



南方科技大学
SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY

通过直接核反应研究奇特核结构以及壳演化

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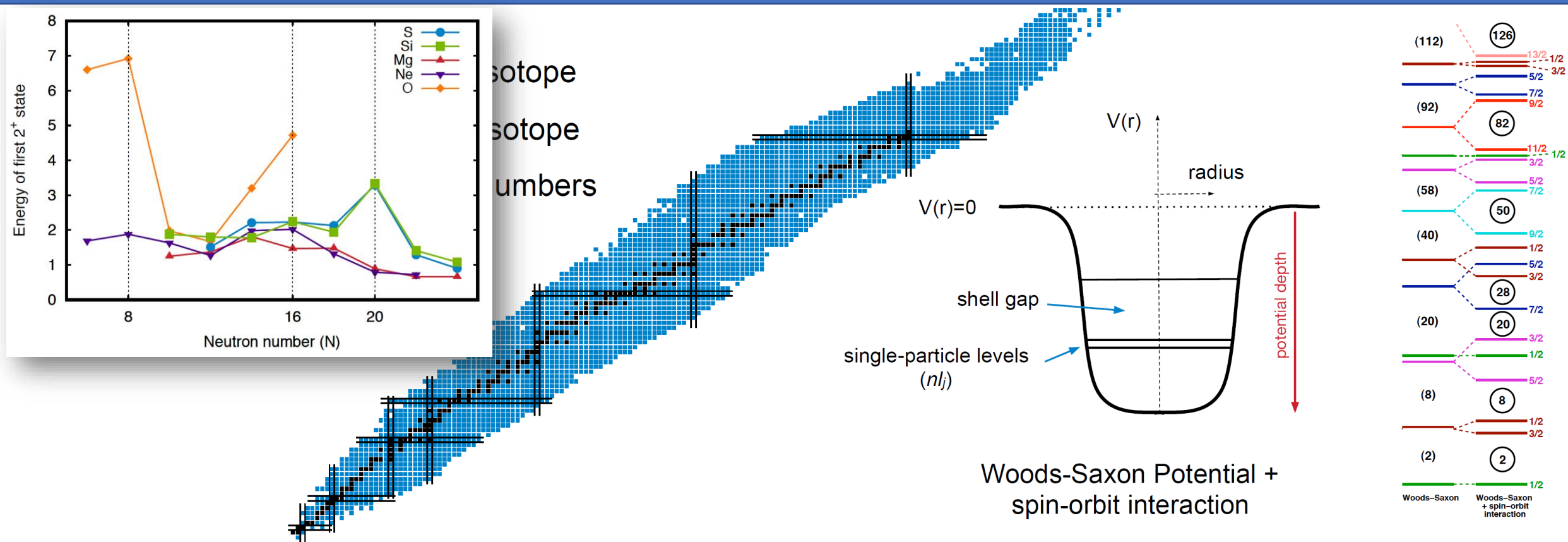
□研究背景：追踪壳演化；奇特核结构

□实验方法

- 转移反应—单粒子结构：
自旋轨道劈裂“气泡核” $^{32}\text{Si}(d,p)^{33}\text{Si}$
- ^{12}Be N=8幻数消失机制
- 非弹性散射反应—集体结构：
 ^{10}Be 偶极共振态的加强； ^{16}C 的Z=6壳层； ^{12}Be ...

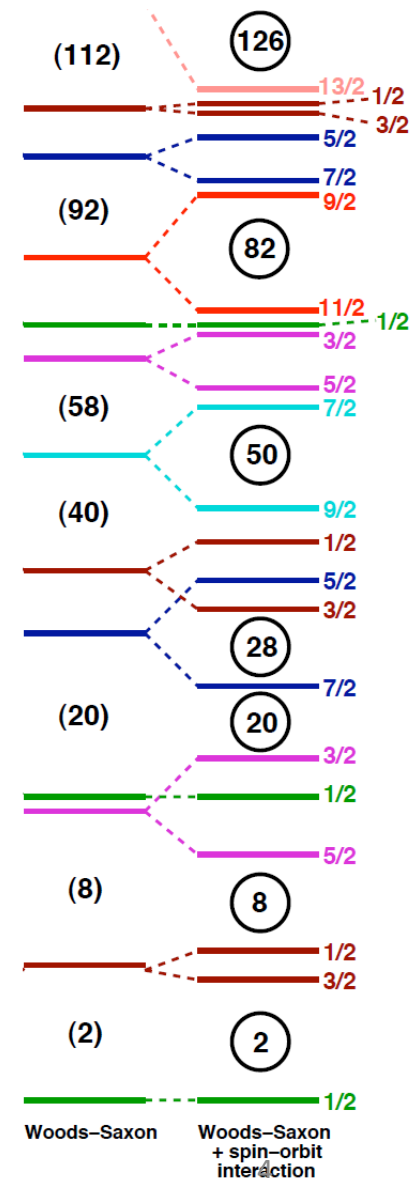
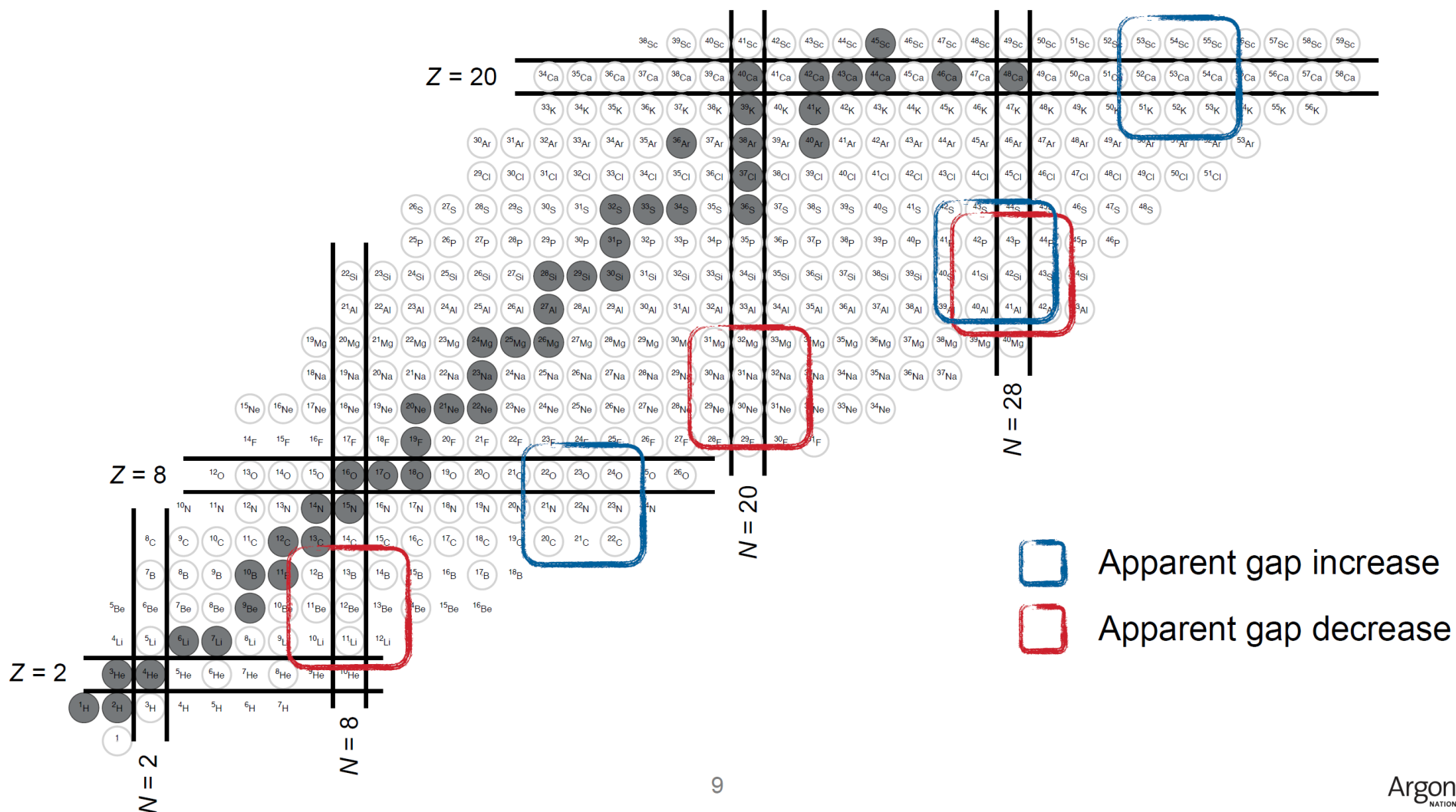
□总结

远离稳定线的奇特核结构和壳演化



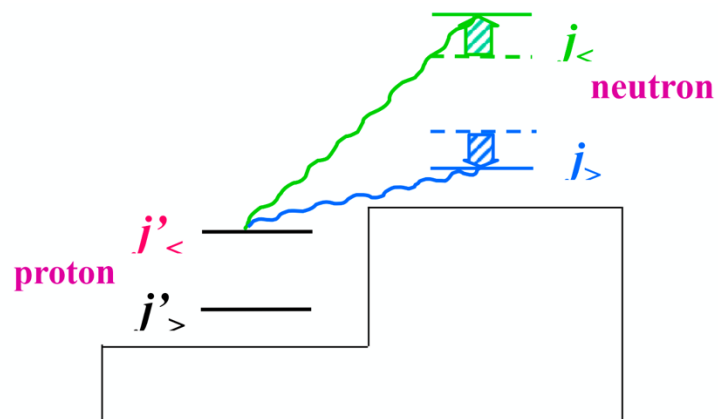
- Describe the [strong] force governing the arrangement of protons & neutrons
- What are the limits of atomic nuclei?
- How & Where are the chemical elements formed?
- What are the origins of the regular emergent patterns observed in nuclei?

不稳定原子核结构——壳层与幻数演化

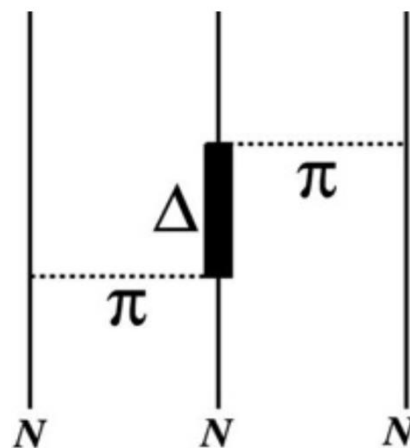


不稳定原子核结构——壳层与幻数演化

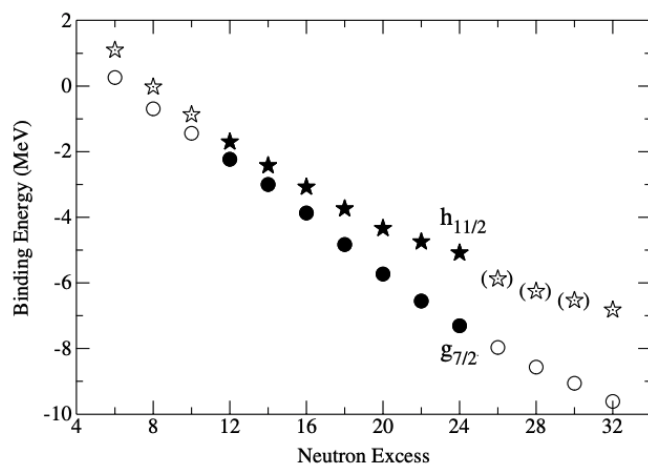
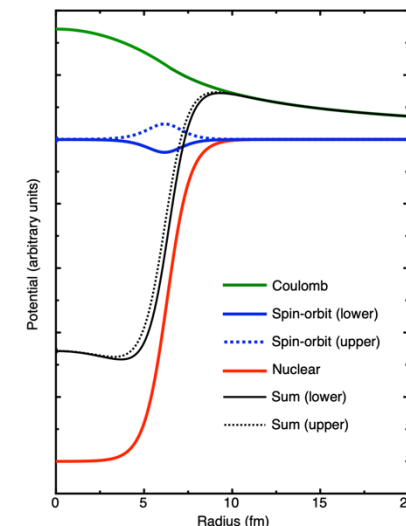
Tensor



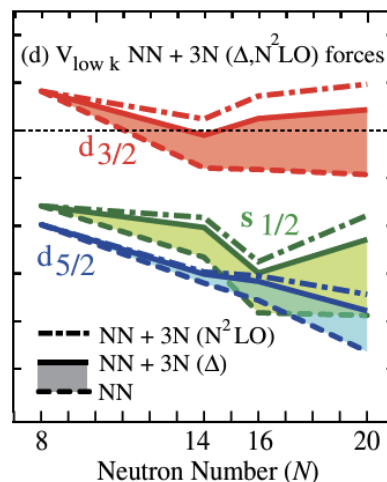
3N force



Weak-binding

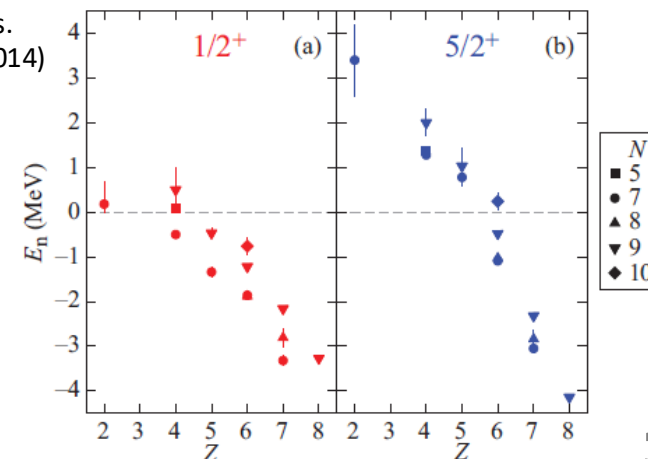


T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005); J. Schiffer et al., Phys. Rev. Lett. 92 (2004) 162501

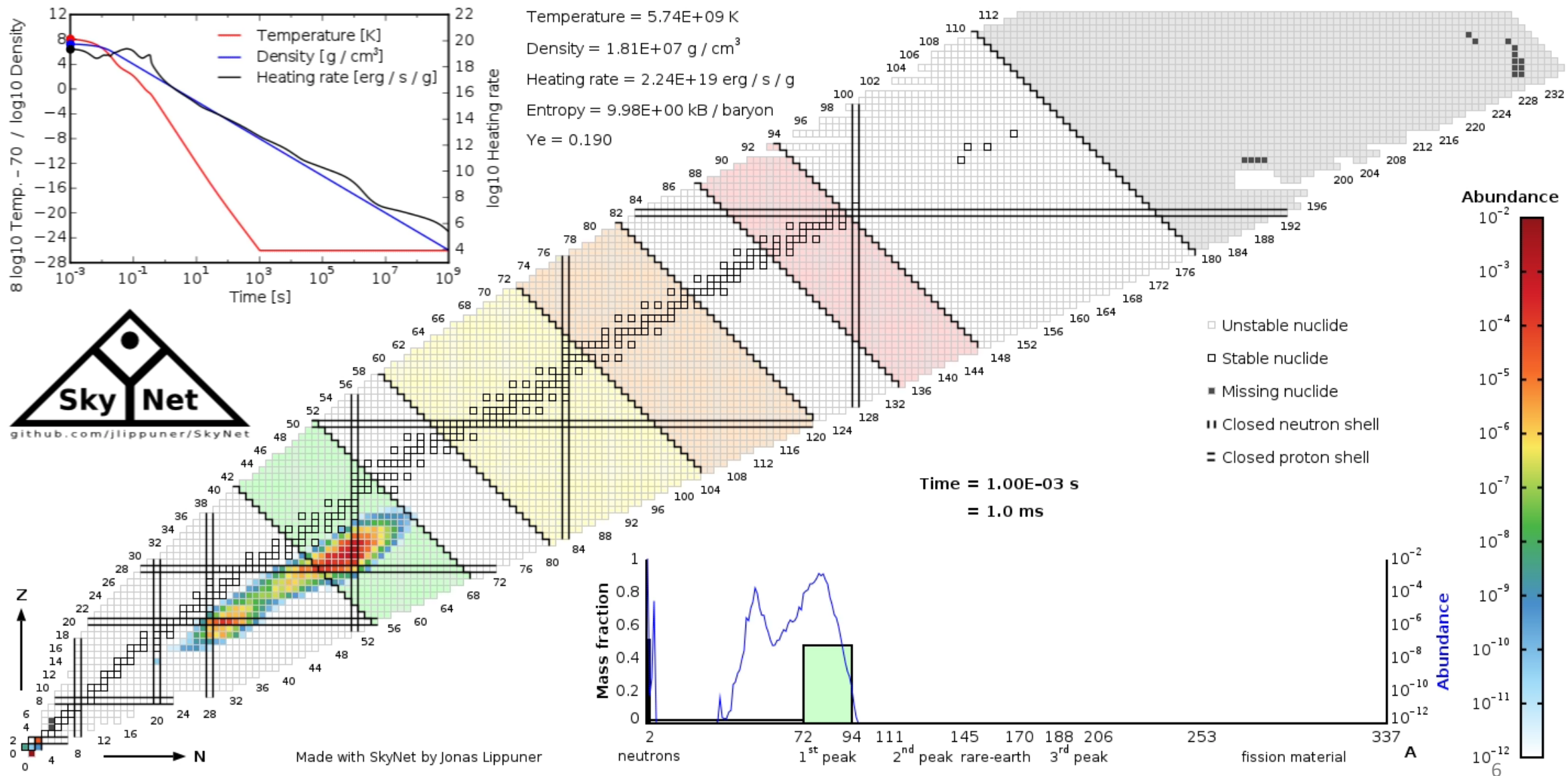


C. R. Hoffman et al. Phys. Rev. C 89, 061305(R) (2014)

T. Otsuka, et al., PRL 105, 032501 (2010); Prog. Theo. Phys. 17(1957)3.

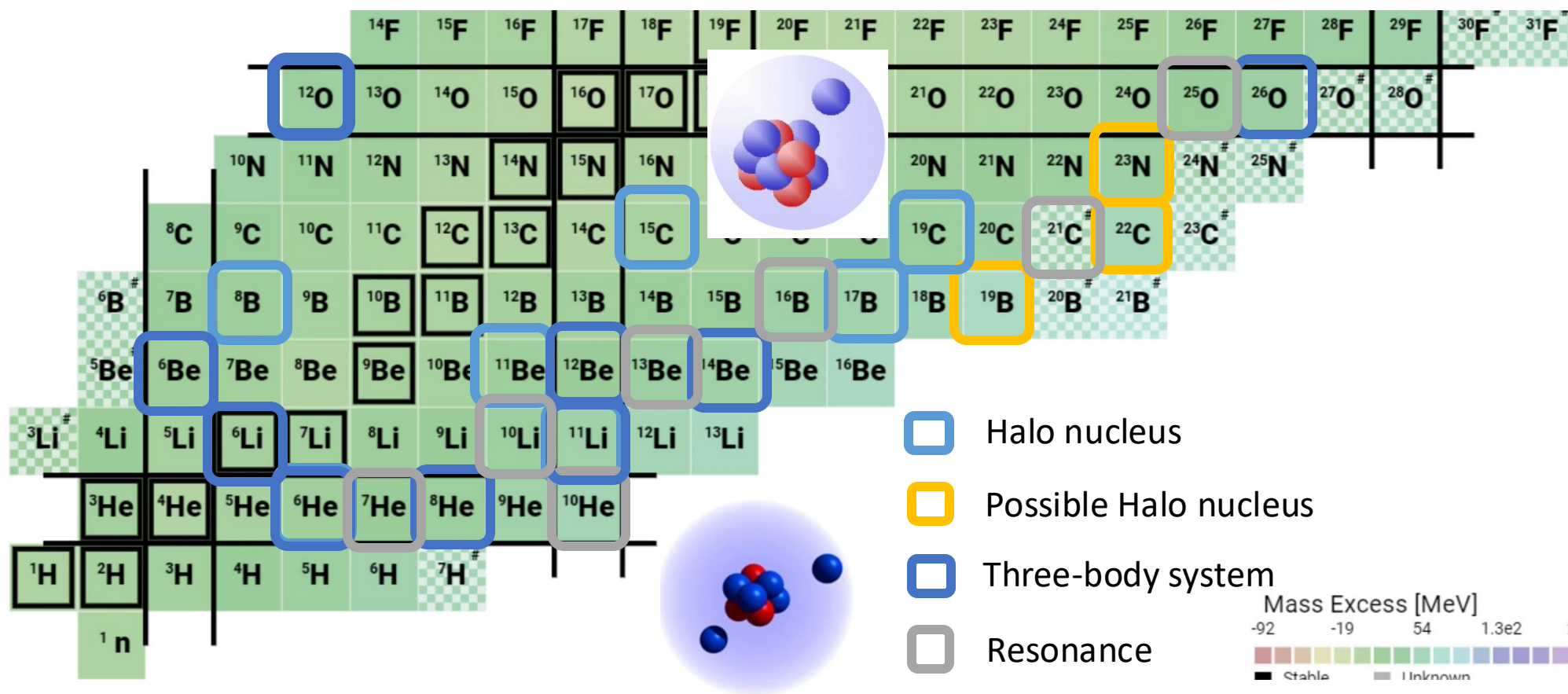


不稳定原子核结构——重元素起源

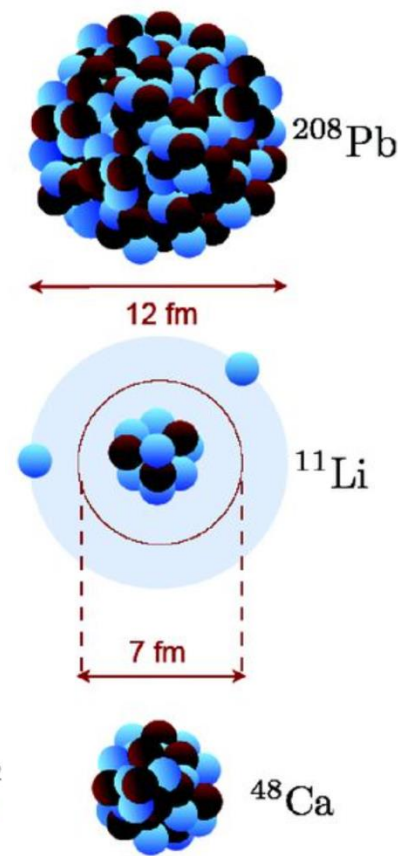


不稳定原子核结构——弱束缚核奇特结构

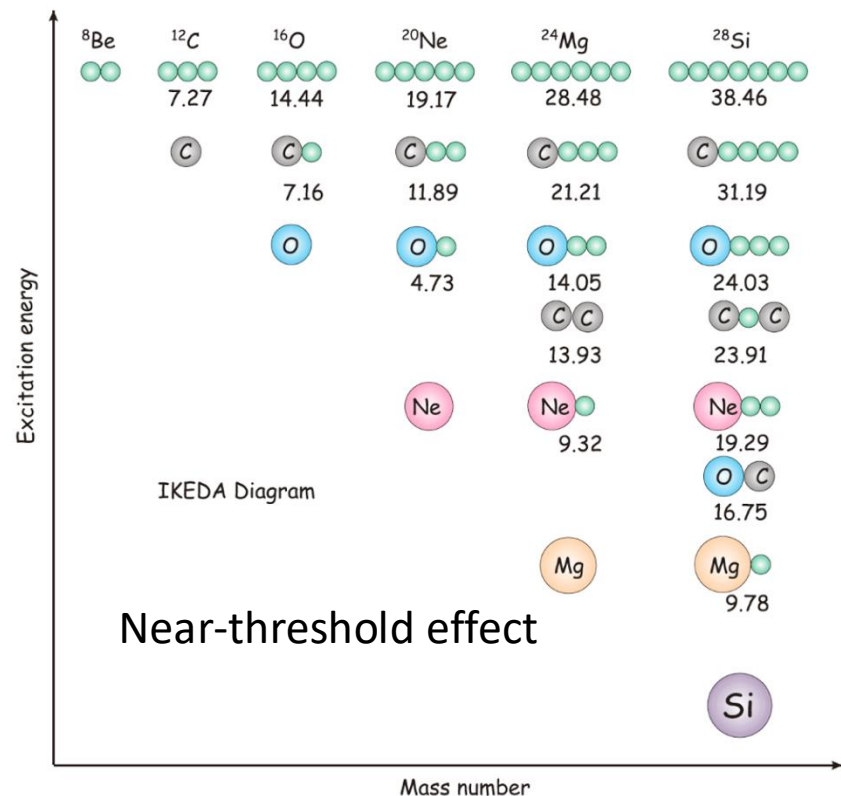
- Halo, Borromean nuclei, three body system, intruder states
- New experimental insights on rare nuclei to challenge theoretical predictions.



