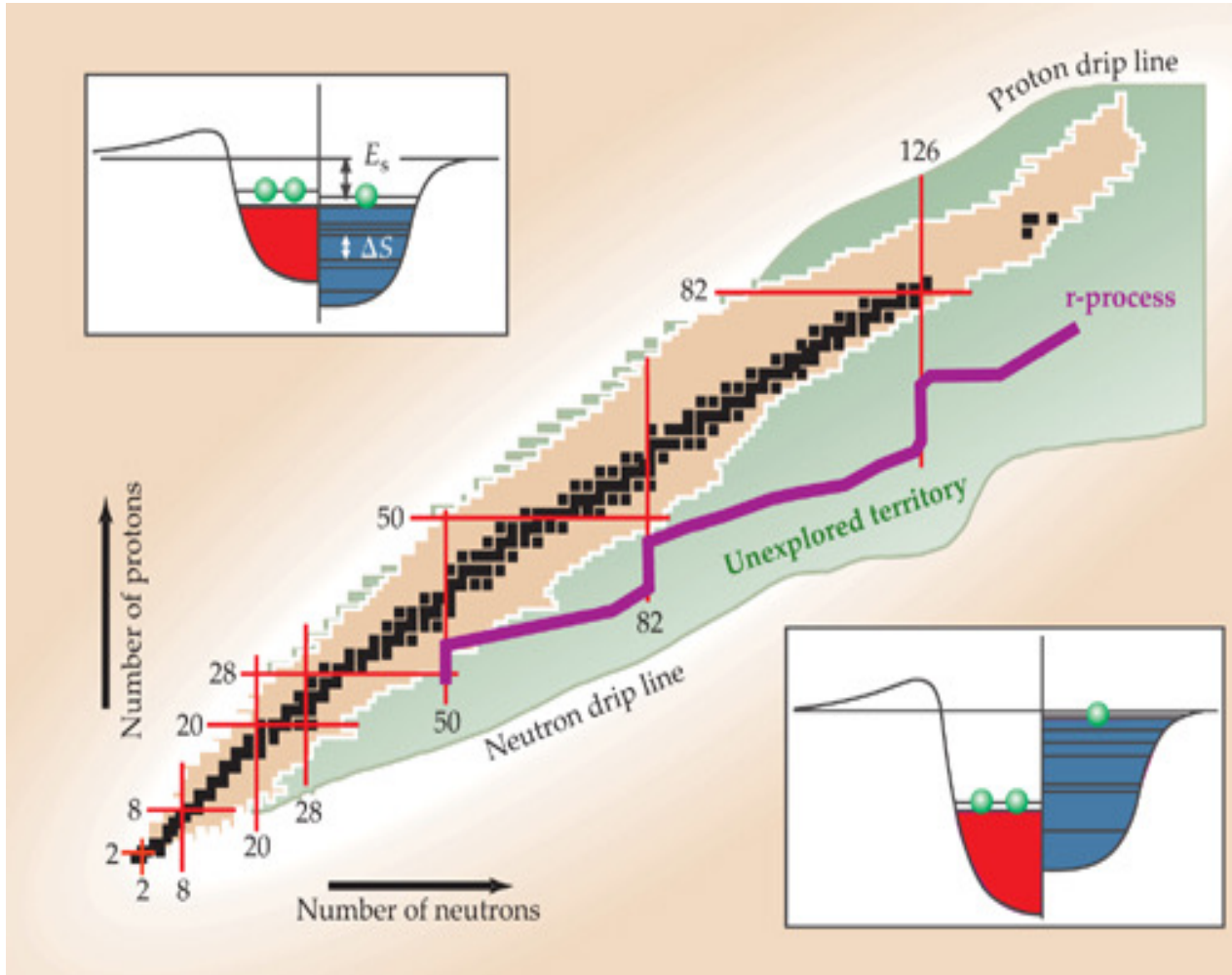


Excitation

Excited state

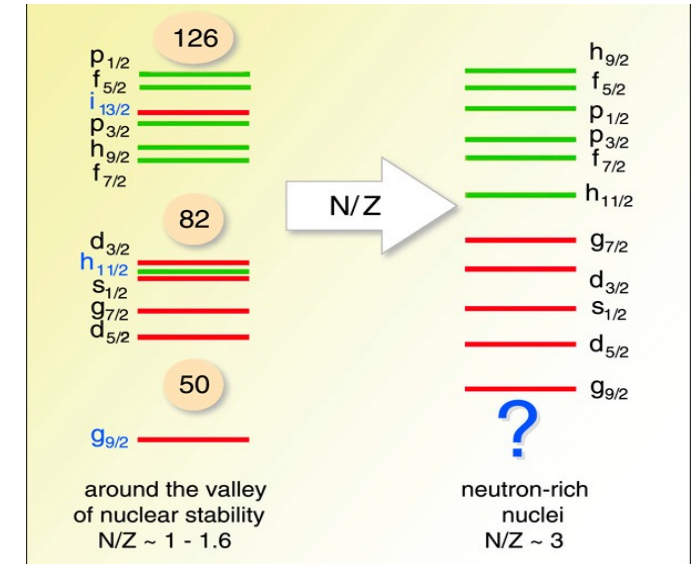


# Evolution of the shell structure and new magic numbers

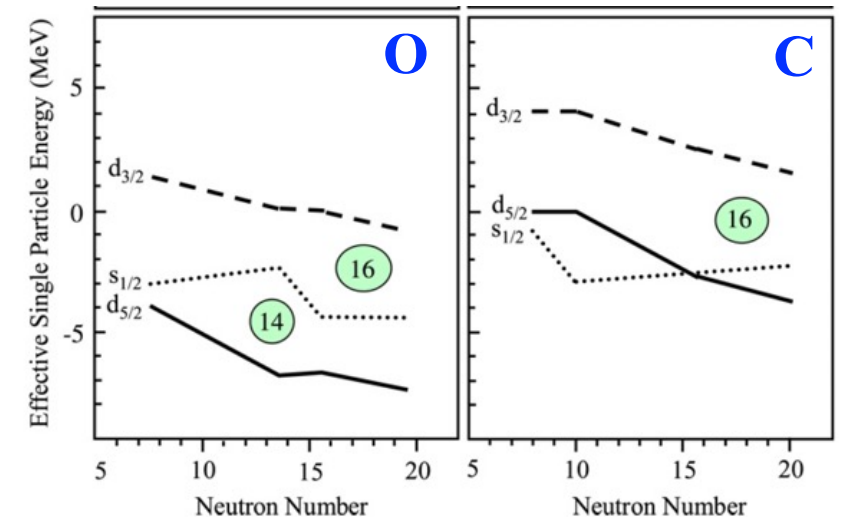


- ✓ Change of density distribution
- ✓ Continuum coupling (from closed- to open-quantum systems)
- ✓ ...

*Otsuka et al. RMP92(20)015002*



*Sorlin et al. PPNP 61(2008)602*

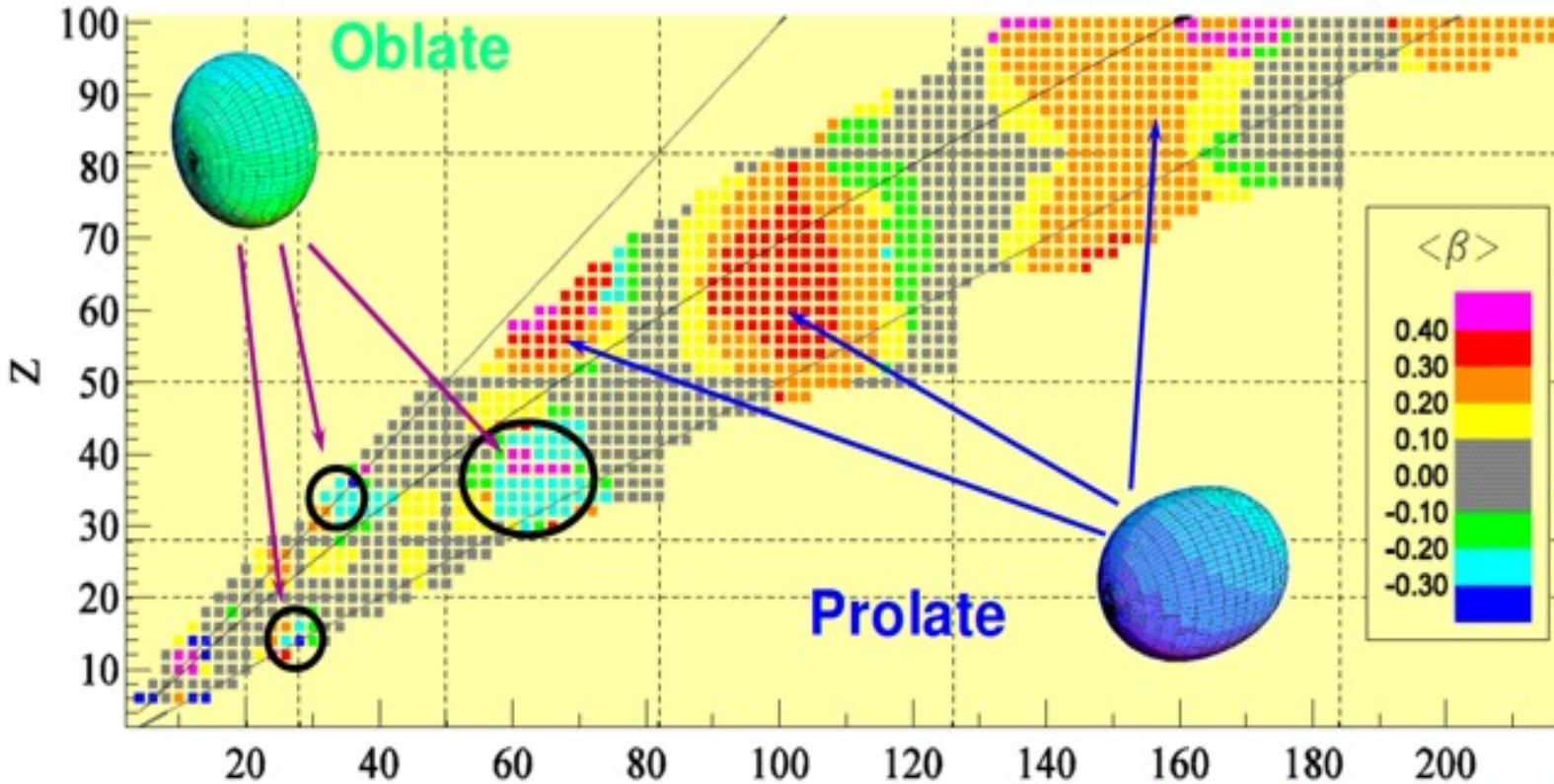
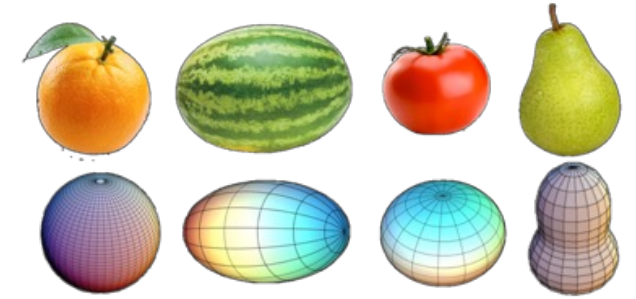


# Shapes and Collective excitation

- ✓ Description of “shape”:

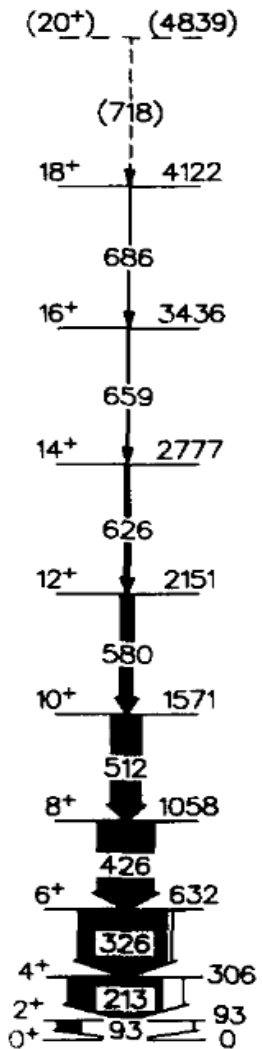
$$R(\theta, \phi) = R_0 \left[ 1 + \sum_{\lambda=0}^{\infty} \sum_{\mu=-\lambda}^{\lambda} a_{\lambda, \mu} Y_{\lambda \mu}(\theta, \phi) \right]$$

- ✓ Nuclei are not always spherical.





# Rotations of deformed nuclei



✓ Check the  $E_x$  systematics

- Experimental data

$J^\pi$	0 <sup>+</sup>	2 <sup>+</sup>	4 <sup>+</sup>	6 <sup>+</sup>	8 <sup>+</sup>
$E_x$ (keV)	0	93.2	306.6	632.2	1058.6
$E_{J^\pi}/E_{2^+}$	0.00	1.00	3.29	6.78	11.36

- Predictions of a simple rotor model:  $E_x \sim J(J + 1) \frac{\hbar^2}{2I}$

$J^\pi$	0 <sup>+</sup>	2 <sup>+</sup>	4 <sup>+</sup>	6 <sup>+</sup>	8 <sup>+</sup>
$E_x$ (keV)	0	$6 \frac{\hbar^2}{2I}$	$20 \frac{\hbar^2}{2I}$	$42 \frac{\hbar^2}{2I}$	$72 \frac{\hbar^2}{2I}$
$E_{J^\pi}/E_{2^+}$	0.00	1.00	3.33	7.00	12.00

$$E_{4^+}/E_{2^+} = 3.33 \text{ for a rotor}$$

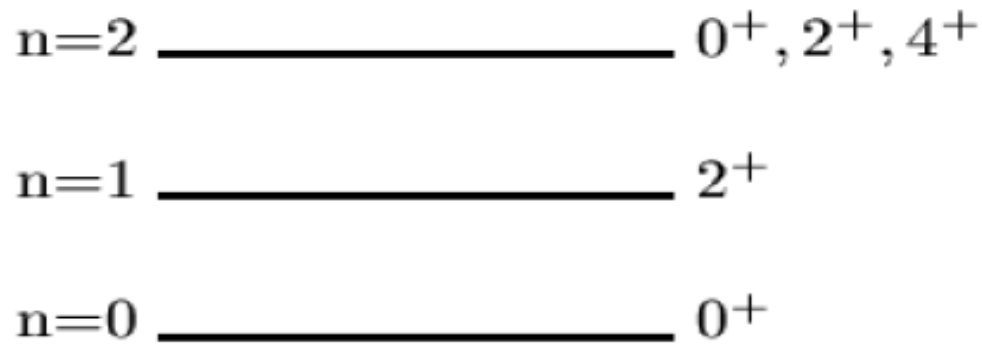


Mullins et al.  
PLB393(97)279

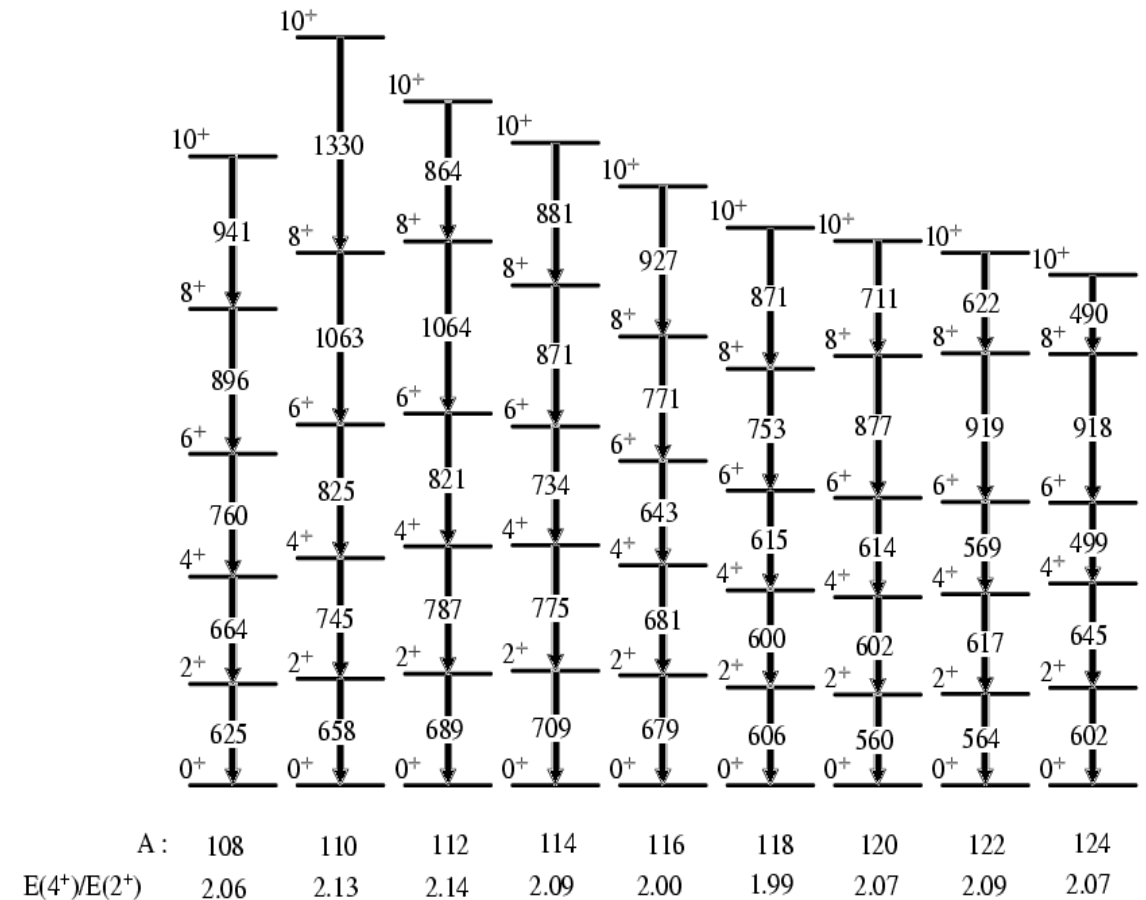
# Vibrations of (nearly) spherical nuclei

- ✓ Excitation energy described by **phonons**

$E_{4+}/E_{2+} = 2$  for vibrator

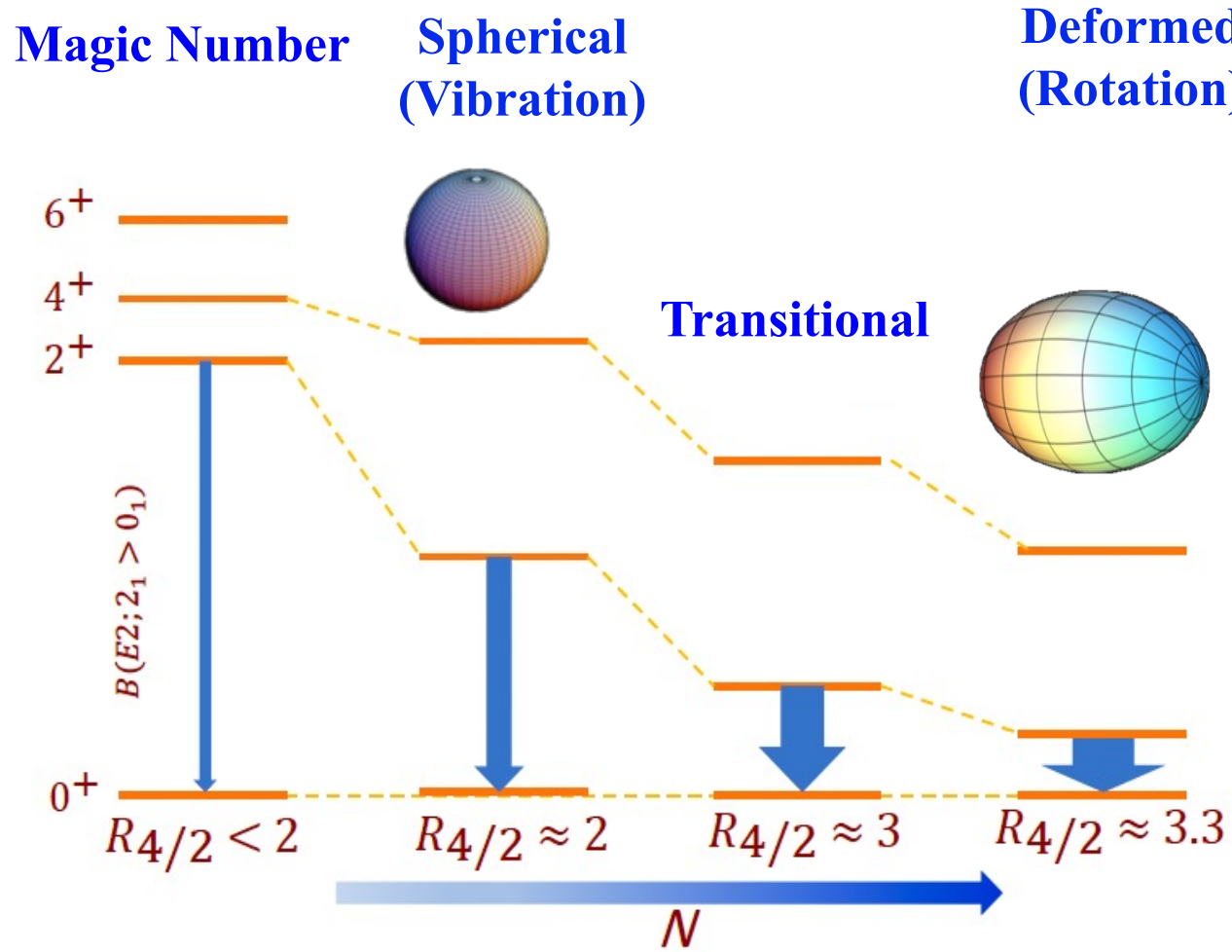


Te Isotopes (Z=52)

