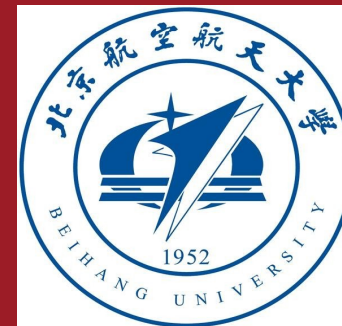


基于 (p, pN) 单核子移除反应的原子核结构研究



孙叶磊

北京航空航天大学物理学院

报告提纲

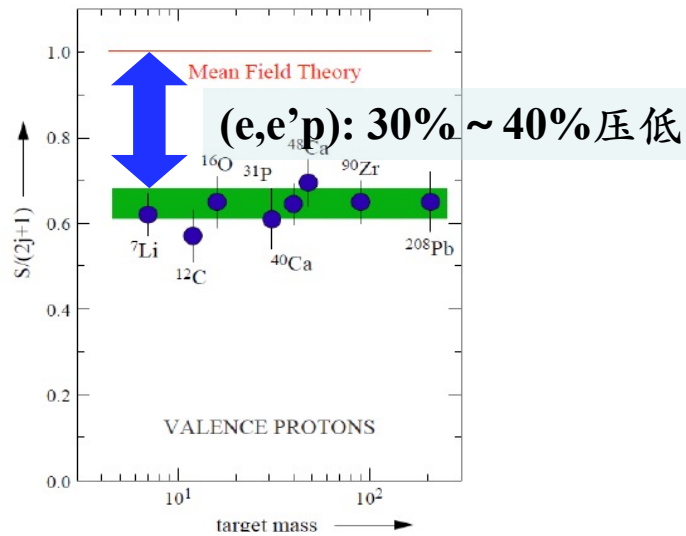
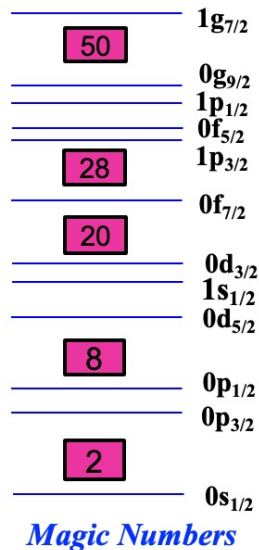
1. 核子-核子关联
2. 单核子移除反应——谱因子压低之“谜”
3. $\sim 100 \text{ MeV/u}$ (p, pN) 单核子移除的多重机制 $\square^{14}\text{O}(p, pN)^{13}\text{N}/^{13}\text{O}$
 $\sim 100 \text{ MeV/u}$
4. (p, pN) 准自由敲出反应的一些最新进展
 $\square^{52,54}\text{Ca}(p, 2p)^{51,53}\text{K}$
 $\square^{52,54}\text{Ca}(p, pn)^{51,53}\text{Ca}$
 $\square^{11}\text{Li}(p, pn)^{10}\text{Li}$
 $\square^{11}\text{Li}(p, 2p)^{10}\text{He}$
 $\sim 250 \text{ MeV/u}$
5. 总结和展望

核子-核子关联

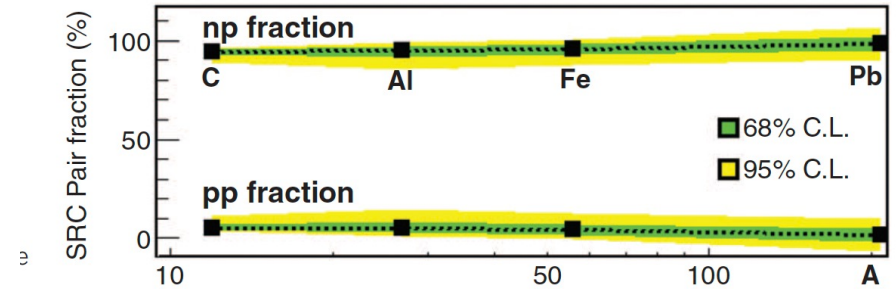
$$H = \sum_i \left[\frac{\vec{p}_i^2}{2m} + U(\vec{r}_i) \right] + \left[\sum_{i<j} V_{NN}(\vec{r}_i - \vec{r}_j) - \sum_i U(\vec{r}_i) \right] = H^{(0)} + H^{(1)}$$

“Shells” are not fully occupied due to “correlations” : LRC (几个费米) + SRC (1fm, np dominated)

IPM model → 平均场、壳结构、幻数…
(Mayer and Jensen 1963 Nobel Prize)



G. J. Kramer *et al.*, NPA 553, 297c(1993).

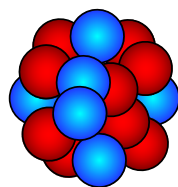


O. Hen, *et al.*, Science 346, 614 (2014)

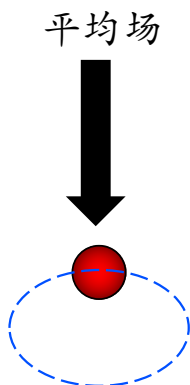
- 稳定核: 核子~2/3概率作独立粒子运动
- ~20% -长程关联; ~15% - 短程关联SRC;
- SRC 95% 是np对

核子-核子关联

- 稳定核: 核子~2/3概率作独立粒子运动
- 20% -长程关联; 15% -短程关联SRC;

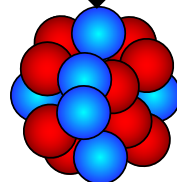


=



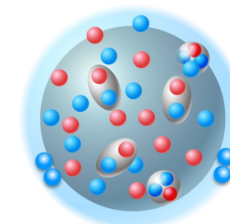
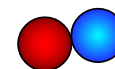
剩余相互作用

LRC



eg. L=0呼吸模式

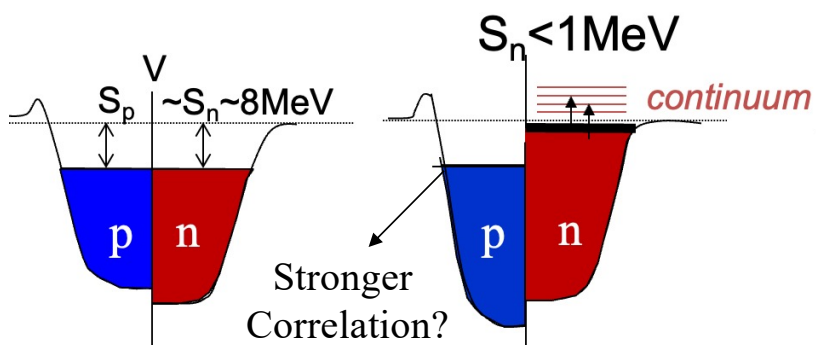
SRC



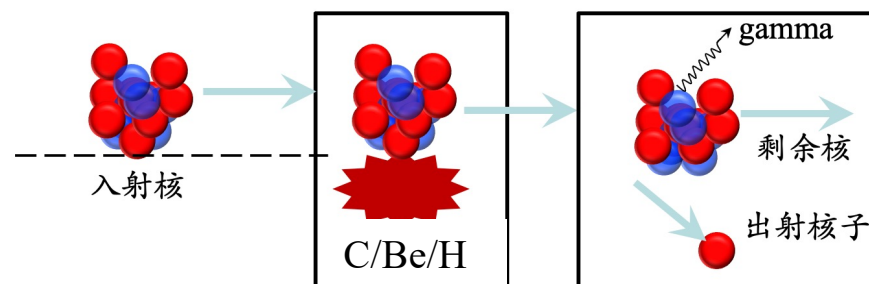
+ 集团结构?

表现形式	独立粒子运动 ~65%	几fm pair ~20%	1 fm pair ~25%	d/t/3He/4He ~? %
实验证据	壳结构、幻数	振动、转动、巨共振...	高动量成分, np 主导	α decay...
实验手段	(e,e'p)、(p,2p)、(d,p)..	(p, p'), Coulomb breakup...	(e,e'pn)、(p, 2pn)..	(p, p α)...

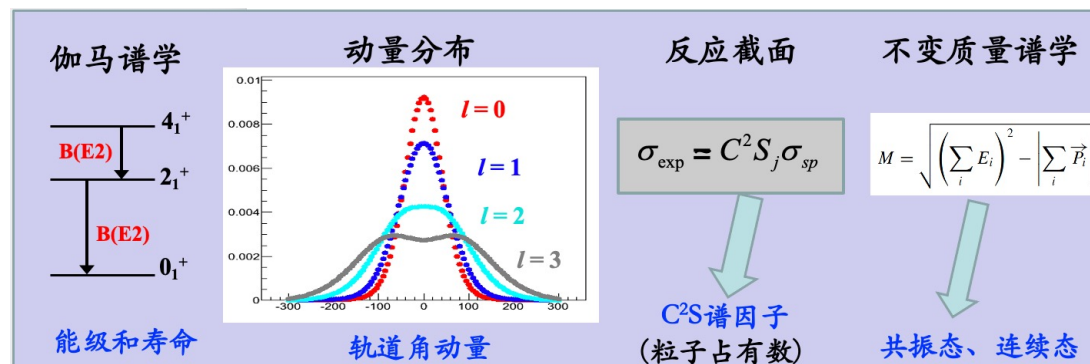
核子-核子关联



研究方法-单核子移除反应



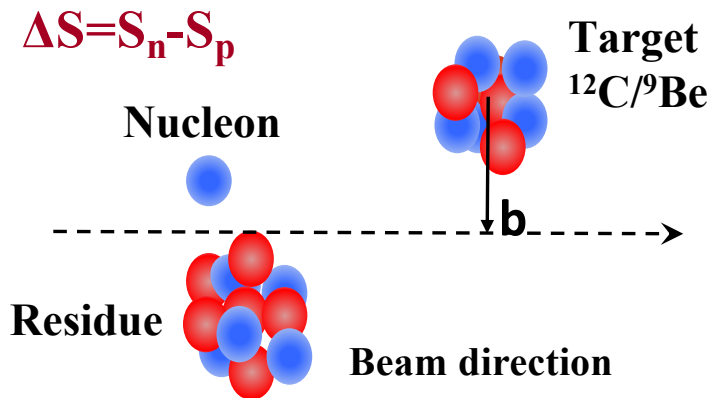
- 稳定核: 核子~2/3概率作独立粒子运动
- ~20% -长程关联; ~15% - 短程关联SRC;
- SRC 95% 是np对
- 不稳定核的图像还是不是这样? ?



核子关联对质子-中子不对称性的依赖

A. 敲出反应

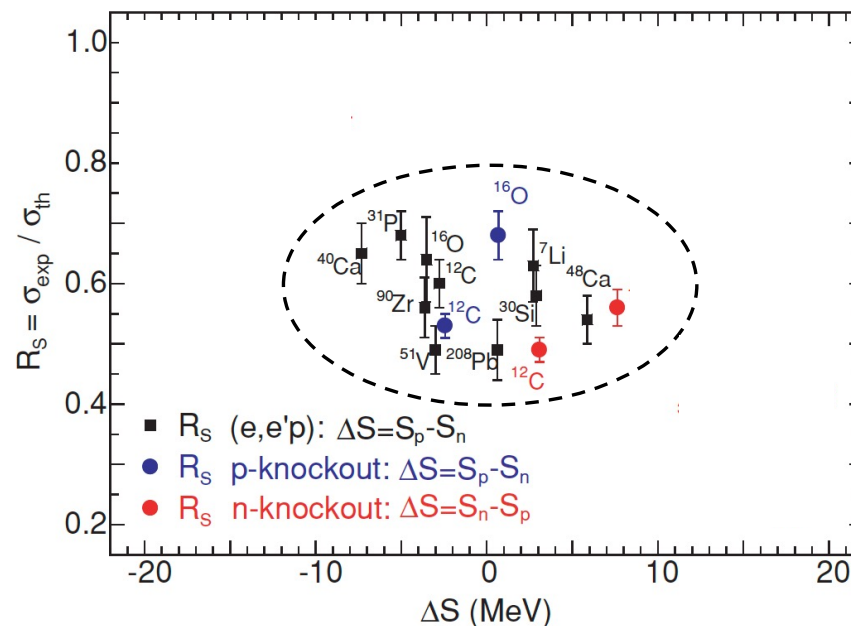
约化因子 $R_S = \sigma_{\text{exp}} / \sigma_{\text{th}}$ 表征核子-核子关联在理论中的缺失



□ Stable nuclei: heavy-ion induced knockout reactions get consistent results with $(e, e'p)$

B.A. Brown *et al.*, PRC, 65, 061601 (2002)

A. Gade *et al.*, Phys. Rev. C 77, 044306 (2008)

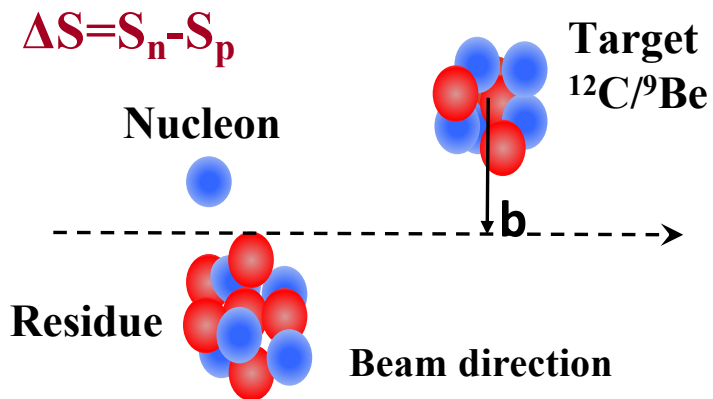


核子关联对质子-中子不对称性的依赖

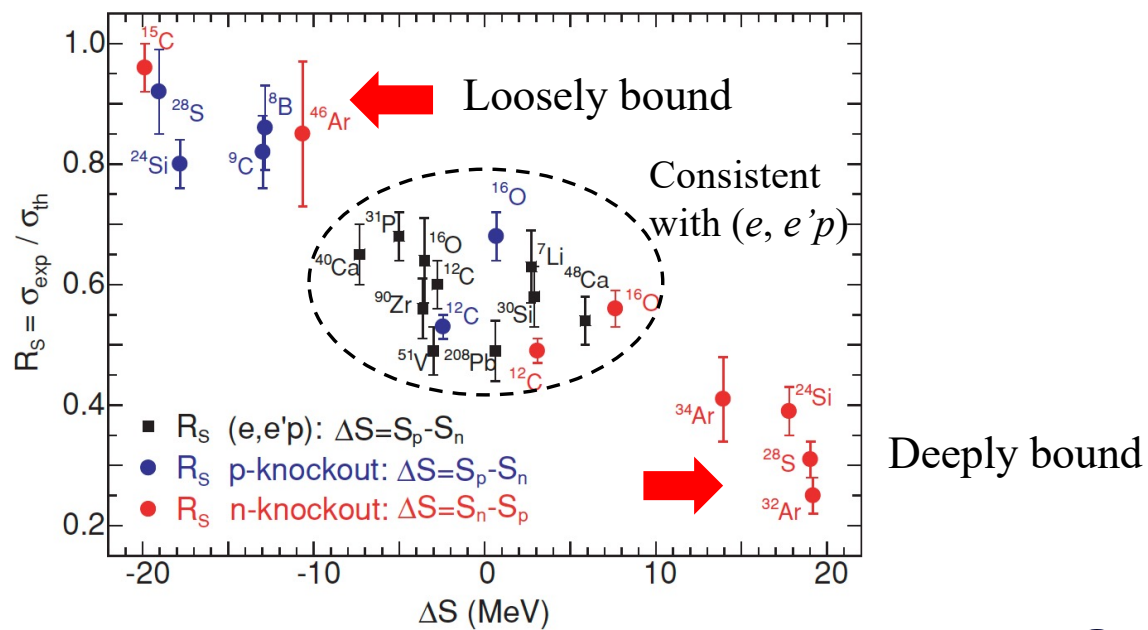
A. 敲出反应

约化因子 $R_s = \sigma_{\text{exp}} / \sigma_{\text{th}}$

A. Gade et al., PRL 94, 042501 (2004); PRC77, 044306 (2008)



✓ R_s 强烈依赖于质子-中子不对称性
 $\Delta S = S_p - S_n$ (-p) or $S_n - S_p$ (-n)

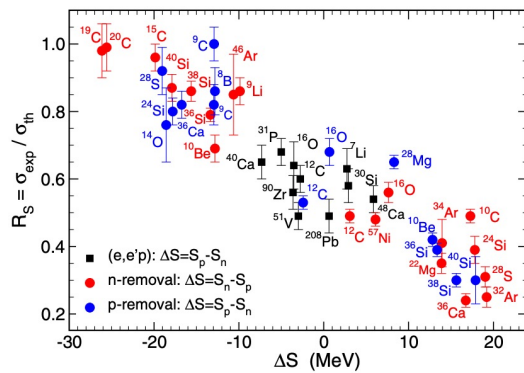


→ 弱束缚核子关联更弱? 深束缚核子关联更强? (关联 beyond shell-model : SRC)

核子关联对质子-中子不对称性的依赖

A. 敲出反应 约化因子 $R_S = \sigma_{\text{exp}} / \sigma_{\text{th}}$

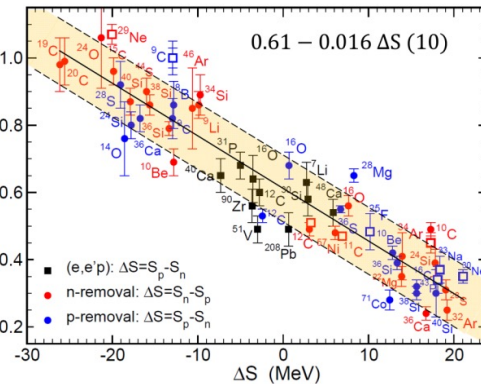
80–100 MeV/nucleon



J. A. Tostevin *et al.*, PRC **90**, 057602 (2014)

$^{19,20}\text{C}(-n)$, 240 MeV/nucleon

$^{14}\text{O}(-p)$, 305 MeV/nucleon



J. A. Tostevin *et al.*, PRC **103**, 054610 (2021)

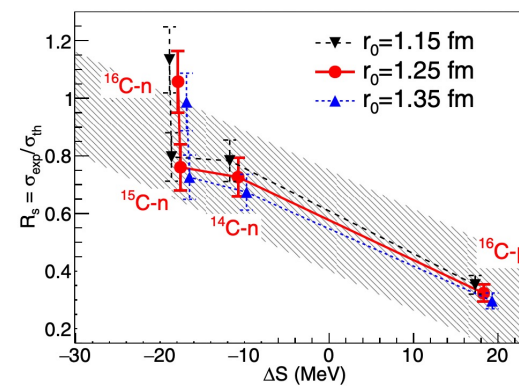
220–240 MeV/nucleon:

$^{29}\text{Ne}(-n)$, $^{25}\text{F}(-p)$, $^{16}\text{C}(-p)$, $^{30}\text{Ne}(-p)$, $^{33}\text{Na}(-p)$,

1.6 GeV/nucleon:

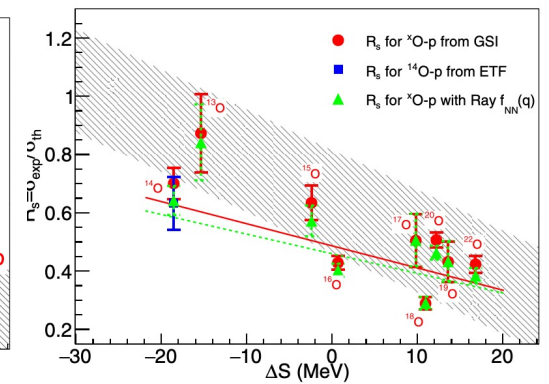
$\text{C}(-p)$, $^{12}\text{C}(-n)$, $^{11}\text{C}(-n)$, and $^{10}\text{C}(-n)$

RIBLL2 data



Y. Z. Sun *et al.*, PRC **104**, 014310 (2021)

240 MeV/nucleon



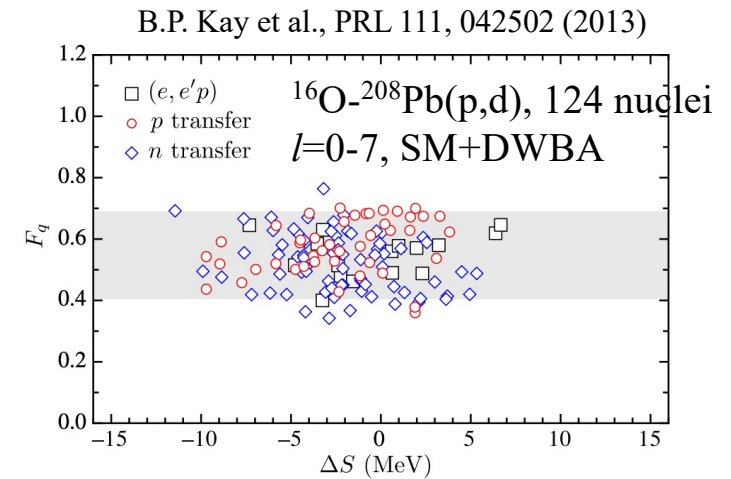
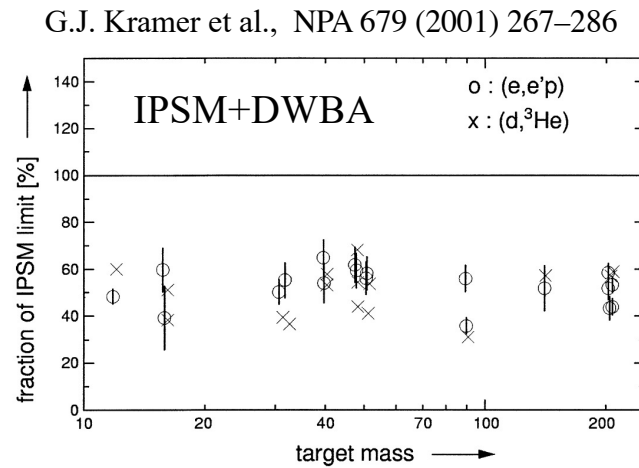
Y. Z. Sun *et al.*, PRC **106**, 034614 (2022)

