基于集团敲出反应
研究原子核体系的集团结构

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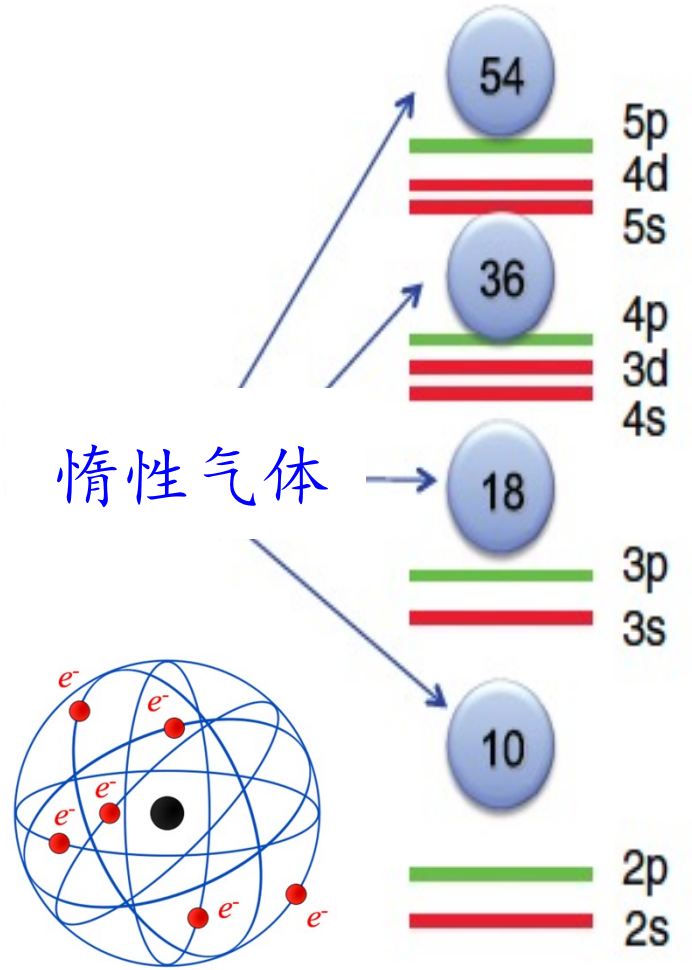
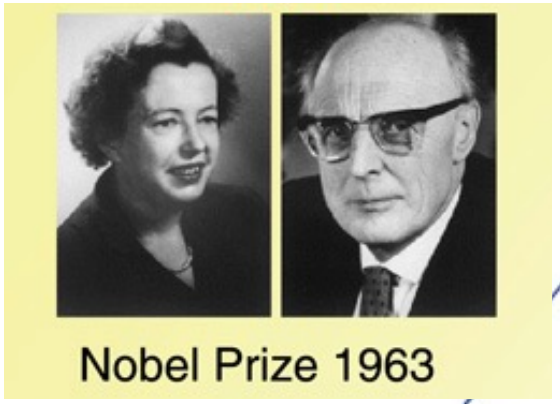
报告提纲

- ✓ 引言
- ✓原子核的集团结构
  - ✓轻核激发态的集团结构
  - ✓基于$(p,p\alpha)$反应研究重核表面的α集团
- ✓多中子关联与中子集团态

原子核的结构是什么？

原子的壳结构



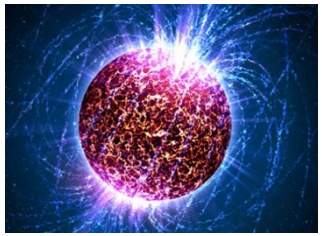


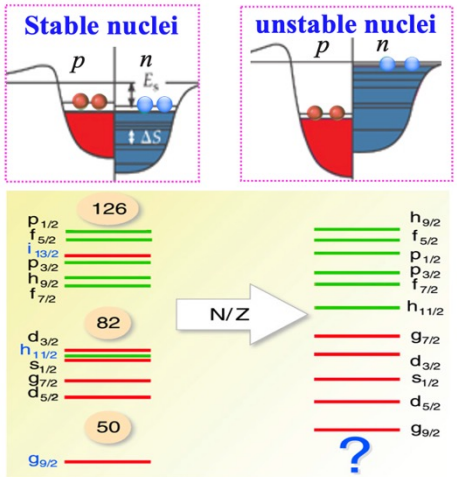
原子核的壳结构

丰中子不稳定核的奇特结构与关联

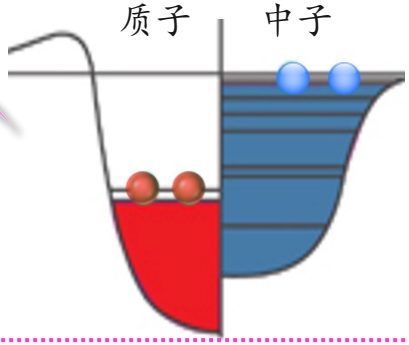
- 原子核存在的极限（滴线、超重岛）？
- 宇宙中重元素的生成？
- 丰中子物质及中子星的性质？

中子星





丰中子不稳定核

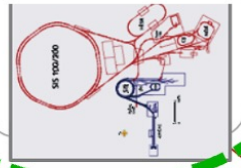


放射性核束物理(RIB)大科学装置

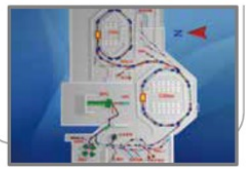
目前最活跃　即将建成

加-ISAC 运行

德-FAIR 2025

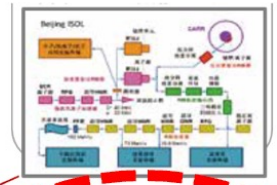


中-HIRFL 运行

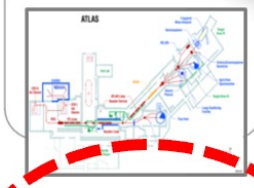


中-BRIF 运行

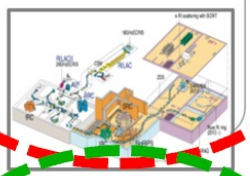
中-BISOL 规划



美-ATLAS 运行

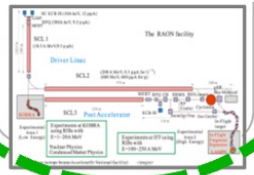


日-RIBF 运行

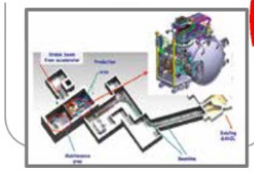


美-FRIB 2022

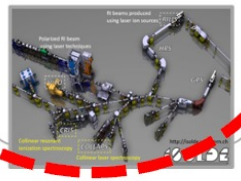
韩-RAON 2025



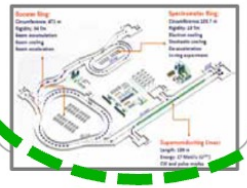
法- SPIRAL 运行



CERN-ISOLDE 运行



中-HIAF 2025



更高流强、更远离稳定线

报告提纲

✓ 引言

✓原子核的集团结构

✓轻核激发态的集团结构

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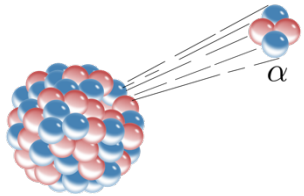
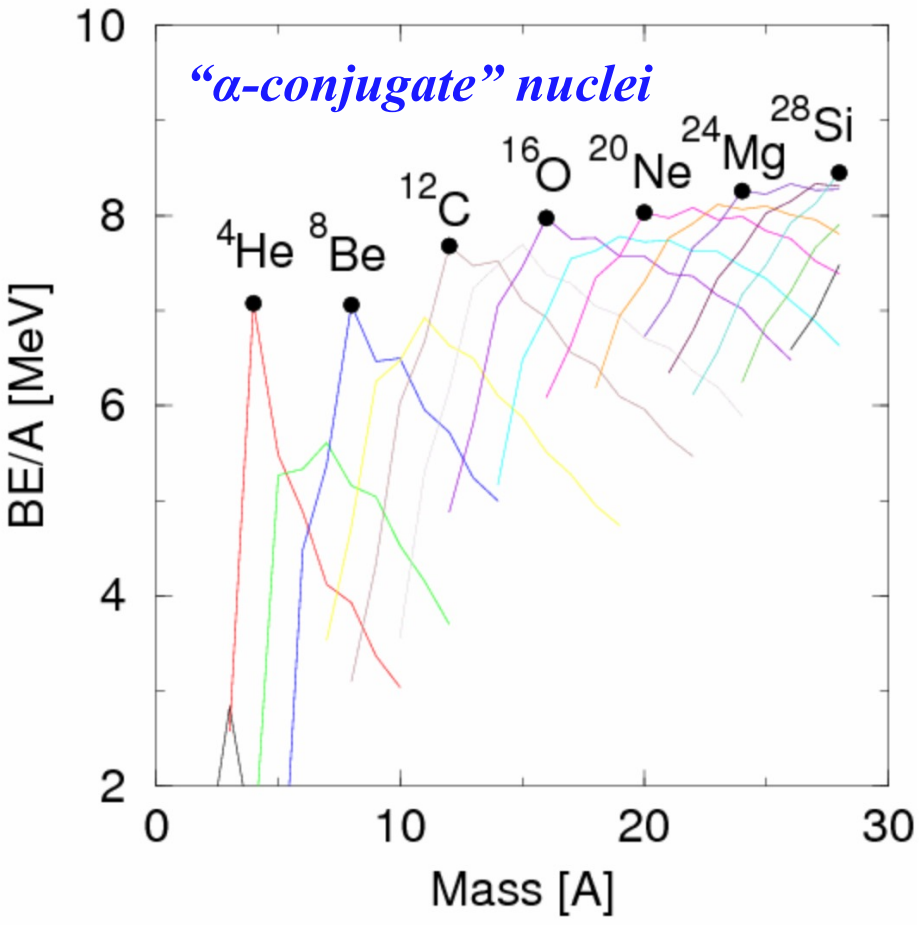
✓多中子关联与中子集团态

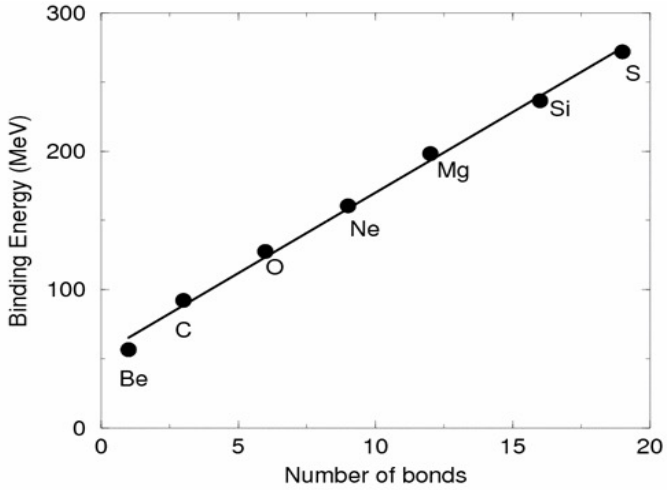
"α particle" nuclei in 1930s

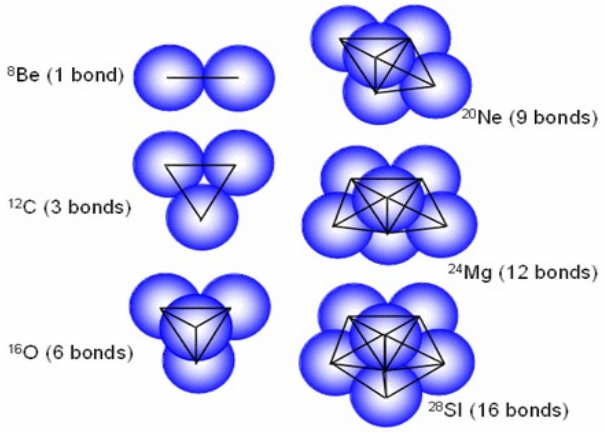
- ✓ Alpha radioactivity: 1890s
- ✓ Alpha decay model (quantum tunneling): Gamow, 1928
- ✓ Discovery of the neutron: 1932, Chadwick



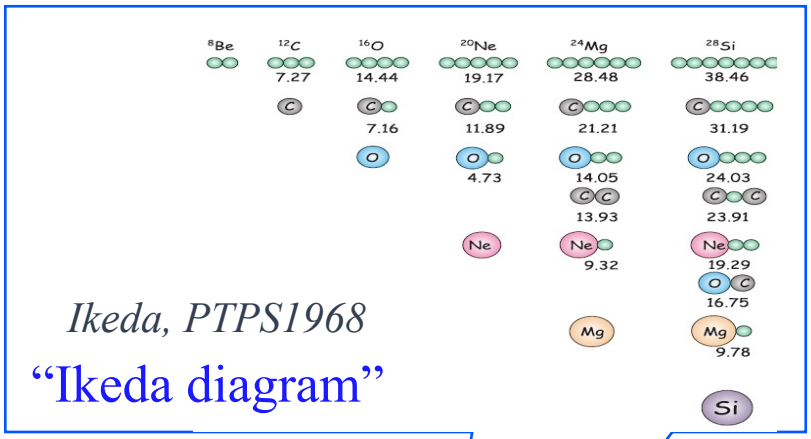
Hafstad and Teller, PR 1938

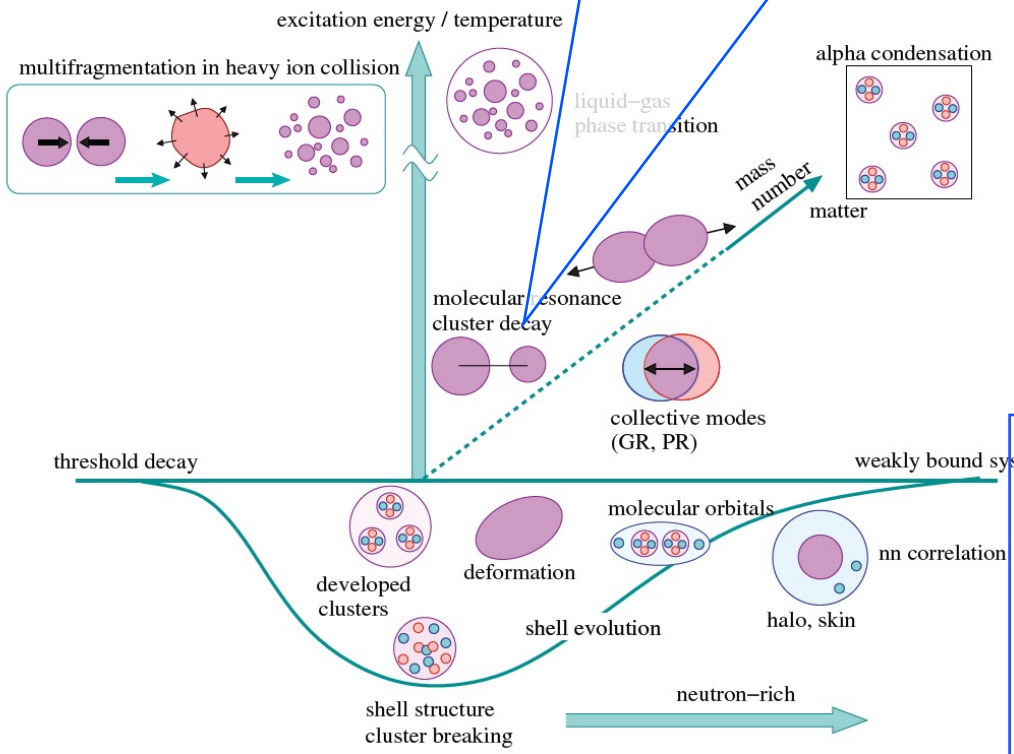






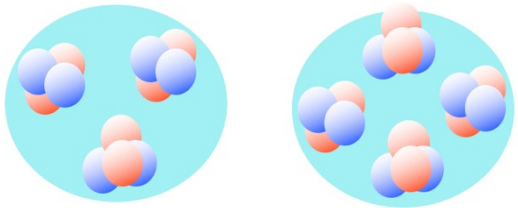
轻核激发态中丰富的集团结构





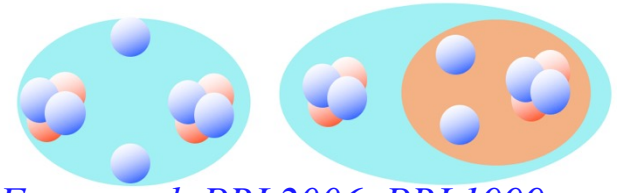
Kanada-Enyo, PTEP 2012

Gas-like (α-condensate) states



e.g., Adachi et al. PLB2021; THSR, PRL2001
Zhou/Ren et al. PRC2012, PRL2013

Molecular states in Be



e.g., Freer et al. PRL2006, PRL1999
Yang/Ye et al., PRL2014; Jiang et al. PRC2020
Ito et al. PRL2008, Lyu/Ren et al. PRC2016

