

利用氢靶开展的敲出反应机制研究和 丰中子Ca区的壳演化研究

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2023年4月27日

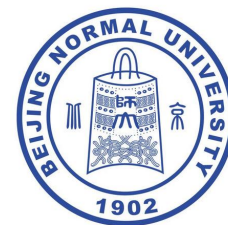


报告提纲

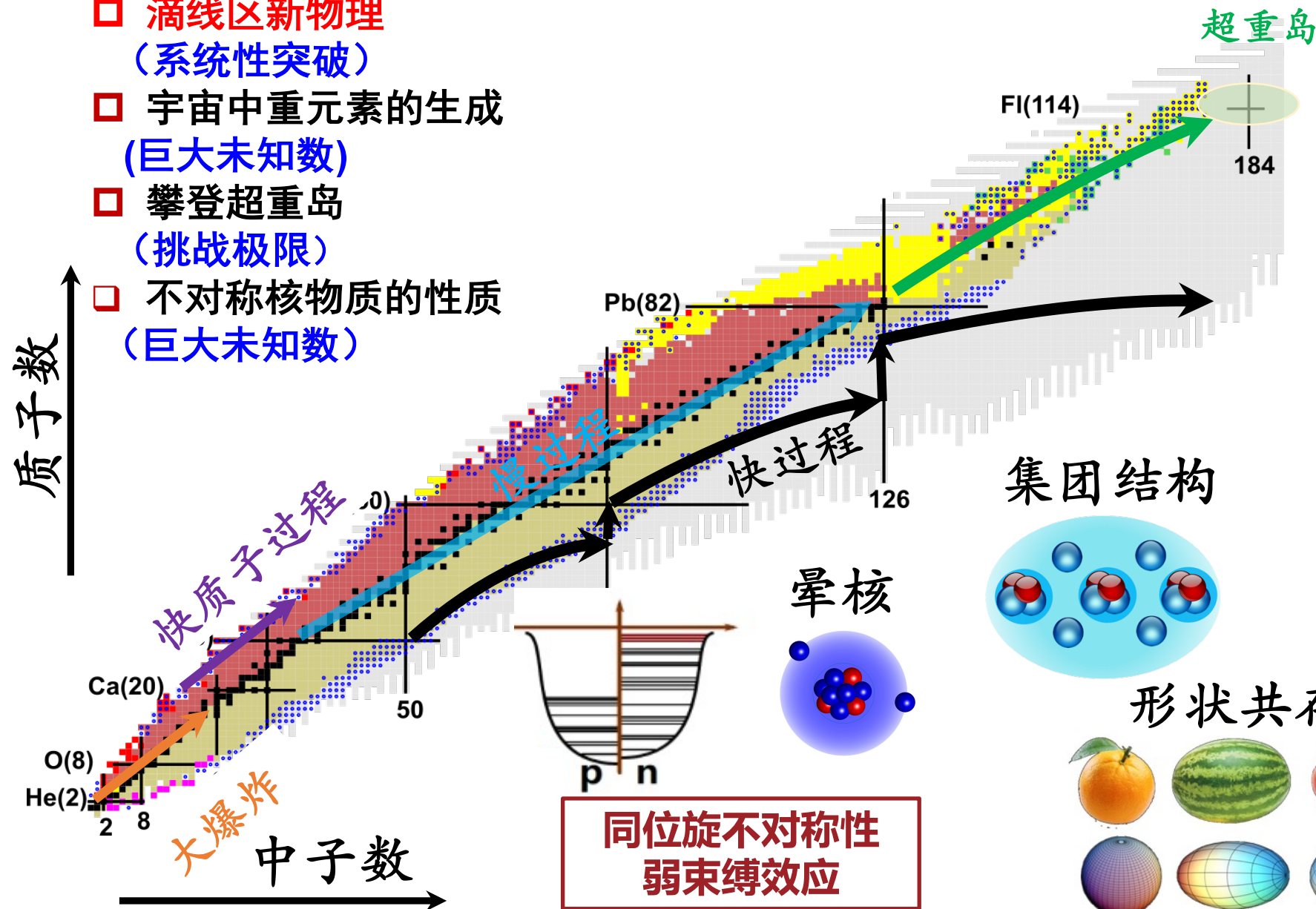
- 研究背景和研究手段
- 利用氢靶开展的敲出反应机制研究
- 利用超厚液氢靶开展的丰中子Ca区域的壳演化研究
- 总结与展望



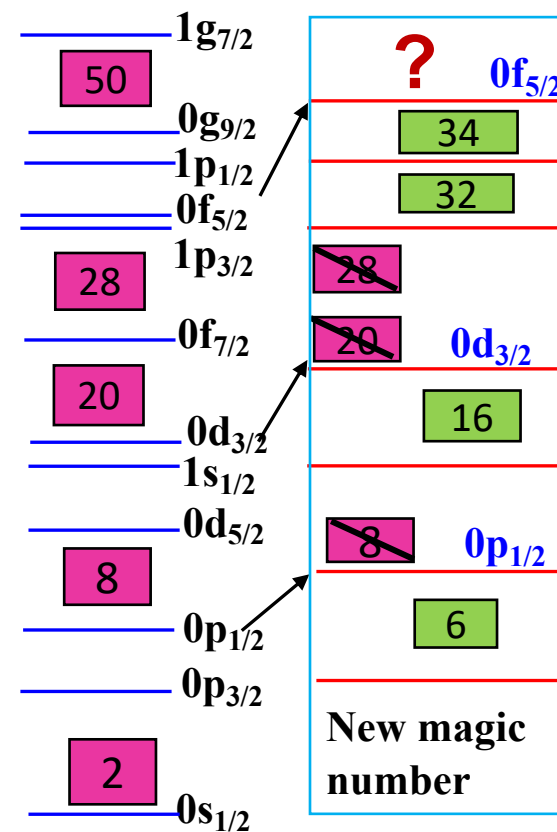
放射性核束 (RIB) 物理重大科学问题



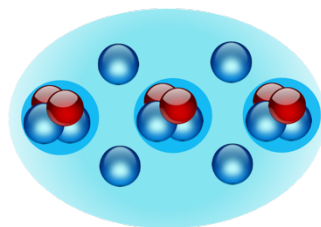
- 滴线区新物理 (系统性突破)
- 宇宙中重元素的生成 (巨大未知数)
- 攀登超重岛 (挑战极限)
- 不对称核物质的性质 (巨大未知数)



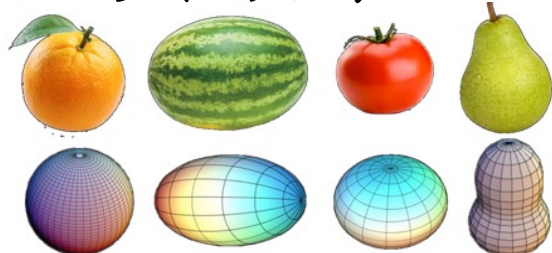
壳演化



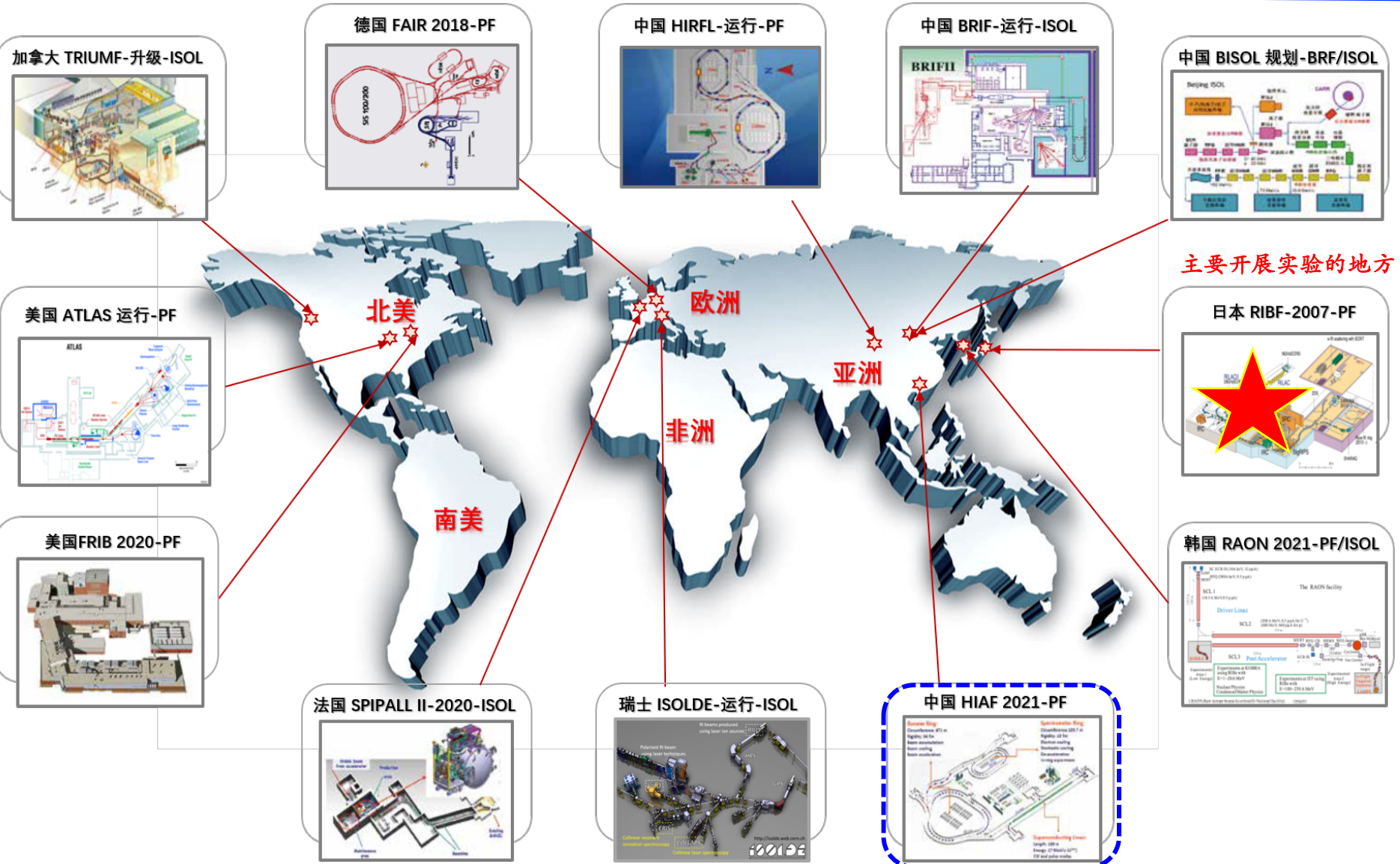
集团结构



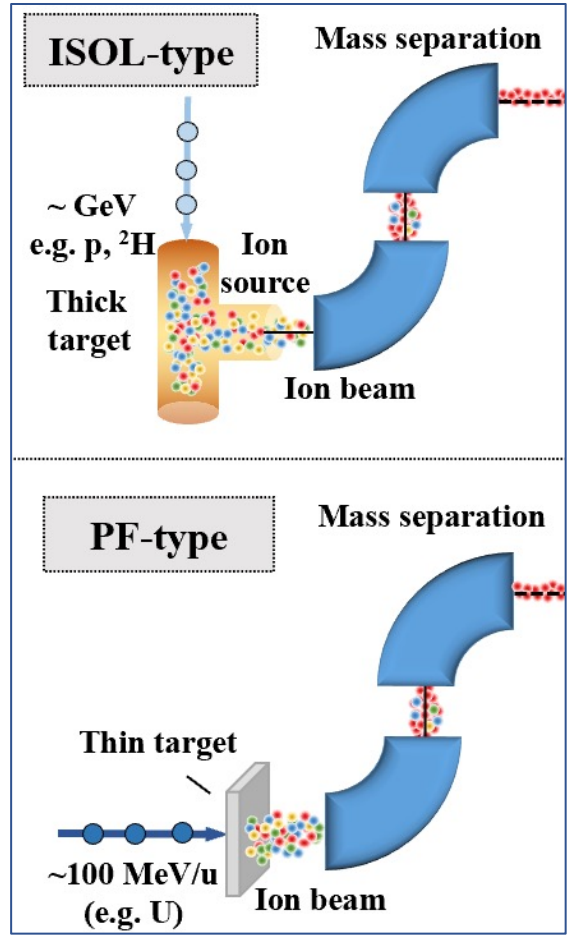
形状共存



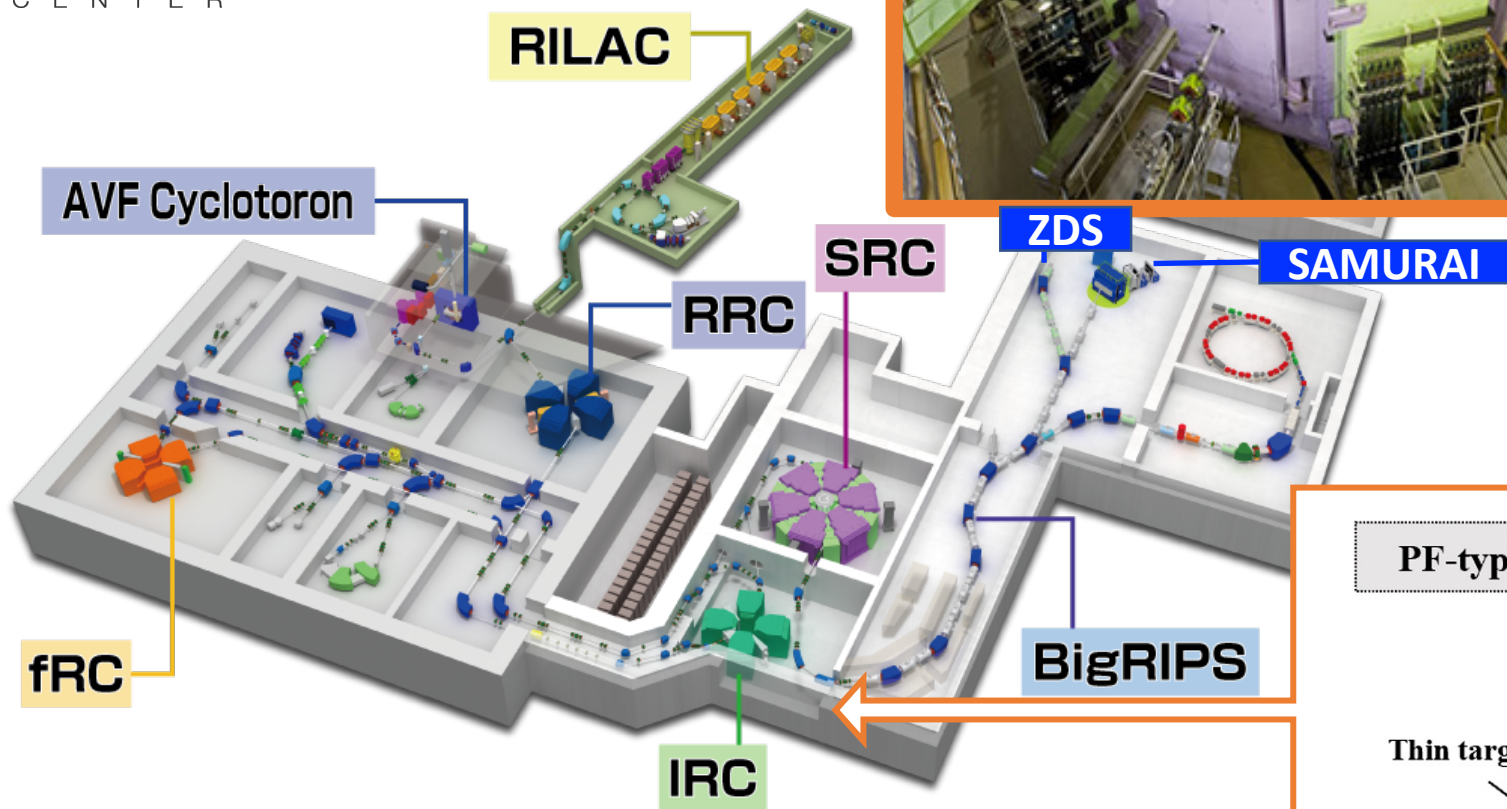
世界上的主要放射性束流装置



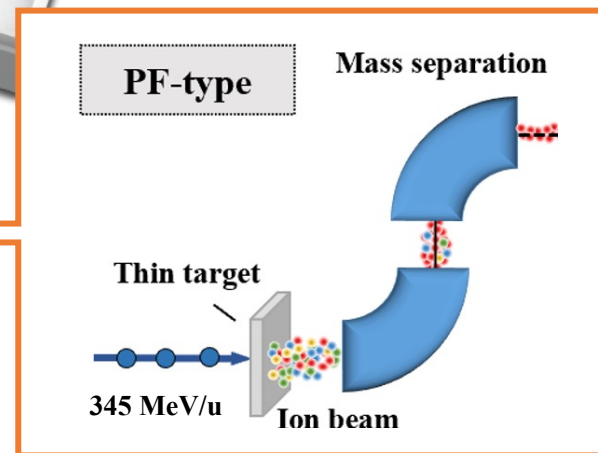
产生RIB的两种机制



日本RIBF束流装置

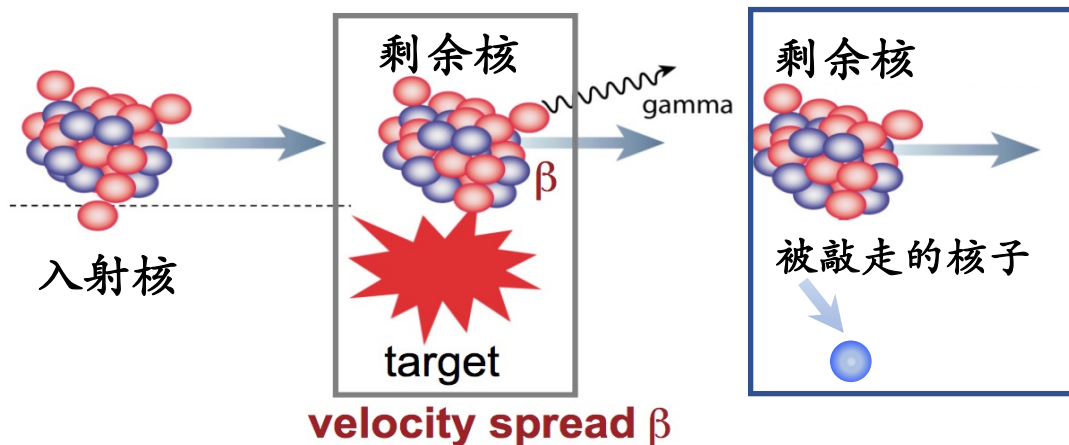


2022年
束流能量最大的回旋加速器
(0.7 光速)



目前在运行的新一代放射性束流装置

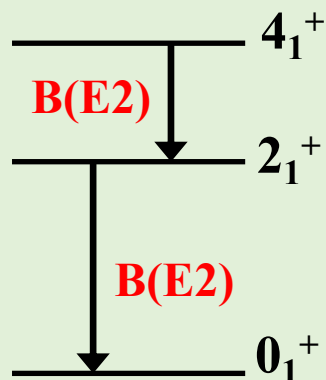
主要研究手段：敲出反应结合在束 γ 谱学



敲出反应(束流能量 >150 MeV/u)

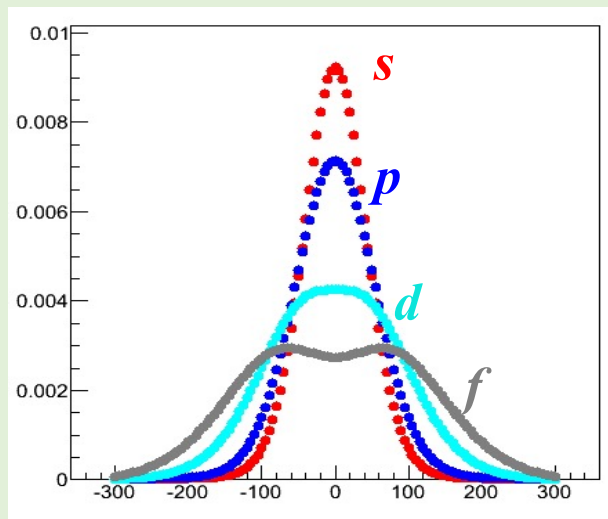
丰富的原子核的结构信息 (壳演化+单粒子结构)
可以使用厚靶 (不稳定原子核壳结构特性的第一个实验可观测)

在束伽马谱学



能级和寿命

动量分布



轨道角动量

反应截面

$$\sigma_{\text{exp}} = C^2 S_j \sigma_{sp}$$

C^2S 谱因子
(粒子占有数)

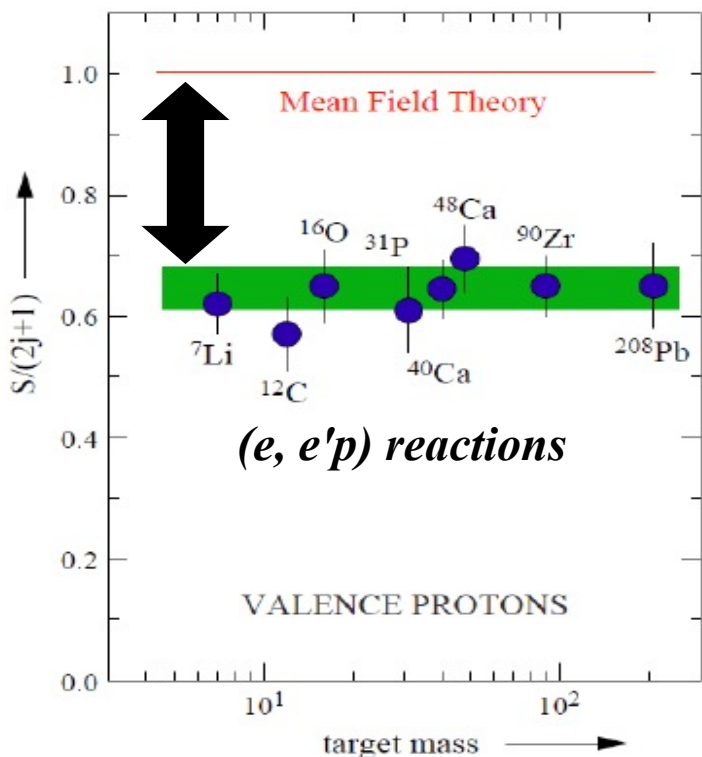
(e, e'p) 反应中的谱因子压低

$$H = \underbrace{\sum_i \left[\frac{\vec{p}_i^2}{2m} + U(\vec{r}_i) \right]}_{\text{Mean Field}} + \underbrace{\left[\sum_{i < j} V_{NN}(\vec{r}_i - \vec{r}_j) - \sum_i U(\vec{r}_i) \right]}_{\text{Correlations}}$$

$$H = H_0 + H_R$$

λ : 整体相互作用(MF)
 Δ : 局部相互作用(Correlations)

$$S = -\lambda - \Delta$$



“Correlation”

“Shells” are not fully occupied

30%~40% 压低

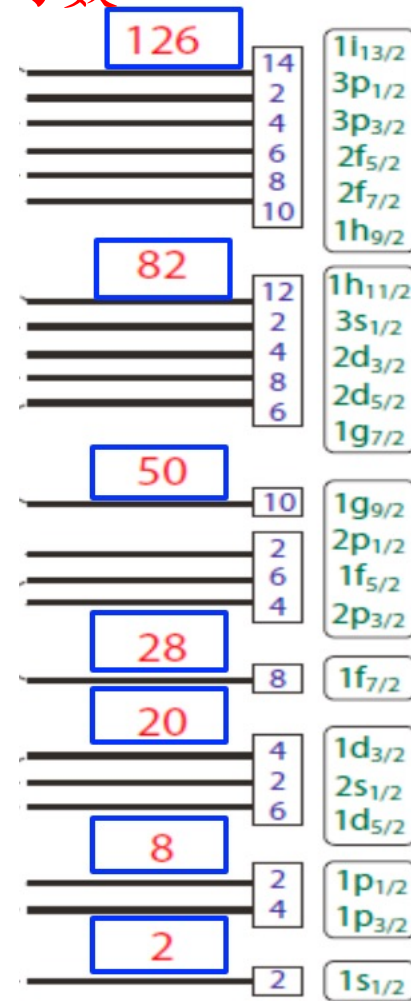
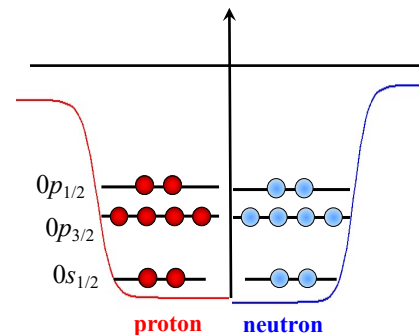
L. Lapikas *et al.*, NPA 553, 297c(1993).

