Spectroscopy of nuclei near and beyond the neutron dripline

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Note: In this version, unpublished data are excluded

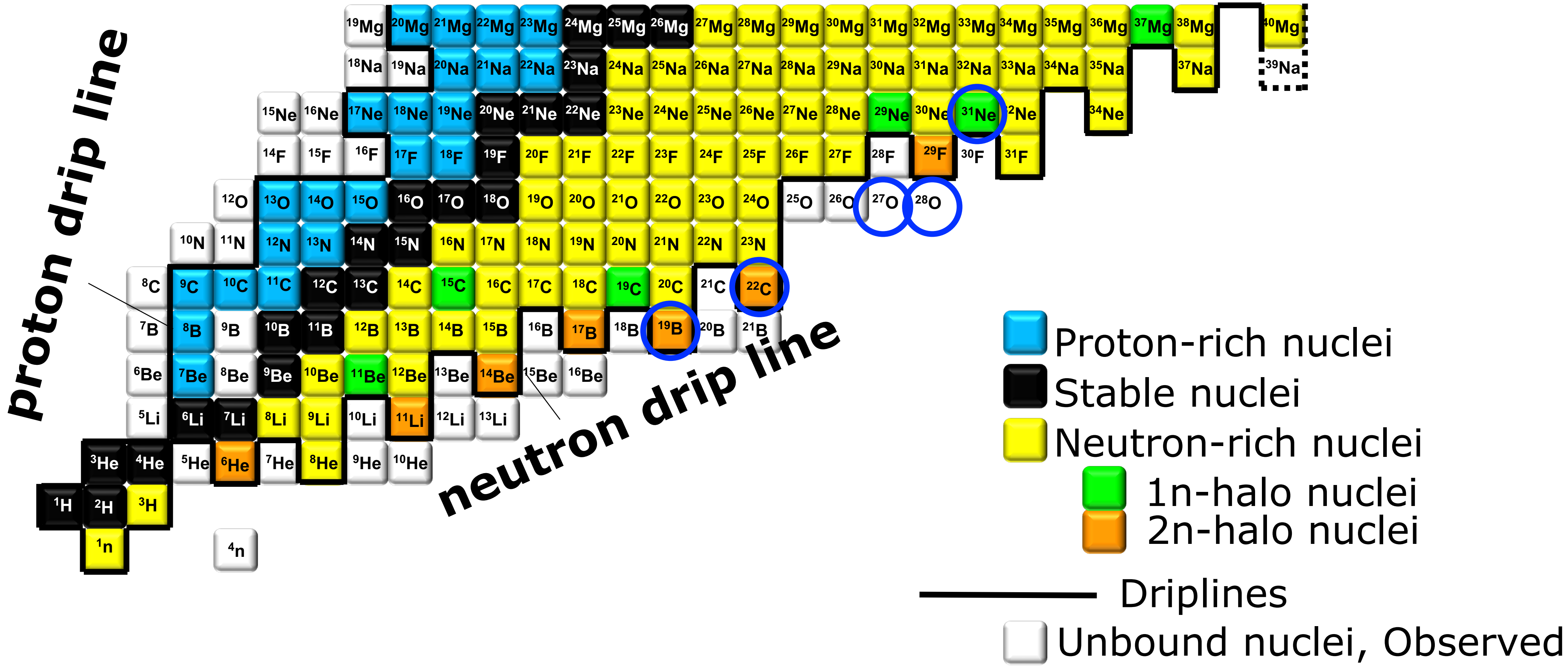
ECT* Workshop on "nuclear Physics at the edge of stability" @4-8, July 2022