305–635 MeV/nucleon

The strong dependence is robust with beam energy

核子关联对质子-中子不对称性的依赖

B. 低能区转移反应
(d, ^3He) / (p, d) 等
Many stable beam
facilities



□ Stable nuclei: p/n transfer reactions get consistent results with (e, e'p)

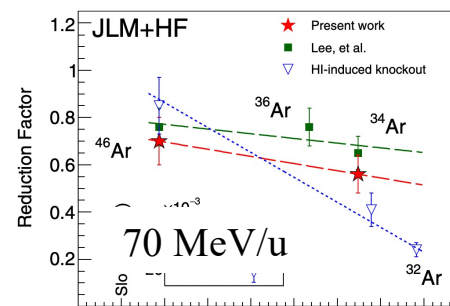
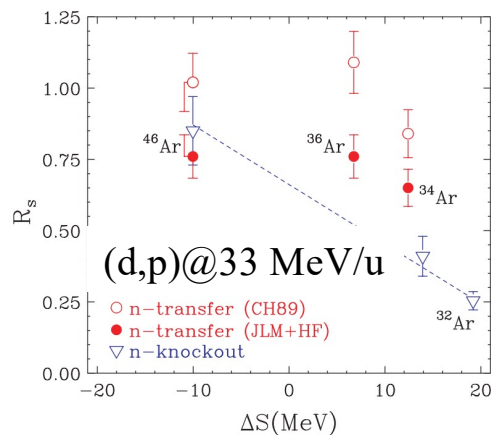
核子关联对质子-中子不对称性的依赖

J. Lee et al, PRL 104, 112701 (2010)

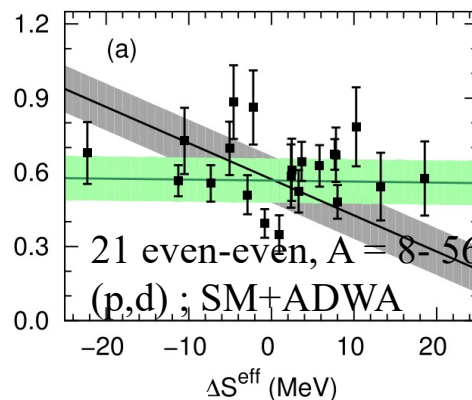
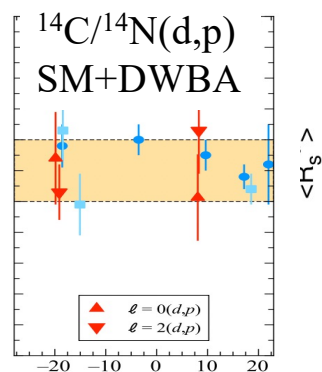
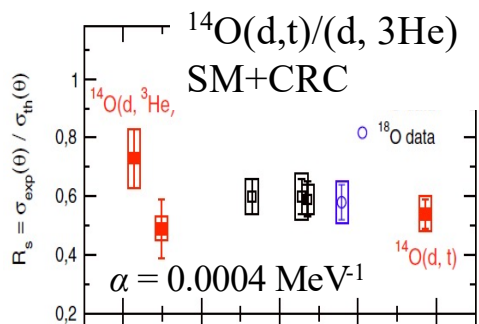
J. Manfredi et al., PRC 104, 024608 (2021)

10~30MeV/u

B. 低能区转移反应
(p,d)/(d,p)/(d,t)等
MSU&GANIL&ANL



SM+ADWA



Weak ΔS dependence from transfer reaction!
Robust with reaction models: DWBA/ADWA/CRC

Y.P. Xu et al., PLB 790, 308 (2019)

F. Flavigny et al., RPL 110, 122503 (2013)

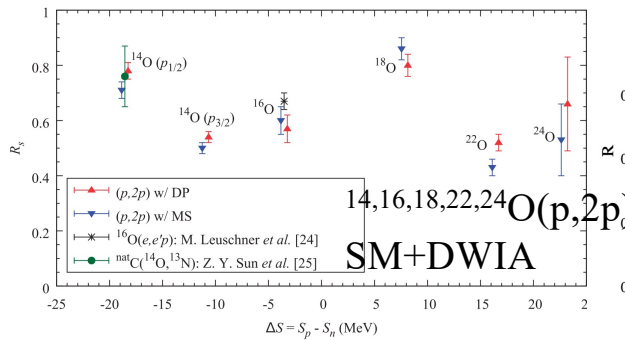
B.P. Kay et al., PRL 129, 152501 (2022)

核子关联对质子-中子不对称性的依赖

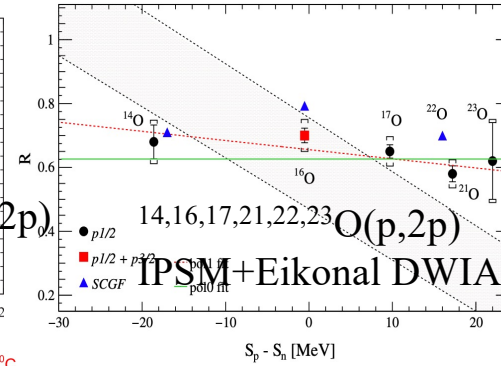
200/250/300~450MeV/u

C. 高能区准自由
敲出反应(p, pN)
RIKEN&RCNP
&GSI

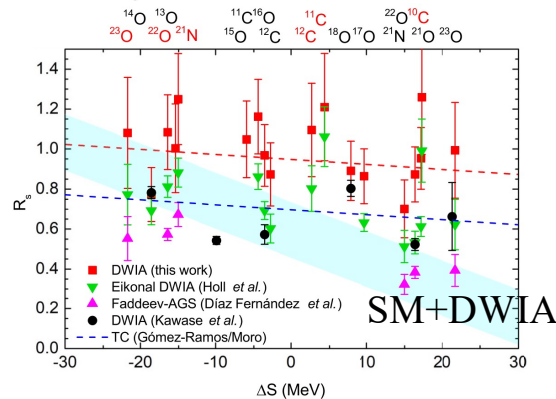
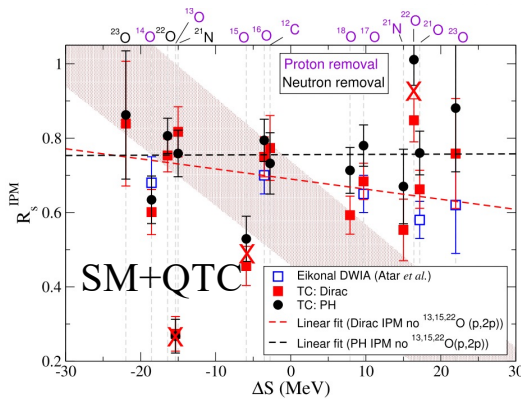
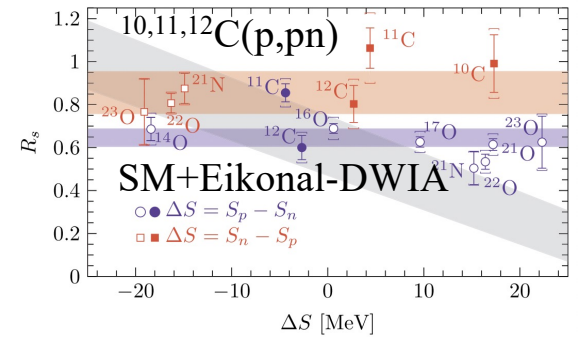
S. Kawase et al., PTEP 2018 (2018)



L. Atar et al., PRL 120, 052501 (2018)



M. Holl et al., PLB 795, 682 (2019)



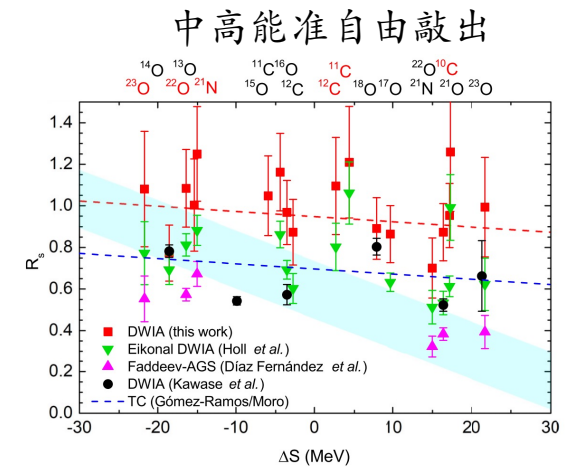
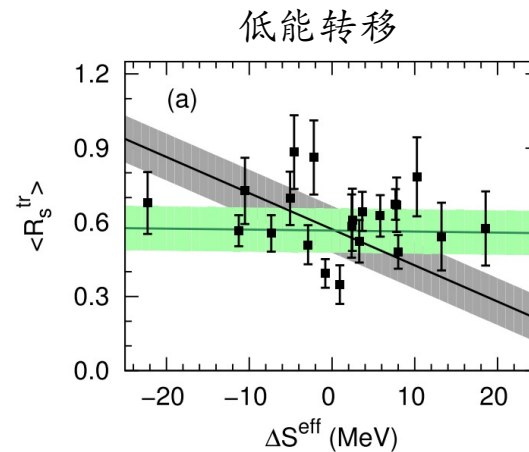
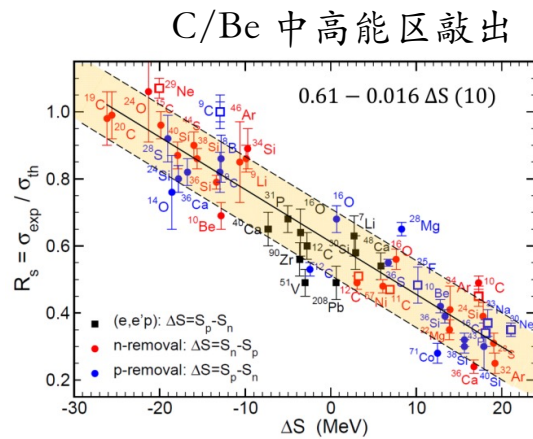
Weak ΔS dependence from (p,pN)
Robust with reaction models:
DWIA/Eikonal-DWIA/QTC/Faddeev-AGS

M. Gómez-Ramos et al., PLB 785, 511 (2018)

N. Phuc et al., PRC 100, 064604 (2019)

核子关联对质子-中子不对称性的依赖

□ 谱因子压低之“谜”，不同实验手段发现 R_s (核子关联)有不同的 ΔS 依赖

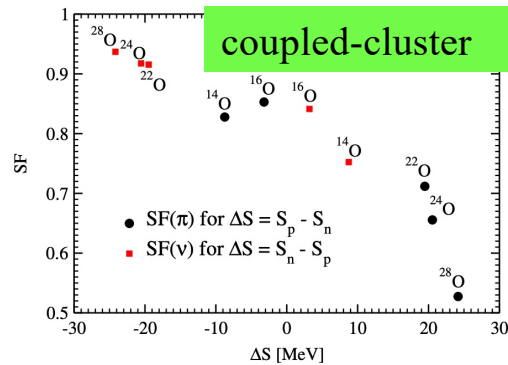


□ We do not have a consistent picture for unstable nuclei.....
Which picture is correct?

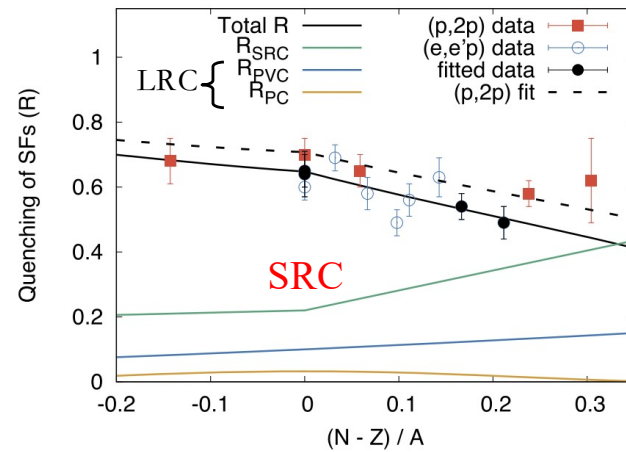


核子关联对质子-中子不对称性的依赖

Ø. Jensen et al., PRL 107, 032501 (2011)

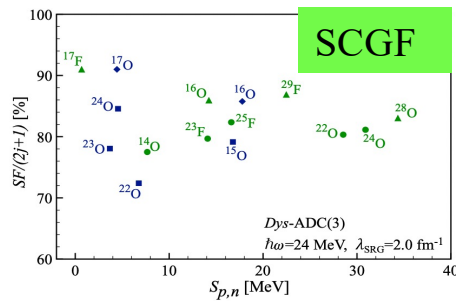


S. Paschalis et al. PLB 800,135110 (2020)



Weak dependence due to SRC fraction increase for minority nucleon

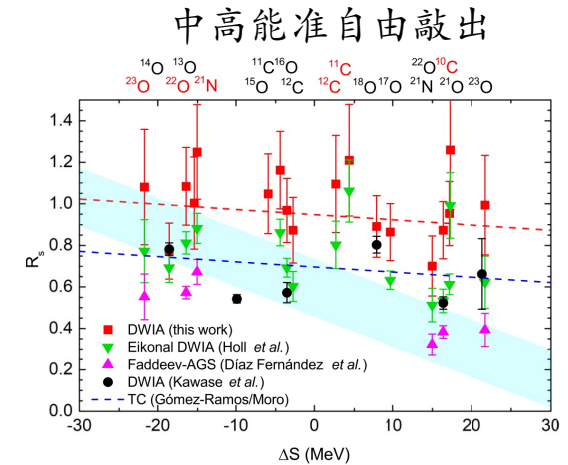
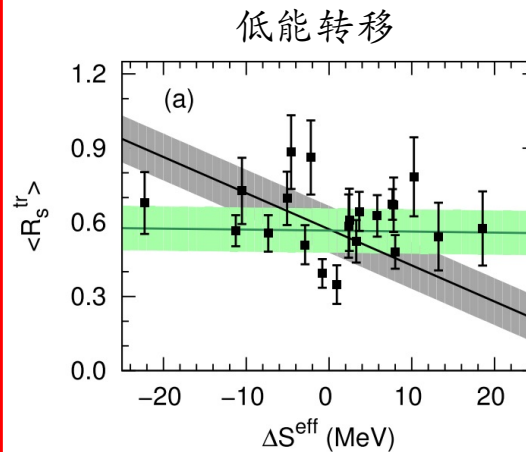
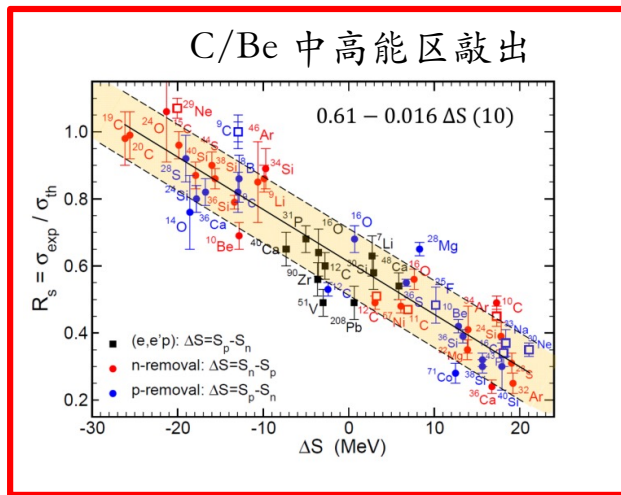
A. Cipollone et al., PRC 92, 014306 (2015)



Weak $\Delta S/p$ -n asymmetry dependence from *ab initio* theories
Weak $\Delta S/p$ -n asymmetry dependence from a recent phenomenological analysis

核子关联对质子-中子不对称性的依赖

□ 谱因子压低之“谜”，不同实验手段发现 R_s (核子关联)有不同的 ΔS 依赖



□ We do not have a consistent picture for unstable nuclei.....

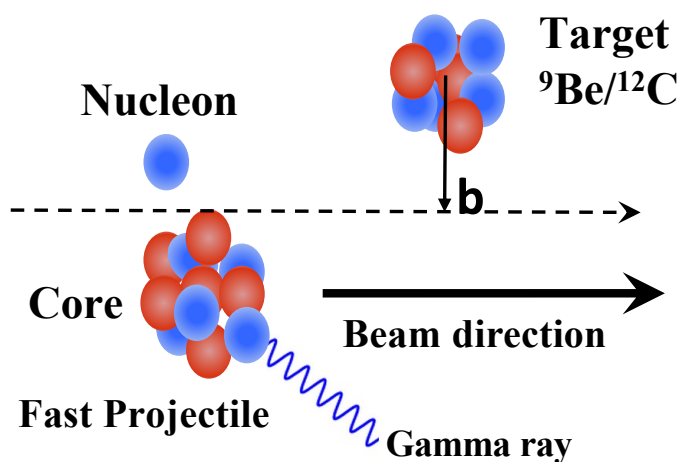
Which picture is correct?

What could be the problem(s)? → 结构模型问题? 反应模型问题?



$$R_s = \sigma_{\text{exp}} / \sigma_{\text{th}}$$

描述敲出反应的Eikonal模型

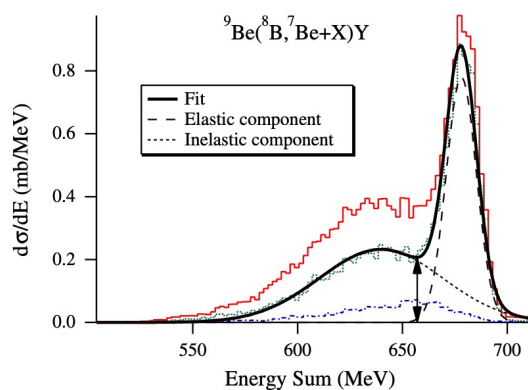


高能下的近似 ($E > 50$ MeV/nucleon),
 反应中剩余核当作“旁观者”:
 □ 绝热近似: 忽略核芯激发
 □ 直线近似: 简化散射矩阵计算

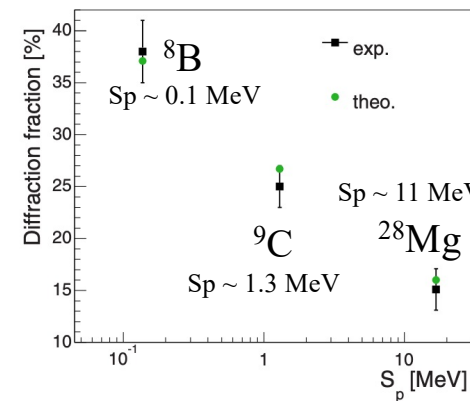
$$\sigma_{th} = \sum_j \left(\frac{A}{A-1} \right)^N C^2 S_{SM}(\alpha, nlj) \sigma_{sp}(nlj, S_\alpha^*)$$

$$\sigma_{sp} = \sigma_{str} + \sigma_{dif} + \sigma_C$$

J. A. Tostevin *et al.*, Nuclear Physics A682 320c(2001).

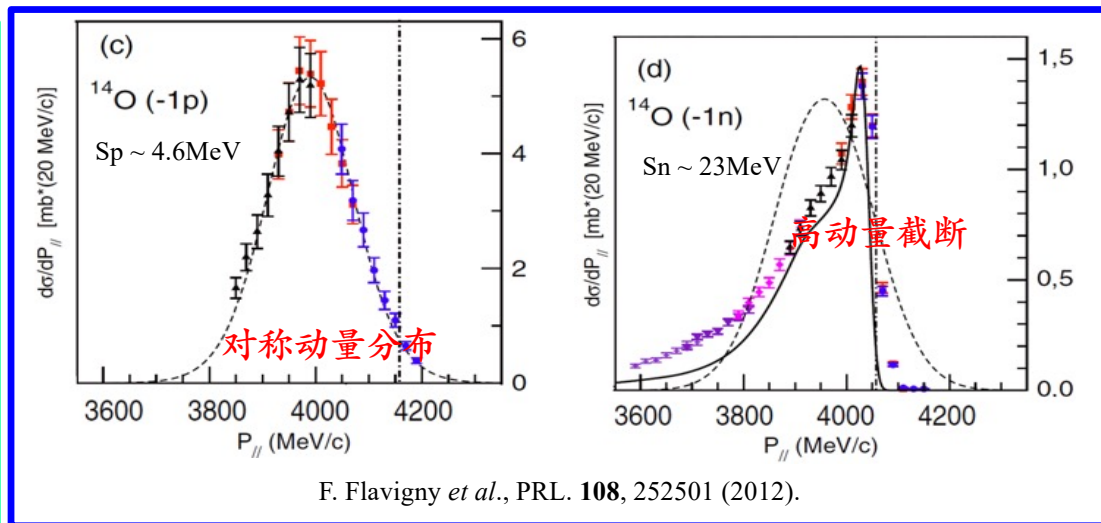
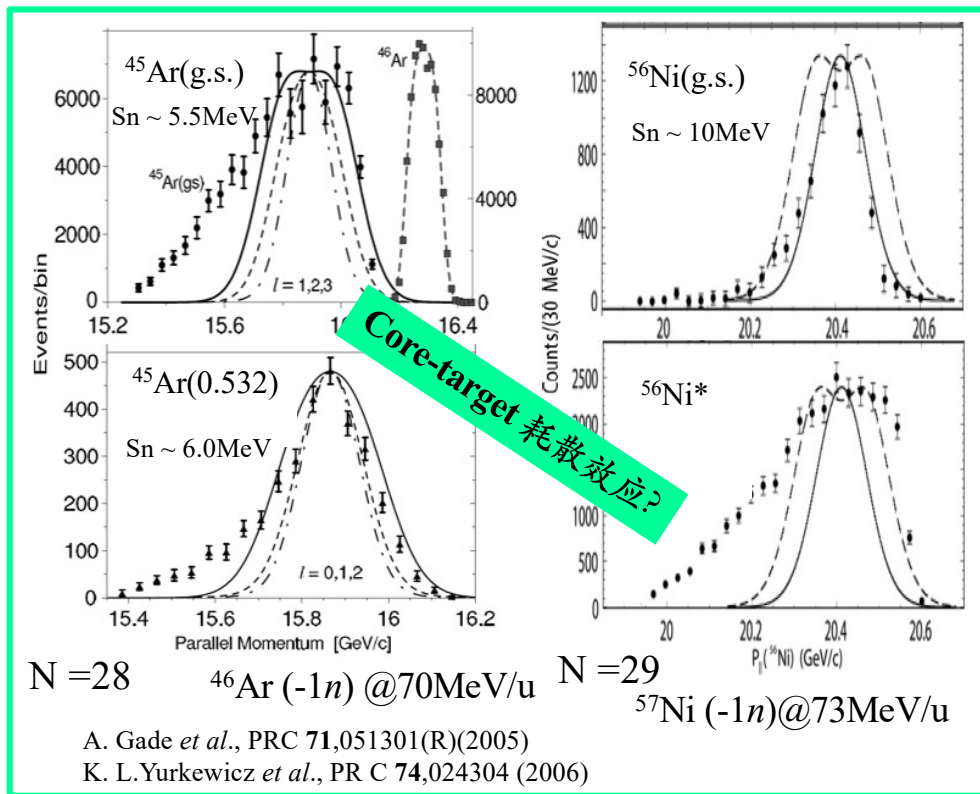