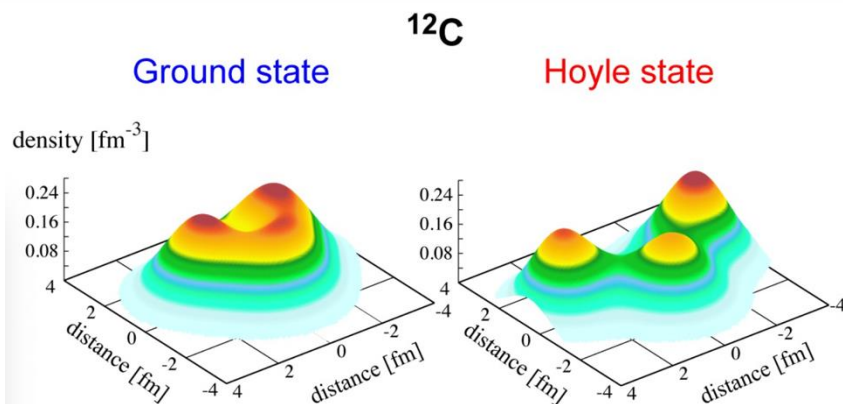
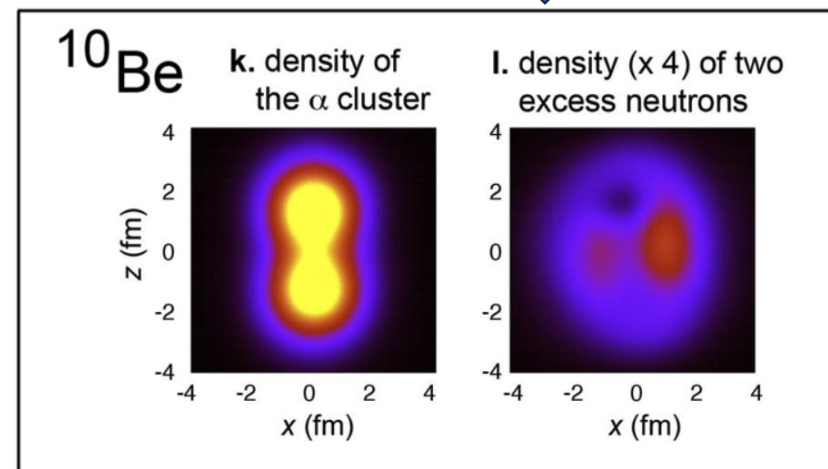
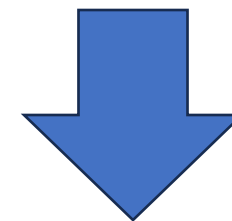
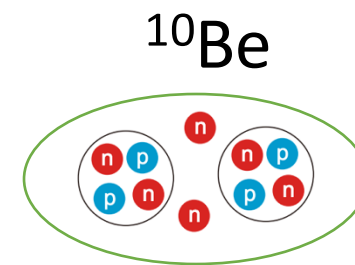
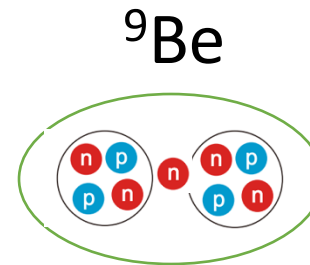
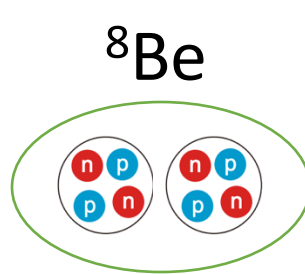
晕核: Halo nuclei



不稳定原子核结构——弱束缚核奇特结构



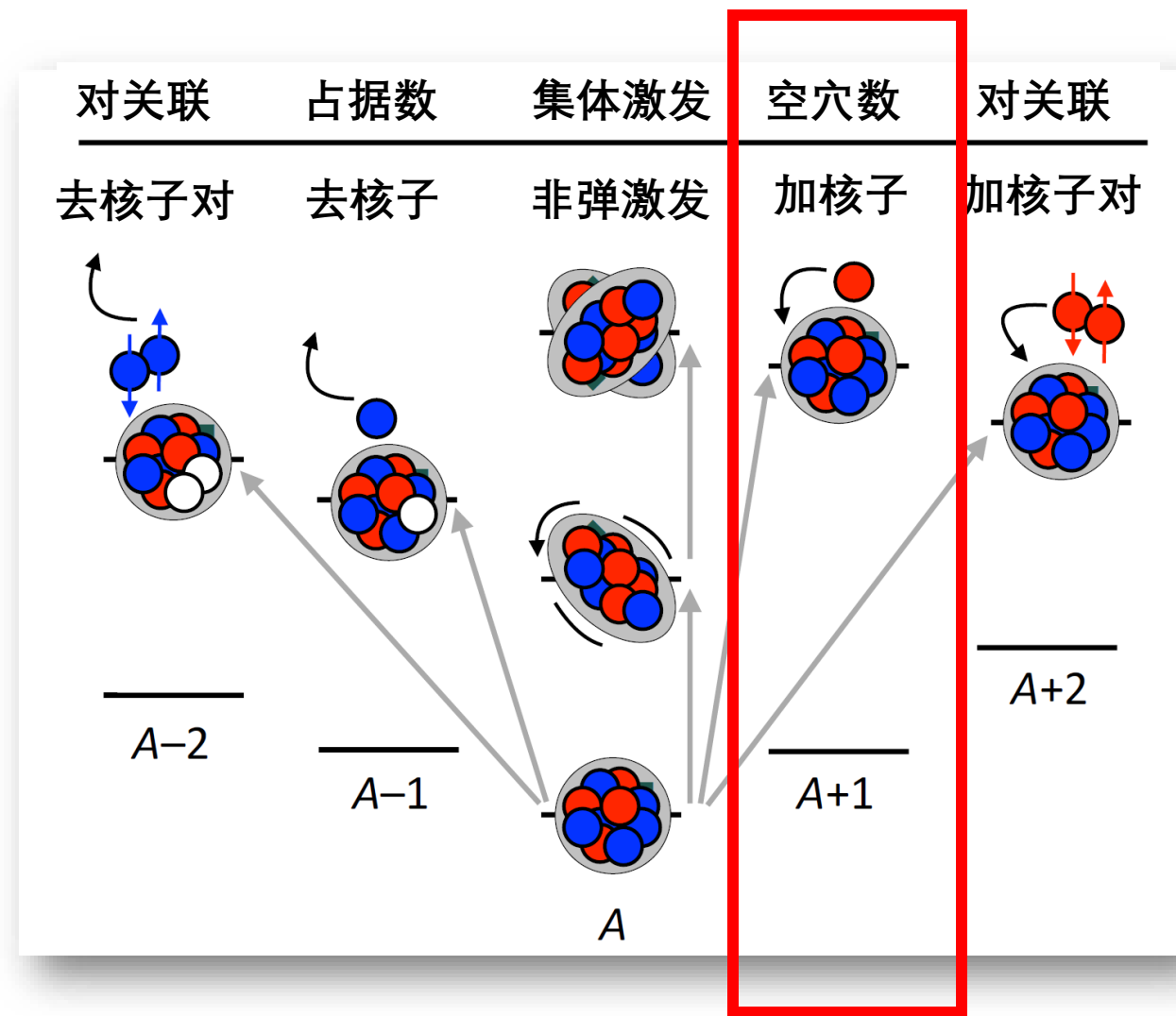
Near-threshold effect



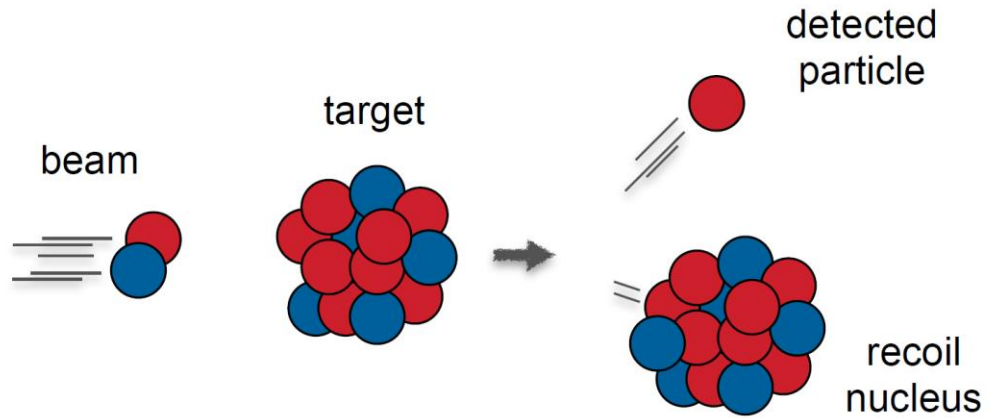
Monte Carlo Shell Model (MCSM)
Otsuka, T., Abe, T., Yoshida, T. *et al.* *Nat Commun* **13**, 2234 (2022).

单粒子转移反应—追踪单粒子轨道能量演化

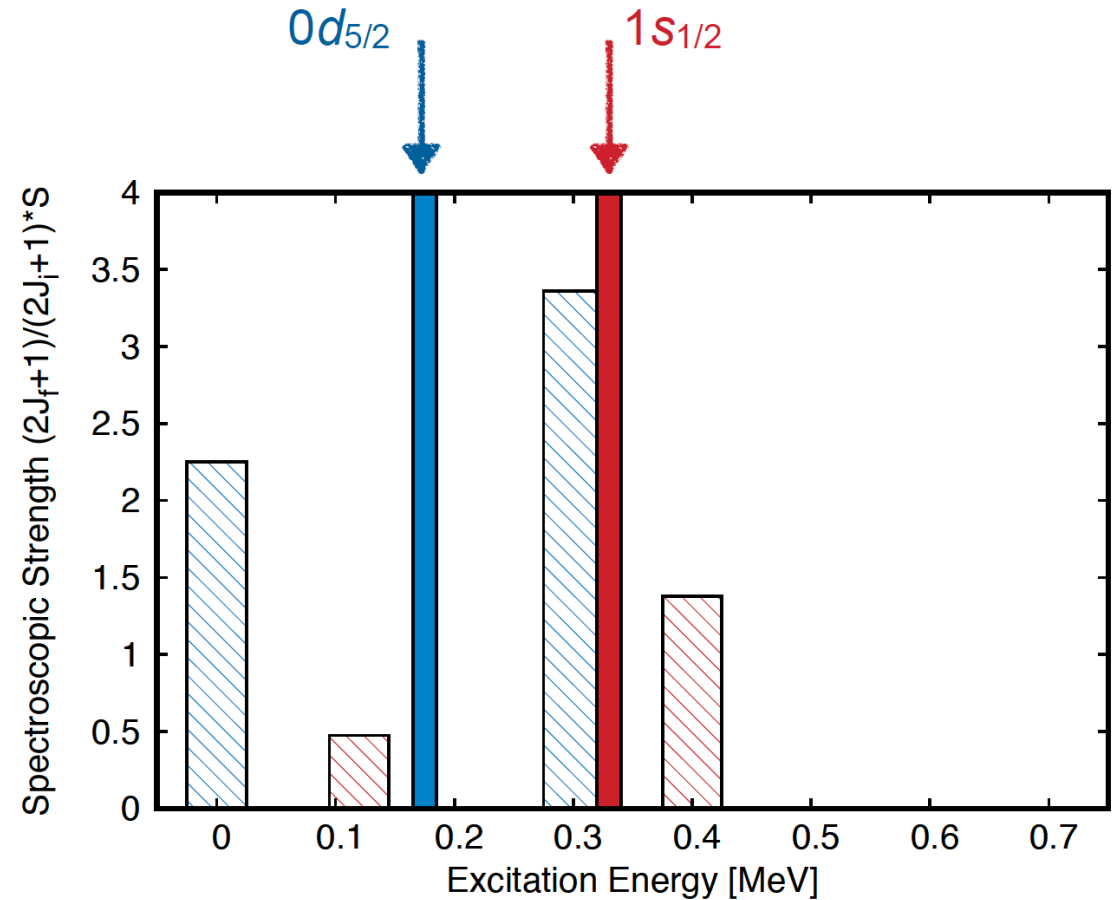
- 单核子转移：单粒子态，激发能，角动量，谱因子，e.g., (d,p) , ...
- 核子对转移：对关联效应，e.g., (p,t) , (t,p) , $(^3\text{He},p)$, ...
- 非弹激发：集体激发模式，e.g., (p,p') , (d,d') , (α,α') , ...



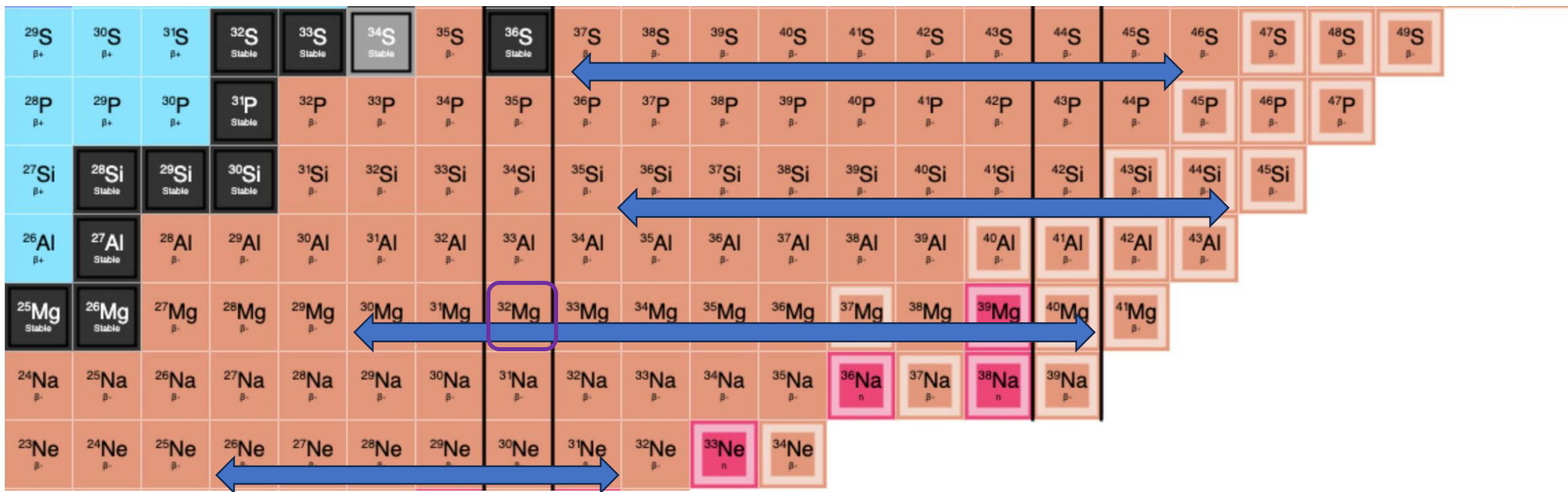
单粒子转移反应—追踪单粒子轨道能量演化



$$E_{centroid} = \frac{\sum (2j_f + 1) S_{lj} * E_{ex}}{\sum (2j_f + 1) S_{lj}}$$



单粒子转移反应—追踪单粒子轨道能量演化

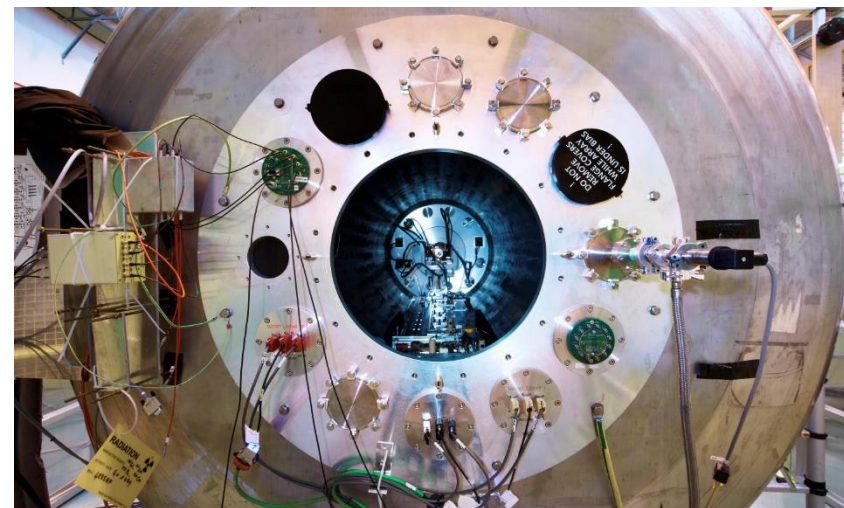


Large gap between the $B(E2)$ (or 2^+ energy) measurements and transfer measurements

- ❑ Inverse kinematics $\rightarrow$ Kinematics compression $\rightarrow$ 超导螺线管装置
- ❑ Resolution $\leftarrow$ Compromise $\rightarrow$ Statistics $\rightarrow$ “活性靶”气体探测器

通过超导螺线圈实现高能量分辨

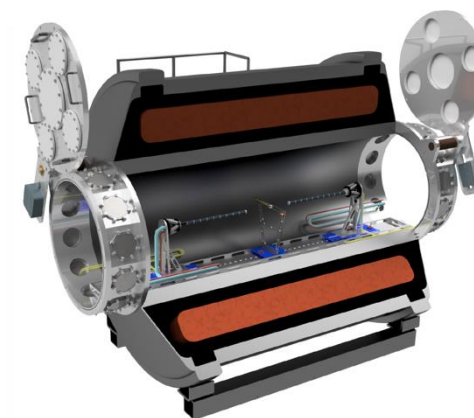
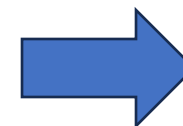
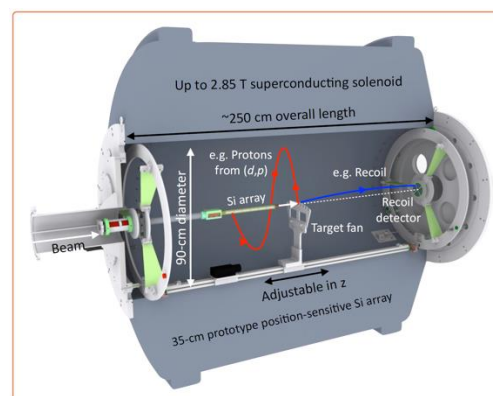
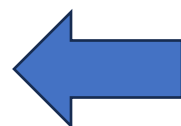
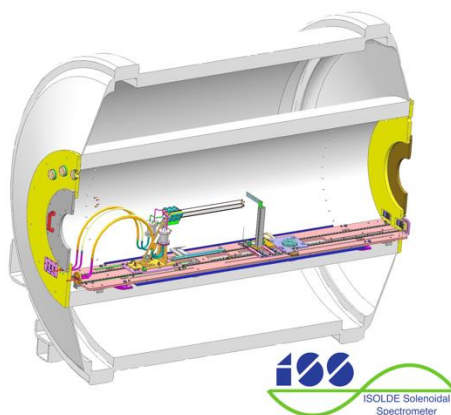
ISS @ CERN



HELIOS @ ANL

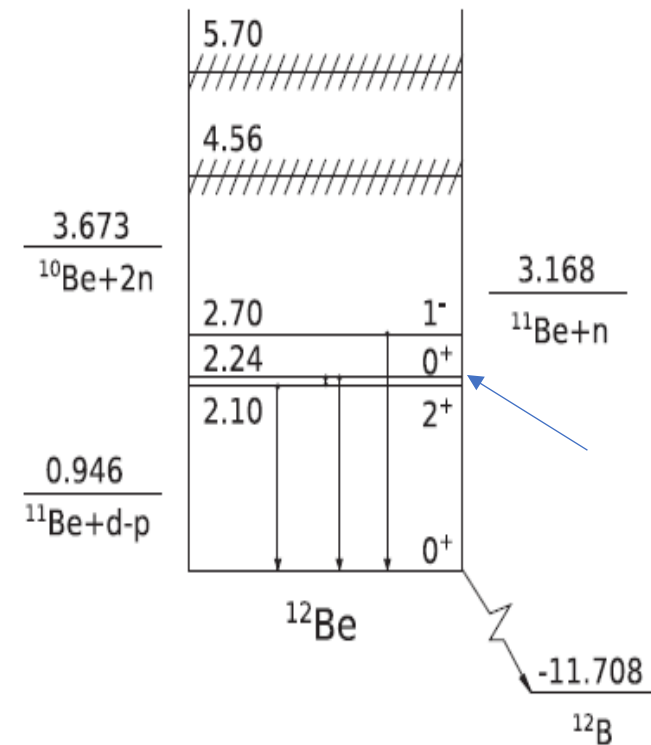
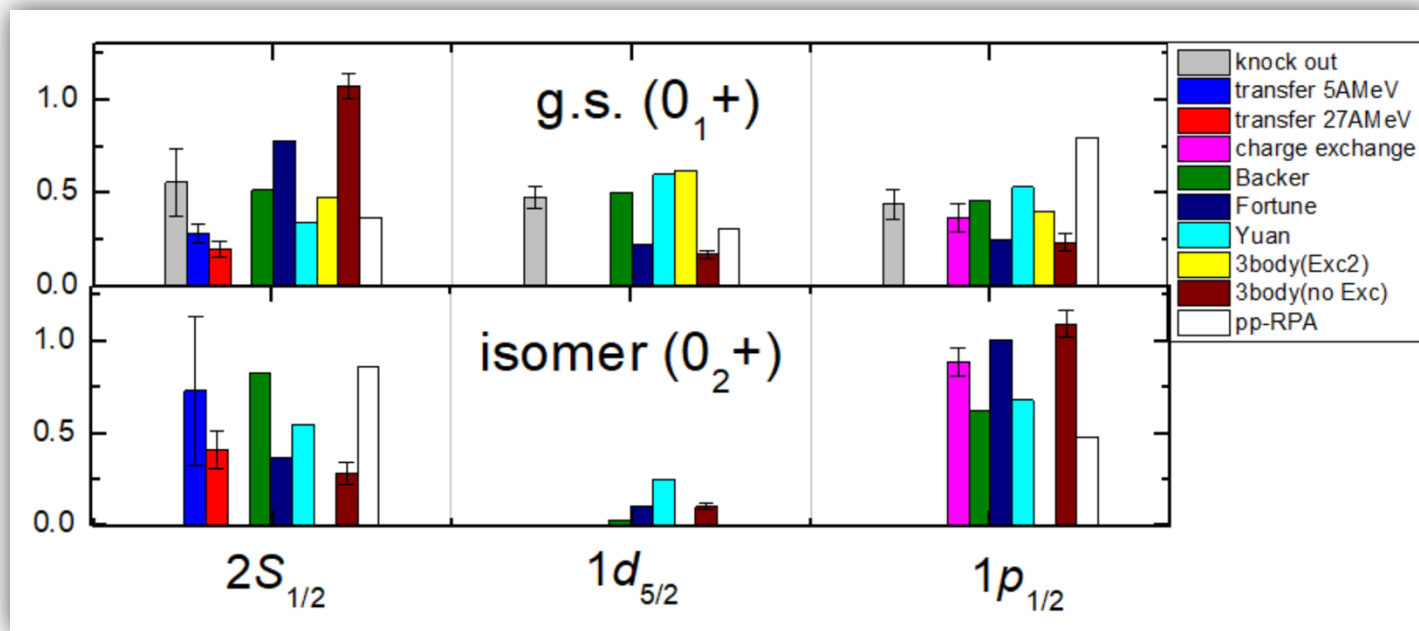


SOLARIS @ FRIB



^{12}Be 闯入态: N=8 幻数的消失机制

- 幻数 N=8 消失
- **Isomeric state**: 0_2^+ 331(12) ns
- E0 decay: e^+e^- pair creation



$$|0_i^+\rangle = a_i |1s_{1/2}^2\rangle + b_i |0d_{5/2}^2\rangle + c_i |0p_{1/2}^2\rangle \quad (i = 1, 2)$$

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

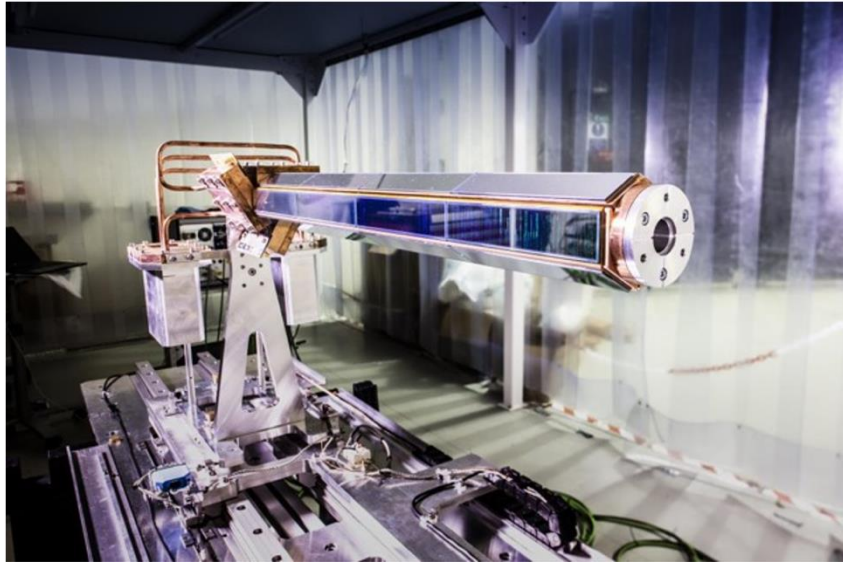
Is there enhanced radius in the excited states?