独立粒子模型(IPM)

壳结构、幻数



(Mayer & Jensen
1963 Nobel Prize)

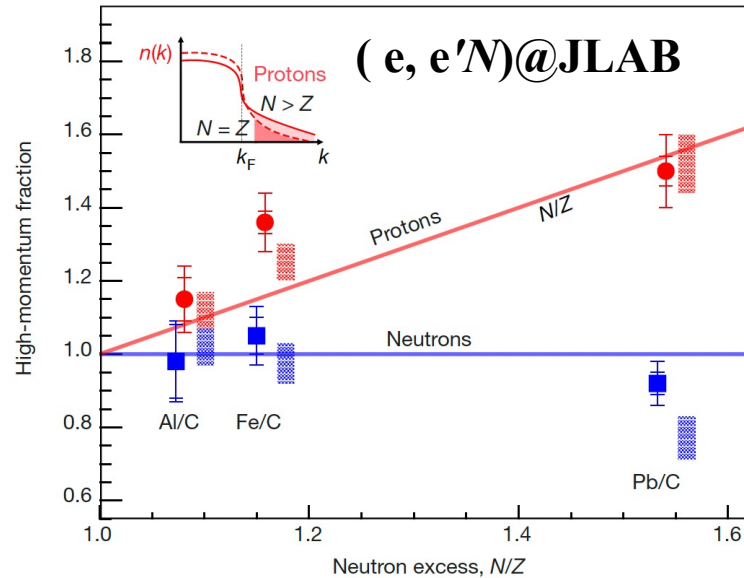
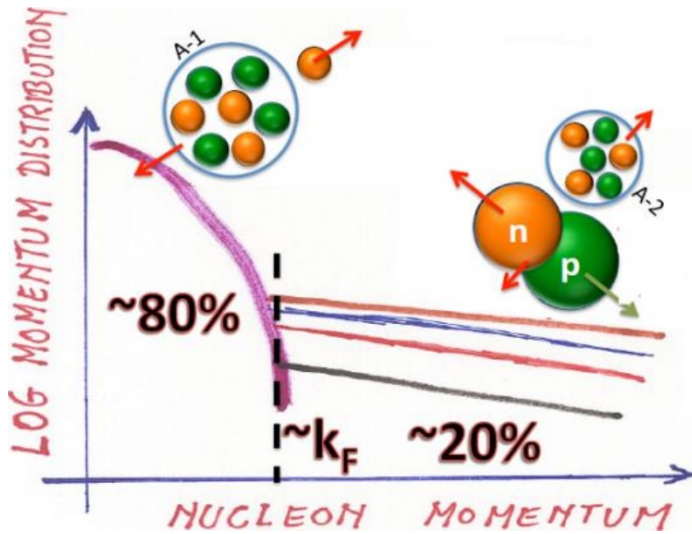
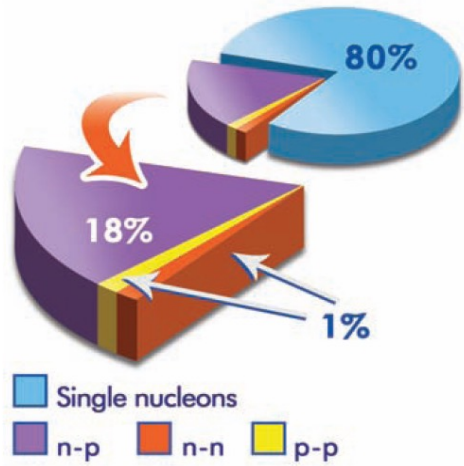


H_0 : Woods-Saxon+ Spin-Orbital Interaction

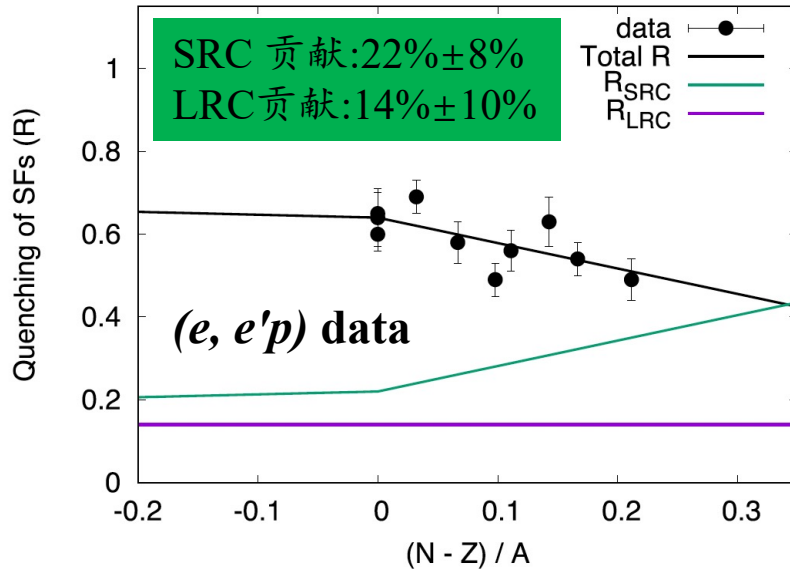
短程关联和长程关联对谱因子压低的贡献

R. Subedi et al., Science 320, 1476(2008)

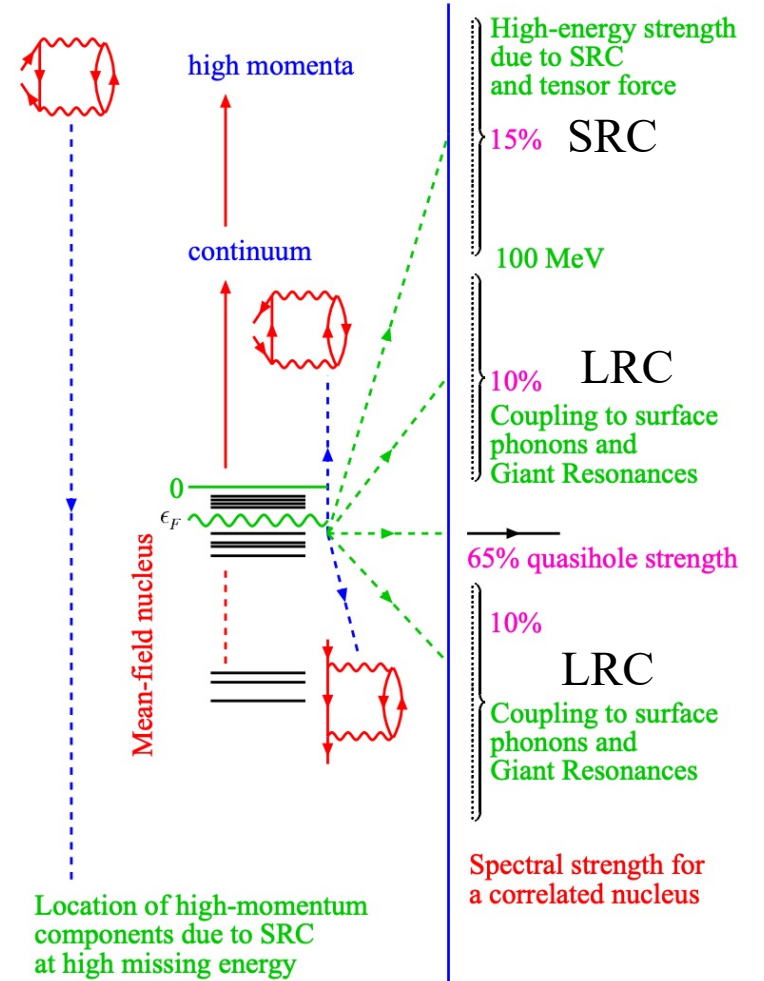
$^{12}\text{C}(e, e' pN)$ @4.627 GeV JLAB



M. Duer, et al., Nature 560, 7720 (2018).



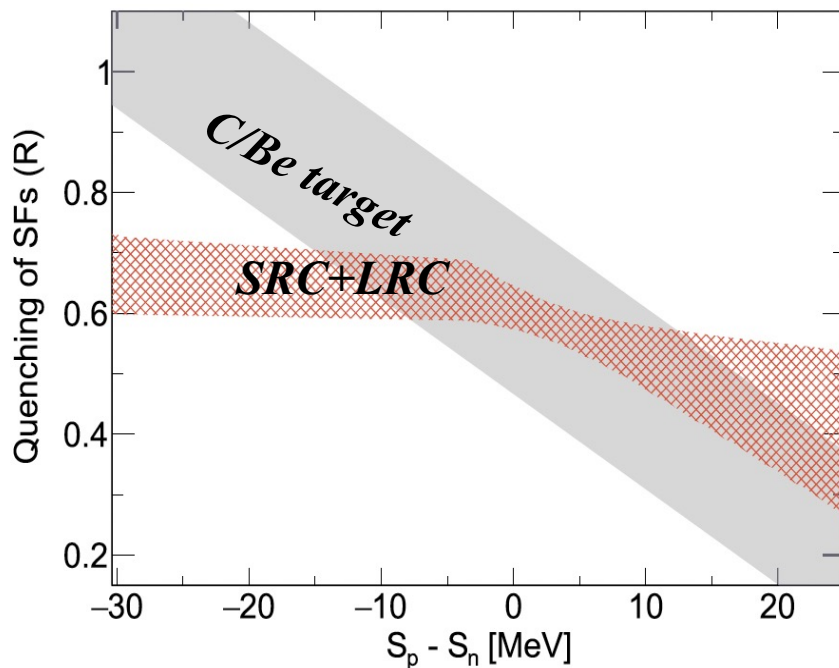
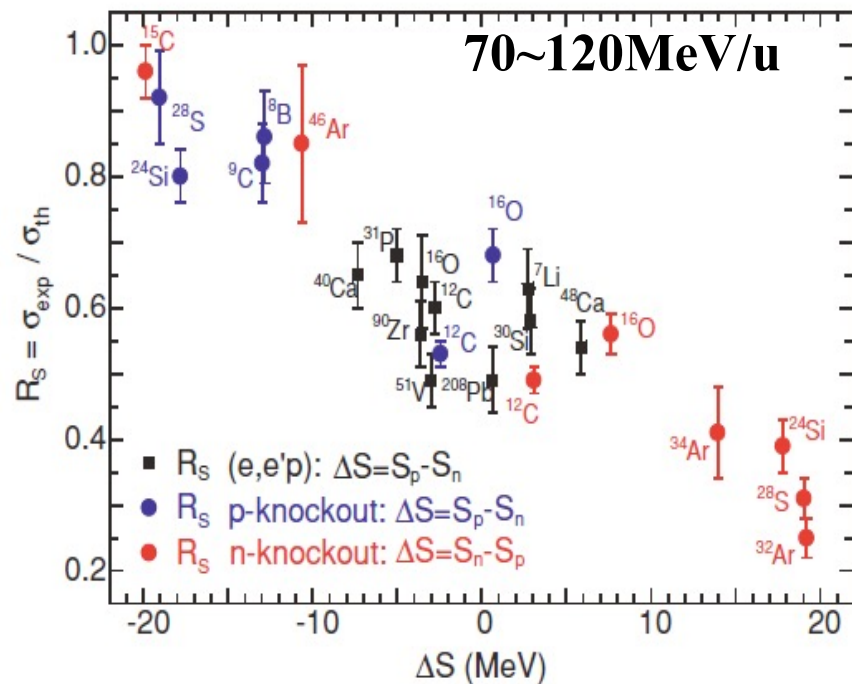
S. Paschalis et al., PLB 800, 135110 (2020).



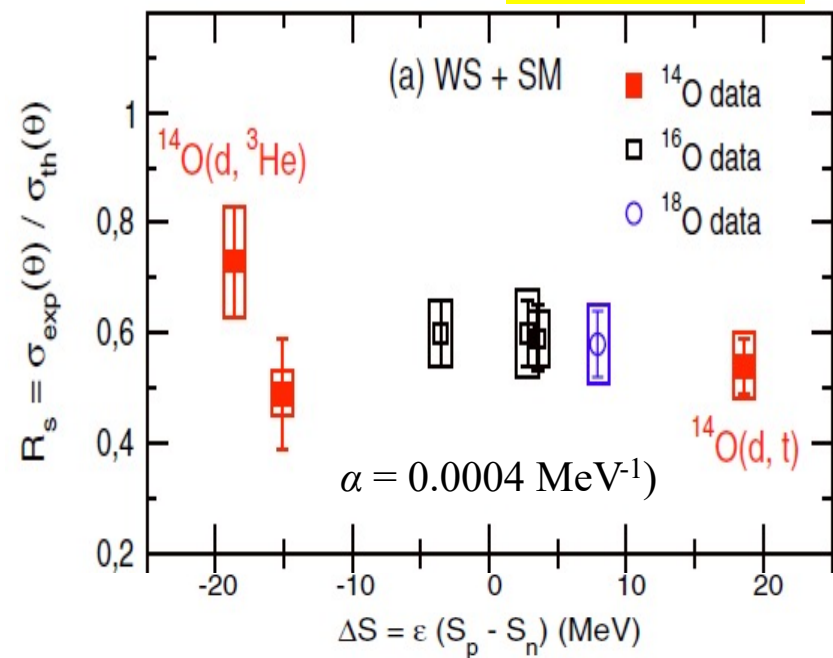
W.H. Dickhoff, C. Barbieri, Prog. Part. Nucl. Phys. 52 (2) (2004) 377–496.

敲出反应中的压低因子疑难

Be/C靶上的敲出反应



转移反应



J. A. Tostevin & A. Gade, PRC 90, 057602 (2014). S. Paschalis et al., PLB 800, 135110 (2020). F. Flavigny et al., PRL 110, 122503 (2013).

$$\sigma_{th}(j^\pi) = \sum_i SF_{th}(j^\pi) \sigma_{sp}$$

$$R_S \equiv \frac{\sigma_{exp}}{\sigma_{th}}$$

核结构: SF谱因子
核反应: σ_{sp}

Eikonal Reaction Model中的假设之一:

剩余核是“旁观者”

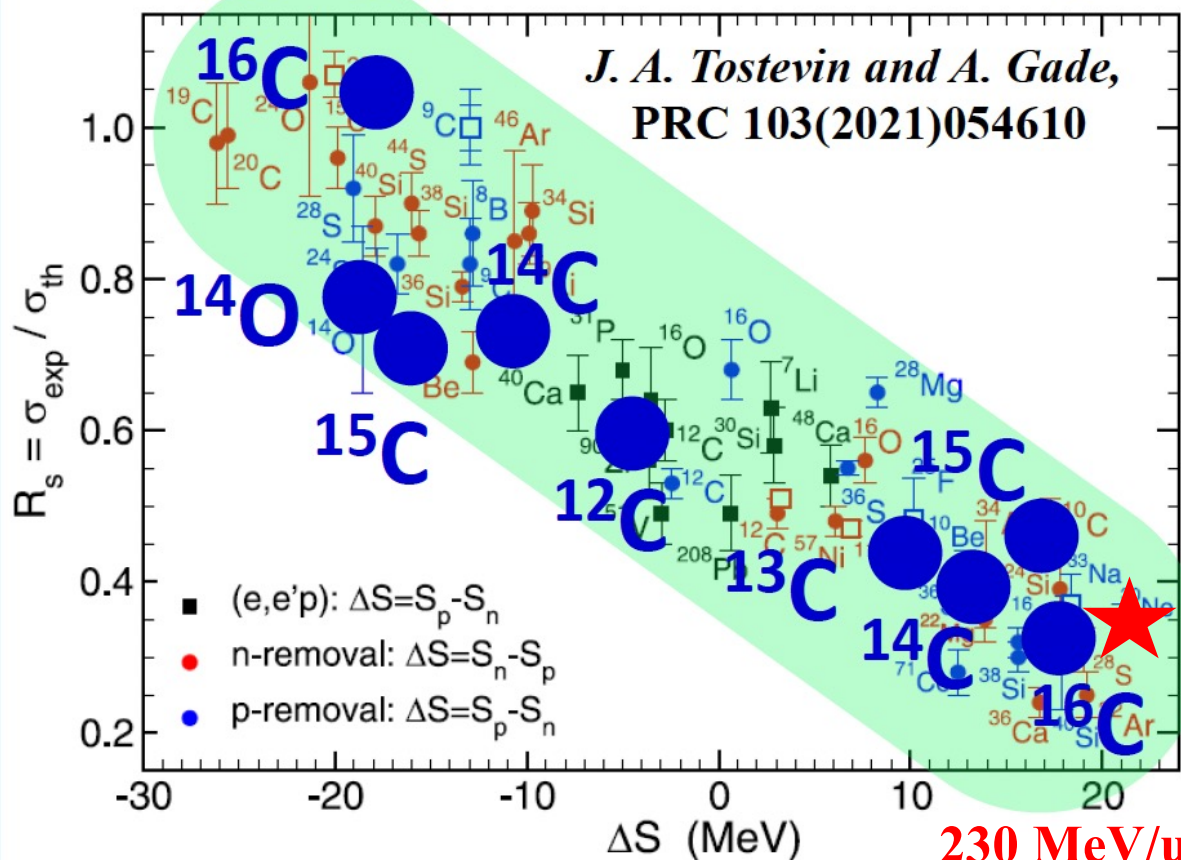
→ 多高的束流能量?

→ 剩余核和被敲出核子之间的末态相互作用?

【Hussein and McVoy, Nuc. Phys. A445 (1985) 124】

谱因子压低的能量依赖

外靶结果：240 - 300 MeV/u



230 MeV/u @RIBF

^{30}Ne @ RIKEN RIBF

$^{30}\text{Ne}(-n)$, H.N. Liu et al., PLB 767, 58(2017).
 $^{30}\text{Ne}(-p)$, J. Lee, H.N. Liu et al., PTEP 2016, 083D01(2016).