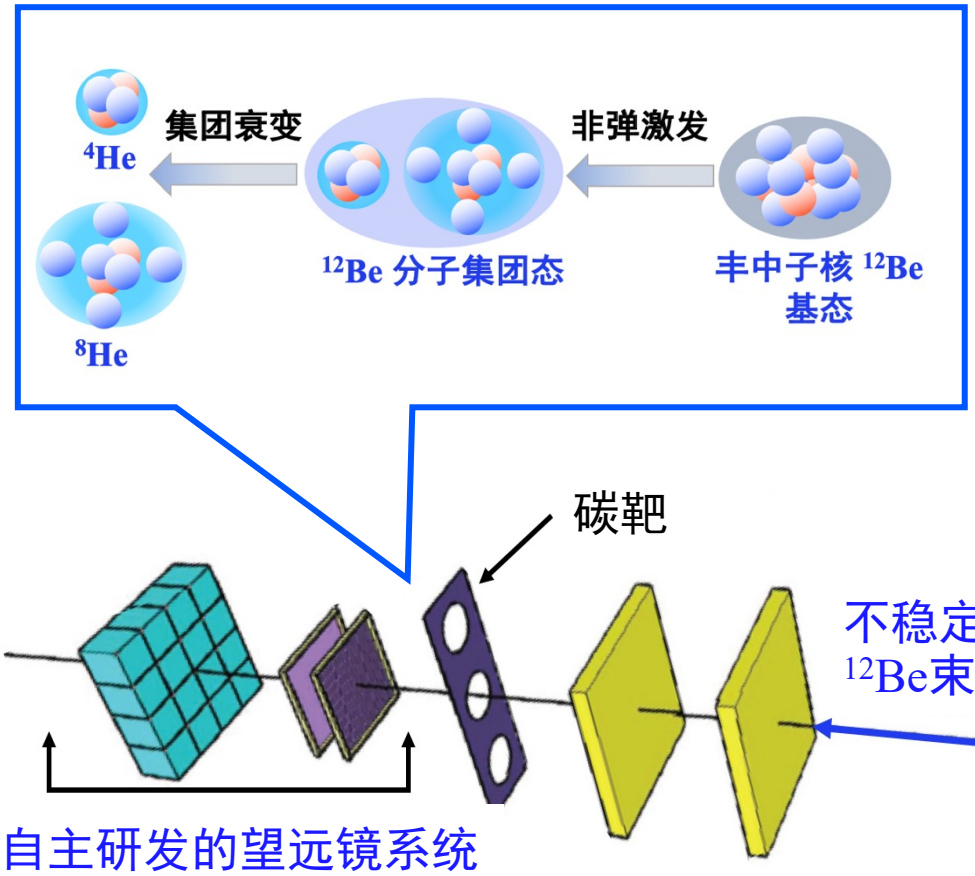
Linear-Chain states in C

e.g., Liu et al. PRL 2020, Li et al. PRC2017
Yamaguchi PLB2017,Fritsch et al.PRC2016
Baba/Kimura PRC2018, Zhao et al. PRL2015

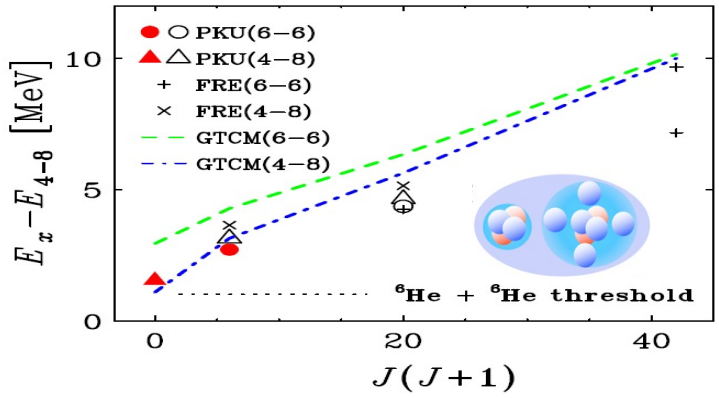
丰中子核^{12}Be的分子型集团结构

ZHY et al. PRL112(14)162501;PRC91(15)024304

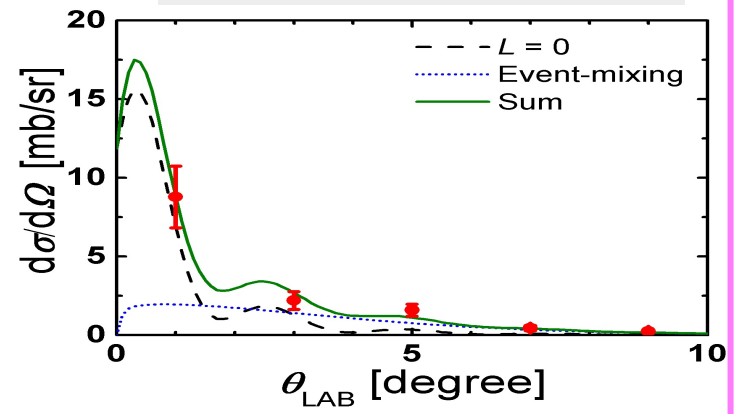
@HIRFL-RIBLL1束流线（中科院近物所）



分子态转动带

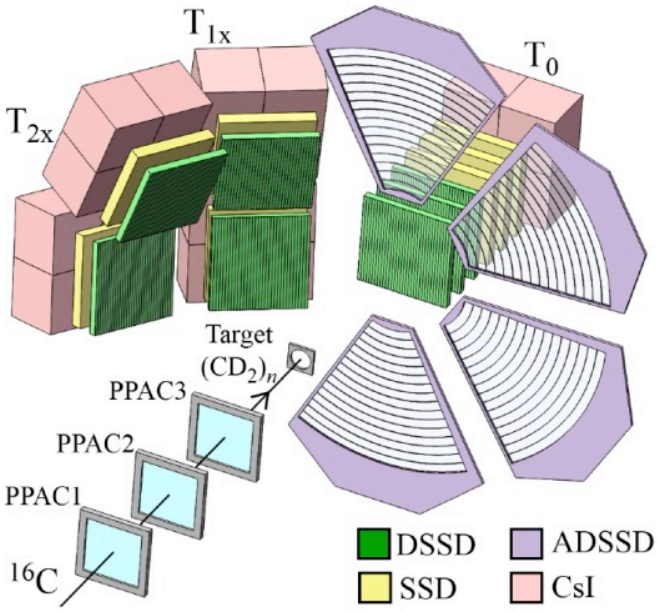


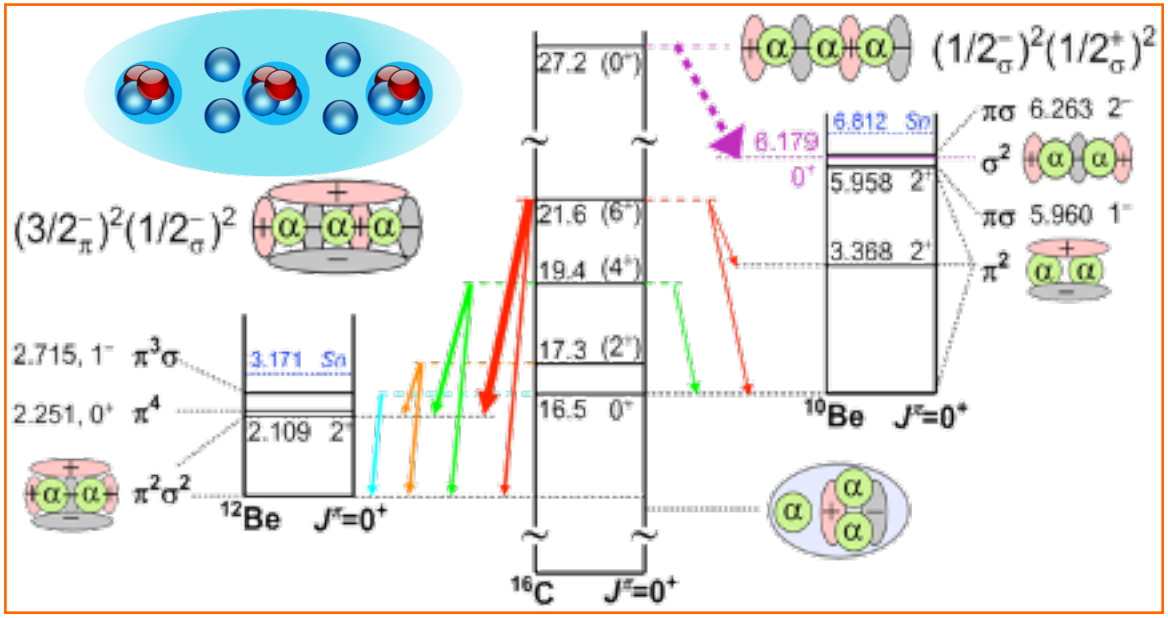
反常增强的单极跃迁



同时测定分子转动带、特征的单极跃迁强度、以及集团谱因子等三个关键物理量，从而确定了^{12}Be的分子型集团结构。

丰中子C同位素的线性链状分子态





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]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Kitami Institute of Technology, 090-8507 Kitami, Japan*

PKU团队
（叶沿林教授等）

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

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

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

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

RAPID COMMUNICATION

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

Selective decay from a candidate of the σ-bond linear-chain state in ^{14}C

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

报告提纲

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✓轻核激发态的集团结构

✓基于(p,pα)反应研究重核表面的α集团

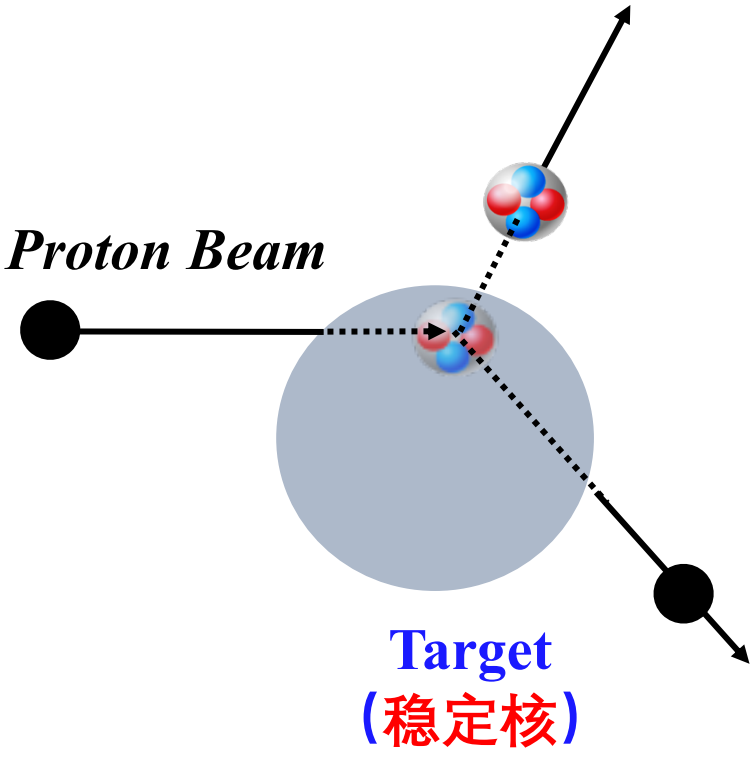
✓多中子关联与中子集团态

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

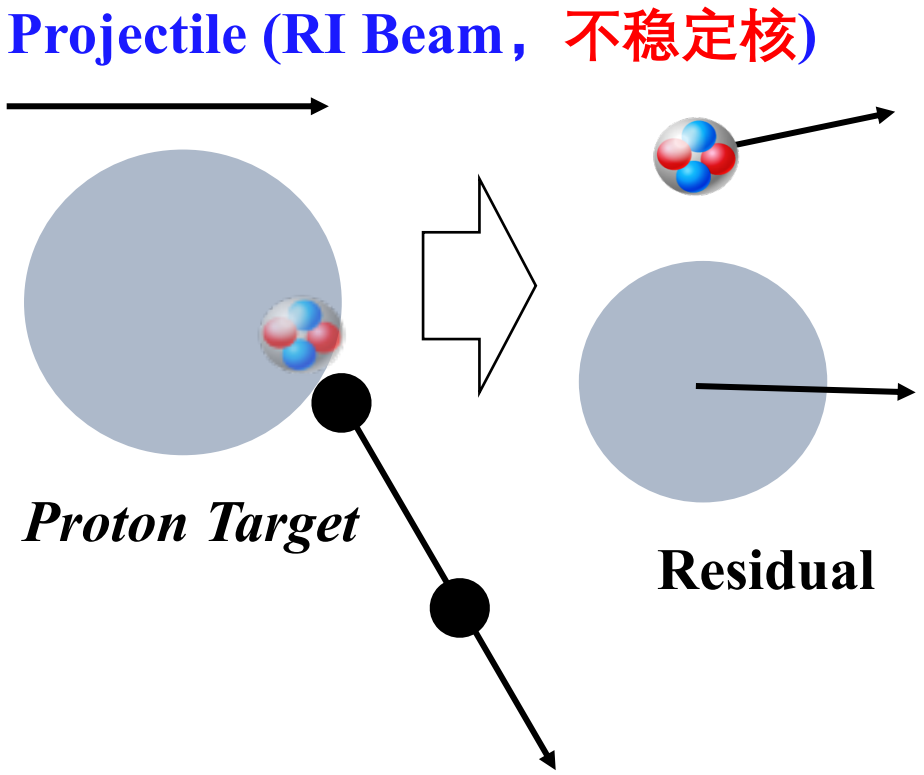
- ✓ Cluster structure in excited states: one may measure cluster fragments
- ✓ Clusters in *g.s*: quasi-free (p,$p\alpha$) [~ several hundred MeV/u]