D. Bazin *et al.*, PRL 102, 232501 (2009)



K. Wimmer *et al.*, PRC 90, 064615 (2014)

Eikonal模型失效的一些例子



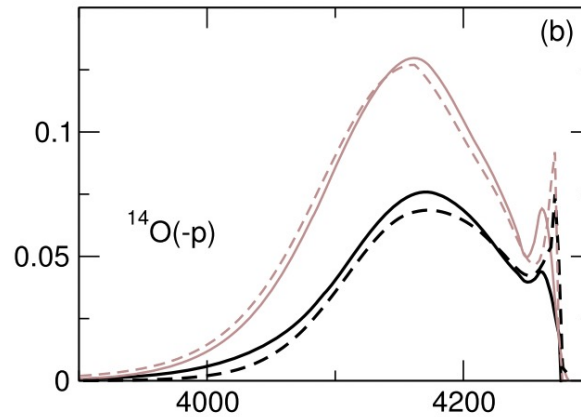
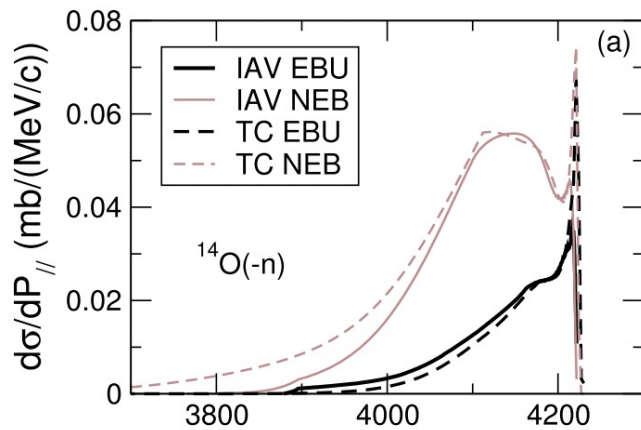
$^{14}\text{O}+^9\text{Be}$ @53MeV/u

→有些情况剩余核不能当作“旁观者”
→Eikonal 近似违反能动量守恒

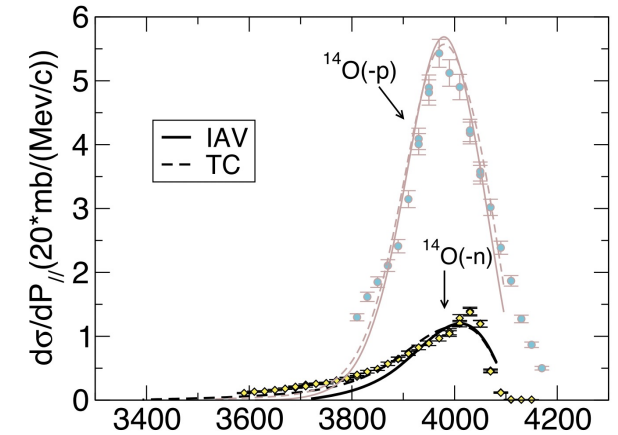


TC and IAV 模型

□ 仍然使用绝热近似；遵守能-动量守恒



卷积实验
分辨率

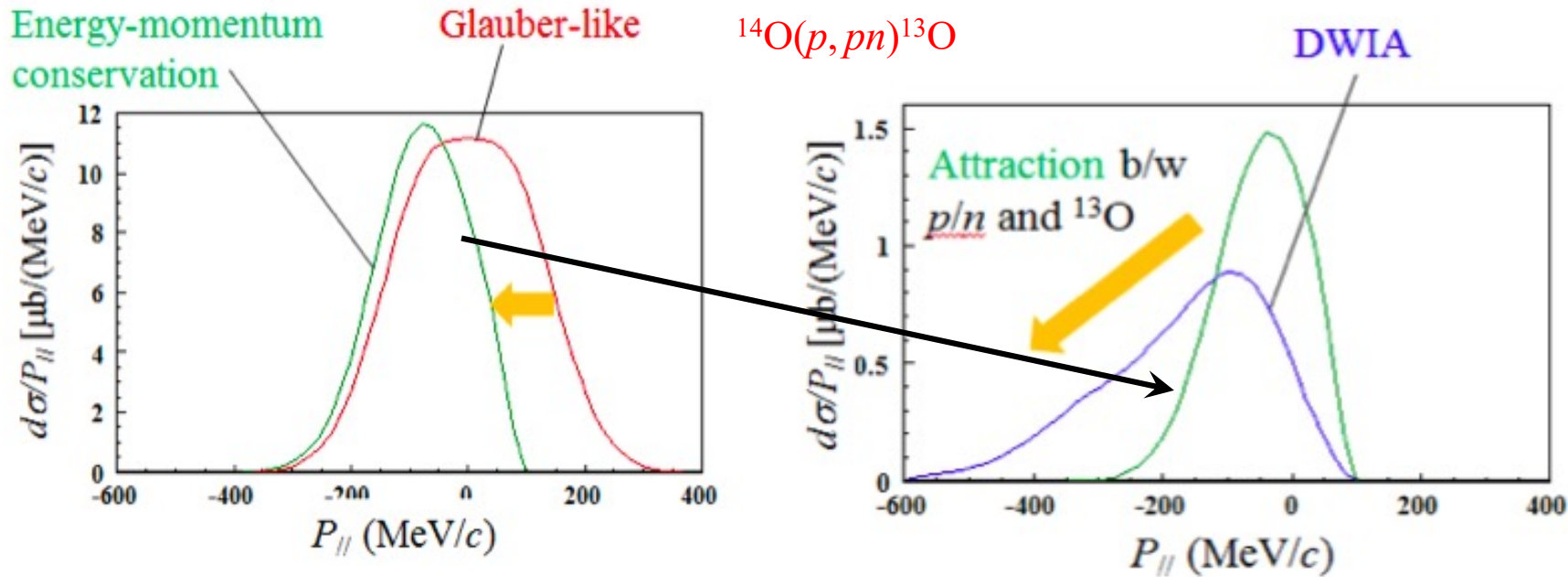


$^{14}\text{O}+^9\text{Be}@53\text{MeV}/u$

	$S_{n(p)}$	nlj	C_i	σ_{IAV}	σ_{TC}	C^2S	σ_{eik}	σ_{exp}	R_f
$^{14}\text{O}(-n)$	23.12	$1p_{3/2}$	17.74	TOT	13.72 (6.86)	3.15	54(0.26)	14	0.3 (0.65)
				EBU	3.55				
				NEB	10.17				
$^{14}\text{O}(-p)$	4.63	$1p_{1/2}$	4.20	TOT	33.91	1.55	55(1.05)	58	1.10
				EBU	12.50				
				NEB	21.41				

J. Lei and A. Bonaccorso PLB 813, 136032 (2021)

DWIA 模型 (p, pN)

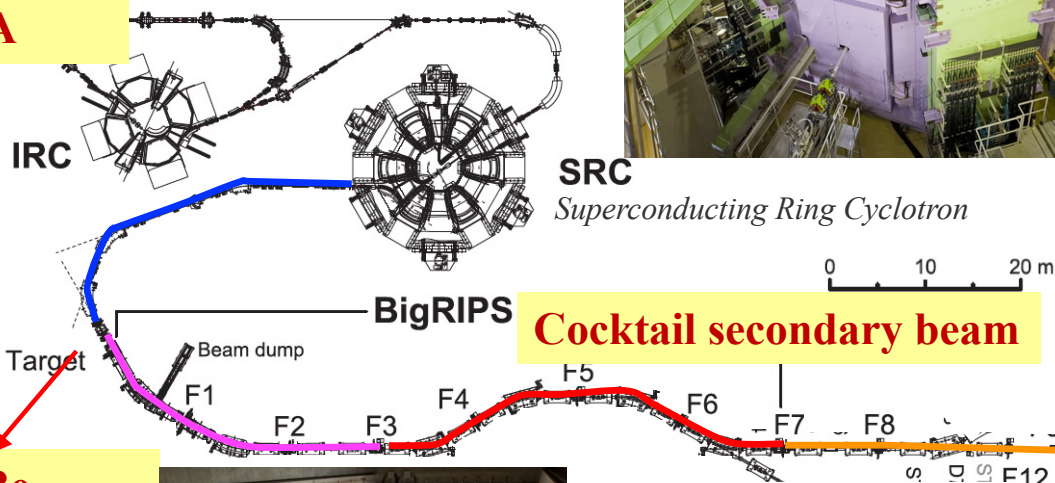
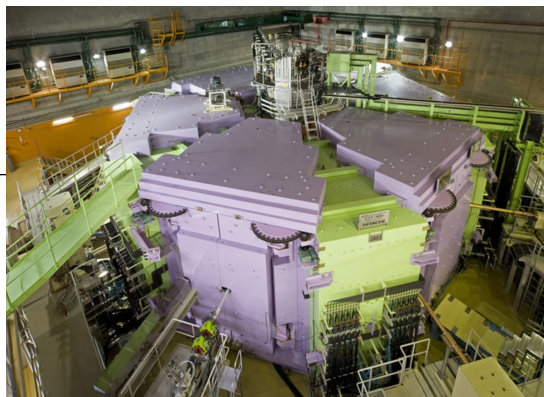


K. Ogata *et al.*, Phys. Rev. C 92, 034616 (2015).

- ❑ 类似于Be/C靶单核子移除的动量不对称
- ❑ 质子靶是一个实验&理论上更干净的探针

实验设置- SAMURAI-31

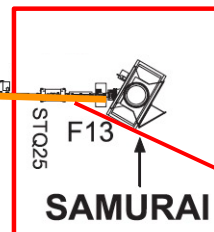
^{18}O beam
230 MeV/u
~500 pA



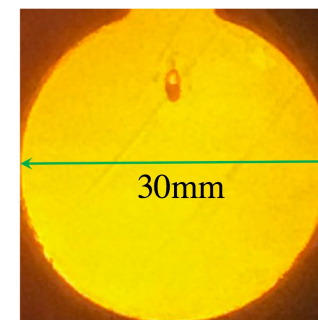
14 mm ^9Be

Cocktail secondary beam

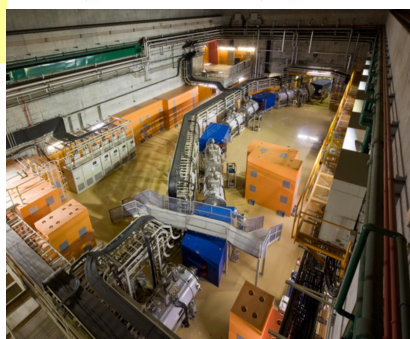
^{14}O 100MeV/u
 9×10^3 pps,
78% purity



2mm-thick solid hydrogen target

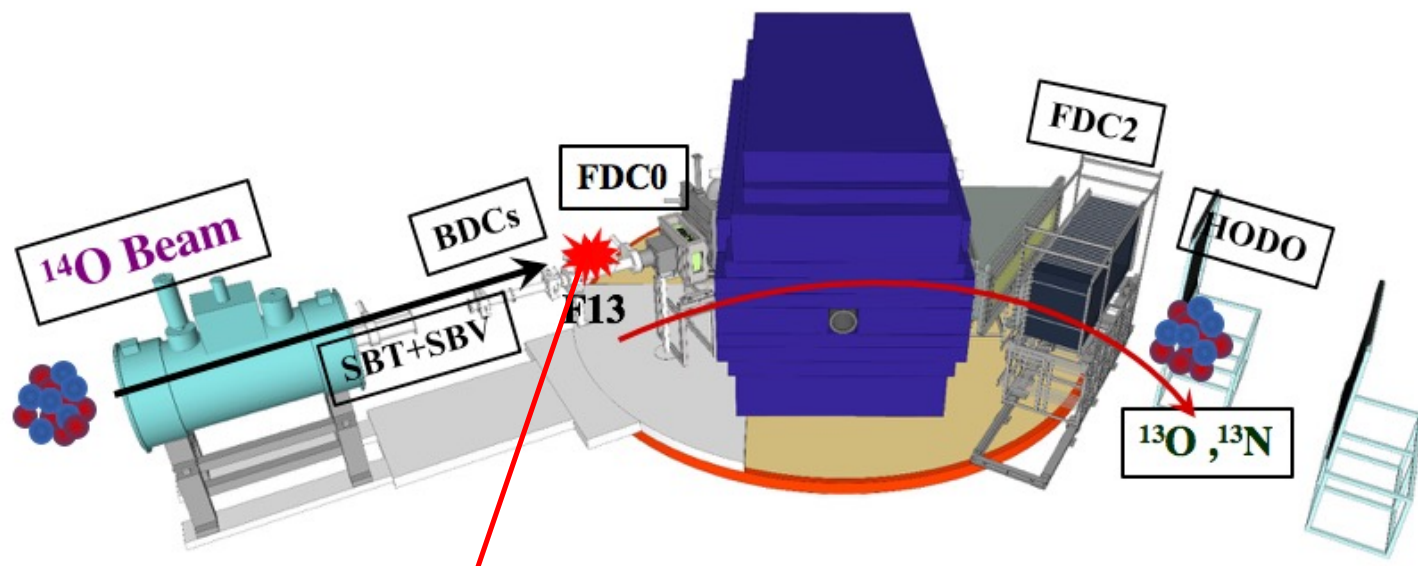


Secondary target

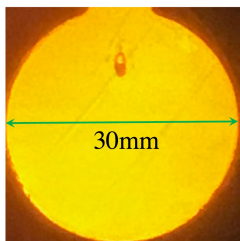


NP1512-SAMURAI31: $^{14}\text{O}(p, pN)$ at 100 MeV/nucleon

截面核动量分布测量



- 无结构H靶，理论更准确
- 测量剩余核动量分布，对反应机制敏感
- $^{13}\text{N}/^{13}\text{O}$ 没有束缚的激发态



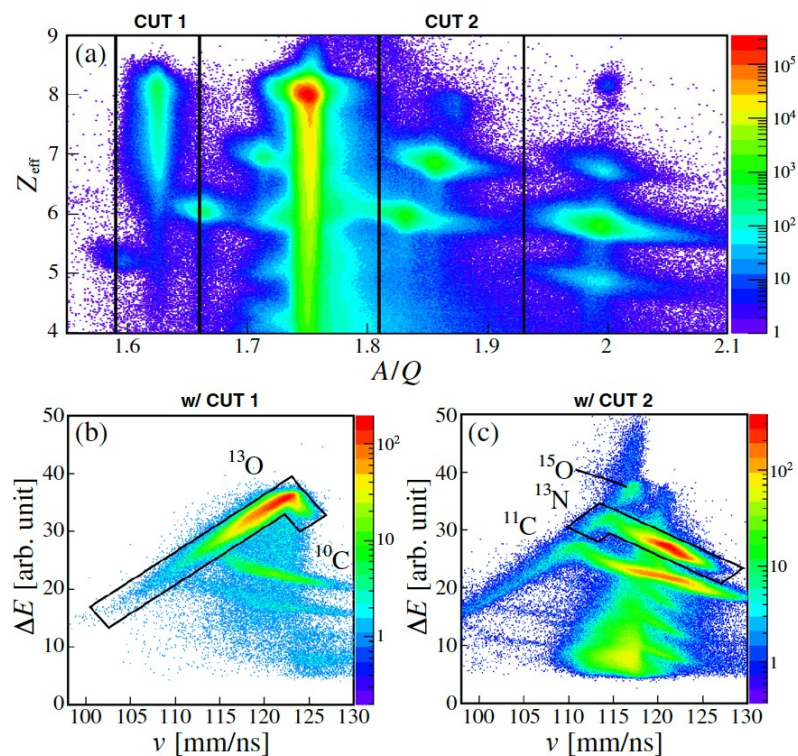
2mm-thick
solid hydrogen target

2016年通过(Grade A)。
2018年实验完成。
2022年完成分析数据。



PhD thesis
T. Pohl

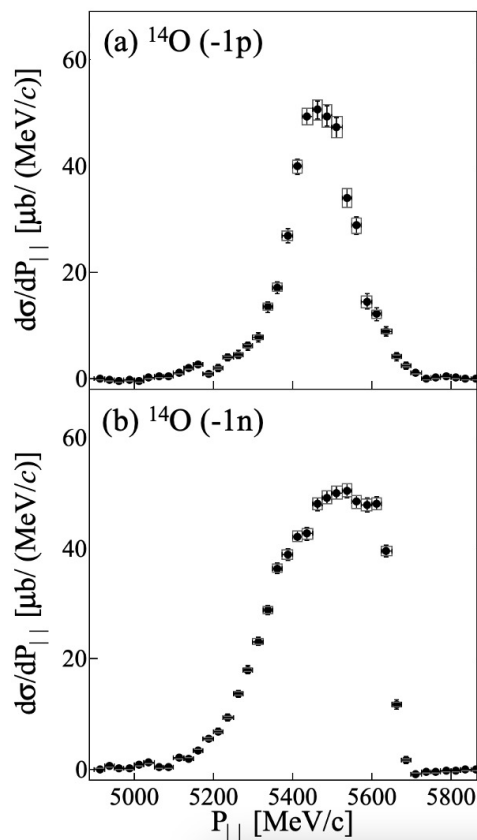
NP1512-SAMURAI31: $^{14}\text{O}(p, pN)$ at 100 MeV/nucleon



粒子鉴别: ΔE - $B\rho$ -TOF & ΔE - v

Residue	J^π	σ_{exp} (mb)
$^{13}\text{N}_{\text{g.s.}}$	$1/2^-$	10.7(16)
$^{13}\text{O}_{\text{g.s.}}$	$3/2^-$	16.7(24)

^{14}O 单核子移除剩余核动量分布



弱束缚质子移除: $^{14}\text{O} \rightarrow ^{13}\text{N}$, $S_p = 4.6\text{MeV}$

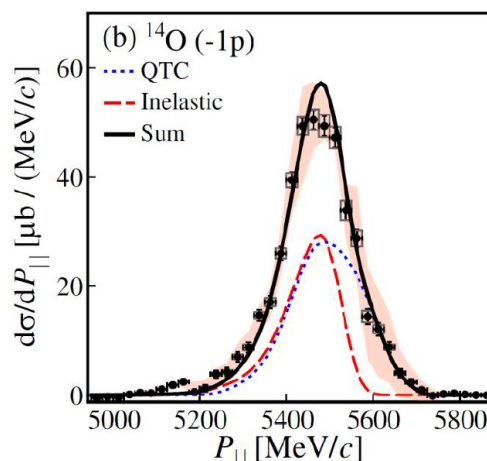
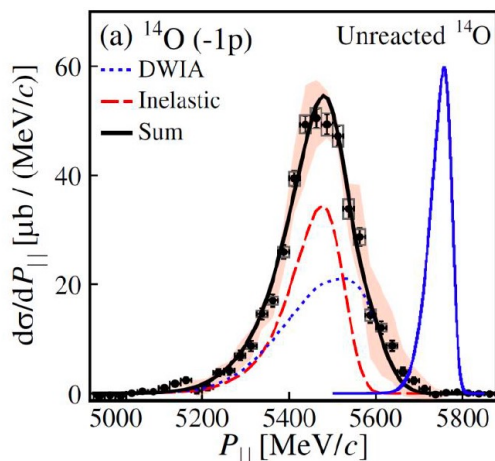
□ ^{13}N 动量分布基本对称