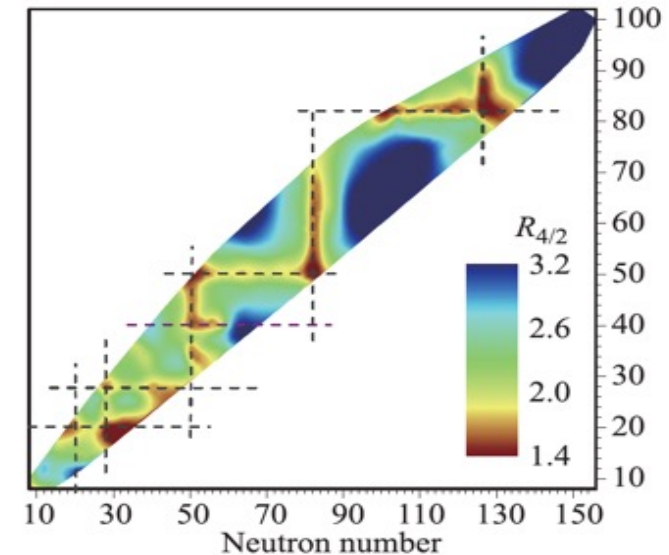
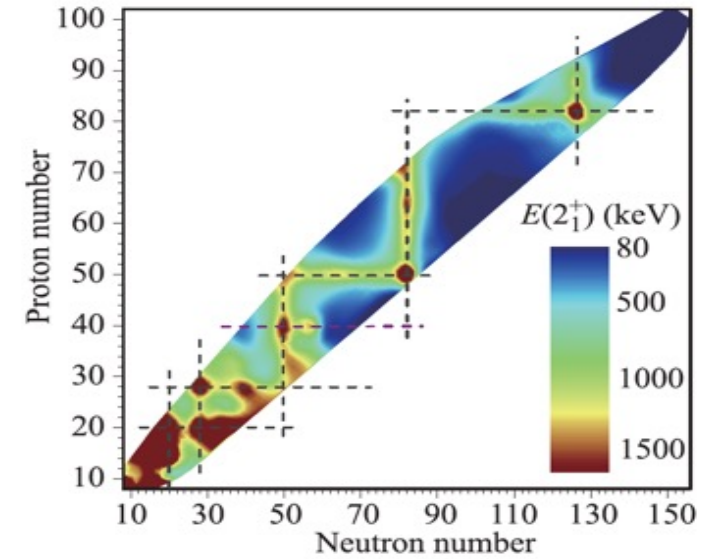


# Evolution of shell structure and shape

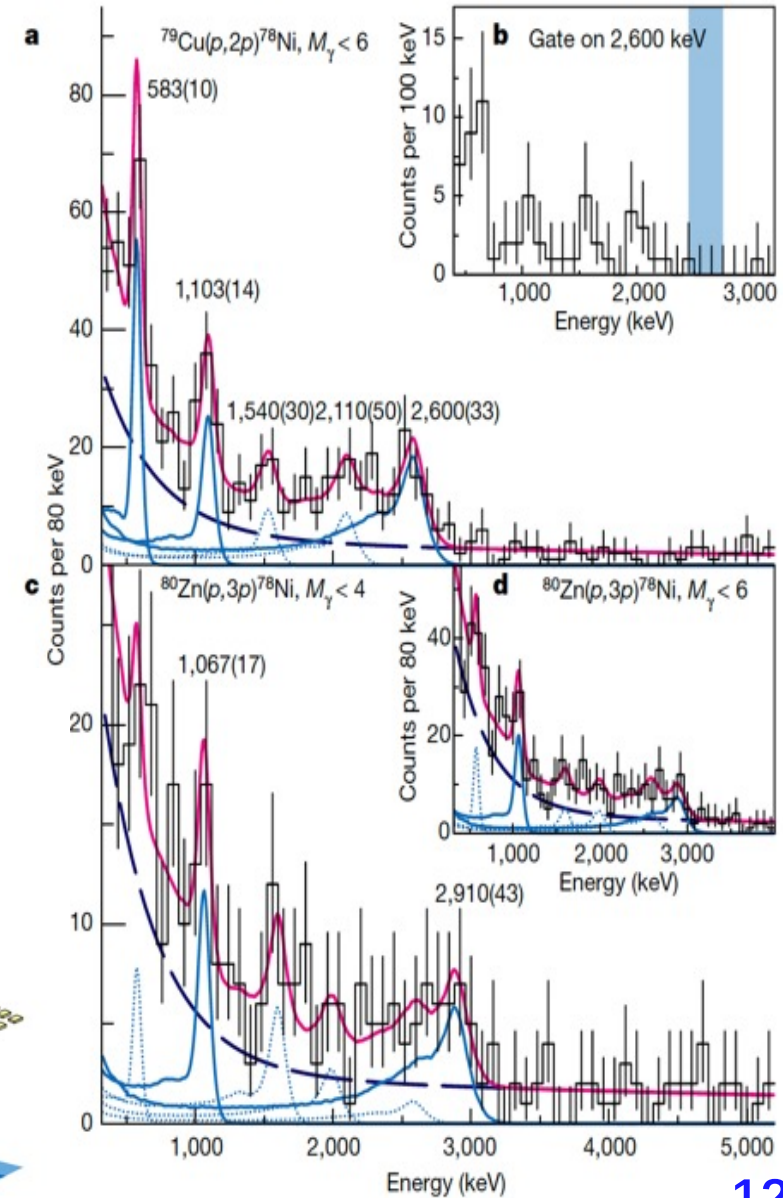
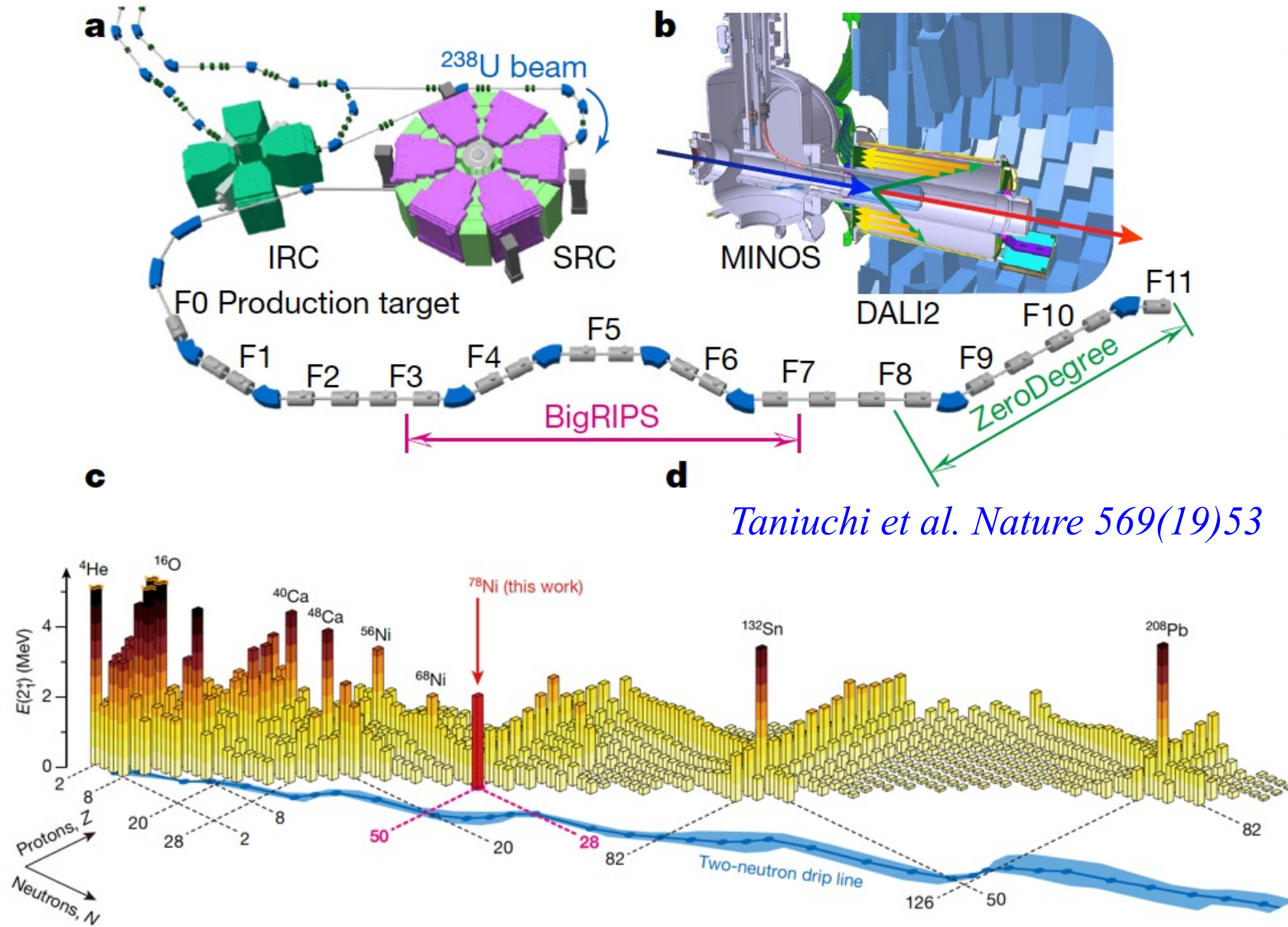
*R. F. Casten. Frontiers of Physics, 13(2018)132104*



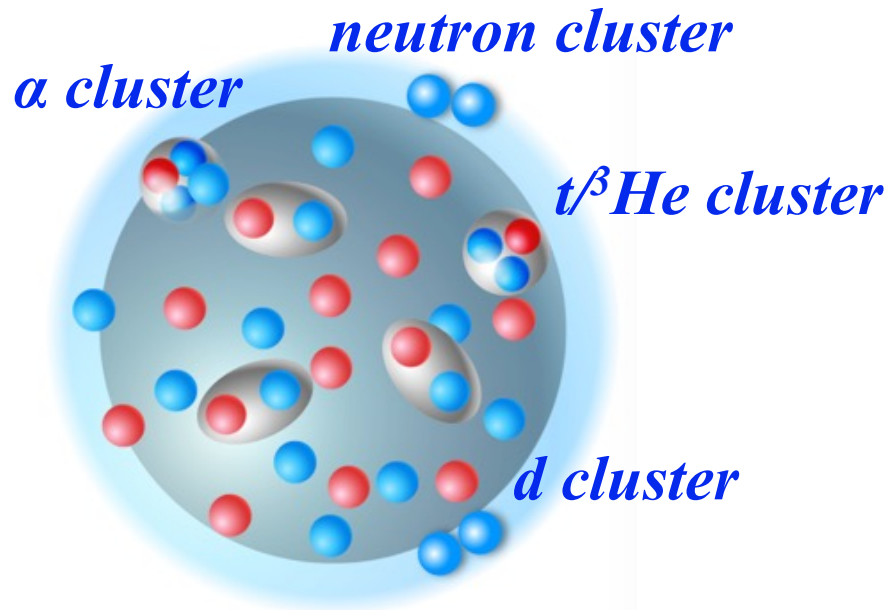
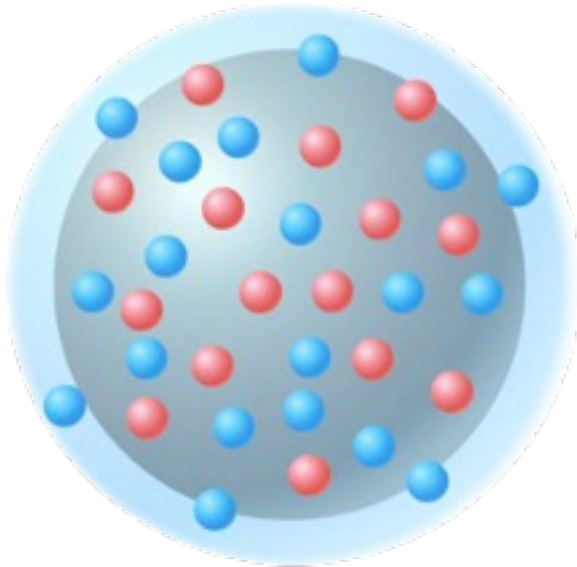
$E_{2+}$  and  $E_{4+}/E_{2+}$  : indicator for the evolution of shell structure and shape.



# $^{78}\text{Ni}$ : Magicity from in-beam $\gamma$ -ray spectroscopy @RIBF



# Non-uniformity in the nucleus: clustering



## Molecular states in Be



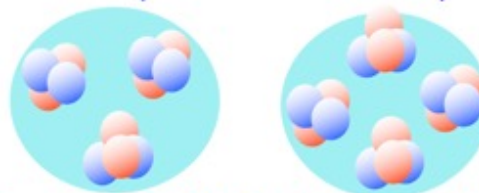
*e.g., ZY et al., PRL2014; Suzuki PRC2013*  
*Freer et al. PRL2006, PRL1999*  
*Ito et al. PRL2008, RPP2014*

## Linear-Chain states in C



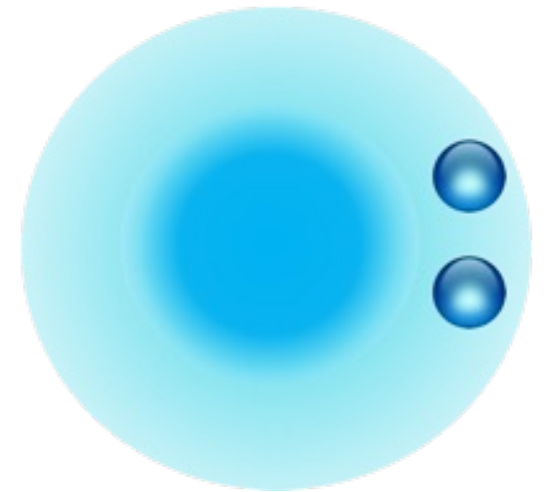
*e.g., Chen et al. Com. Phys 2023*  
*Liu et al. PRL 2020, Li et al. PRC2017*  
*Yamaguchi PLB2017, Baba/Kimura PRC2018*

## Gas-like ( $\alpha$ -condensate) states

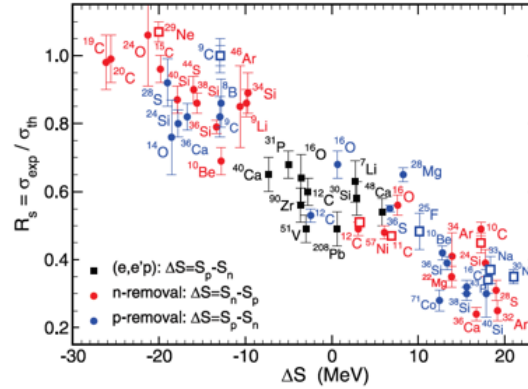
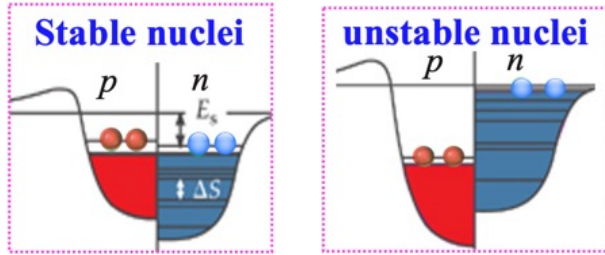


*e.g., Chen et al. SC2023; Zhou et al. NC 2023*  
*Adachi et al. PLB2021;*  
*THSR, PRL2001; Zhou/Ren et al. PRL2013*

## Neutron halo

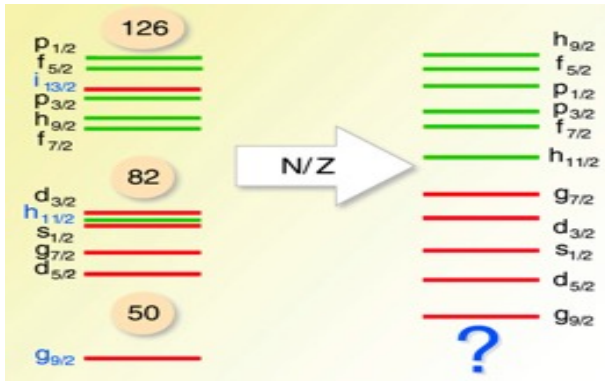


# What is the structure of (unstable) nuclei?

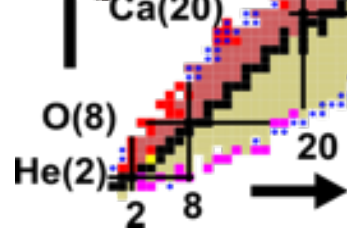
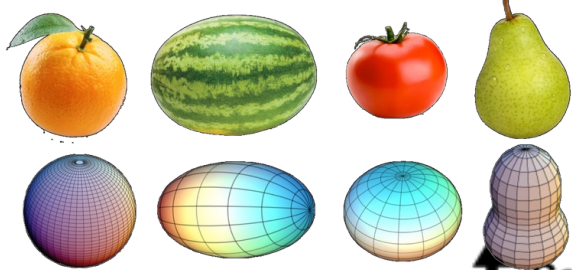


## SF quenching

*Tostevin/Gade PRC2021*  
*Aumann et al. PPNP 2021*



## Shell structure evolution

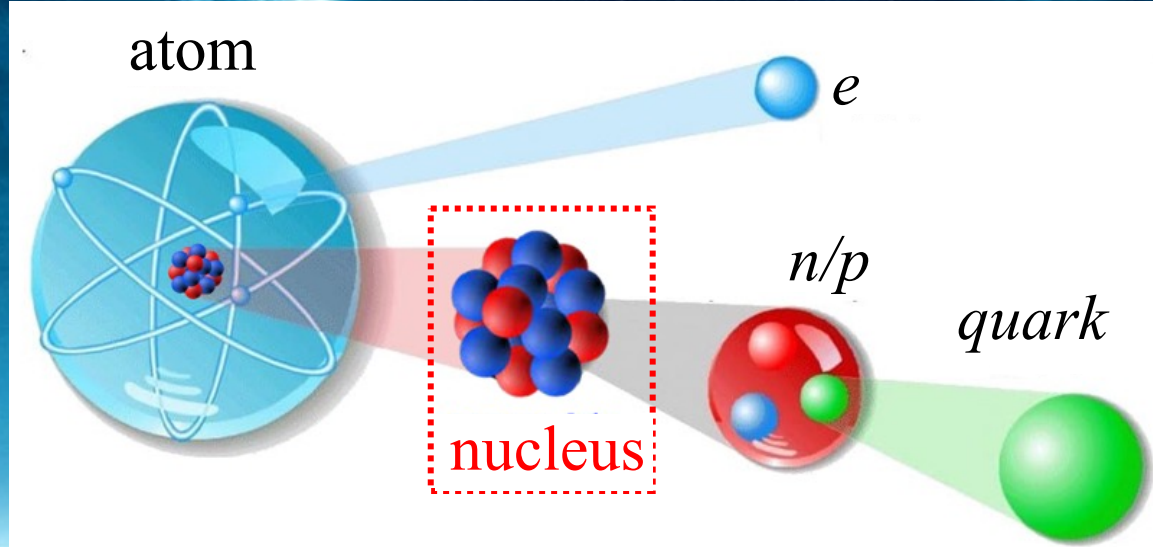
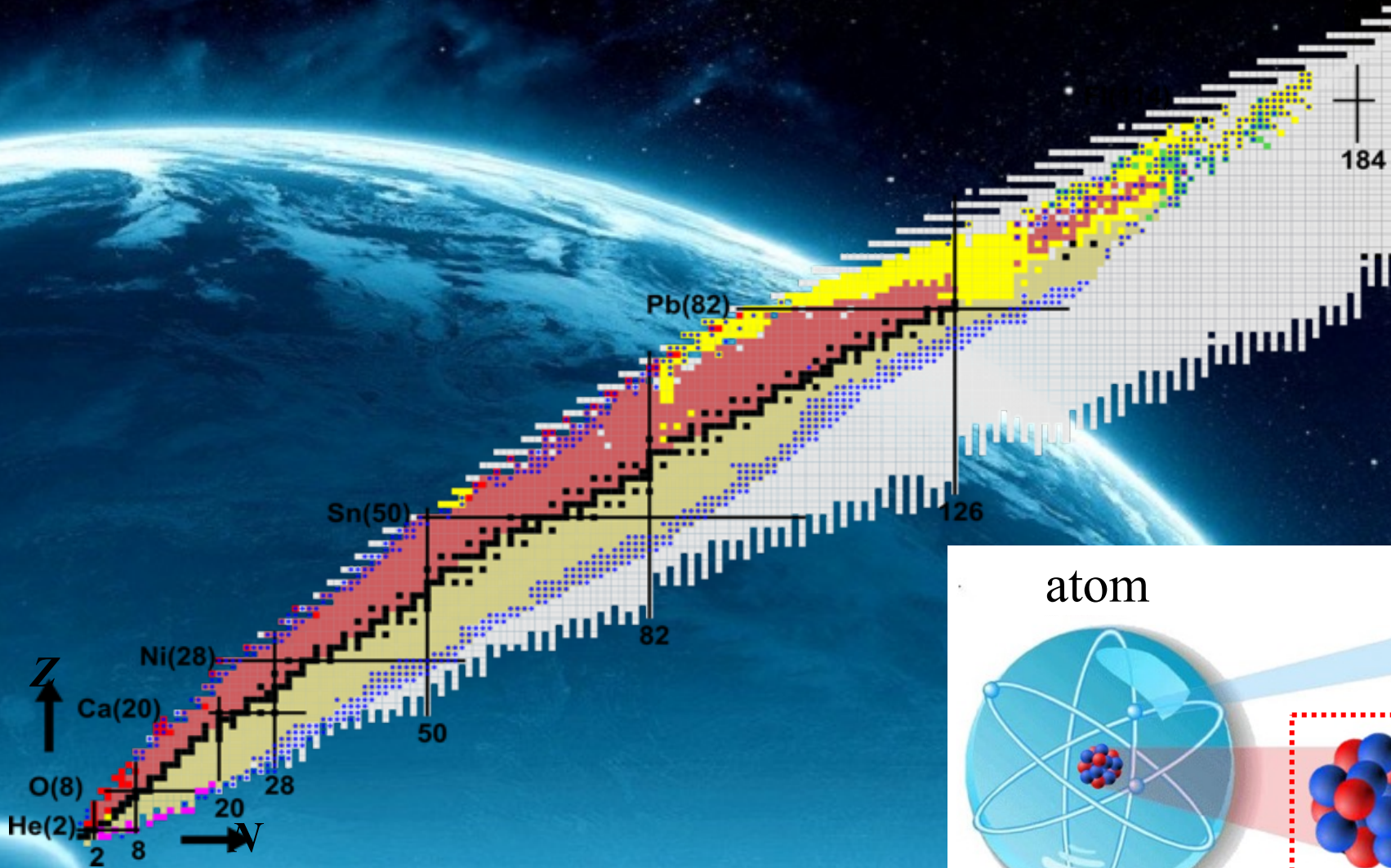