Yoshida, PRC2016/PRC2018/PRC2019

Normal kinematics

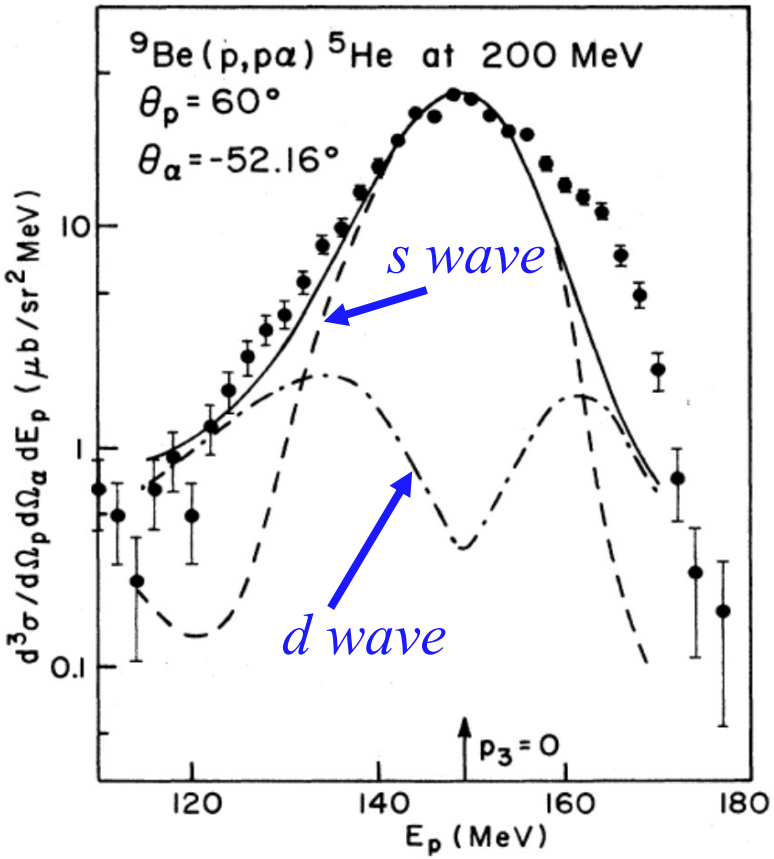


Inverse kinematics

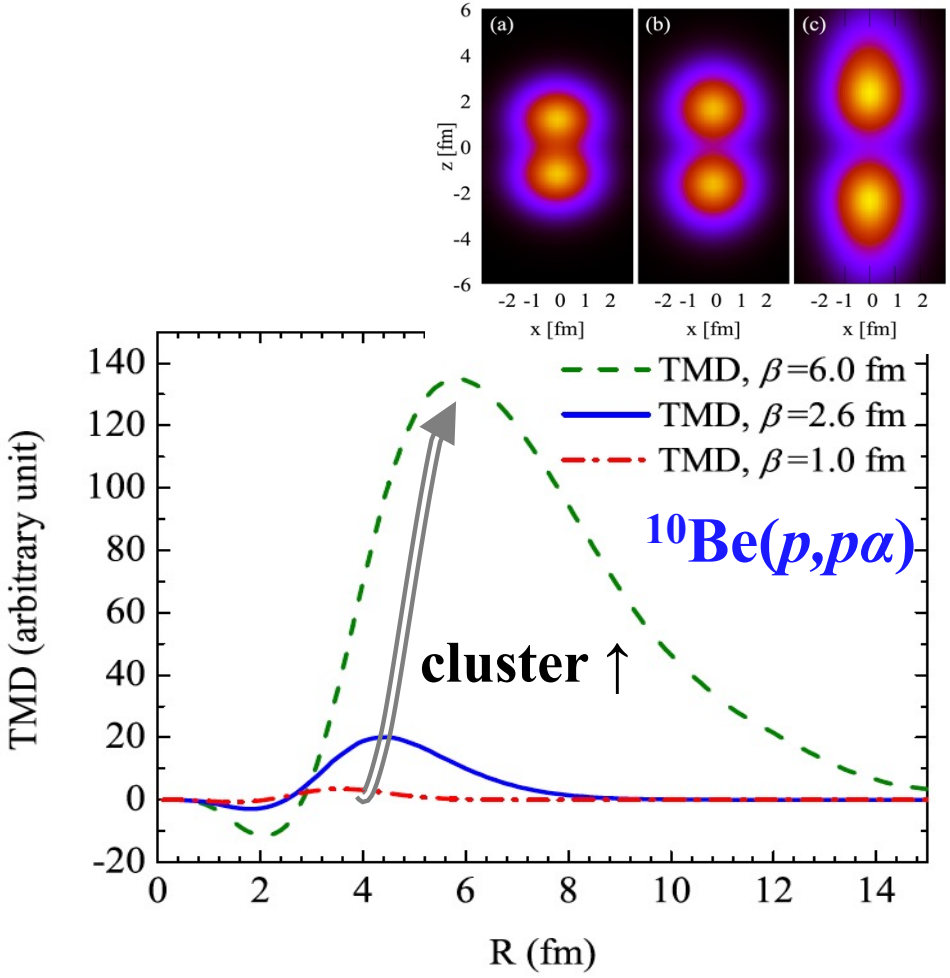


(p,$p\alpha$): probe α clusters in light nuclei

- ✓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.)*

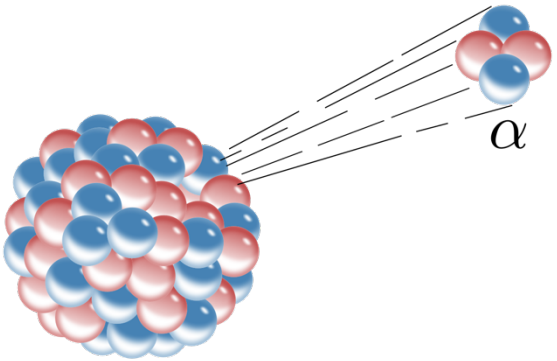


Nadasen et al. PRC1989
Chan and Roos PRC1977;Carey et al. PRC1981



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

Are there α clusters in heavy nuclei?

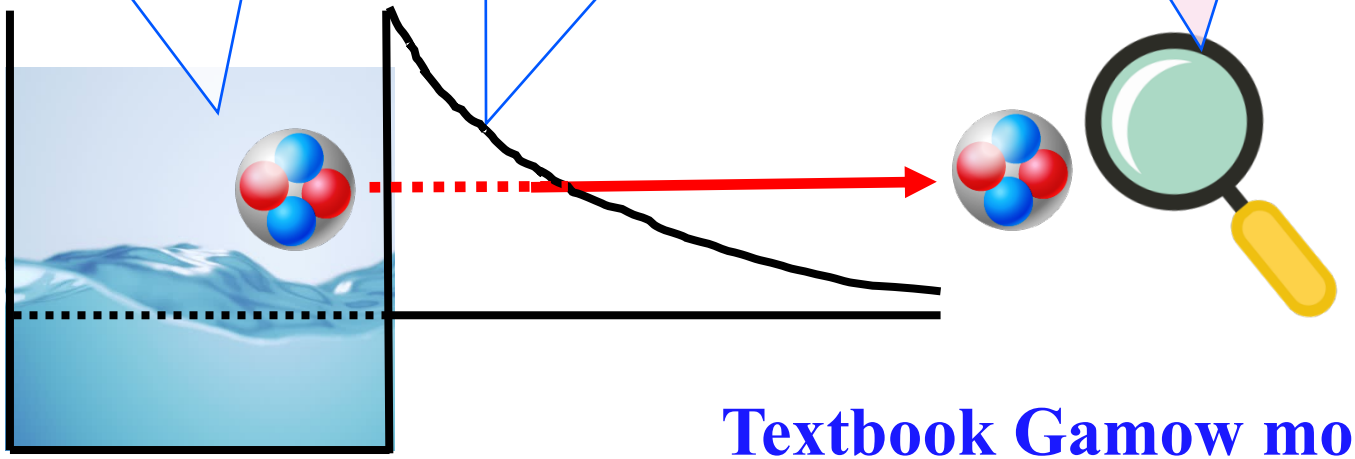


Origin of *α* particles in *α* decay?

(1st) α particle formation

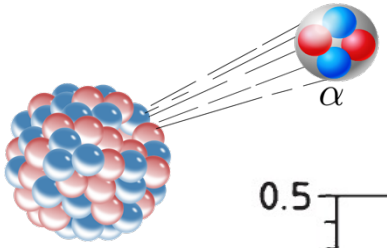
(2nd) Quantum tunneling

Half life !

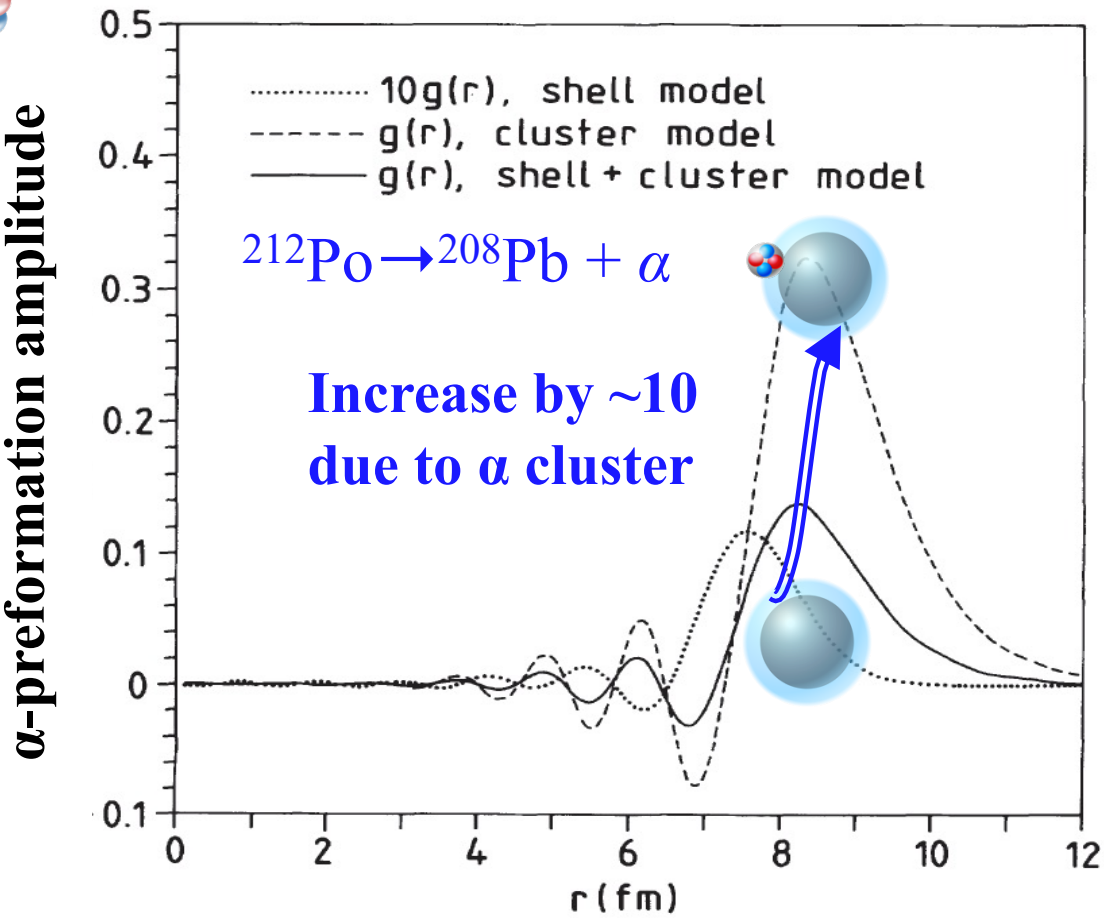


Textbook Gamow model

Are there α clusters in heavy nuclei?



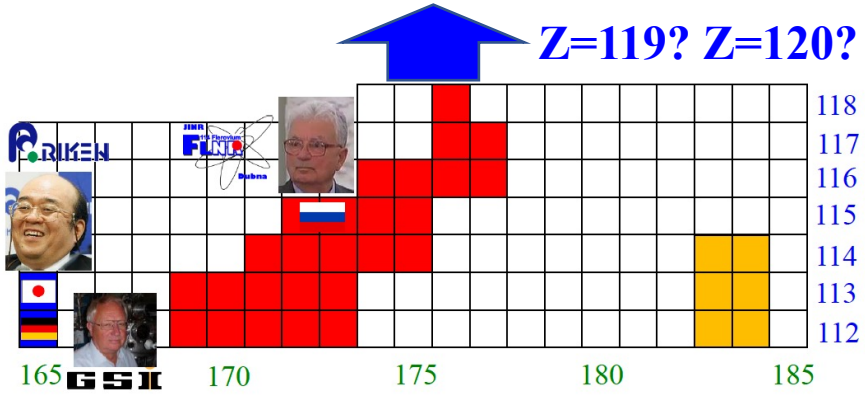
α decay half life: $T_{1/2} = \frac{\hbar \ln 2}{\Gamma_\alpha}, \Gamma_\alpha \propto |g(r)|^2$



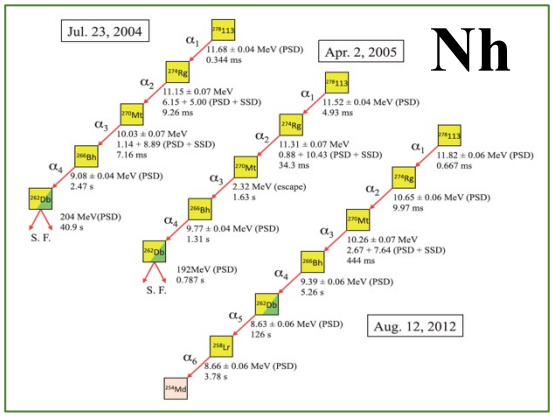
Varga et al. PRL 1992
Delion et al. PRC 2012

✓Theoretical calculations *Xu/Ren et al. PRC93(2016)011306*
Ren/Zhou Front. Phys. 13(2018)132110

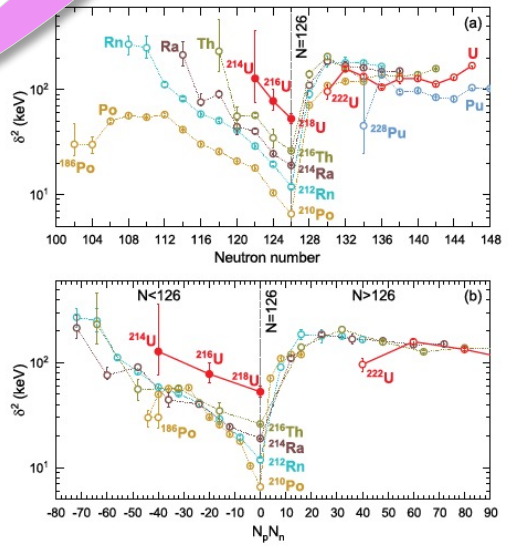
α decay in heavy and superheavy nuclei



"Island of stability"



Morita et al., JPS. Jpn. 2012.