深束缚中子移除: $^{14}\text{O} \rightarrow ^{13}\text{O}$, $S_n = 23.1\text{MeV}$

□ 低动量拖尾

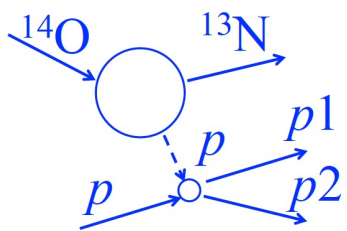
□ 高动量截断

弱束缚质子移除: $^{14}\text{O} \rightarrow ^{13}\text{N}$

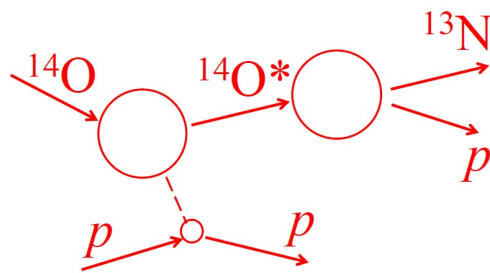


DWIA: K. Ogata (日本九州大学)
 K. Yoshida(日本原子能机构)
 QTC: M. Gómez-Ramos (西班牙塞维利亚大学)
 ^{14}O 壳模型:
 B. S. Cai, C. X. Yuan (中山大学)
 B.A. Brown(美国密西根州立大学)

(a) 49% DWIA + 51% 非弹激发
 (b) 57% QTC + 43% 非弹激发



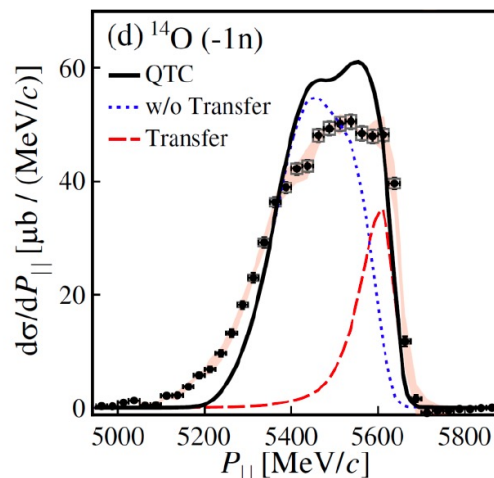
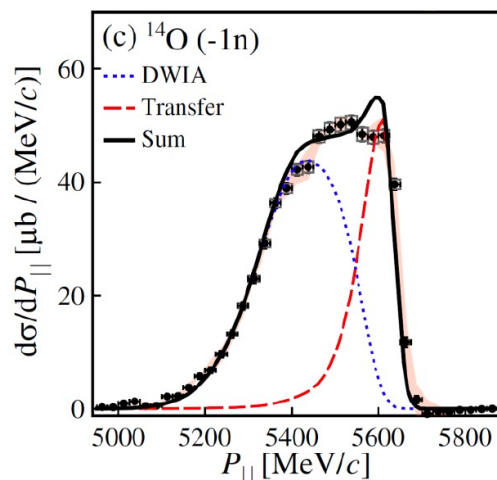
质子准自由敲出



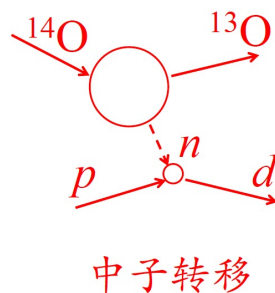
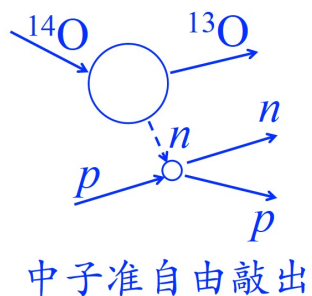
非弹激发

弱束缚质子移除, 非弹激发贡献
 43%/51%!

深束缚中子移除: $^{14}\text{O} \rightarrow ^{13}\text{O}$



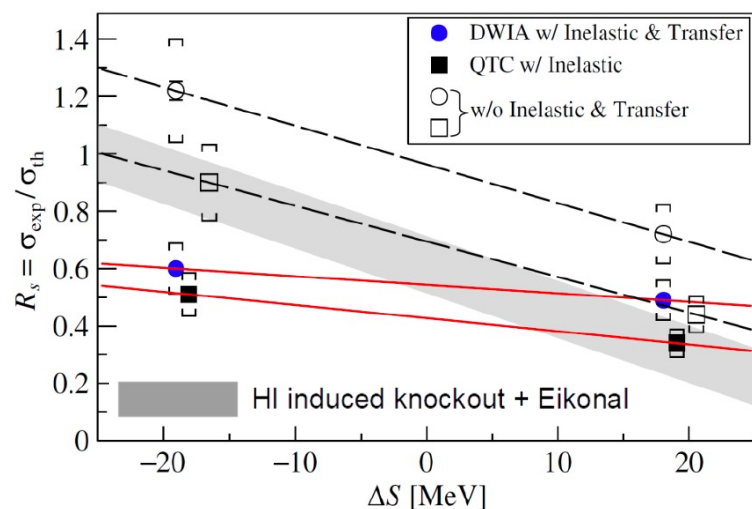
DWIA: K. Ogata (日本九州大学)
K. Yoshida(日本原子能机构)
QTC: M. Gómez-Ramos (西班牙塞维利亚大学)
 ^{14}O 壳模型:
B. S. Cai, C. X. Yuan (中山大学)
B.A. Brown(美国密西根州立大学)



- 首次在100MeV能区观察到显著的(p, d)转移成分!
- 30% 转移 + 准自由敲出(DWIA)

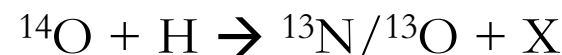
94MeV/u 3mb: $qR \rightarrow 1\sim 2 \hbar @ 0\text{deg}$
300MeV/u 0.2mb: $qR \rightarrow 3\sim 5 \hbar @ 0\text{deg}$

多重移除机制对约化因子的影响



↑
弱束缚质子

↑
深束缚中子



□ 不考虑非弹激发+转移成分

→ 约化因子明显依赖于费米面不对称性

□ 考虑非弹激发+转移成分 -0.003~-0.0046

→ 约化因子基本不依赖于费米面不对称性

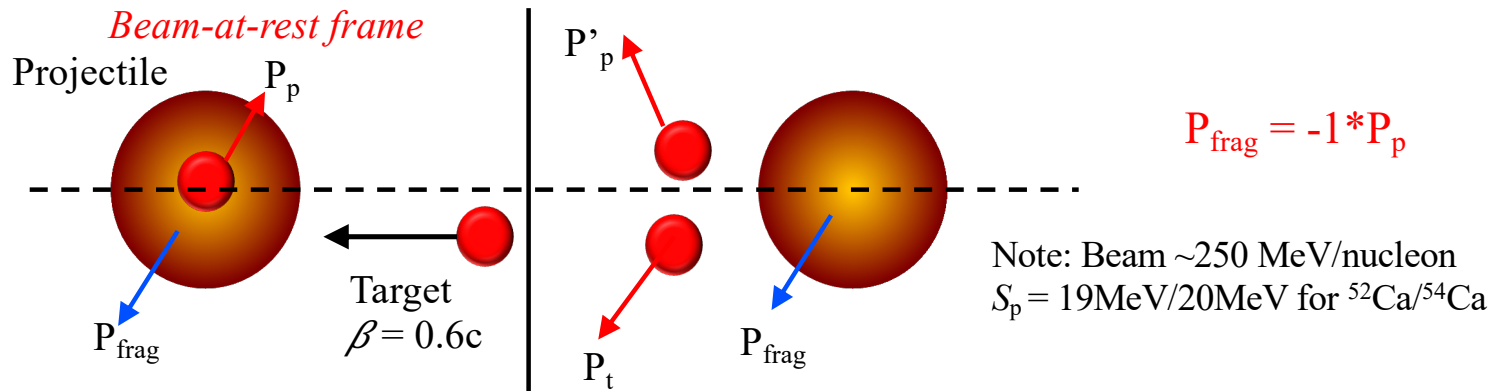
□ 分析中能区C/Be靶实验截面时，
也需要考虑非弹激发、转移等机制的贡献

T. Pohl, YLS* et al., PRL 130, 172501 (2023)

报告提纲

1. 核子-核子关联
2. 单核子移除反应——谱因子压低之“谜”
3. $\sim 100 \text{ MeV/u}$ (p, pN) 单核子移除的多重机制 $\square^{14}\text{O}(p, pN)^{13}\text{N}/^{13}\text{O}$
 $\sim 100 \text{ MeV/u}$
4. (p, pN) 准自由敲出反应的一些最新进展
 $\square^{52,54}\text{Ca}(p, 2p)^{51,53}\text{K}$
 $\square^{52,54}\text{Ca}(p, pn)^{51,53}\text{Ca}$
 $\square^{11}\text{Li}(p, pn)^{10}\text{Li}$
 $\square^{11}\text{Li}(p, 2p)^{10}\text{He}$
 $\sim 250 \text{ MeV/u}$
5. 总结和展望

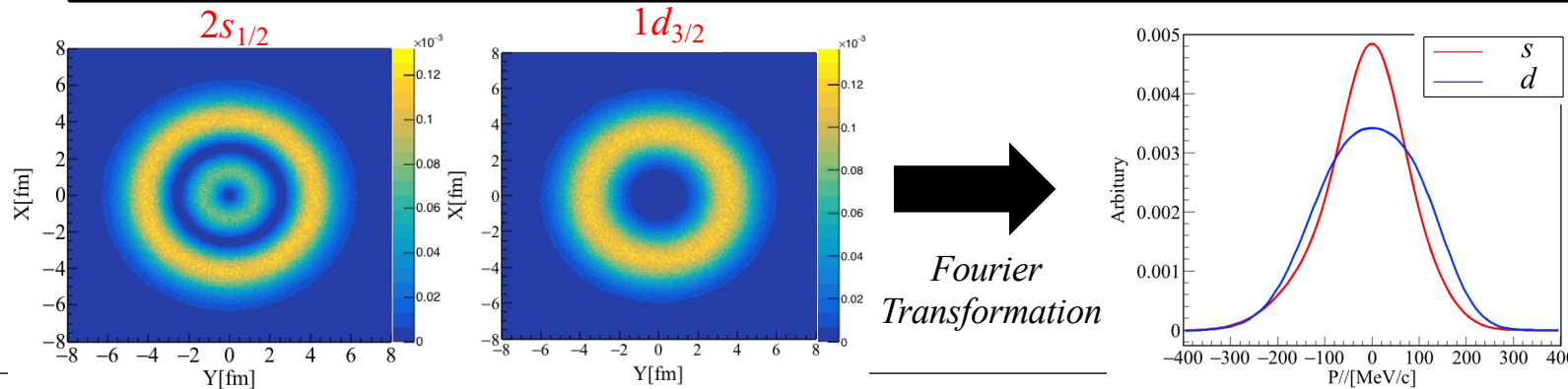
(p, pN) 准自由敲出



$\beta > \beta_F = 0.27c$
 “Sudden approximation”

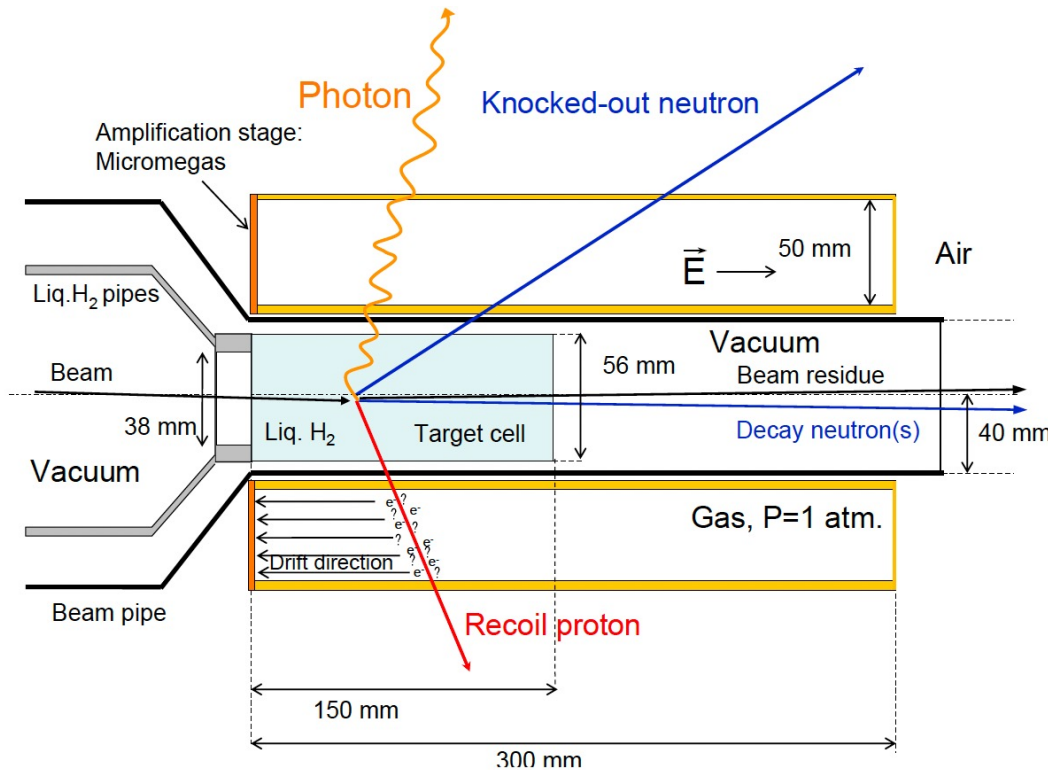
Ebeam > 10* Sn or Sp

Momentum of the residue \rightarrow Momentum of the knocked out nucleon \rightarrow angular momentum



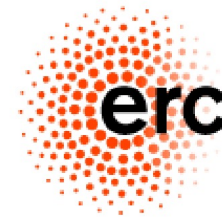
DWIA calculation
 (distortion...)
 (K. Ogata, K. Yoshida,
 Y. Chazono)

MINOS (nuclear Magic Numbers Off Stability) 装置



解决远离稳定线束流强度很低的困难

- ❑ 厚液氢靶提高统计 (5-10倍)
- ❑ 顶点探测器保证分辨率



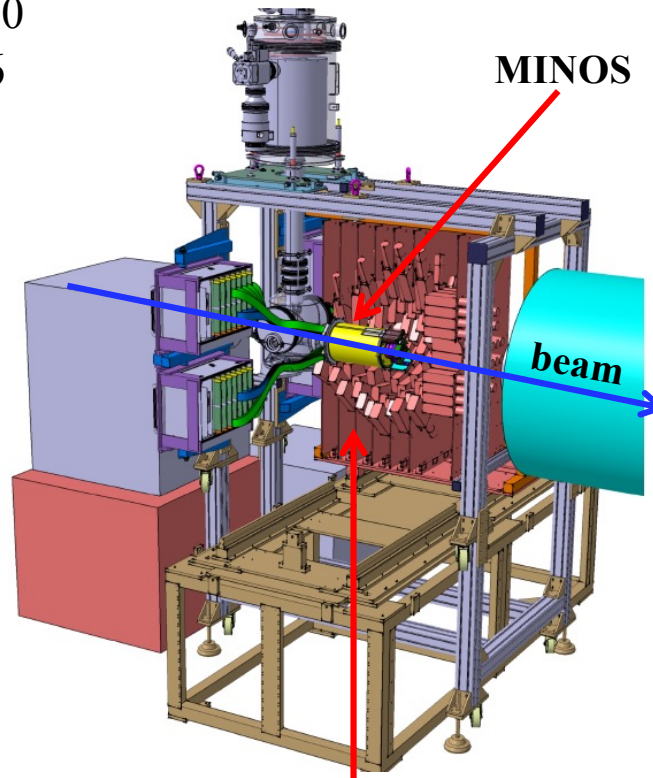
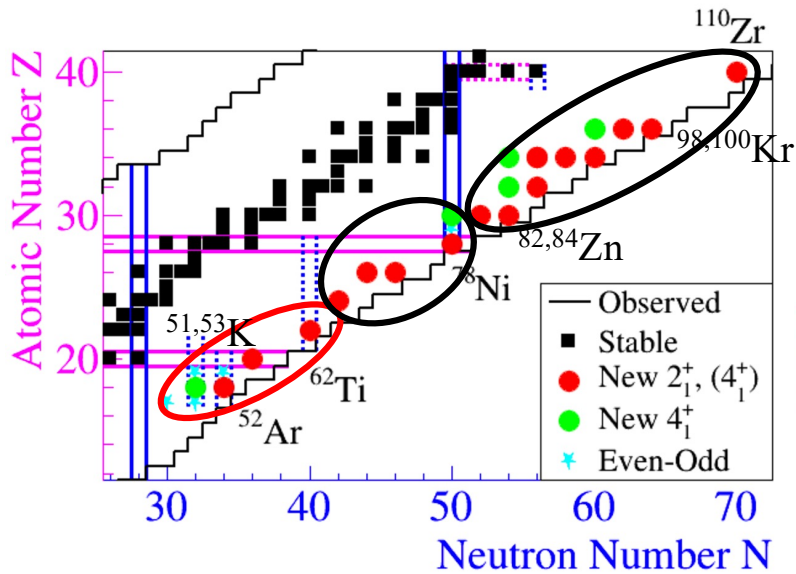
~1M Euro



A. Obertelli

SEASTAR (Shell Evolution And Search for Two-plus energies At RIBF) – 3 campaign

1st SEASTAR: 2014 April 30 – May 10
 2nd SEASTAR: 2015 April 27 – May 6
 3rd SEASTAR: 2017 May 6 – May 14



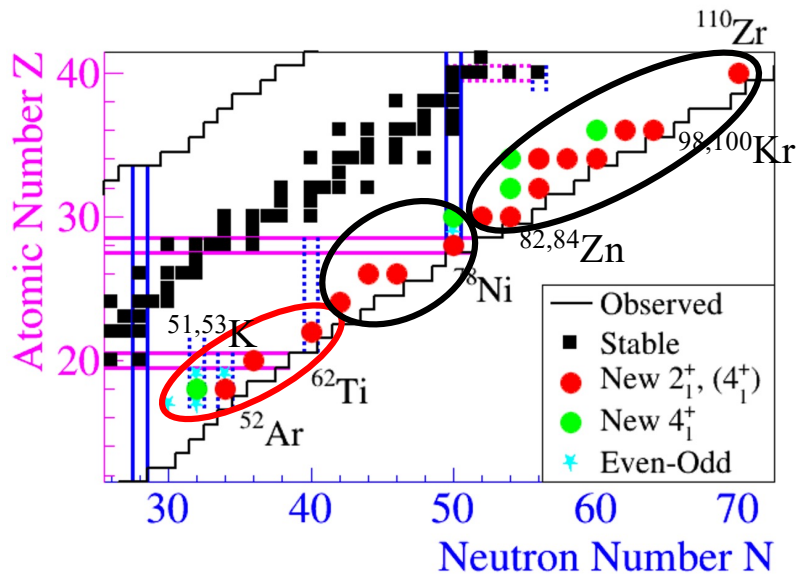
P. Doornenbal



A. Obertelli

DALI2 : 186 NaI (2010-2016); 226 NaI (2017 -)

SEASTAR (Shell Evolution And Search for Two-plus energies At RIBF) – 3 campaigns



56,58Ca: PLB, 843:138025 (2023)

52Ca: PRL, 129:262501 (2022)

55K, 55,57Ca PLB, 827:136953 (2022)

54Ca: PRL 126:252501 (2021)

51Ar: PLB 814:136108 (2021)

51,53K: PLB 802:135215 (2020)

62Ti: PLB 800:135071 (2020)

78Ni: *Nature* **569**, 53–58 (2019)

54Ca: PRL, 123:142501 (2019)

52Ar: PRL 122:072502 (2019)

65,67Mn: PLB 784:392 (2018)

79Cu: PRL 119:192501 (2017)

110Zr: PRL 118:032501 (2017)

81-84Zn: PLB 773:492 (2017)

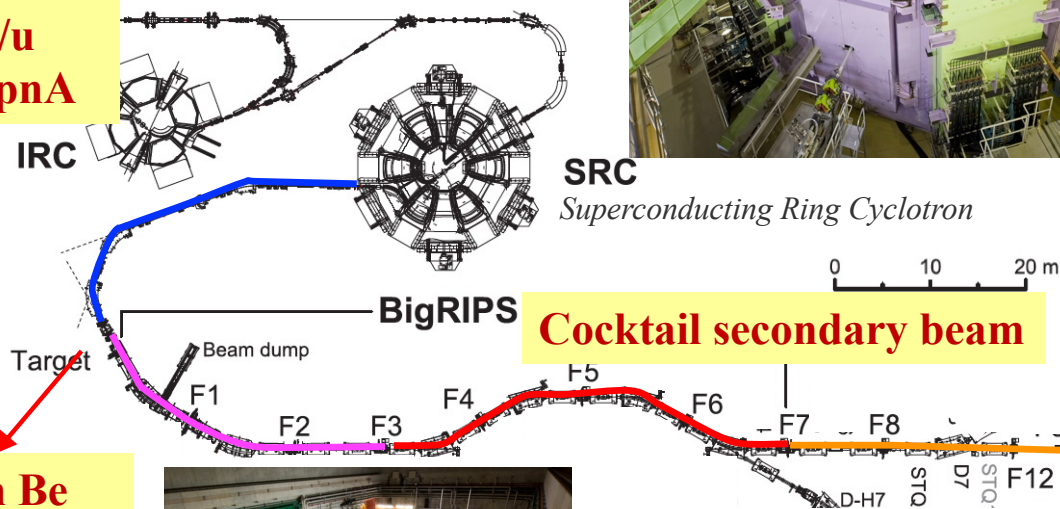
98,100Kr: PRL 118:242501 (2017)

66Cr, 70,72Fe: PRL 115:192501 (2015)

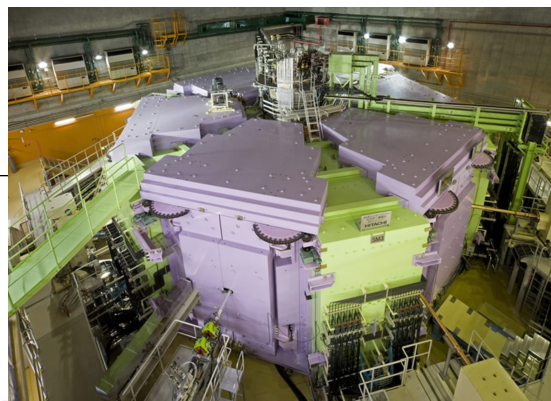
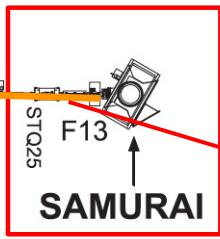
.....