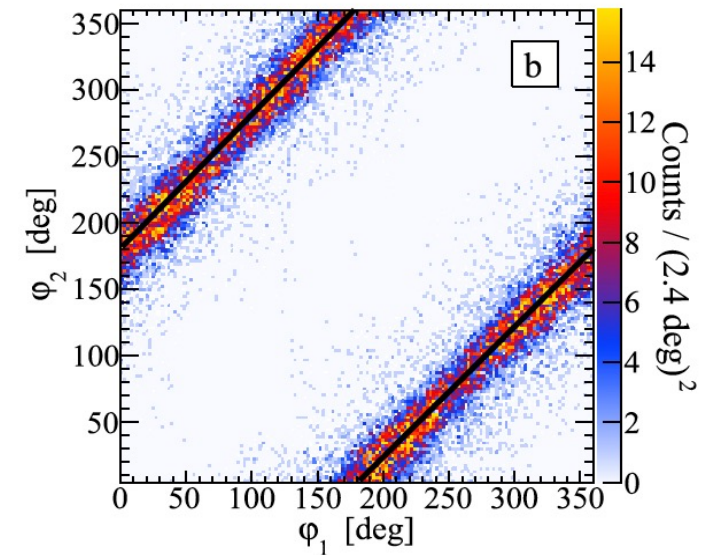
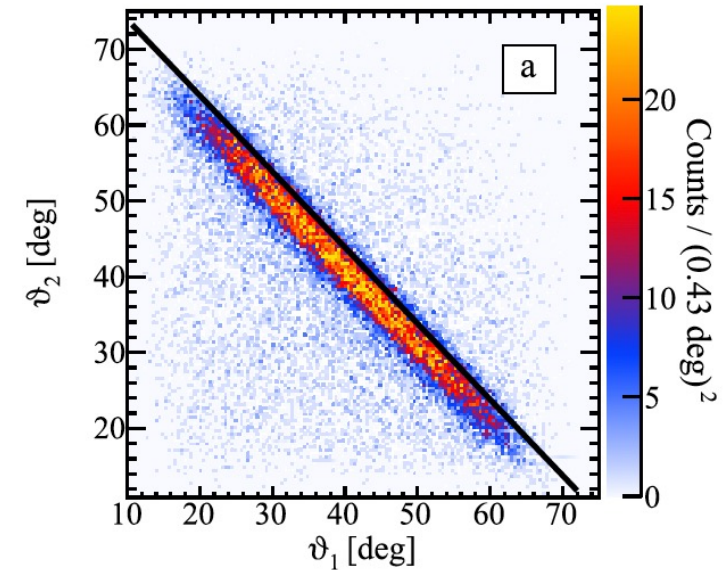
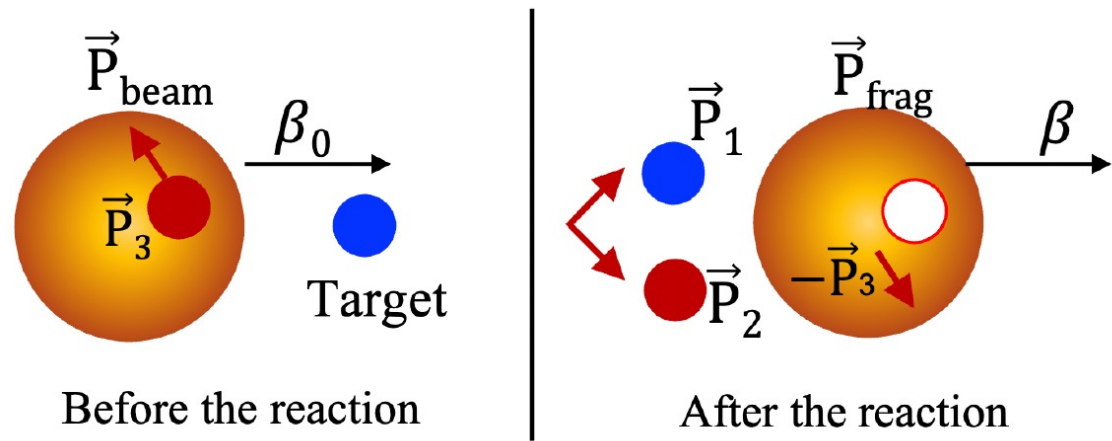
对于C靶，高能区的结果和低能区的实验结果一致：谱因子压低表现出对 neutron-proton 不对称的强依赖关系。

^{14}O , $^{12-16}\text{C}$ @ IMP RIBLL2

$^{14}\text{O}(-p)$, *Phys. Rev. C* 90 (2014) 037601
 $^{16}\text{C}(-p)$, *Phys. Rev. C* 100 (2019) 044609
 $^{14-16}\text{C}(-n)$, *Phys. Rev. C* 104 (2021) 014310
 $^{12-15}\text{C}$, $^{14-17}\text{N}(-p)$, Paper in preparation

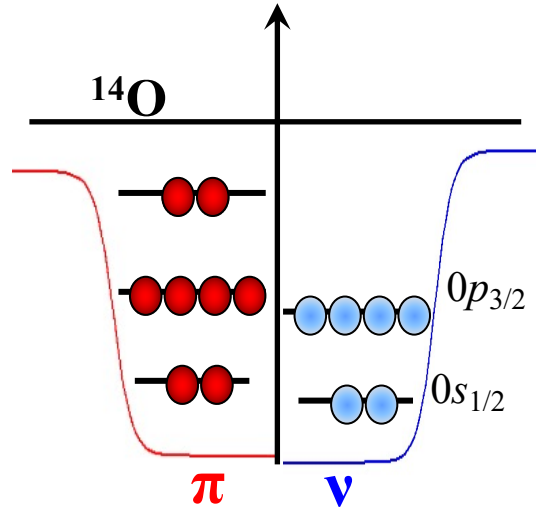
质子靶上的敲出反应

质子靶，更干净的探针，准自由散射



- 实验可测量反应后的出射质子，反应过程明确；
- DWIA理论描述更加准确(譬如：考虑了剩余核和被敲出核子间的相互作用)。

100MeV/u 能量下的¹⁴O(p, pN)

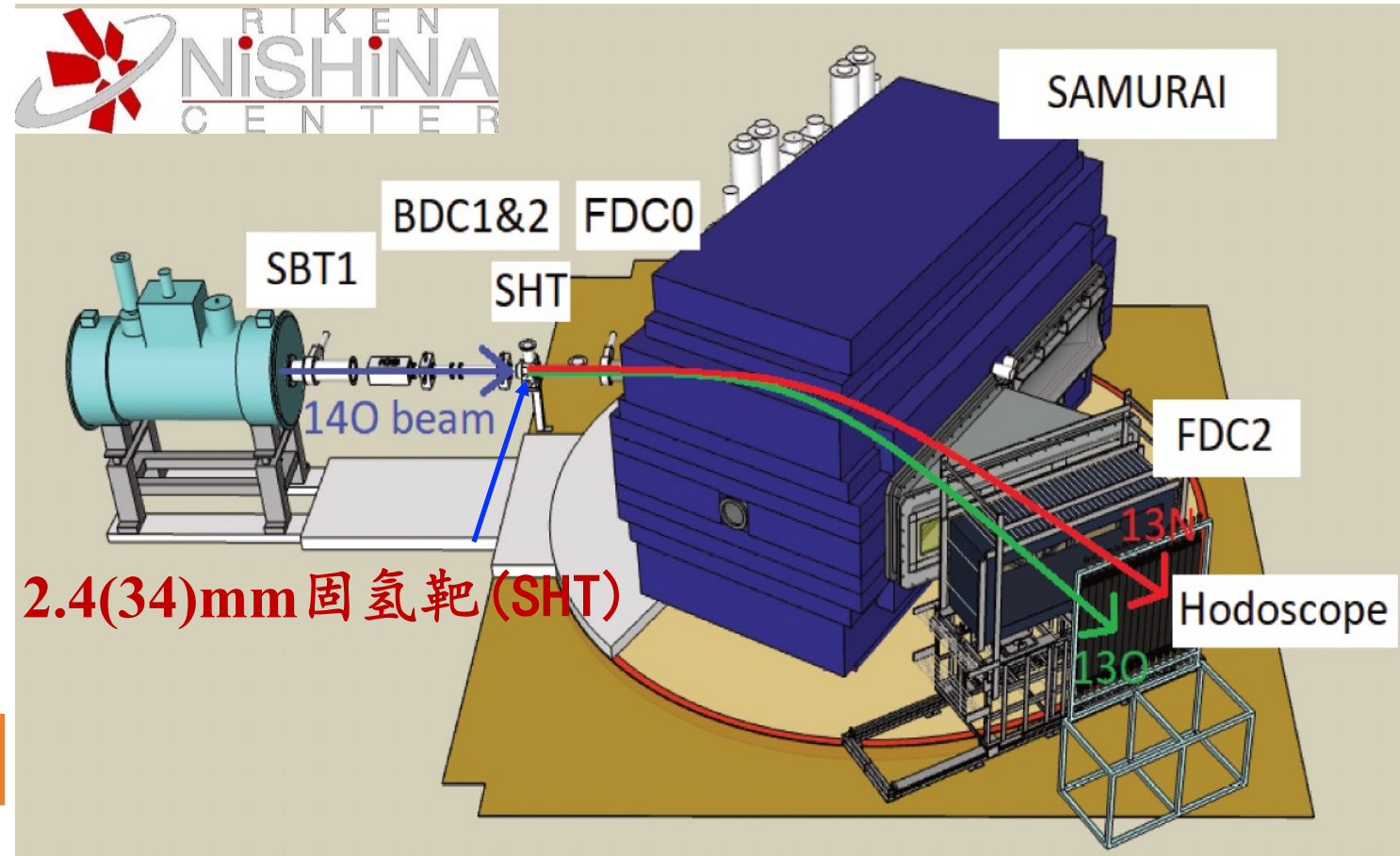


$S_n = 23.2 \text{ MeV}$,
 $S_p = 4.6 \text{ MeV}$
 $\Delta S = 18.6 \text{ MeV}$

1. Very asymmetry

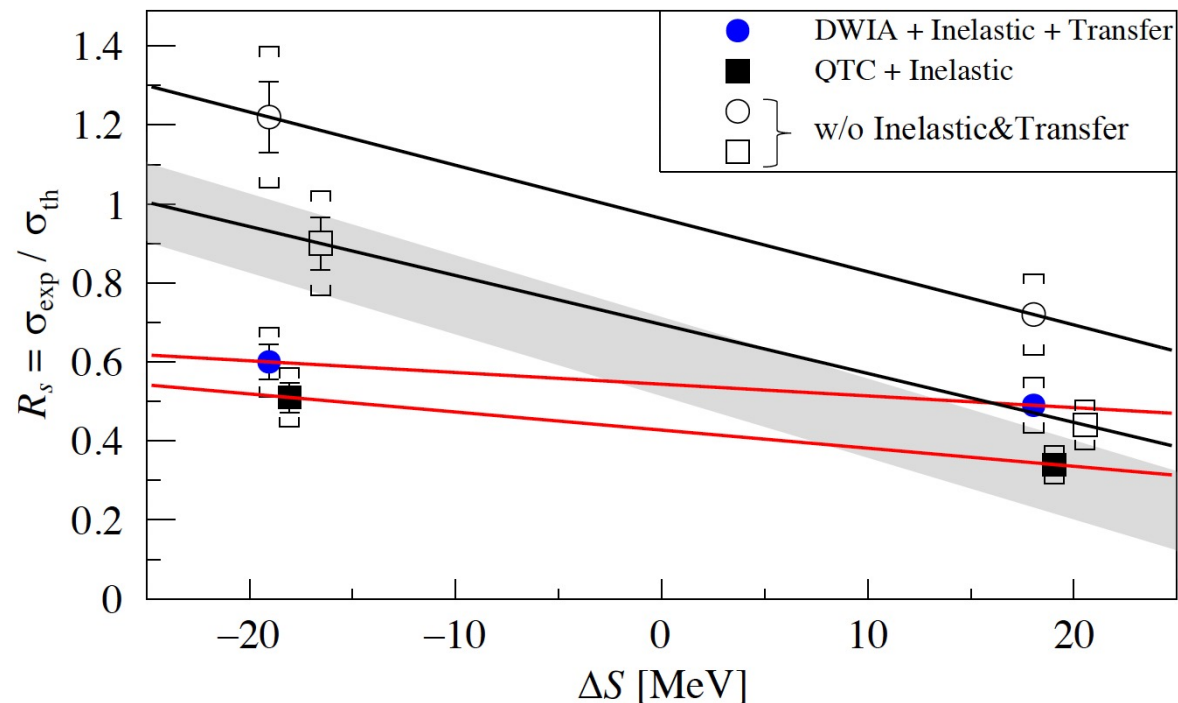
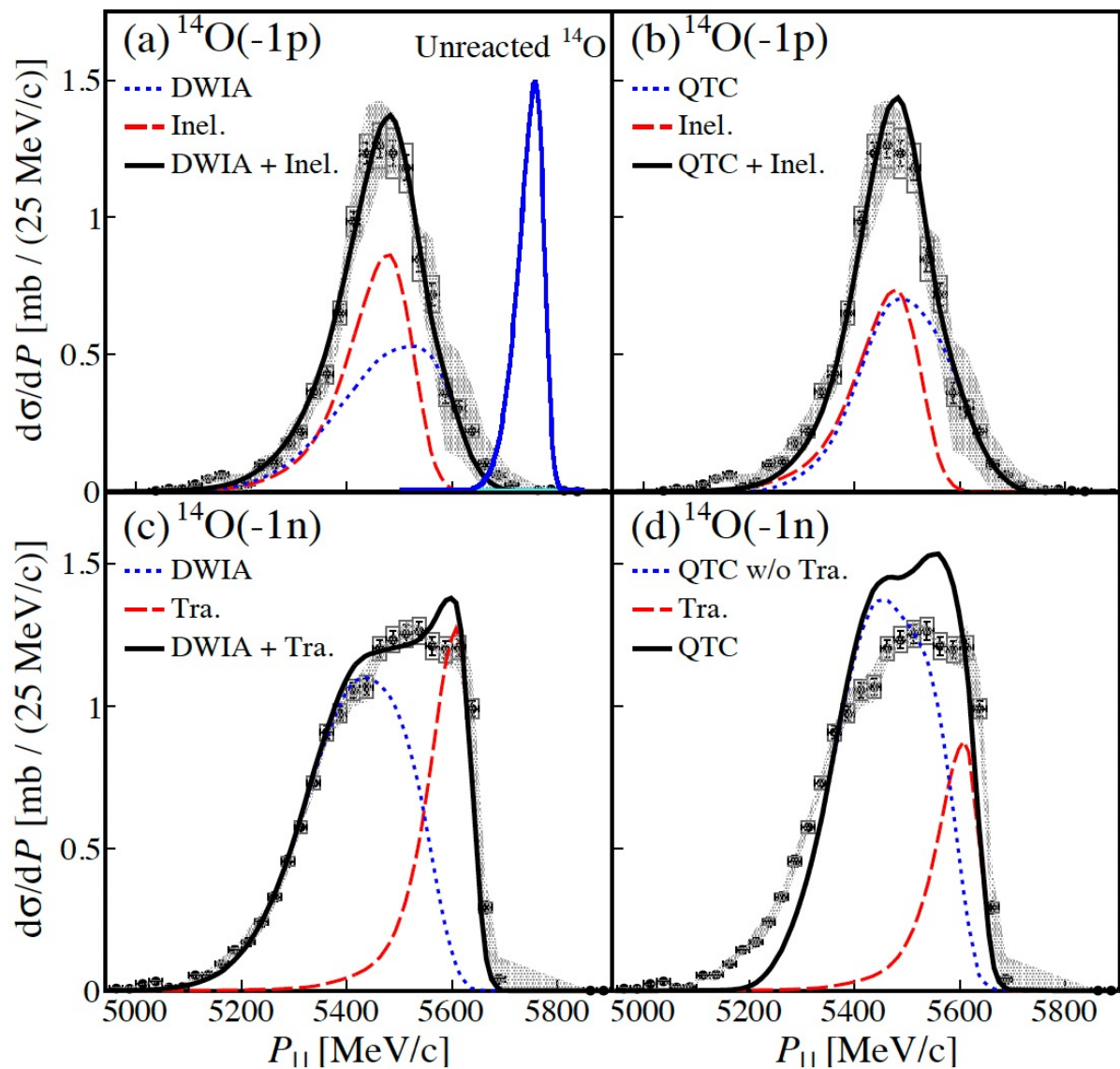
2. ¹³N and ¹³O 没有束缚的激发态

¹⁴O 是用来研究反应机制的理想对象



Spokersperson: Yelei Sun, TU Darmstadt

100MeV/u能量下的(p, pN)反应包含多种反应机制



多种反应机制：准自由移除、非弹散射、转移反应

$^{14}\text{O}(-p)$: 非弹散射 $^{14}\text{O}(p, p')^{14}\text{O}^* \rightarrow p + ^{13}\text{N}$ 的贡献占 $\sim 50\%$

$^{14}\text{O}(-n)$: 转移反应 $^{14}\text{O}(p, d)^{13}\text{O}$ 的贡献占 $\sim 30\%$

T. Pohl, Y. L. Sun et al., accepted by PRL (2023).

^{14}O - $^{22}\text{O}(p, 2p)$ 反应提取的 R_s

(p,2p) 反应提取的 R_s 对 中子-质子 不对称的依赖很弱，与转移反应类似。

不同能量下的 (p,2p) 反应利用 DWIA 提取的 R_s 表现出了系统性的差异？

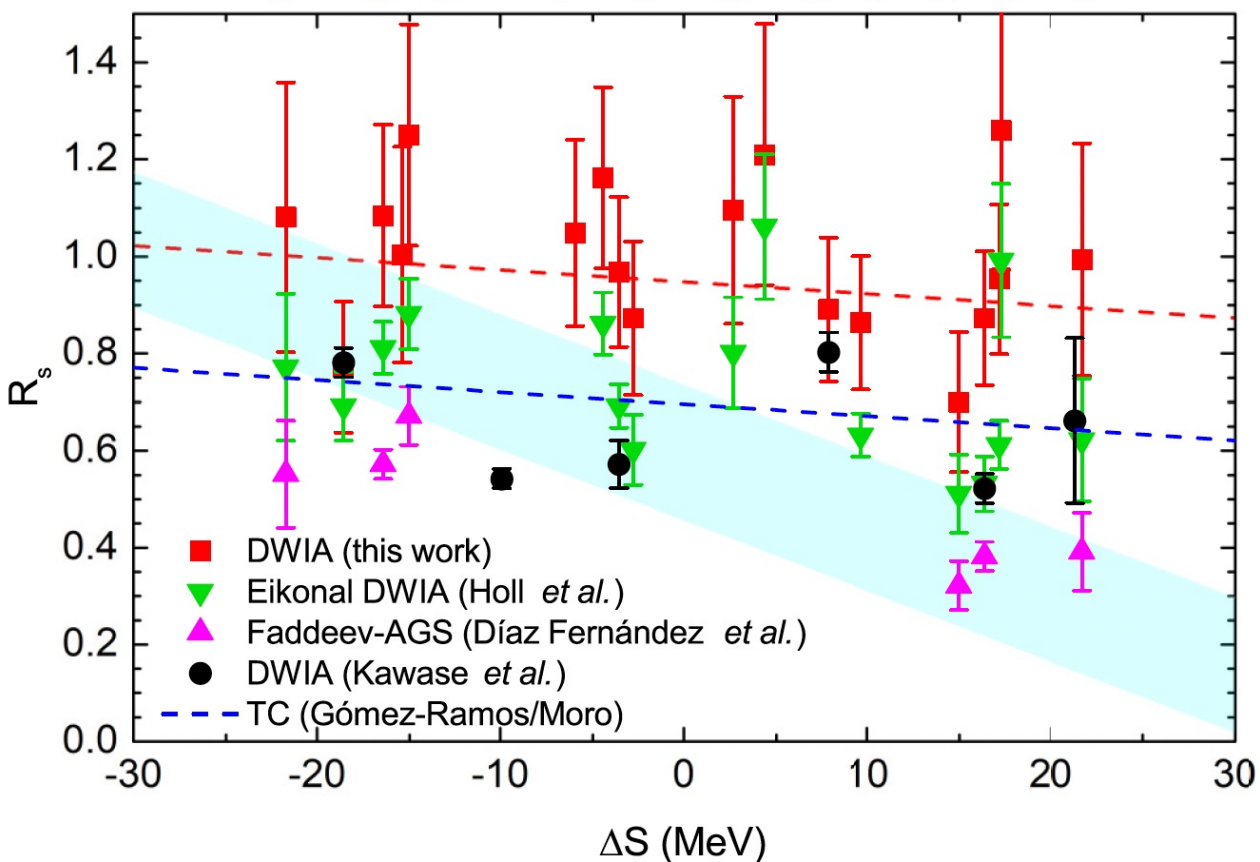
GSI @ 400 MeV/u: $R_s \sim 1.0$
 $10^\circ < \theta < 70^\circ, |\phi| < 180^\circ$

RIKEN-RCNP @ 250 MeV/u: $R_s \sim 0.7$
 $20^\circ < \theta < 60^\circ, |\phi| < 15^\circ, T_p > 30 \text{ MeV}$

L. Atar et al., Phys. Rev. Lett. 120, 052501 (2018).

S. Kawase et al., Prog. Theor. Exp. Phys. 2018, 201D01 (2018).

^{14}O ^{13}O ^{11}C ^{16}O ^{11}C ^{22}O ^{10}C
 ^{23}O ^{22}O ^{21}N ^{15}O ^{12}C ^{12}C ^{18}O ^{17}O ^{21}N ^{21}O ^{23}O



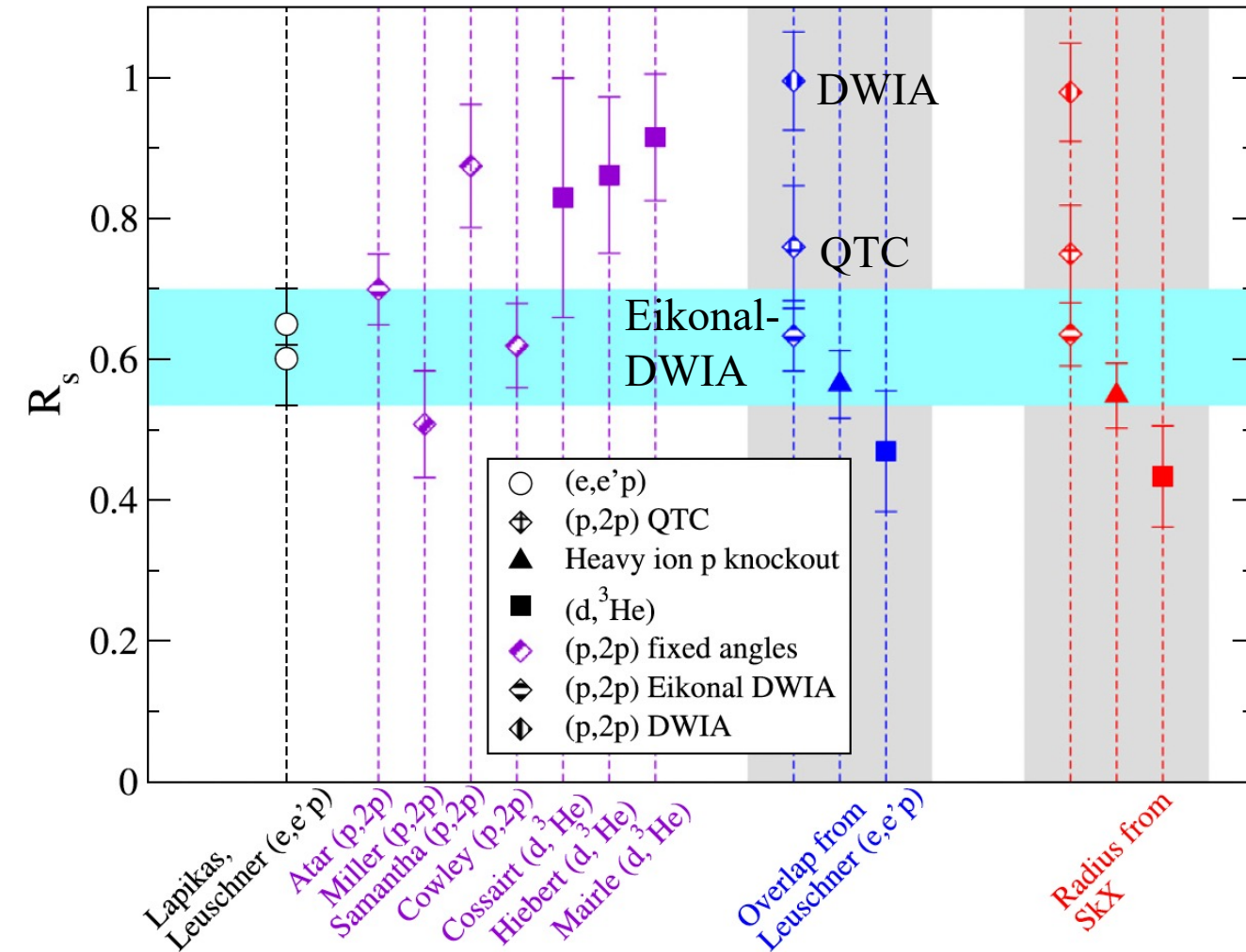
N. T. T. Phuc et al., Phys. Rev. C 100, 064604 (2019).