Zhang et al. PRL 2021

EoS and symmetry energy

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

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

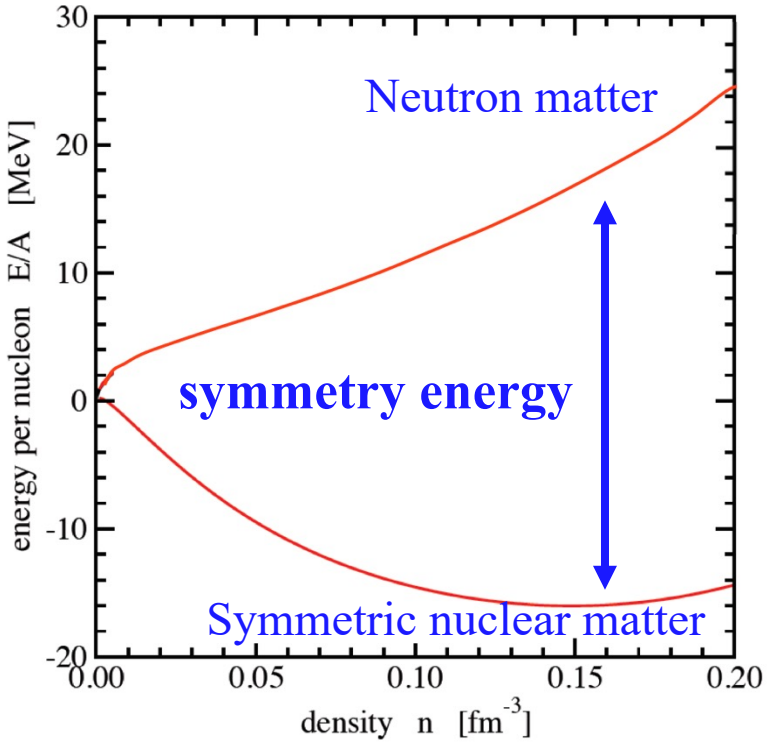
$$\rho(r) = \rho_n(r) + \rho_p(r)$$

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

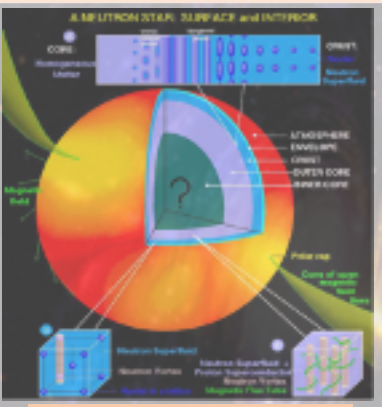
✓ **Symmetry energy**

Slope parameter

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



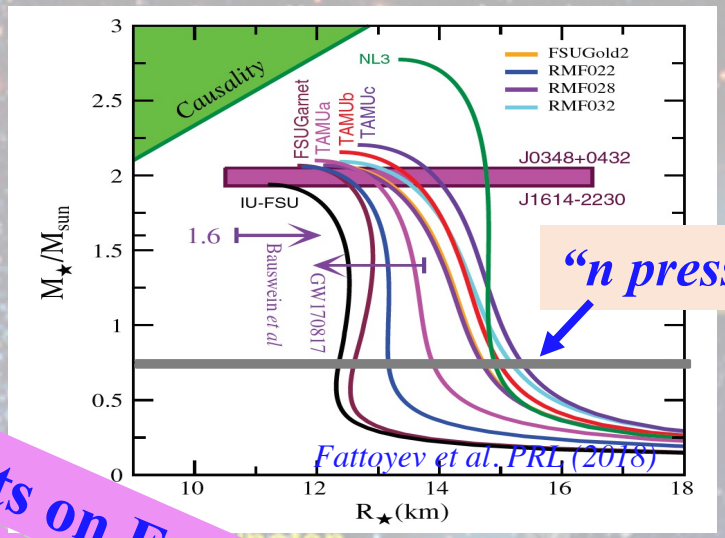
EoS: from nucleus to neutron stars



Neutron star
- ✓ **Structure**
- ✓ **Cooling**
- ✓ **Merger**

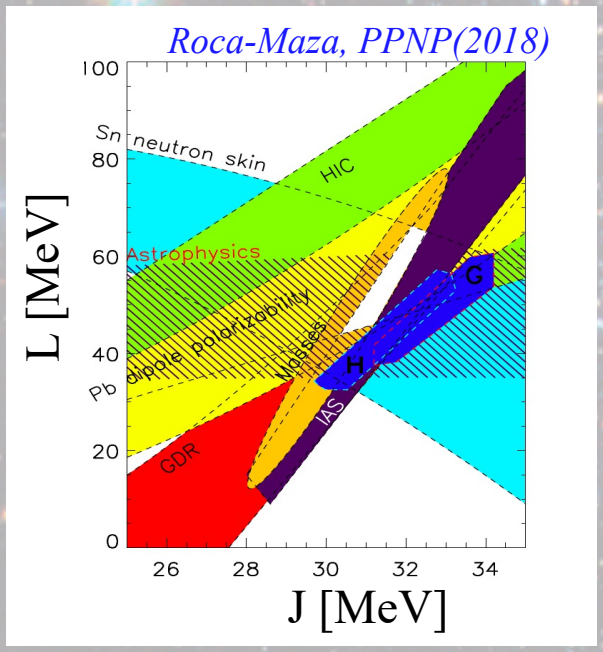
In Heaven

Mass-radius relation

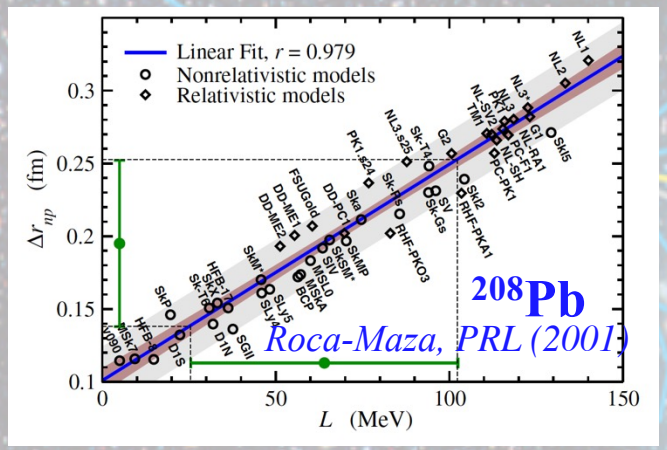


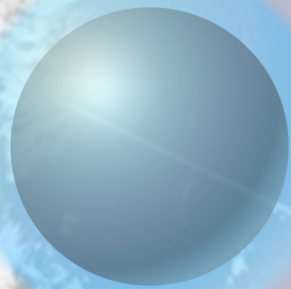
Constraints on EoS
EoS predictions

Laboratory constraints



$\Delta_{np} \sim L$ **(slope parameter)**





On Earth

Impact of clustering on EoS

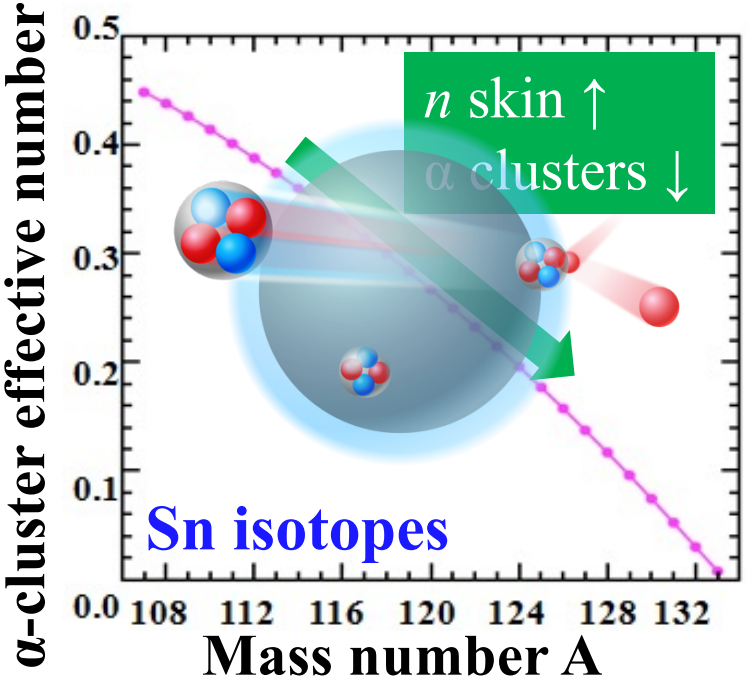
Typel, PRC89(2014) 064321,PRC 81(2010) 015803

✓ Theoretical (gRDF) predictions of α clusters in low-density environments like the surface of heavy nuclei:

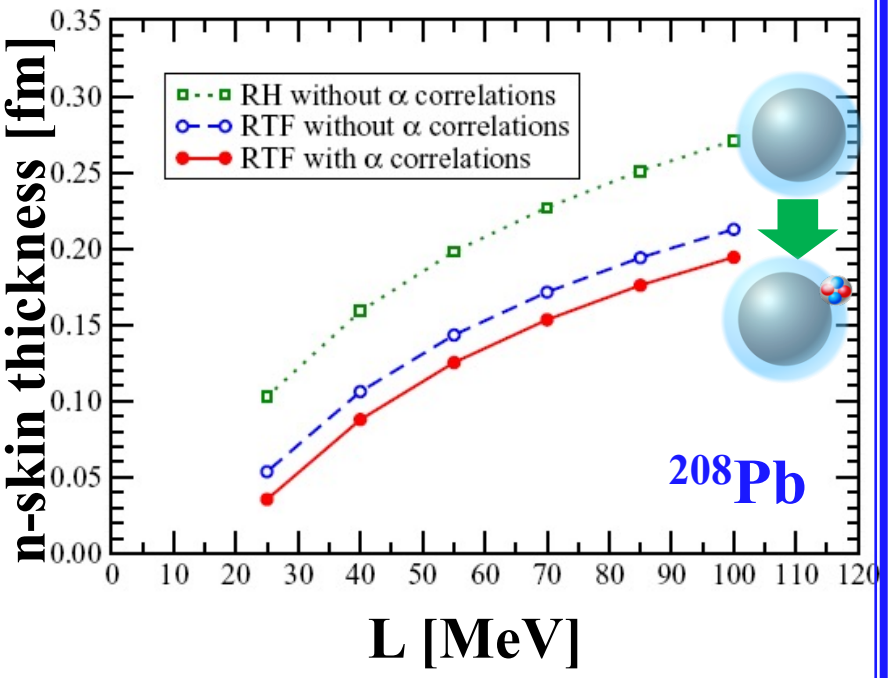
Tight interplay

α cluster ⟷ **neutron skin**

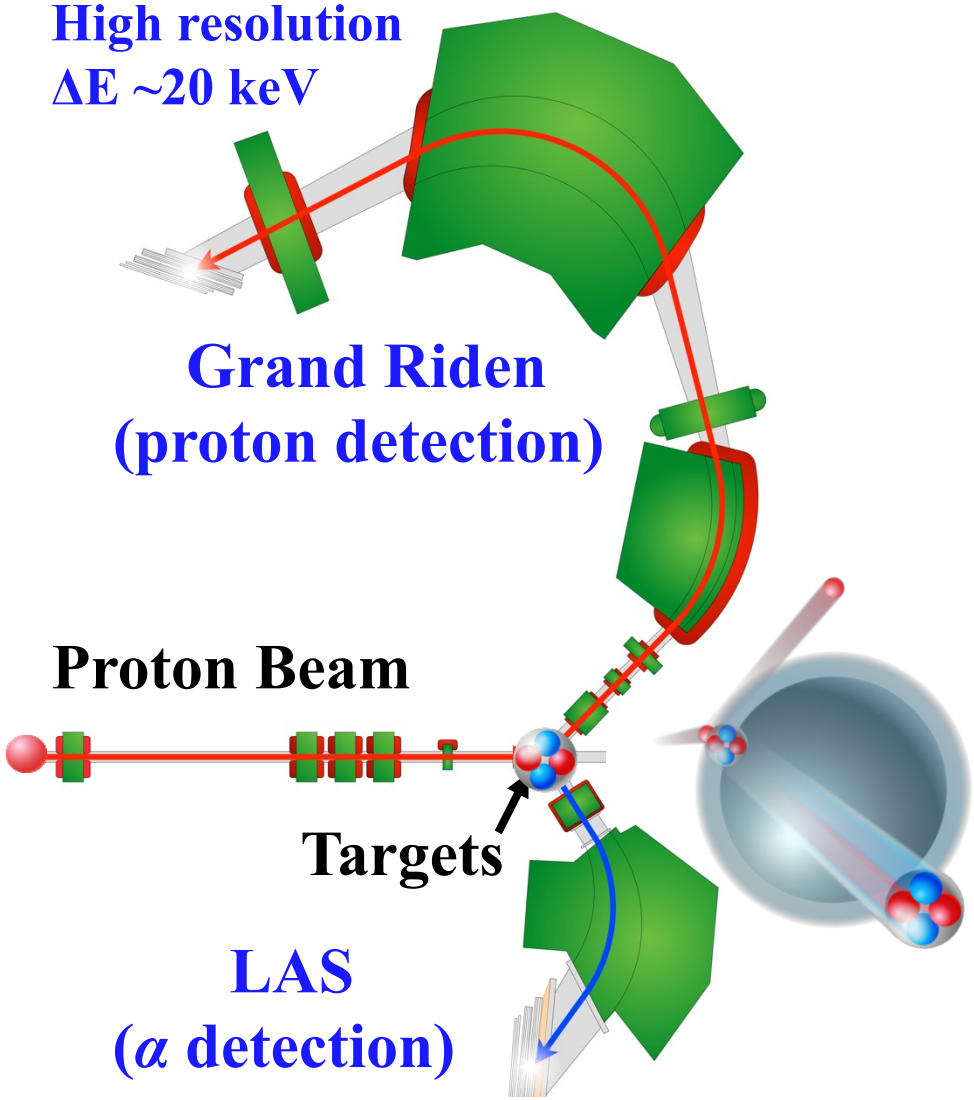
n-skin suppress α-cluster

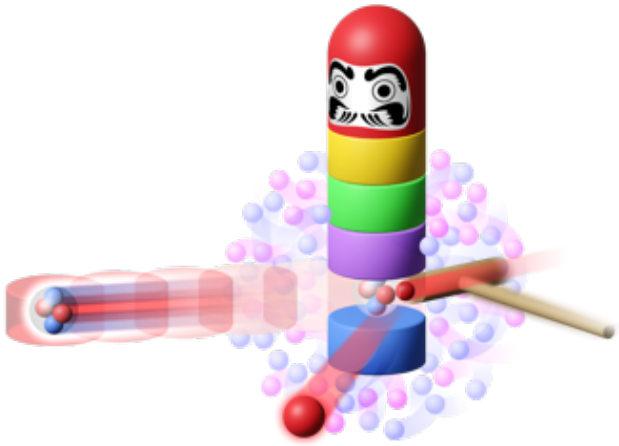


α cluster suppress n skin

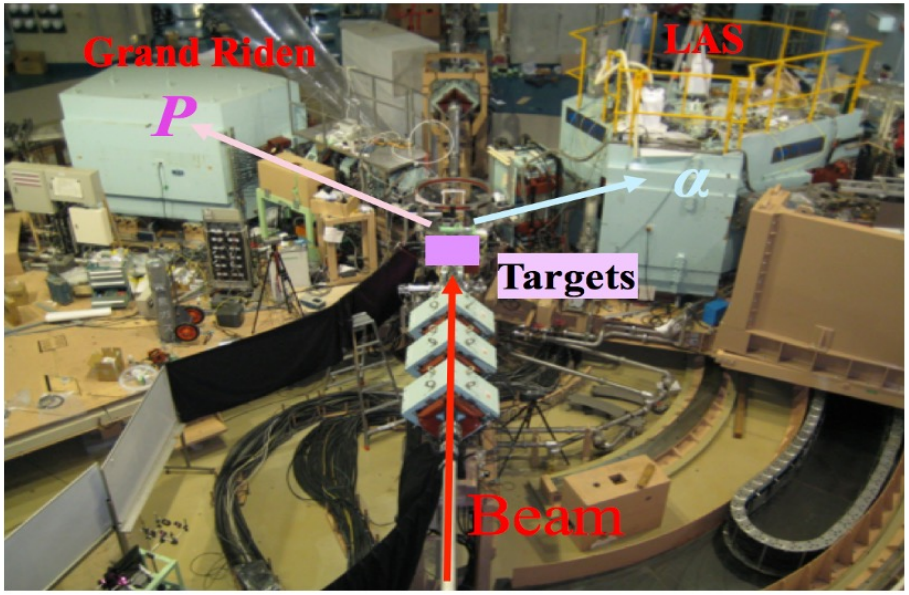


Quasi-free ($p,p\alpha$) at RCNP (Osaka/Japan)