实验设置- SEASTAR3

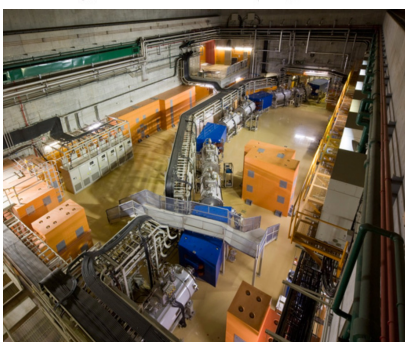
^{70}Zn beam
345 MeV/u
200~250 pA



$\beta: \sim 0.6c$

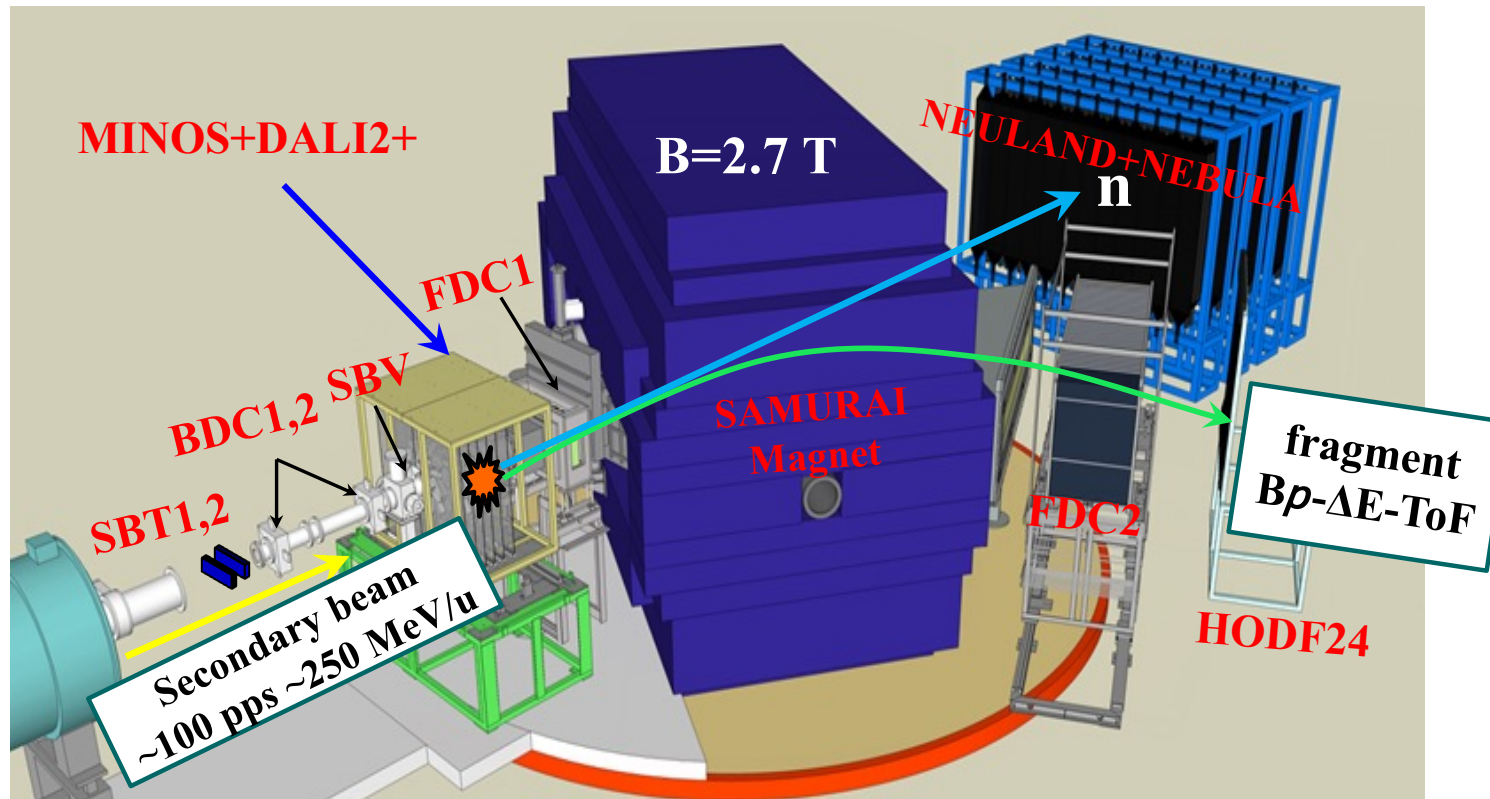


10mm Be



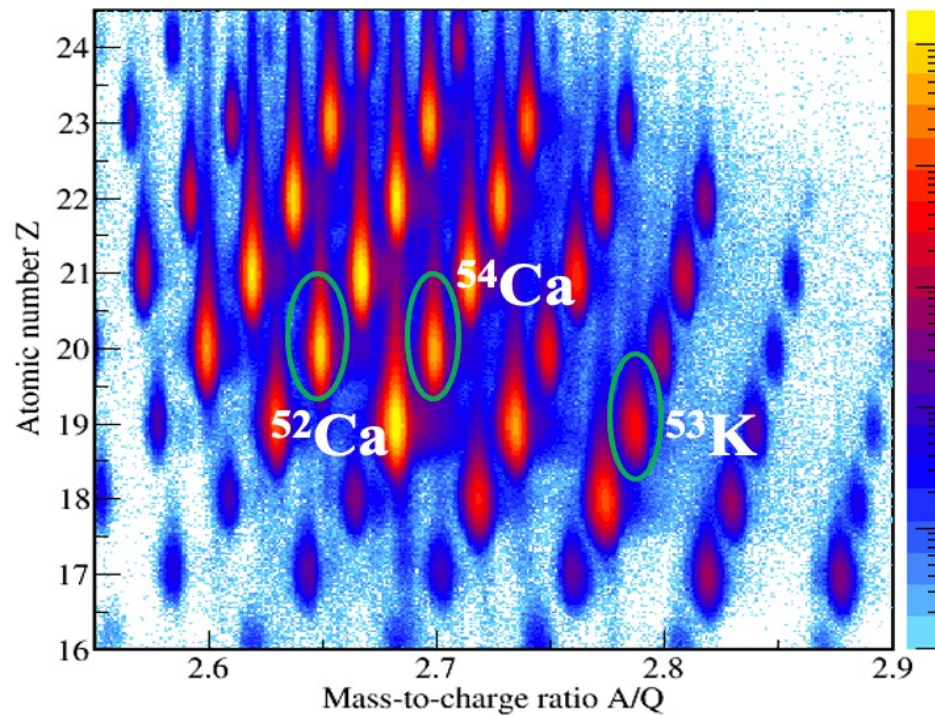
Secondary target
150mm LH2

Experimental Setup@ SAMURAI

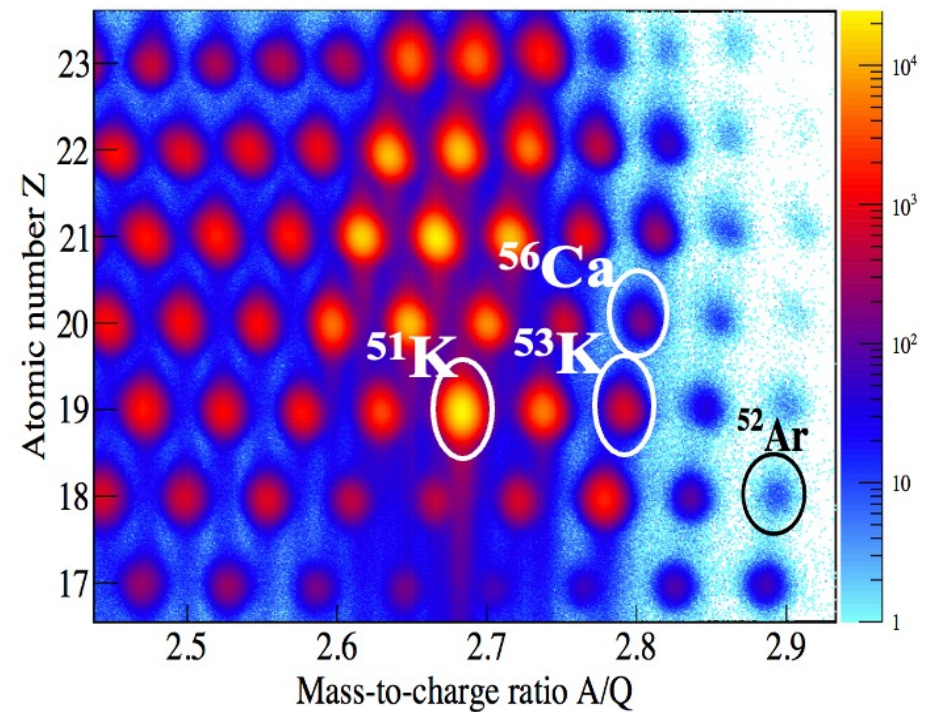


SEASTAR3 Partical identification

Projectile PID at BigRIPS

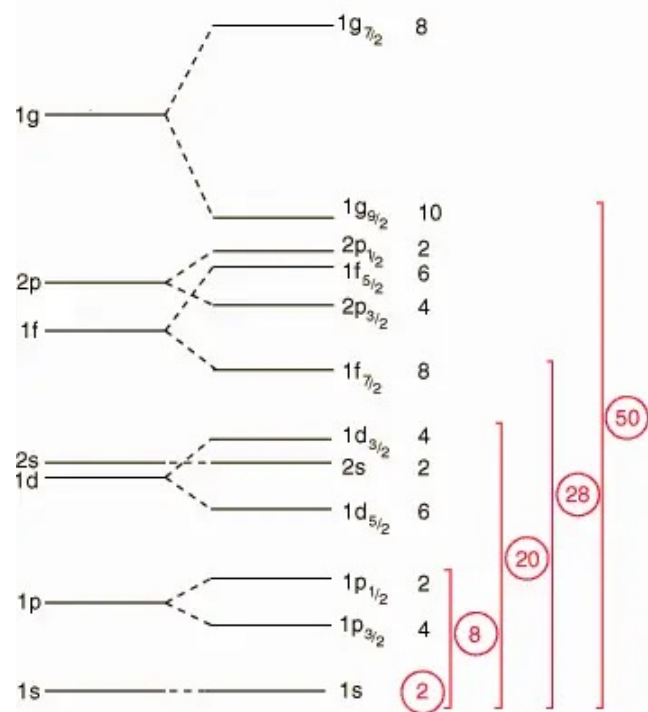


Fragment PID at SAMURAI



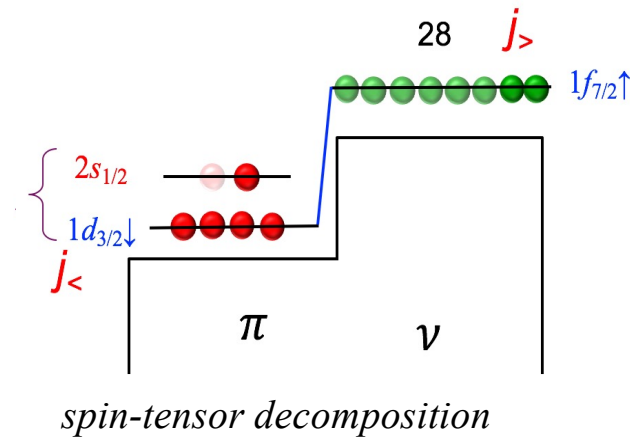
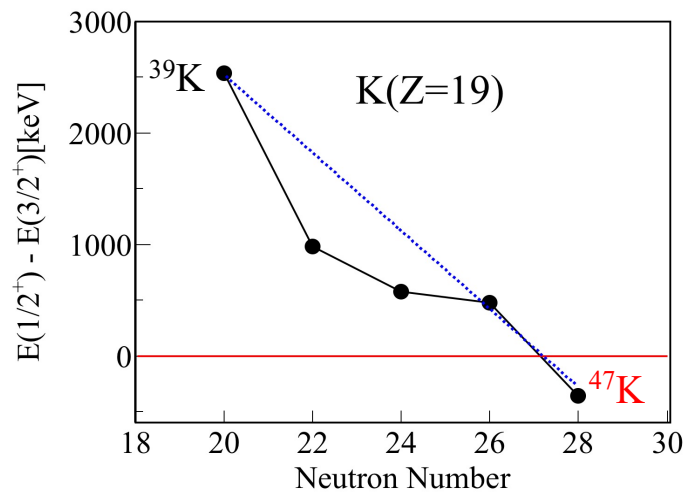
Monopole shift in odd-K isotopes

Relation between shell model and magic numbers



质子-中子各排各的?

Monopole shift in odd-K isotopes



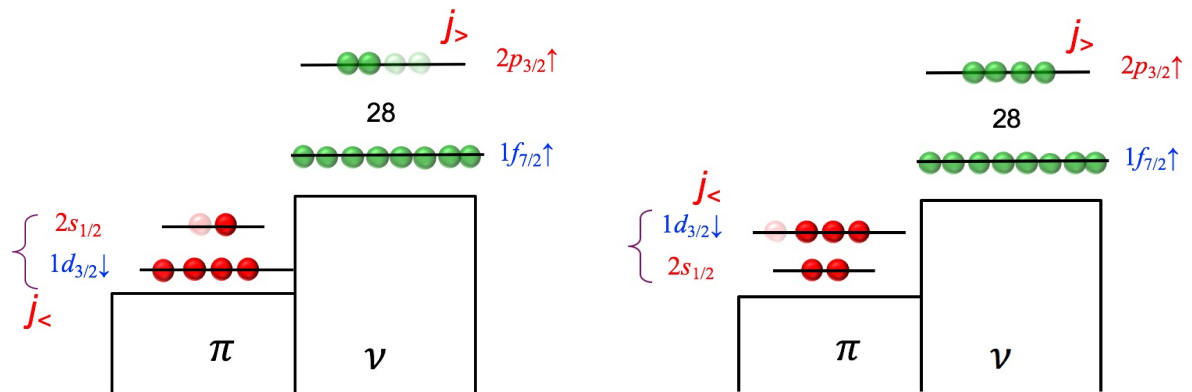
Interaction	Component	$V_{d_{3/2}, f_{7/2}}^{\pi\nu}$	$V_{s_{1/2}, f_{7/2}}^{\pi\nu}$
SDPF-U	Central	-1.51	-1.21
	Vector	+0.09	+0.07
	Tensor	-0.28	0.00
	Total	-1.70	-1.14

J. Papuga *et al.* PRC, 90, 034321 (2014).

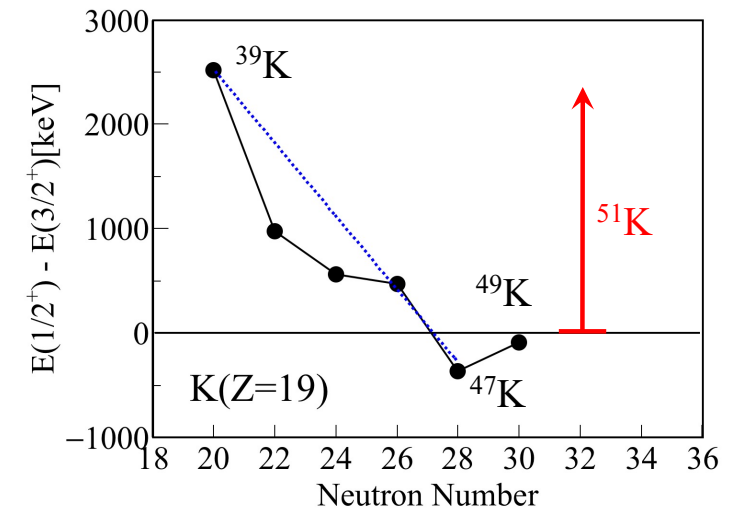
$\Delta E \propto n \times (V_{d_{3/2}, f_{7/2}}^{\text{pn}} - V_{s_{1/2}, f_{7/2}}^{\text{pn}})$
 → Deviation from linear change,
 quadruple and pairing interaction

- ✓ Filling of $\nu 1f_{7/2}$ gradually decreases the gap between $\pi 1d_{3/2}$ and $\pi 1s_{1/2}$ ($d_{3/2}$ more bound than $s_{1/2}$)
- ✓ Inversion happens at ^{47}K ($I = 1/2$, $E(1/2^+) - E(3/2^+) = -360 \text{ keV}$)

Monopole shift in odd-K isotopes

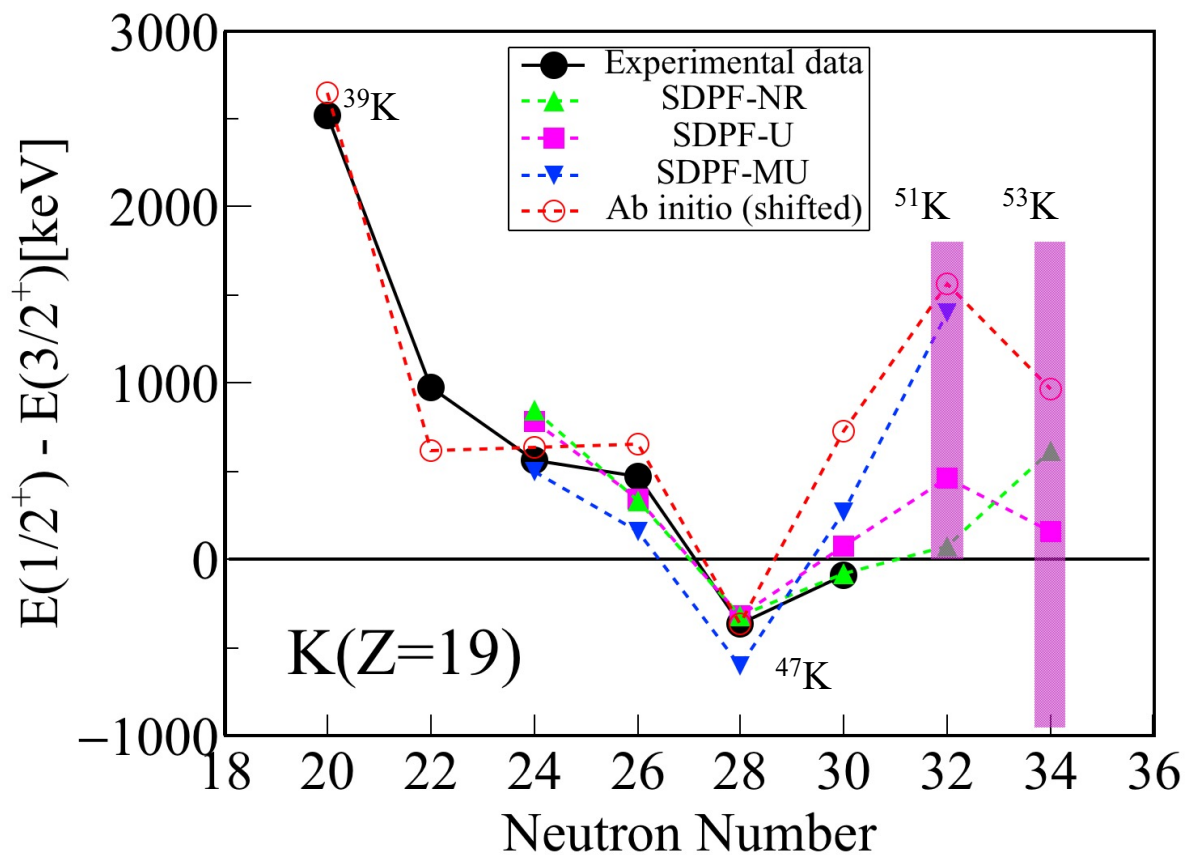


$\pi 1d_{3/2}$ and $\pi 2s_{1/2}$ revert at ^{51}K

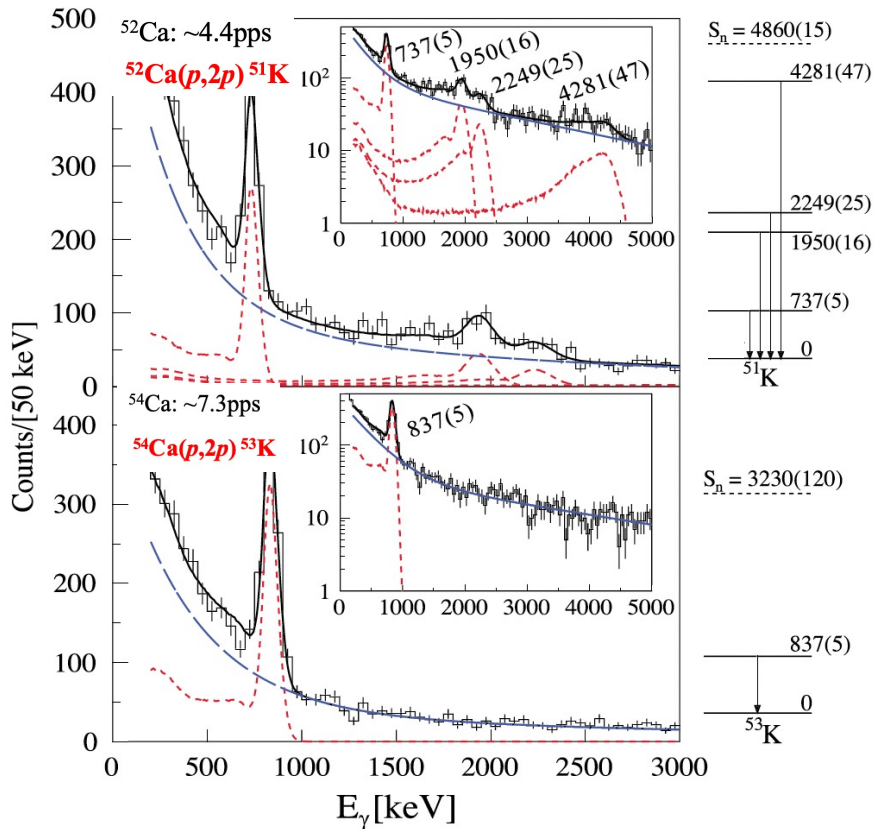


- ^{51}K ($N = 32$), $I = 3/2$, excited state unknown
 - ^{53}K ($N = 34$), no information
 - Guide further theory development $sd \otimes$ higher $p_{3/2}$ and $p_{1/2}$
- ➔ Identify the $1/2^+$ and $3/2^+$ states in $^{51,53}\text{K}$ and measure their energy difference.