Contents

Tokyo Tech

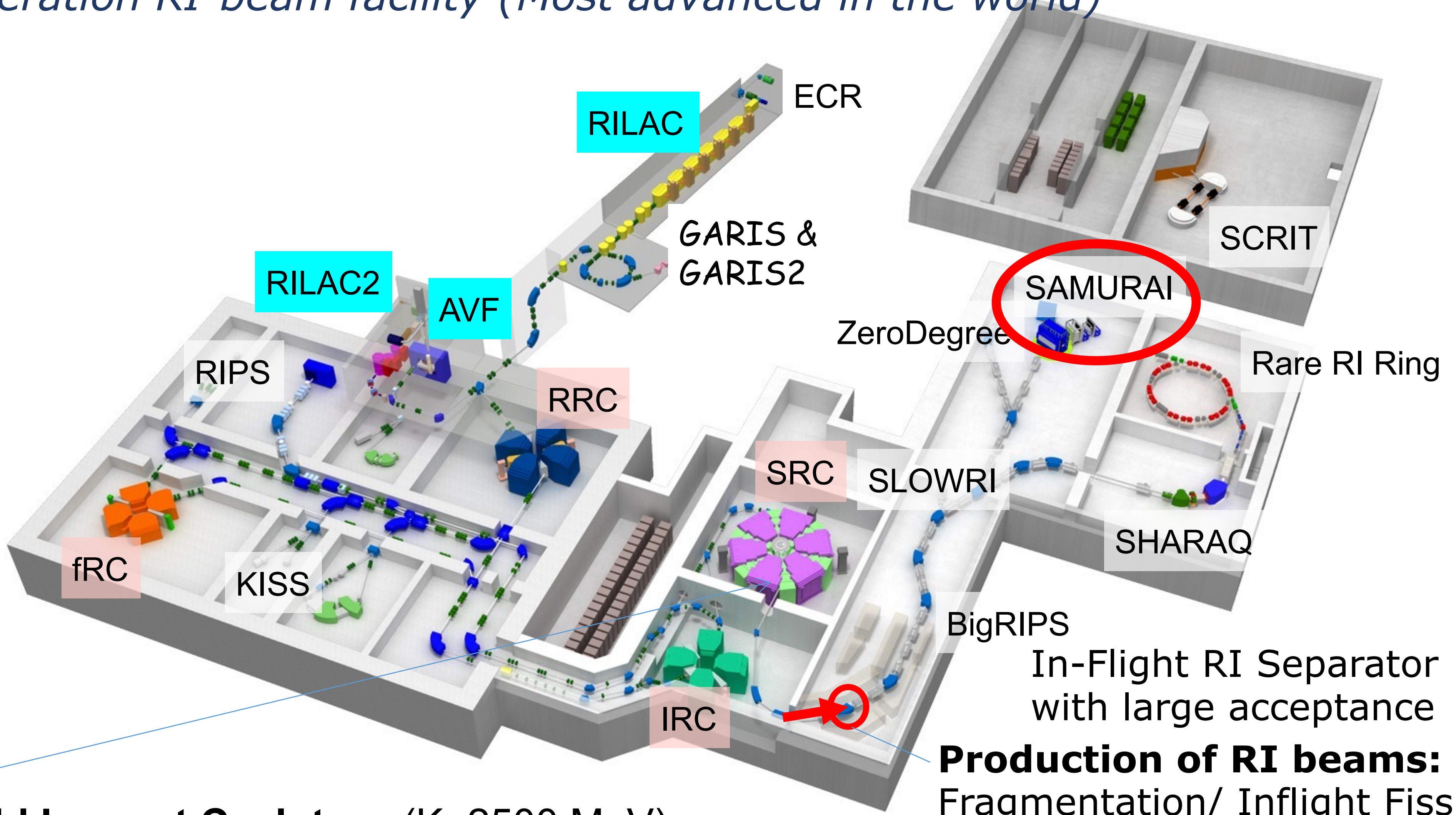
Nuclear Landscape at the limit

Dripline– Boundary of Closed/Open quantum systems
→Clusters/Halo/Shell Evolution



RI Beam Factory (RIBF) at RIKEN 2007~

The 3rd-generation RI-beam facility (Most advanced in the world)