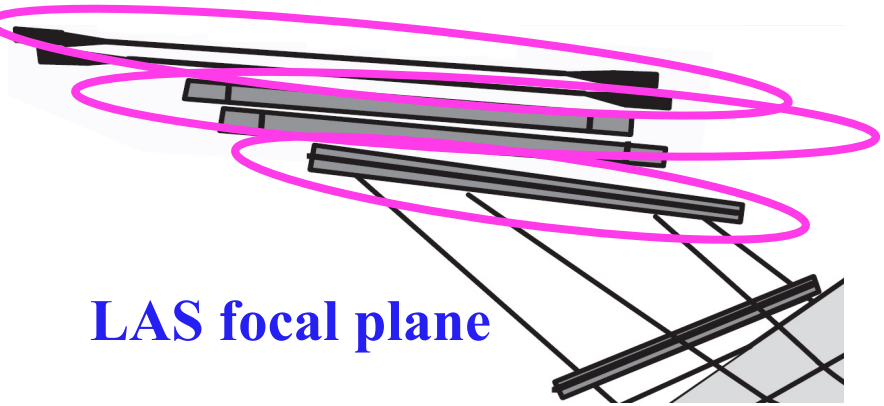


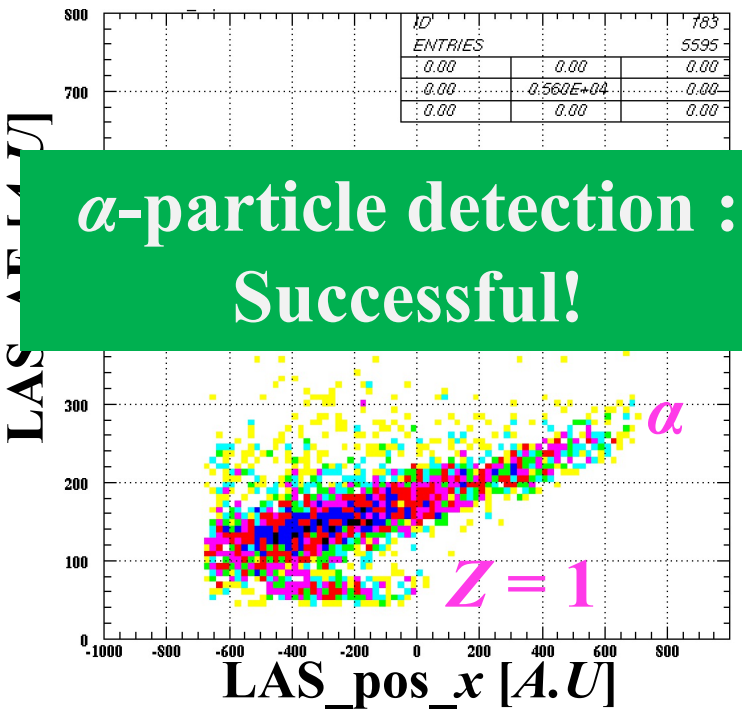


- ✓ **Beam:** 392 MeV proton, ~100 pnA
- ✓ **Targets:** ^{112,116,120,124}Sn (~40 mg/cm^2)



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





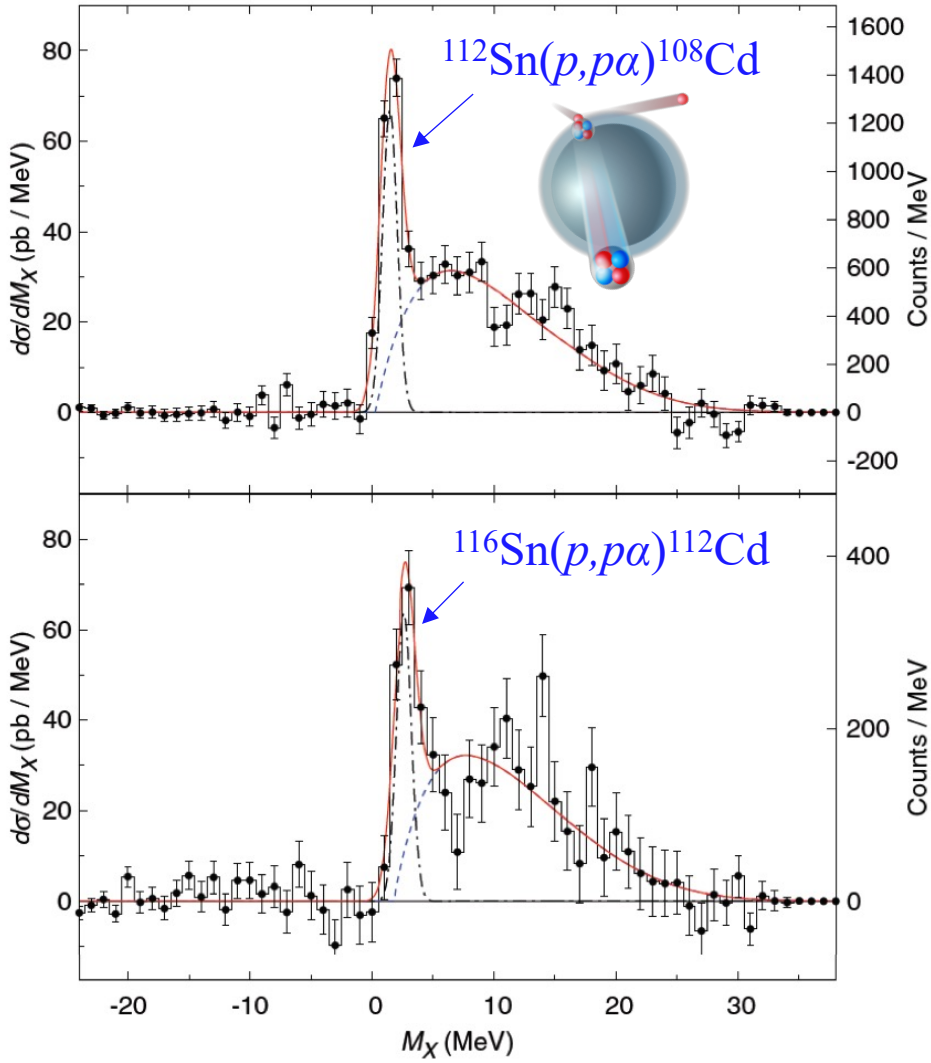
α-particle detection : Successful!

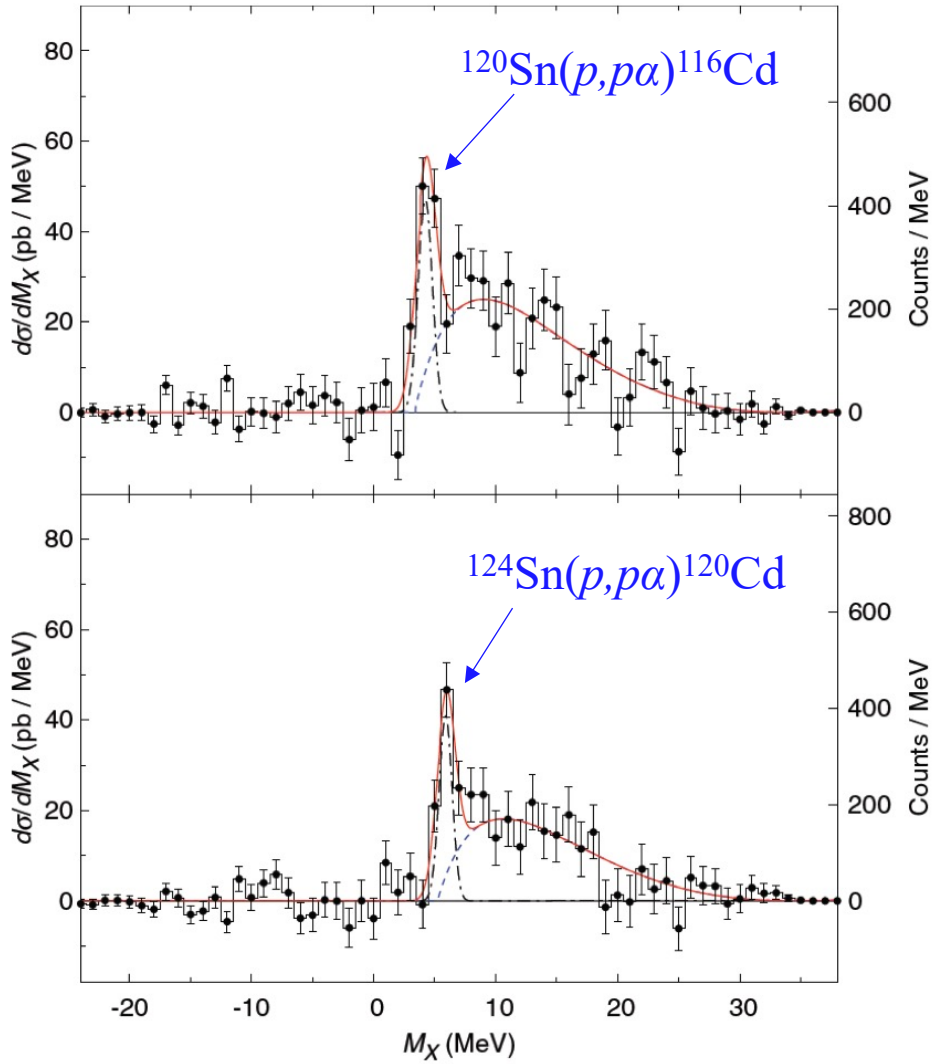
Physics run in 2018

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

Project started in 2015

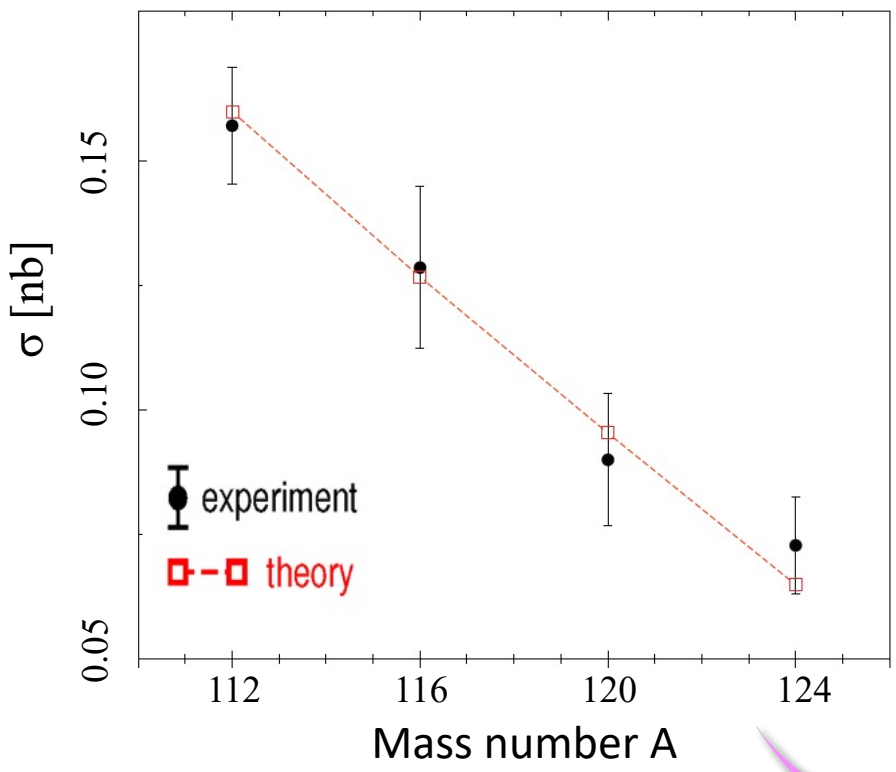
α separation energy spectrum

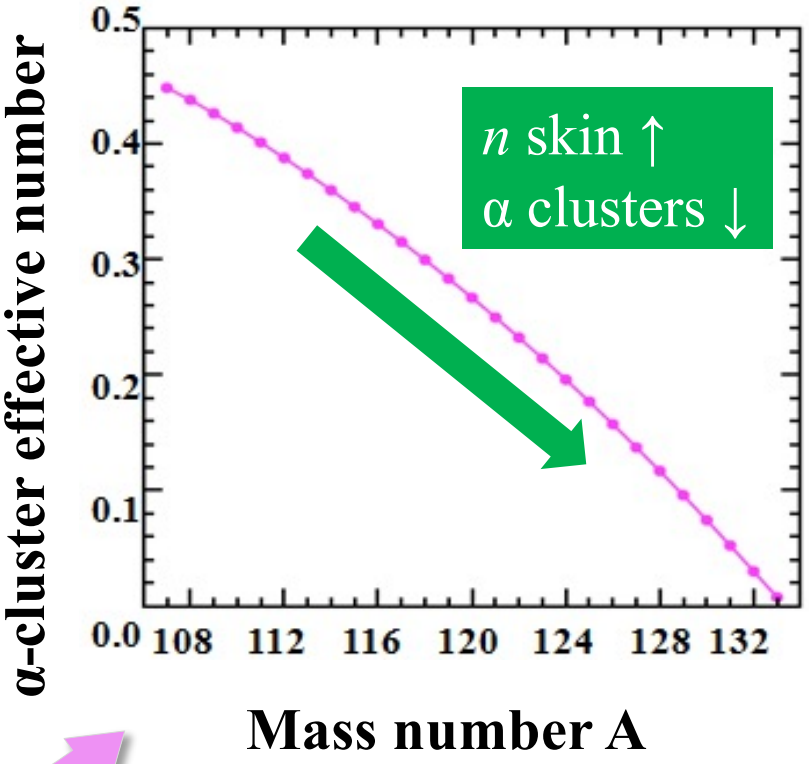




- ✓ E_{sep} Peak clearly observed for each Sn isotope ^{112,116,120,124}Sn.
- ✓ Fitted using a gaussian peak and the continuum background.