Neutron clusters

Halo

Molecular cluster states

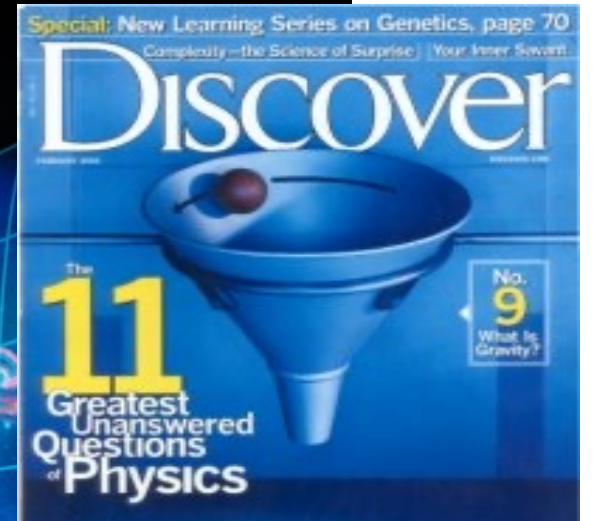
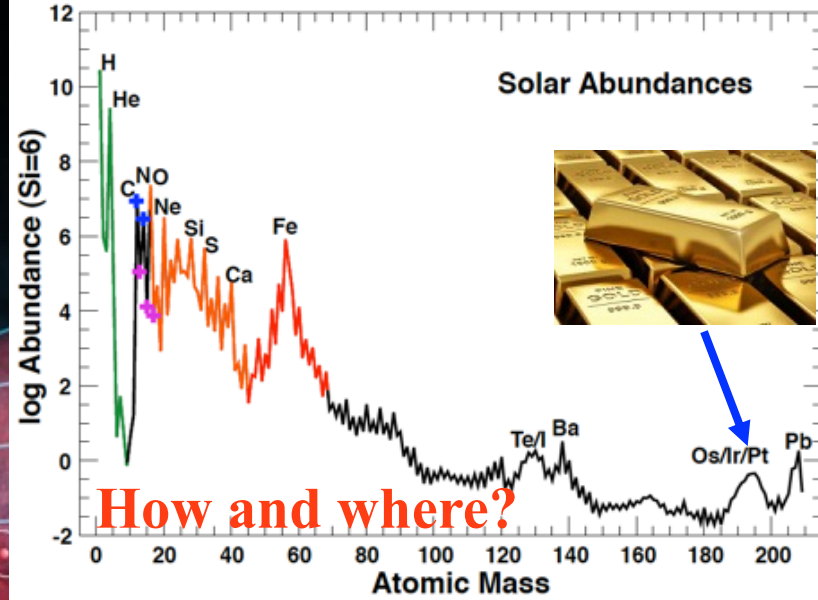
# Nucleus: from tiny to infinity



# The Origin of (heavy) elements?



Alchemy (錬金術)



(3) How were the heavy elements from iron to uranium made?

Periodic Table of the Elements

1 1A SA	2 2A SA	18 VIA SA
H Hydrogen 1.008	He Helium 4.003	
3 1A SA		

Periodic Table of the Elements

1 1A SA	2 2A SA	10 VIIIA SA	11 IB SA	12 IIB SA	13 IIIA SA	14 IVA SA	15 VA SA	16 VIA SA	17 VIIA SA	18 VIIIA SA
H Hydrogen 1.008	He Helium 4.003				B Boron 10.811	C Carbon 12.011	N Nitrogen 14.007	O Oxygen 15.999	F Fluorine 18.998	Ne Neon 20.180
3 1A SA	4 IIA SA	5 IIIB SA	6 IVB SA	7 VB SA	8 VIB SA	9 VIIB SA	10 VIII SA	11 VIII SA	12 VIII SA	13 IIIA SA
Li Lithium 6.941	Be Beryllium 9.012	Sc Scandium 44.956	Ti Titanium 47.88	V Vanadium 50.942	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.845	Co Cobalt 58.933	Ni Nickel 58.693	Cu Copper 63.546
Na Sodium 22.990	Mg Magnesium 24.305	Y Yttrium 88.906	Zr Zirconium 91.224	Nb Niobium 92.906	Mo Molybdenum 95.94	Tc Technetium 98.906	Ru Ruthenium 101.07	Rh Rhodium 102.905	Pd Palladium 106.36	Ag Silver 107.868
K Potassium 39.098	Ca Calcium 40.078									
Rb Rubidium 85.468	Sr Strontium 87.62									
Cs Cesium 132.905	Ba Barium 137.327	71-72 Lanthanide Series	73 Hf Hafnium 178.49	74 Ta Tantalum 180.948	75 W Tungsten 183.84	76 Re Rhenium 186.207	77 Os Osmium 190.23	78 Ir Iridium 192.222	79 Pt Platinum 195.084	80 Au Gold 196.967
Fr Francium 223	Ra Radium 226	73-74 Actinide Series	75 Rf Rutherfordium 261	76 Db Dubnium 262	77 Sg Seaborgium 263	78 Bh Bohrium 264	79 Hs Hassium 265	80 Mt Meitnerium 266	81 Ds Darmstadtium 267	82 Cn Copernicium 268
		87 La Lanthanum 138.905	88 Ce Cerium 140.12	89 Pr Praseodymium 140.908	90 Nd Neodymium 144.24	91 Pm Promethium 144.913	92 Sm Samarium 150.36	93 Eu Europium 151.964	94 Gd Gadolinium 157.25	95 Tb Terbium 158.925
		89 Ac Actinium 227	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.07	97 Bk Berkelium 247.07
		97 La Lanthanum 138.905	98 Ce Cerium 140.12	99 Pr Praseodymium 140.908	100 Nd Neodymium 144.24	101 Pm Promethium 144.913	102 Sm Samarium 150.36	103 Eu Europium 151.964	104 Gd Gadolinium 157.25	105 Tb Terbium 158.925
		103 Ac Actinium 227	104 Th Thorium 232.038	105 Pa Protactinium 231.036	106 U Uranium 238.029	107 Np Neptunium 237.048	108 Pu Plutonium 244.064	109 Am Americium 243.061	110 Cm Curium 247.07	111 Bk Berkelium 247.07
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		137 La Lanthanum 138.905	138 Ce Cerium 140.12	139 Pr Praseodymium 140.908	140 Nd Neodymium 144.24	141 Pm Promethium 144.913	142 Sm Samarium 150.36	143 Eu Europium 151.964	144 Gd Gadolinium 157.25	145 Tb Terbium 158.925
		145 Ac Actinium 227	146 Th Thorium 232.038	147 Pa Protactinium 231.036	148 U Uranium 238.029	149 Np Neptunium 237.048	150 Pu Plutonium 244.064	151 Am Americium 243.061	152 Cm Curium 247.07	153 Bk Berkelium 247.07
		153 La Lanthanum 138.905	154 Ce Cerium 140.12	155 Pr Praseodymium 140.908	156 Nd Neodymium 144.24	157 Pm Promethium 144.913	158 Sm Samarium 150.36	159 Eu Europium 151.964	160 Gd Gadolinium 157.25	161 Tb Terbium 158.925
		161 Ac Actinium 227	162 Th Thorium 232.038	163 Pa Protactinium 231.036	164 U Uranium 238.029	165 Np Neptunium 237.048	166 Pu Plutonium 244.064	167 Am Americium 243.061	168 Cm Curium 247.07	169 Bk Berkelium 247.07
		169 La Lanthanum 138.905	170 Ce Cerium 140.12	171 Pr Praseodymium 140.908	172 Nd Neodymium 144.24	173 Pm Promethium 144.913	174 Sm Samarium 150.36	175 Eu Europium 151.964	176 Gd Gadolinium 157.25	177 Tb Terbium 158.925
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		201 La Lanthanum 138.905	202 Ce Cerium 140.12	203 Pr Praseodymium 140.908	204 Nd Neodymium 144.24	205 Pm Promethium 144.913	206 Sm Samarium 150.36	207 Eu Europium 151.964	208 Gd Gadolinium 157.25	209 Tb Terbium 158.925
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		217 La Lanthanum 138.905	218 Ce Cerium 140.12	219 Pr Praseodymium 140.908	220 Nd Neodymium 144.24	221 Pm Promethium 144.913	222 Sm Samarium 150.36	223 Eu Europium 151.964	224 Gd Gadolinium 157.25	225 Tb Terbium 158.925
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		233 La Lanthanum 138.905	234 Ce Cerium 140.12	235 Pr Praseodymium 140.908	236 Nd Neodymium 144.24	237 Pm Promethium 144.913	238 Sm Samarium 150.36	239 Eu Europium 151.964	240 Gd Gadolinium 157.25	241 Tb Terbium 158.925
		241 Ac Actinium 227	242 Th Thorium 232.038	243 Pa Protactinium 231.036	244 U Uranium 238.029	245 Np Neptunium 237.048	246 Pu Plutonium 244.064	247 Am Americium 243.061	248 Cm Curium 247.07	249 Bk Berkelium 247.07
		249 La Lanthanum 138.905	250 Ce Cerium 140.12	251 Pr Praseodymium 140.908	252 Nd Neodymium 144.24	253 Pm Promethium 144.913	254 Sm Samarium 150.36	255 Eu Europium 151.964	256 Gd Gadolinium 157.25	257 Tb Terbium 158.925
		257 Ac Actinium 227	258 Th Thorium 232.038	259 Pa Protactinium 231.036	260 U Uranium 238.029	261 Np Neptunium 237.048	262 Pu Plutonium 244.064	263 Am Americium 243.061	264 Cm Curium 247.07	265 Bk Berkelium 247.07
		265 La Lanthanum 138.905	266 Ce Cerium 140.12	267 Pr Praseodymium 140.908	268 Nd Neodymium 144.24	269 Pm Promethium 144.913	270 Sm Samarium 150.36	271 Eu Europium 151.964	272 Gd Gadolinium 157.25	273 Tb Terbium 158.925
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		281 La Lanthanum 138.905	282 Ce Cerium 140.12	283 Pr Praseodymium 140.908	284 Nd Neodymium 144.24	285 Pm Promethium 144.913	286 Sm Samarium 150.36	287 Eu Europium 151.964	288 Gd Gadolinium 157.25	289 Tb Terbium 158.925
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		313 La Lanthanum 138.905	314 Ce Cerium 140.12	315 Pr Praseodymium 140.908	316 Nd Neodymium 144.24	317 Pm Promethium 144.913	318 Sm Samarium 150.36	319 Eu Europium 151.964	320 Gd Gadolinium 157.25	321 Tb Terbium 158.925
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		329 La Lanthanum 138.905	330 Ce Cerium 140.12	331 Pr Praseodymium 140.908	332 Nd Neodymium 144.24	333 Pm Promethium 144.913	334 Sm Samarium 150.36	335 Eu Europium 151.964	336 Gd Gadolinium 157.25	337 Tb Terbium 158.925
		337 Ac Actinium 227	338 Th Thorium 232.038	339 Pa Protactinium 231.036	340 U Uranium 238.029	341 Np Neptunium 237.048	342 Pu Plutonium 244.064	343 Am Americium 243.061	344 Cm Curium 247.07	345 Bk Berkelium 247.07
		345 La Lanthanum 138.905	346 Ce Cerium 140.12	347 Pr Praseodymium 140.908	348 Nd Neodymium 144.24	349 Pm Promethium 144.913	350 Sm Samarium 150.36	351 Eu Europium 151.964	352 Gd Gadolinium 157.25	353 Tb Terbium 158.925
		353 Ac Actinium 227	354 Th Thorium 232.038	355 Pa Protactinium 231.036	356 U Uranium 238.029	357 Np Neptunium 237.048	358 Pu Plutonium 244.064	359 Am Americium 243.061	360 Cm Curium 247.07	361 Bk Berkelium 247.07
		361 La Lanthanum 138.905	362 Ce Cerium 140.12	363 Pr Praseodymium 140.908	364 Nd Neodymium 144.24	365 Pm Promethium 144.913	366 Sm Samarium 150.36	367 Eu Europium 151.964	368 Gd Gadolinium 157.25	369 Tb Terbium 158.925
		369 Ac Actinium 227	370 Th Thorium 232.038	371 Pa Protactinium 231.036	372 U Uranium 238.029	373 Np Neptunium 237.048	374 Pu Plutonium 244.064	375 Am Americium 243.061	376 Cm Curium 247.07	377 Bk Berkelium 247.07
		377 La Lanthanum 138.905	378 Ce Cerium 140.12	379 Pr Praseodymium 140.908	380 Nd Neodymium 144.24	381 Pm Promethium 144.913	382 Sm Samarium 150.36	383 Eu Europium 151.964	384 Gd Gadolinium 157.25	385 Tb Terbium 158.925
		385 Ac Actinium 227	386 Th Thorium 232.038	387 Pa Protactinium 231.036	388 U Uranium 238.029	389 Np Neptunium 237.048	390 Pu Plutonium 244.064	391 Am Americium 243.061	392 Cm Curium 247.07	393 Bk Berkelium 247.07
		393 La Lanthanum 138.905	394 Ce Cerium 140.12	395 Pr Praseodymium 140.90						



# Long history of understanding energy generation of the sun

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- ✓ 1928, G.Gamow: tunneling effect
- ✓ Rutherford's work on nuclear transmutations (1919~): energy may be generated from nuclear reactions in stars
- ✓ 1938, Bethe and Critchfield: "formation of deuterons by proton combination" (H burning)
- ✓ 1938/1939, Weizaecker and Bethe: CNO cycle
- ✓ 1946, Hoyle: nuclear reactions in genesis of the chemical elements
- ✓ 1950s, essential framework of stellar nucleosynthesis (B2FH)

## REVIEWS OF MODERN PHYSICS

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VOLUME 29, NUMBER 4

OCTOBER, 1957

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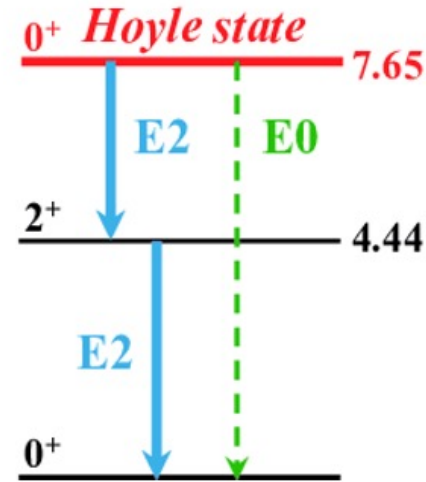
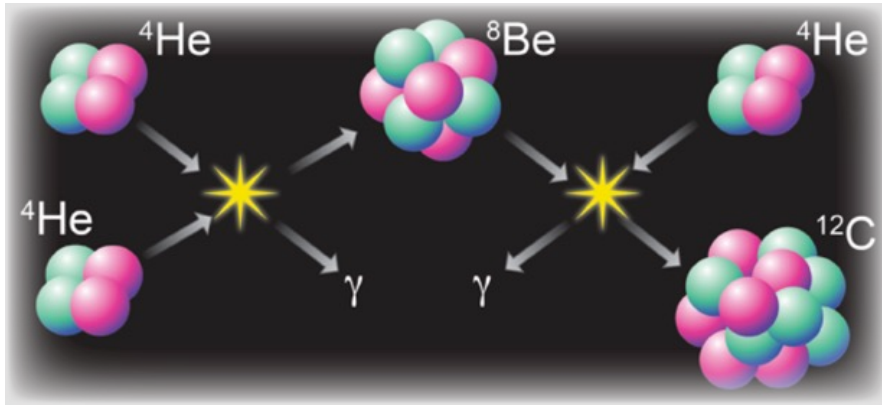
### **Synthesis of the Elements in Stars\***

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and  
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,  
California Institute of Technology, Pasadena, California*

# Helium Burning $3\alpha \rightarrow {}^{12}\text{C}$ and the Hoyle state

- ✓ No long-lived nuclei with  $A=5$  and  $A=8$
- ✓ Direct  $3\text{-}\alpha$  capture Rate is too low to explain the  ${}^{12}\text{C}$  abundance



Hoyle, APJ Suppl.1(54)121

- ✓ The  $3\alpha$  (resonant) reaction rate is :  $r_{3\alpha} = \rho^2 N_A^2 Y_{8\text{Be}} Y_\alpha \langle \sigma v \rangle_{8\text{Be}+\alpha}$   
(narrow resonant state)



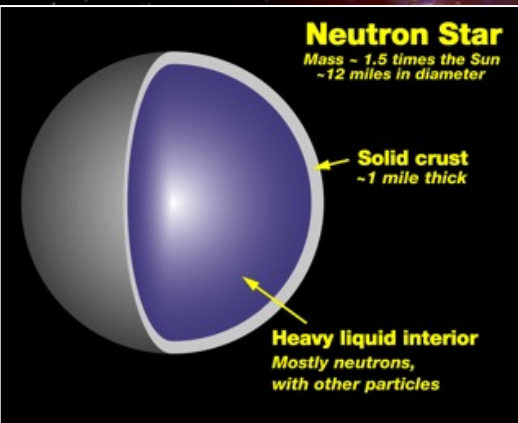
$$\langle \sigma v \rangle = \left( \frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 (\omega\gamma)_r \exp\left(-\frac{E_r}{kT}\right) \quad \omega\gamma = \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma}$$

$$r_{3\alpha \rightarrow {}^{12}\text{C}} = \rho^3 N_A^3 \frac{Y_\alpha^3}{2} 3^{3/2} \left( \frac{2\pi\hbar^2}{M_\alpha kT} \right)^3 f \omega \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma \hbar} \exp\left(-\frac{Q}{kT}\right) \quad Q_{3\alpha} = 380\text{keV}$$

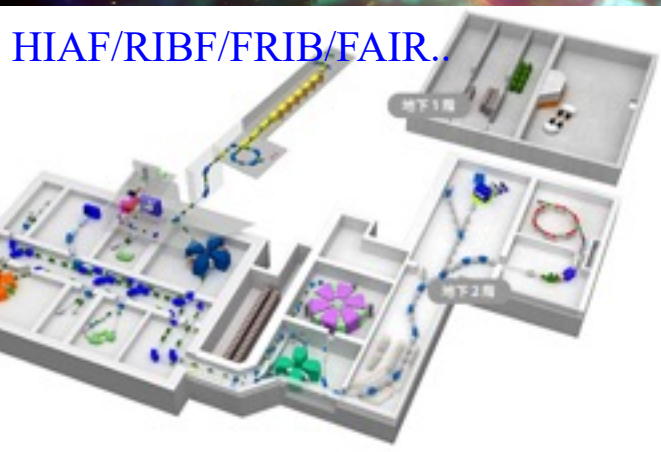
# Neutron star and dense matter

- Equation of state of nuclear matter?
- Phases of dense nuclear matter?
- Elements created in supernovae?
- Elements ejected in neutron star mergers