BigRIPS In-Flight RI Separator with large acceptance

Production of RI beams:
Fragmentation/ Inflight Fission

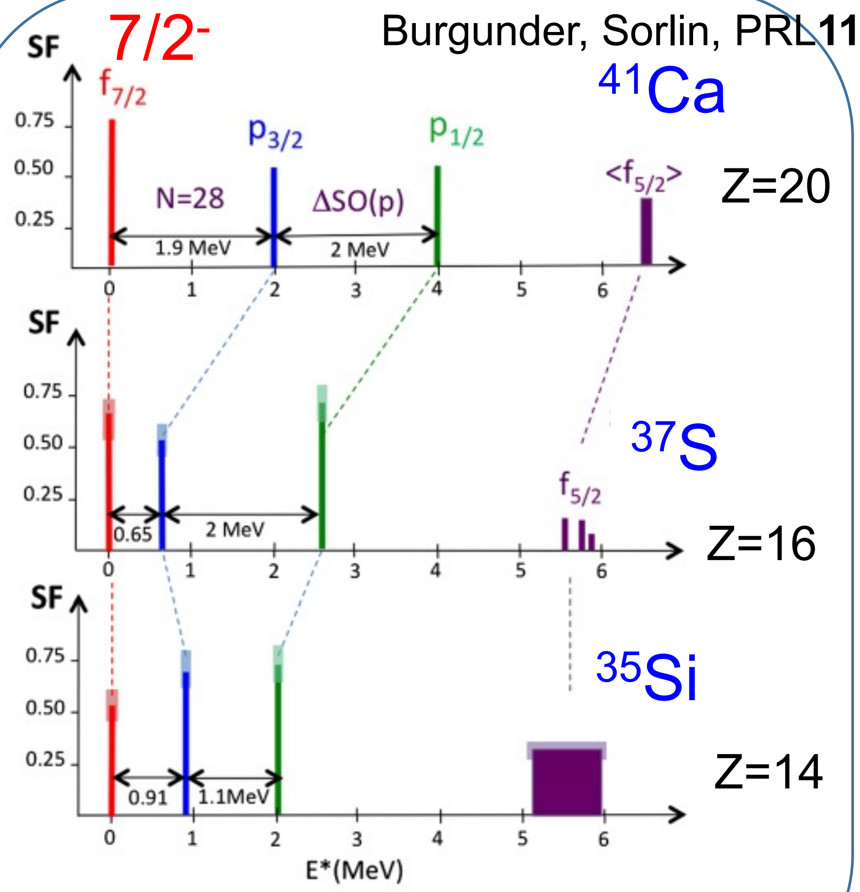
SRC: World Largest Cyclotron (K=2500 MeV)
High-Intense Heavy Ion Beams up to ^{238}U at 345MeV/u
eg. ^{48}Ca: ~700pnA (~4x10^{12}pps) *~10 times compared to 2008*
^{238}U: ~100pnA (~6x10^{11} pps) *~10^3 times compared to 2007*

Halo-Shell Interplay -- ^{31}Ne

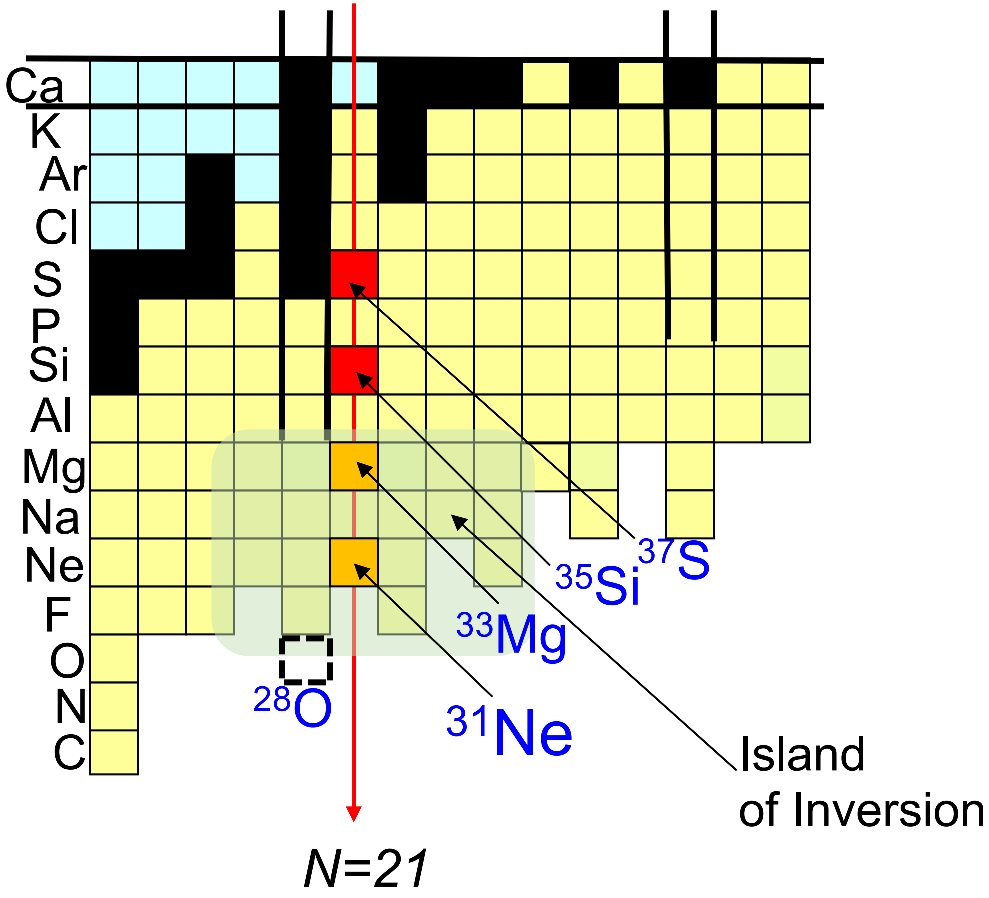
T. Tomai, et al.