(p, pN) 反应：不同反应模型得到的 R_s

1p-removal from ^{16}O

Same SF

Same SF



同样的核结构信息SF

QTC : $R_s \sim 0.7$

Eikonal-DWIA : $R_s \sim 0.65$

DWIA : $R_s \sim 1$



报告提纲

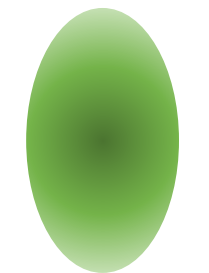
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- 总结与展望



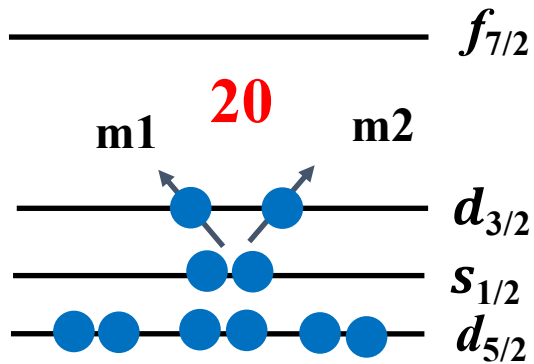
壳结构的探针: $E(2_1^+)$ 的系统演化



价核子磁量子数的重新组合



Deformed

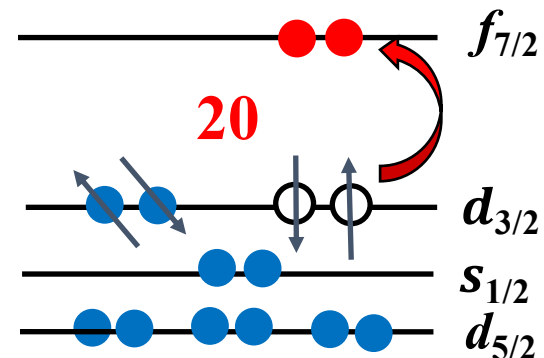


开壳

2_1^+ 的组态

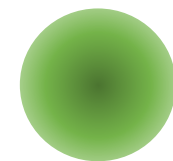
$$E(2_1^+) \propto 1/\beta^2$$

跨壳激发

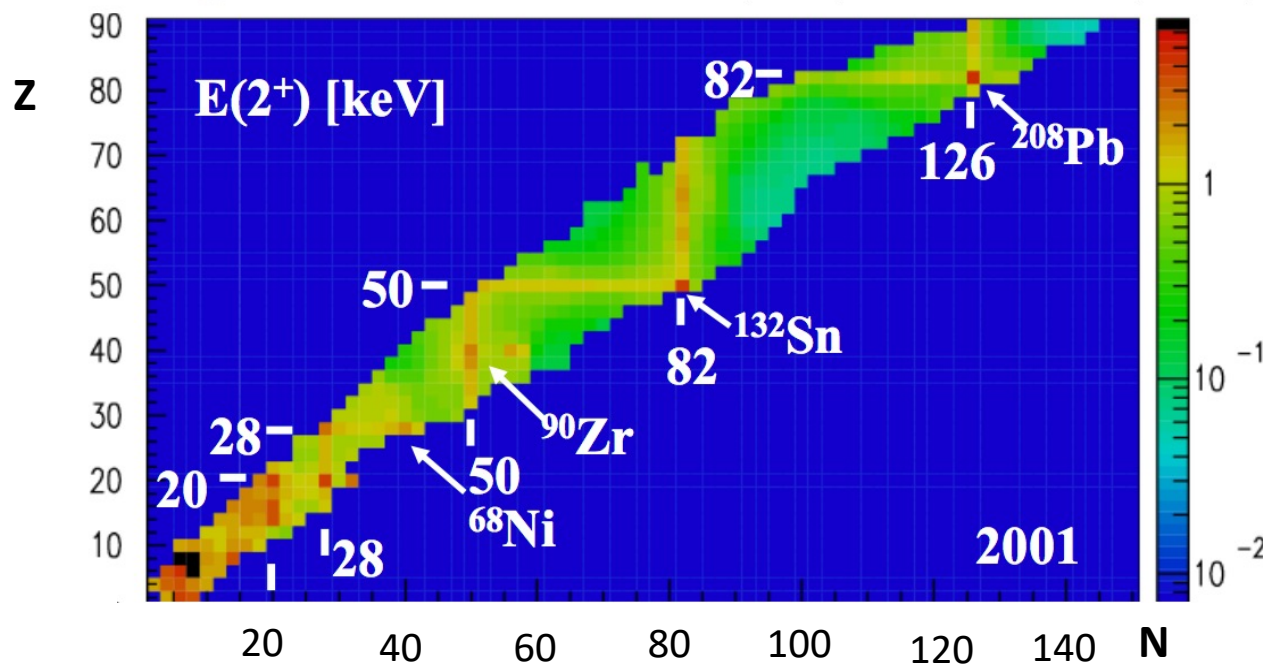


at magic number

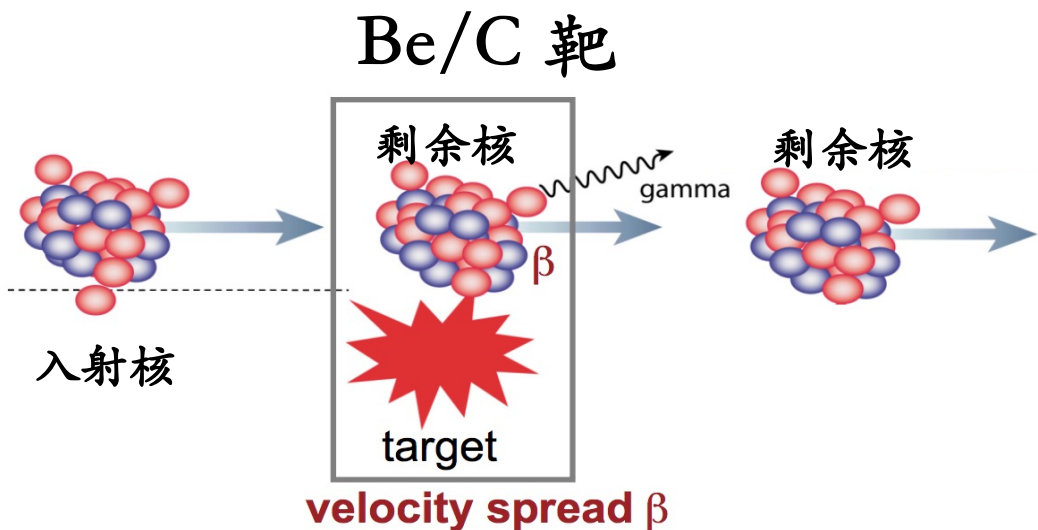
闭壳



Spherical

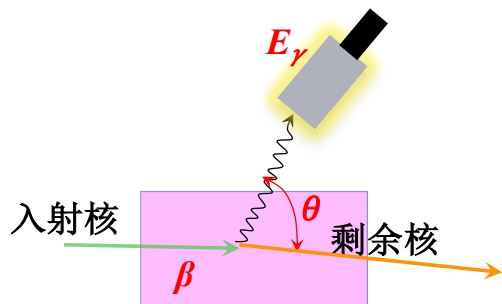


不稳定原子核的在束 γ 谱学



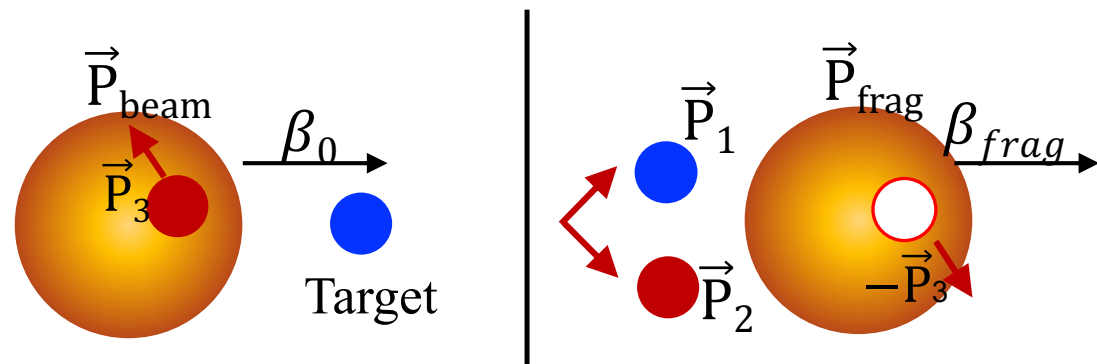
Doppler 效应

$$E_0 = \frac{E_\gamma (1 - \beta \cos \theta)}{\sqrt{1 - \beta^2}}$$



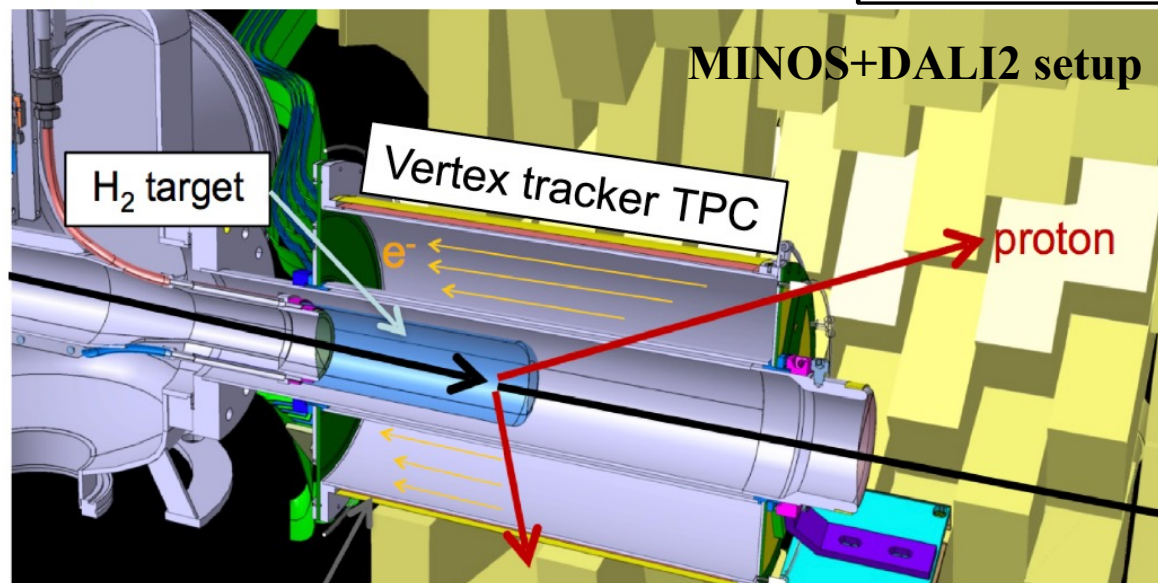
厚靶：
 提高统计 😊
 降低 γ 谱的能量分辨率 😞

准自由的(p, 2p)反应



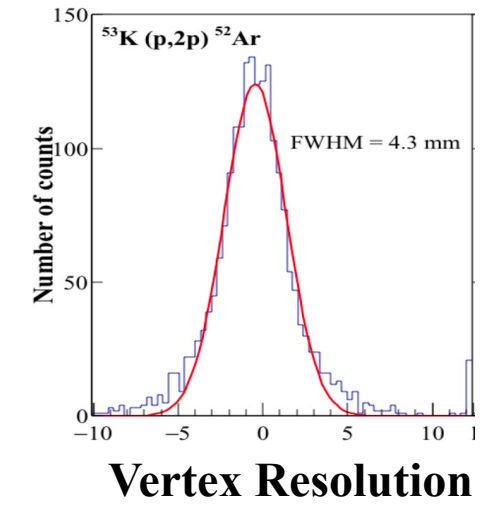
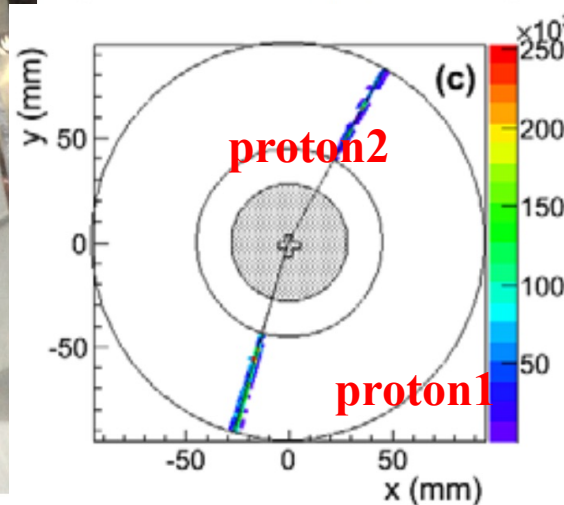
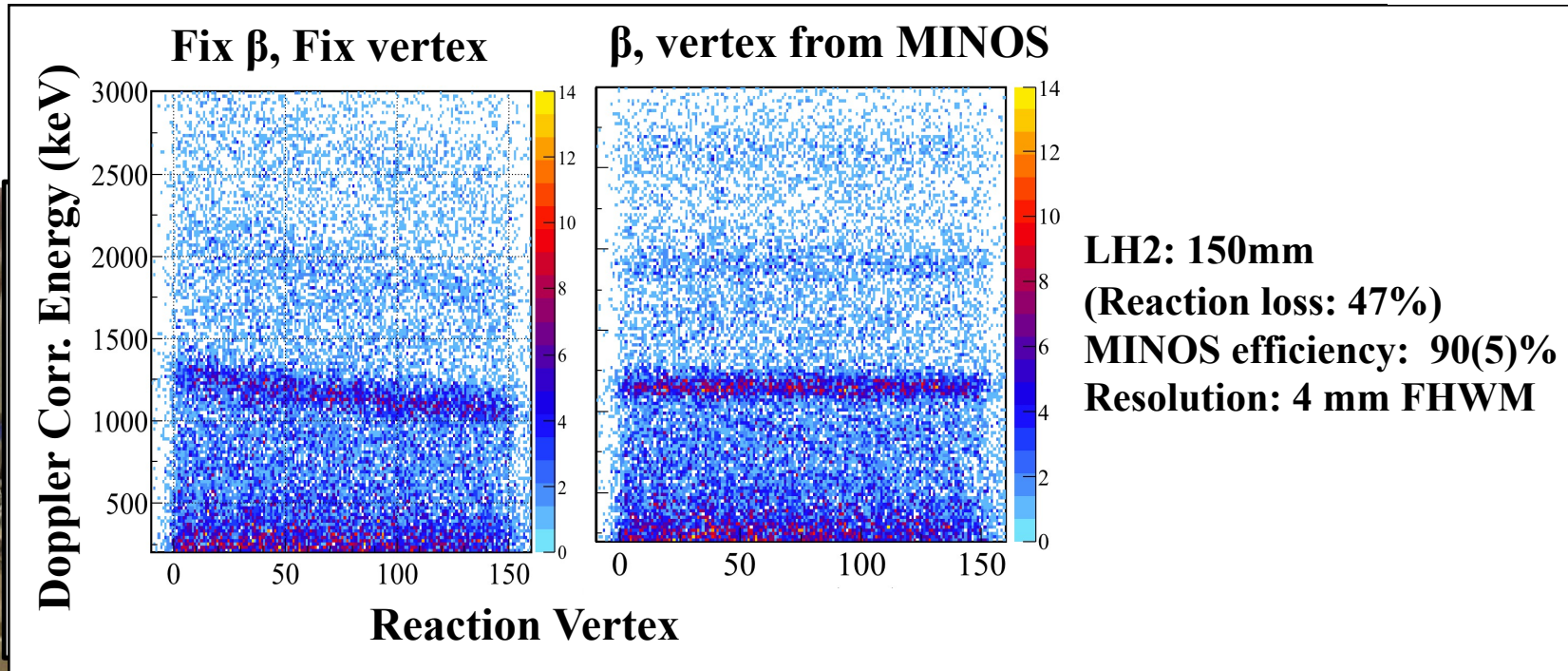
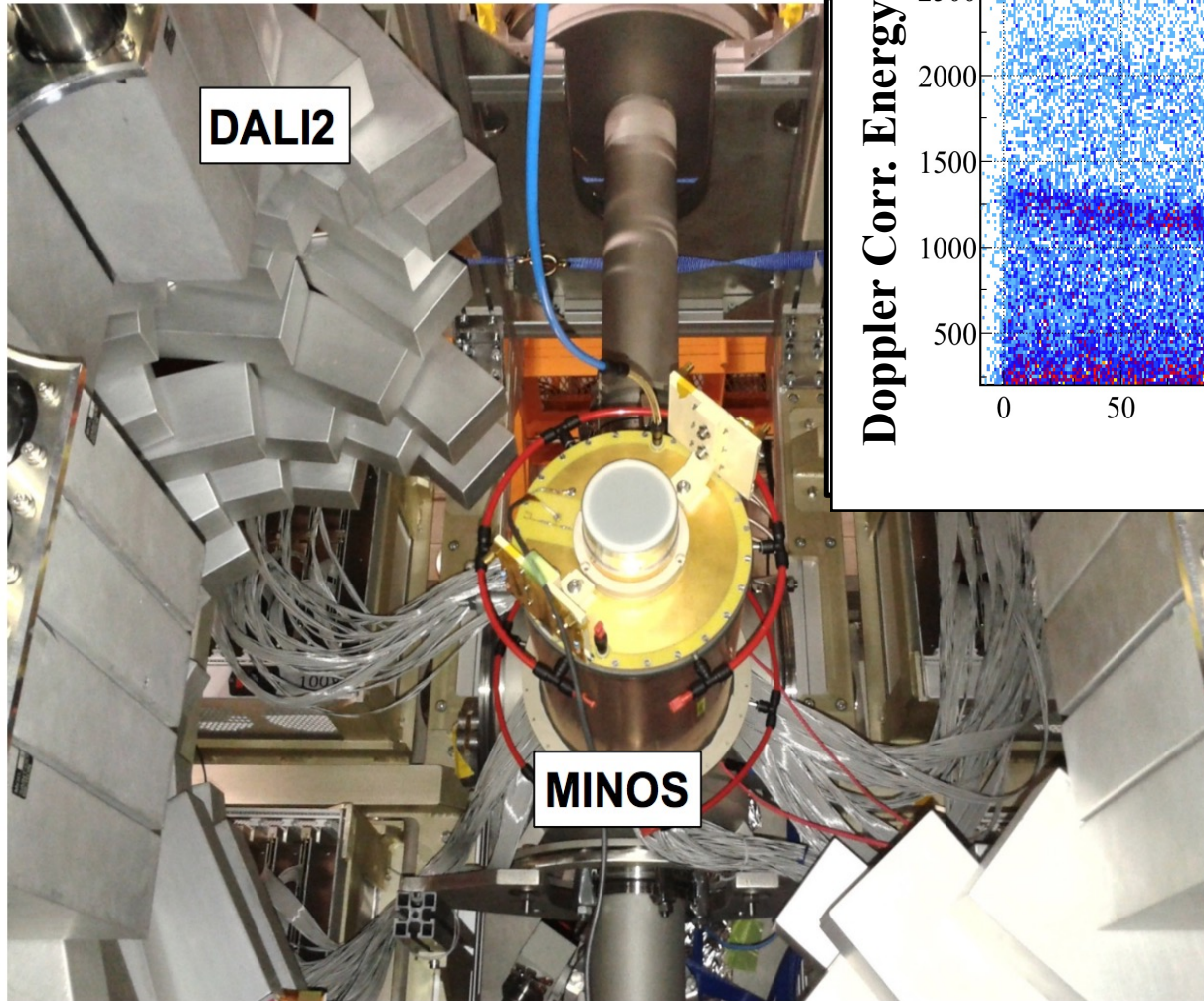
超厚液氢靶+粒子径迹探测器