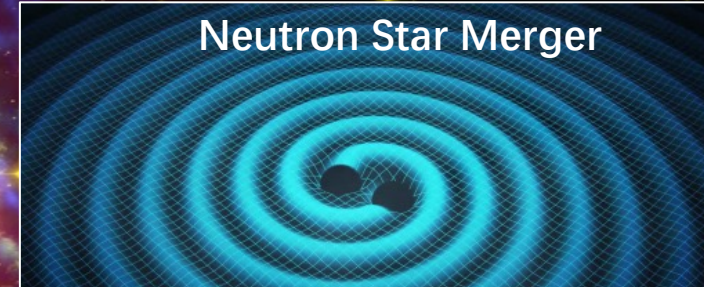
## Neutron Stars



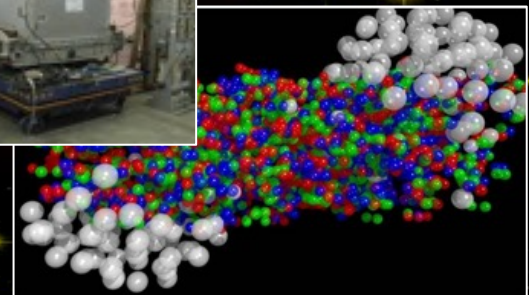
## RIB reactions



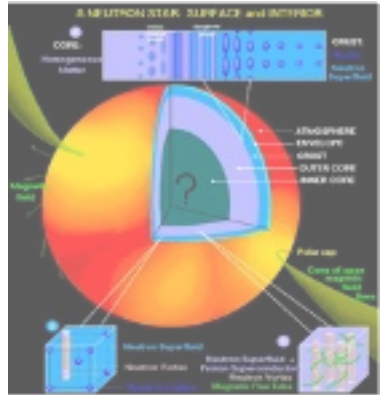
## Astrophysical observations



## Heavy Ion Collisions



# EoS: from nucleus to neutron stars

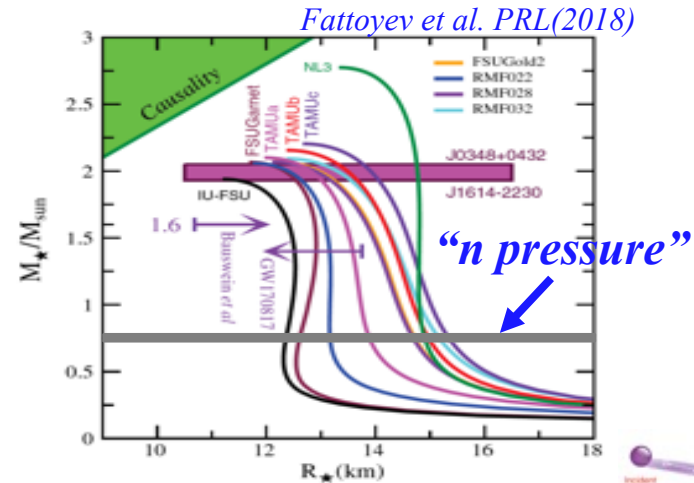


In Heaven

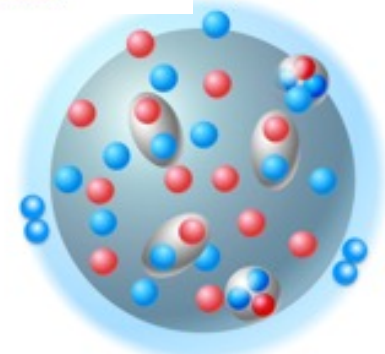
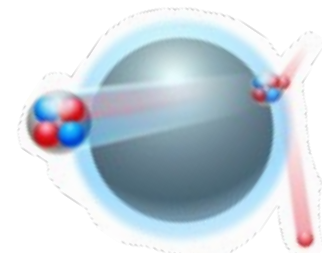
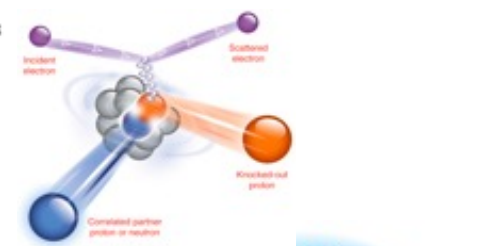
## Neutron star

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

## Mass-radius relation

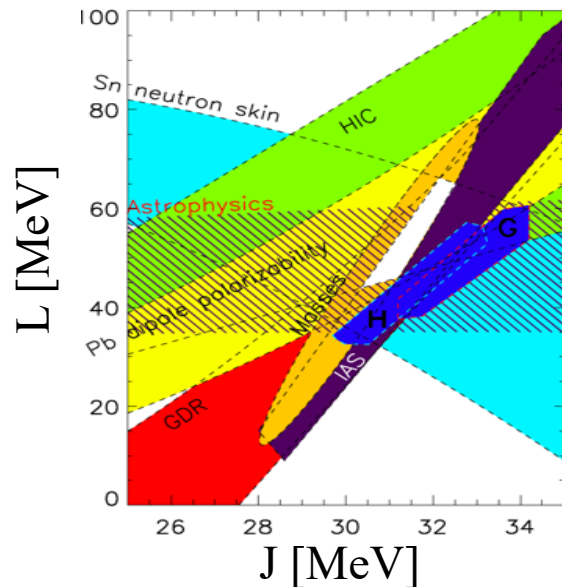


Nuclear matter EoS



On Earth

Roca-Maza, PPNP(2018)



## Better constraints

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

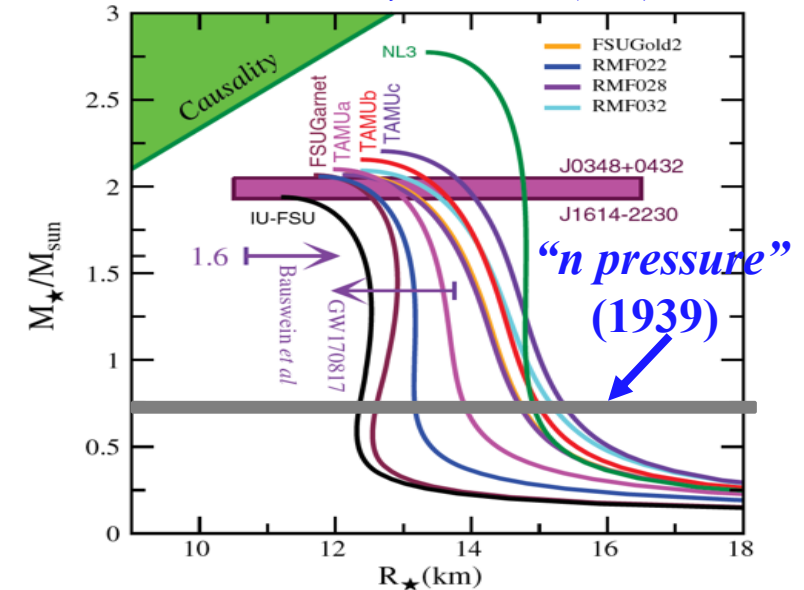


# EoS: from nucleus to neutron stars

- ✓ Born in the core-collapse supernova of massive stars.
- ✓ Typical mass:  $\sim 1.4 M_{\odot}$
- ✓ Typical size: radius  $\sim 10$  km

## Mass-radius relation

Fattoyev et al. PRL(2018)

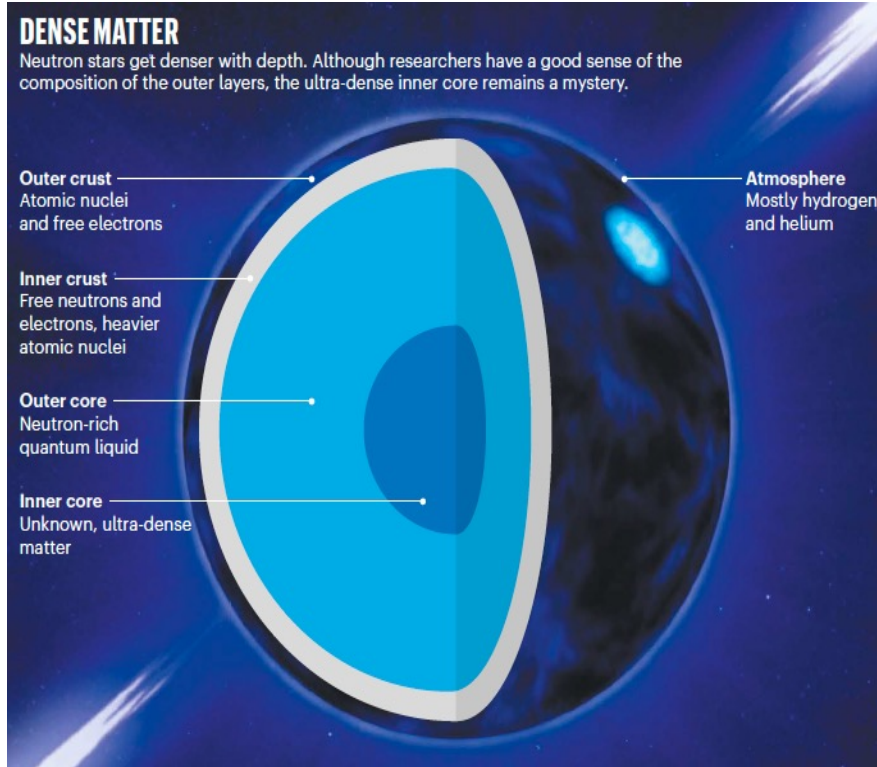


Tolman-Oppenheimer-Volkoff (TOV) equations with parameters of Nuclear EoS

$$\frac{dp}{dr} = -G \frac{\epsilon m}{r^2} \left(1 + \frac{p}{\epsilon}\right) \left(1 + \frac{4\pi p r^3}{m}\right) \left(1 - \frac{2Gm}{r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon,$$

- $G$  is the gravitational constant  
 - $p$  is pressure and  $\epsilon$  is energy density



**Core scenarios**  
 A number of possibilities have been suggested for the inner core, including these three options.

● Up quark      ● Strange quark  
● Down quark    ● Anti-down quark



**Quarks**  
 The constituents of protons and neutrons — up and down quarks — roam freely.

**Bose-Einstein condensate**  
 Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.

**Hyperons**  
 Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

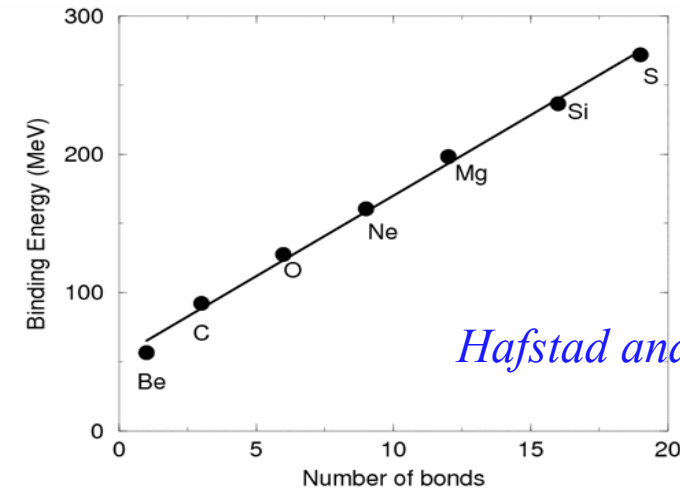
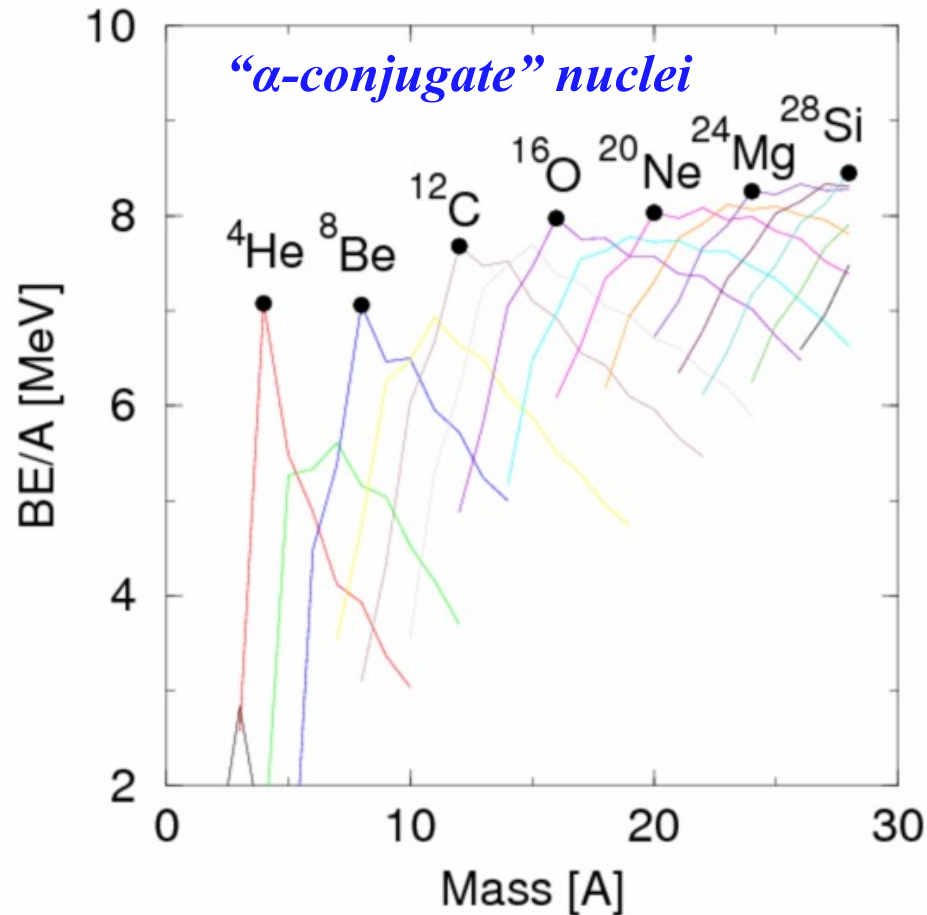
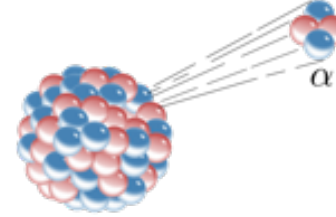
# Outline

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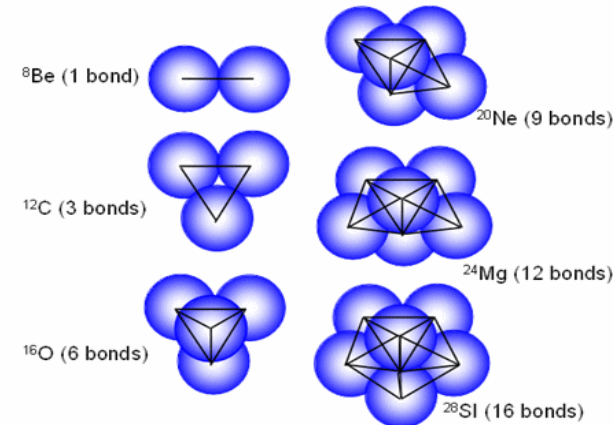
- ✓ Introduction: basics about the structure of nucleus
- ✓ **Clustering in nuclear systems**
- ✓ **Halo and neutron correlations**
- ✓ **Summary and Perspective**

# “ $\alpha$ 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 structures



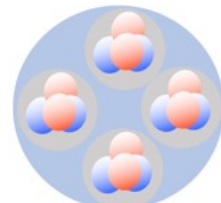
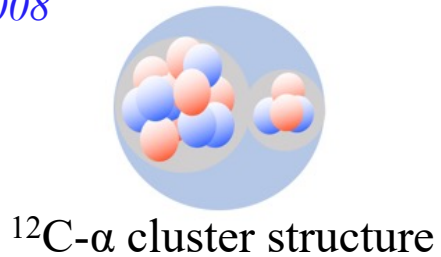
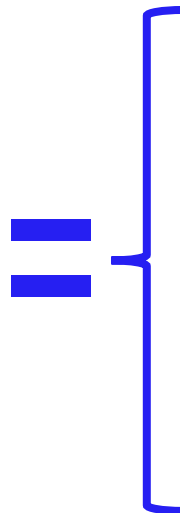
## Duality of nuclear WF

✓ Bayman-Bohr theorem *Nucl. Phys.* 1958  
 Yamada et al. *PTPS* 2008

$^{16}\text{O}$

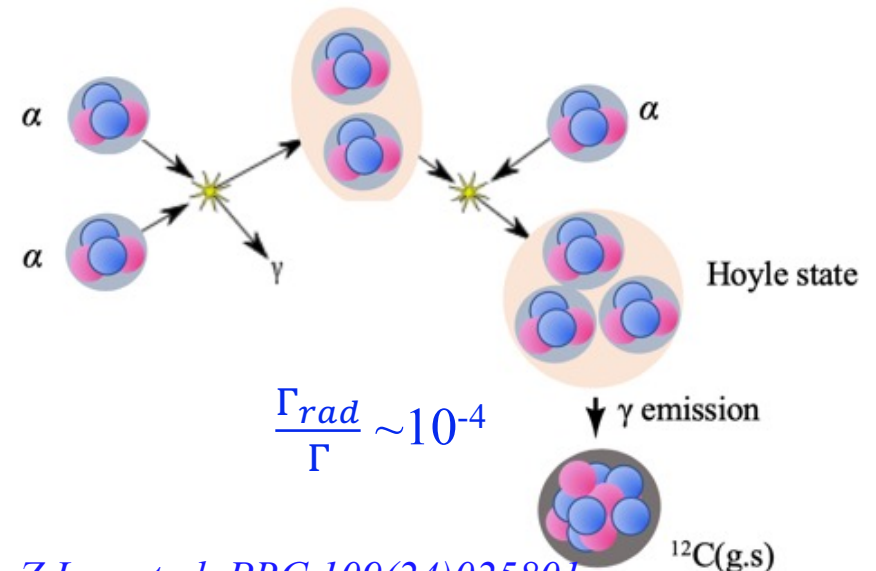


Shell model  
 $(0s)^4(0p)^{12}$



$4\alpha$  cluster structure

## The Hoyle state



Z.Luo et al. *PRC* 109(24)025801

Freer et al. *PPNP*78(14)1

# Cluster structures in excited states of light nuclei

## 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

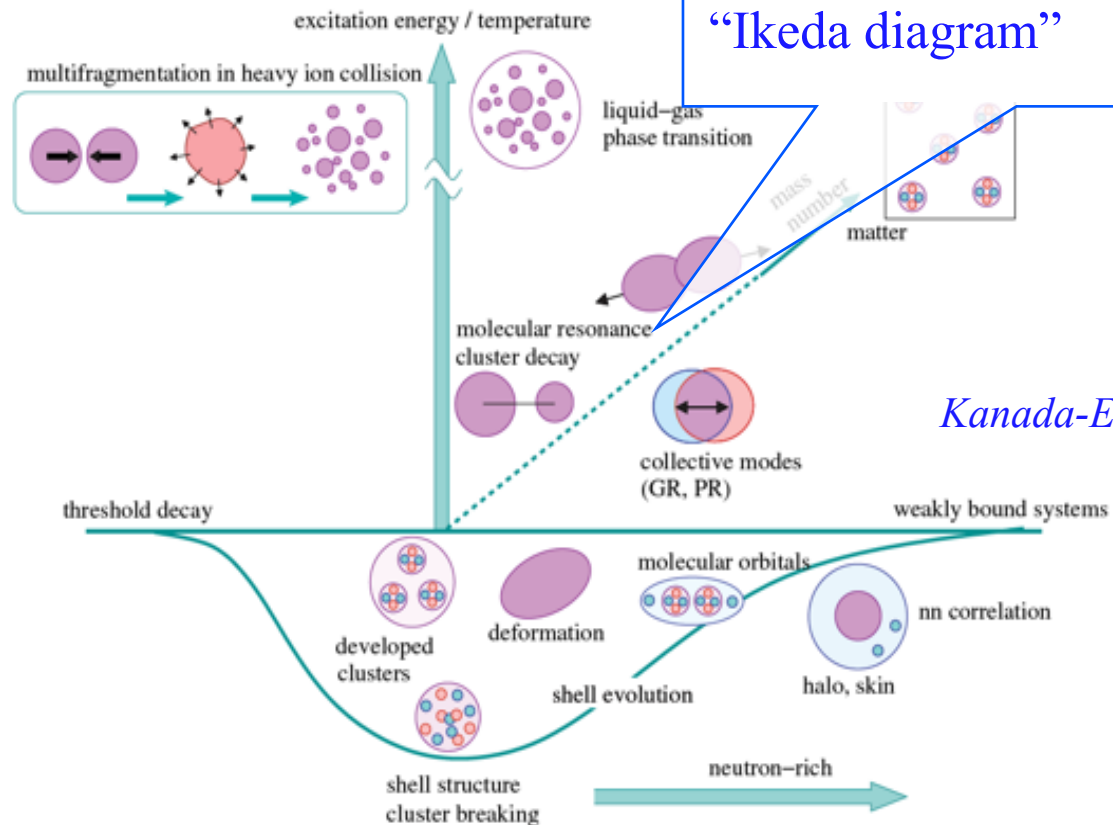
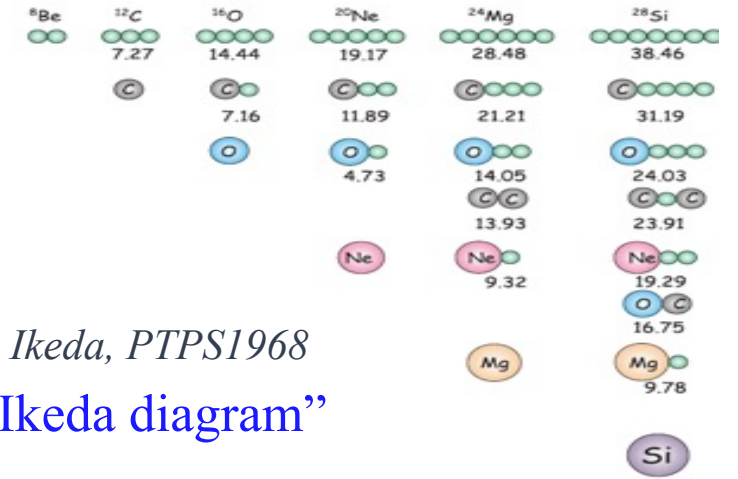


e.g., Chen et al. Com. Phys 2023  
Liu et al. PRL 2020, Li et al. PRC2017  
Yamaguchi PLB2017, Baba/Kimura PRC2018