Systematics of α-clustering along Sn isotopic chain





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

Acknowledgement to collaborators of ^{A}Sn(p,$p\alpha$)

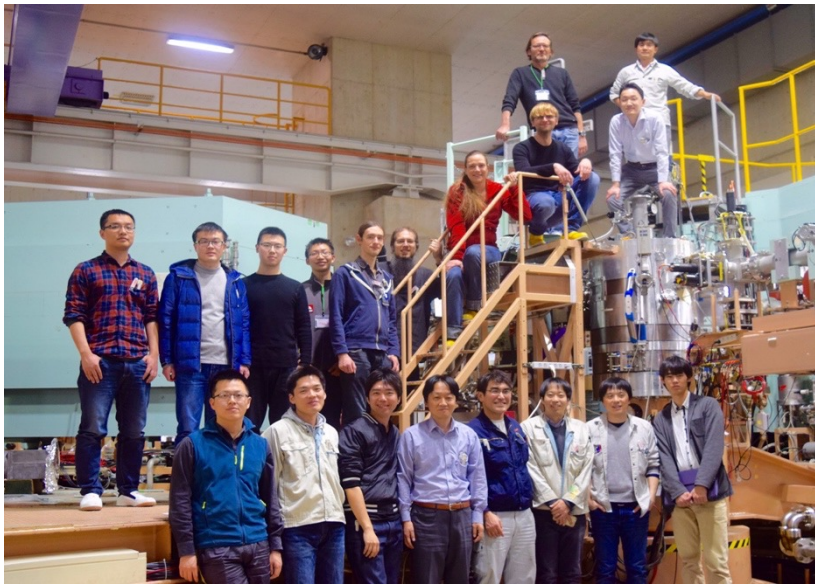
Science Contents News Careers Journals

REPORT

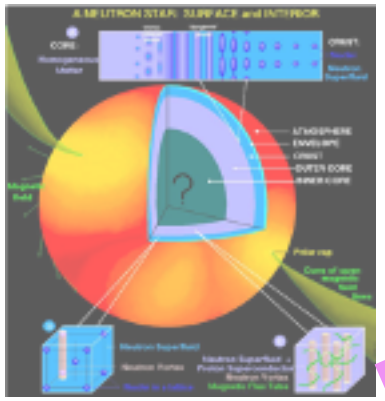
Formation of α clusters in dilute neutron-rich matter

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, "Perspectives"专栏点评】**



Clusters: from nucleus to neutron stars



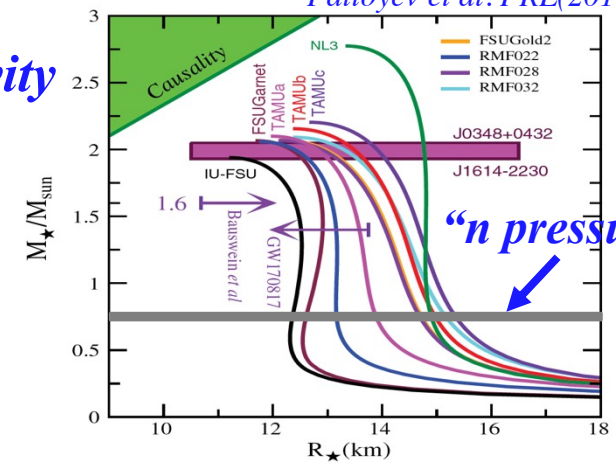
Neutron star

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

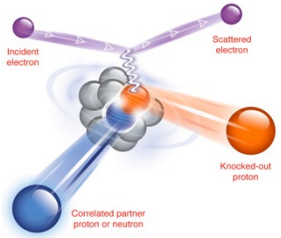
In Heaven

Mass-radius relation

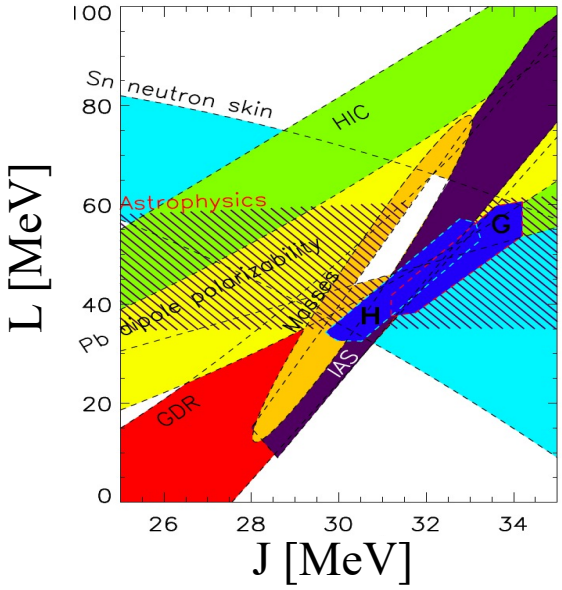
Fattoyev et al. PRL(2018)



Nuclar matter EoS

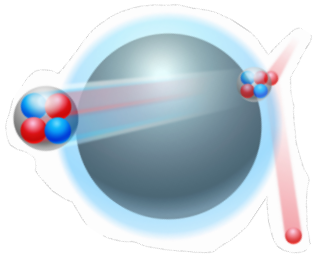


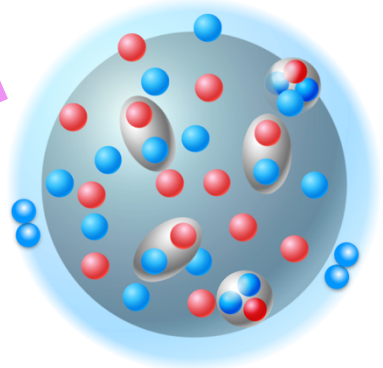
Roca-Maza, PPNP(2018)



Better constraints

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



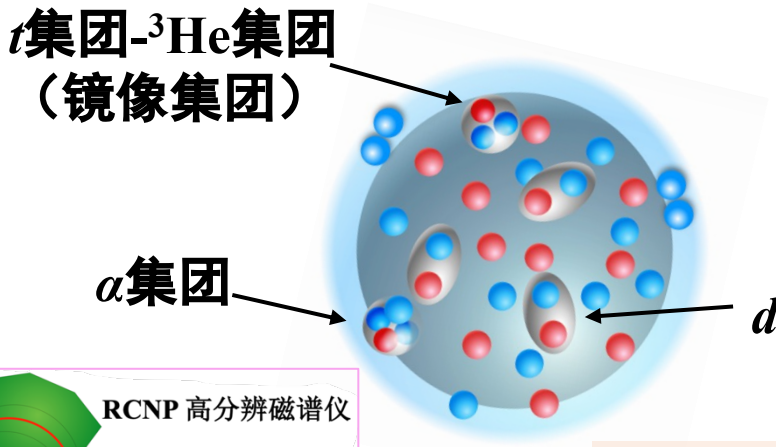


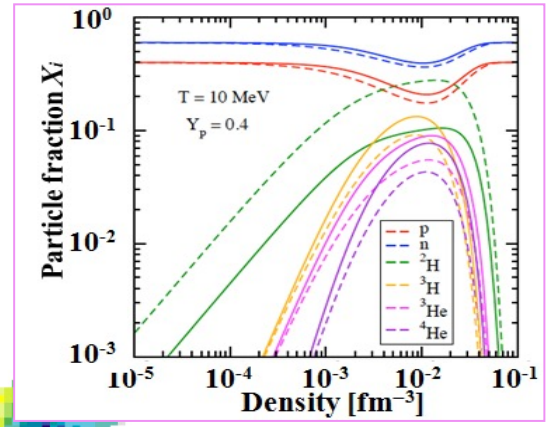
On Earth

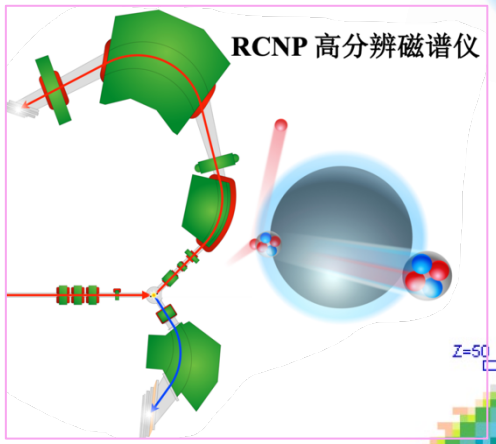
A new era of cluster knockout

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

Typel PRC2010; Zhang/Chen PRC2017





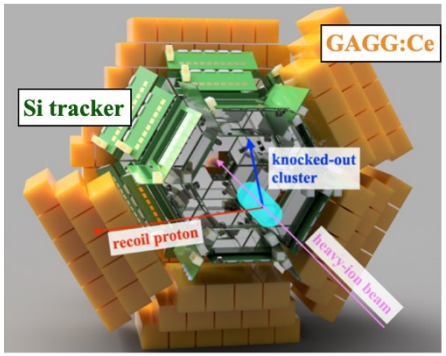


Radioactive nuclei: (*p*,*pα*) at RIBF

Heavy nuclei: (*p*,*pα*) with Nd and Sm at RCNP

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

Light neutron-rich nuclei : (*p*,*pα*) with C at RIBF



TOGAXSI@RIBF (Uesaka et al.)

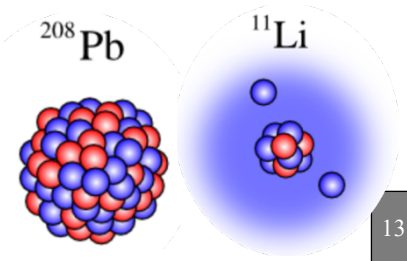
报告提纲

- ✓ 引言
- ✓原子核的集团结构
  - ✓轻核激发态的集团结构
  - ✓基于$(p,p\alpha)$反应研究重核表面的α集团
- **✓多中子关联与中子集团态**

中子滴线区的晕结构与中子关联

Ahn et al. PRL 123, 212501(2019), PRL129, 212502 (2022)

✓ Neutron drip line established up to Z = 9 (^{31}F) and Z = 10 (^{34}Ne)



Halo

Bagchi et al. PRL 124, 222504 (2020).

Tanaka et al. PRL 104, 062701 (2010).
Togano et al. PLB 761, 412 (2016).

Cook et al. PRL 124, 212503 (2020)
Estradé et al. PRL113, 132501(2014)

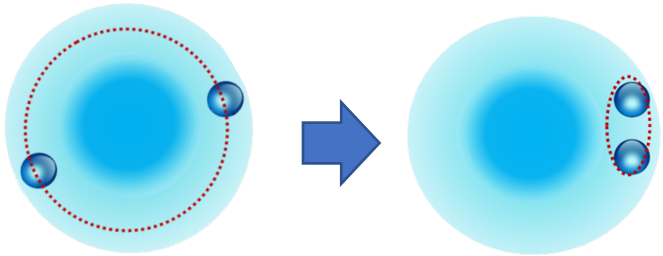
ZHY et al. PRL126, 082501(2021)

Corsi et al. PLB 797, 134843(2019)

Kubota et al. PRL 124, 212503 (2020)

Sun et al. PLB 814, 136072(2021)
Cao et al. PLB 707, 46(2012)

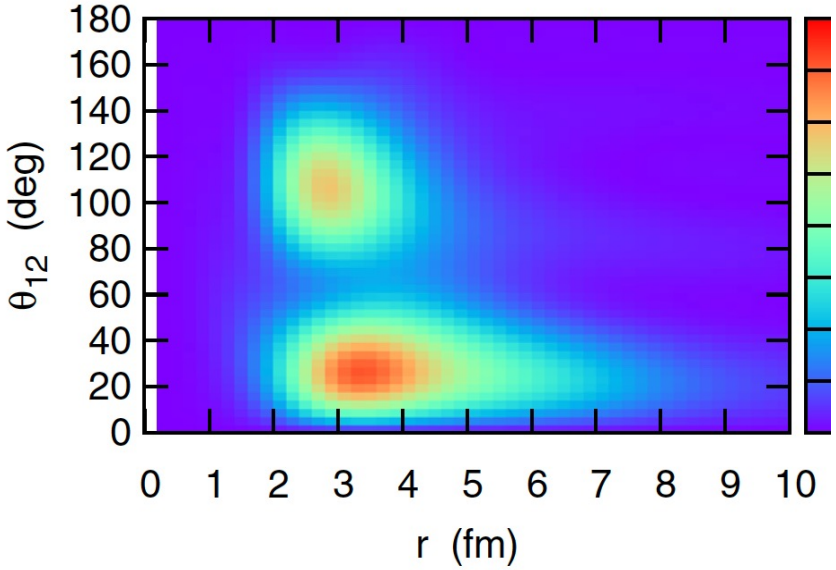
Tanihata et al. PPNP 68 (2013) 215

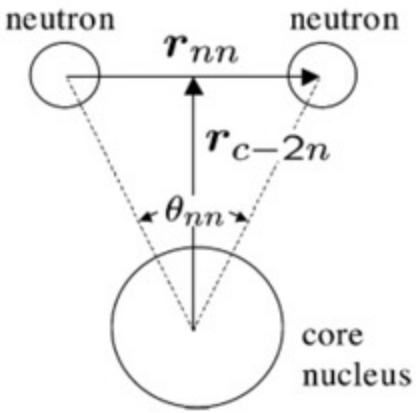


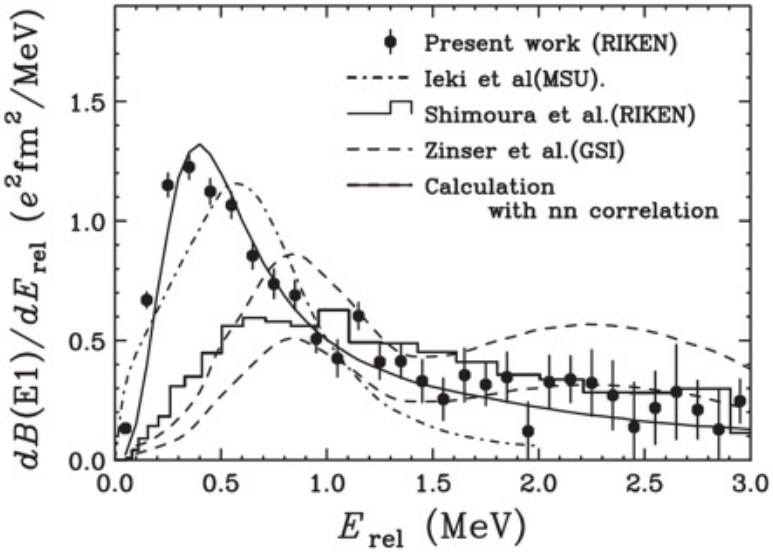
(Weak) BCS-like (Strong) dineutron

丰中子核的双中子关联：^{11}Li为例

- ✓3-body model calculation by Hagino et al. [PRL 99,022506(2007)
- ✓GCC calculaiton by S.M. Wang et al. [PRL 122, 122501 (2019)]
- ✓Strong B(E1) from Coulomb disso. [Nakamura et al. PRL96(06)252502]







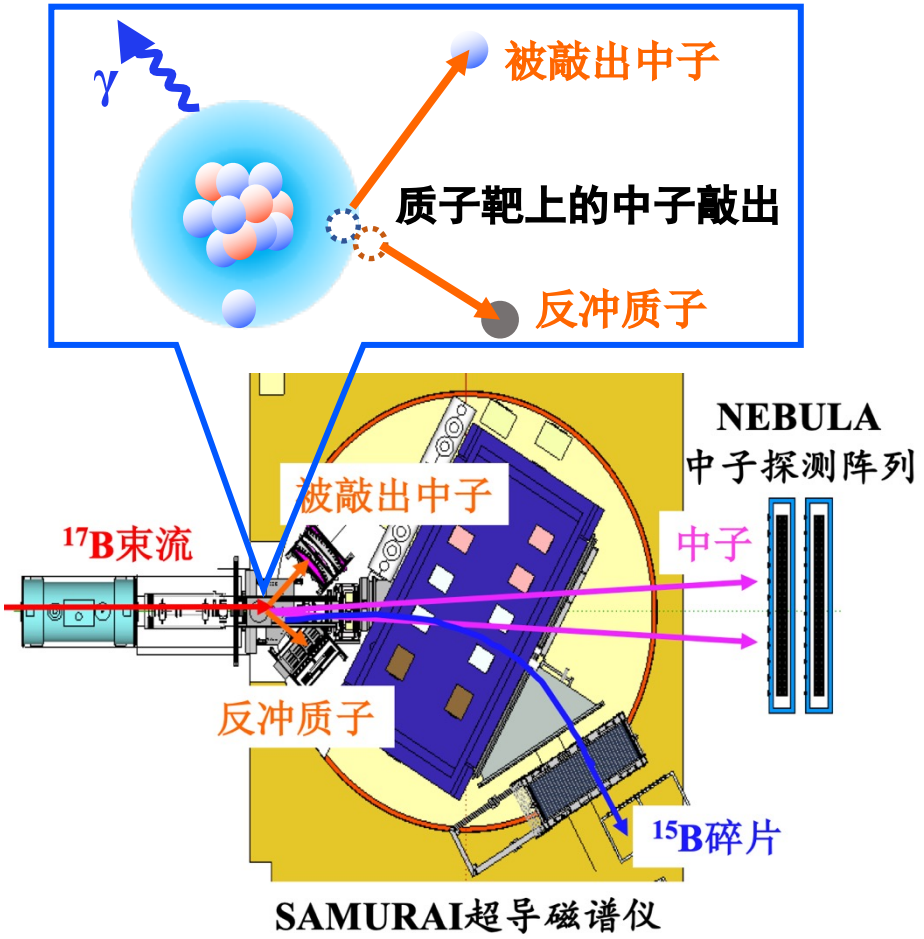
$$B(E1) = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2\langle r_1^2 + r_2^2 + 2\boldsymbol{r}_1\cdot\boldsymbol{r}_2\rangle = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2\langle r_{c,2n}^2\rangle$$