Monopole shift in odd-K isotopes



51, 53K Doppler corrected γ -spectrum



	E_{exp} (keV)	J^π	σ_{exp} (mb)	σ_{sp} (mb)	SF
^{51}K	0	$3/2^+$	5.2(4)	1.73	3.0(2)
	737(5)	$1/2^+$	1.7(2)	1.88	0.9(1)
^{53}K	0	$3/2^+$	3.8(3)	1.49	2.6(2)
	837(5)	$1/2^+$	1.5(2)	1.64	0.9(1)

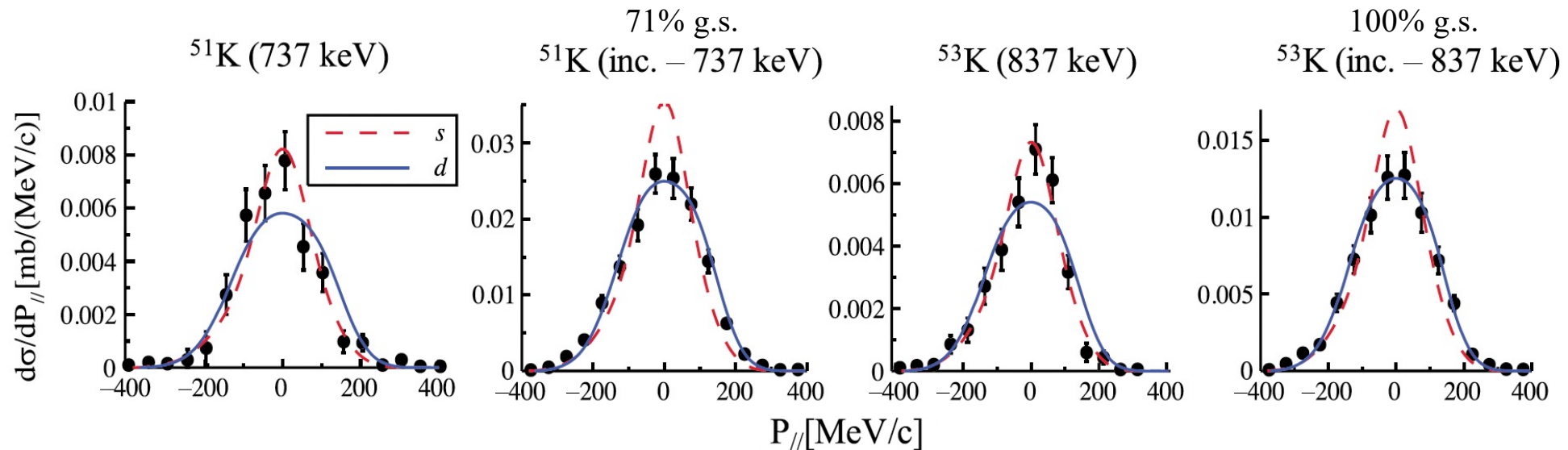
$$\text{SF} = \sigma_{\text{th}} / \sigma_{\text{sp}}$$

σ_{sp} : DWIA calculation
 (K. Ogata, K. Yoshida, Y. Chazono)

Degeneracy: $2J+1$
 $d_{3/2} \rightarrow 4, s_{1/2} \rightarrow 2$

→ Extract angular momentum using
 Parallel momentum distribution (PMD)

$^{51,53}\text{K}$ Parallel momentum distribution



^{52}Ca Sp ~ 19 MeV

^{54}Ca Sp ~ 20 MeV

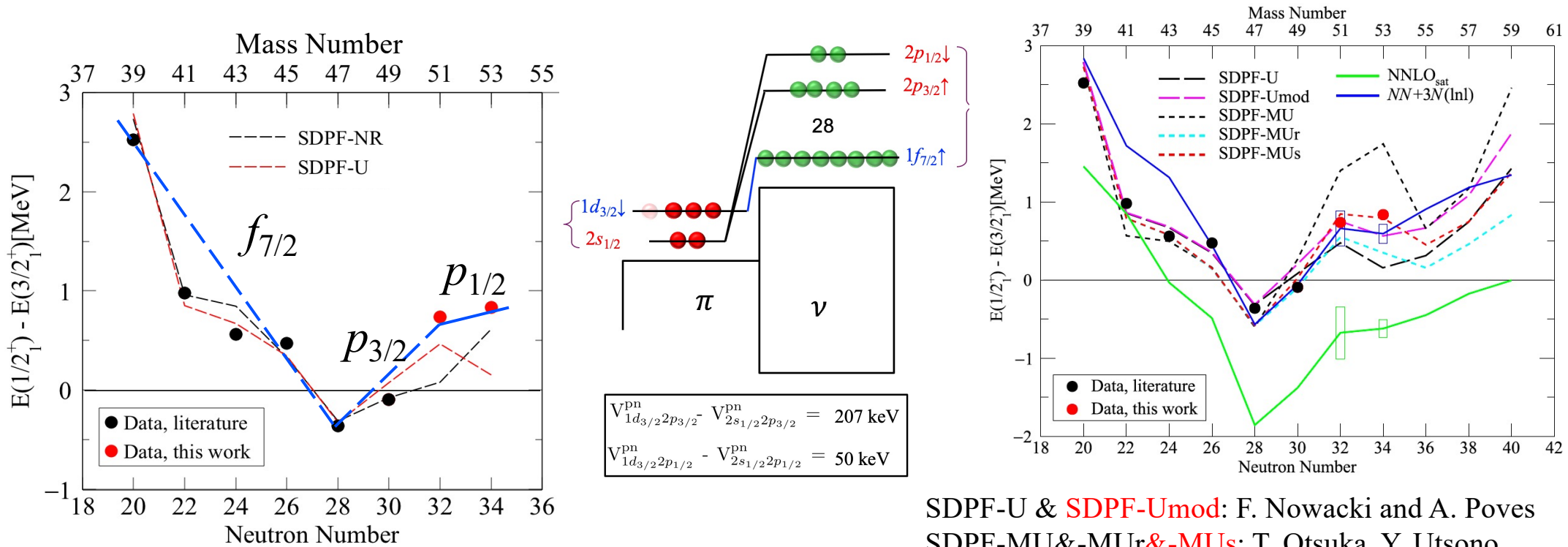
□ Comparison with DWIA calculation after folding with experimental resolution, clear *s/d*-wave assignments:

➤ ^{51}K 1st excited state is *s*-wave, $J^\pi = 1/2^+$, ground state is *d*-wave, $J^\pi = 3/2^+$

➤ ^{53}K 1st excited state is *s*-wave, $J^\pi = 1/2^+$, ground state is *d*-wave, $J^\pi = 3/2^+$

1/2⁺ - 3/2⁺ energy splitting in odd-K isotopes

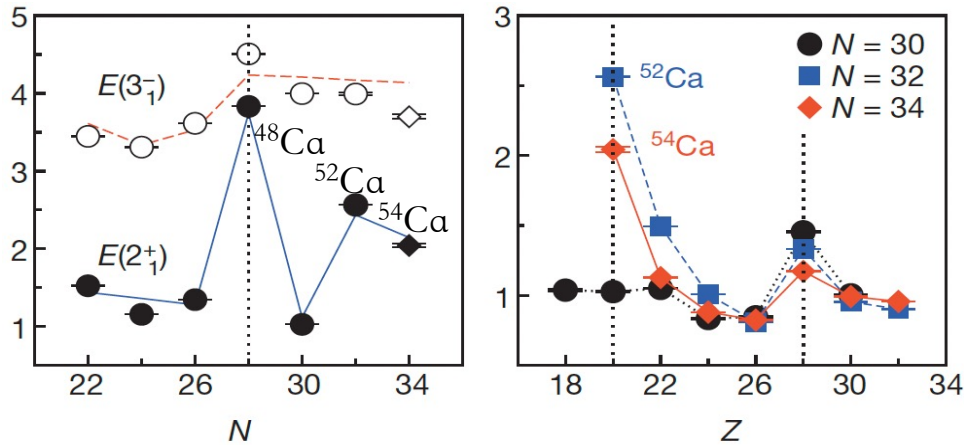
YLS et al., PLB 802 (2020) 135215



- Reversion continues from ⁵¹K(N=32) to ⁵³K(N=34).
- Determine the monopole matrix elements differences.

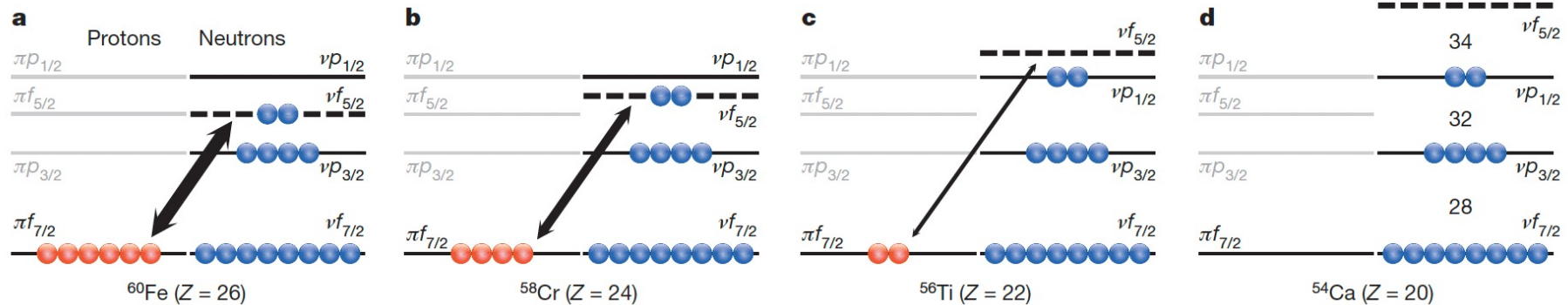
SDPF-U & SDPF-Umod: F. Nowacki and A. Poves
 SDPF-MU&-MUr&-MUs: T. Otsuka, Y. Utsono
 GGF with NNLO_{sat}/NN+3N(lnl):
 C. Barbieri, T. Duguet, F. Raimondi, V. Soma

$^{54}\text{Ca}(p, pn)^{53}\text{Ca}$ & $^{52}\text{Ca}(p, pn)^{51}\text{Ca}$



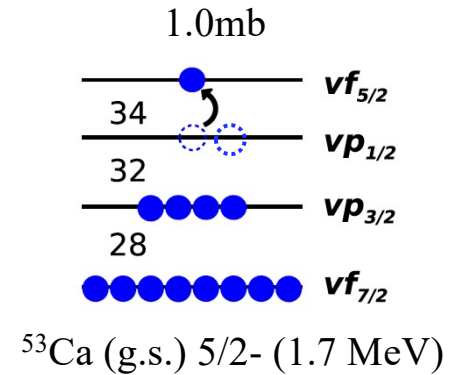
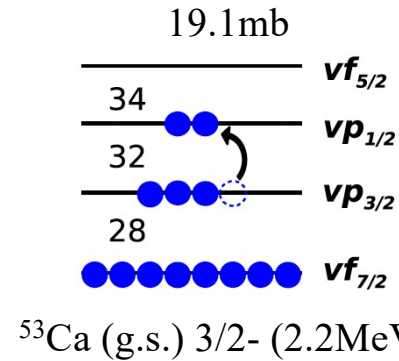
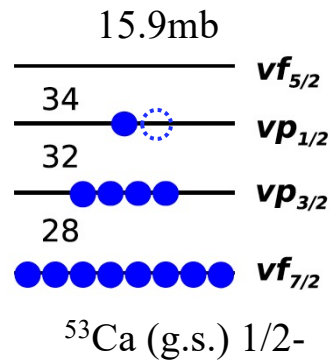
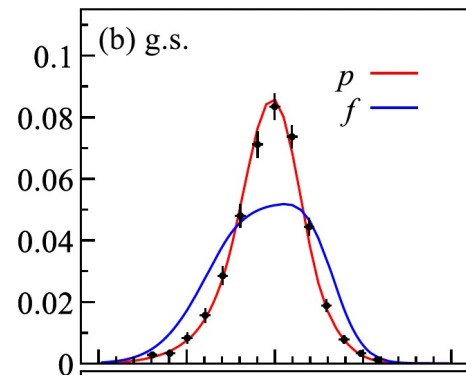
Nature 502, 207–210 (2013)

- $2+$ systematics \rightarrow new magic numbers $N = 32$ & 34
- Neutron occupy p-shell instead of f -shell?



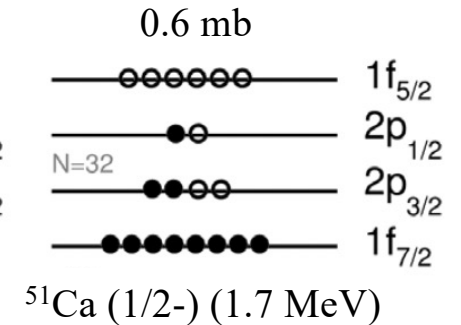
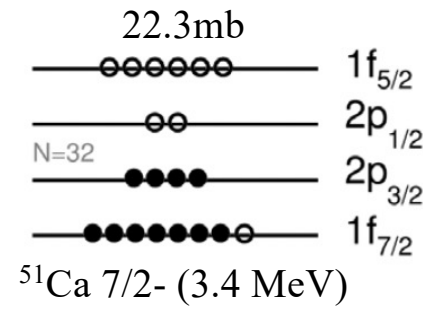
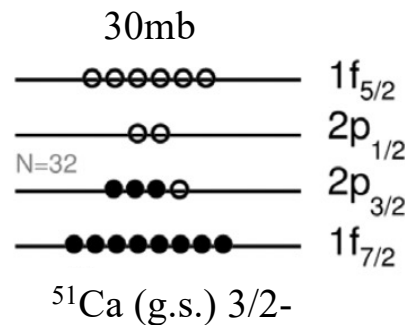
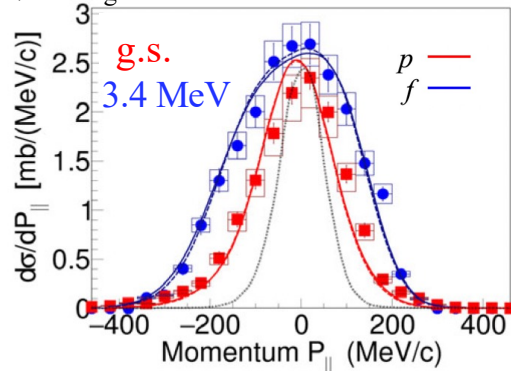
$^{54}\text{Ca}(p, pn)^{53}\text{Ca}$ & $^{52}\text{Ca}(p, pn)^{51}\text{Ca}$

$^{54}\text{Ca}(p, pn)^{53}\text{Ca}_{\text{g.s.}}$



S. Chen... YLS ...PRL 123, 142501 (2019)

$^{52}\text{Ca}(p, pn)^{51}\text{Ca}_{\text{g.s.}}$



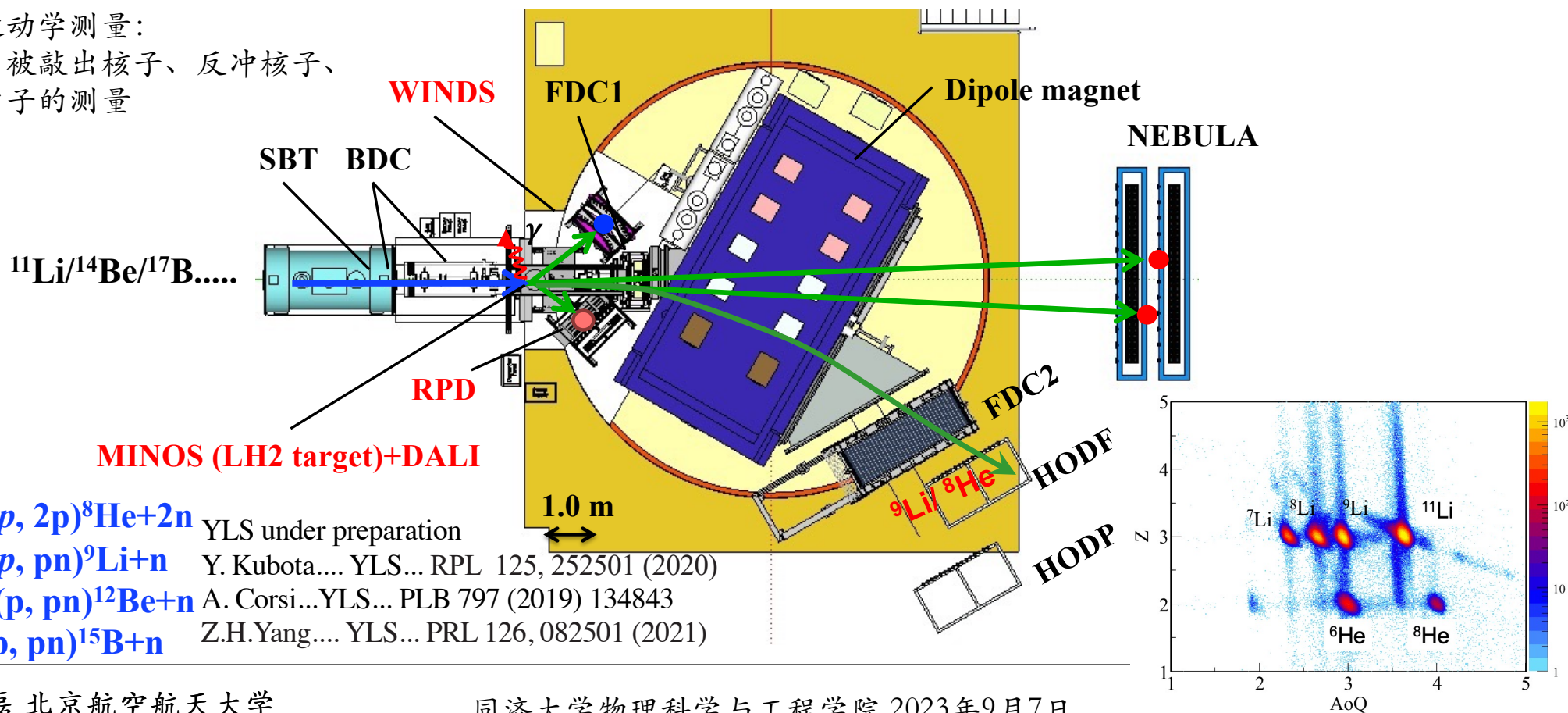
M. Enciu...YLS...PRL 129, 262501 (2022)

报告提纲

1. 核子-核子关联
2. 单核子移除反应——谱因子压低之“谜”
3. $\sim 100 \text{ MeV/u}$ (p, pN) 单核子移除的多重机制 $\square^{14}\text{O}(p, pN)^{13}\text{N}/^{13}\text{O}$
 $\sim 100 \text{ MeV/u}$
4. (p, pN) 准自由敲出反应的一些最新进展
 $\square^{52,54}\text{Ca}(p, 2p)^{51,53}\text{K}$
 $\square^{52,54}\text{Ca}(p, pn)^{51,53}\text{Ca}$ $\sim 250 \text{ MeV/u}$
 $\square^{11}\text{Li}(p, pn)^{10}\text{Li}$
 $\square^{11}\text{Li}(p, 2p)^{10}\text{He}$
5. 总结和展望