DALI2 array

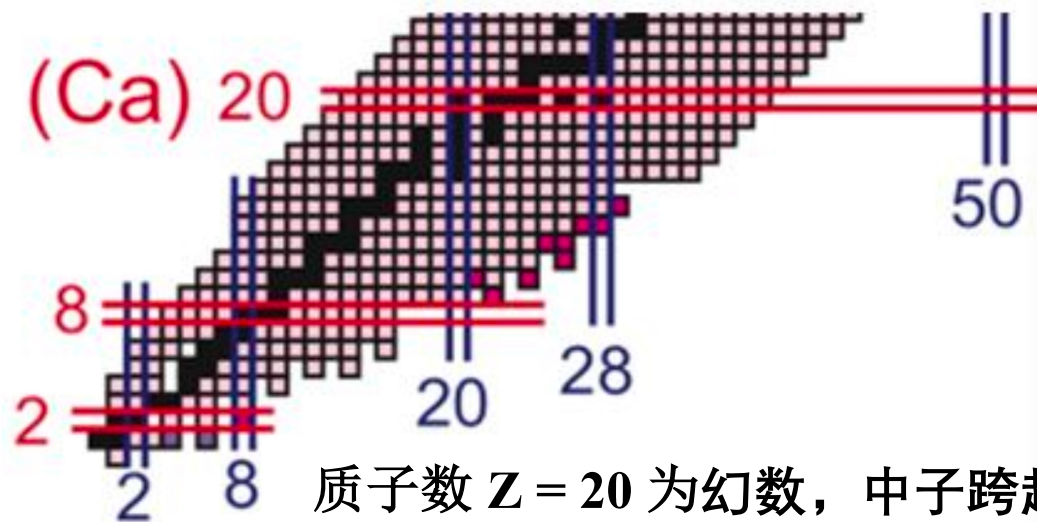


MINOS的性能

NaI(Tl)探测阵列 DALI2: 226 detectors
 Efficiency: 30% @ 1MeV
 Resolution: 10% @1MeV

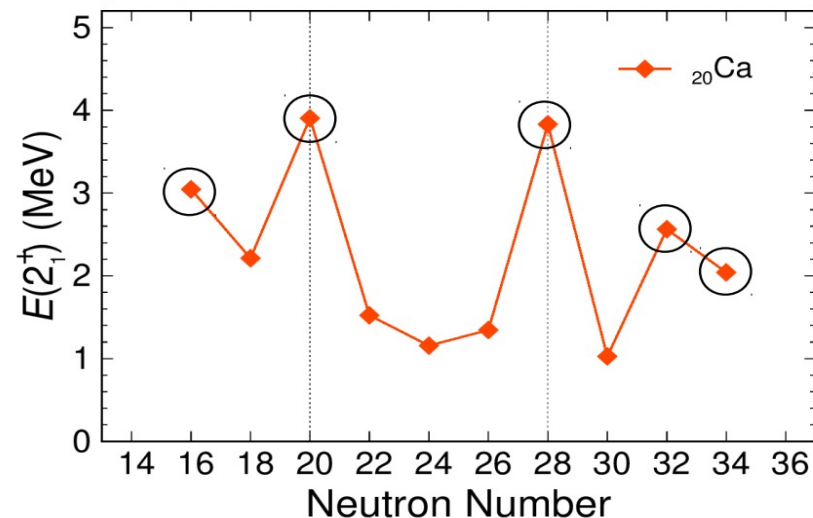


丰中子Ca区的壳演化

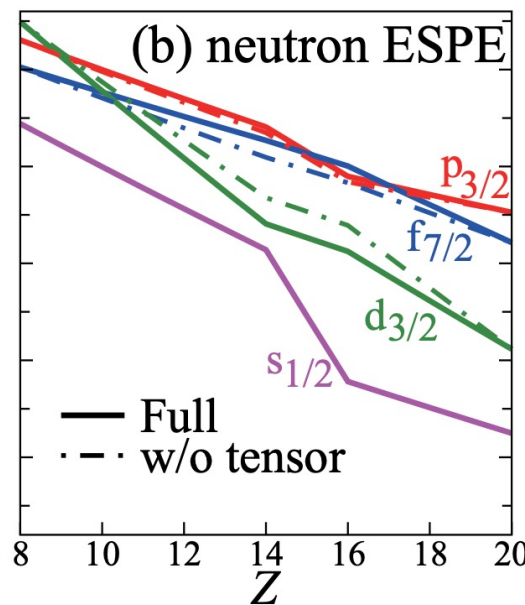
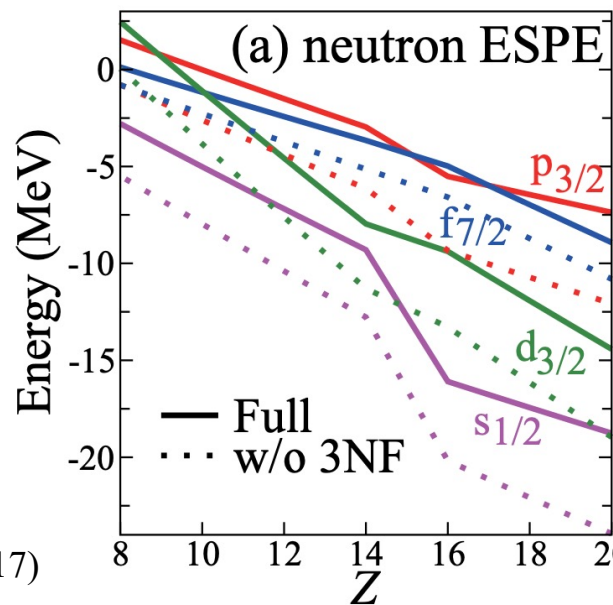


质子数 $Z = 20$ 为幻数，中子跨越多个幻数

(sub-)shell closure at $N = 16, 20, 28, 32, 34$

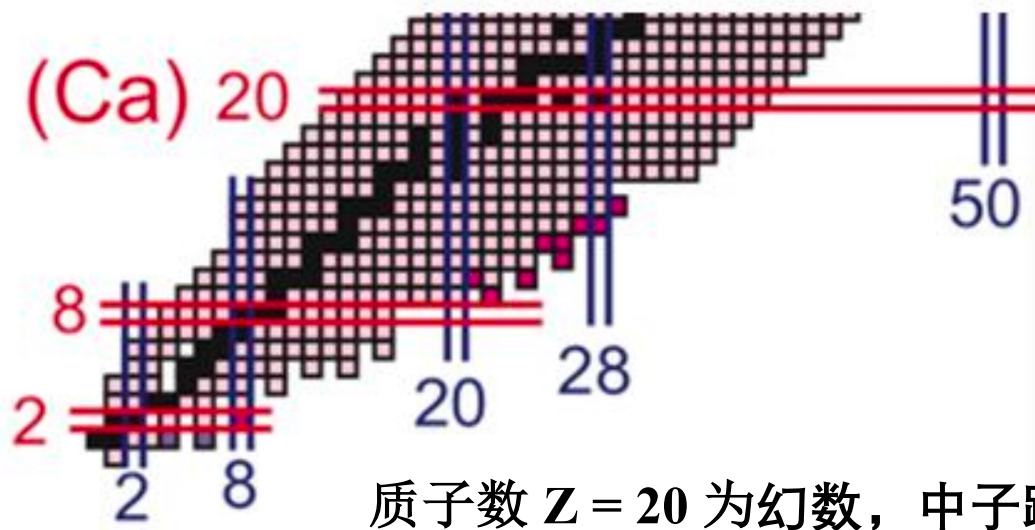


三体力：整体抬高各轨道的能量，排斥作用，避免原子核“过于束缚”。



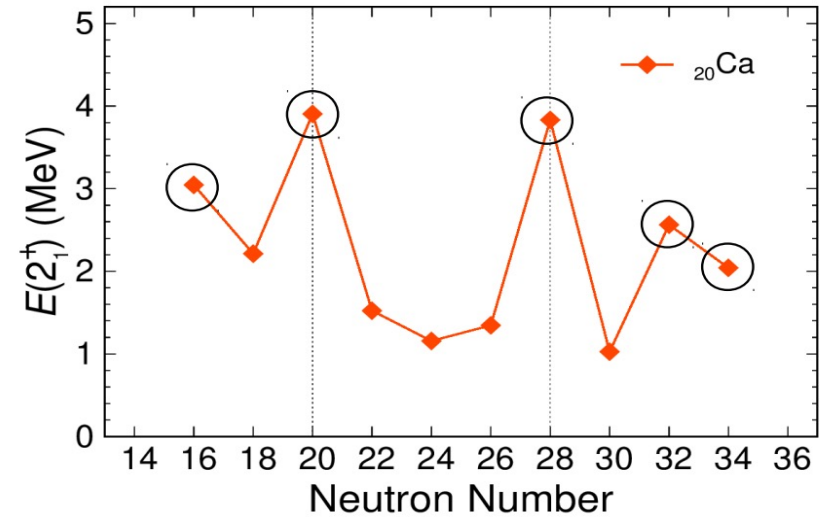
张量力：提高或者降低某些轨道，吸引或者排斥，驱动壳演化。

丰中子Ca区的壳演化

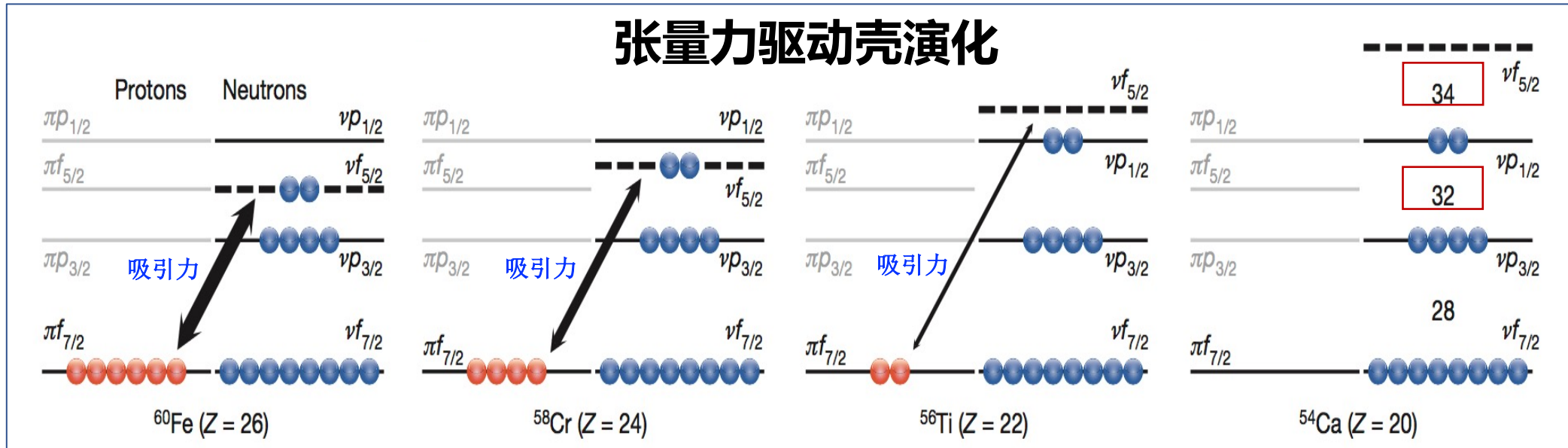


质子数 $Z = 20$ 为幻数，中子跨越多个幻数

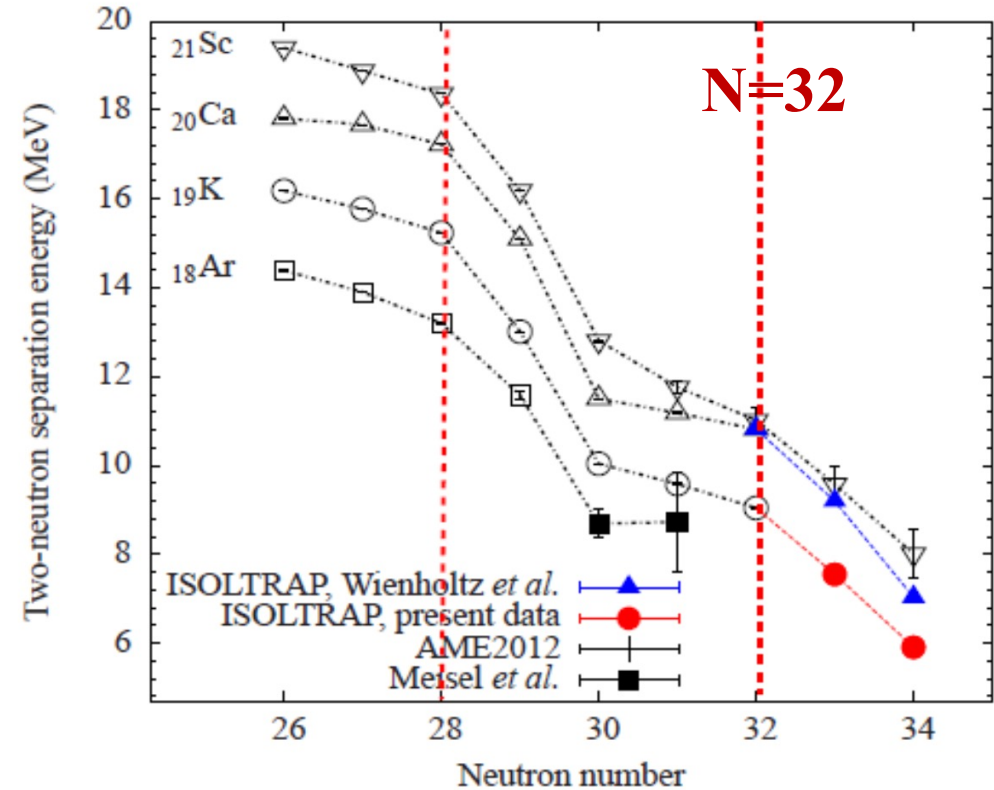
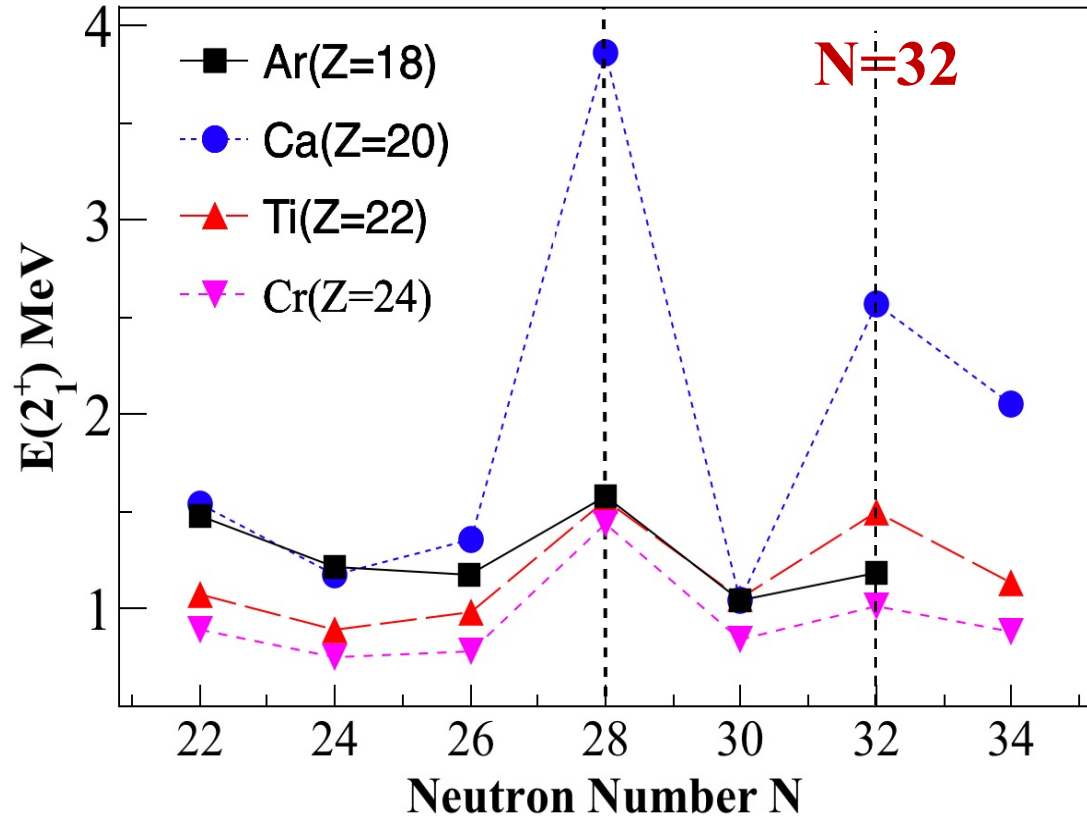
(sub-)shell closure at $N = 16, 20, 28, 32, 34$



张量力驱动壳演化



在 $N = 32$ 是否为新幻数?



在 Ar, K, Ca, Sc, Ti, Cr 中均看到了 $N = 32$ 的幻数效应

难题：在N = 32处异常增大的电荷半径

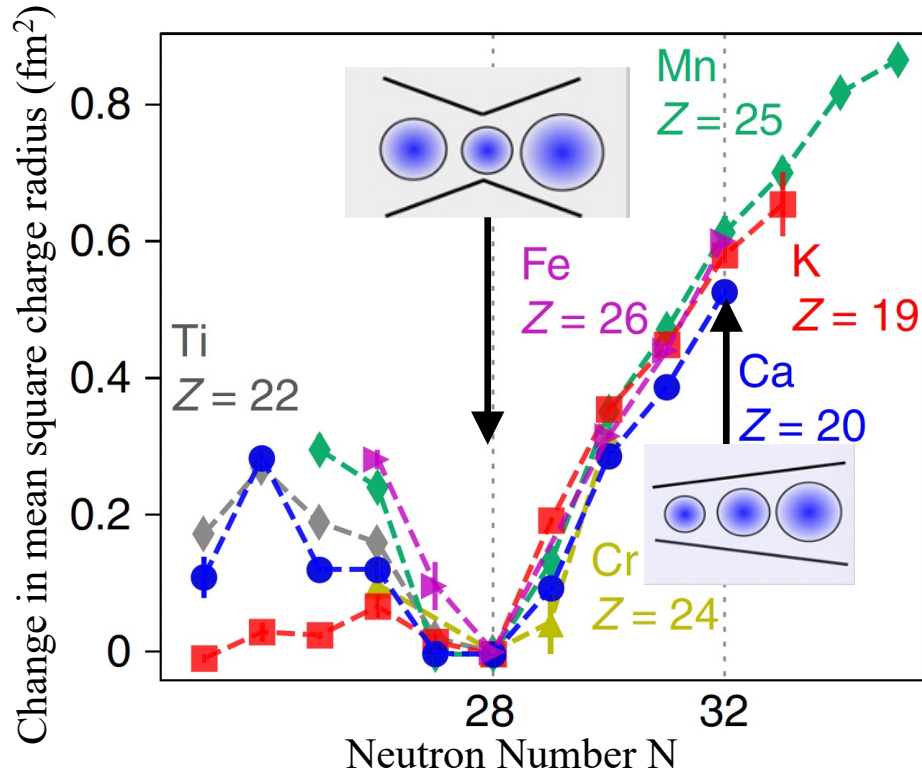
R. F. Garcia Ruiz et al., Nature Physics 12, 594-598 (2016)

M. Tanaka et al., PRL, 124, 102501 (2020).

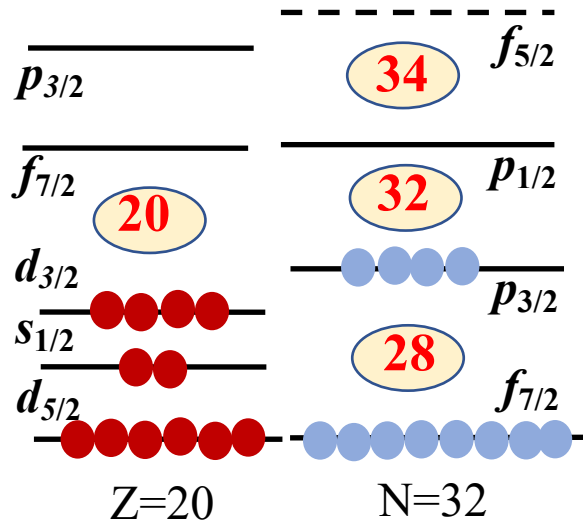
A. Koszorúset al., Nature Physics 17, 439 (2021)

Y. L. Sun et al, PLB 802, 135215(2020);

K. Wimmer et al., PLB 827, 136953 (2022)

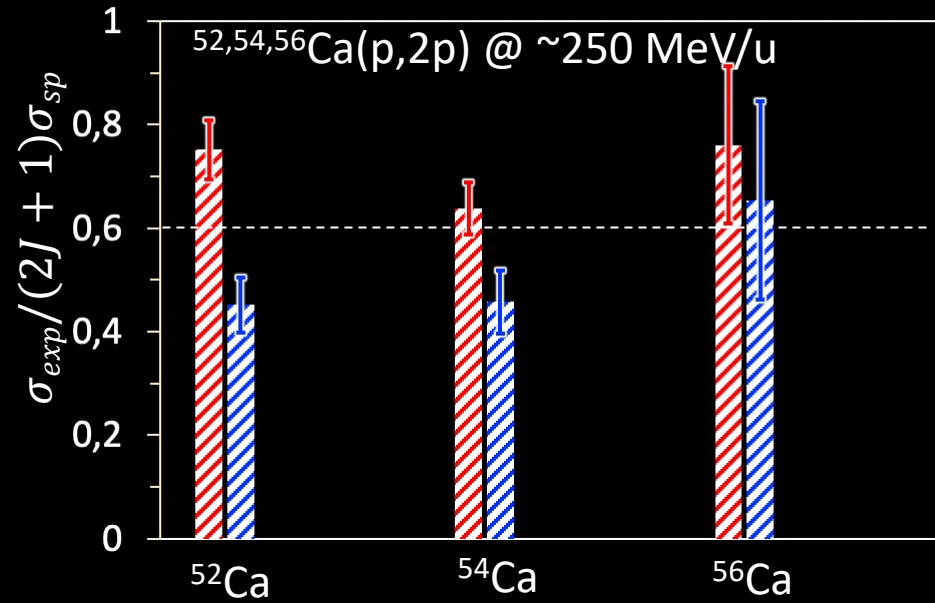


Z = 20 Core breaking?