$$\langle r_m^2\rangle = \frac{A_c}{A}\langle r_m^2\rangle_{A_c} + \frac{2A_c}{A^2}\langle r_{c-2n}^2\rangle + \frac{1}{2A}\langle r_{nn}^2\rangle,$$

$$\langle\theta_{12}\rangle = 48^{+14}_{-18}\ \text{degrees}$$

丰中子核的双中子关联实验研究

✓ 基于理化学研究所的超导磁谱仪开展了^{11}Li/^{14}Be/^{17}B的**中子敲出实验。**

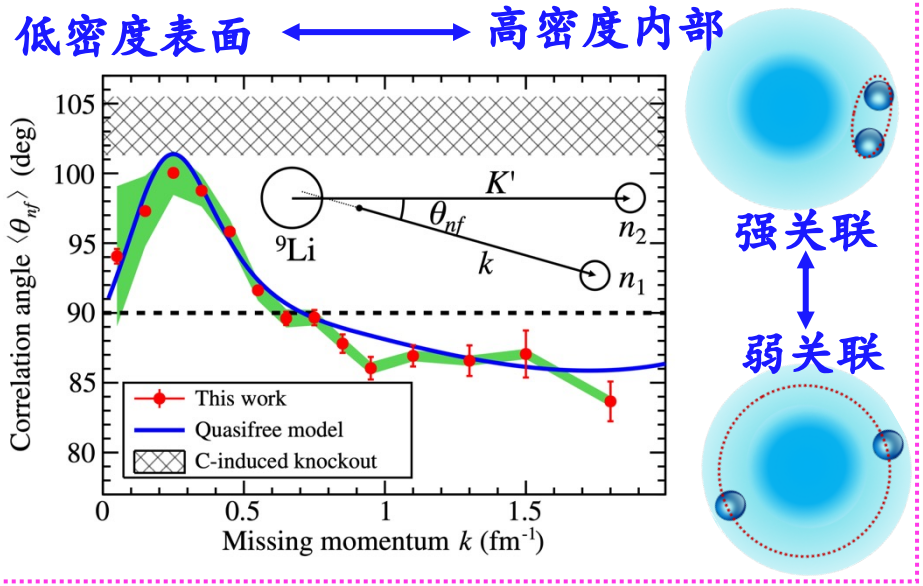


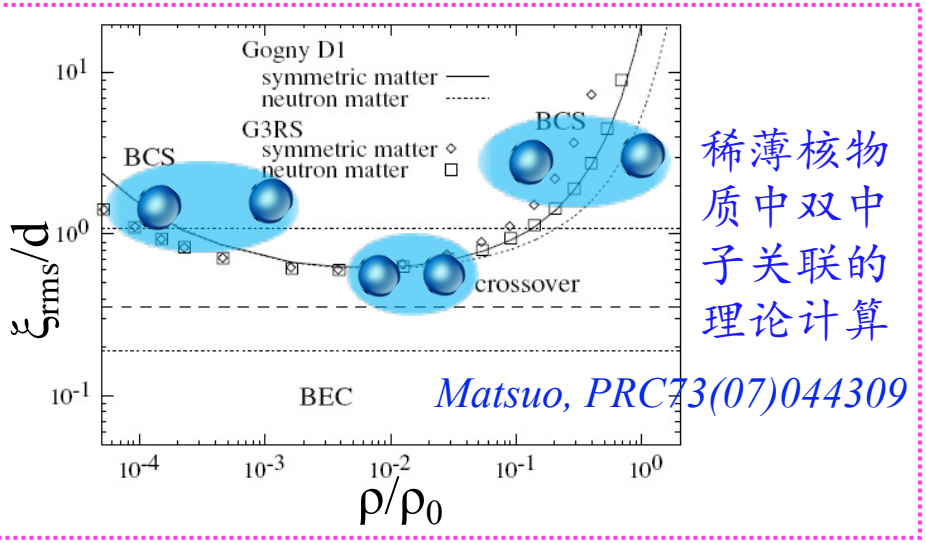
Kubota et al. PRL 125 (2020) 252501

Yang et al PRL 126 (2021) 082501

Corsi et al. PLB 840 (2023) 137875

*Li, **Yang** et al., in progress*



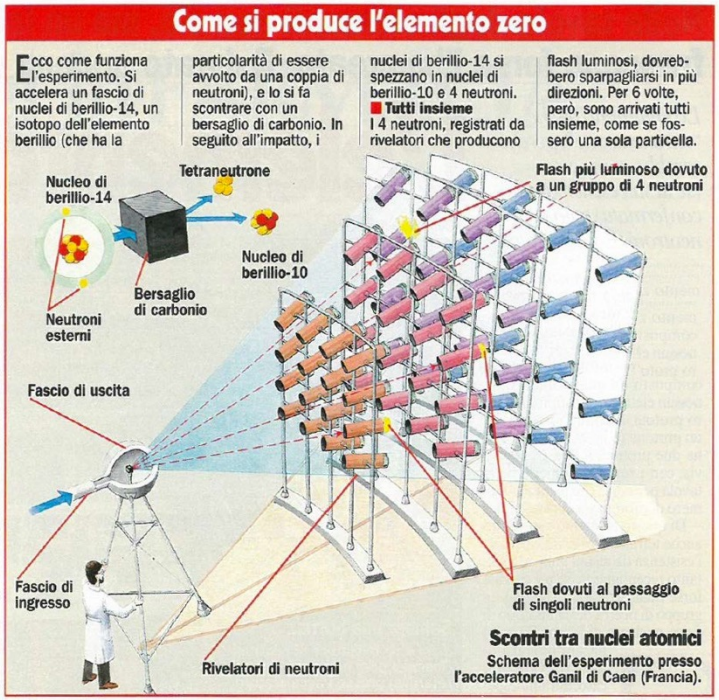


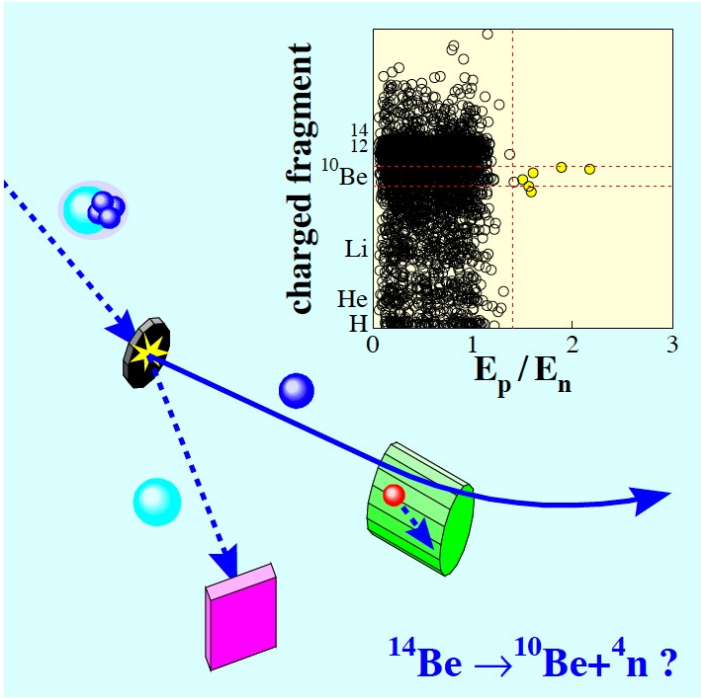
稀薄核物质中双中子关联的理论计算

Matsuo, PRC73(07)044309

寻找四中子态?

- ✓ $^4He(\pi^-,\pi^+)^4n$ by *Ungar et al., PLB 1984*
- ✓ $^4He(\pi^-,\pi^+)^4n$ by *Gorringe et al., PRC 1989*
- ✓ $^7Li(^{11}B, ^{14}O)^4n$ and $^9Be(^9Be, ^{14}O)^4n$ by *Belozyorov et al., NPA1988*





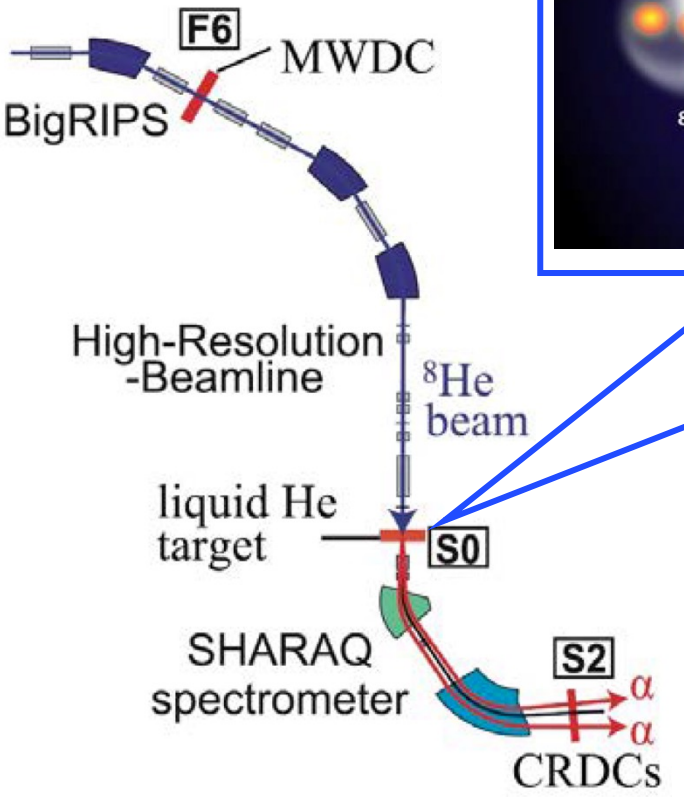
Marques et al., PRC2002, arXiv:nucl-ex/0504009

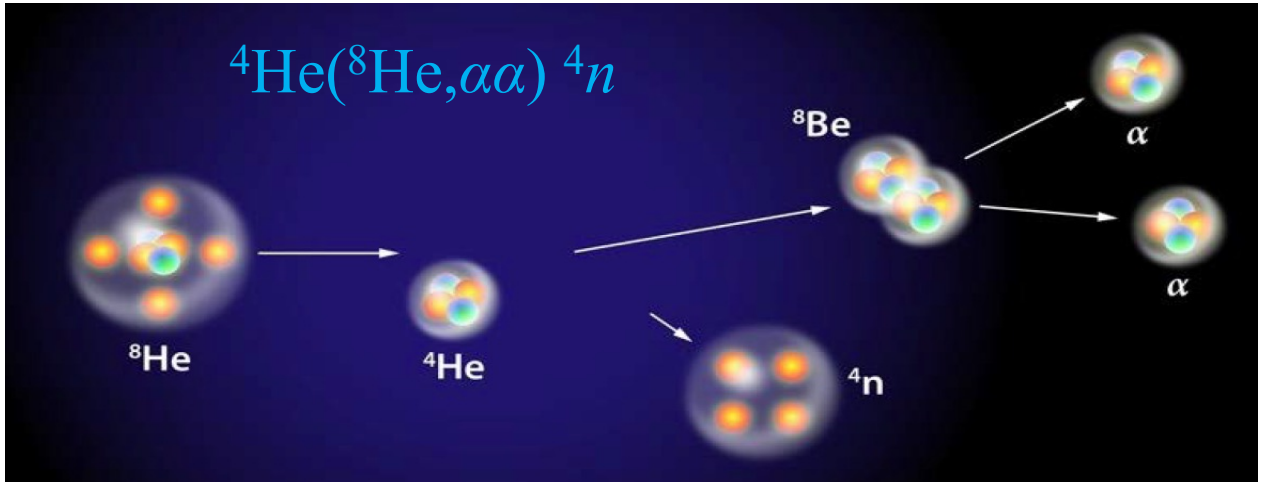
Several (abnormal) events : hint of a bound or low-lying ^4n

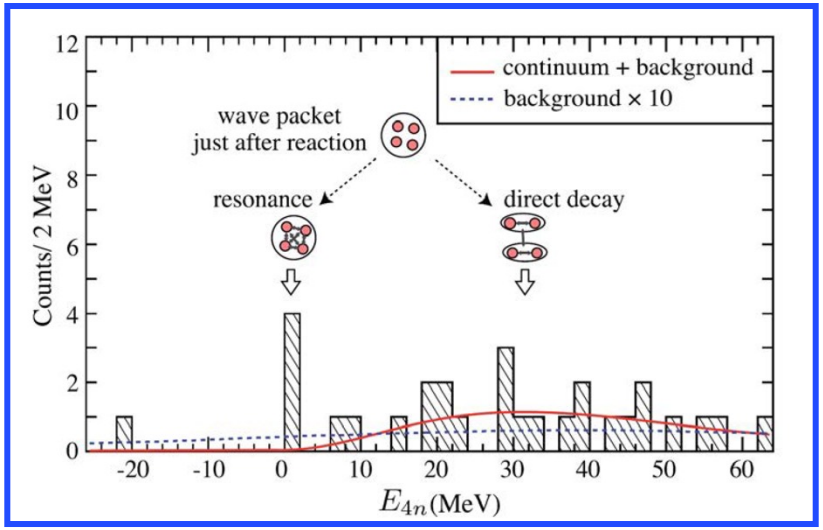
- Followup projects not successful [^{12,14}Be(- α), ^{8}He(- α),..]