J. Chen *et al.* PLB 781 (2018) 412–416

J. Chen *et al.* Phys. Rev. C L031302 (2021)

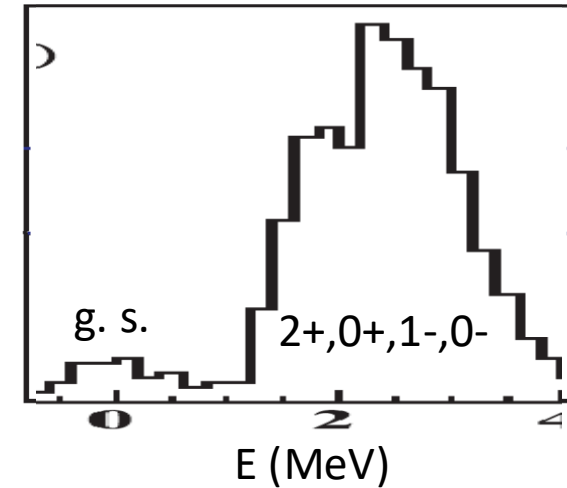
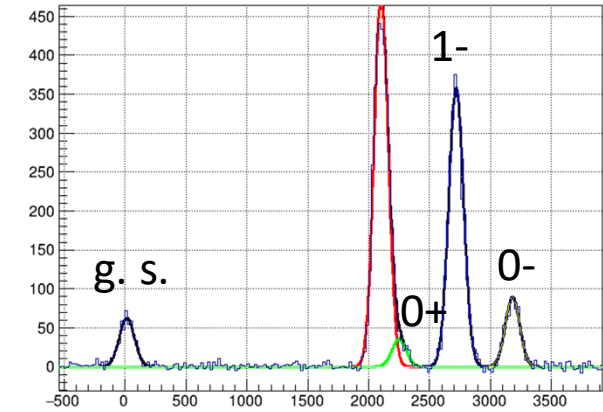
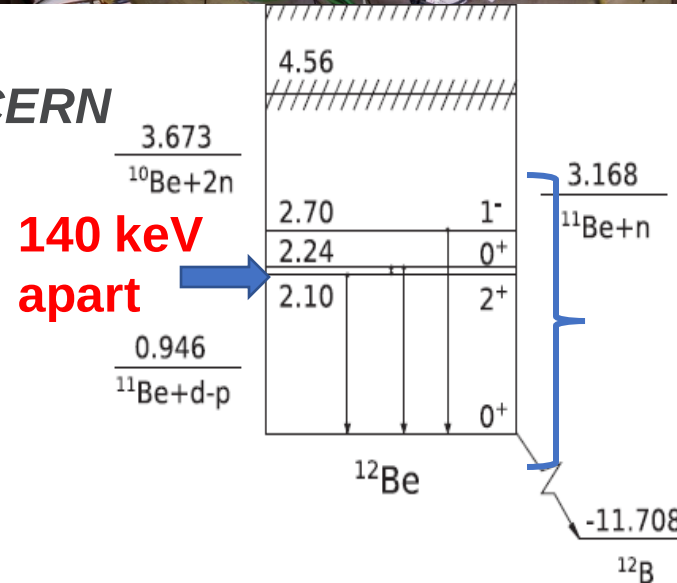
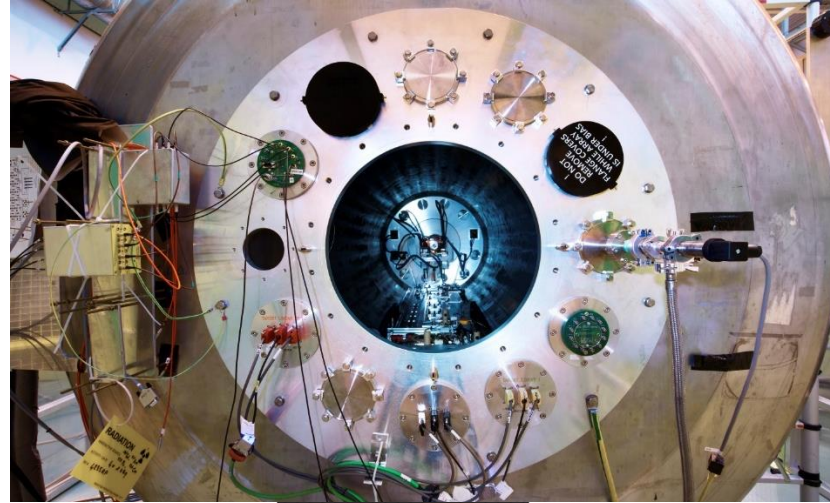
ISS & HIE-ISOLDE @CERN : $^{11}\text{Be}(d,p)^{12}\text{Be}$ 实验测量

- Directly resolve the isomer 0^+_2 state



ISOLDE Solenoidal Spectrometer at CERN

ideal energy: 10MeV/u
130-keV FWHM resolution



Comparison with
conventional silicon array

PI: Jie Chen

^{12}Be 闯入态: N=8 幻数的消失机制

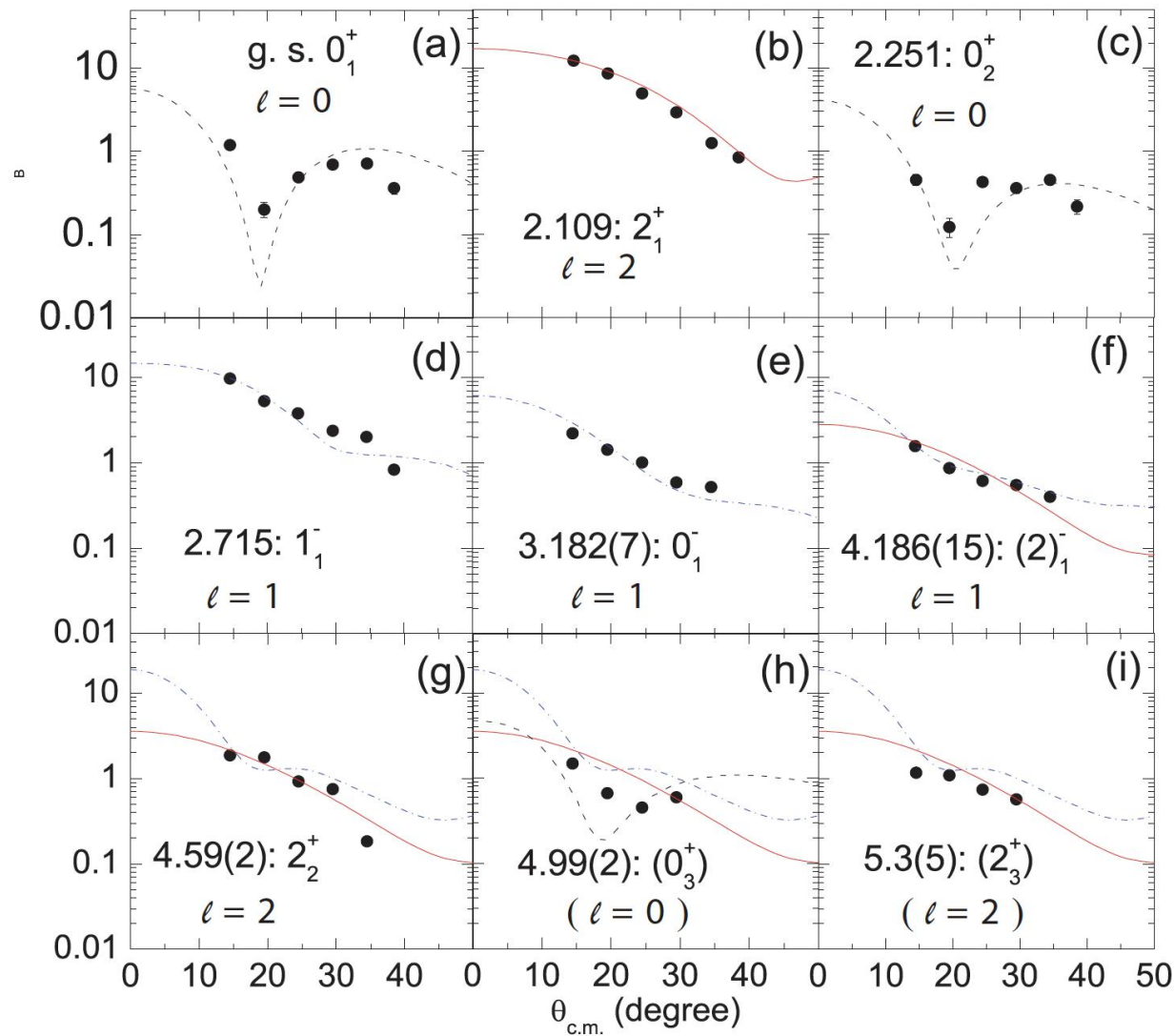
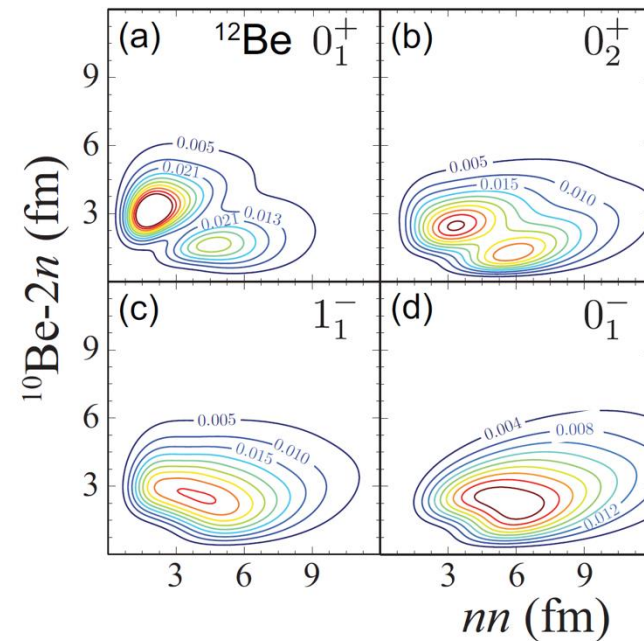
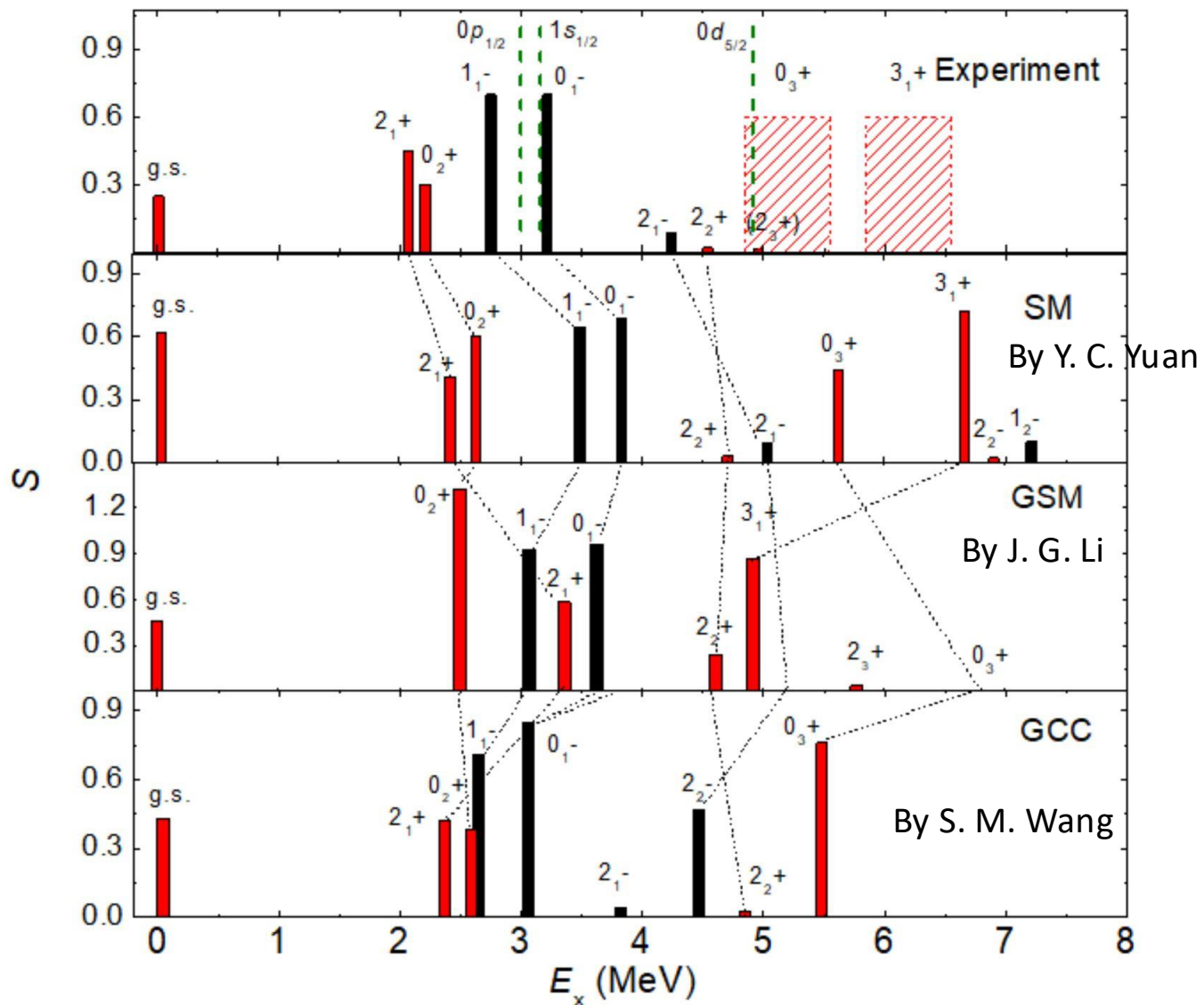


TABLE I. Excitation energies E_x , transferred orbital angular momentum ℓ , spin-parities J^π , shell-model orbital nls and spectroscopic factors S for the low-lying states in ^{12}Be observed in the present $^{11}\text{Be}(d,p)^{12}\text{Be}$ reaction.

E_x (MeV))	ℓ	J^π	nls	S
g. s.	0	0^+	$1s_{1/2}$	0.3(3)
2.109	2	2^+	$1d_{5/2}$	0.45(4)
2.251	3	0^+	$1s_{1/2}$	0.39(6)
2.715	1	1^-	$0p_{1/2}$	0.72(6)
3.182(7)	1	0^-	$(0p_{1/2})$	0.71(7)
4.186(15)	1	2^-	$2p_{1/2}$	0.08(1)
4.59(2)	2	2^+	$0d_{5/2}$	0.02(1)
4.99(2)	(0)	0^+	$(1s_{1/2})$	0.70(20)
5.30	(2)	2^+	$0d_{5/2}$	

^{12}Be 闯入态: N=8 幻数的消失机制



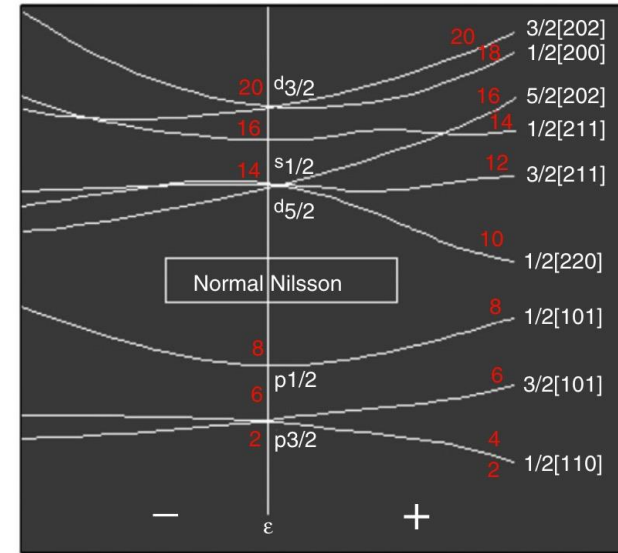
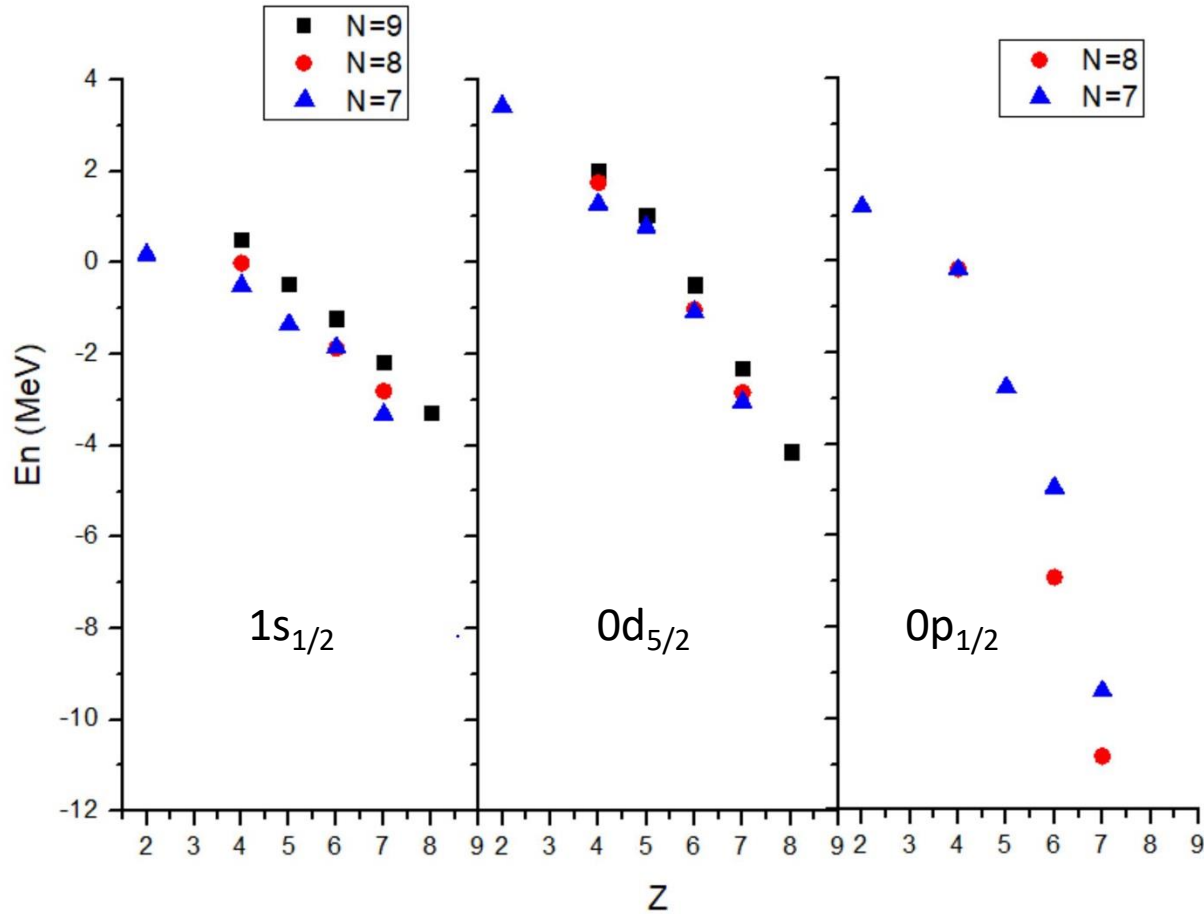
By S. M. Wang

Two-nucleon density distributions

➡ Halo structures in excited states

- g.s: mixture of a dineutron structure and a cigar-like configuration
- 0_2^+ state: Enhanced radius: Two-neutron halo structure?
- 0- states: Near-threshold state! Halo-like structure

^{12}Be 闯入态: N=8 幻数的消失机制



C. R. Hoffman *et al.* Phys. Rev. C 89, 061305(R) (2014)

Isomeric state 0_2^+ : radius estimation

Halo structure?