Shell Evolution along N=21

Burgunder, Sorlin, PRL**112**,042502 (2014).^{34}Si(d,p)^{35}Si



Spherical ($f_{7/2}p_{3/2}$ gap is smaller for Z=16,14, though)



^{33}Mg gs: 3/2$^-$ Z=12

^{31}Ne gs: 3/2$^-$ Z=10

Deformed: Island of inversion

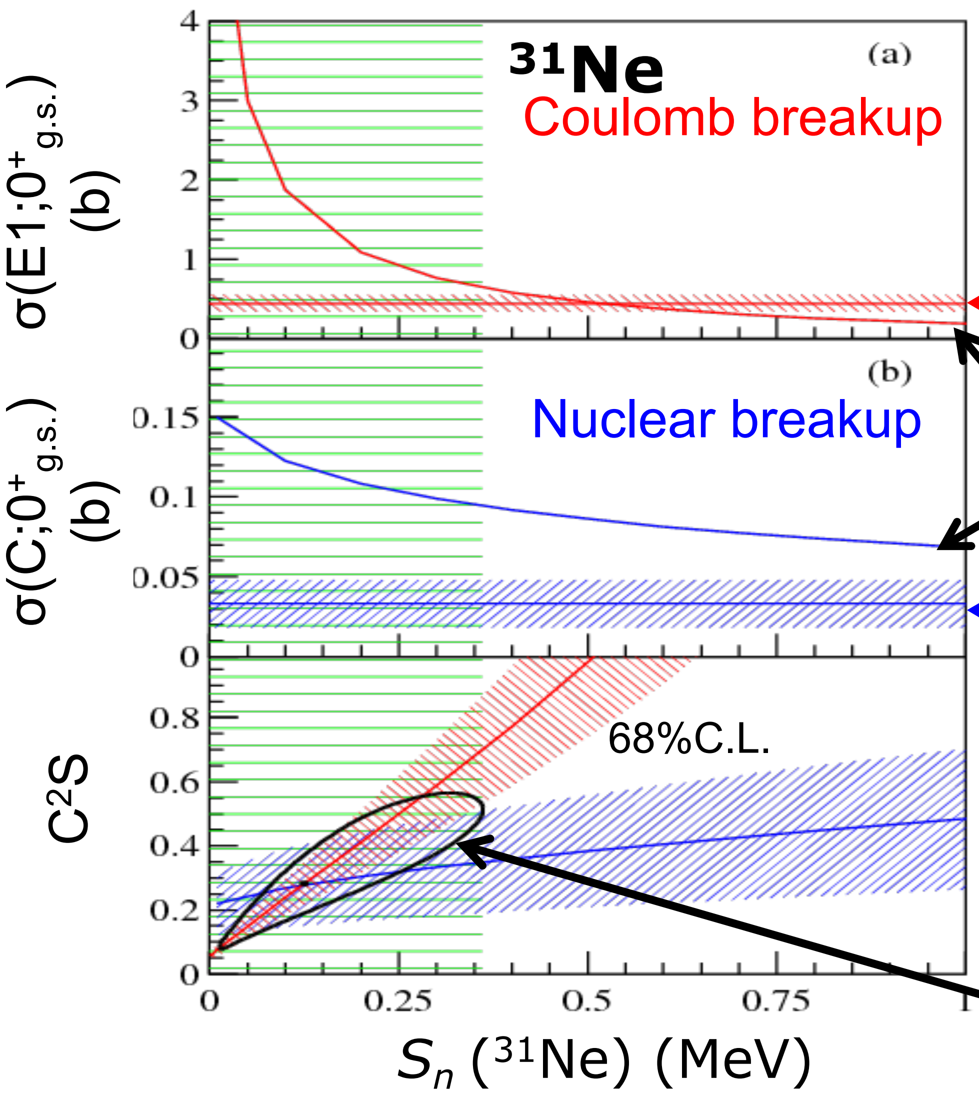
Both N=20, N=28 Shell gaps: LOST!