四中子态："Candidate ^{4}n" (RIKEN/CNS, 2016)

Kisamori et al. ,
PRL 116, 052501 (2016)





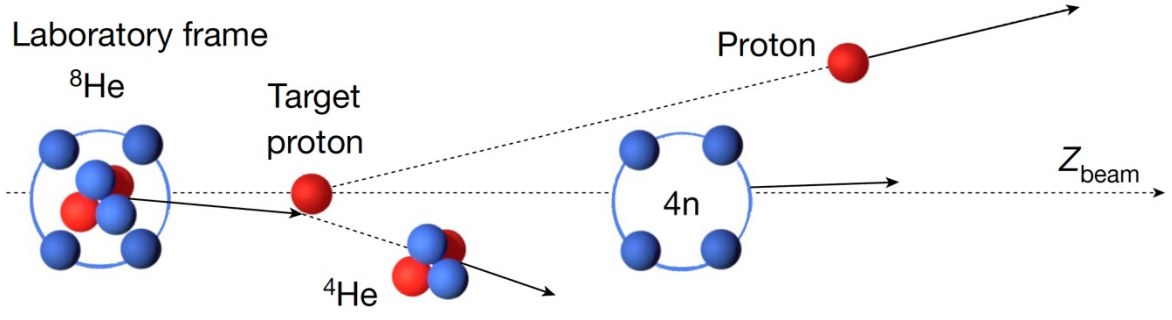


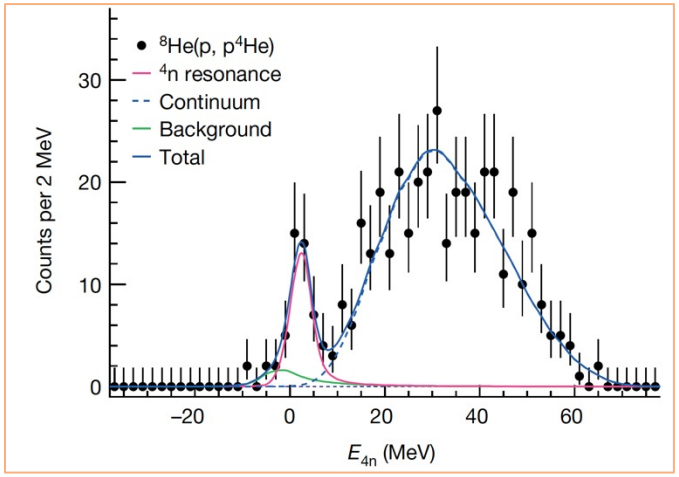
Four events : "candidate ^4n" (0.83 ± 0.65(stat.) ± 1.25(sys.) MeV)

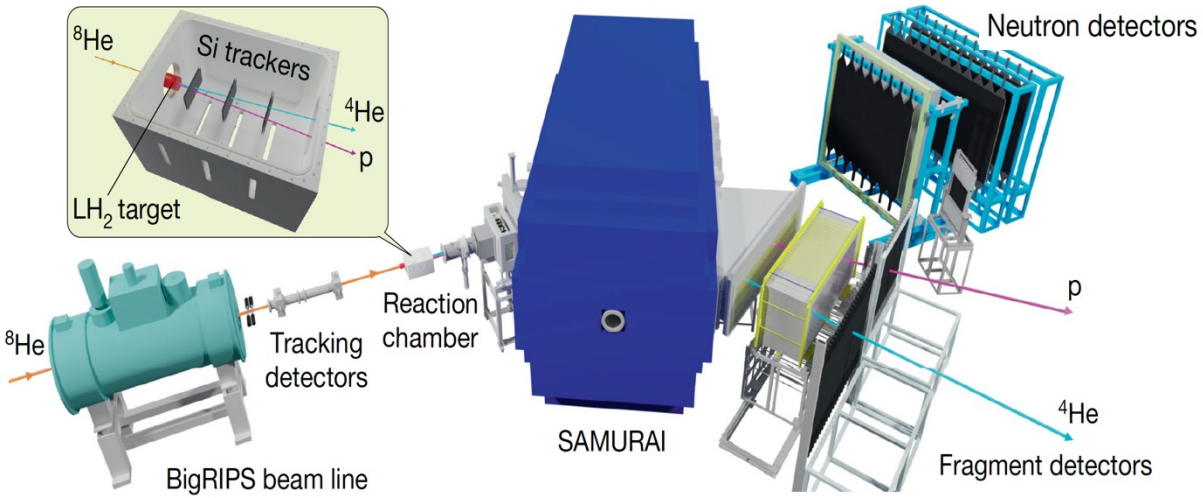
四中子态:^{8}He (p,$p\alpha$) @ RIKEN-RIBF (2022)

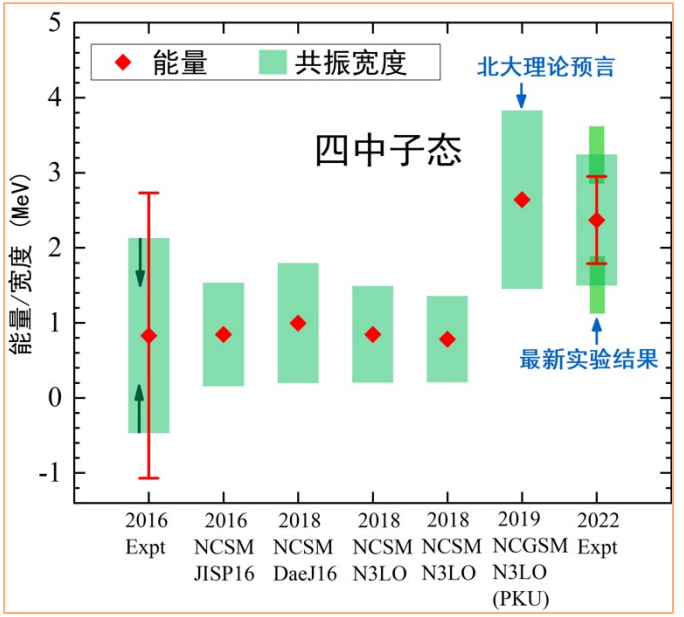
$E_r = 2.37(38)(44)MeV$

$\Gamma = 1.75(22)(30)MeV$



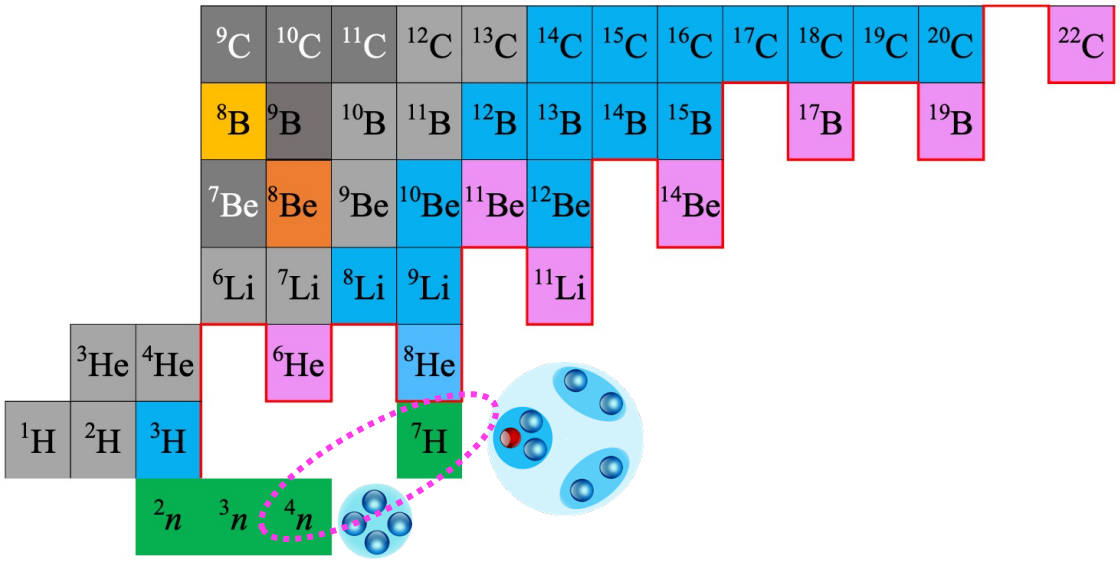




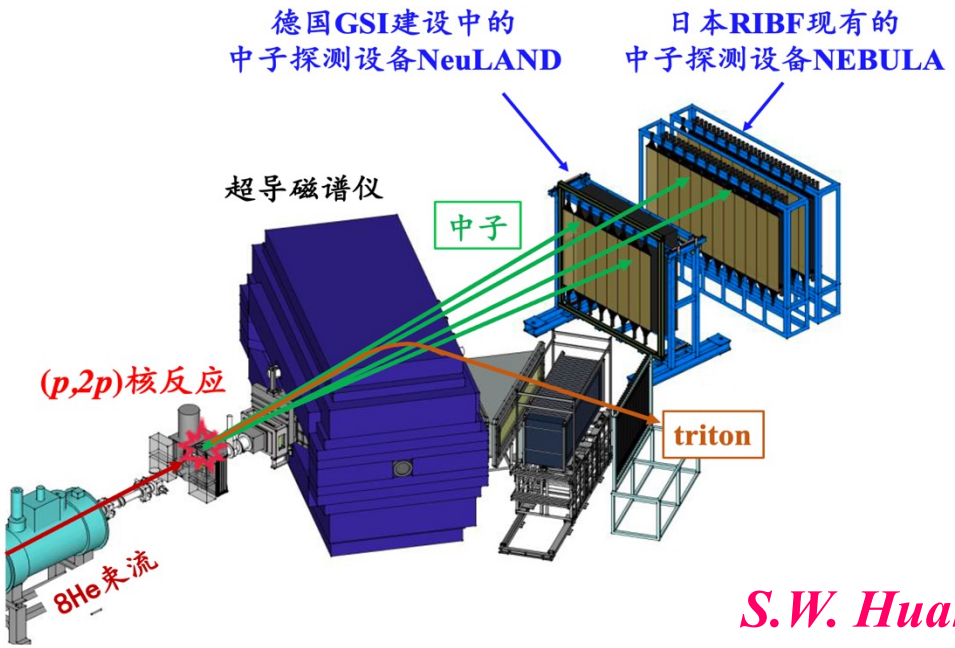


Duer et al. Nature 606(2022)678

^{7}H及其四中子关联实验研究（@RIBF）

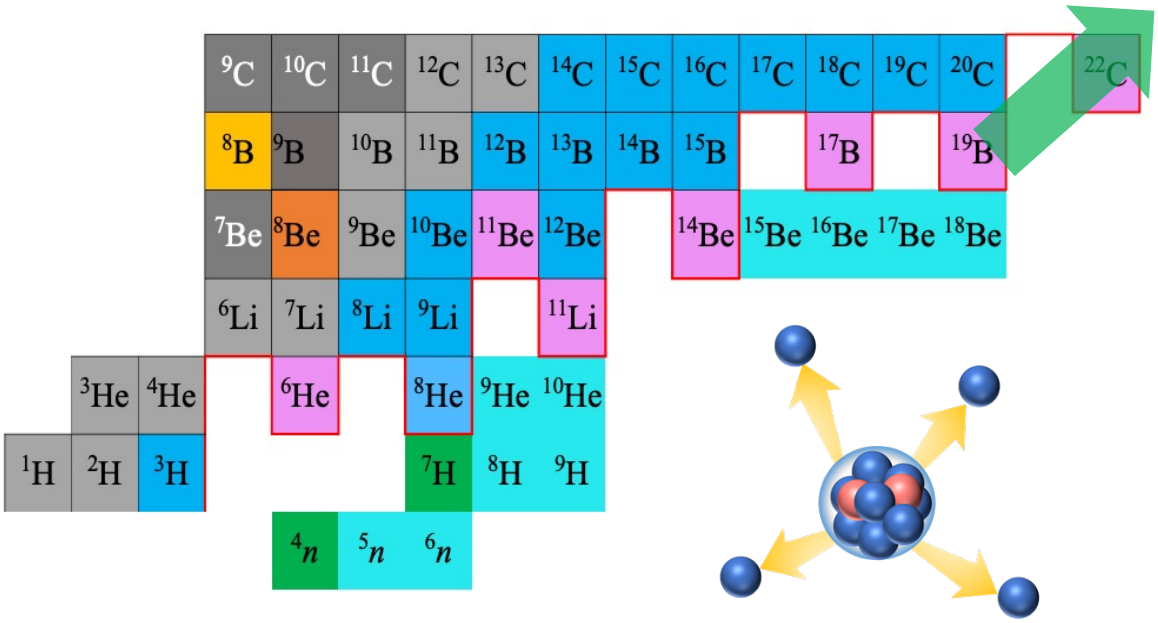


Data analysis:
Siwei Huang
(postdoc)



S.W. Huang, ZHY et al. in progress

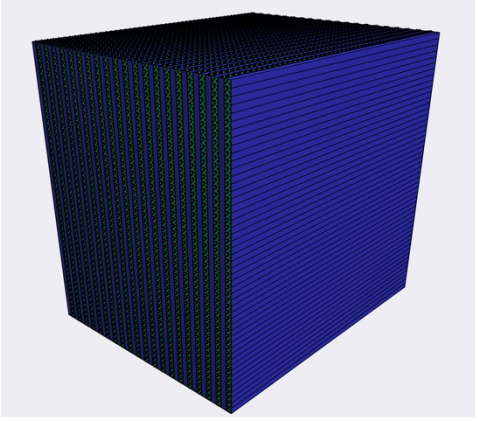
发展多中子探测设备



中重核区:多中子探测更加重要!

HIAF(~2025)

AMDA (funding application)

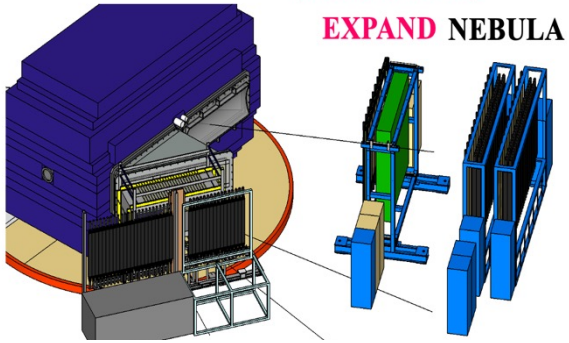


NEBULA++@日RIBF

升级中

SAMURAI 超导磁谱仪 *(法国-LPC升级中)*

EXPAND NEBULA

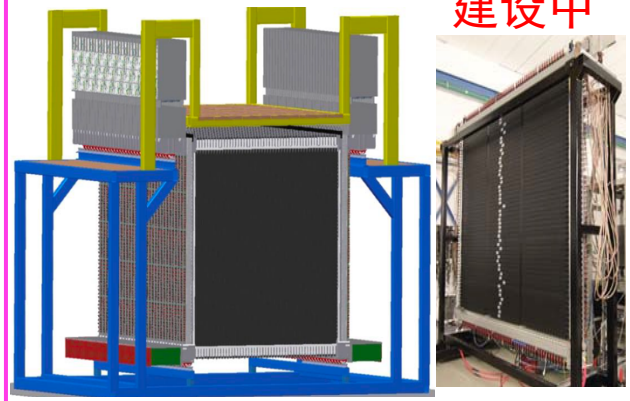


MONA@美FRIB

升级中

NeuLAND@德FAIR

建设中



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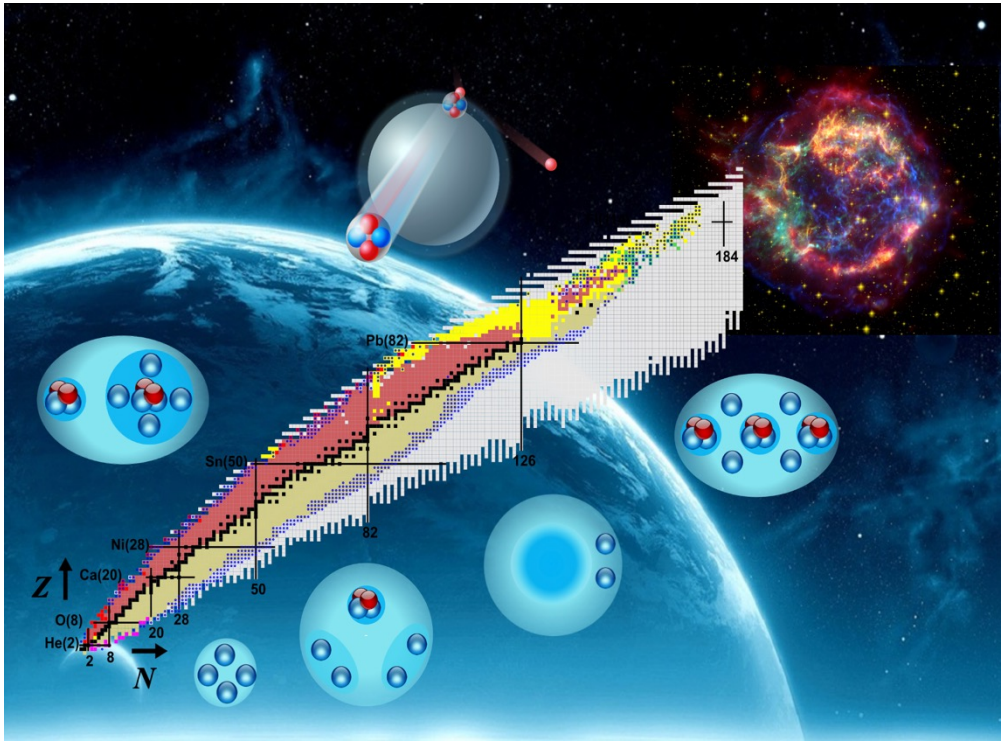
基于集团敲出反应研究原子核体系的集团结构



- ✓ 引言
- ✓原子核的集团结构
  - ✓轻核激发态的集团结构
  - ✓基于$(p,p\alpha)$反应研究重核表面的α集团
- ✓多中子关联与中子集团态

谢谢大家！