$$S(\text{g.s.})=0.30(3)$$

$$S(0_2^+)=0.39(6)$$

Their matter radius can be estimated with:

$$R_m^2 = ((A - 2)/A)(R_c^2 + 2R_v^2/A).$$

$$R^2 = 10/12(R_{10\text{Be}}^2 + 2R_v^2/12)$$

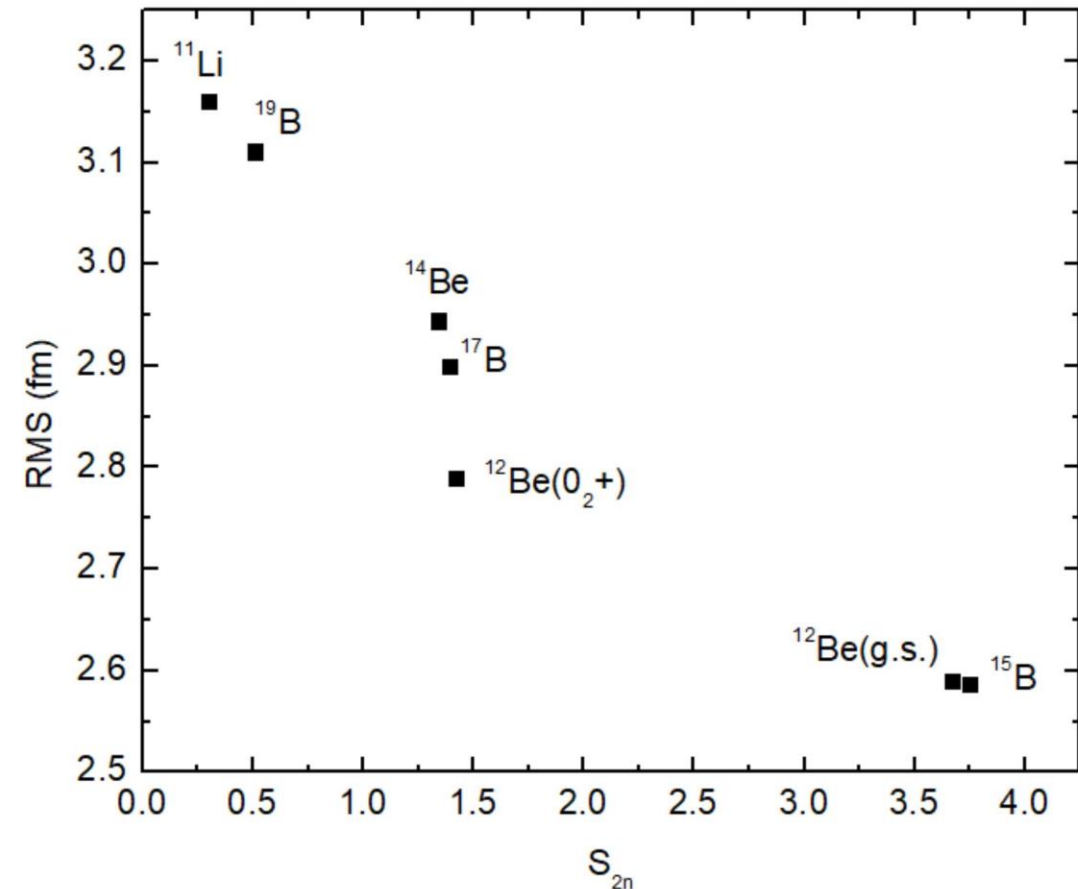
$$R_{10\text{Be}} = 2.40 \text{ fm}$$

$$0_1^+ = 19\% (s) + 24\% (p) + 57\% (d); S_n = 3.17 \text{ MeV}$$

$$0_2^+ = 23\% (s) + 59\% (p) + 18\% (d); S_n = 0.93 \text{ MeV}$$

$$\text{Therefore, } R_{0_1^+} = 2.56 \text{ fm} \quad \text{experimental: } 2.57(10) \text{ fm}$$

$$R_{0_2^+} = 2.79 \text{ fm}$$

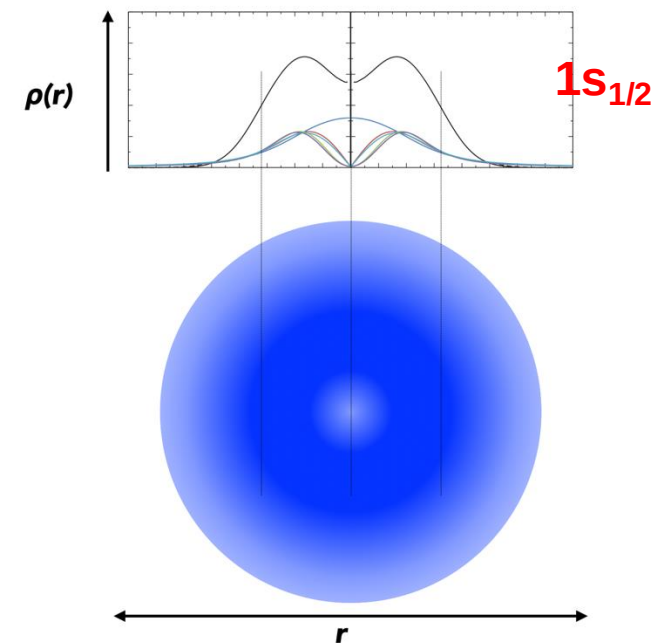
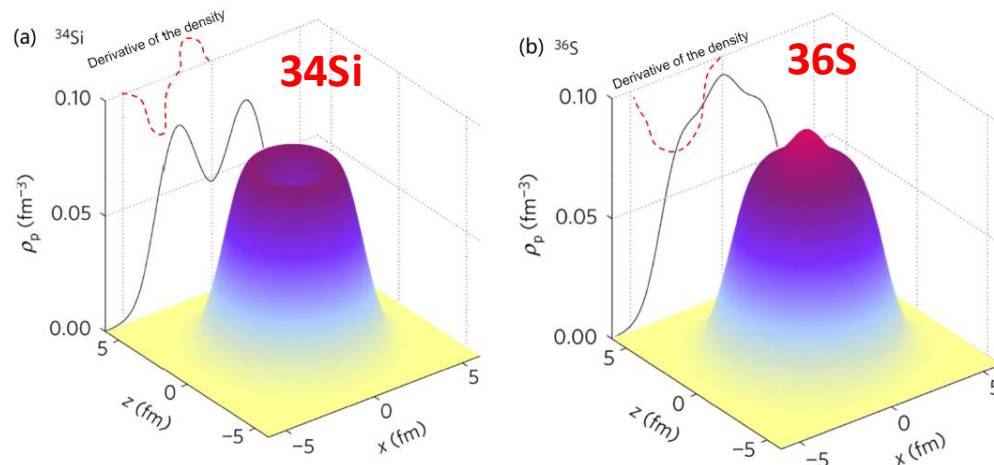


质子气泡核

- ❑ 质子敲出反应：
1s_{1/2}轨道低占据数
- ❑ 幻数 N=20, Z=14



中心密度降低



		36Sc	37Sc	38Sc	39Sc	40Sc	41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc	50Sc
	34Ca	35Ca	36Ca	37Ca	38Ca	39Ca	40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca
32K	33K	34K	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K
31Ar	32Ar	33Ar	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar	46Ar	47Ar
30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl	44Cl	45Cl	46Cl
29S	30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S	43S	44S	45S
28P	29P	30P	31P	32P	33P	34P	35P	36P	37P	38P	39P	40P	41P	42P	43P	44P
27Si	28Si	29Si	30Si	31Si	32Si	33Si	34Si	35Si	36Si	37Si	38Si	39Si	40Si	41Si	42Si	43Si
26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al	40Al	41Al	42Al

$0d_{3/2}$

$1s_{1/2}$

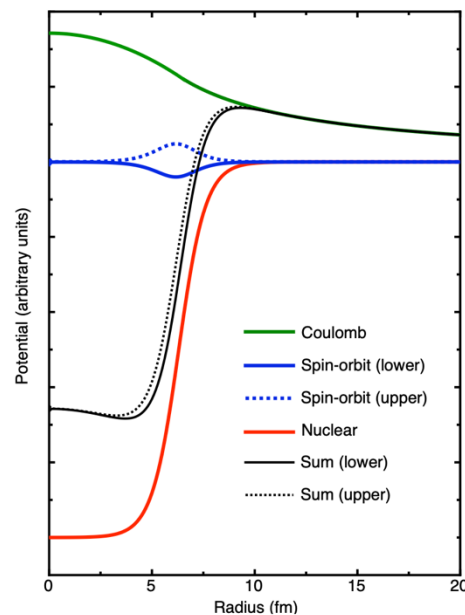
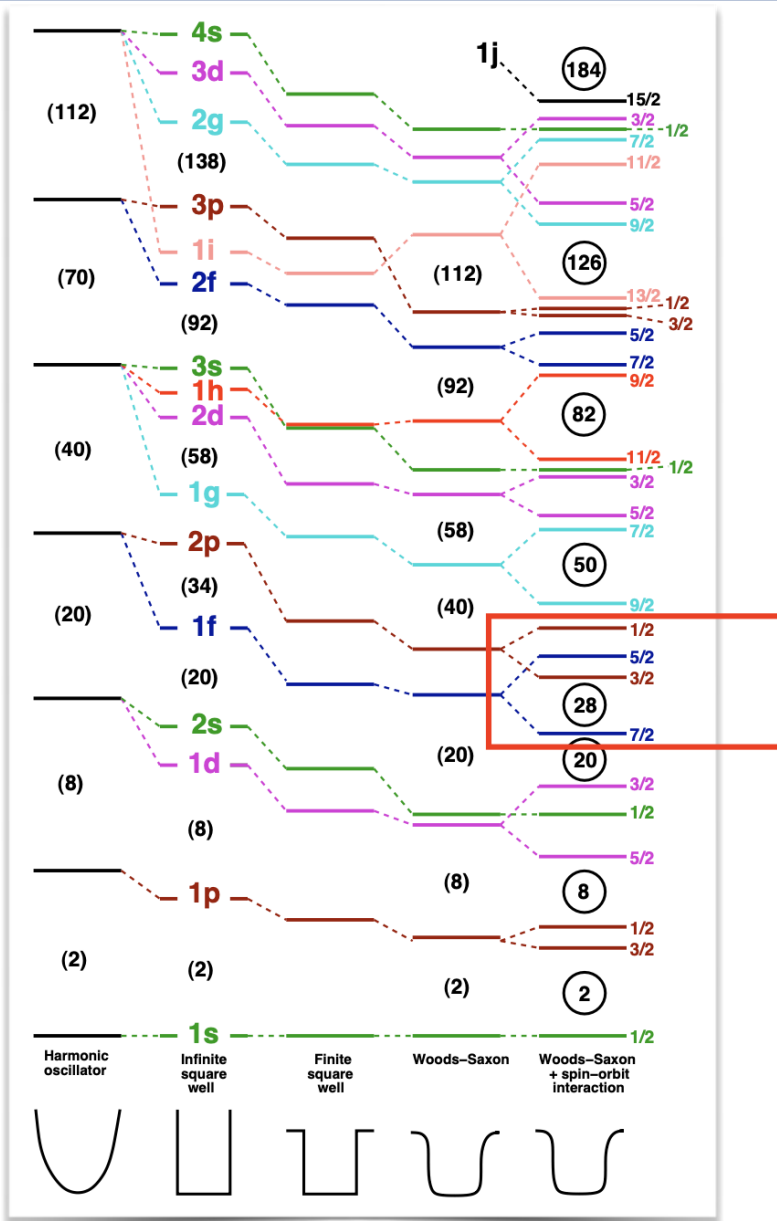
PROTONS

A. Mutschler, et al, Nature Physics13, 155 (2016)

G. Burgunder, et al, *Phy. Rev. Lett.* 112, 042502 (2014)

B. P. Kay, et al, *Phy. Rev. Lett.* **119**, 182502 (2017).

自旋轨道劈裂



Maria Goeppert Mayer

$l \cdot s$

自旋轨道劈裂

质子中心
密度降低

+

自旋轨道相互作用
正比核密度的导数

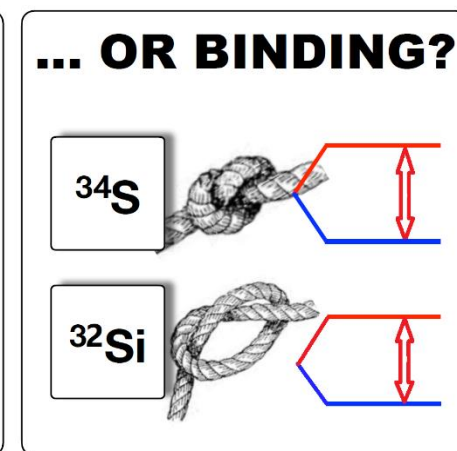
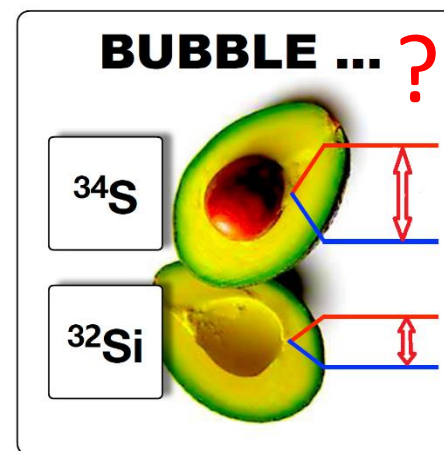
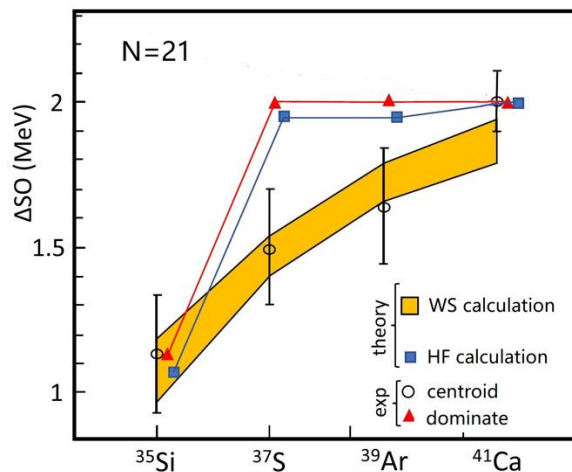
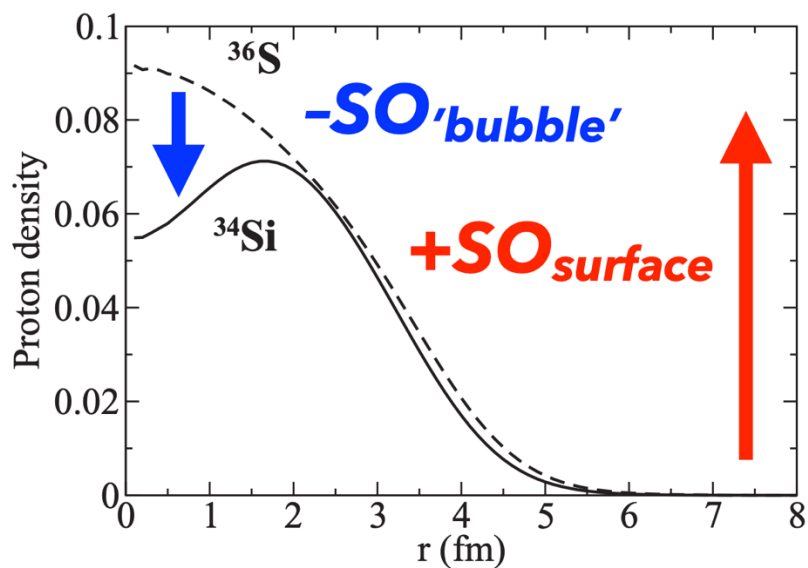
+

1p轨道对接近中心的
相互作用敏感



1p轨道受到影响而
自旋轨道劈裂降低

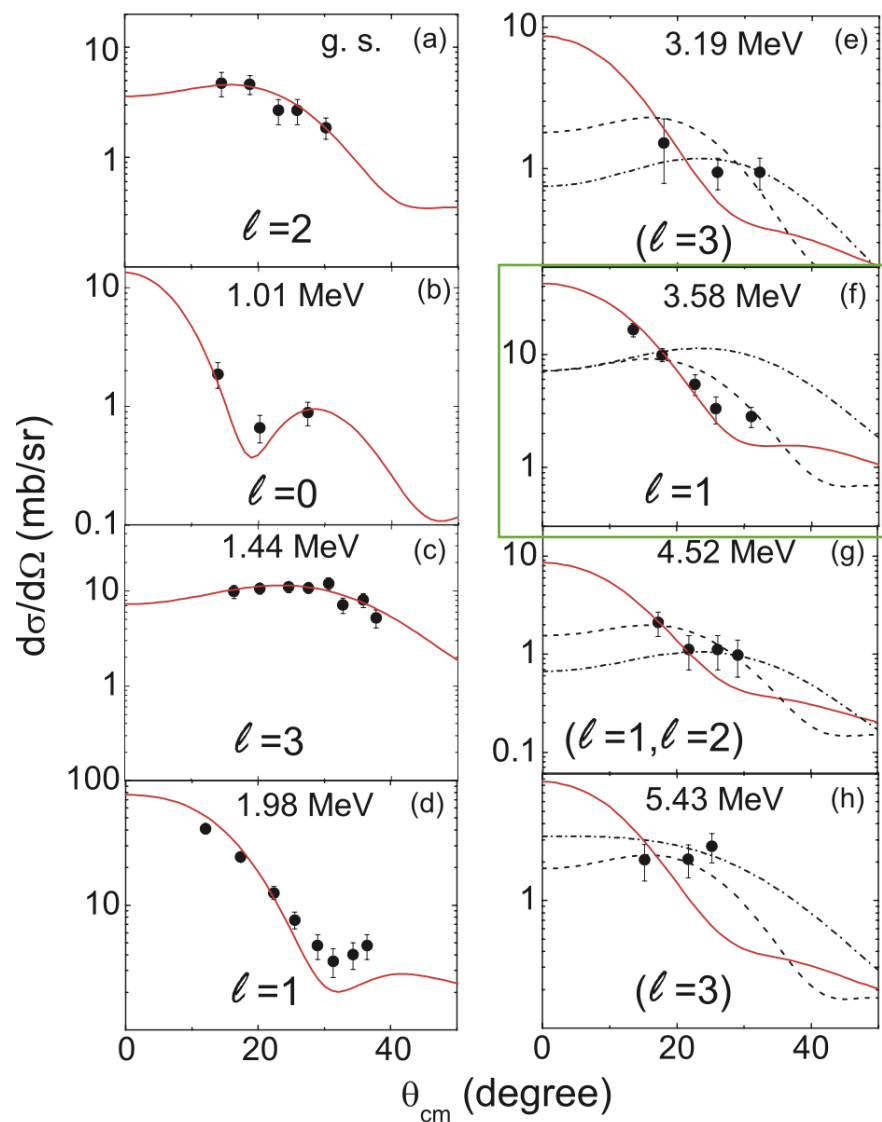
“气泡核”



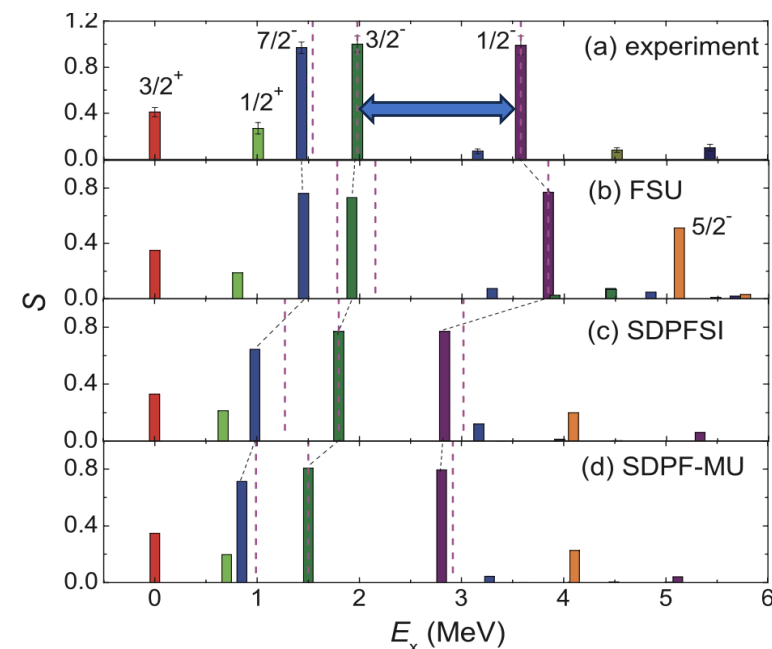
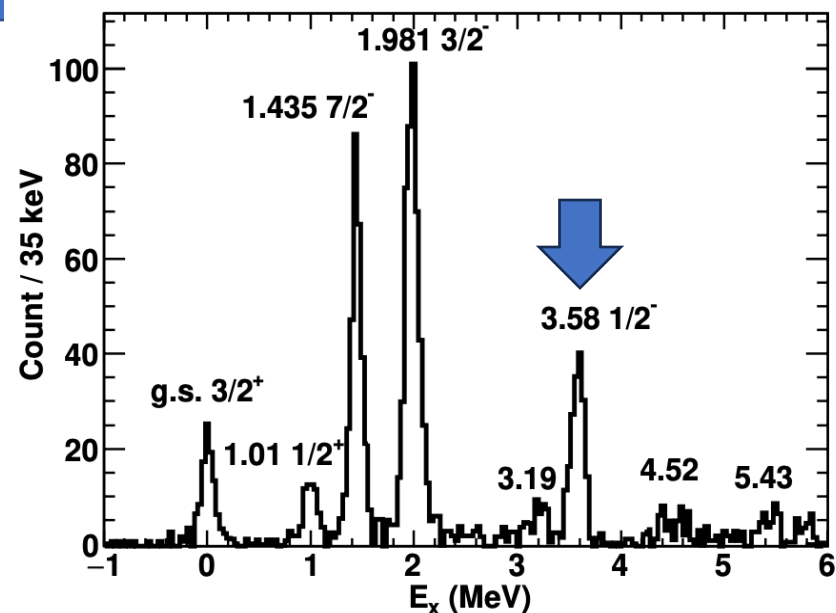
G. Burgunder, et al, Phys. Rev. Lett. 112, 042502 (2014)