Same DWIA

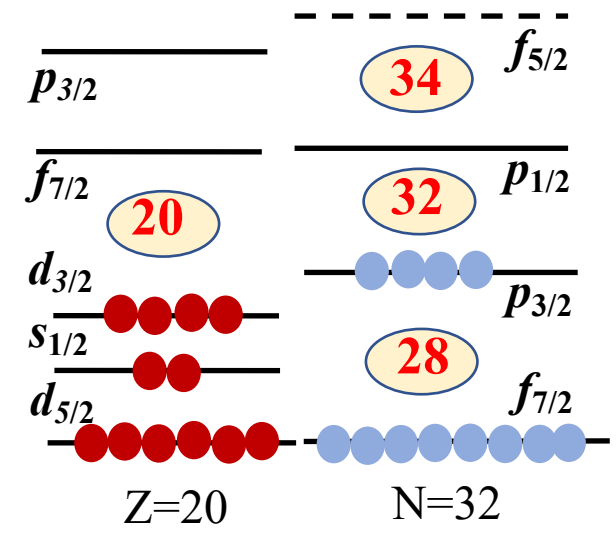
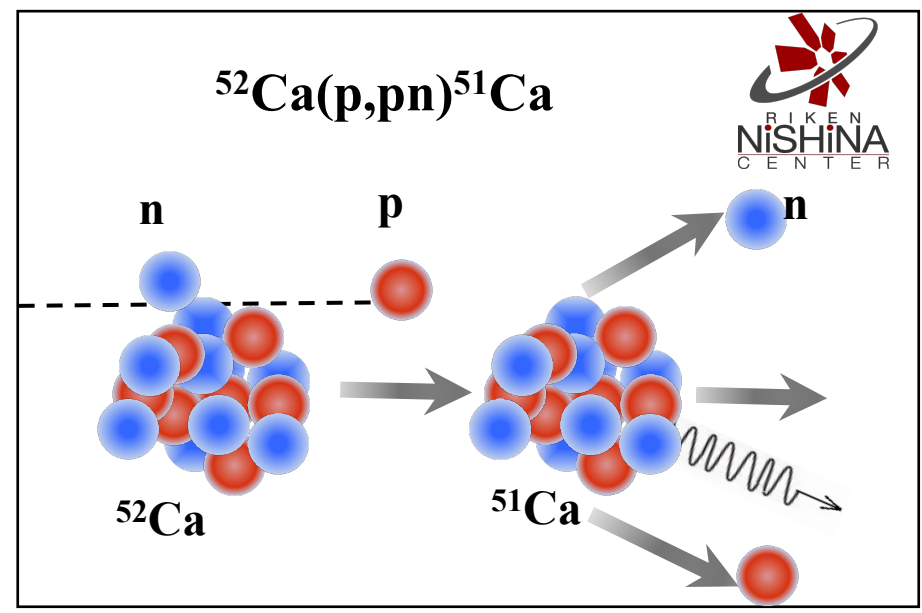
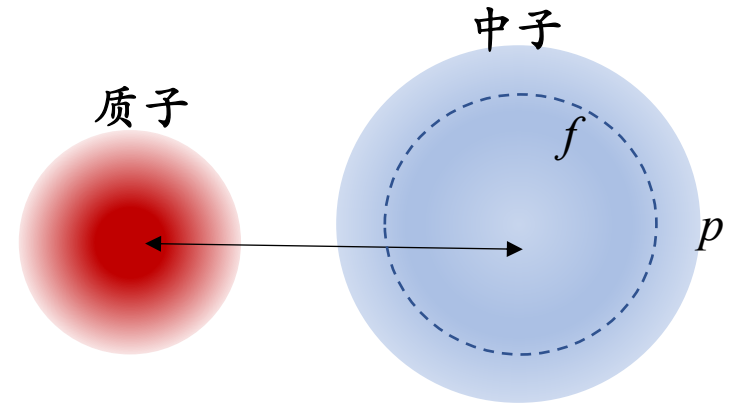
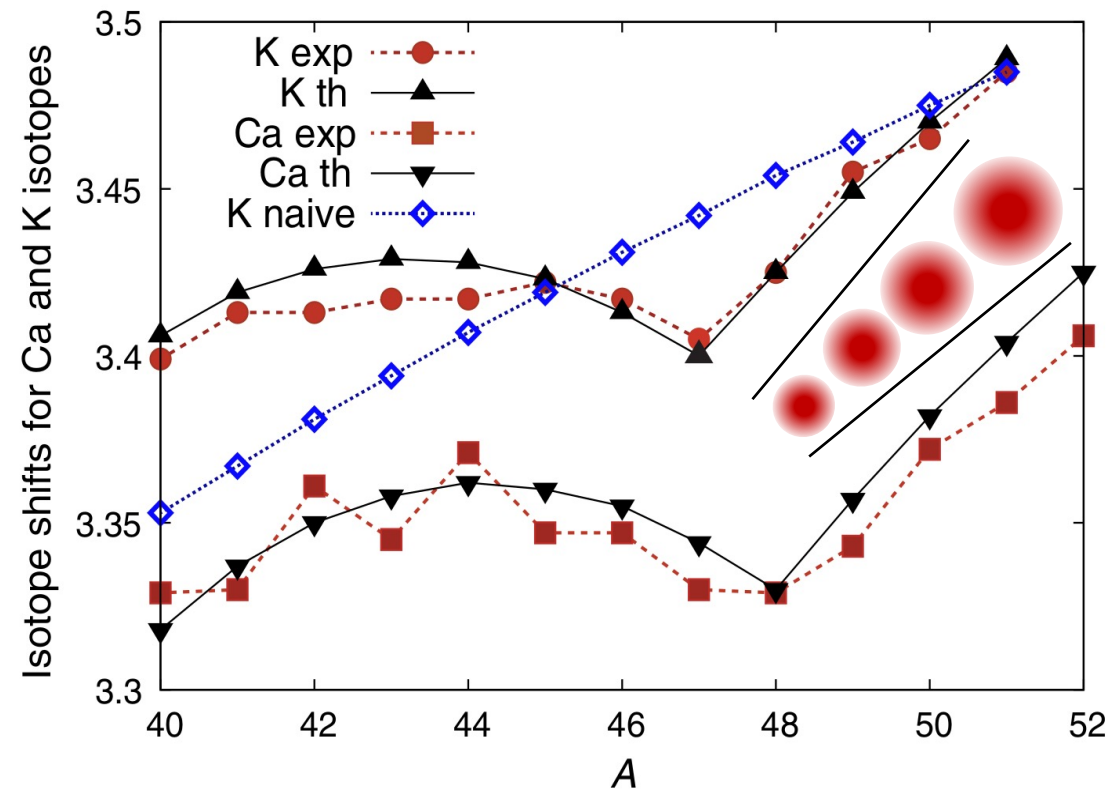
▨ d3/2 ▨ s1/2



可能的解释：延展的p中子轨道（类晕结构）？



J. Bonnard et al., PRL 116, 212501 (2016)



不确定原理

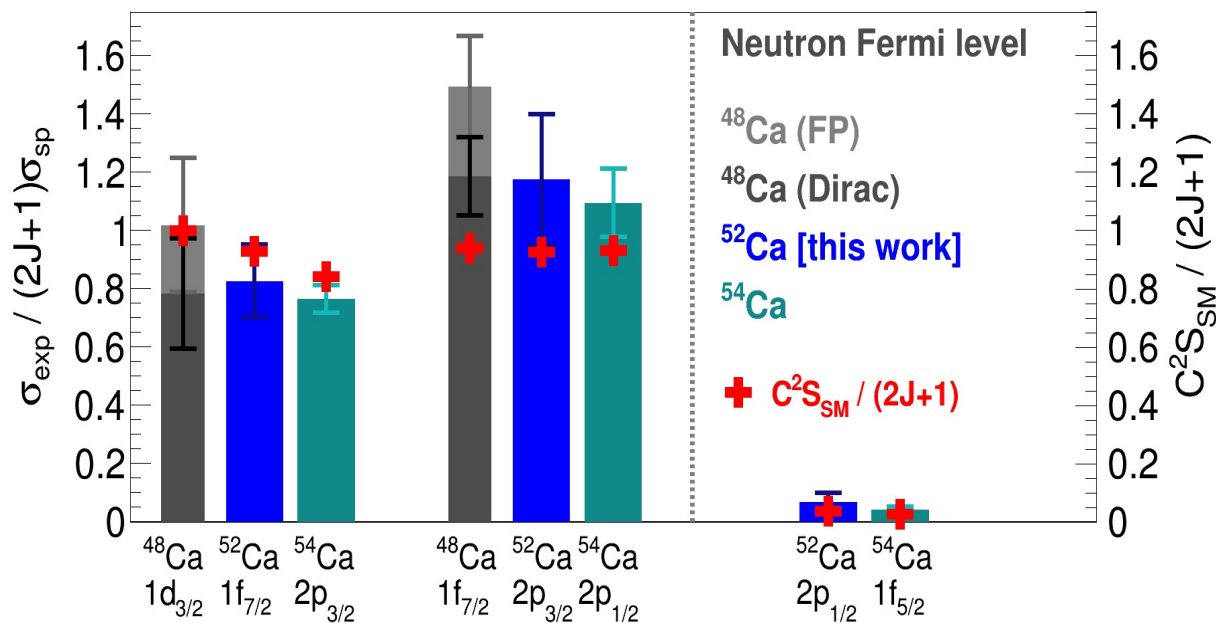
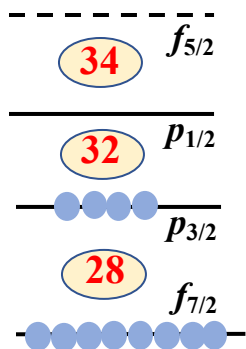
$$\Delta p \Delta x \geq \frac{\hbar}{2}$$

被移除中子的动量 →
单粒子轨道的半径

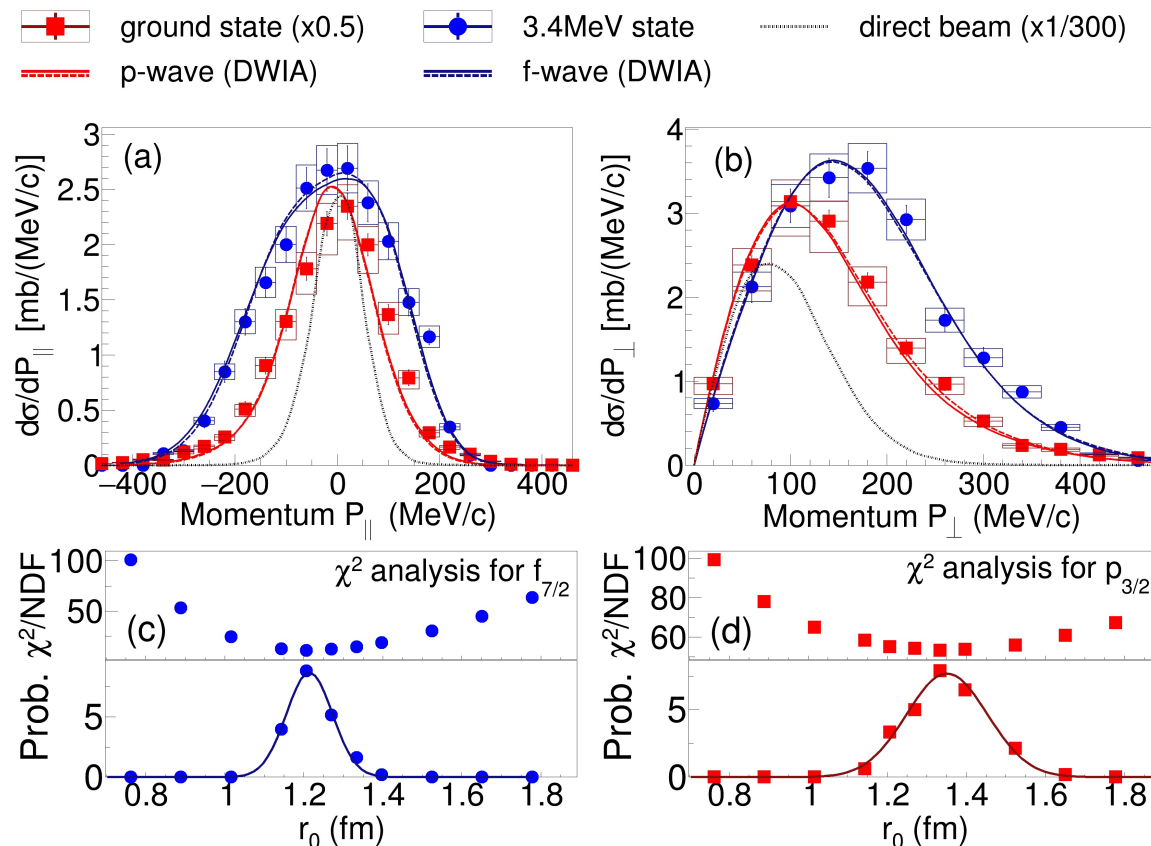
实验结果：发现 $p_{3/2}$ “类晕”结构，支持 $N = 32$ 是新幻数

Reaction model: DWIA
(by K. Yoshida and K. Ogata)

$$\sigma_{\text{exp}} \sim C^2 S_j \sigma_{\text{sp}}$$



M. Enciu*, H. N. Liu* et al., PRL 129, 262501 (2022).

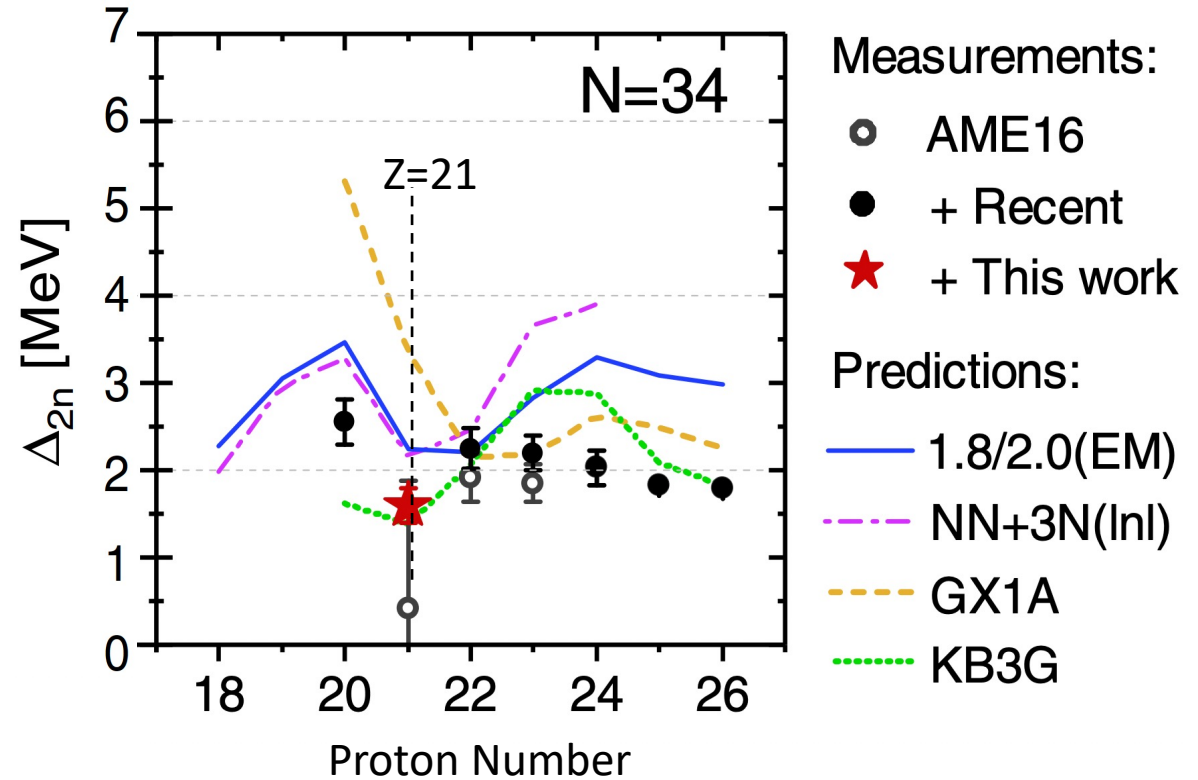
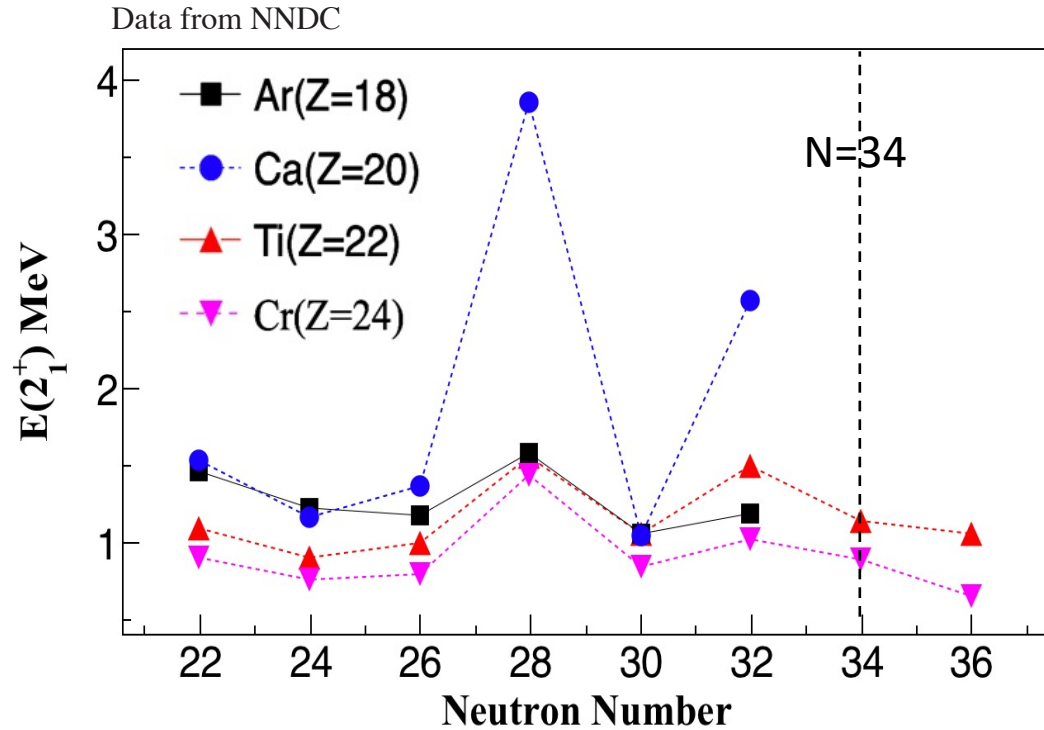


^{52}Ca 表现出和已确立的双幻核 $^{48,54}\text{Ca}$ 同样的闭壳特征

$p_{3/2}$ 的均方根半径比 $f_{7/2}$ 大0.61(23)fm \rightarrow 理论预言值0.7fm

N = 34 是否为新幻数?