## Gas-like ( $\alpha$ -condensate) states

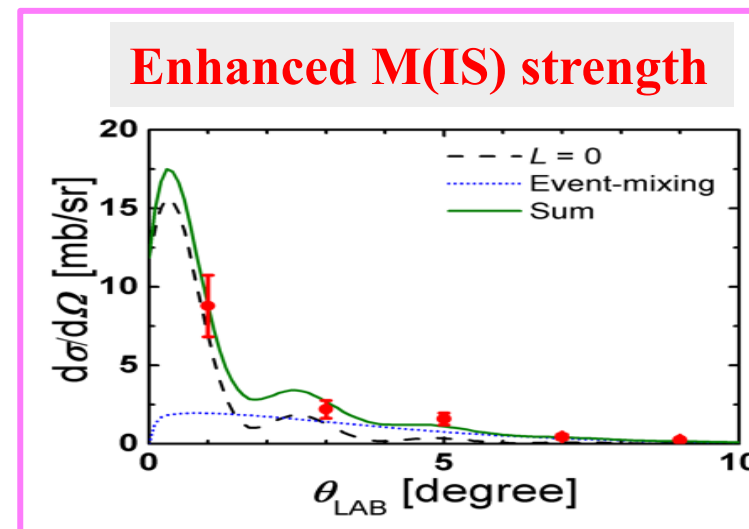
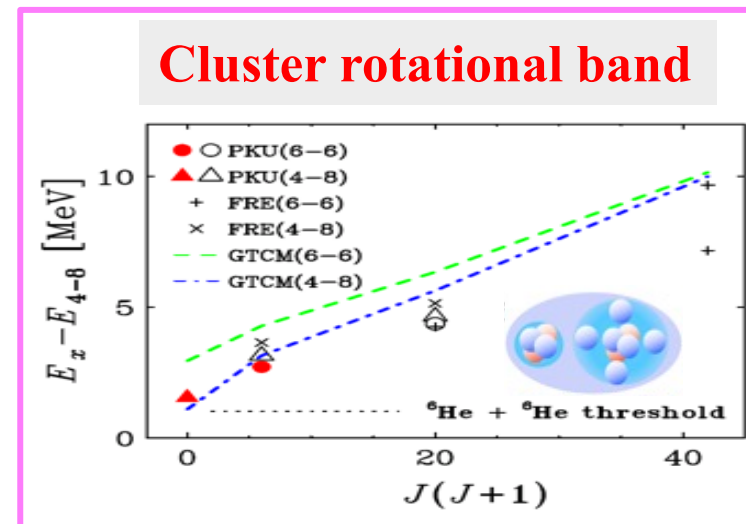
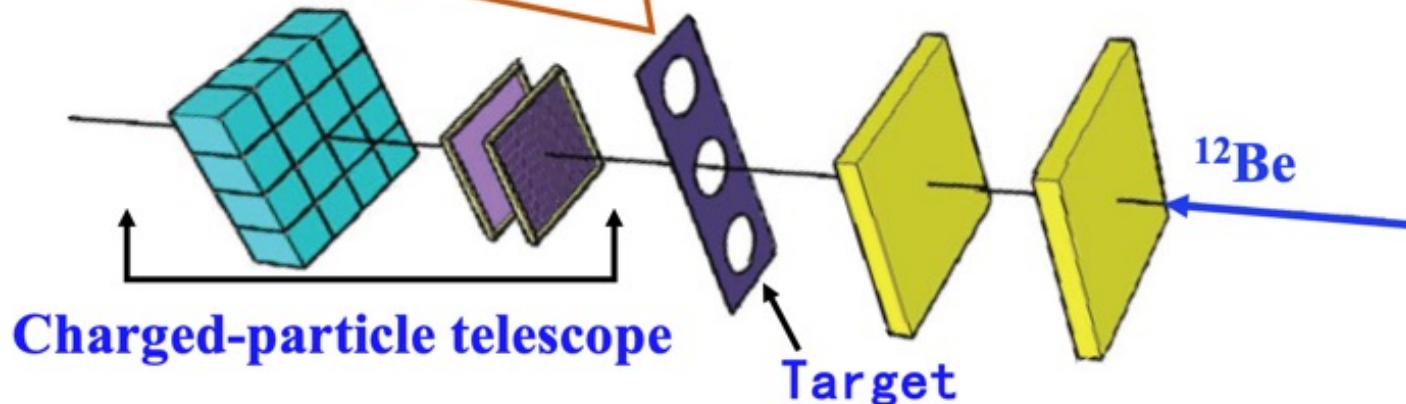
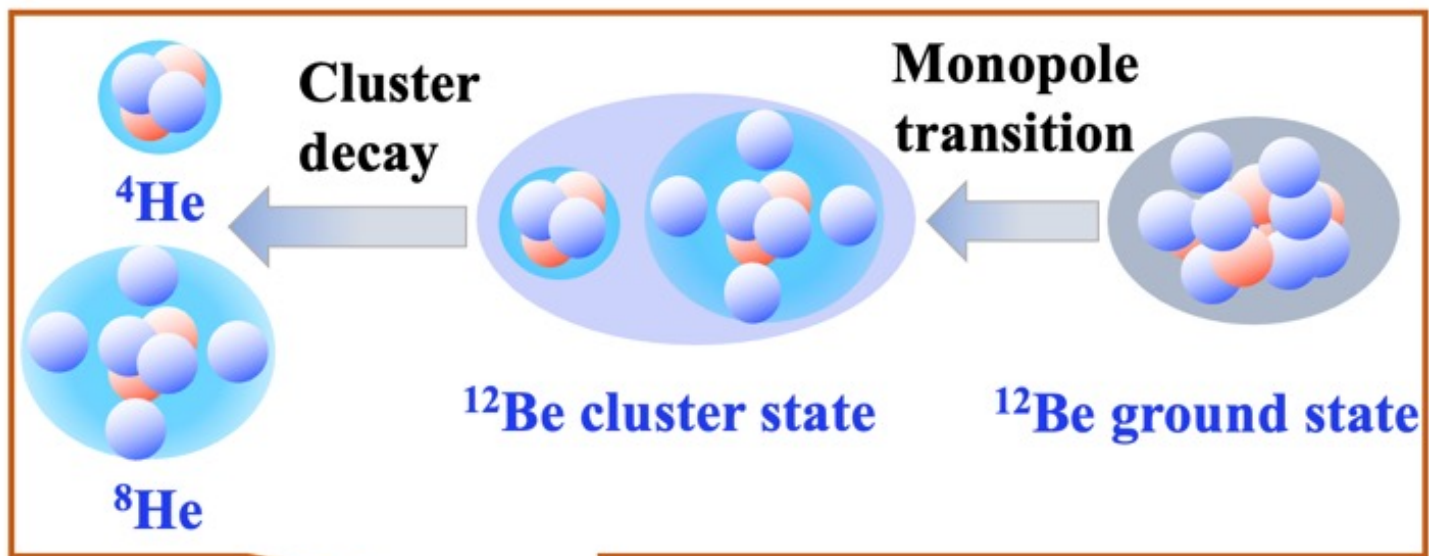


e.g., Chen et al. SC2023; Zhou et al. NC 2023  
Adachi et al. PLB2021;  
THSR, PRL2001; Zhou/Ren et al. PRL2013



# e. g. : Molecular cluster structure in $^{12}\text{Be}$

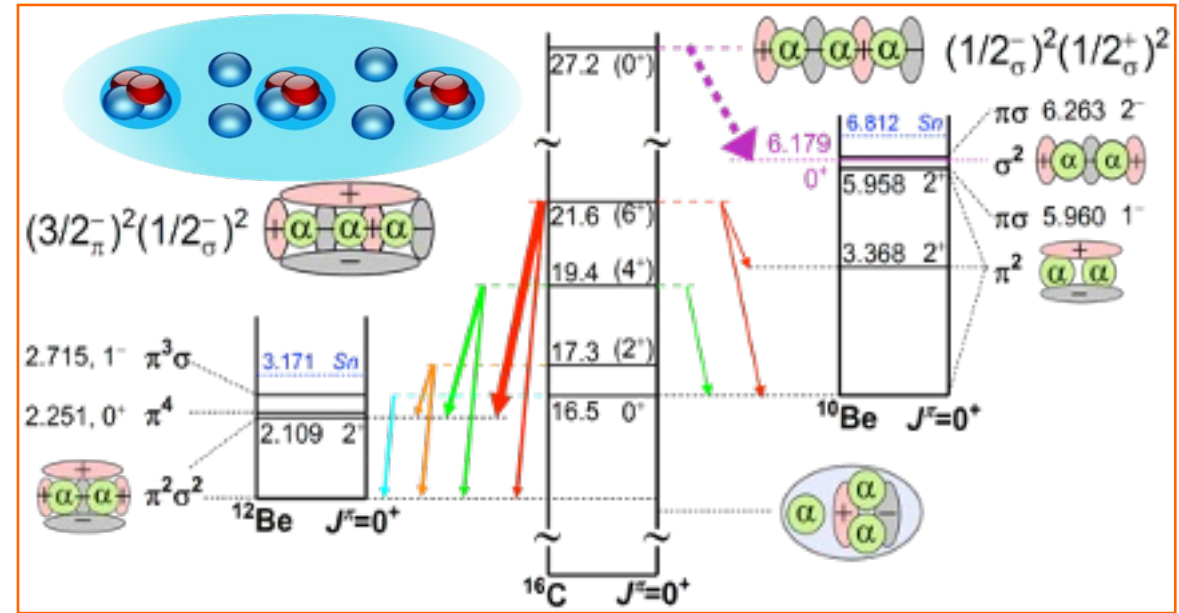
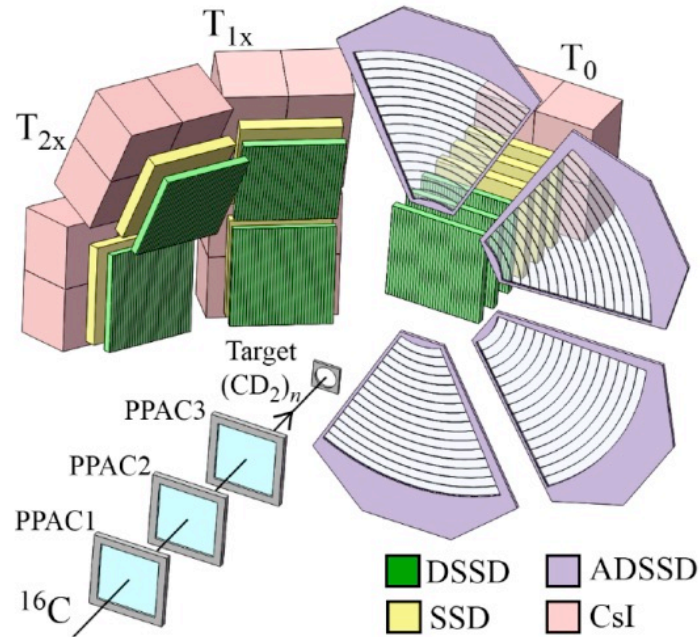
@HIRFL-RIBLL1 beamline (IMP, Lanzhou, China)



ZHY et al. PRL112(14)162501;PRC91(14)024304

# e. g. : Linear-chain cluster structure in C

@HIRFL-RIBLL1 beamline (IMP, Lanzhou, China)



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

## Positive-Parity Linear-Chain Molecular Band in $^{16}\text{C}$

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

<sup>1</sup>School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

<sup>2</sup>Kitami Institute of Technology, 090-8507 Kitami, Japan

<sup>3</sup>Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan

<sup>4</sup>School of Science, Huzhou University, Huzhou 313000, China

<sup>5</sup>Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China

<sup>6</sup>Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China

PHYSICAL REVIEW C **105**, 044302 (2022)

## Observation of the $\pi^2\sigma^2$ -bond linear-chain molecular structure in $^{16}\text{C}$

J. X. Han,<sup>1</sup> Y. Liu,<sup>1,2,\*</sup> Y. L. Ye,<sup>1,†</sup> J. L. Lou,<sup>1</sup> X. F. Yang,<sup>1</sup> T. Baba,<sup>3</sup> M. Kimura,<sup>4</sup> B. Yang,<sup>1</sup> Z. H. Li,<sup>1</sup> Q. T. Li,<sup>1</sup> J. Y. Xu,<sup>1</sup> Y. C. Ge,<sup>1</sup> H. Hua,<sup>1</sup> Z. H. Yang,<sup>5</sup> J. S. Wang,<sup>6,7</sup> Y. Y. Yang,<sup>7</sup> P. Ma,<sup>7</sup> Z. Bai,<sup>7</sup> Q. Hu,<sup>7</sup> W. Liu,<sup>7</sup> K. Ma,<sup>1</sup> L. C. Tao,<sup>1</sup> Y. Jiang,<sup>1</sup> L. Y. Hu,<sup>8</sup> H. L. Zang,<sup>1</sup> J. Feng,<sup>1</sup> H. Y. Wu,<sup>1</sup> S. W. Bai,<sup>1</sup> G. Li,<sup>1</sup> H. Z. Yu,<sup>1</sup> S. W. Huang,<sup>1</sup> Z. Q. Chen,<sup>1</sup> X. H. Sun,<sup>1</sup> J. J. Li,<sup>1</sup> Z. W. Tan,<sup>1</sup> Z. H. Gao,<sup>7</sup> F. F. Duan,<sup>7</sup> J. H. Tan,<sup>8</sup> S. Q. Sun,<sup>8</sup> and Y. S. Song<sup>8</sup>

<sup>1</sup>School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **95**, 021303(R) (2017)

## Selective decay from a candidate of the $\sigma$ -bond linear-chain state in $^{14}\text{C}$

J. Li,<sup>1</sup> Y. L. Ye,<sup>1,†</sup> Z. H. Li,<sup>1</sup> C. J. Lin,<sup>2</sup> Q. T. Li,<sup>1</sup> Y. C. Ge,<sup>1</sup> J. L. Lou,<sup>1</sup> Z. Y. Tian,<sup>1</sup> W. Jiang,<sup>1</sup> Z. H. Yang,<sup>3</sup> J. Feng,<sup>1</sup> P. J. Li,<sup>1</sup> J. Chen,<sup>1</sup> Q. Liu,<sup>1</sup> H. L. Zang,<sup>1</sup> B. Yang,<sup>1</sup> Y. Zhang,<sup>1</sup> Z. Q. Chen,<sup>1</sup> Y. Liu,<sup>1</sup> X. H. Sun,<sup>1</sup> J. Ma,<sup>1</sup> H. M. Jia,<sup>2</sup> X. X. Xu,<sup>2</sup> L. Yang,<sup>2</sup> N. R. Ma,<sup>2</sup> and L. J. Sun<sup>2</sup>

# Cluster structures of light nuclei

## 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

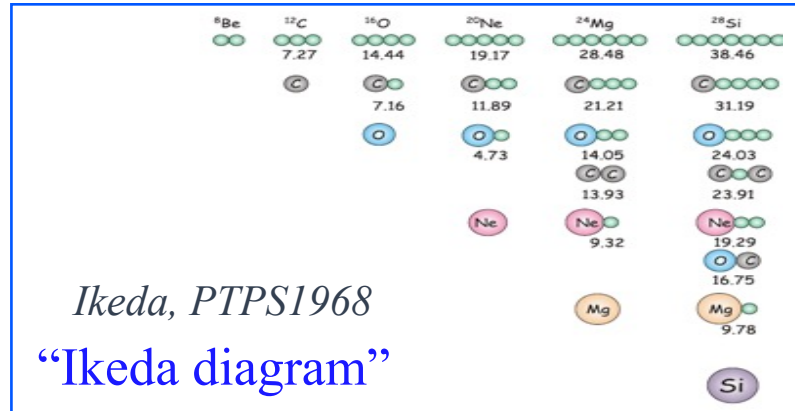


e.g., *Han et al. Com. Phys 2023*  
*Liu et al. PRL 2020, Li et al. PRC2017*  
*Yamaguchi PLB2017, Baba/Kimura PRC2018*

## Gas-like ( $\alpha$ -condensate) states

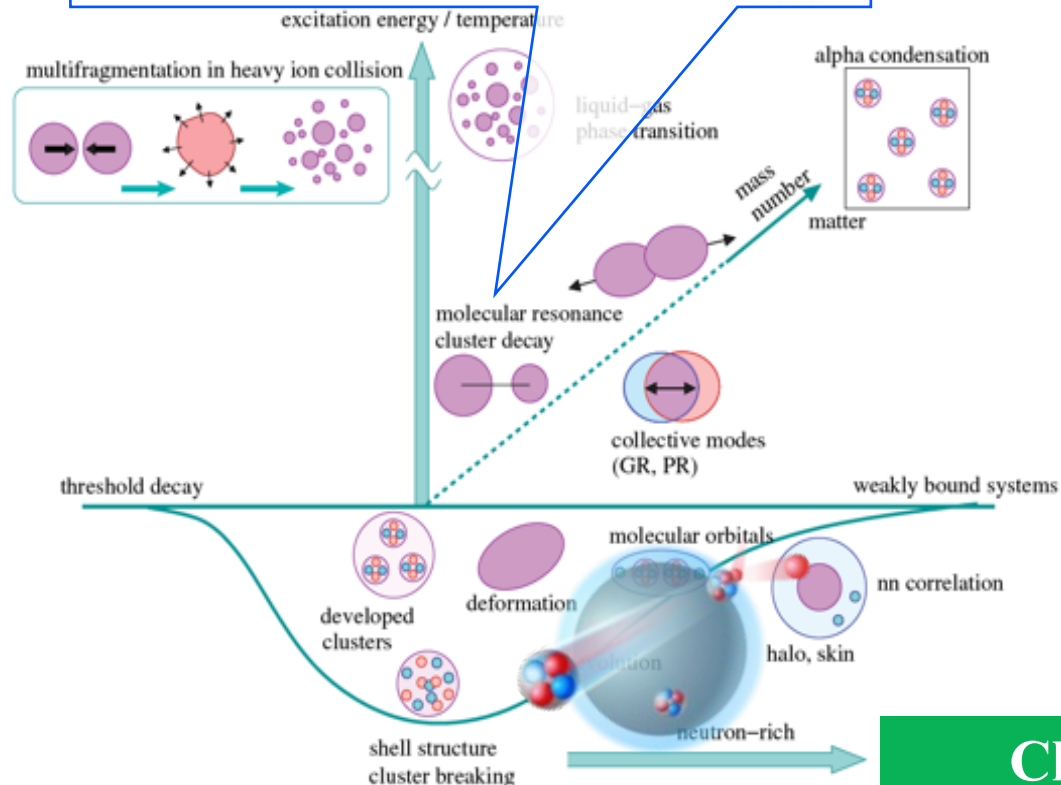


e.g., *Chen et al. SC2023; Zhou et al. NC 2023*  
*Adachi et al. PLB2021;*  
*THSR, PRL2001; Zhou/Ren et al. PRL2013*



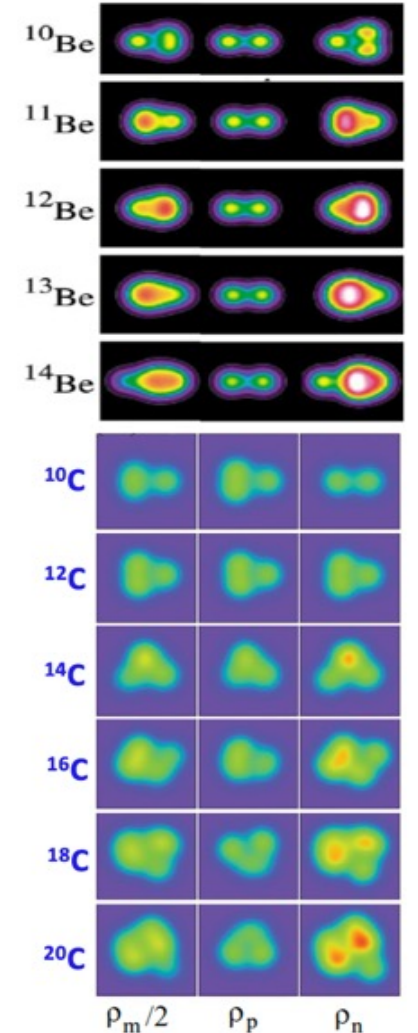
*Ikeda, PTPS1968*

“Ikeda diagram”