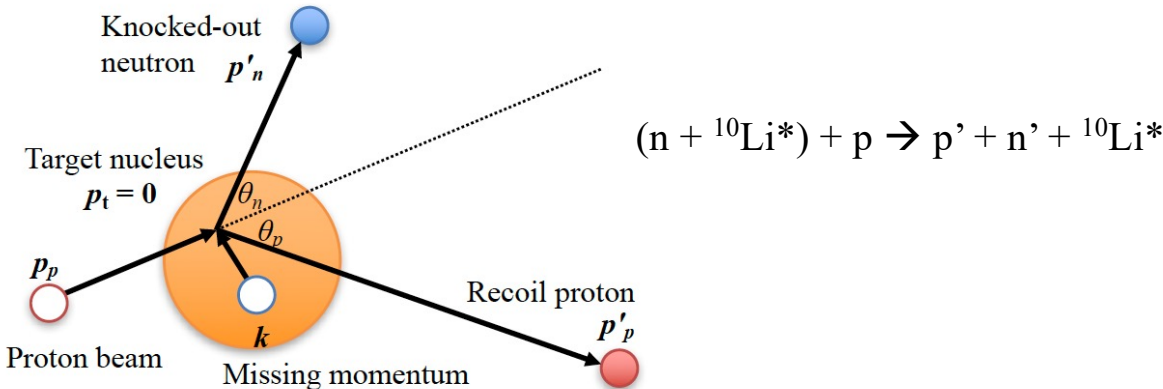
实验设置- SAMURAI-018

完全运动学测量：
增加了被敲出核子、反冲核子、
衰变中子的测量



- $^{11}\text{Li}(p, 2p)^8\text{He}+2n$ YLS under preparation
- $^{11}\text{Li}(p, pn)^9\text{Li}+n$ Y. Kubota.... YLS... RPL 125, 252501 (2020)
- $^{14}\text{Be}(p, pn)^{12}\text{Be}+n$ A. Corsi...YLS... PLB 797 (2019) 134843
- $^{17}\text{B}(p, pn)^{15}\text{B}+n$ Z.H.Yang.... YLS... PRL 126, 082501 (2021)

缺失质量法&不变质量法

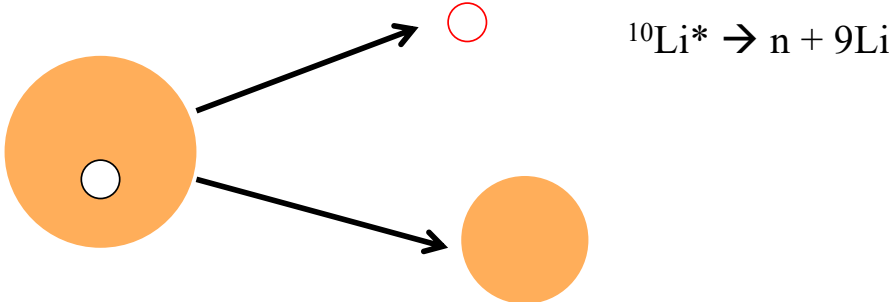


Missing-momentum

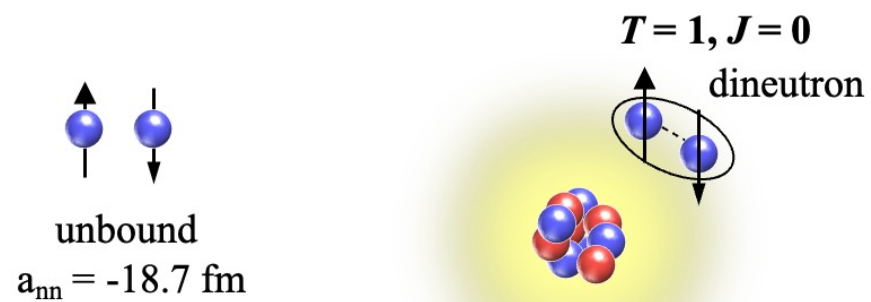
$$k = p'_n + p'_p - p_p$$

Invariant-mass

$$M = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{P}_i\right|^2}$$

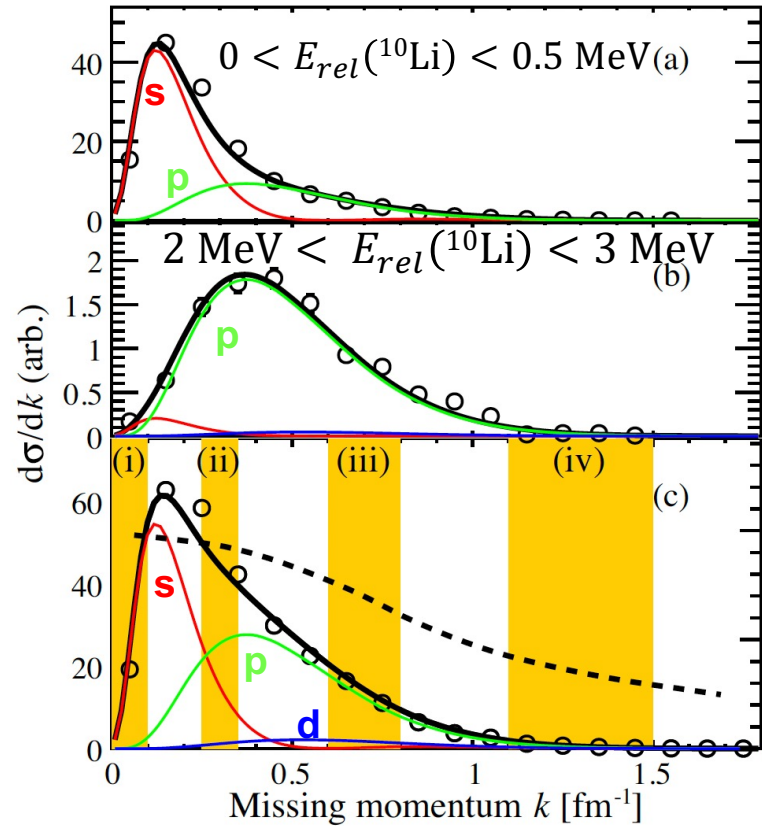
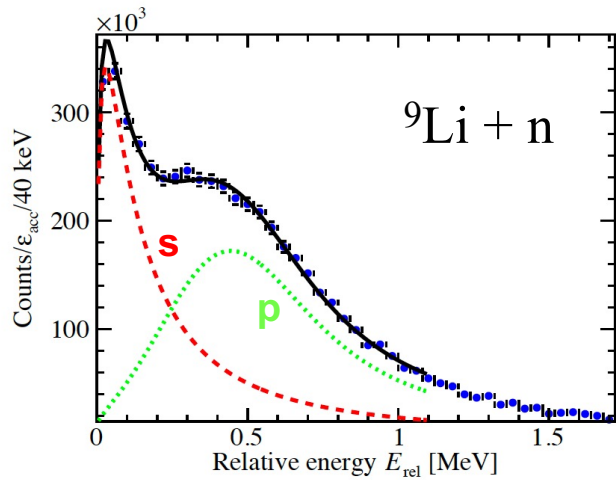


$$E_{\text{decay}} = M - \sum_i M_i$$

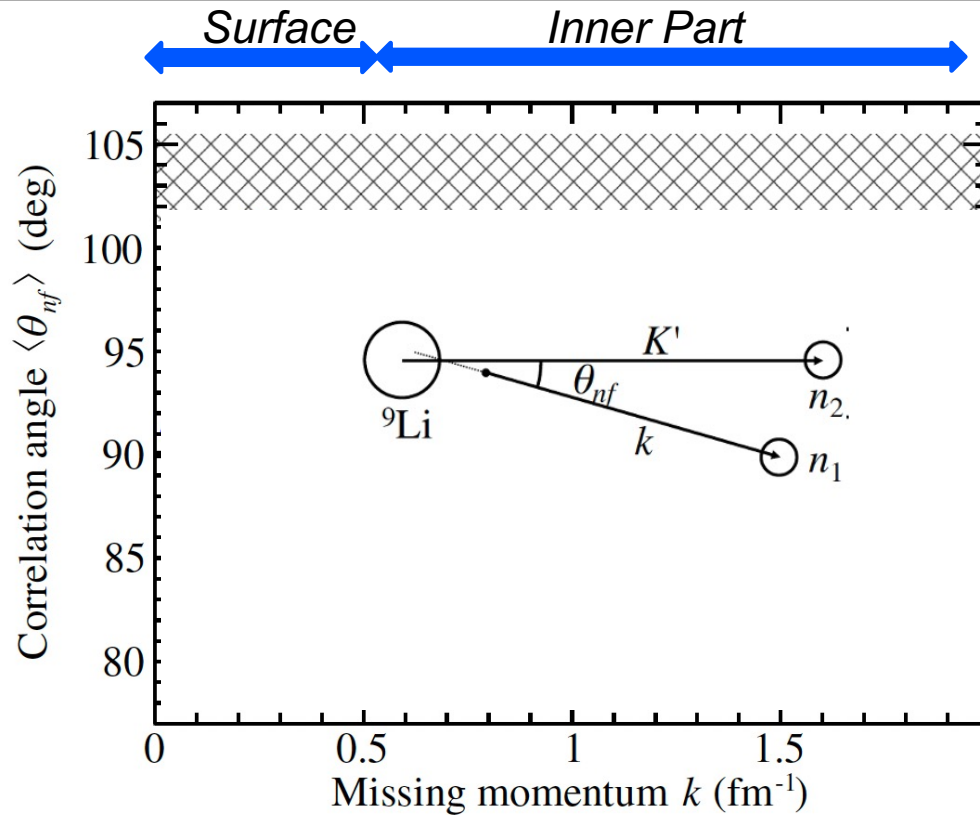


$^{11}\text{Li}(p, pn)^9\text{Li}+n$

Y. Kubota ...YLS...et al., RPL 125, 252501 (2020)



□ 2n configuration of ^{11}Li
 $(2s)^2$: 35(4)%
 $(1p)^2$: 59(1)%
 $(1d)^2$: 6(4)%

$^{11}\text{Li}(p, pn)^9\text{Li}+n$


k : momentum of n_1
 K' : momentum of n_2 relative to ^9Li
 θ_{nf} : angle between k and K'
 θ_{12} : angle between n_1 & n_2 in coordinate space

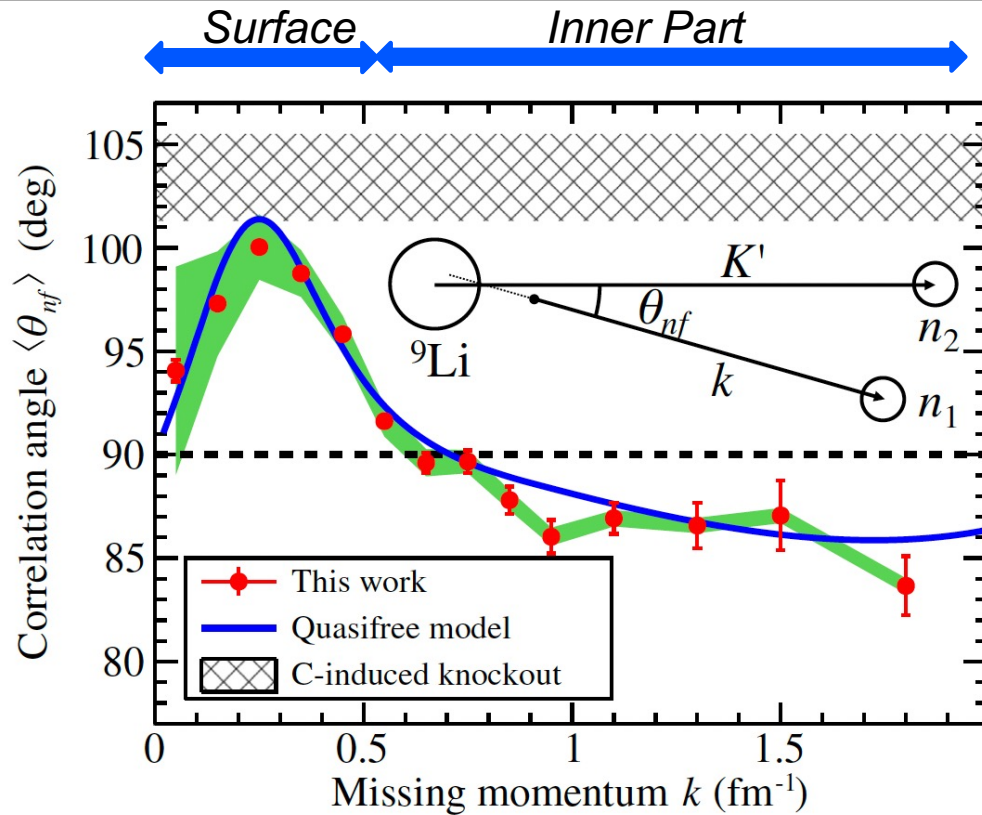
动量空间 \swarrow
 位置空间 \searrow
 $\theta_{nf} \sim 180^\circ - \theta_{12}$

H. Simon et al., *Phys. Rev. Lett.* 83, 496 (1999).

$103.4(2.1)^\circ$

$^{11}\text{Li}(p, pn)^9\text{Li}+n$

Y. Kubota ...YLS...et al., RPL 125, 252501 (2020)



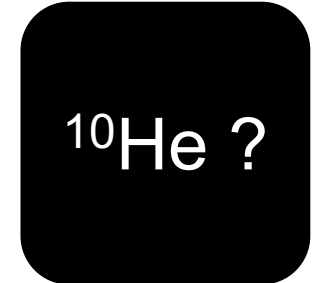
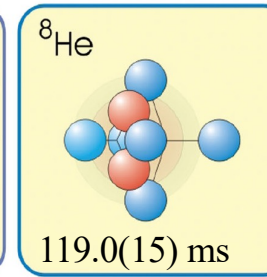
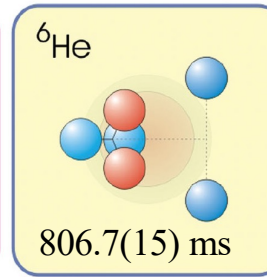
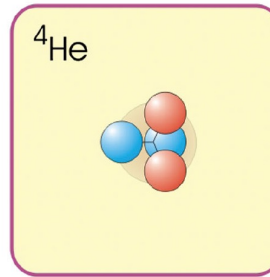
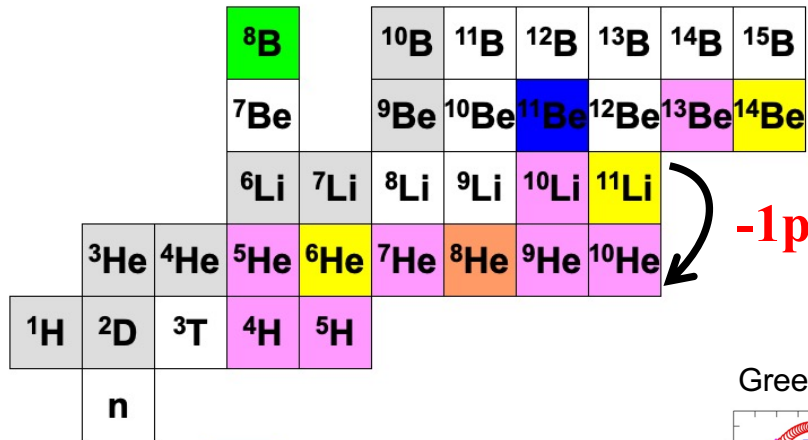
$$\theta_{nf} \sim 180^\circ - \theta_{12}$$

$$\langle \theta_{12} \rangle \sim 80 \text{ deg at } k \sim 0.25 \text{ fm}^{-1}$$

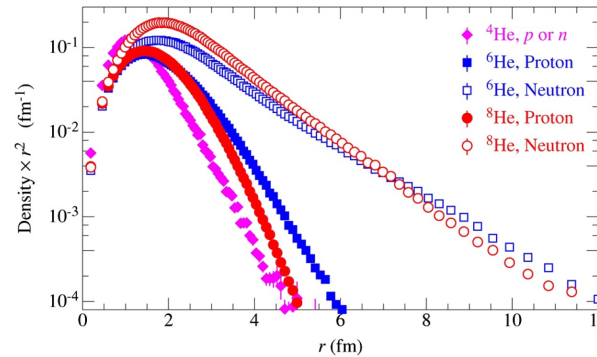
□ Dineutron is localized on the surface of ^9Li core

$$10^{-3} < \frac{\rho}{\rho_0} < 10^{-2}$$

超越He中子滴线的 ^{10}He



Green's function Monte Carlo



Z.-T. Lu *et al.*, Rev. Mod. Phys. **85**, 1383(2013)

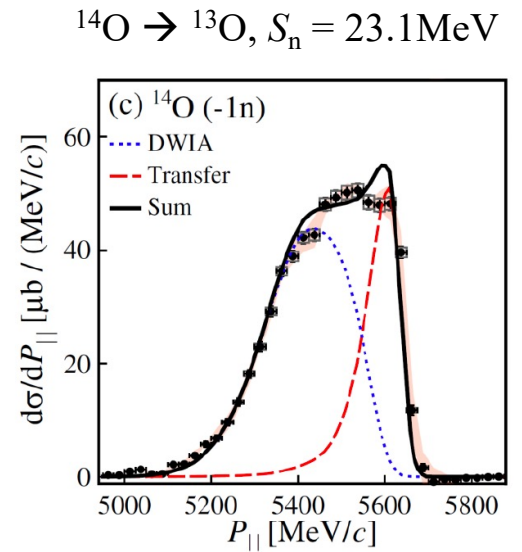
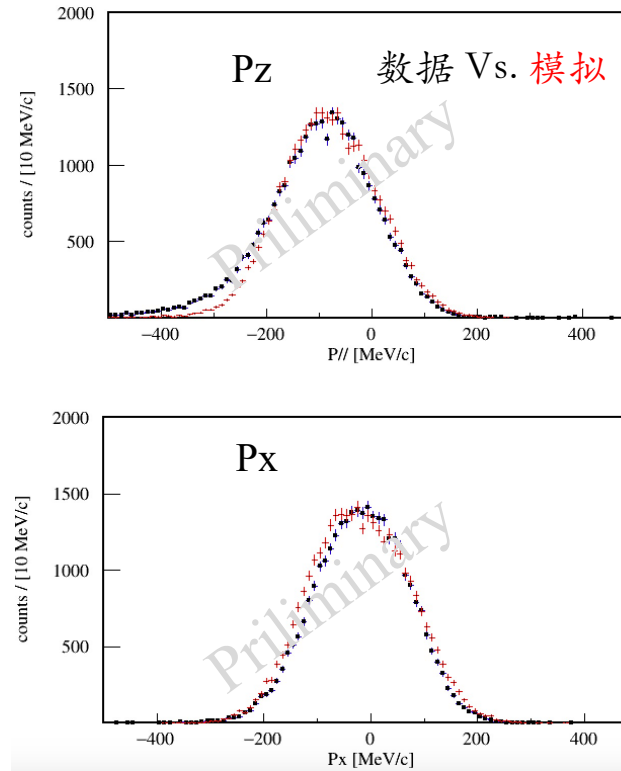
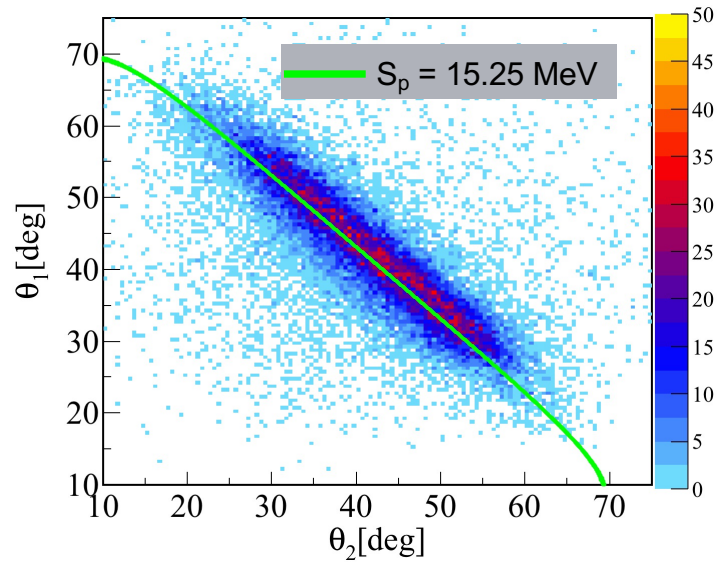
1. 双幻核 $Z=2, N=8$
2. 三明治晕核 $\alpha + 4n + 2n?$

Density matrix renormalization group (DMRG):

The almost identical energies and partial-wave occupations of the ground states of ^8He and ^{10}He support the $^8\text{He} + 2n$ cluster picture of ^{10}He in which an extended dineutron structure is present atop the four-neutron halo in ^8He . In other words, ^{10}He is predicted to be on the brink of forming a nuclear double-halo structure ($^4\text{He} + 4n + 2n$) if not for a few tens of keV, similar to the known $^3\text{He} ^4\text{He}_2$ trimer [80].