^{33}Mg: R.Kanungo PLB**685**, 253 (2010).
D.Bazin PRC**103**, 064318 (2021).

^{31}Ne: TN, N.Kobayashi et al., PRL**103**,262501(2009), PRL**112**, 142501(2014)

Previous work: Inclusive Coulomb/nuclear breakup of ^{31}Ne ($\rightarrow ^{30}$Ne+X+(γ))

TN, N.Kobayashi et al., PRL **112**, 142501 (2014).



$|^{31}Ne_{g.s.}\rangle$: 3/2$^-$ $|^{30}Ne(0^+_{g.s.}) \otimes p_{3/2}\rangle$ component

Exp. $\sigma_{-1n}(E1;0^+_{g.s.})$ = 448(108) mb

Theoretical calc. for
$|^{31}Ne_{g.s.}\rangle = |^{30}Ne(0^+_{g.s.}) \otimes p_{3/2}\rangle$ (C^2S = 1)

Exp. $\sigma_{-1n}(C;0^+_{g.s.})$ = 33(15) mb

^{31}Ne: **3/2$^-$** **p**-wave halo
Deformed in spite of **N=21**

$$C^2S = 0.32^{+0.21}_{-0.17}$$

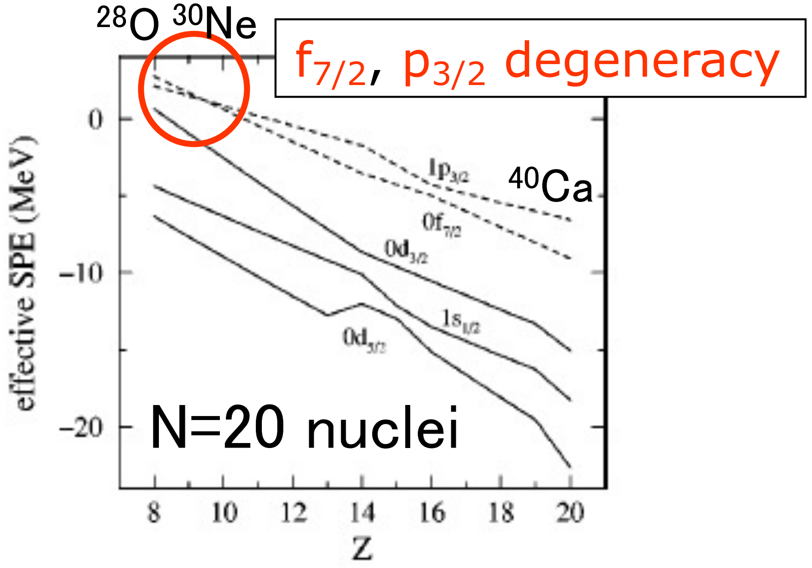
$$S_n = 0.15^{+0.16}_{-0.10}\ \mathrm{MeV}$$

S_n (^{31}Ne)=-0.06(0.42) MeV L.Gaudefroy et al., PRL(2012)