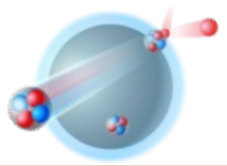
*Kanada-Enyo, PTEP 2012*

*Y. Kanada-Enyo, et al., C. R. Physique 2003*



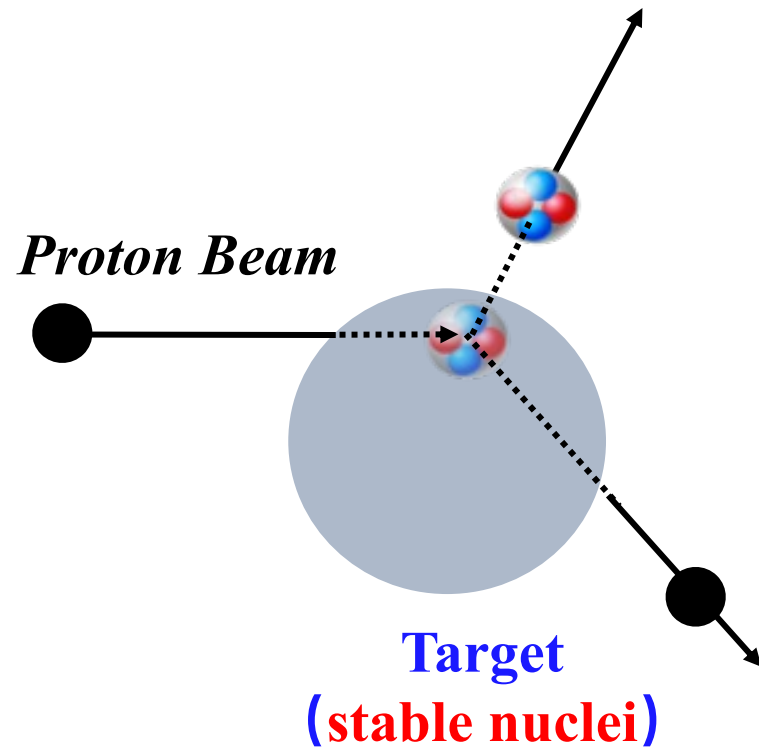
**Cluster knockout**

# $(p,p\alpha)$ : a probe for clusters in ground state

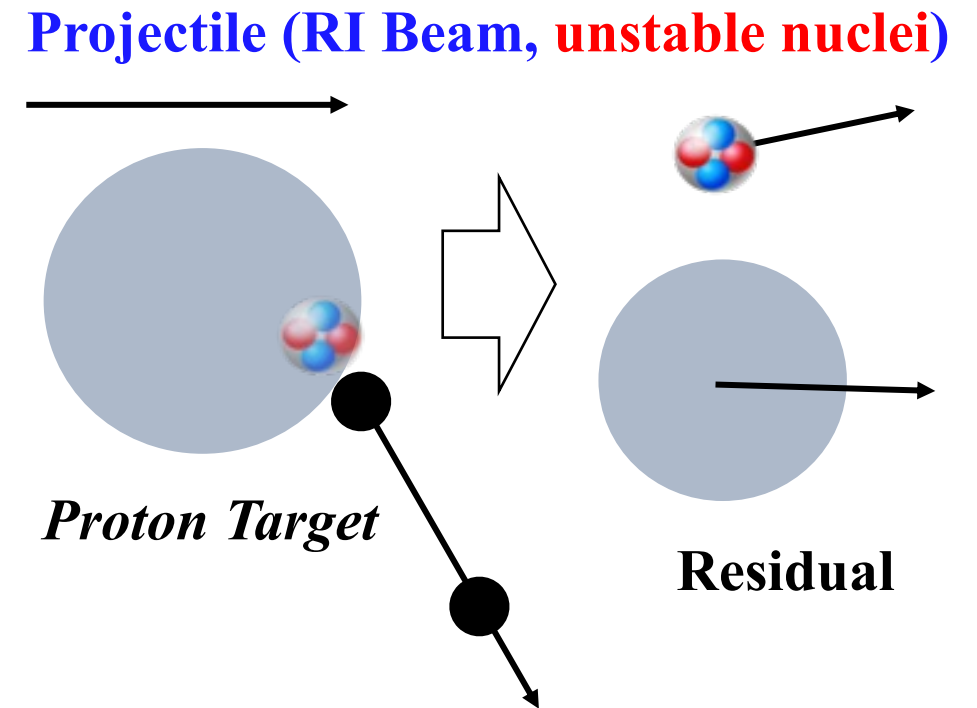


- ✓ Cluster structure in excited states: one can measure cluster decay fragments
- ✓ Clusters in g.s: quasi-free  $(p,p\alpha)$  [ $\sim$  several hundred MeV/u] *Yoshida, PRC2016/PRC2018/PRC2019*

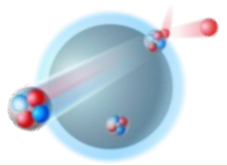
## Normal kinematics



## Inverse kinematics



# $(p,p\alpha)$ : a probe for clusters in ground state



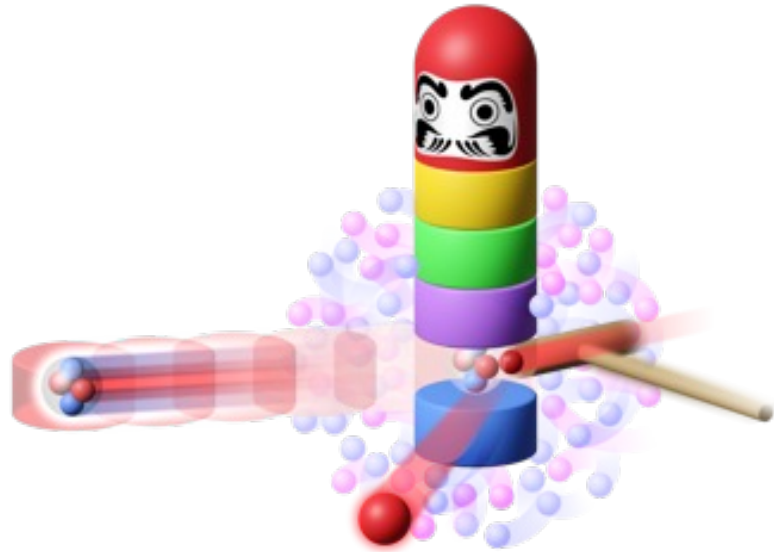
✓ In 1970s and 1980s: with light stable nuclei like  ${}^7\text{Li}/{}^9\text{Be}/{}^{12}\text{C}$ .

✓ Analysis of triple differential cross sections utilizing DWIA

$$\frac{d^3\sigma}{dE_1^L d\Omega_1^L d\Omega_2^L} = S_\alpha F_{\text{kin}} C_0 \sum_m |\bar{T}_{K_0 K_1 K_2}^{nljm}|^2$$

✓ Recent theoretical development for  $(p,p\alpha)$  (*Ogata et al.*)

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

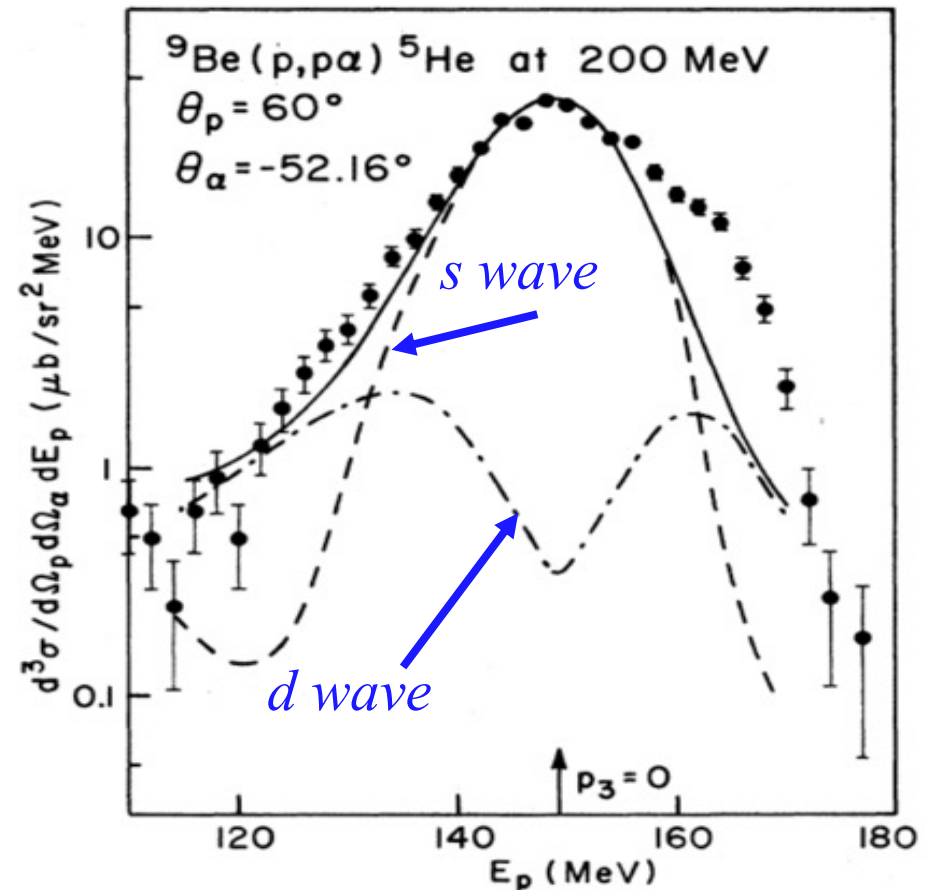


quasi-free knockout with large momentum transfer

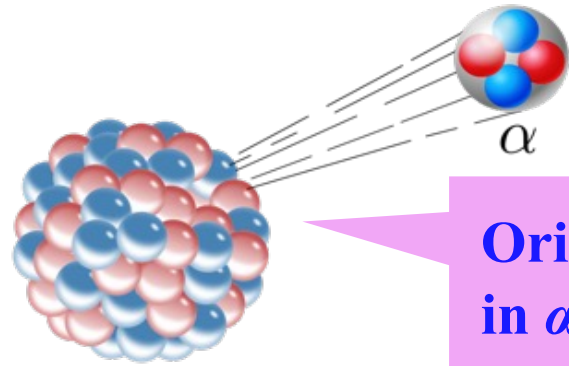
*Nadasen et al. PRC1989*

*Chan and Roos PRC1977;*

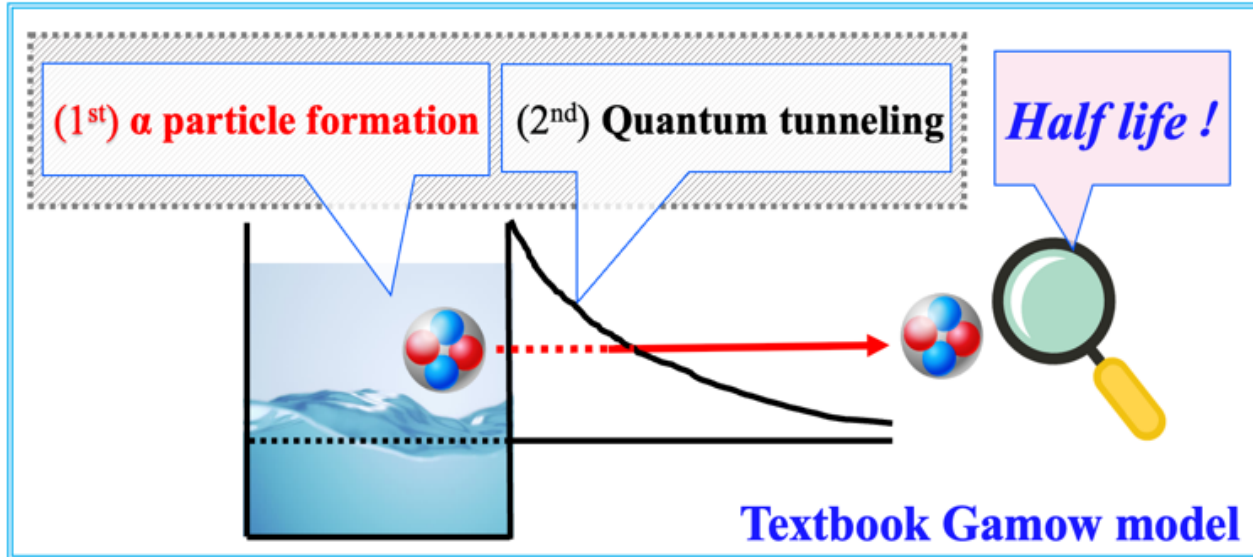
*Carey et al. PRC1981*



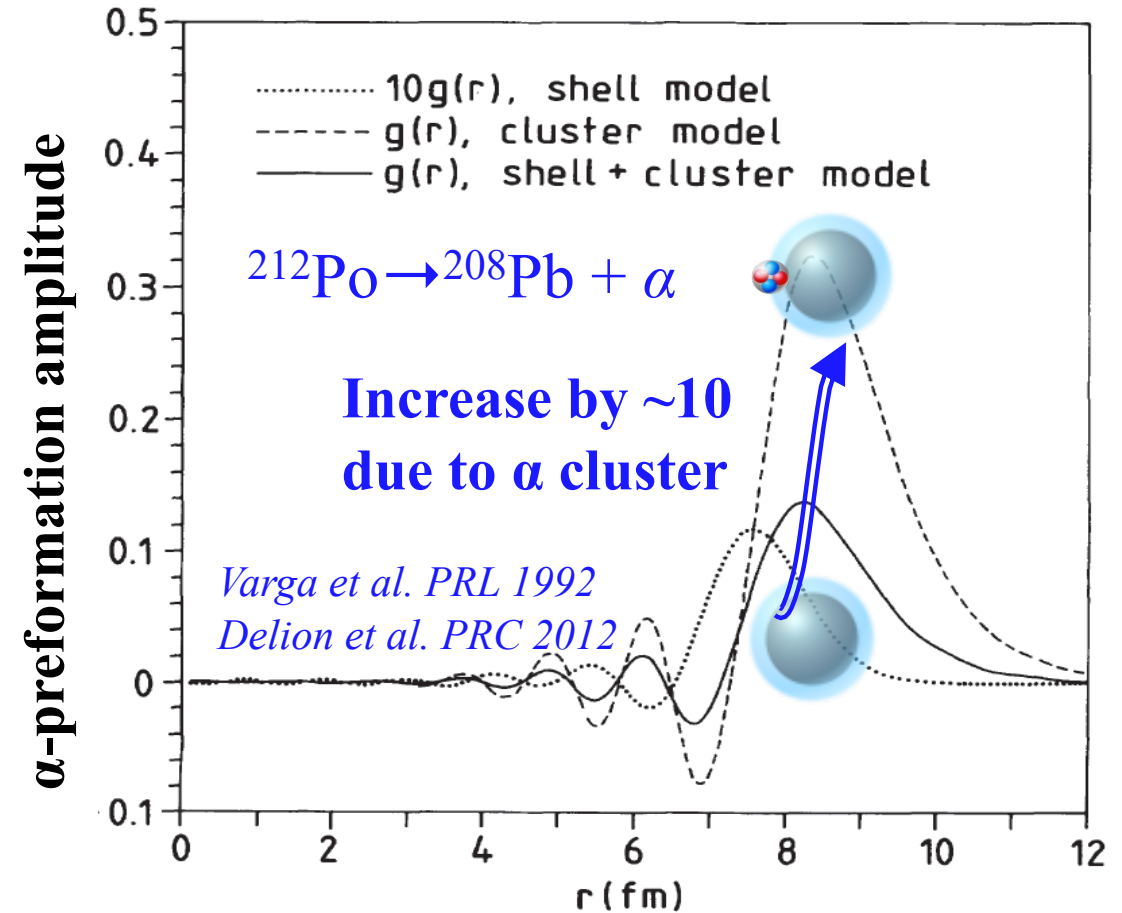
# Heavy nuclei: $\alpha$ preformation in $\alpha$ decay?



Origin of  $\alpha$  particles in  $\alpha$  decay?



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

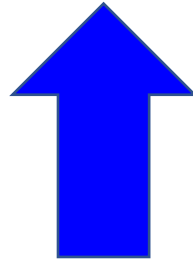


✓ Theoretical calculations

*e.g. Xu/Ren et al. PRC93(16)011306; PRC104(21)034302*  
*J.M.Dong et al. PLB813(21) 136063*



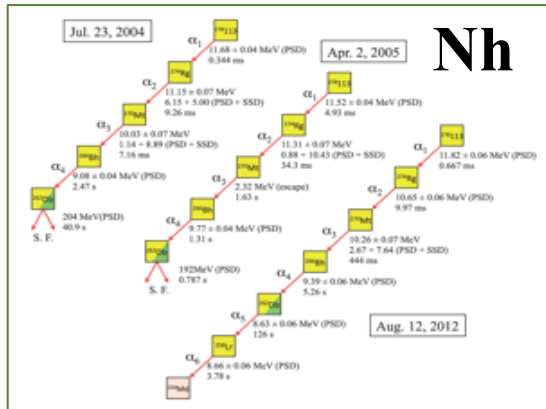
# $\alpha$ decay in heavy and superheavy nuclei



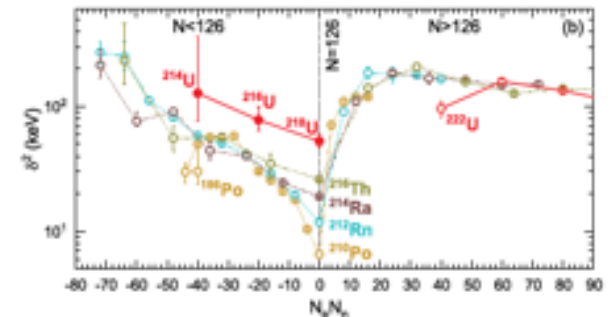
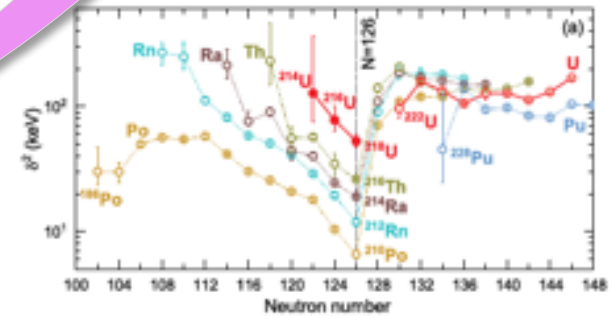
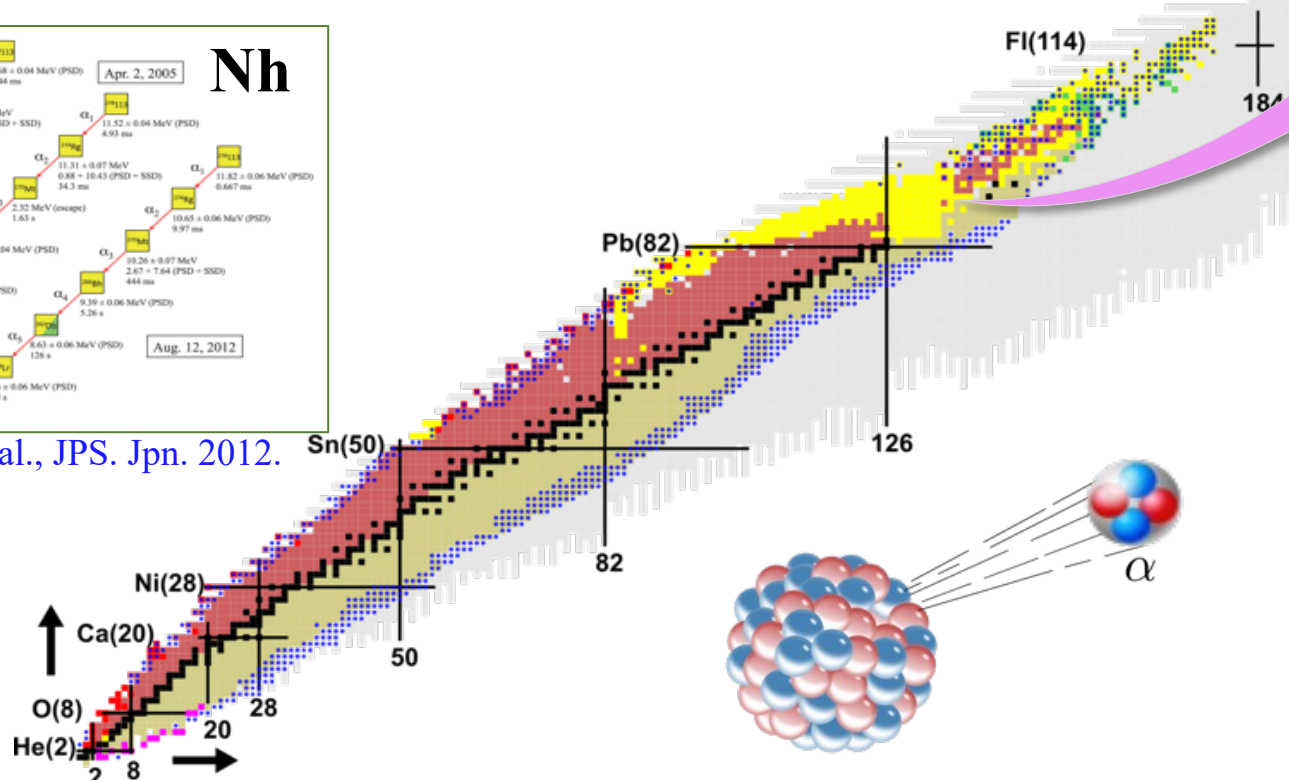
Z=119? Z=120?



“Island of stability”



Morita et al., JPS. Jpn. 2012.