B. P. Kay, et al, Phys. Rev. Lett. 119, 182502 (2017).

使用SOLARIS测量 $^{32}\text{Si}(d,p)^{33}\text{Si}$

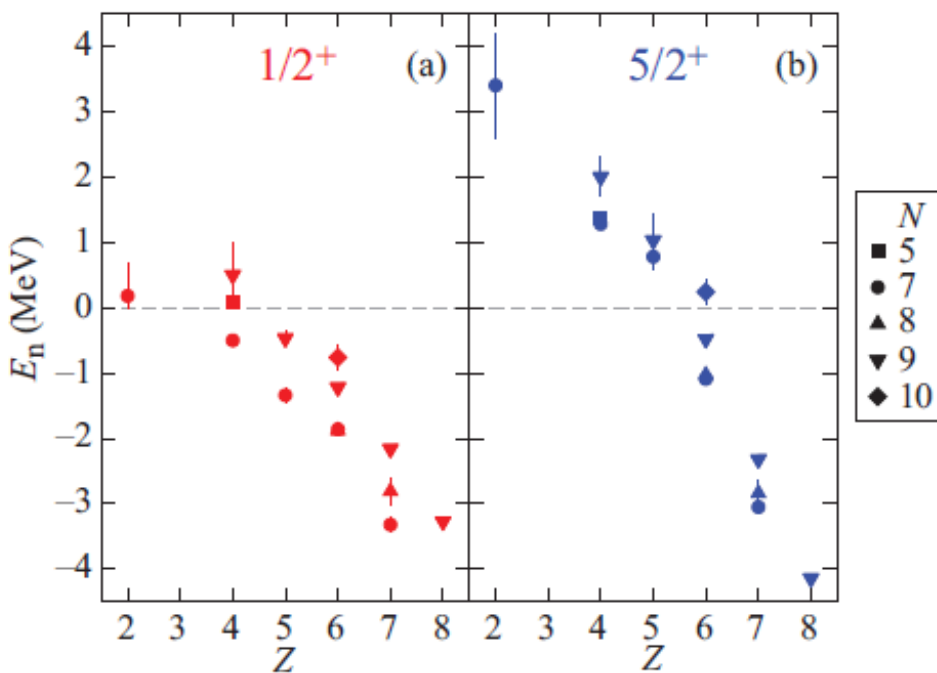


- FRIB-ReA束流:
7.8 MeV/u ^{32}Si
 $\sim 10^6$ pps
- SOLARIS
- 分辨率: 140 keV
- 1/2- 态:
3.58 MeV
- 自旋轨道劈裂: 1.6 MeV
- $1p_{1/2}, 1p_{3/2}, 0f_{7/2}$ 轨道能量



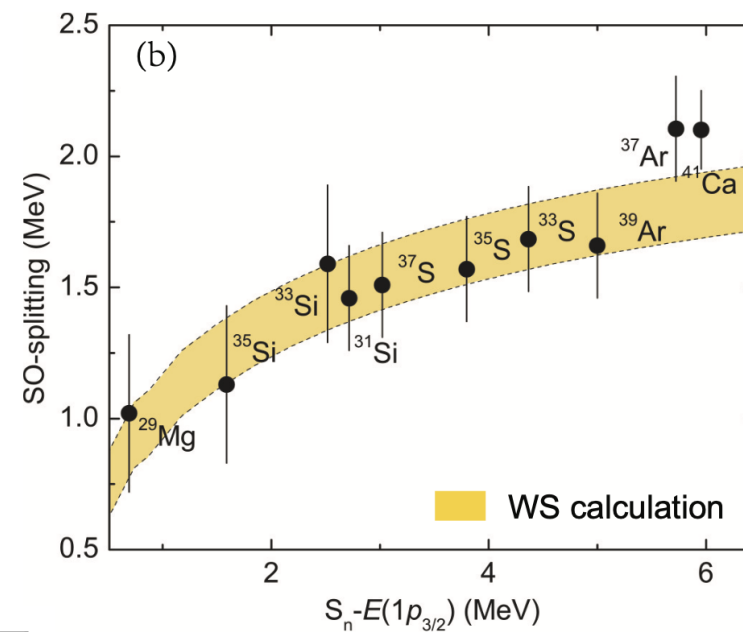
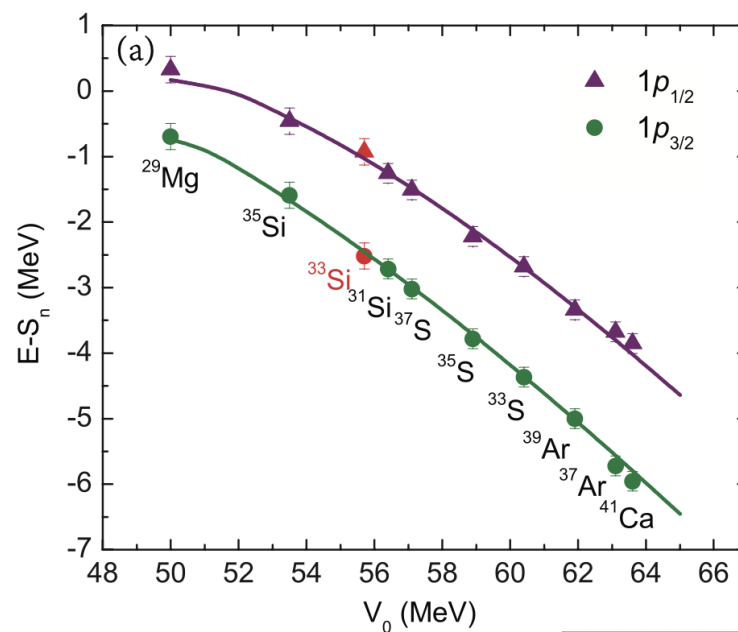
自旋轨道劈裂演化趋势

--Z=12-20, N=17-21附近的自旋轨道劈裂由弱束缚主导，可以被1p轨道接近中子分离能阈值的效应所描述

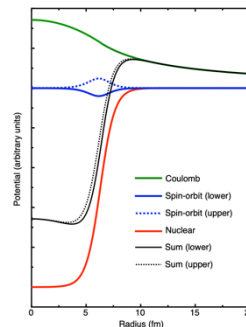


Lingering effect of $1s_{1/2}$ orbitals

C. R. Hoffman *et al.* Phys. Rev. C 89, 061305(R) (2014)

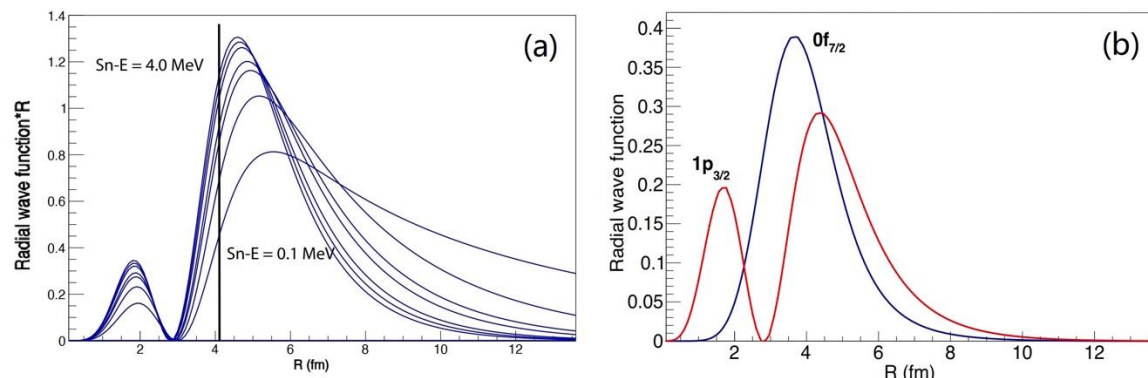
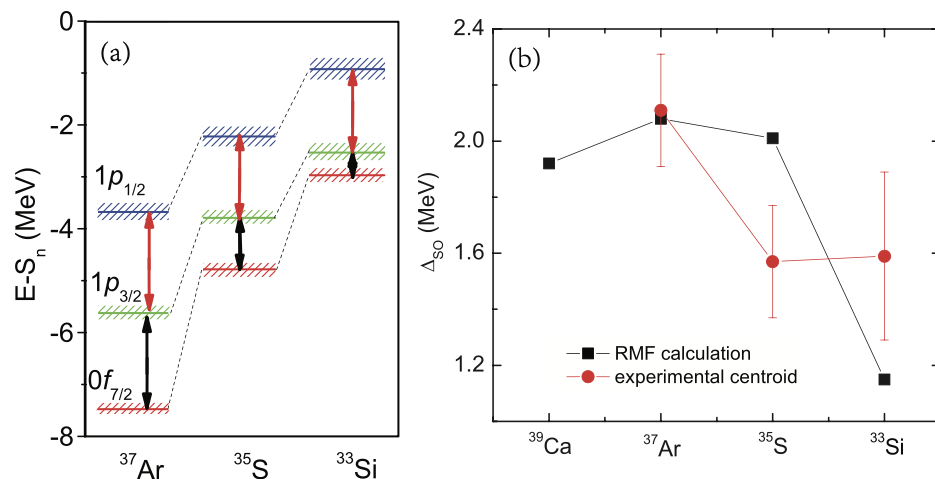


Woods-Saxon势:



自旋轨道劈裂演化趋势

- RMF 计算不能描述实验观测的N=19自旋轨道演化趋势
- 原因：缺少核子关联？自旋轨道相互作用只是表面项？



Letter

Evolution of the nuclear spin-orbit splitting explored via the $^{32}\text{Si}(d,p)^{33}\text{Si}$ reaction using SOLARIS

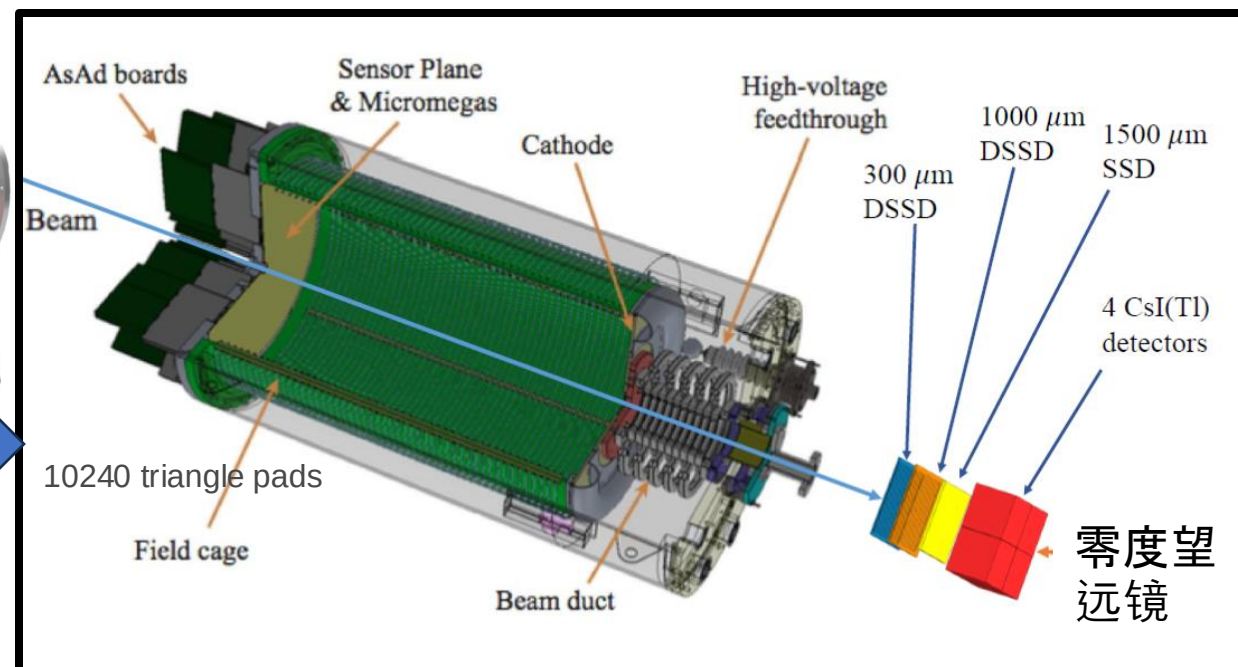
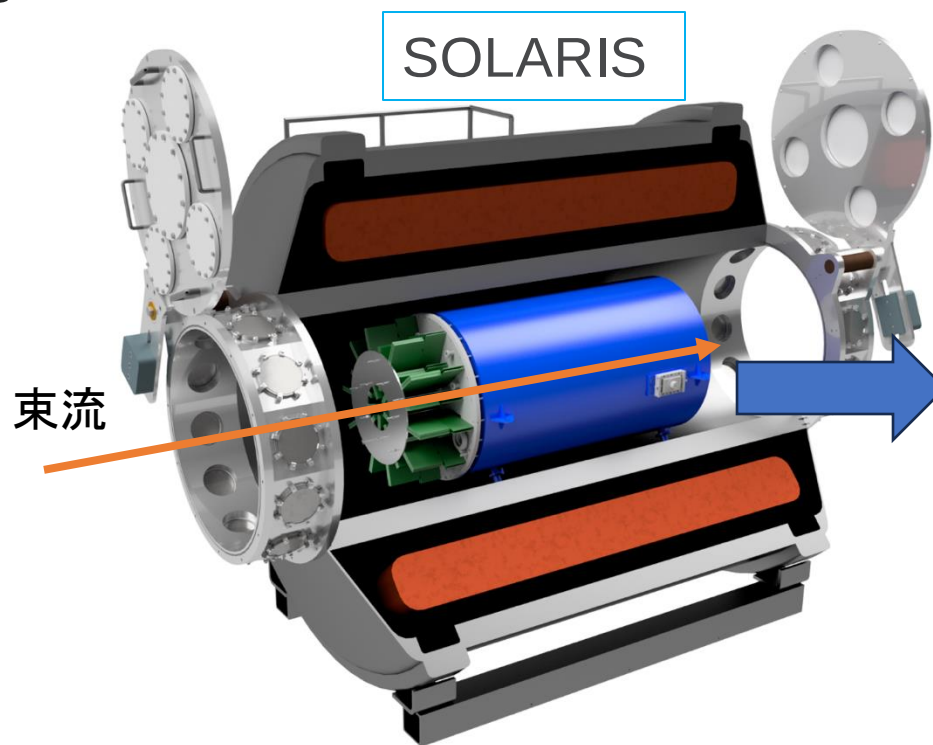
J. Chen^{a,b,*}, B.P. Kay^b, C.R. Hoffman^b, T.L. Tang^b, I.A. Tolstukhin^b, D. Bazin^c, R.S. Lubna^c, Y. Ayyad^d, S. Beceiro-Novo^c, B.J. Coombes^e, S.J. Freeman^{f,g}, L.P. Gaffney^h, R. Garg^c, H. Jayatissa^b, A.N. Kucheraⁱ, P. MacGregor^f, A.J. Mitchell^e, W. Mittig^c, B. Monteagudo^{c,j}, A. Munoz-Ramos^d, C. Müller-Gatermann^b, F. Recchia^{k,l}, N. Rijal^c, C. Santamaria^c, I.Z. Serikow^c, D.K. Sharp^f, J. Smith^m, J.K. Stecenko^m, G.L. Wilsonⁿ, A.H. Wuosmaa^m, L.X. Yuan^o, J.C. Zamora^c, Y.N. Zhang^o

所需束流强度: 10^4 pps

How about weak beams?

通过活性靶气体探测器AT-TPC研究直接核反应

- 大体积活性靶气体探测器 (1米*0.5米) $\longleftrightarrow$ 气体同时是探测媒介和反应靶
- 很高的有效靶厚度 $\longleftrightarrow$ 可以进行几百粒子每秒的测量
- 可以使用纯的氖或氢气 $\longleftrightarrow$ 有效降低本底, 副反应道
- 加磁场 $B = 4\text{ T}$

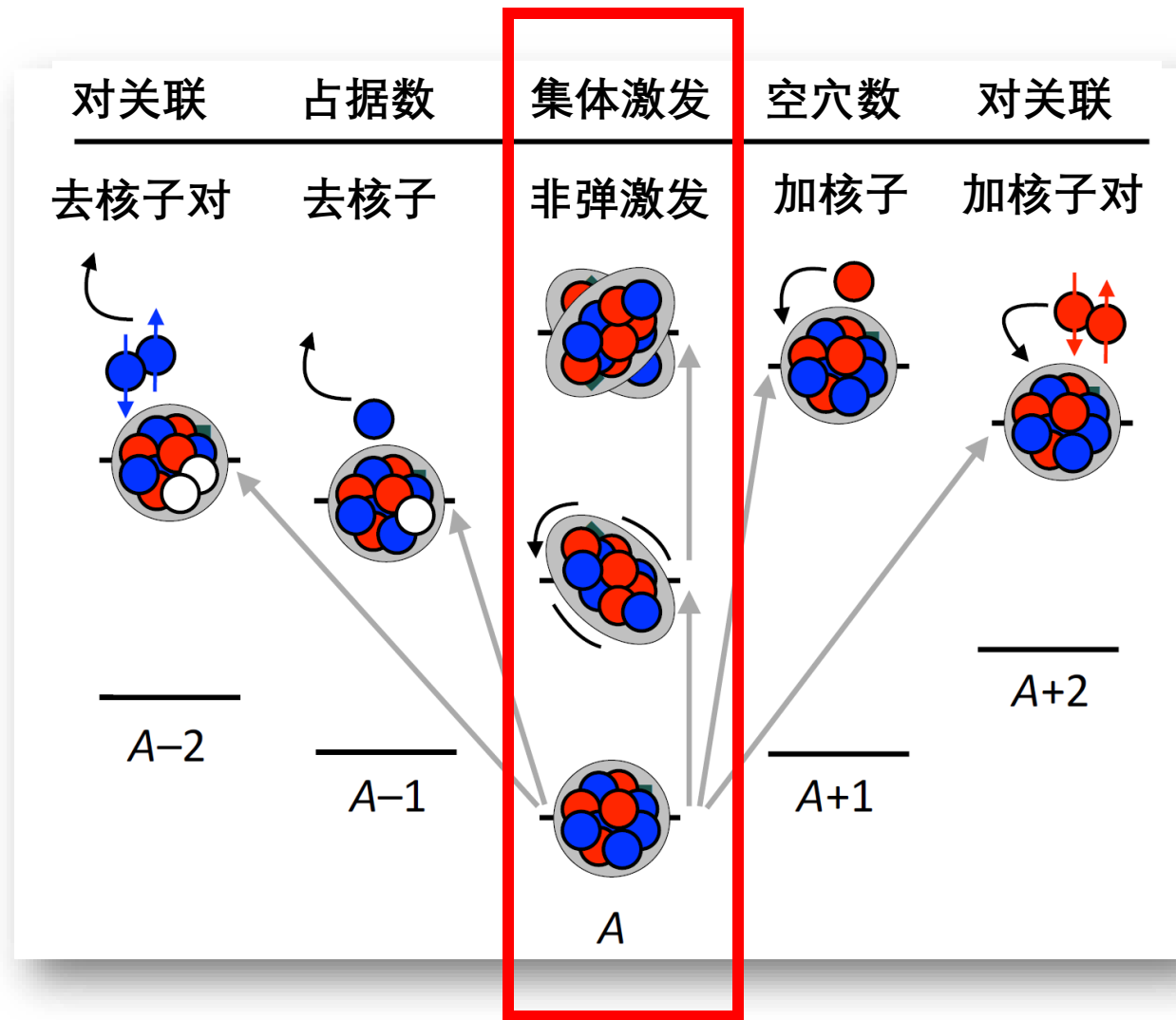


密歇根州立大学FRIB: AT-TPC

J. Bradt et al., Nucl. Instrum. and Methods in Phys. Res. A 875, 65 (2017)

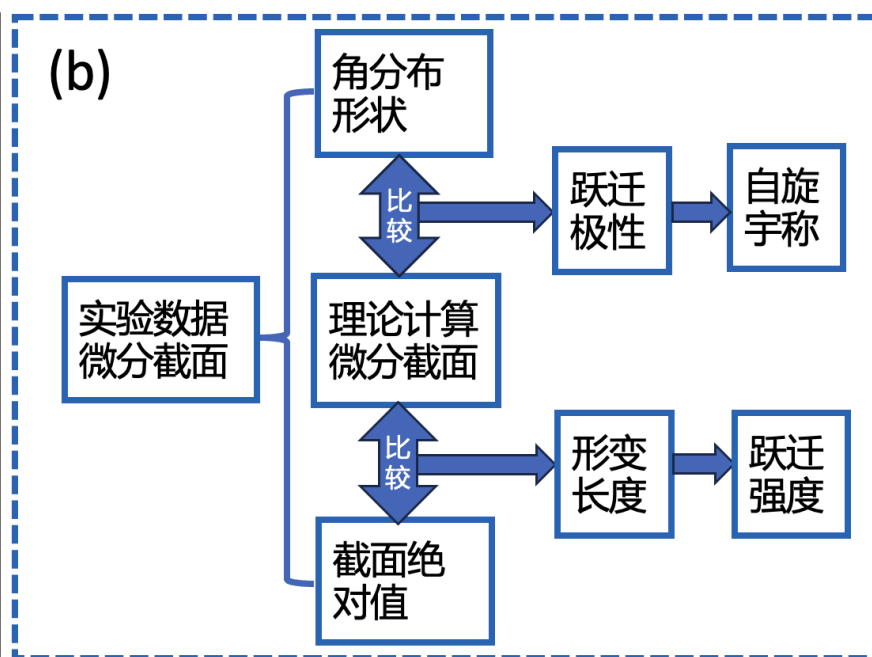
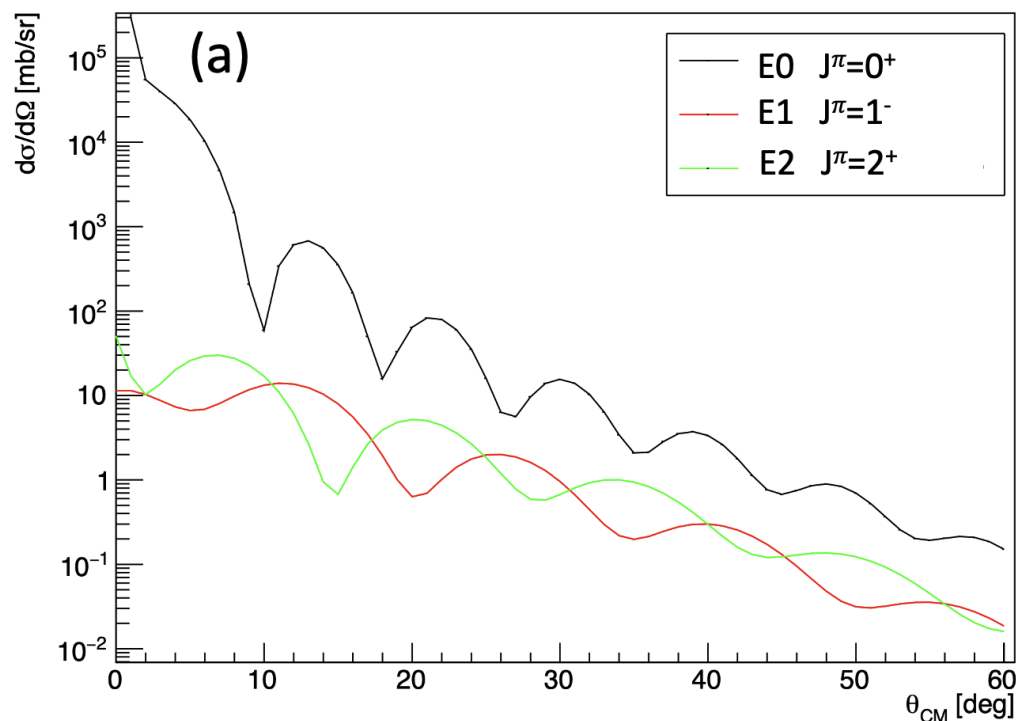
非弹性散射反应—原子核的集体激发

- 单核子转移：单粒子态，激发能，角动量，谱因子，e.g., (d,p) , ...
- 核子对转移：对关联效应，e.g., (p,t) , (t,p) , $(^3\text{He},p)$, ...
- 非弹激发：集体激发模式，e.g., (p,p') , (d,d') , (α,α') , ...