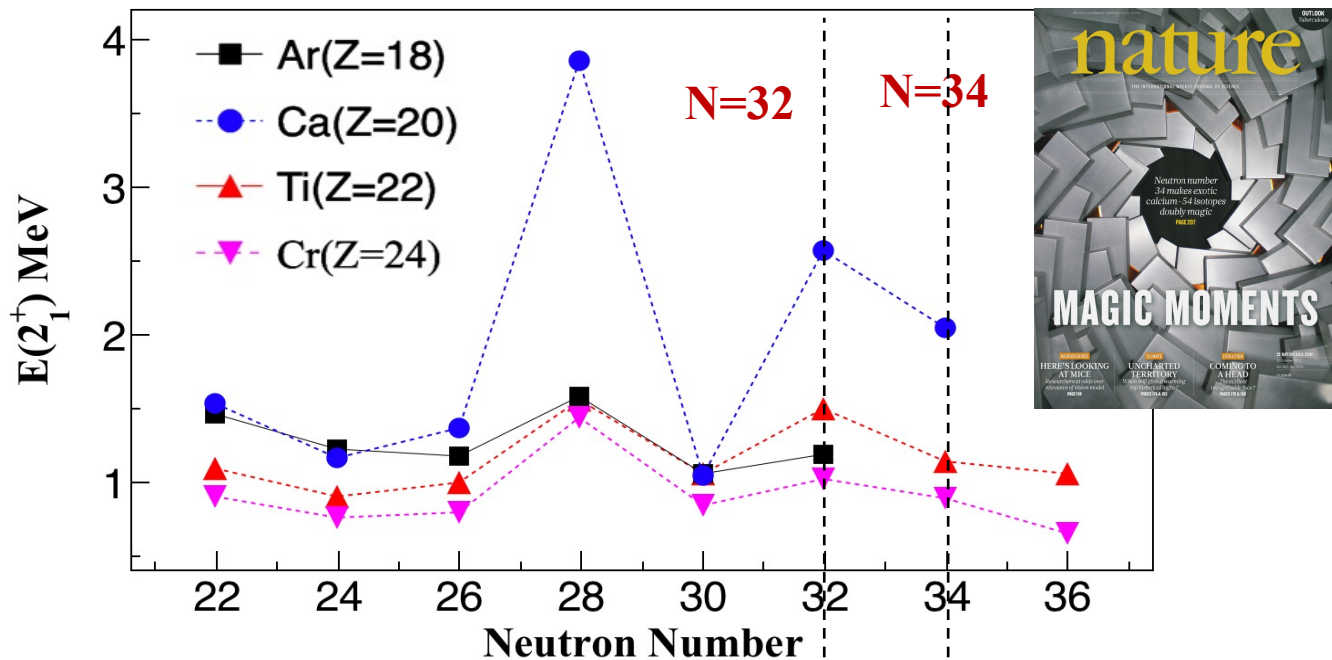
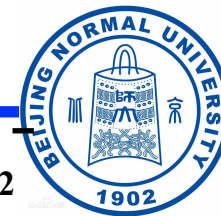
E. Leistenschneider et al., PRL126, 042501 (2021)



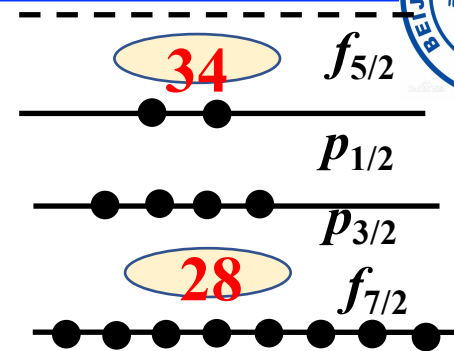
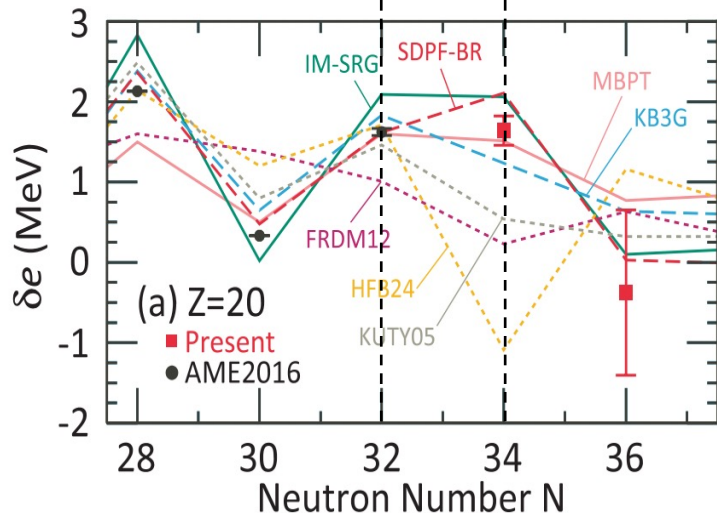
Excitation energy of the negative parity state in ⁵⁵Sc
 D.Steppenbeck et al., PRC 96(2017) 064310

Z > 20 未观察到 N = 34 的亚壳结构

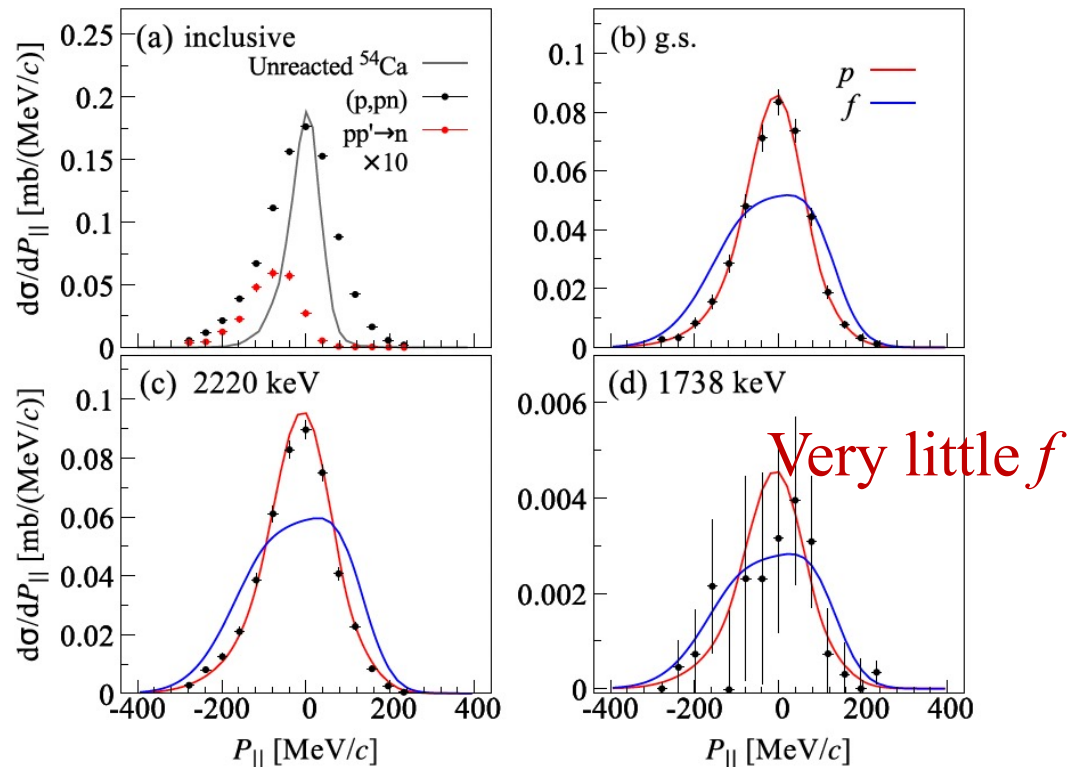
N = 34 是否为新幻数?



Mass of $^{55-57}\text{Ca}$



S. Chen et al. PRL. 123, 142501 (2019)

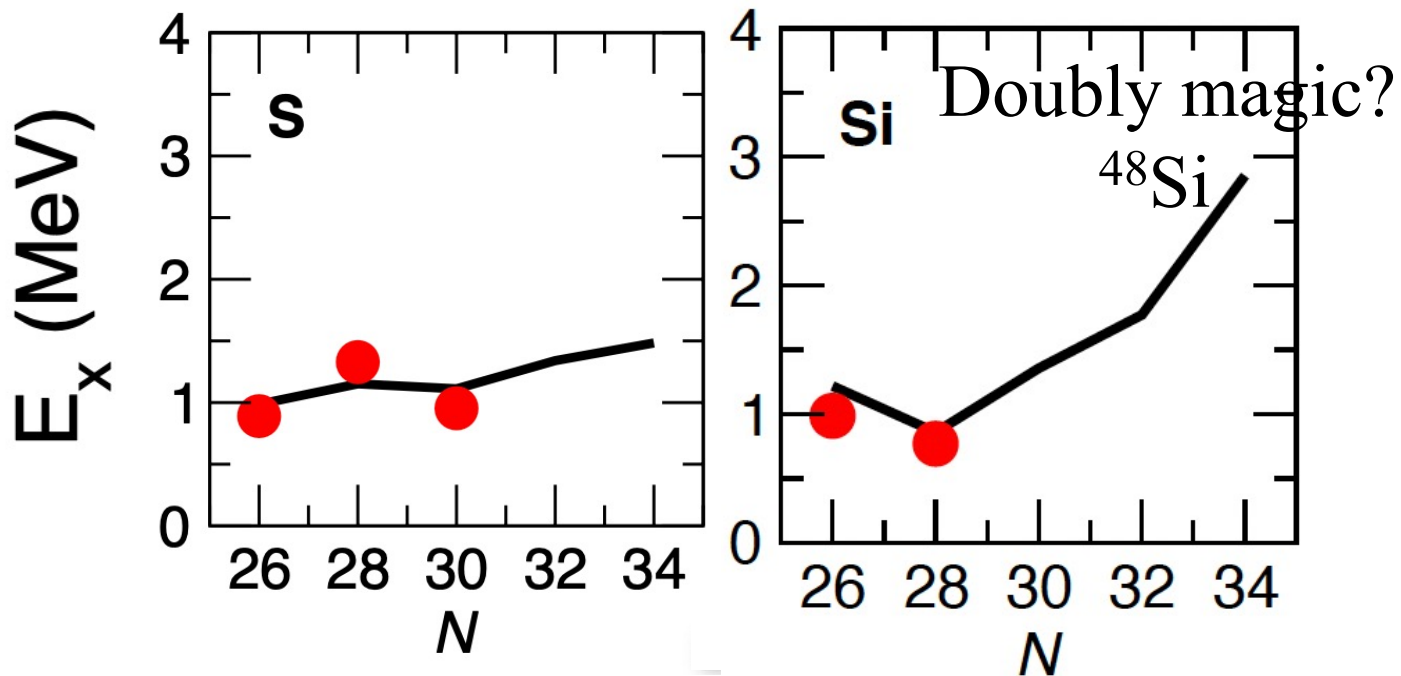
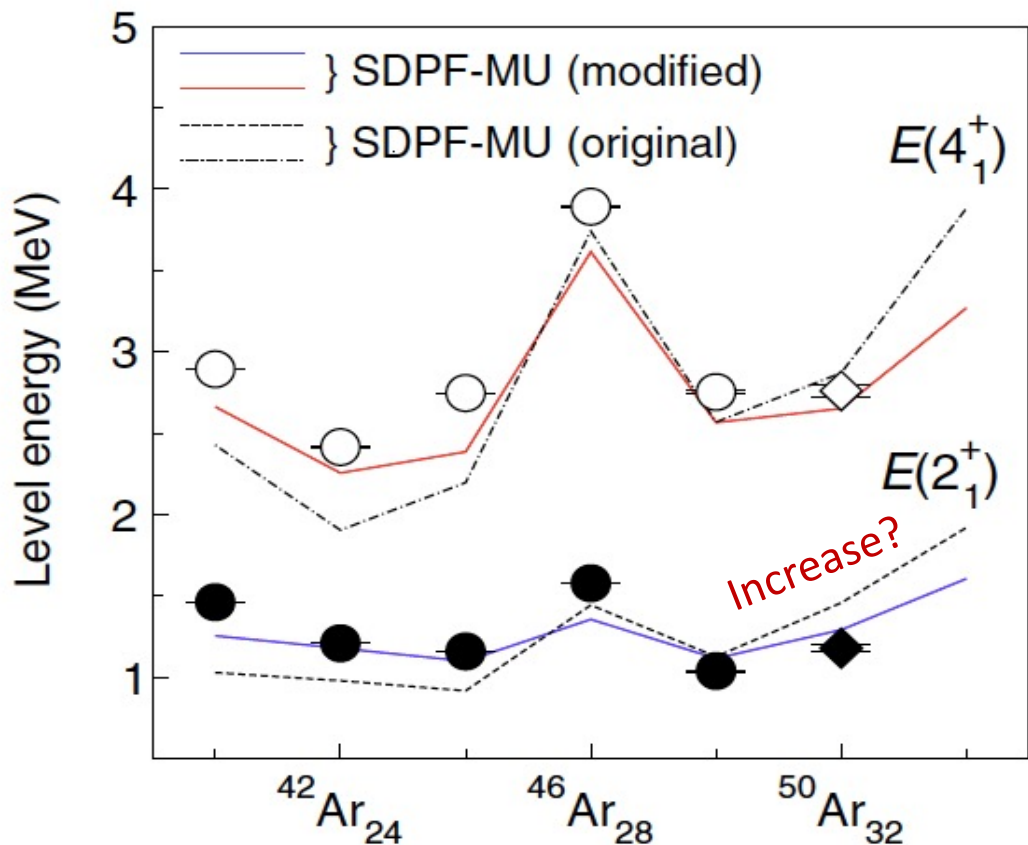


Z=20 存在显著的N=34 的亚壳结构

N = 34 亚壳结构在 Z < 20 区域如何演化?

Shell gaps predicted by SDPF-MU

| | Ti | Ca | Ar |
|--------|----------|----------|----------|
| N = 32 | 2.54 MeV | 2.43 MeV | 2.27 MeV |
| N = 34 | 1.77 MeV | 2.64 MeV | 3.13 MeV |



Y. Utsuno et al, JPS Conf. Proc. 6, 010007 (2015).

D. S. et al., PRL 114, 252501 (2015)

^{52}Ar (Z=18, N=34) 是目前实验上可测得的最丰中子的原子核。

证实 ^{52}Ar 中 $N = 34$ 的亚壳结构

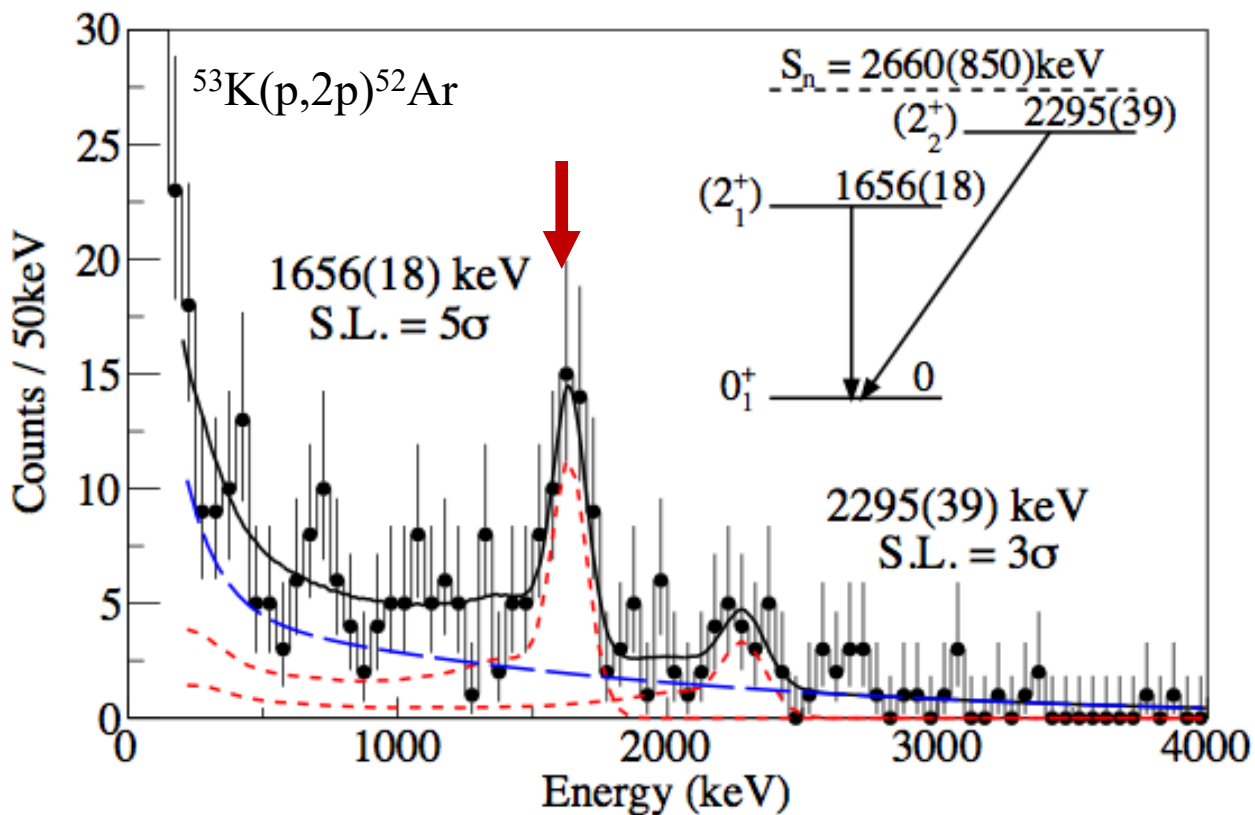


^{70}Zn beam 345MeV/u 200~250pnA

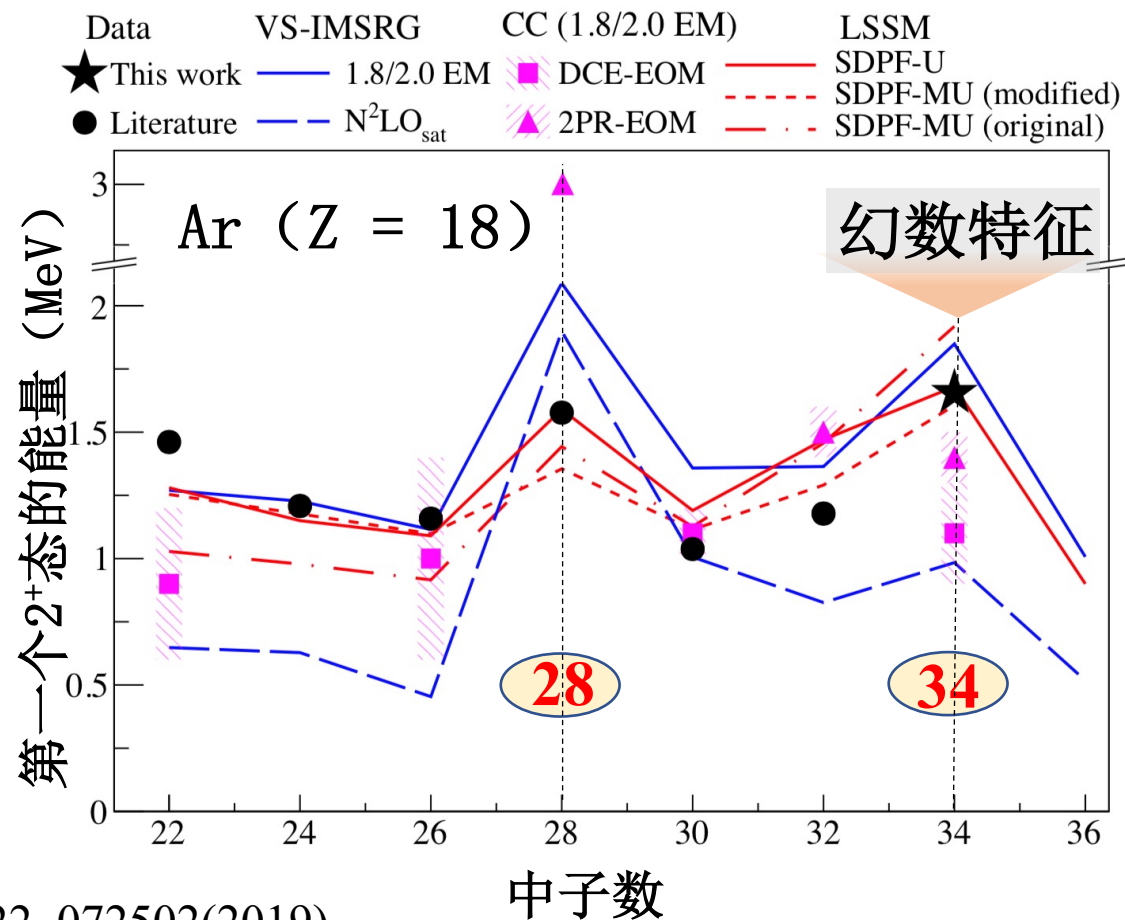
^{53}K intensity: 1.0 pps

150 mm MINOS LH2 target

7 day beam time: 438 counts of ^{52}Ar



- 首次发现在 $Z < 20$ 的区域中 $N=34$ 作为新幻数的实验证据
- 对使用现实核力的最先进的核结构模型进行了有效检验



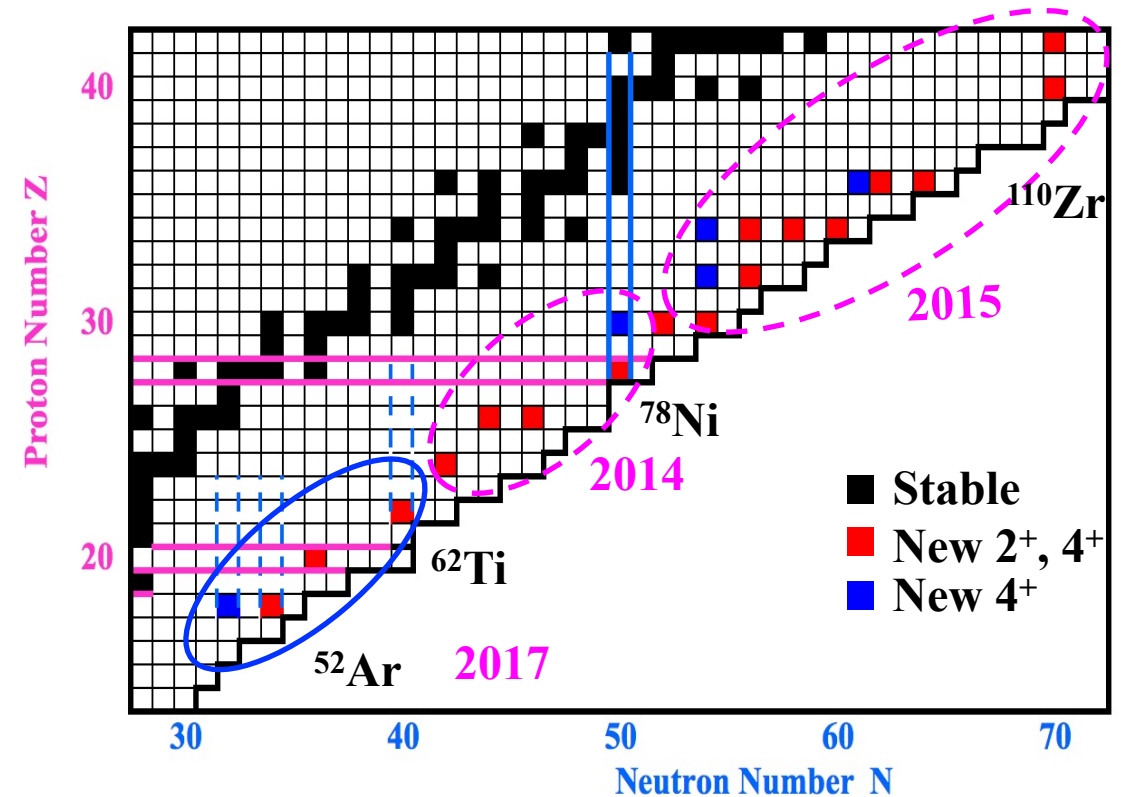
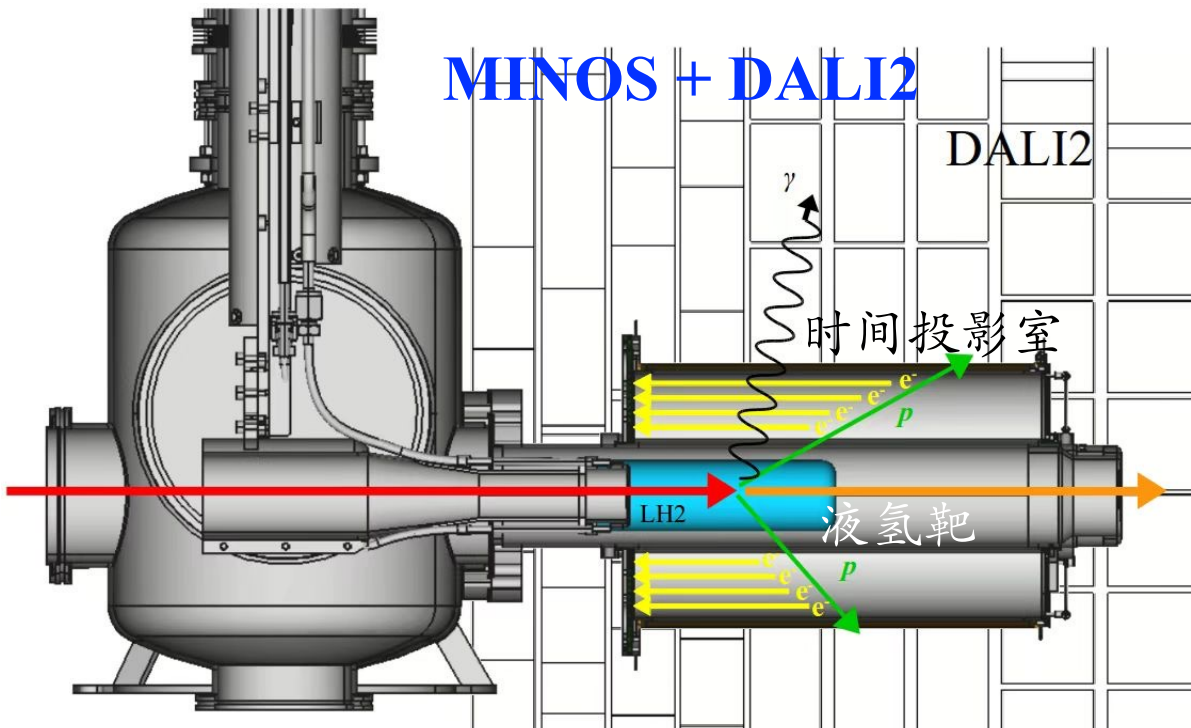
H.N. Liu* et al., PRL 122, 072502(2019)