K. Fossez *et al.*, PRC 98, 061302(R) (2018)

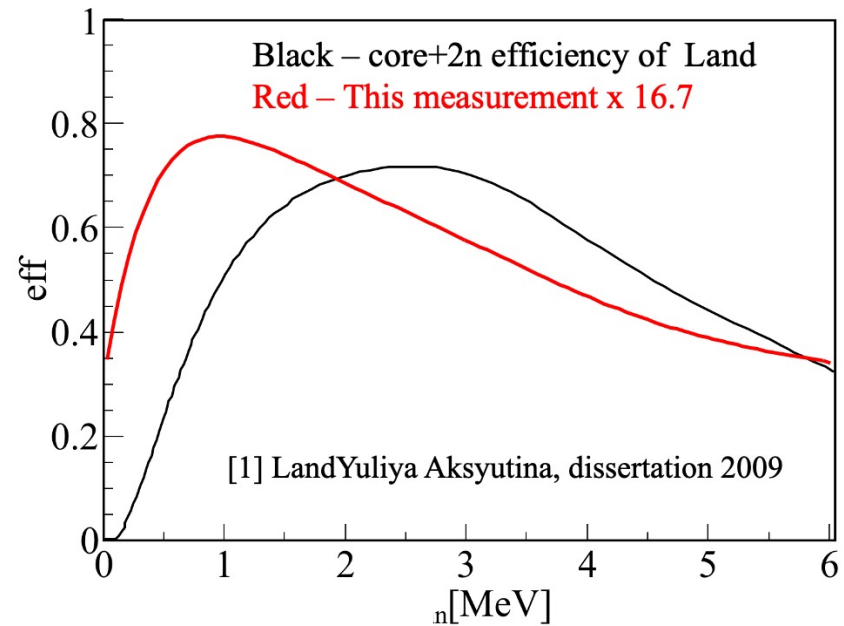
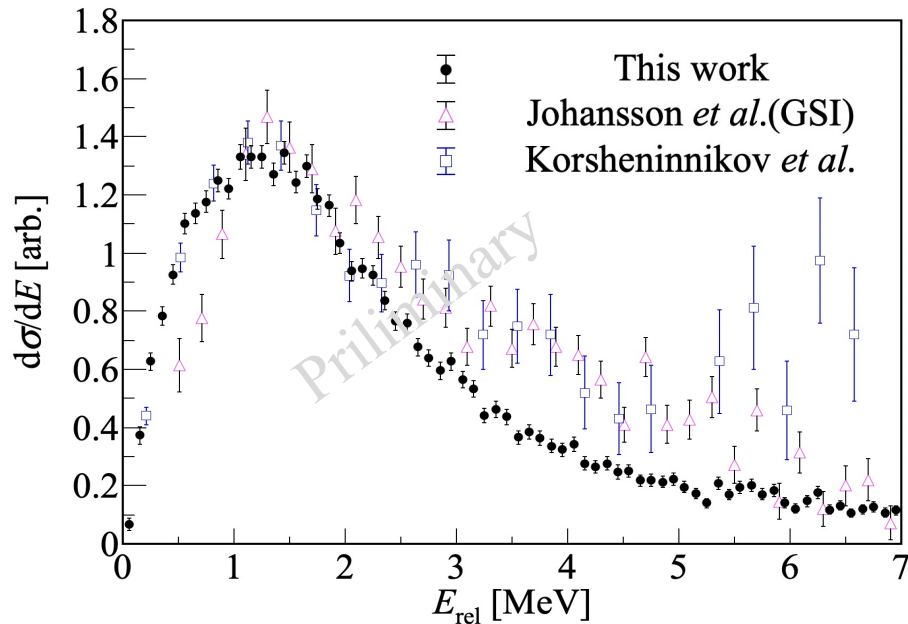
$^{11}\text{Li}(p, 2p)^8\text{He}+2n$



Px/Pz, calculation by **M.Gomez**
→ Removal of a *p*-wave proton

$$^{11}\text{Li} \rightarrow ^{10}\text{He}, S_p = 15.25 \text{ MeV}$$

8He+2n 不变质量谱



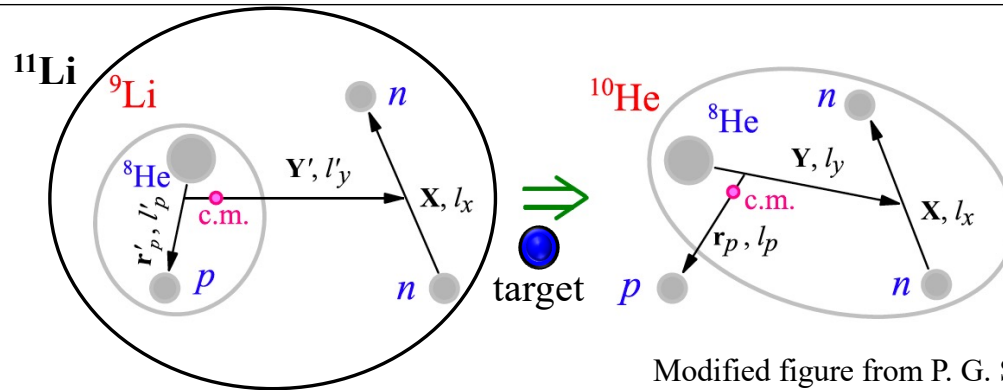
☐ Shoulder below 1MeV

➤ consistent with Korsheninnikov *et al.* (1994), but not with Johansson *et al.* (2010).
(due to enhanced sensitivity at low energy?)

☐ > 2MeV, much better data quality

简化的5体计算

Calculation by Yuma Kikuchi



Modified figure from P. G. Sharov *et al.*, PRC 90, 024610 (2014)

□ ^{11}Li wave function $^9\text{Li}(^8\text{He}+p) + 2n$:

- $2n$: $47\%[0p_{1/2}]^2 + 44\%[1s_{1/2}]^2 + \text{others}$
- reproduce the S_{2n} , matter radius, charge radius and (p, pn) data

Y. Kikuchi *et al.*, PRC 87, 034606 (2013)

Y. Kubota *et al.*, PRL 125, 252501 (2020)

□ Quasifree knockout of a p -wave proton from ^9Li core \rightarrow ^8He ground state $[0s_{1/2}]^2[0p_{3/2}]^4$

Y. Kikuchi *et al.*, PTEP 2016 (2016)

□ ACCC calculation for the ^{10}He states ($^8\text{He} + n + n$)

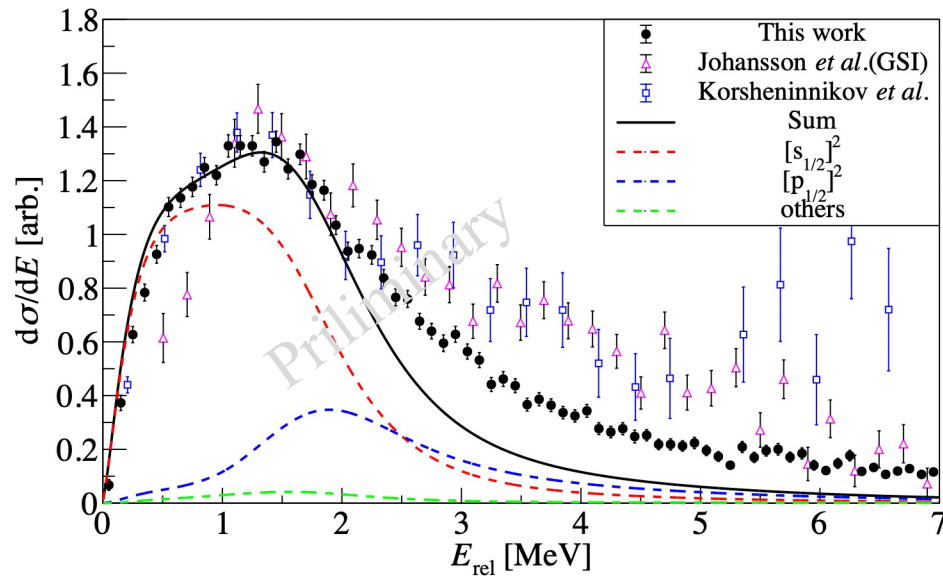
- $^8\text{He} + n$ folding potential
- Av18 nn potential

\rightarrow $^8\text{He} + n$ 相互作用的不确定性

8He + n 相互作用的不确定性

	Reaction	J^π	a_s	note	Ref.
Double charge exchange	${}^9\text{Be}(\pi^-, \pi^+)$	1/2-	x		K. K. Seth et al., PRL 58, 1930 (1987)
	${}^9\text{Be}({}^{13}\text{C}, {}^{13}\text{O})$	1/2-	x		H. G. Bohlen et al., ZPA 330, 227 (1988)
	${}^9\text{Be}({}^{14}\text{C}, {}^{14}\text{O})$	1/2-	x		W. von Oertzen, NPA 588, c129 (1995)
Knockout	$\text{Be}({}^{11}\text{Be}, {}^8\text{He}+n)$	1/2+	≤ -10 fm	Strong	L. Chen et al., Phys. Lett. B 505, 21 (2001)
	$\text{C}({}^{14}\text{B}, {}^8\text{He}+n)$	1/2+	-3 fm ~ 0	Weak	H. Al Falou et al., JPC 312, 092012 (2011)
	$\text{C}({}^{11}\text{Be}, {}^8\text{He}+n)$				
	$\text{H}({}^{11}\text{Li}, {}^8\text{He}+n)$	1/2+	-3.17(66) fm	Weak	H. T. Johansson et al., NPA 842, 15 (2010)
	$\text{Be}({}^{11}\text{Be}, {}^8\text{He}+n)$	1/2+	-2.0 (6)(2) fm -6.8(12)(7) fm	Weak	<u>D. Votaw, et al., PRC 102, 014325 (2020)</u>
Transfer	${}^8\text{He}(d, p)$	1/2+	> -20 fm		M. S. Golovkov et al., PRC 76, 021605(R) (2007)
	${}^8\text{He}(d, p)$	1/2+	x		S. Fortier et al., AIP Conf. Proc. 912, 3 (2007)
	${}^8\text{He}(d, p)$	(1/2+)	-12 ± 3 fm	Strong	T. Al Kalanee et al., PRC 88, 034301 (2013)
Elastic scattering	${}^8\text{He}(p, p')$	1/2+	-1.7fm ~ 0	Weak	E. Uberseder et al., PLB 754 323-327(2016) <u>Grigory Rogachev private communication</u>

理论和数据比较



$$-1.7 \text{ fm} < a_s < 0$$

E. Uberseder *et al.*, PLB 754 323-327(2016)
Grigory Rogachev private communication

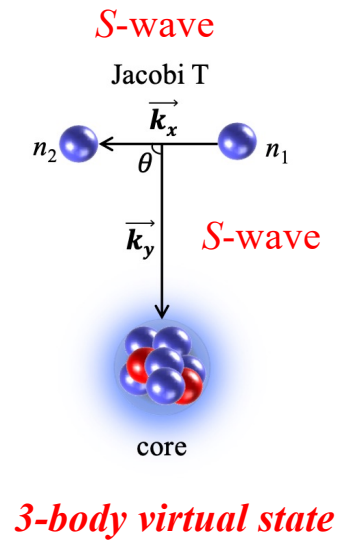
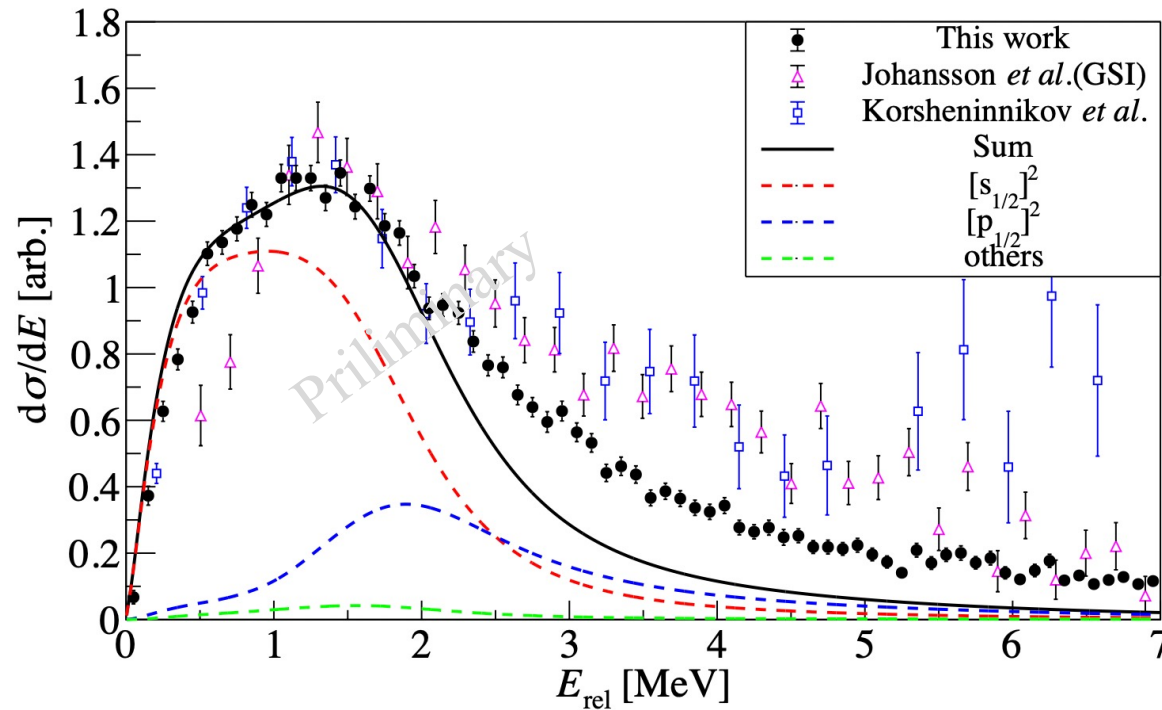
$$a_s = -2.0 (6)(2) \text{ fm}$$

$$a_s = -6.8(12)(7) \text{ fm}$$

D. Votaw, *et al.*, PRC 102, 014325 (2020)

- ❑ ^8He -n interaction based on current ^{10}He spectrum
- s -wave scattering length -3.45 fm (close to recent ^9He results)
- ❑ Calculation reproduce the data below 2 MeV, underestimates strength above

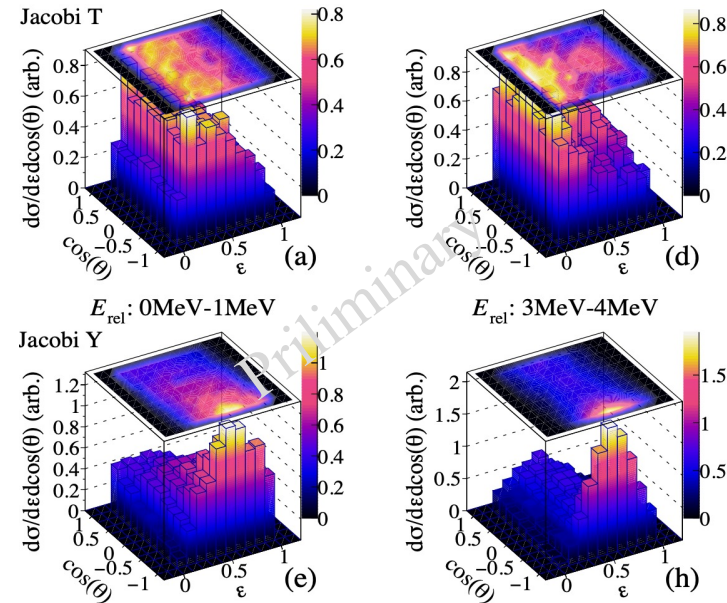
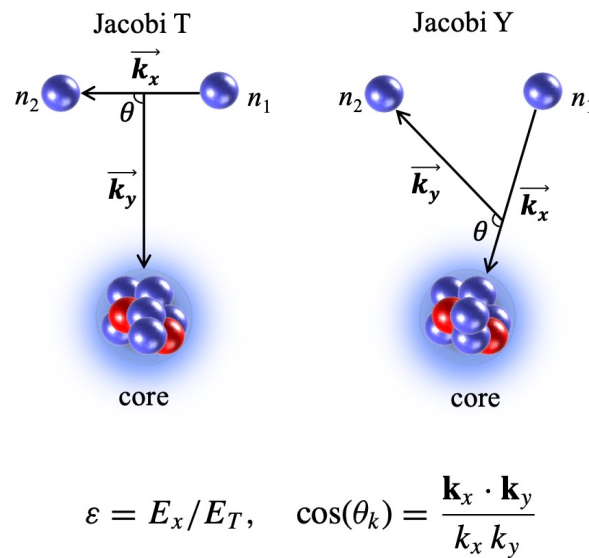
理论和数据比较



Calculation by Yuma Kikuchi

- Calculation reproduce the data below 2 MeV, underestimates strength above.
- Co-existing of two 0^+ with $[s_{1/2}]^2$ and $[p_{1/2}]^2$ configurations.

第一个零正态的特征：三体s波虚态？

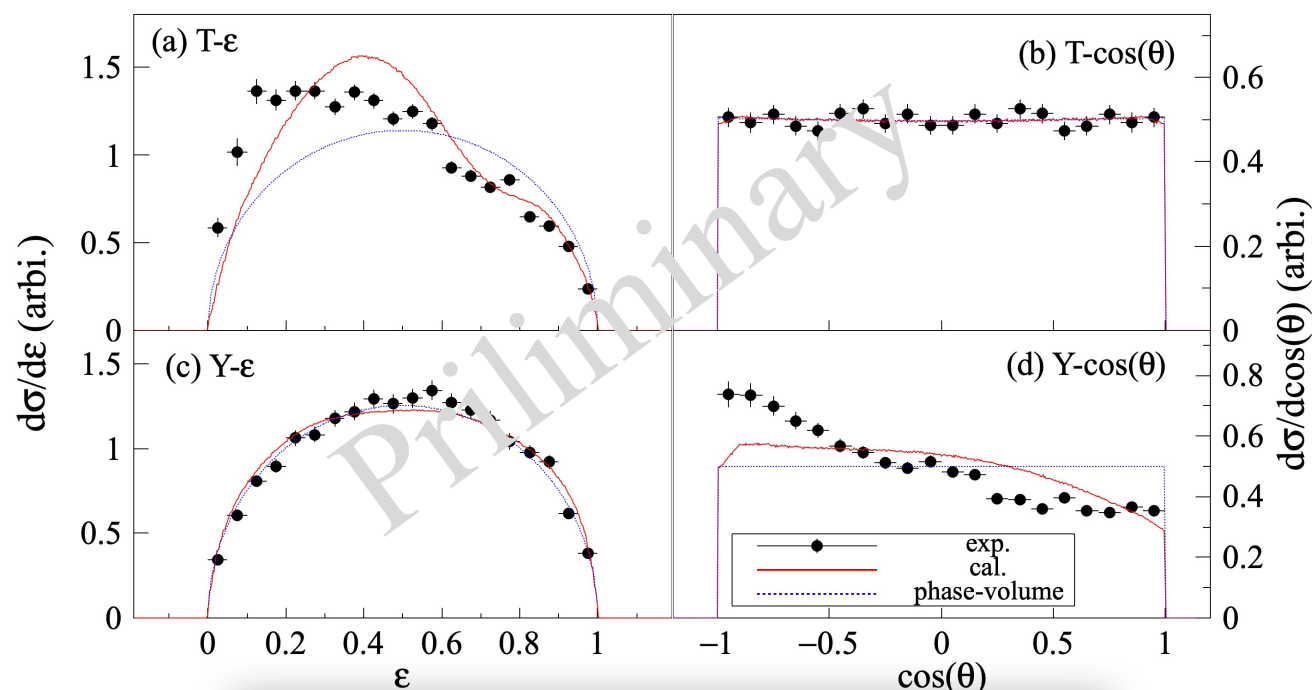


“pure $[s]^2$ configuration produce a featureless “phase-volume” energy distribution”

$$dj/dE_x \sim \sqrt{E_x(E_T - E_x)}. \quad \text{L. V. Grigorenko et al., PRC 80, 034602 (2009)}$$

第一个零正态的特征：三体s波虚态？

0 – 1MeV, $[s_{1/2}]^2$ 占主导, 无量三体衰变Vs. 有关联三体衰变



Calculation by Yuma Kikuchi

总结和展望

- SAMURAI31: $^{14}\text{O}(p, pN)^{13}\text{O}/^{13}\text{N}$ @ $\sim 100\text{MeV/u}$, 提取了单核子移除截面和剩余核动量分布。
 - ✓ 通过和反应模型比比较: 非弹激发对弱束缚质子移除贡献40-50%, (p, d)转移对深束缚中子移除贡献约30%; 考虑非弹激发、转移等机制后, 提取的约化因子不显著依赖于 ΔS 。

- SEASTAR3: RIBF + MINOS + SAMURAI @ $\sim 250\text{MeV/u}$, 在 $Z = 20$ 丰中子区系列(p, pN) 反应。
 - ✓ $^{52,54}\text{Ca}(p, 2p)^{51,53}\text{K}$, 截面和剩余核动量分布, 揭示了质子 $s_{1/2}$, $d_{3/2}$ 壳随中子数的演化。
 - ✓ $^{52,54}\text{Ca}(p, pn)^{51,53}\text{Ca}$, 截面和剩余核动量分布, 再次证实了 $N = 32, 34$ 这两个新幻数。

- SAMURAI018 : RIBF + MINOS + SAMURAI @ $\sim 250\text{MeV/u}$
 - ✓ $^{11}\text{Li}(p, pn)^{10}\text{Li}$, 截面和缺失动量分布, 提取了 ^{11}Li 的价中子构型; 发现双中子在 ^9Li 表面结团。
 - ✓ $^{11}\text{Li}(p, 2p)^{10}\text{He}$, 新的高质量 ^{10}He 不变质量谱; 通过三体关联分析发现 ^{10}He 的基态可能是一个三体s波虚态。