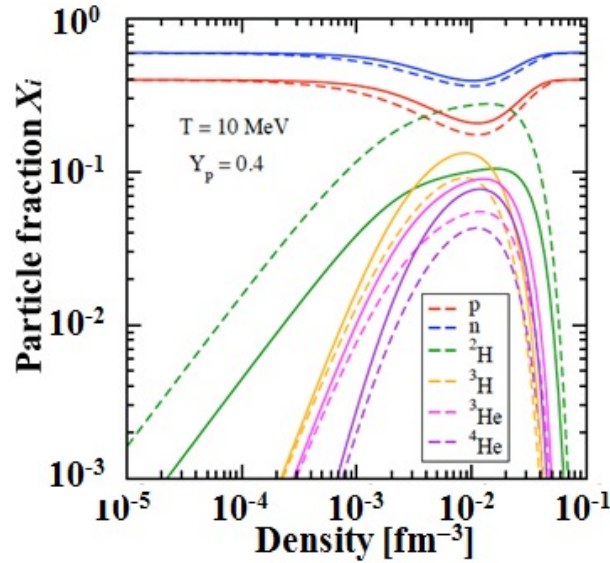
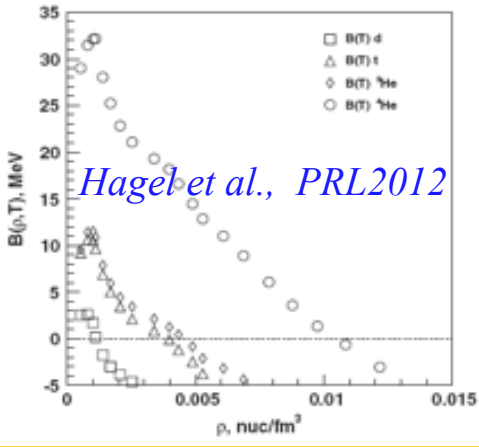


Zhang et al. PRL 2021

# Nuclear matter: Impact of clustering on EoS

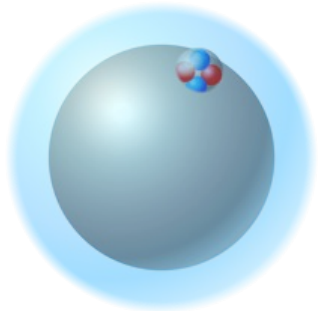
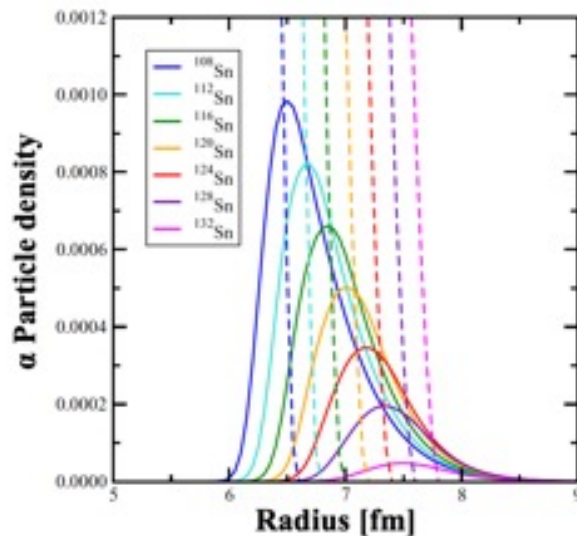
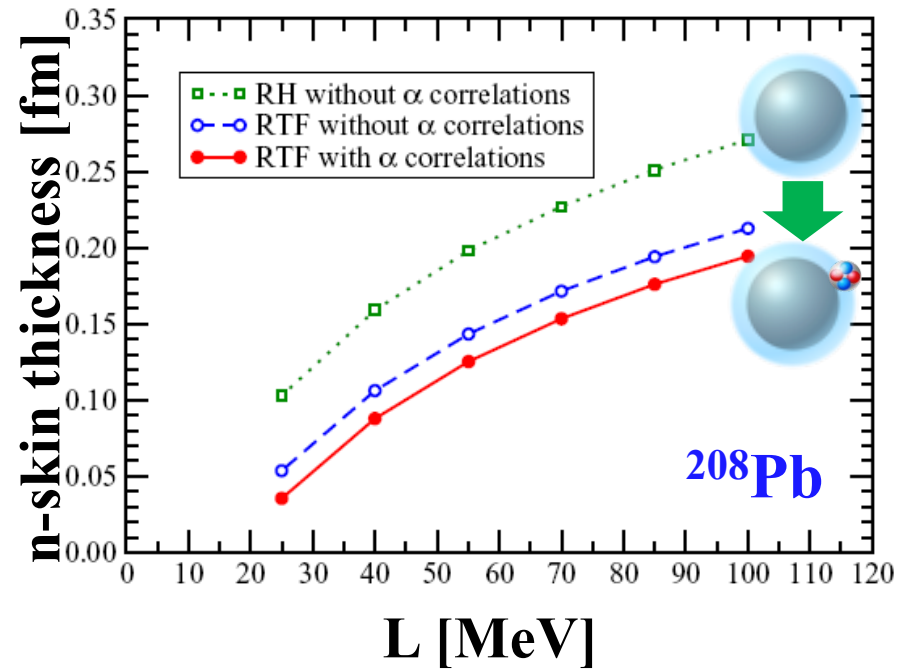
- ✓ Theoretical predictions of  $\alpha$  clusters in low-density environments like the surface of heavy nuclei:

## Heavy-ion collisions

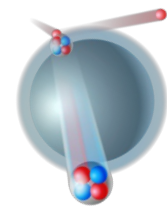


*Typel, PRC89(2014) 064321, PRC 81(2010) 015803*

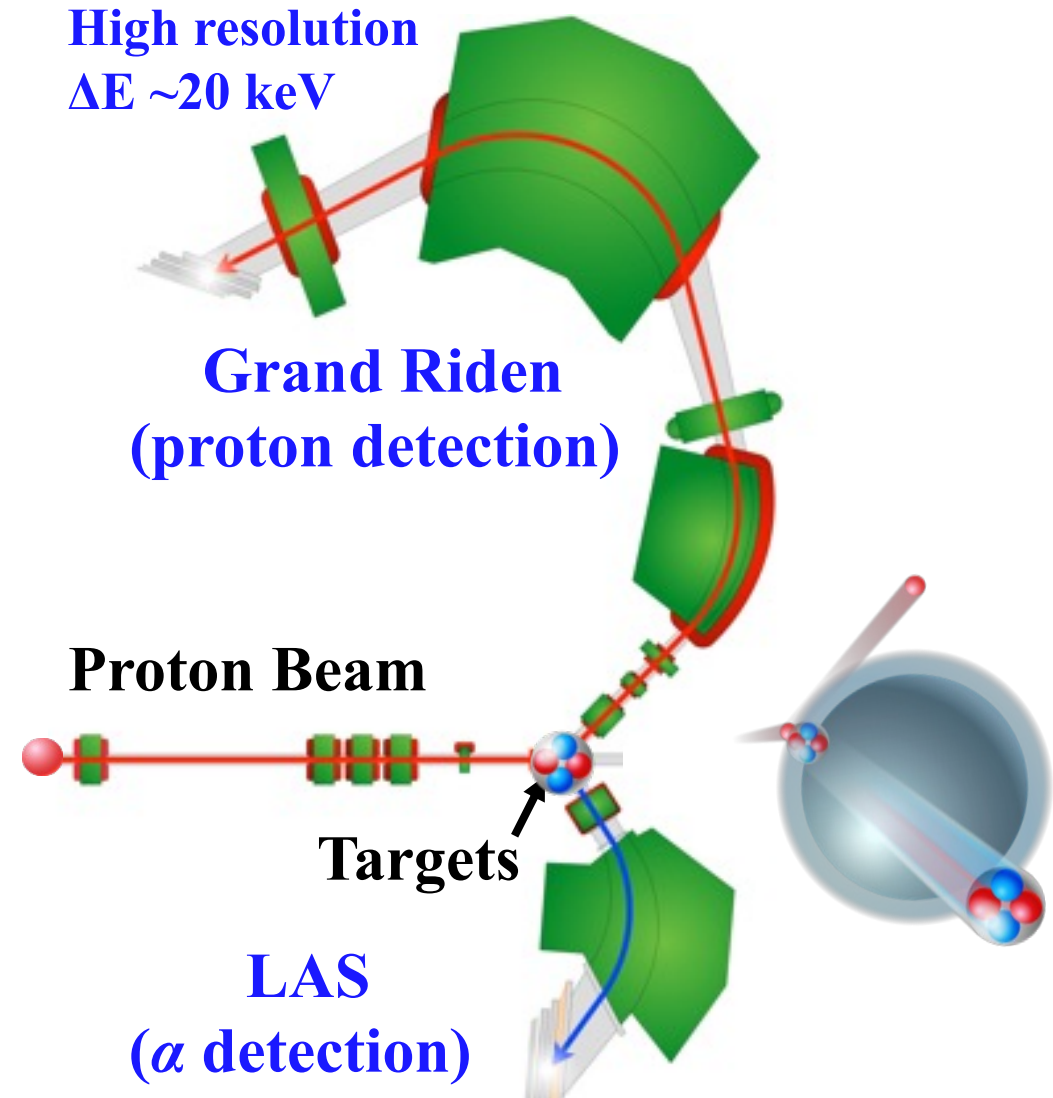
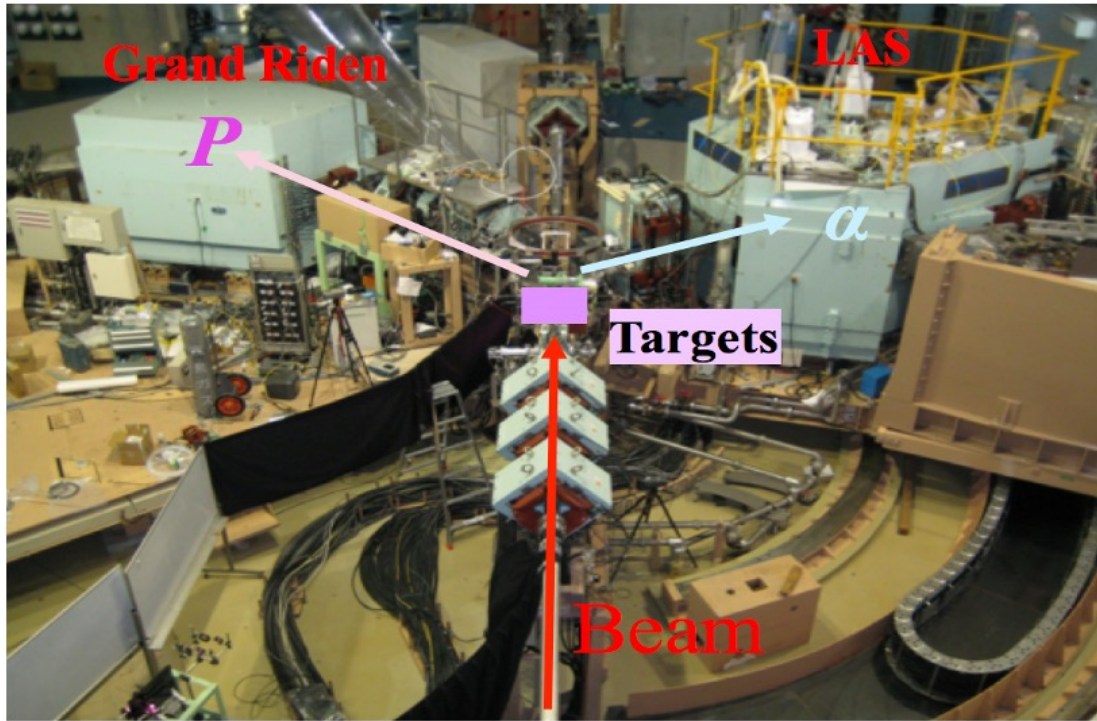
**$\alpha$  cluster suppress  $n$  skin**



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



- ✓ **Beam:** 392 MeV proton,  $\sim 100$  pA
- ✓ **Targets:**  $^{112,116,120,124}\text{Sn}$  ( $\sim 40$  mg/cm $^2$ )

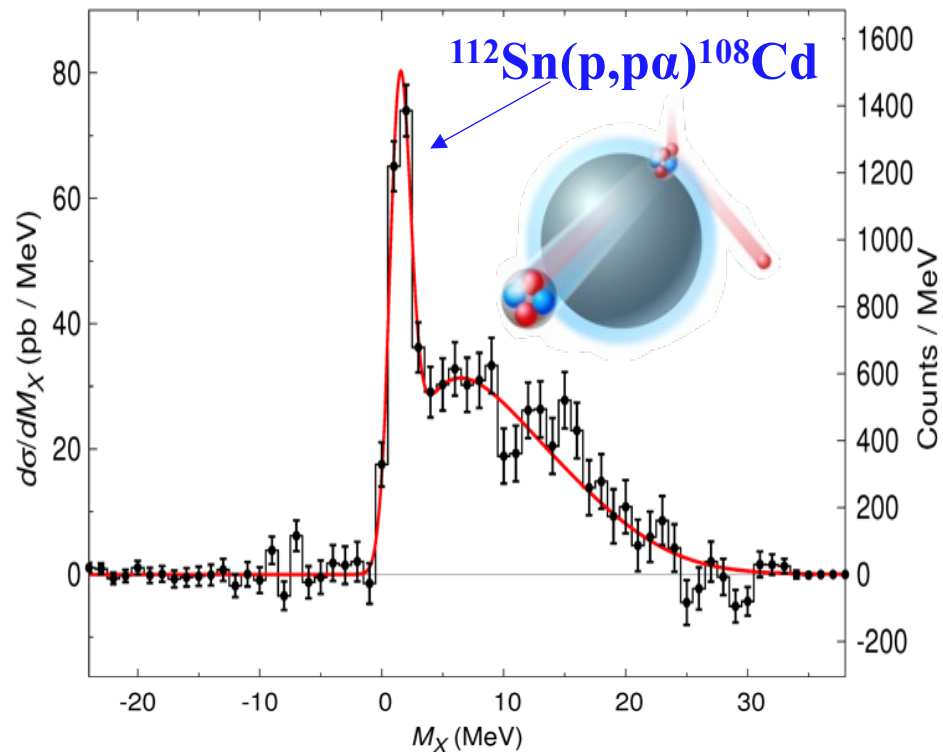


# knockout $\alpha$ clusters from heavy nuclei $^{112-124}\text{Sn}$



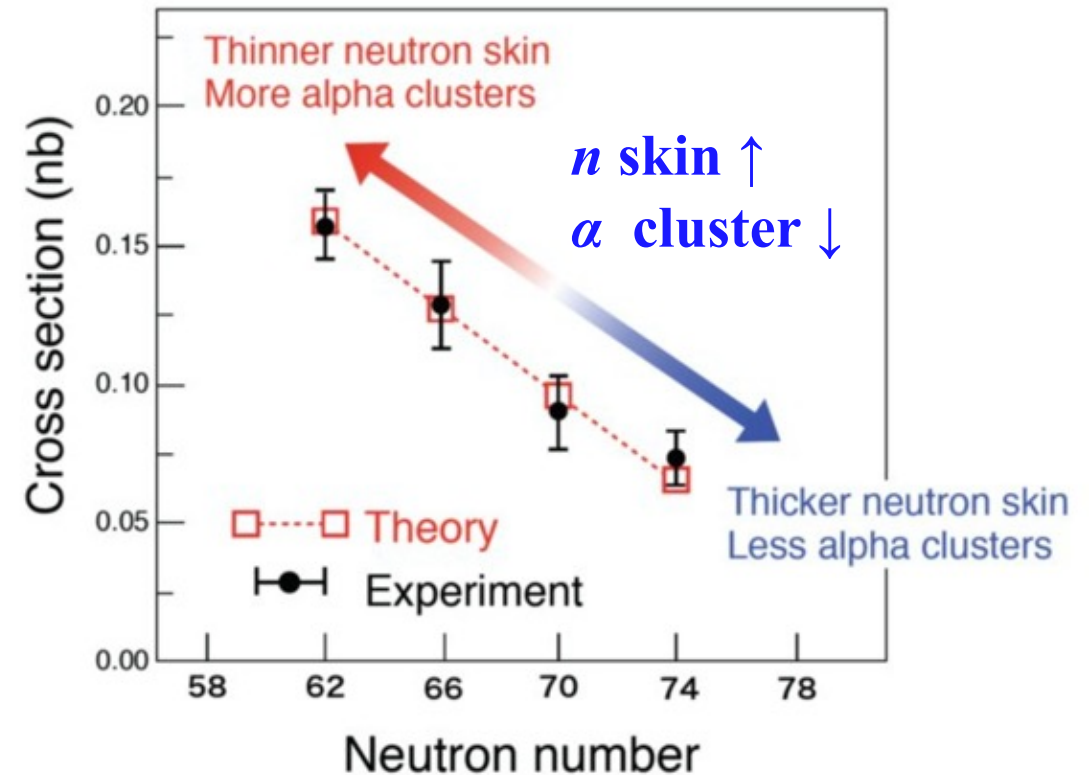
Tanaka, Yang et al. *Science* 371, 260–264 (2021)

## $\alpha$ separation energy spectrum



- ✓  $E_{\text{sep}}$  Peak clearly observed for all Sn isotope  $^{112,116,120,124}\text{Sn}$ .

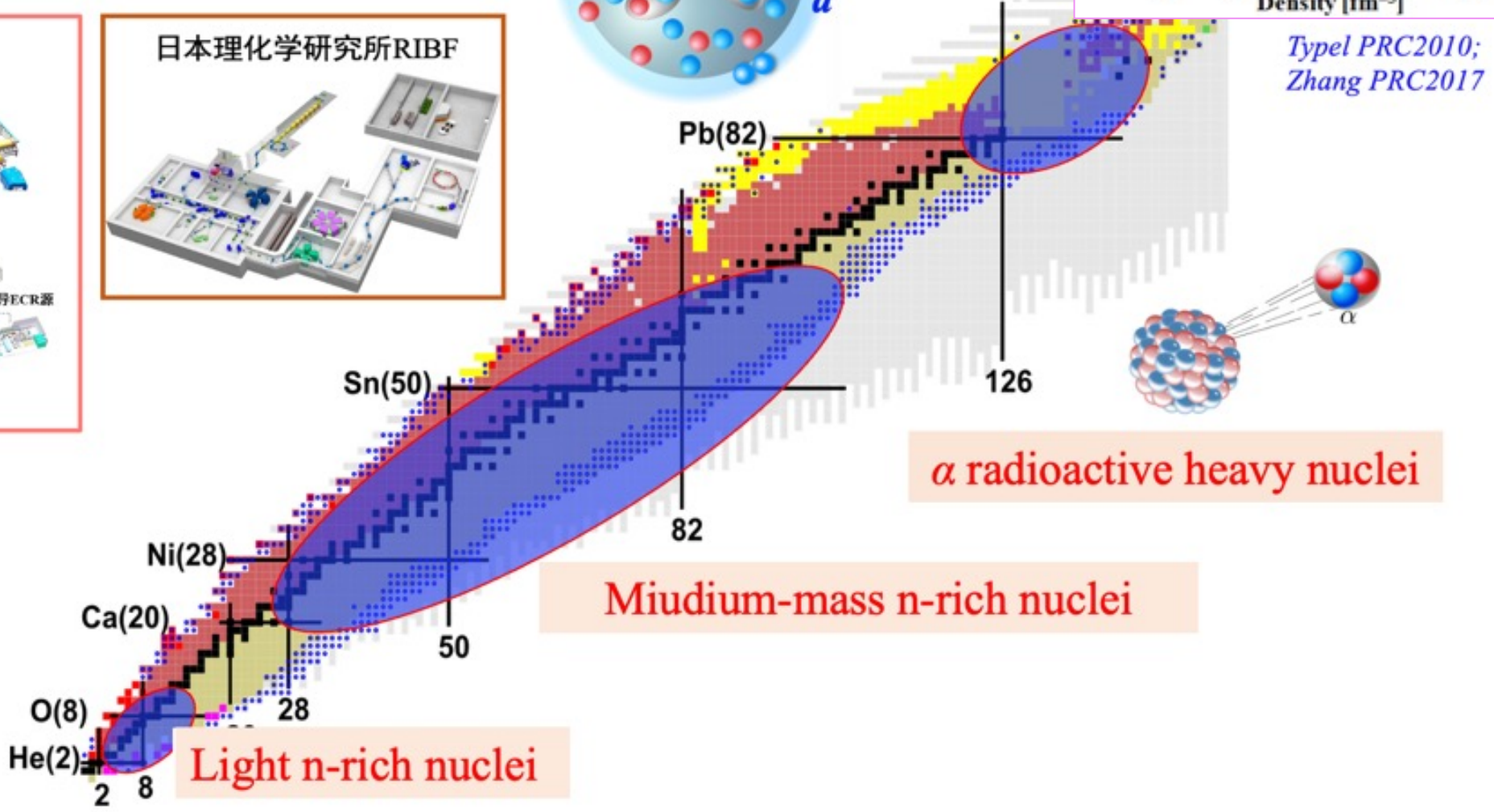
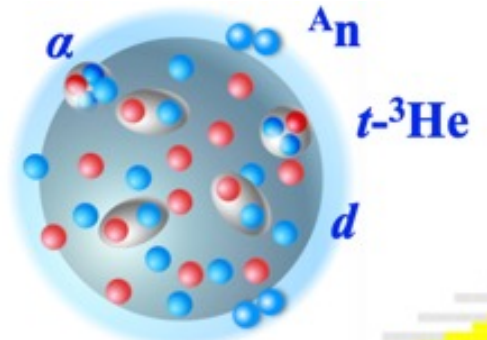
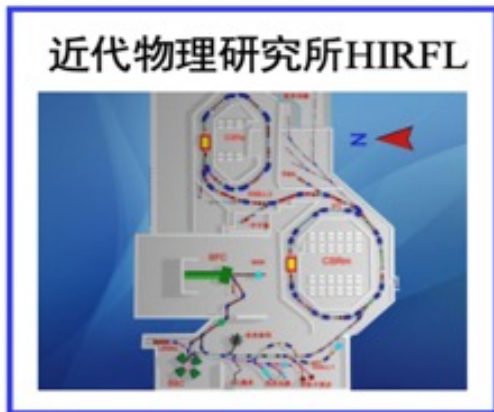
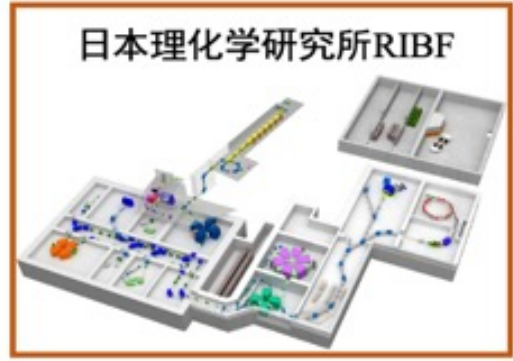
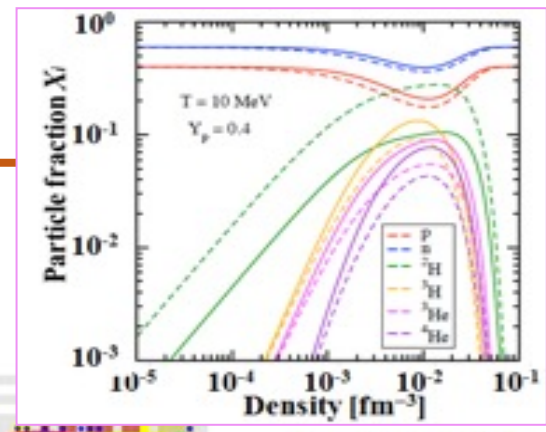
## $\alpha$ cluster knockout reaction