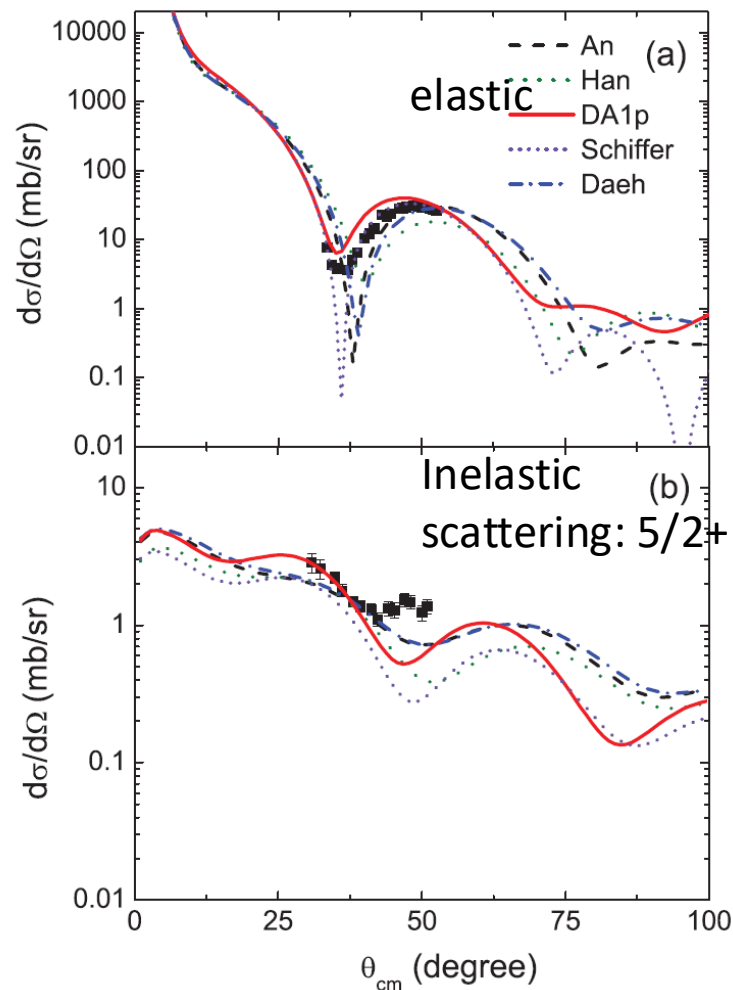
非弹性散射反应—原子核的集体激发

原子核非弹性散射 → 单极、偶极、四级激发模式以及强度测量



非弹性散射反应—原子核的集体激发

ATLAS beam with HELIOS
Beam: ^{15}C at 7.1 MeV/u



-- Deducing deformation length using two experiments approaches

Life time of the $5/2^+$ state

$$B(E2, J_i^+ \rightarrow 0^+) = e^2 \frac{M_p^2}{2J_i + 1}$$

$$\delta_p = \frac{4\pi}{3ZR} M_p$$

Inelastic scattering on deuterons

$$(d\sigma/d\Omega)_{\text{exp}} = \delta_d^2 (d\sigma/d\Omega)_{\text{DWBA}}$$

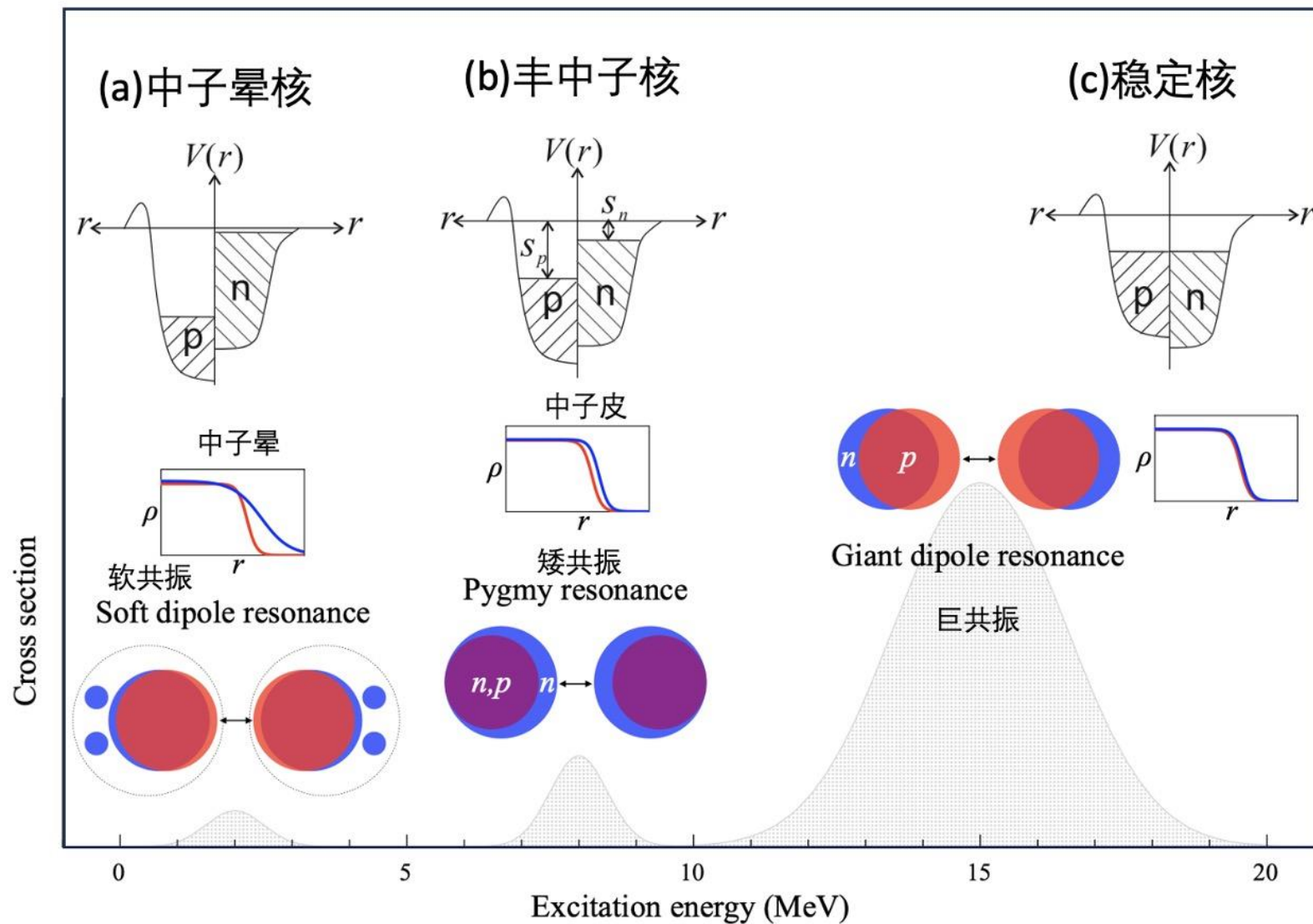
$$\frac{\delta_m^F}{\delta_p} = \frac{1 + (b_n^F/b_p^F) (M_n/M_p)}{1 + (b_n^F/b_p^F) (N/Z)}$$

	M_n/M_p	e_n	$(M_n/M_p)/(N/Z)$
^{15}C	3.6 (4)	0.4	2.4 (3)
^{17}O	2.63(4)	0.42	2.34(5)

J. Chen *et al.*, Phys. Rev. C 106, 064312 (2022)

A. M. Bernstein, V. R. Brown, and V. A. Madsen, Comments Nucl. Part. Phys. 11, 203 (1983).
A. M. Bernstein, V. R. Brown, and V. A. Madsen, Phys. Rev. Lett. 42, 425 (1979)

原子核中的偶极共振



Isoscalar-dipole excitation operator :

$$\frac{e}{2} r^3 Y_1$$

- 与核物质的压缩性质密切相关
- 相较于isovector dipole excitation operator是高阶项, 较难观测
- 晕核大的半径使得 isoscalar-dipole excitation 强度较大
- 也是不对称集团结构的标志

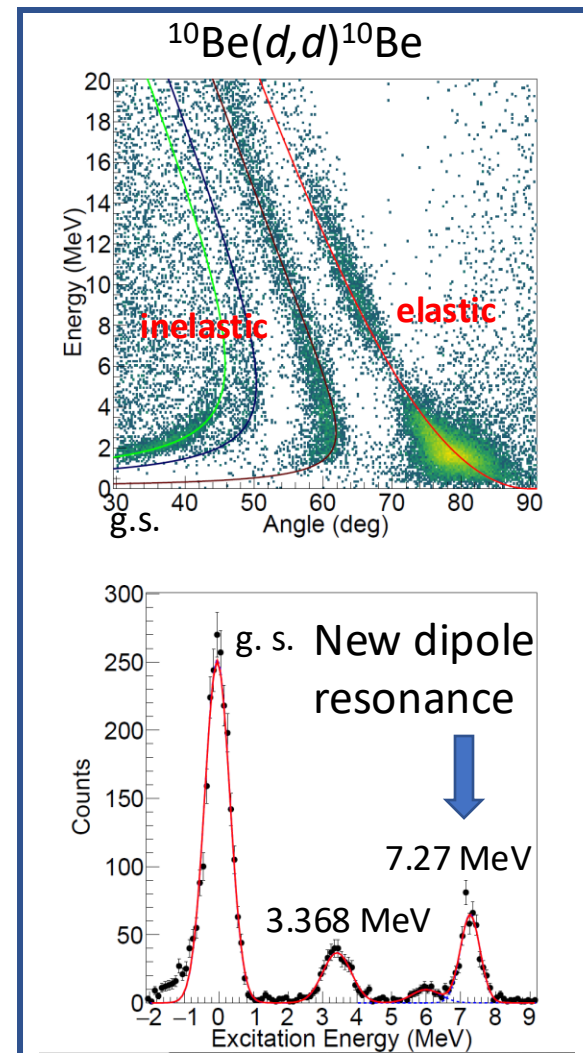
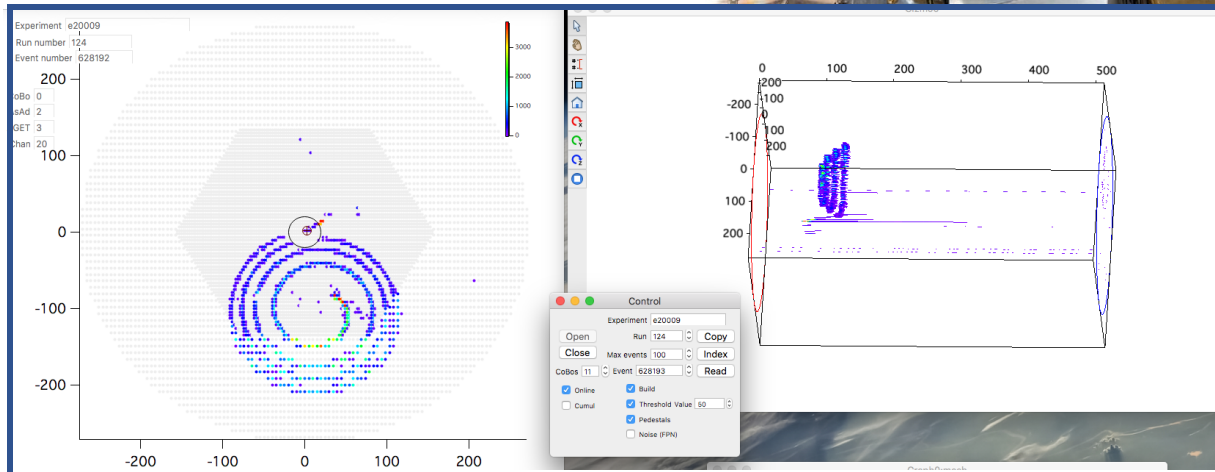
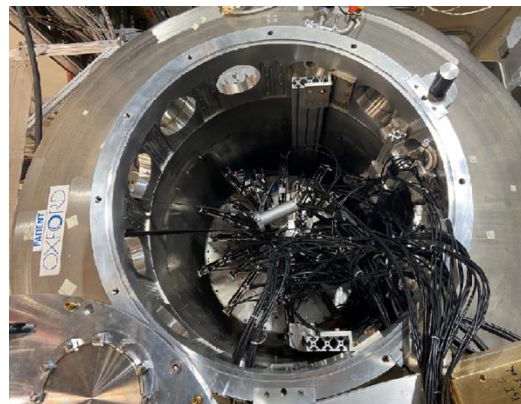
AT-TPC & SOLARIS 耦合使用的首次实验

-- Testing its capability for measuring direct reactions

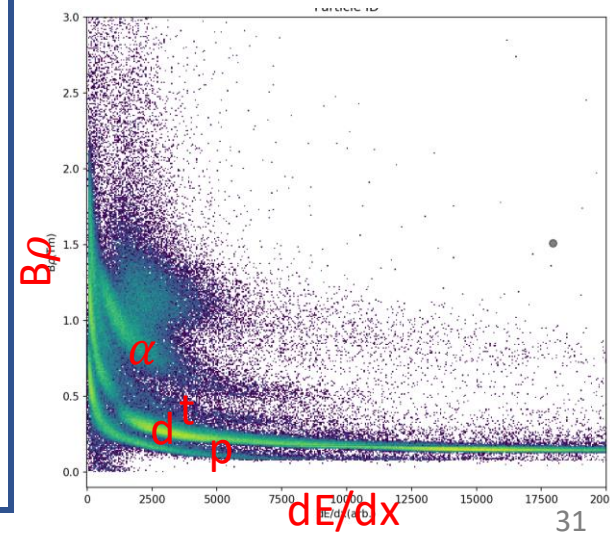
➤ $^{10}\text{Be}(d,d')^{10}\text{Be}$ and $^{10}\text{Be}(d,p)^{11}\text{Be}$: First direct reaction measurement using the AT-TPC coupling with SOLARIS

Filled with D_2 : 600 Torr
 ^{10}Be beams @ 9.1 MeV/u
2000 pps
 $B=3\text{ T}$

Spokesperson:
Daniel Bazin; Jie Chen

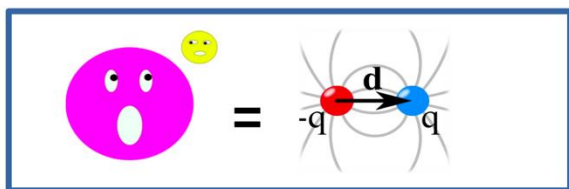


- Energy resolution $\sim 700\text{ keV}$
- Simultaneous measurement of (d,p) , (d,t) and (d,d') reactions with $\sim 100\text{ pps}$ beam within one week!
- Open wide opportunities in the future with weak exotic beams



^{10}Be 同位旋标量软偶极共振态

-- ^{10}Be 中的近阈值偶极共振态



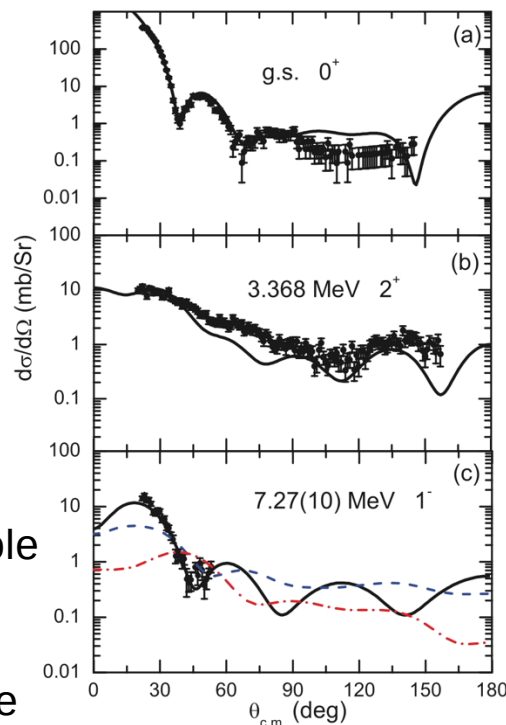
❖ Asymmetric distribution → a permanent dipole momentum!

❖ Just near $S_\alpha S_n S_{2n}$

❖ 5%~10% of the isoscalar dipole energy-weighted sum rule

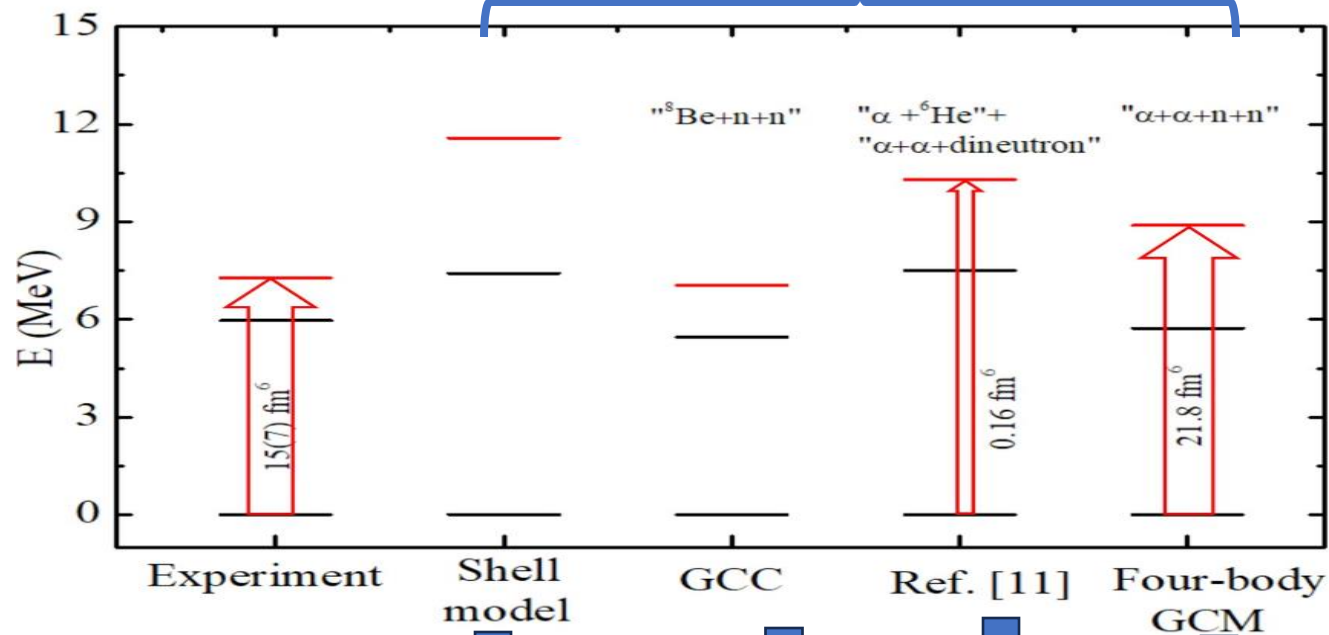
❖ Enhanced α cluster structure

❖ $\alpha+\alpha+n+n$ 4-body cluster structure is essential to describe the enhanced dipole strength

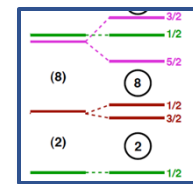


实验

理论计算

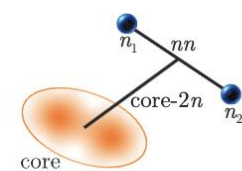


Within psd



By Cenxi Yuan

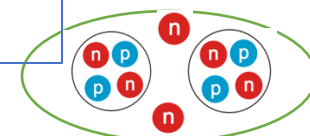
Deformed $^8\text{Be}+2n$



By Simin Wang

Y. Kanada-En'yo et al., Phys. Rev. C 95, 064319 (2017)

$\alpha+\alpha+n+n$



By Bo Zhou

^{10}Be 同位旋标量软偶极共振态

-- ^{10}Be 中的近阈值偶极共振态

Near-Threshold Dipole Strength in ^{10}Be with Isoscalar Character

[J. Chen](#) ^{1,2,*}, [Y. Ayyad](#) ^{3,†}, [D. Bazin](#) ⁴, [W. Mittig](#)⁴, [M. Z. Serikow](#) ⁴, [N. Keeley](#)⁵, [S. M. Wang](#) ^{6,7}, [B. Zhou](#)^{6,7}, [J. C. Zamora](#) ⁴
et al.

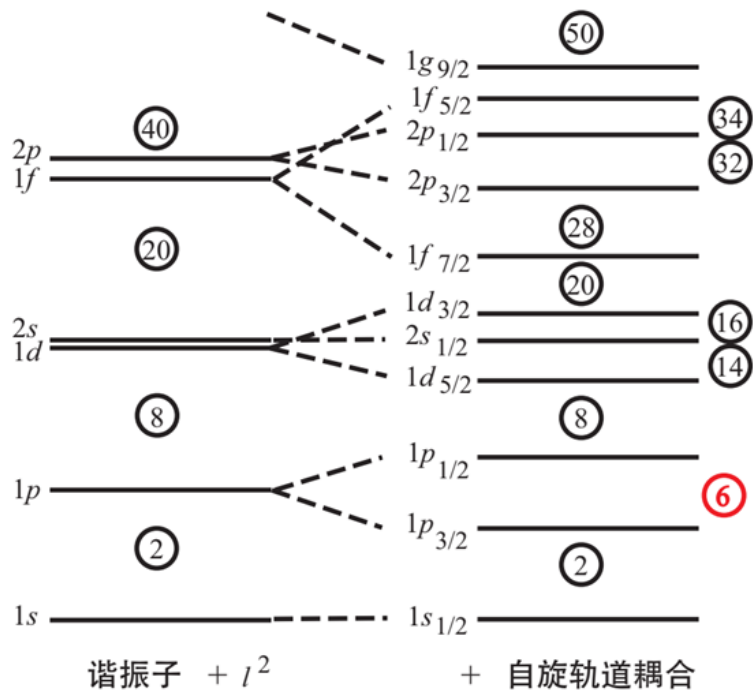
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Phys. Rev. Lett. **134**, 012502 – Published 9 January, 2025

DOI: <https://doi.org/10.1103/PhysRevLett.134.012502>

Ex

^{16}C 是否存在 $Z=6$ 的幻数？

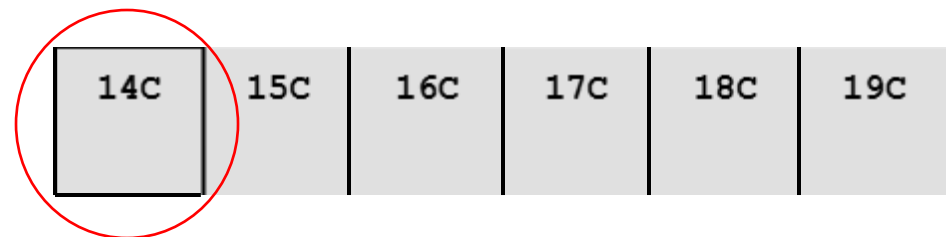


幻数 $Z=6$ 是存在的，
但它很难被观测到。

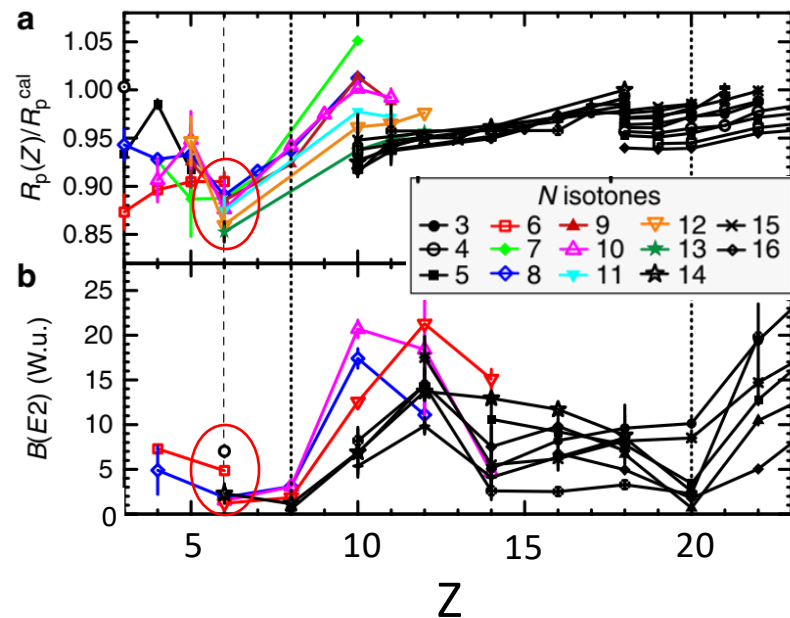


1963年诺贝尔奖
玛丽亚·格佩特-梅耶

幻数 $Z=6$ 的实验证据

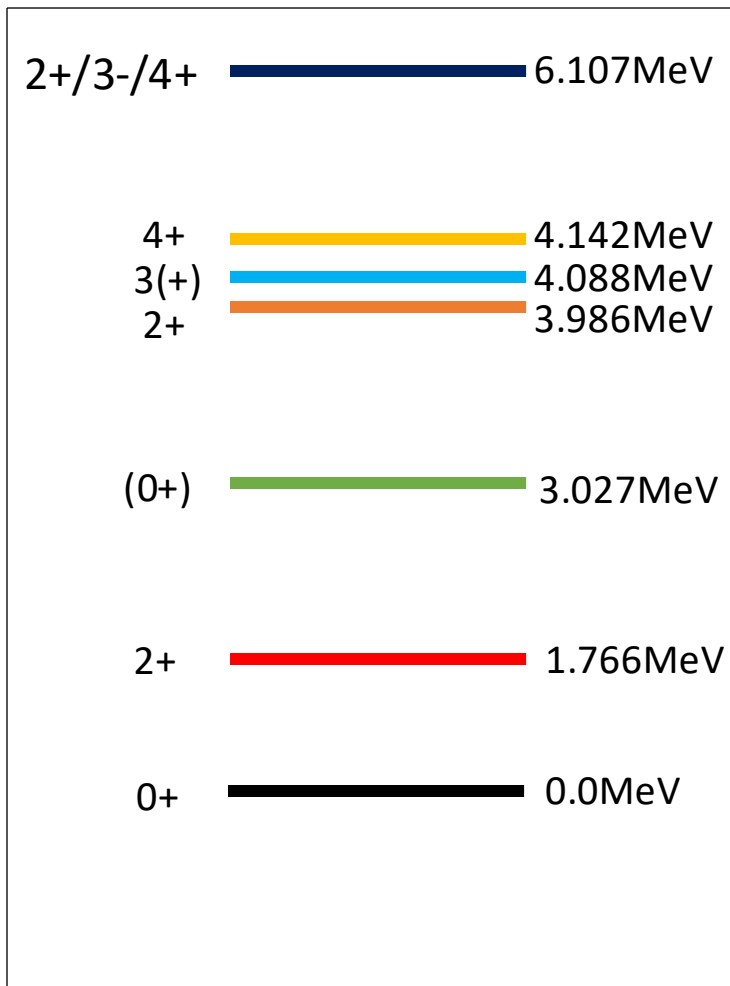


碳同位素质子分布半径、 $B(E2)$ 压低



^{16}C 是否存在 $Z=6$ 的幻数?