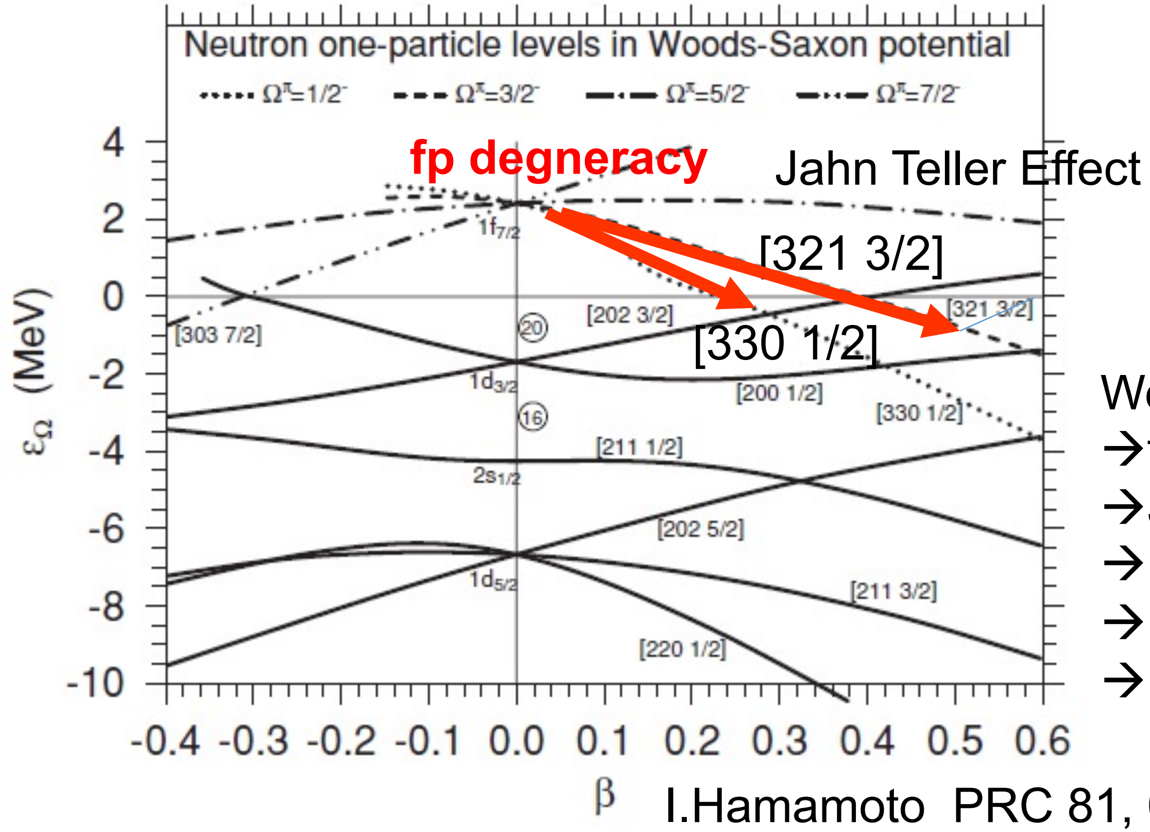
^{37}Mg: N.Kobayashi, TN et al., PRL **112**, 242501 (2014). 3/2$^-$/1/2$^-$ S_n=220(12)keV
^{29}Ne: N.Kobayashi, TN et al., PRC **93**, 014613 (2016). 3/2$^-$ S_n=960(140) keV

Deformation Driven p-wave Halo nucleus ^{31}Ne

Large Scale Shell Model (SDPF-M)



Y.Utsuno, T.Otsuka et al.
PRC 054315 (1999).



Weakly-bound effect
→fp degeneracy
→Jahn Teller effect
→ Strongly deformed
→ pf mixed, p enhanced
→ Halo developed

I.Hamamoto PRC 81, 021304(R) (2010)
I.Hamamoto PRC 85, 064329 (2012)

How deformed quantitatively?, [330 1/2] or [321 3/2]?,
Shell Structure of halo nuclei (Weakly-bound/continuum effects)?
What is the mechanism of fp degeneracy?