- ✓ Reaction Theory: Distorted-Wave Eikonal Approximation
  - ✓  $\alpha$ -cluster wave function from gRDF
  - ✓ Distortion effect considered

# What's next: More Cluster, More exotic

- More exotic nuclei, more types of cluster ( $\alpha$ ,  $t$ ,  ${}^3\text{He}$ ,  $d$ )



Type1 PRC2010;  
Zhang PRC2017

$\alpha$  radioactive heavy nuclei

Medium-mass n-rich nuclei

Light n-rich nuclei

# Outline

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- ✓ Introduction: basics about the structure of nucleus
- ✓ Clustering in nuclear systems
- ✓ **Halo and neutron correlations (skipped)**
- ✓ **Summary and Perspective**

# Cluster structures in excited states of light nuclei

## 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

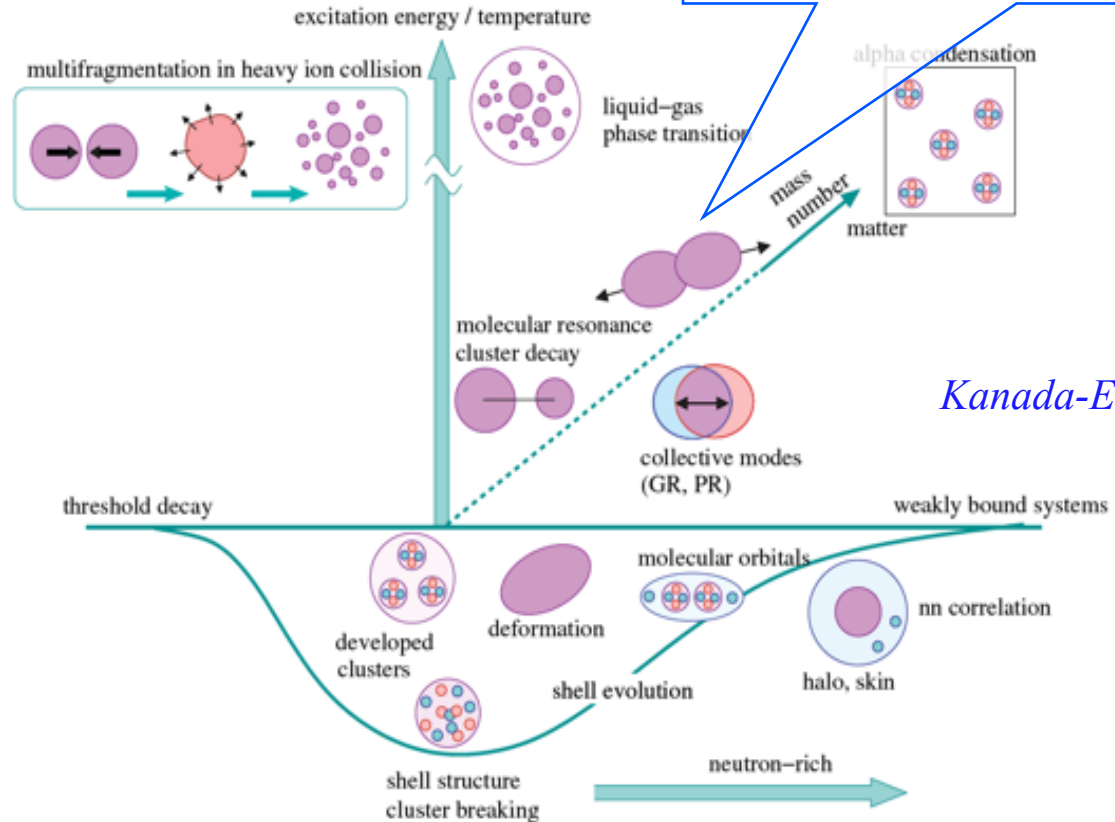
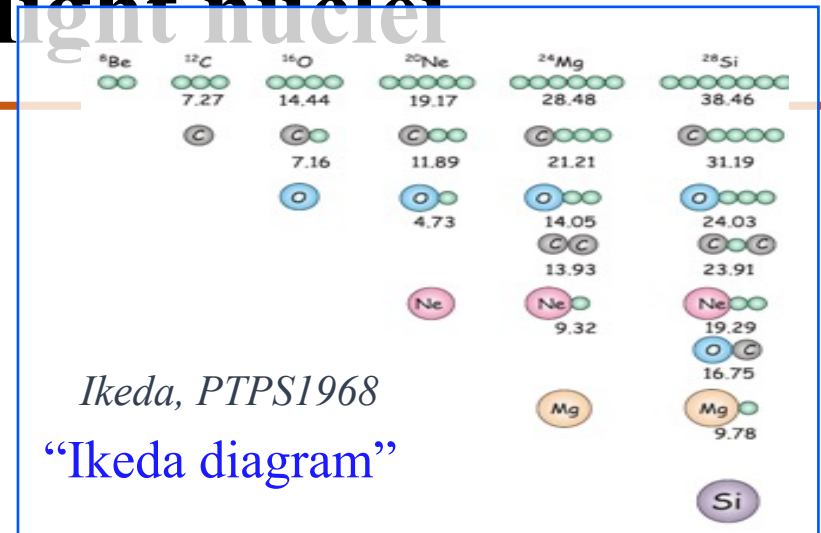


e.g., Chen et al. Com. Phys 2023  
 Liu et al. PRL 2020, Li et al. PRC2017  
 Yamaguchi PLB2017, Baba/Kimura PRC2018

## Gas-like ( $\alpha$ -condensate) states

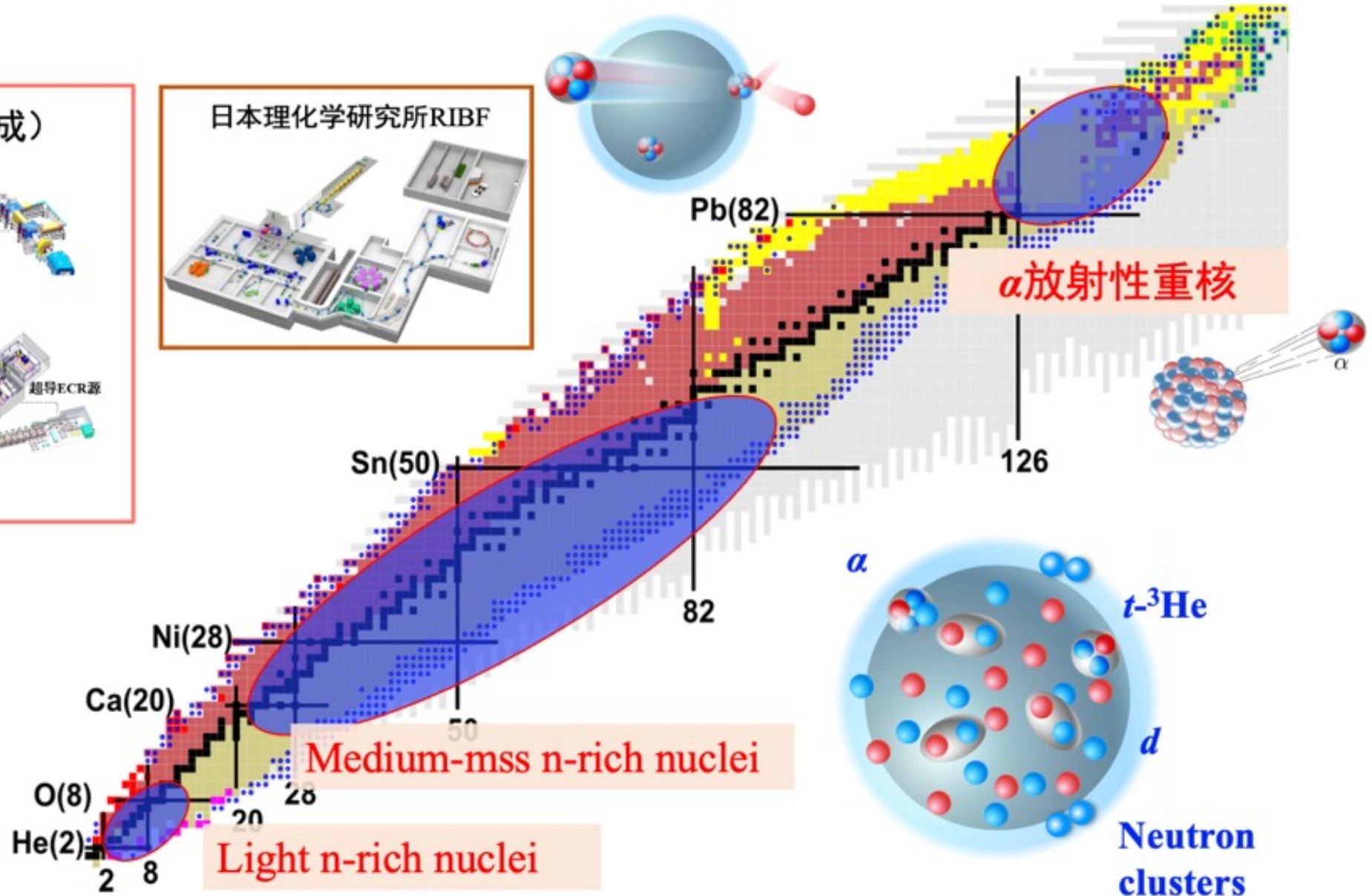
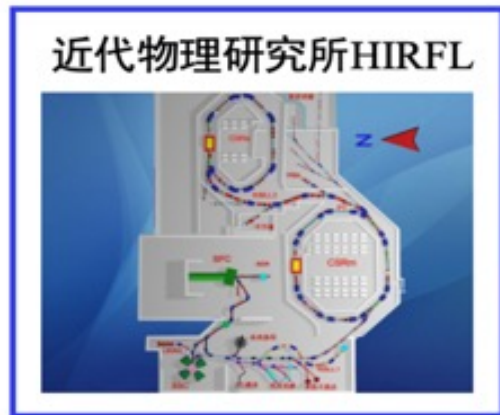
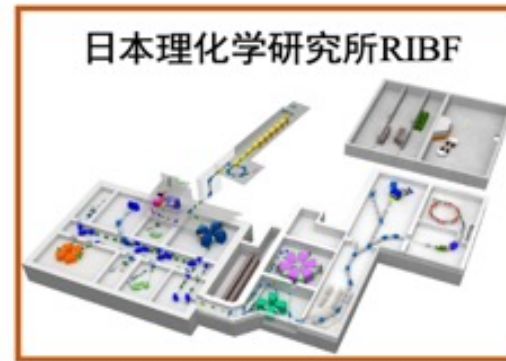


e.g., Chen et al. SC2023; Zhou et al. NC 2023  
 Adachi et al. PLB2021;  
 THSR, PRL2001; Zhou/Ren et al. PRL2013



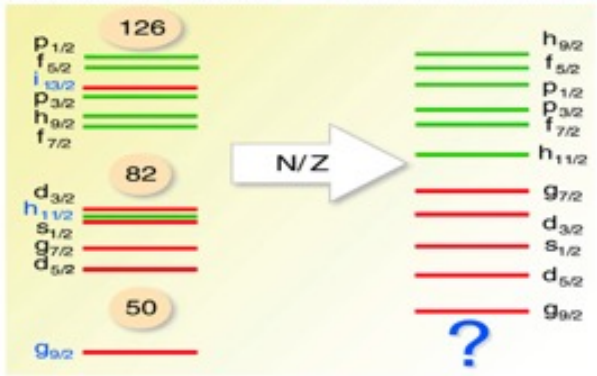
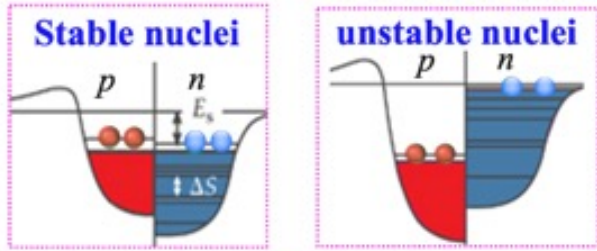
Kanada-Enyo, PTEP 2012

# Cluster structure in ground states probed by knockout reaction

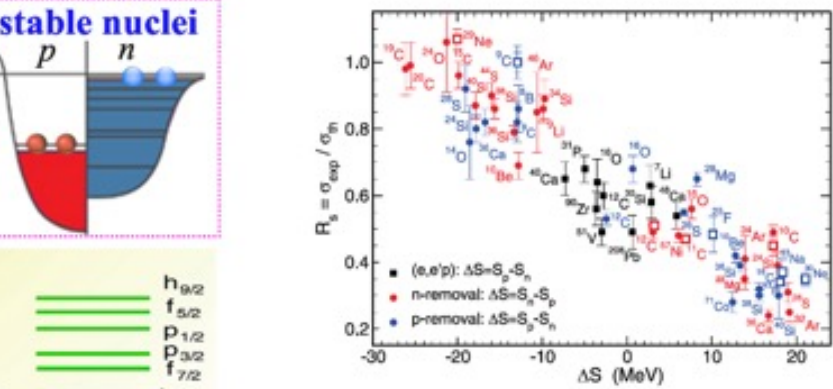
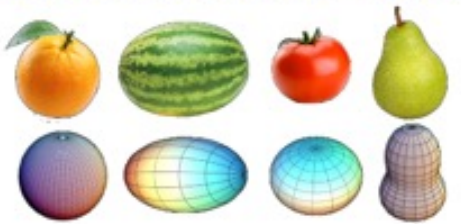




# What is the structure of (unstable) nuclei?

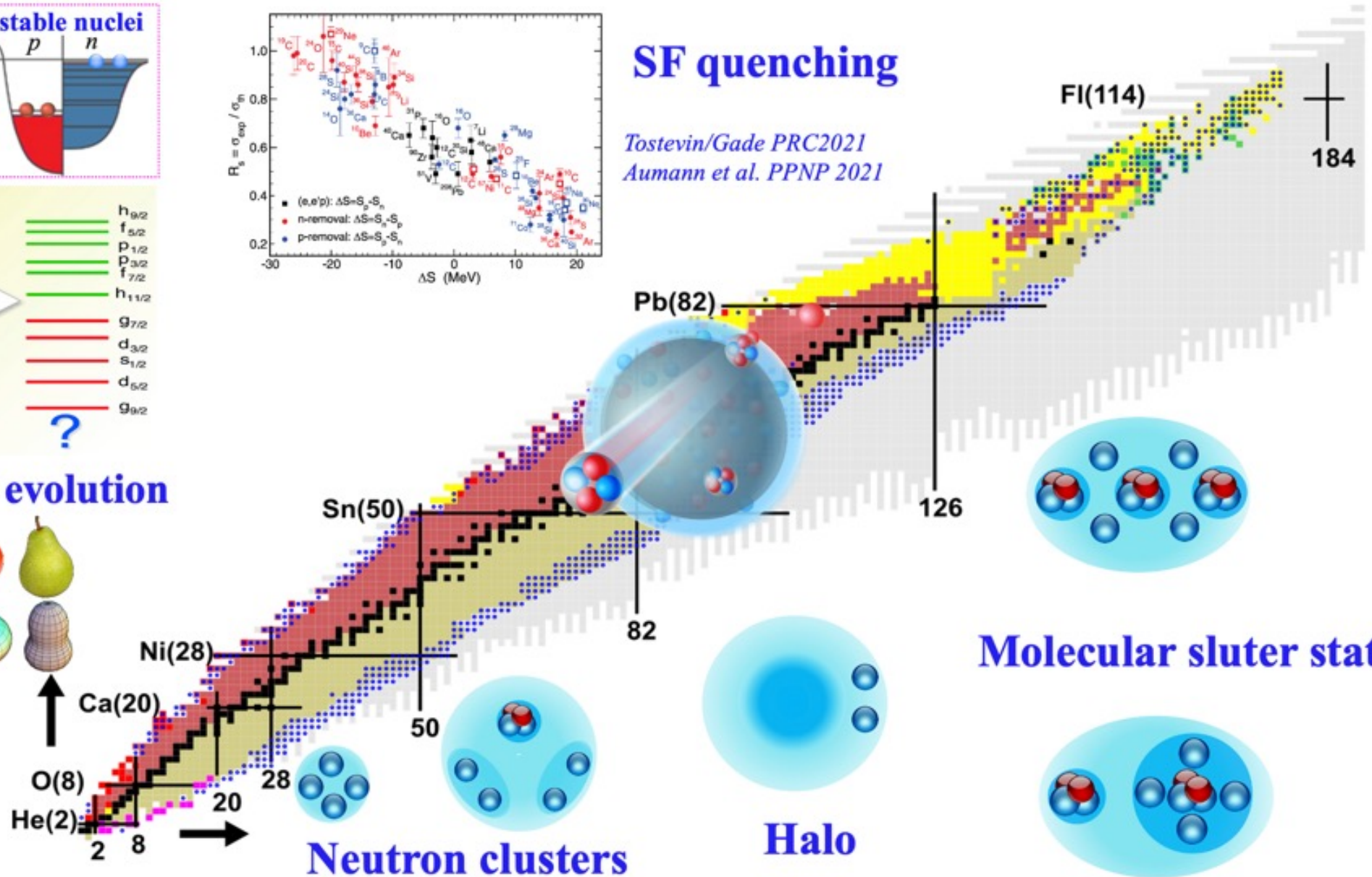


## Shell structure evolution



## SF quenching

Tostevin/Gade PRC2021  
Aumann et al. PPNP 2021



Neutron clusters

Halo

Molecular sluter states



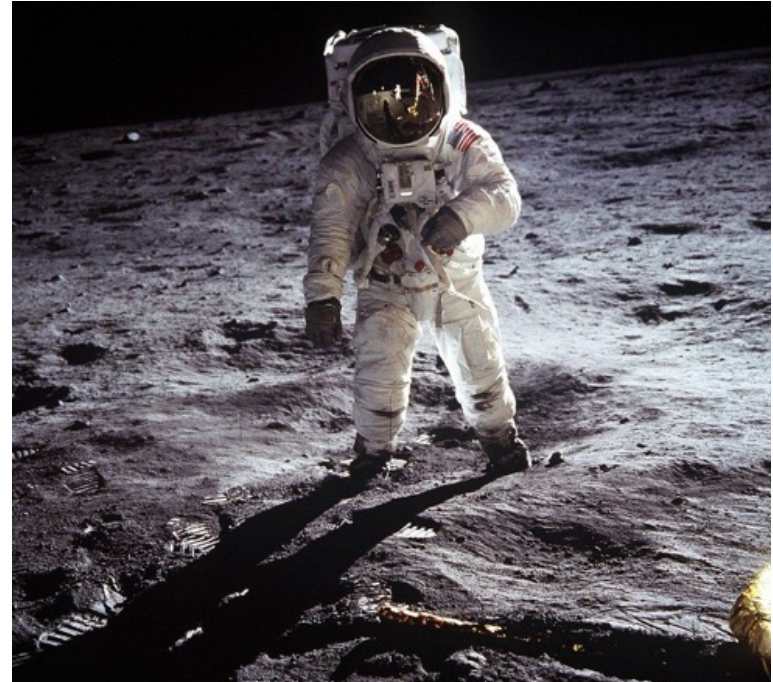
# A wonderworld of atomic nuclei: from tiny to infinity

✓ **Introduction**

✓ **Clustering in nuclear systems**

✓ **Halo and neutron correlations**

✓ **Summary and Perspective**



*“That’s one small step for man. One giant leap for mankind.”*

-Neil Armstrong, July, 1969, Moon.

**Thank you!**