^{16}C 能级



以质子激发为主的 $2+$ 态激发能决定了 $Z=6$ 壳层是否闭壳

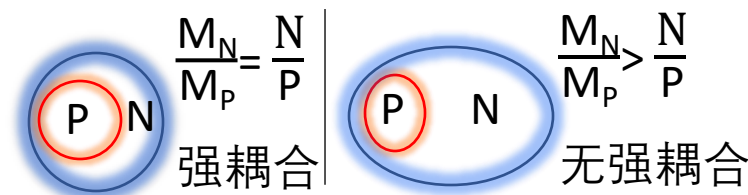
直接核反应

$^{16}\text{C} (d, d) ^{16}\text{C}$

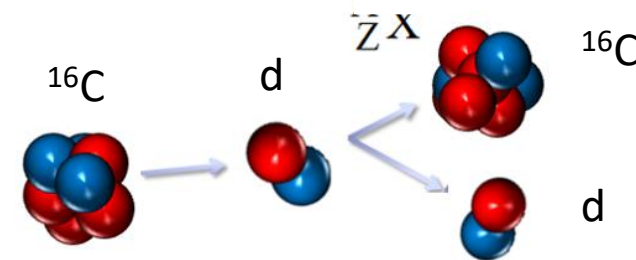
弹性散射: 验证不稳定核光学势计算

非弹性散射: 获取激发态角分布, 提取中子质子跃迁矩阵元比值, 寻找质子激发为主导的 $2+$ 态, 验证质子支壳层结构

以中子激发为主, 但是 $\frac{M_N}{M_P}$ 值测量结果不一致

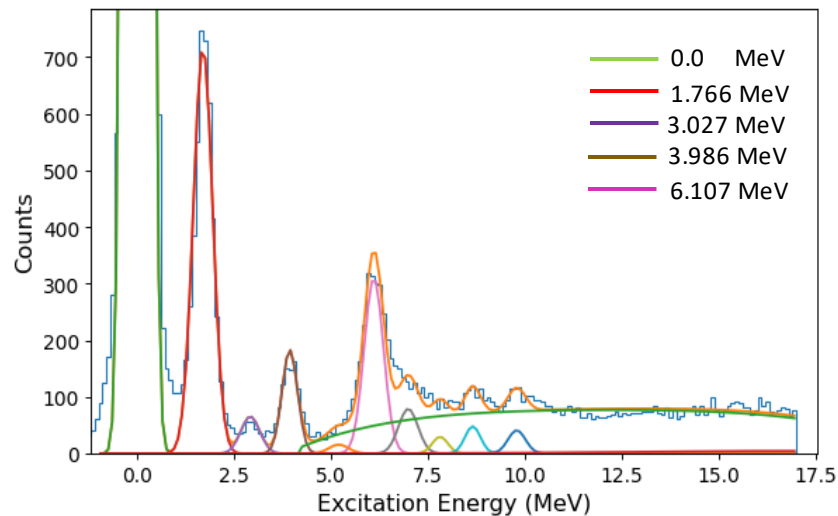


Jiang Y, Lou J L, Ye Y L, et al. PRC, 2020, 101(2): 024601.

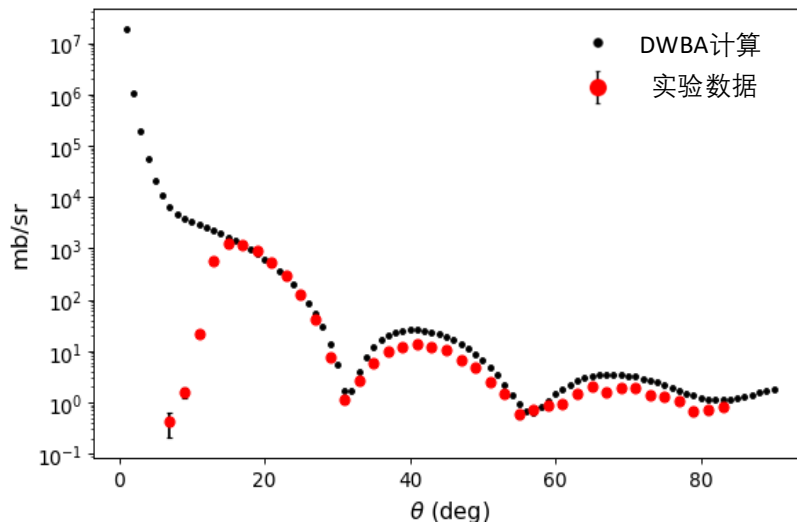


^{16}C 非弹性散射的实验结果

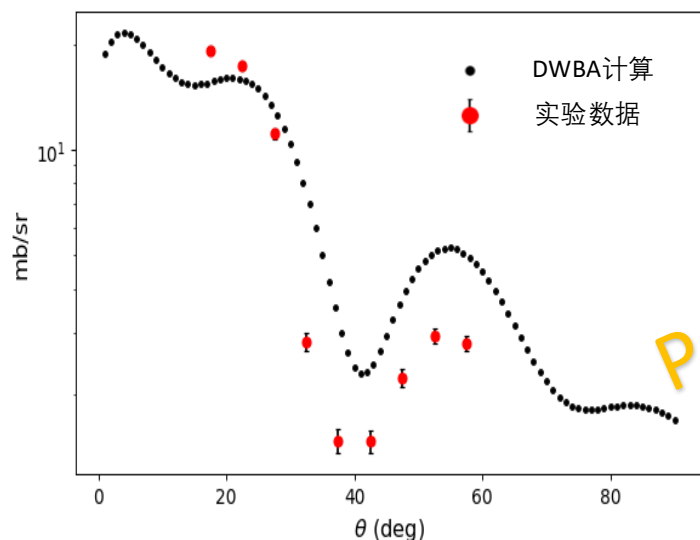
$^{16}\text{C}(\text{d},\text{d})^{16}\text{C}$ 激发能谱



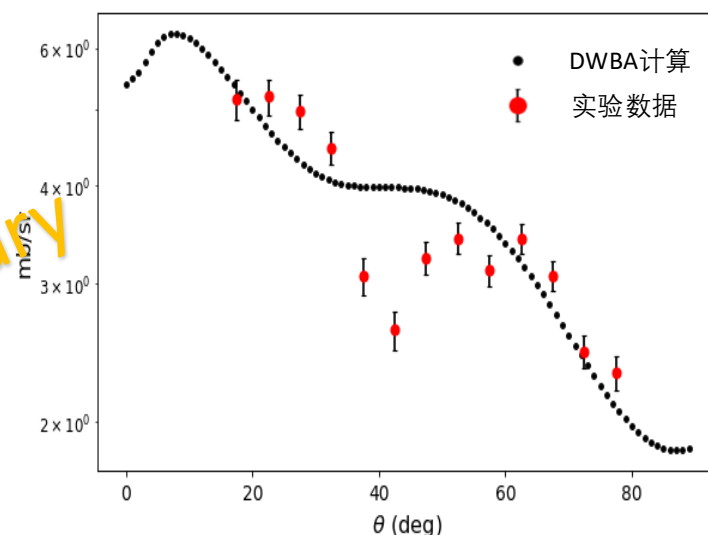
弹性散射反应截面角分布



$^{16}\text{C}(\text{d},\text{d})^{16}\text{C}$ 1.766MeV 激发态角分布



$^{16}\text{C}(\text{p},\text{p})^{16}\text{C}$ 1.766MeV 激发态角分布



计算结果

往期实验结果

$$\delta_p^m = 1.59 \text{ fm}$$

$$\delta_d^m = 1.44 \text{ fm}$$

$$\frac{M_N}{M_p} = 3.04$$

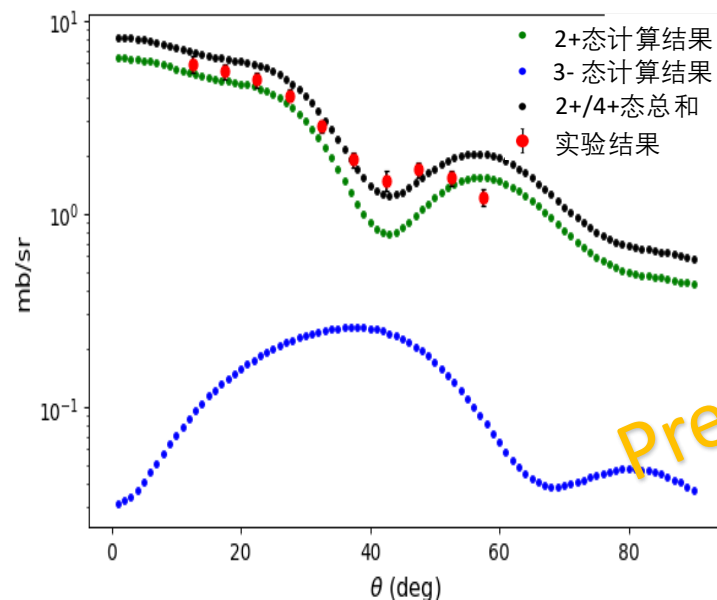
$$\frac{M_N}{M_p} = 3-6$$

$$\delta_p = 0.94 \text{ fm}$$

$$\delta_p = 1.2-0.9 \text{ fm}$$

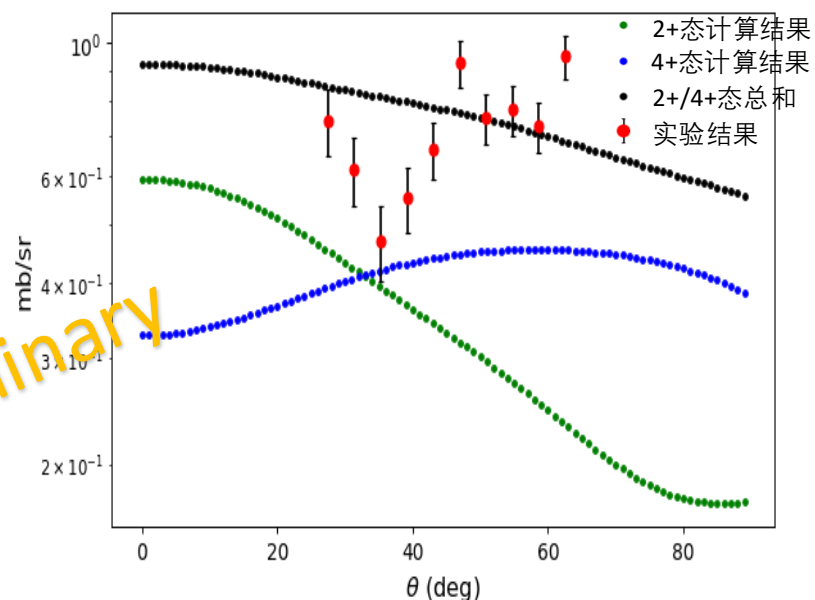
^{16}C 非弹性散射的实验结果

$^{16}\text{C}(\text{d},\text{d})^{16}\text{C}$ 6.107MeV 激发态角分布



2+态能量: ^{16}O – 6.917 MeV
 ^{14}C – 7.012 MeV
 ^{16}C – 6.100 MeV

$^{16}\text{C}(\text{p},\text{p})^{16}\text{C}$ 6.107MeV 激发态角分布



计算结果

$$\delta_p^m = 0.67 \text{ fm}$$

$$\delta_d^m = 1.00 \text{ fm}$$

$$\frac{M_N}{M_p} = 0.36$$

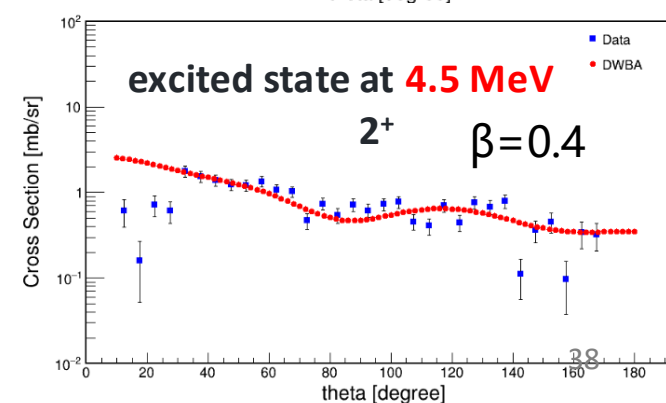
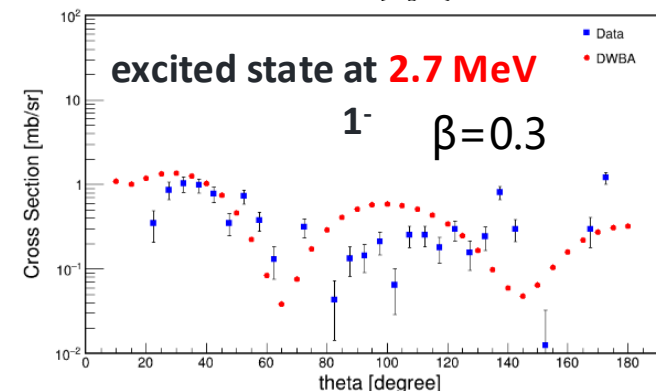
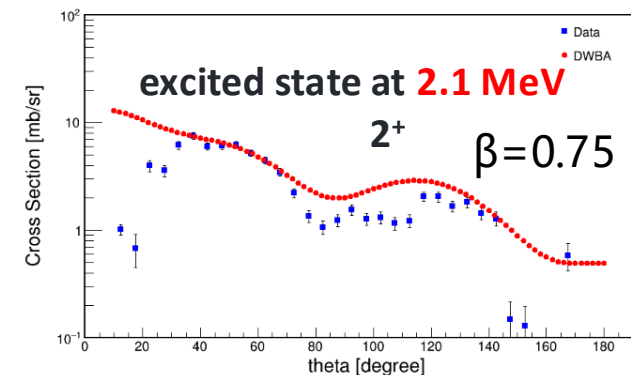
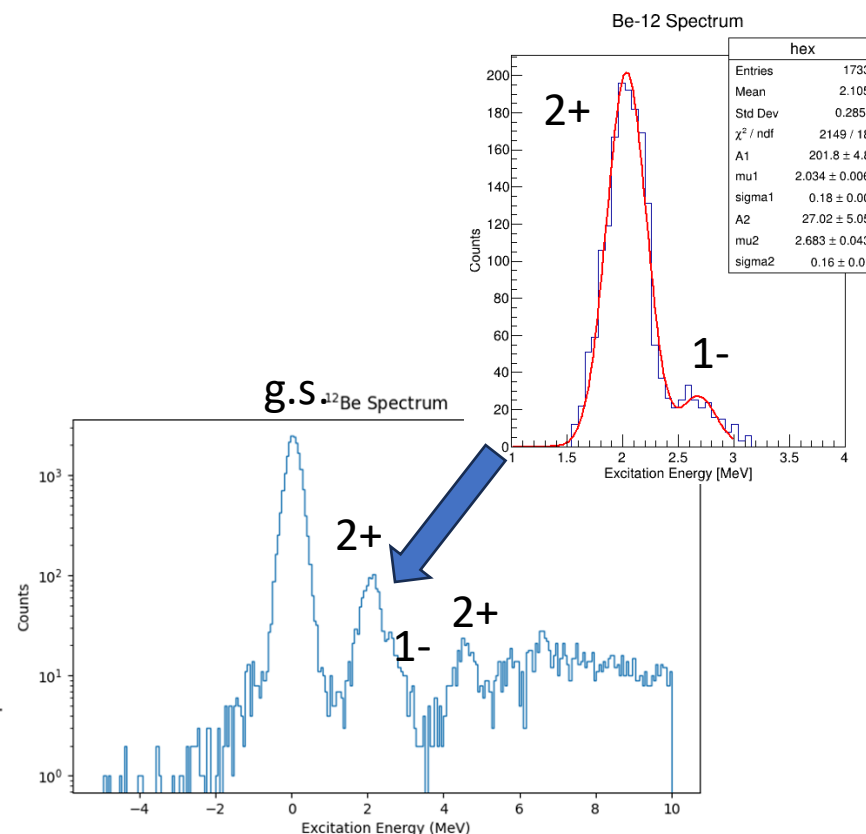
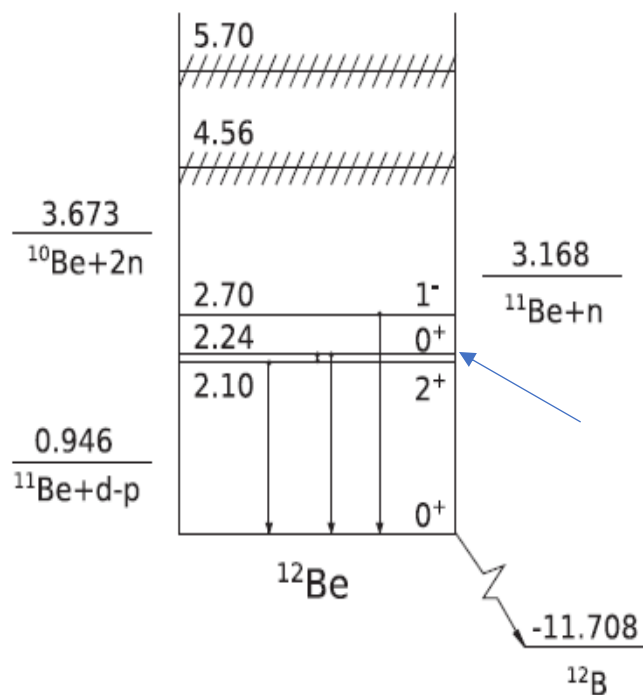
$$\delta_p = 1.95 \text{ fm}$$

^{12}Be 非弹性散射与转移反应

- 幻数 $N=8$ 消失
- 低激发态存在大形变

$$\delta = \beta R = \beta r_0 A^{1/3}$$

基态的结构? $1s_{1/2}, 0p_{1/2}, 0d_{5/2}$ 的占据数分别是多少?