MINOS的成功

MINOS: 15cm的超厚液氢靶 + TPC径迹探测器 (可重建反应点)

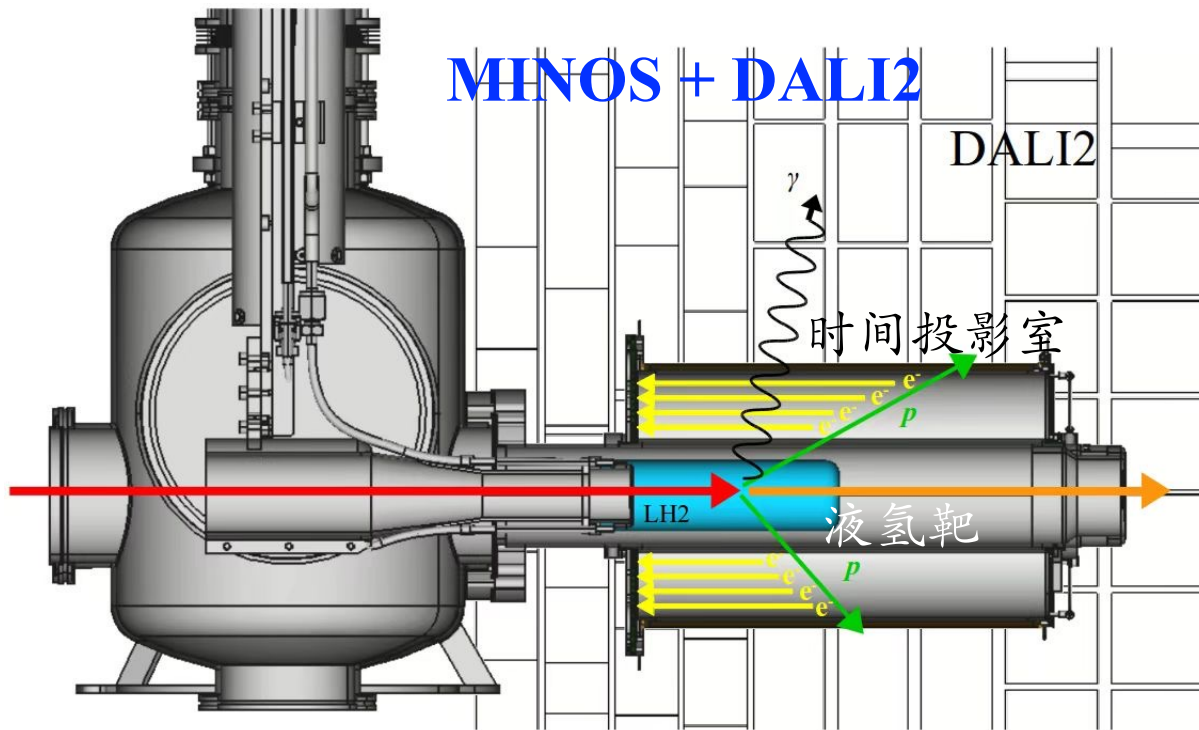
可将统计提高5~10倍, 从而允许测量极丰中子原子核的 $E(2^+)$

Three SEASTAR Campaigns

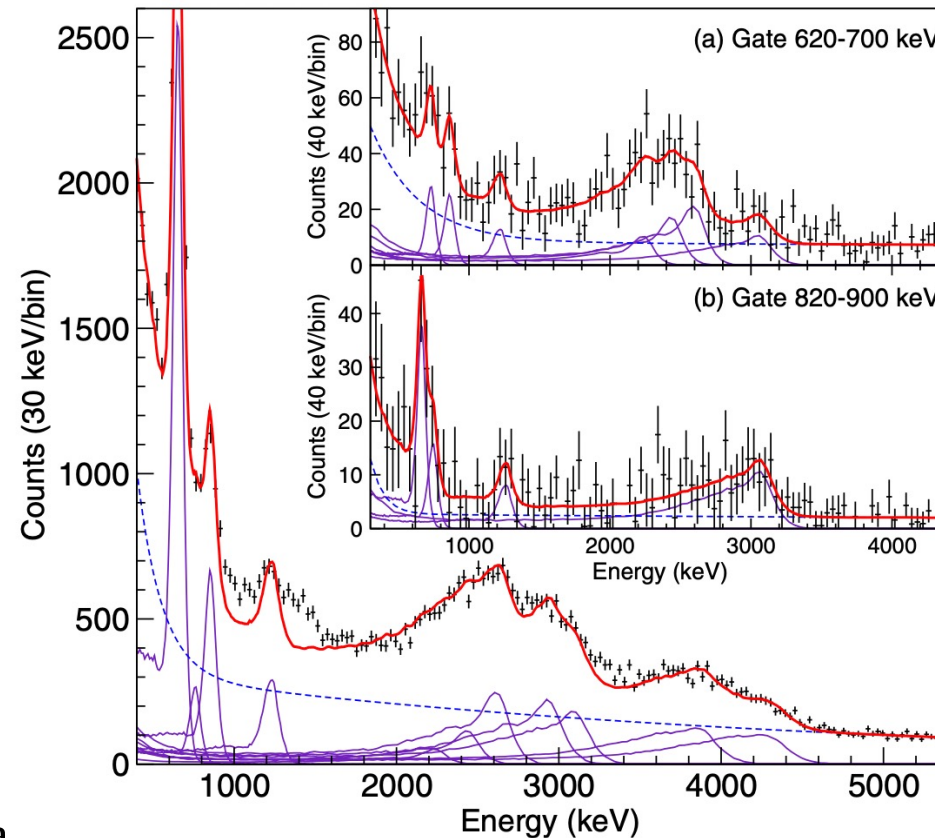


截至目前为止发表28篇文章, 包括1篇Nature, 10篇PRL, 5篇PLB

MINOS+DALI2的局限性



$^{80}\text{Zn}(p,2p)^{79}\text{Cu}$



❖ **Moderate Vertex resolution:** 4.5 mm (FWHM)

❖ **Passive Materials:** Target radius: 26 mm / 2mm Al cha

MINOS的局限性:

1. 在束伽玛谱学分辨率: 10% (FWHM) at 1 MeV
2. 缺失质量谱学分辨率: Not usable (6MeV in σ)

新装置STRASSE

→ 1% ?

→ 1-2 MeV

STRASSE 装置

H. N. Liu* et al., arXiv:2301.09276 (submitted to EPJA).



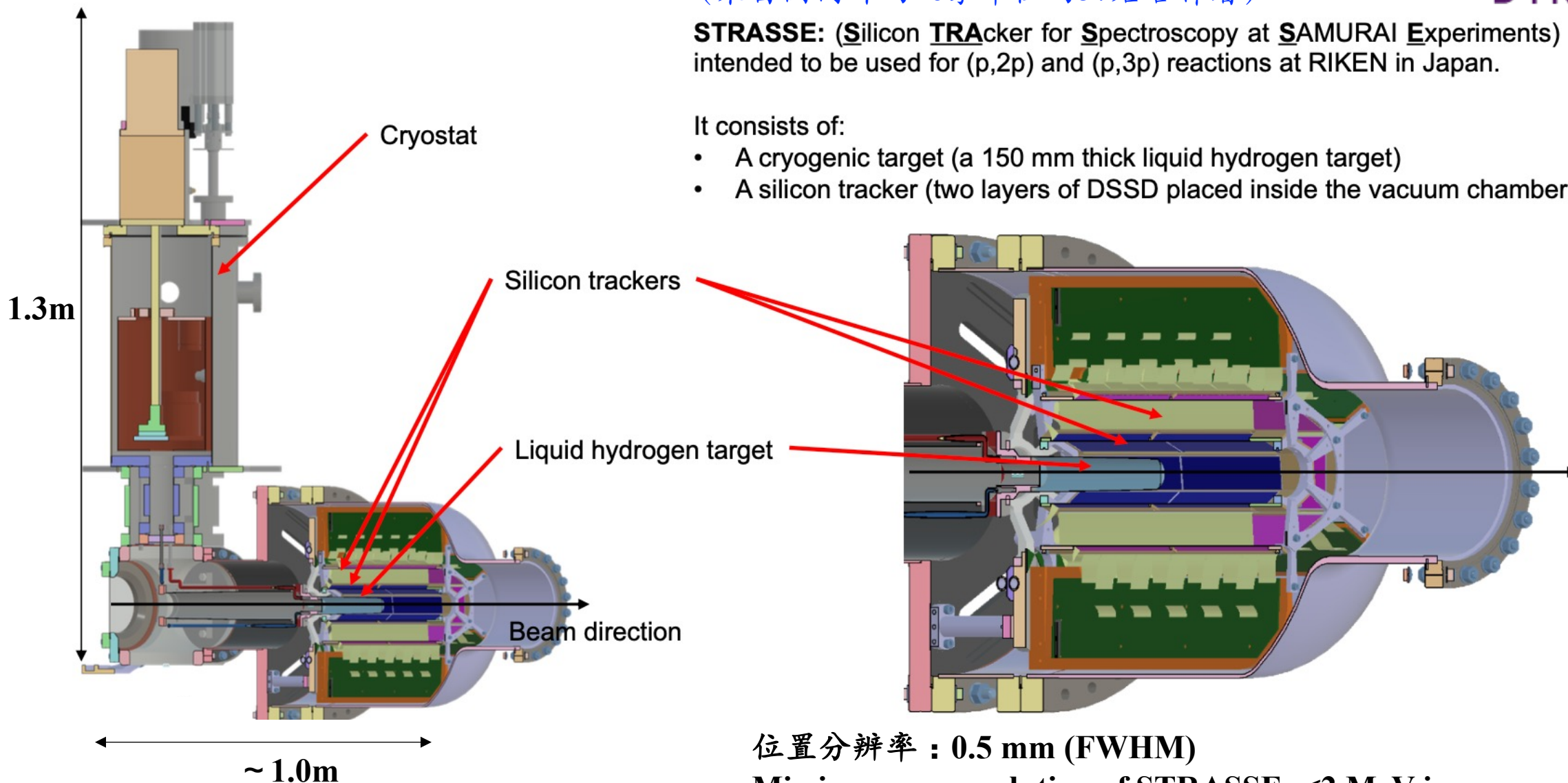
STRASSE

(来自国内外的16家单位的57名合作者)

STRASSE: (**S**ilicon **T**Racker for **S**pectroscopy at **S**AMURAI **E**xperiments) is a device intended to be used for (p,2p) and (p,3p) reactions at RIKEN in Japan.

It consists of:

- A cryogenic target (a 150 mm thick liquid hydrogen target)
- A silicon tracker (two layers of DSSD placed inside the vacuum chamber)

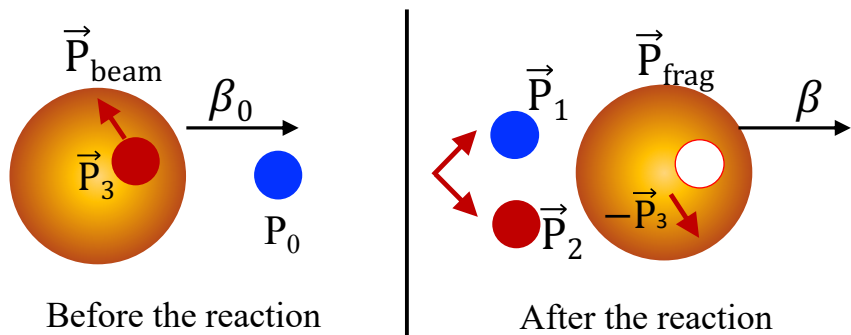


位置分辨率 : 0.5 mm (FWHM)

Missing-mass resolution of STRASSE: < 2 MeV in σ

国内发展的新机遇

质子靶：结构简单，可对反应末态进行全举测量



束流能量: 150 MeV/u~1 GeV/u, 厚靶

用途广泛:

$(p, 2p), (p, pn)$: 核结构和敲出反应机制

R. Taniuchi et al., Nature 569, 53 (2019).

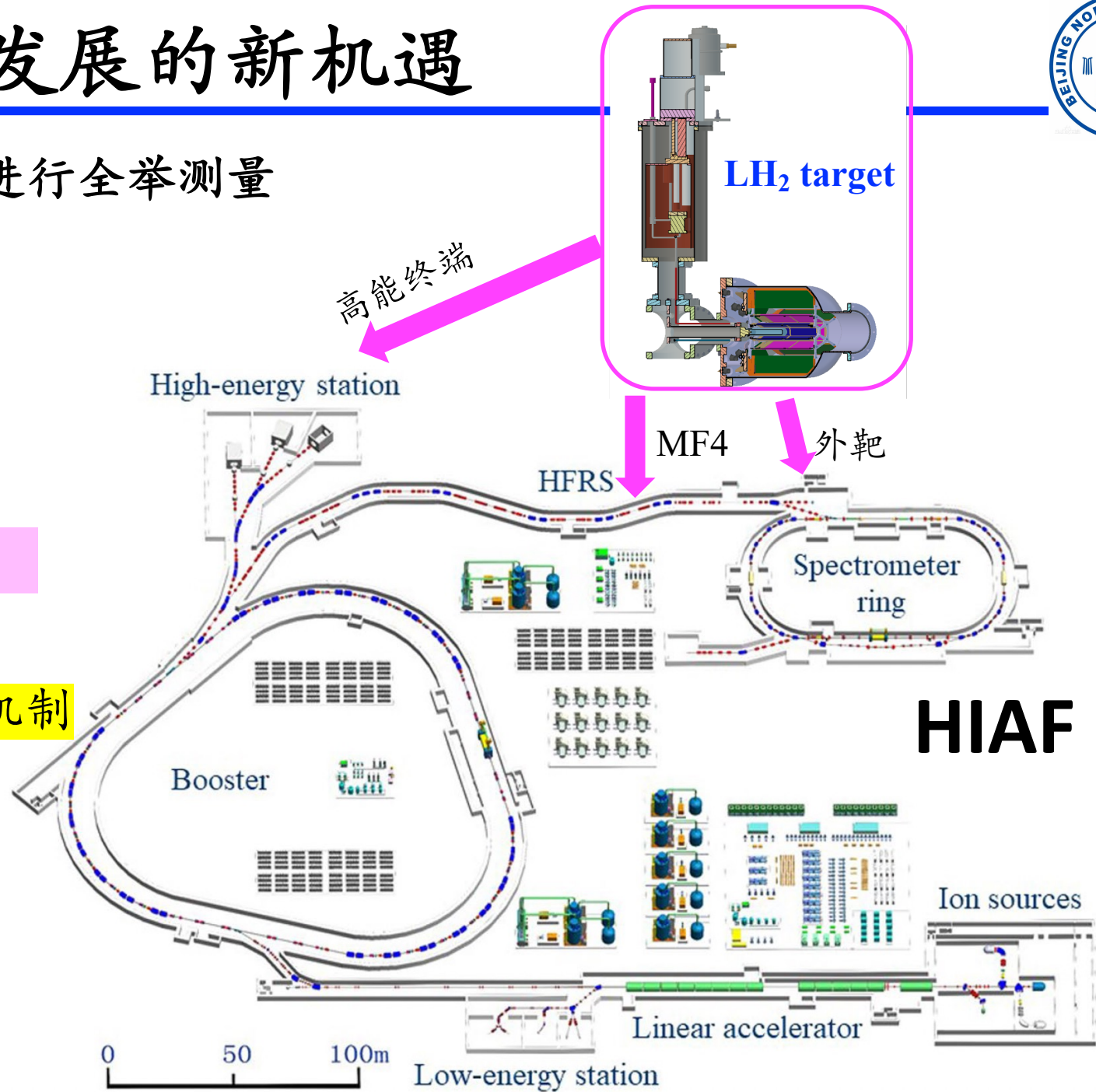
T. Pohl, Y. L. Sun* et al, PRL (accepted).

$(p, p\alpha)$: 集团结构

J. Tanaka et al., Science 371,260 (2021).

$(p, 2pn), (p, pd)$: 核子短程关联

M. Patsyuk et al. Nature Physics 17, 693 (2021).



HIAF

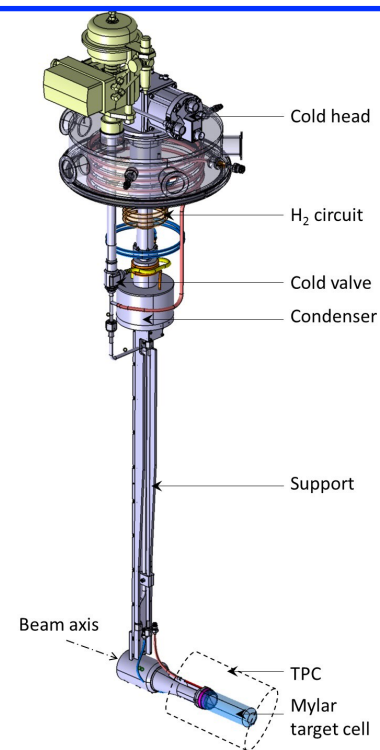
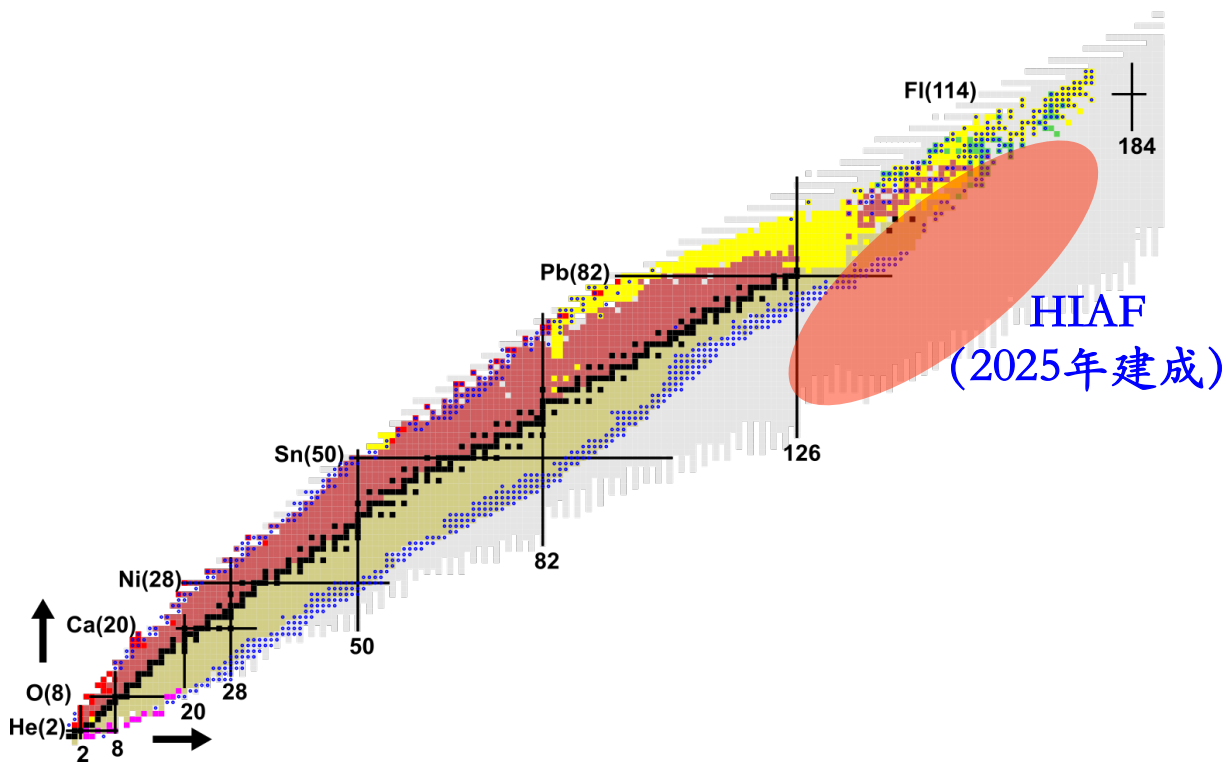
总结和展望

总结

- 物理研究：利用超厚液氢靶在日本理化所开展了丰中子Ca区域在 $N = 32, 34$ 以朝向 $N = 40$ 的壳演化研究。
- 设备建设：牵头（来自国内外的16家单位的57名合作者）开发新一代的核谱学装置STRASSE。

展望

- 物理研究：依托国内外大科学装置，持续开展不同核区奇特核结构的研究。依托兰州的外靶装置开展直接核反应机制的研究。
- 设备建设：开发适合国内束流线的液氢靶装置。



谢谢!