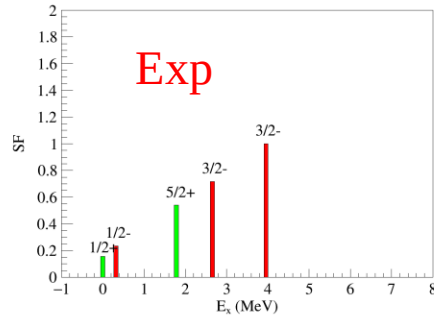
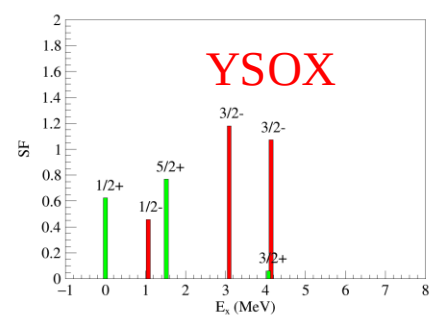
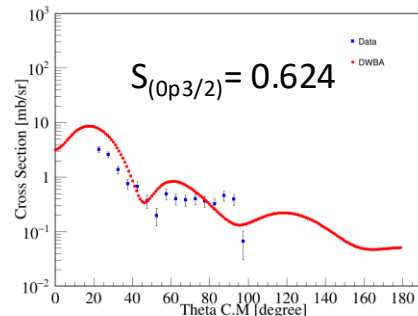
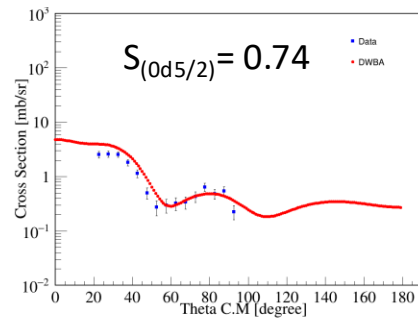
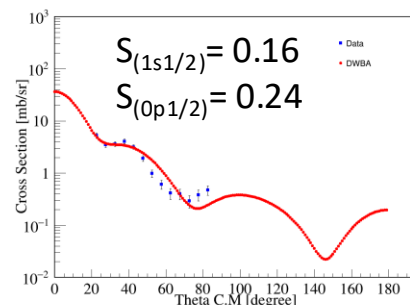
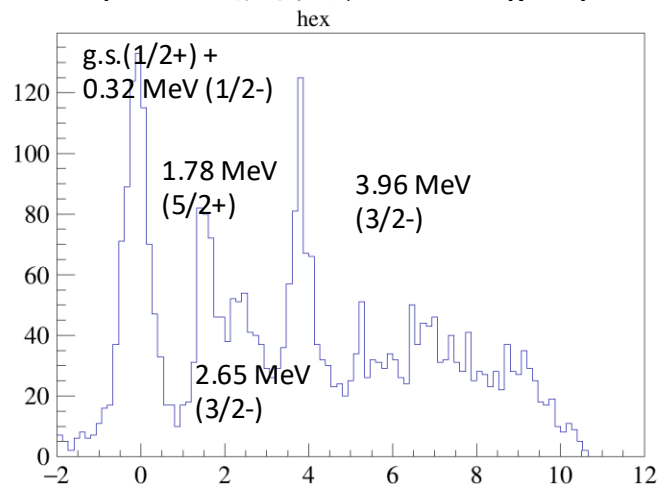


^{12}Be 非弹性散射与转移反应

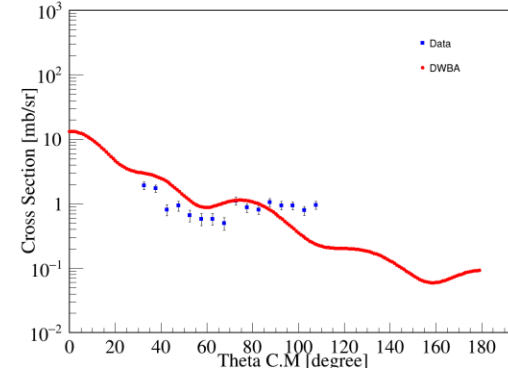
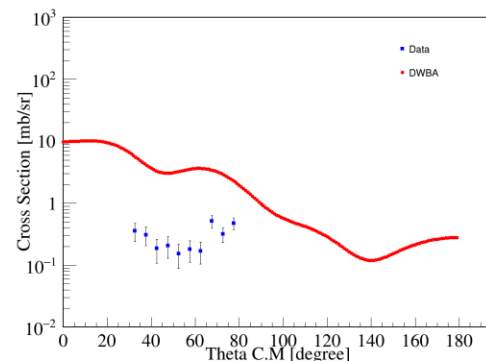
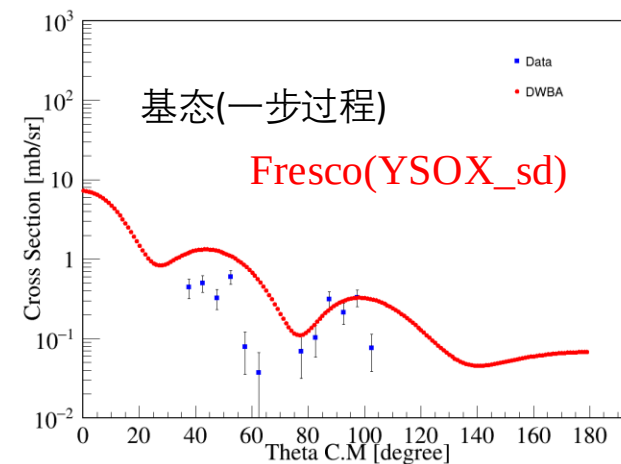
• 幻数 $N=8$ 消失

基态的结构? $1s_{1/2}, 0p_{1/2}, 0d_{5/2}$ 的占据数分别是多少?

单中子移除截面 $^{12}\text{Be}(p,d)^{11}\text{Be}$



双中子移除截面 $^{12}\text{Be}(p,t)^{10}\text{Be}$



^6He 偶极共振态的实验理论结果总结

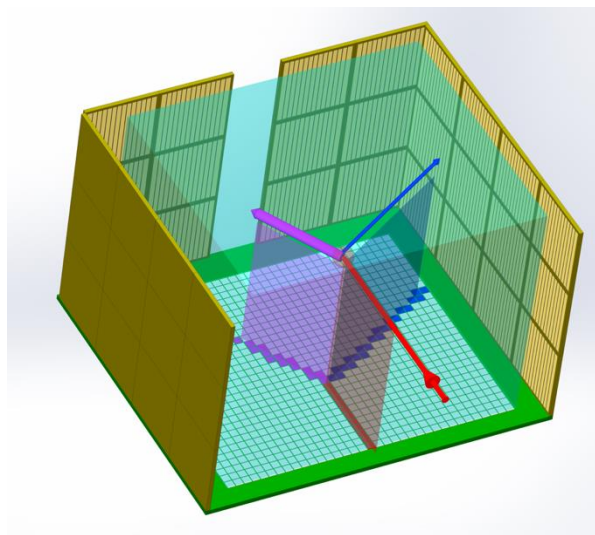
表 1 实验与理论上给出的 ^6He 的 1-偶极共振态可能的能量和宽度

文献	实验反应道或理论模型	$E_x(\text{MeV})$	$\Gamma(\text{MeV})$
[17]	$^6\text{Li}(^7\text{Li}, ^7\text{Be})^6\text{He}$ (50 MeV/u)	未发现	---
[18]	$^6\text{Li}(^7\text{Li}, ^7\text{Be})^6\text{He}$ (65 MeV/u)	~ 4.0	4 ± 1
[19]	$^6\text{Li}(t, ^3\text{He})^6\text{He}$	~ 5.0	≈ 2.5
[21]	$^{10}\text{B}(\pi^-, \text{pt})$	4-5	≈ 1.5
[22]	$^8\text{He}(\text{p}, t)$	5.3	2 ± 1
[24]	NCSM/RGM	不存在	---
[25]	六体计算	$\approx 3-4$	---

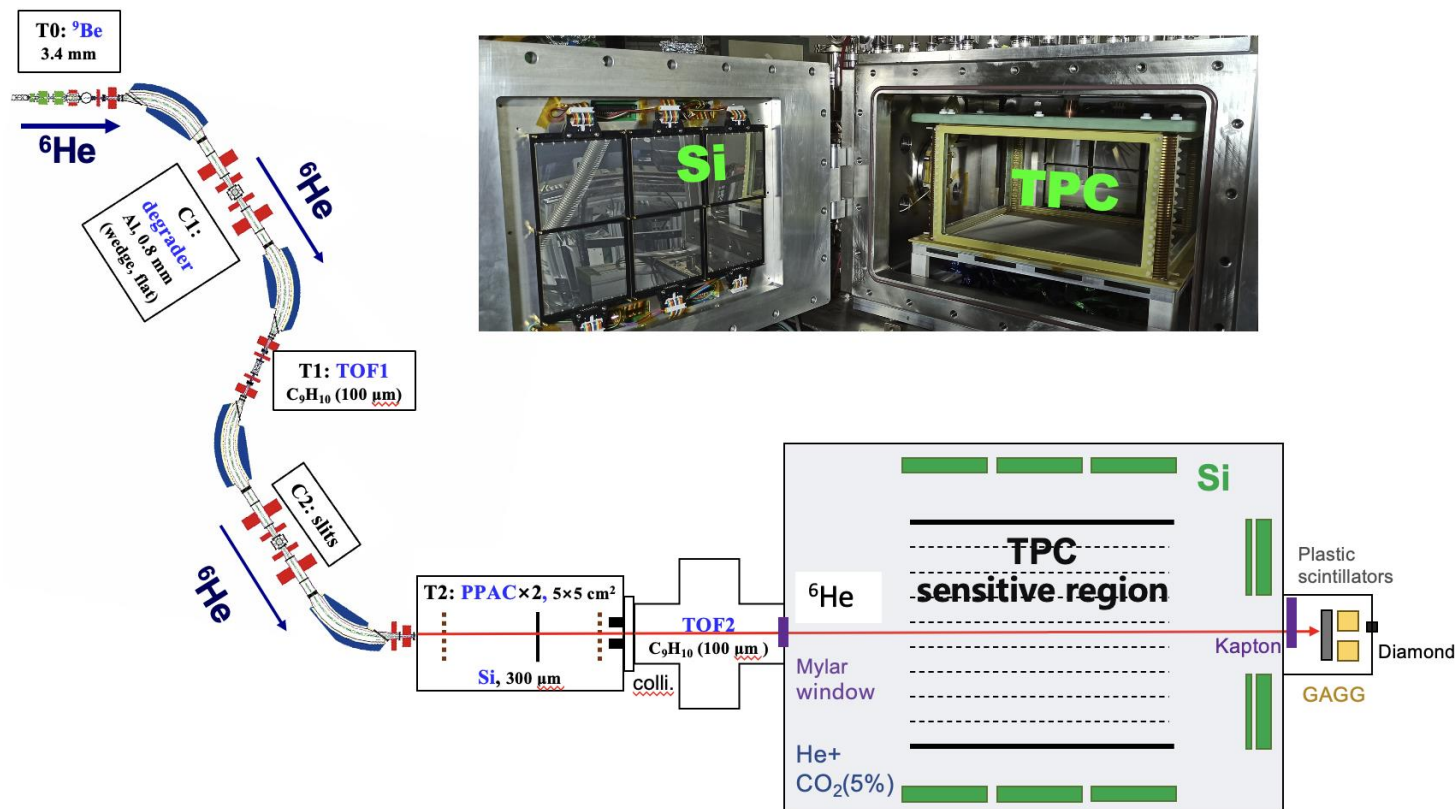
- Theoretically, soft dipole excitation in ^6He can be explained as an isoscalar compressional dipole resonance.
- In order to clarify isoscalar resonance character in ^6He , it is necessary to study the soft dipole resonance via (d, d') or (α, α') reactions, which was suggested by L. V. Chulkov.
- There is yet no evidence of isoscalar soft dipole resonance of ^6He .

通过非弹性散射研究 ^6He 和偶极共振

利用活性靶气体探测器MATE测量42MeV/u能量下的 ^6He 束流与 α 和质子非弹性散射反应来布局 ^6He 的束缚激发态以及共振态



活性靶探测器的基本工作原理示意图

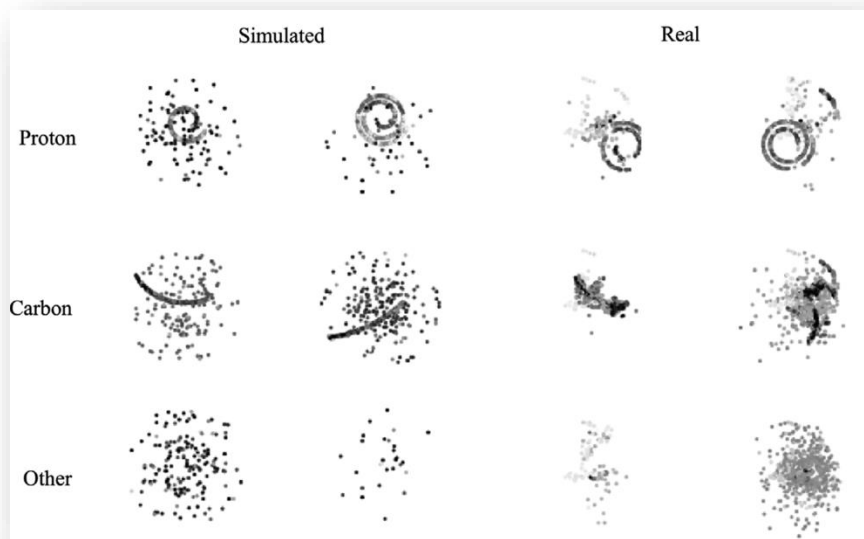


- ❖ MATE将先后被充满200Torr的异丁烷和 $\text{He}+\text{CO}_2$ 混合气体
- ❖ 零度探测器将被用于测量 beam-like recoil

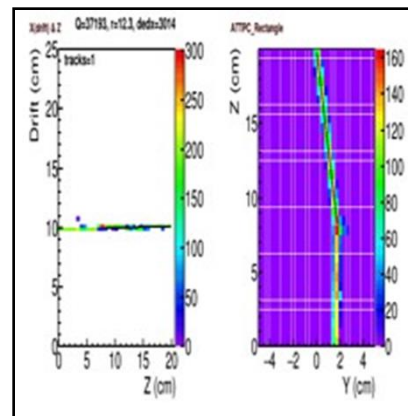
机器学习方法进行数据处理

机器学习方法用于AT-TPC实验数据分析

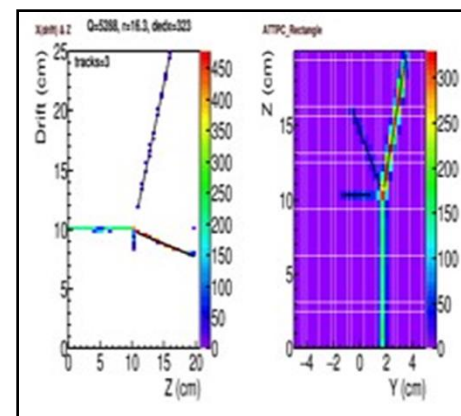
M. P. Kuchera et al., NIM A940, 156 (2019)



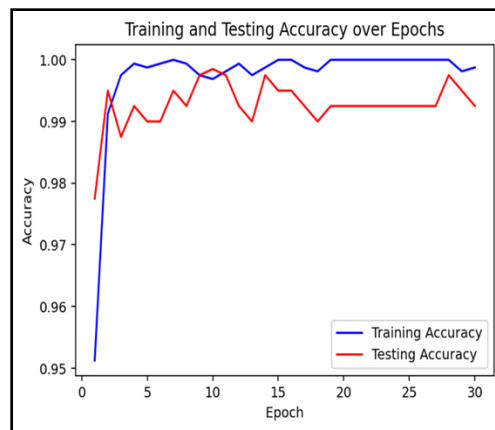
卷积神经网络方法 CNN



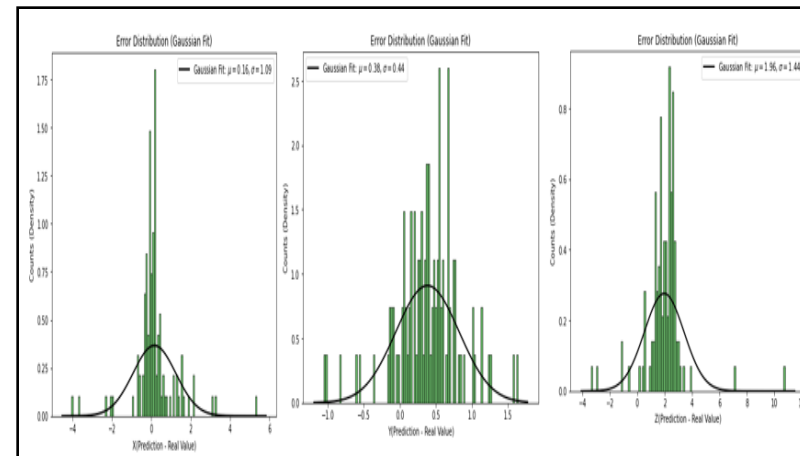
弹性散射事件在不同平面的径迹投影



熔合反应事件在不同平面的径迹投影

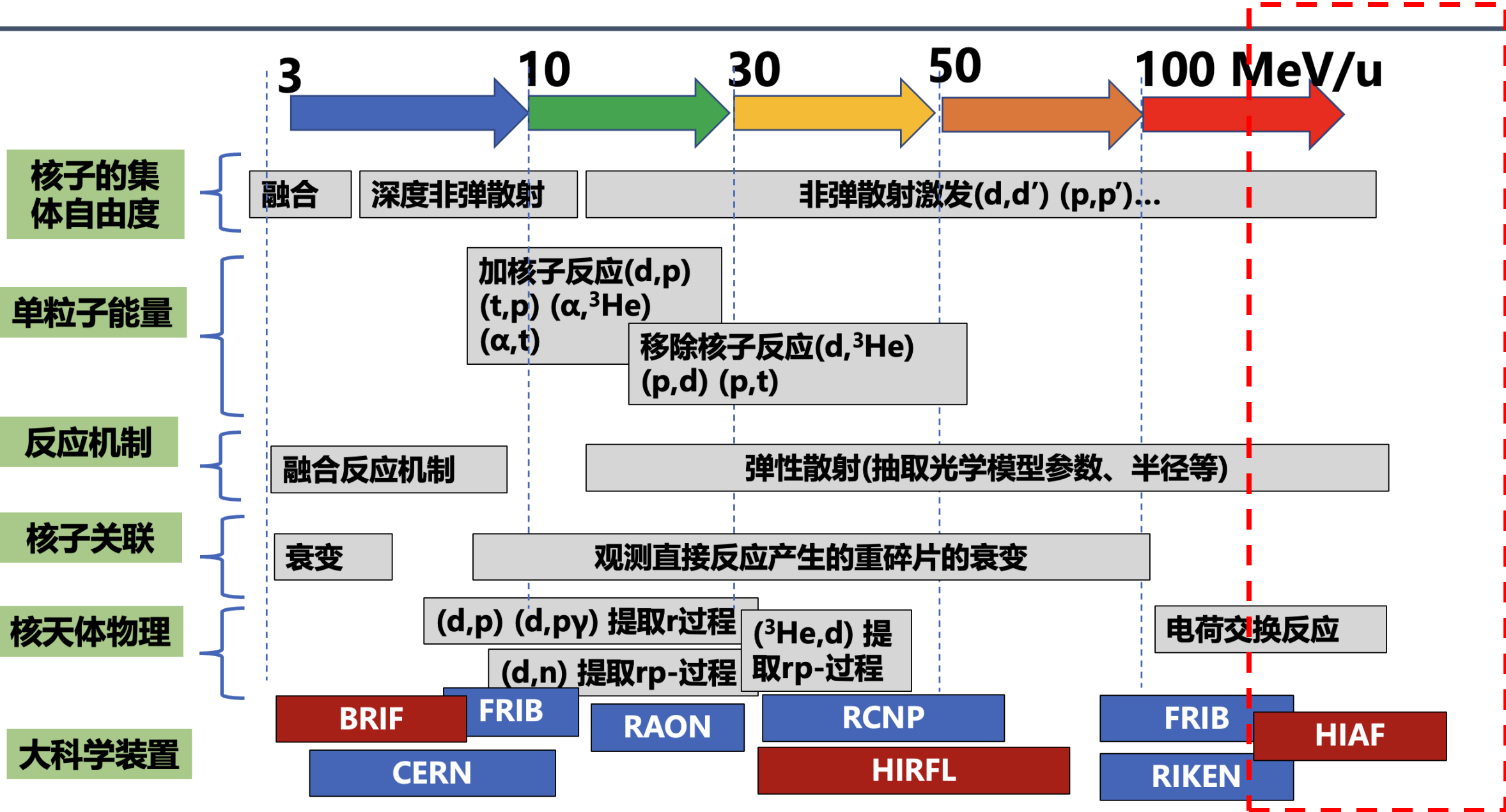


利用Resnet对弹性散射事件和熔合反应事件进行分类，准确率为99.25%



利用Resnet对反应顶点进行重建

研究手段：直接核反应

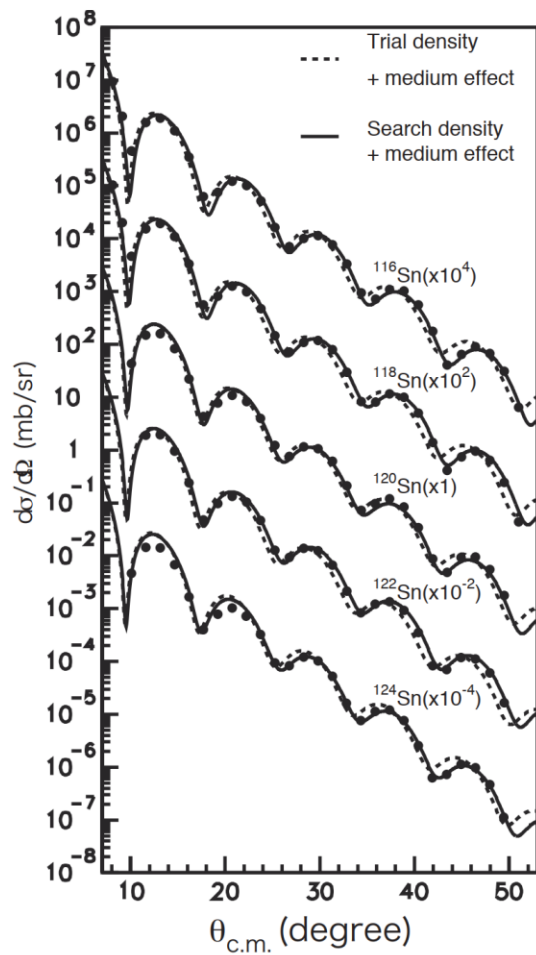


原子核的密度分布

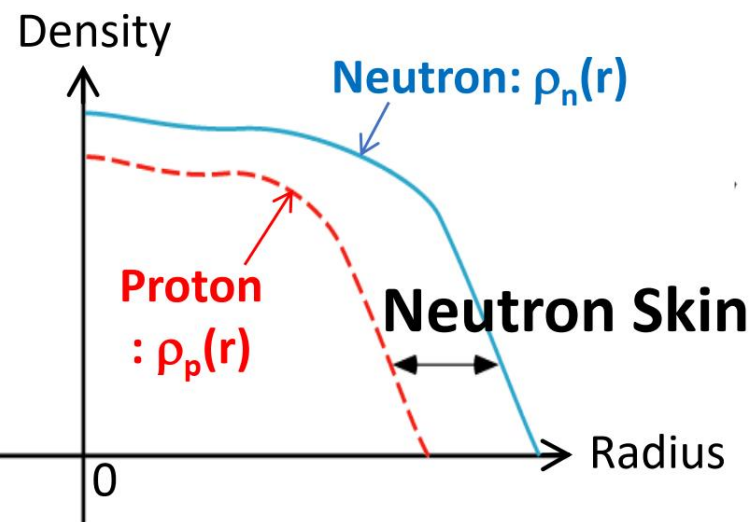
弹性散射的测量



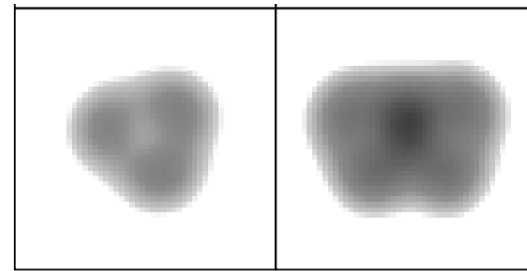
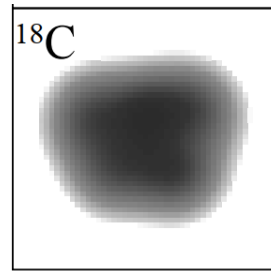
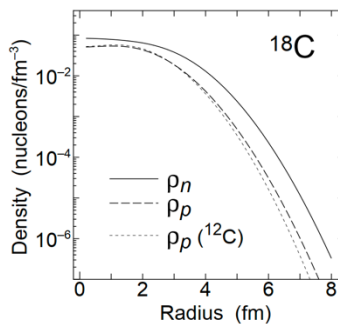
密度分布



中重核：中子皮 (EOS)



轻核：晕、cluster



总结

□ 直接核反应是研究壳演化与奇特核结构的重要实验手段

转移反应—单粒子结构：

$^{32}\text{Si}(d,p)^{33}\text{Si}$ ：自旋轨道劈裂存在光滑的演化，与“气泡核”假设矛盾

□ 实验方法

$^{11}\text{Be}(d,p)^{12}\text{Be}$ ：N=8幻数的消失与核心形变、连续态耦合等效应密切相关

非弹性散射反应—集体结构：

^{10}Be 偶极共振态的加强：集团结构效应

□ 国内外装置为相关研究提供了广泛的实验机会

致谢



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