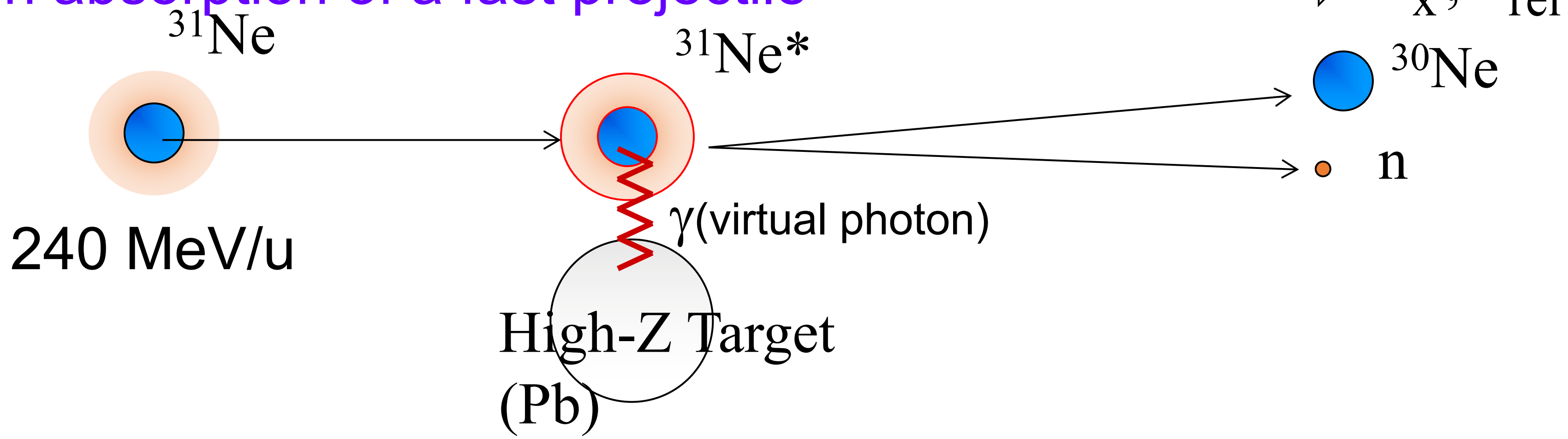
Exclusive Coulomb Breakup

→Photon absorption of a fast projectile

$\vec{P}(n), \vec{P}(^{30}\mathrm{Ne})$

Invariant Mass

⇨ E_x, E_{rel}

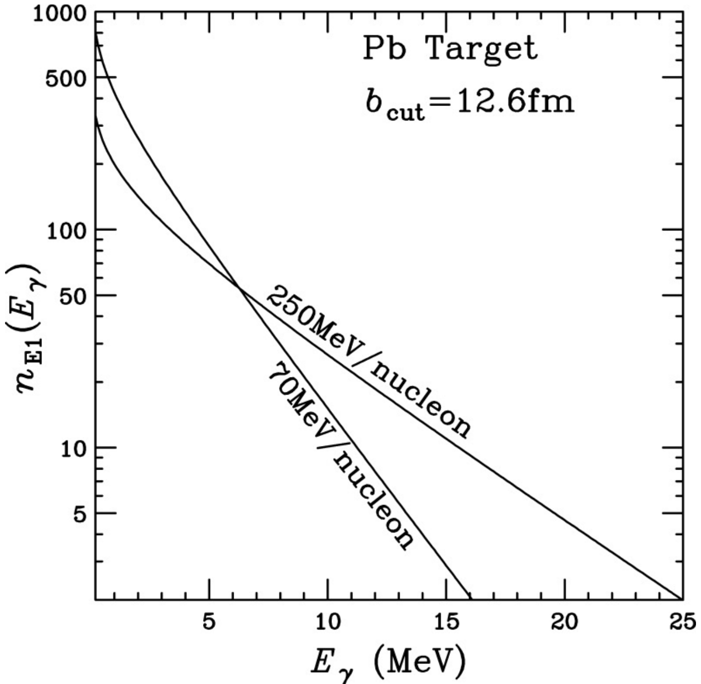


Equivalent Photon Method

$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)x(Transition Probability)

C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).

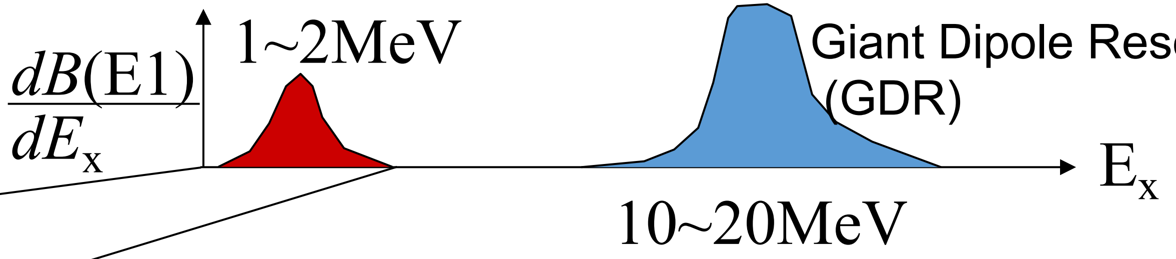


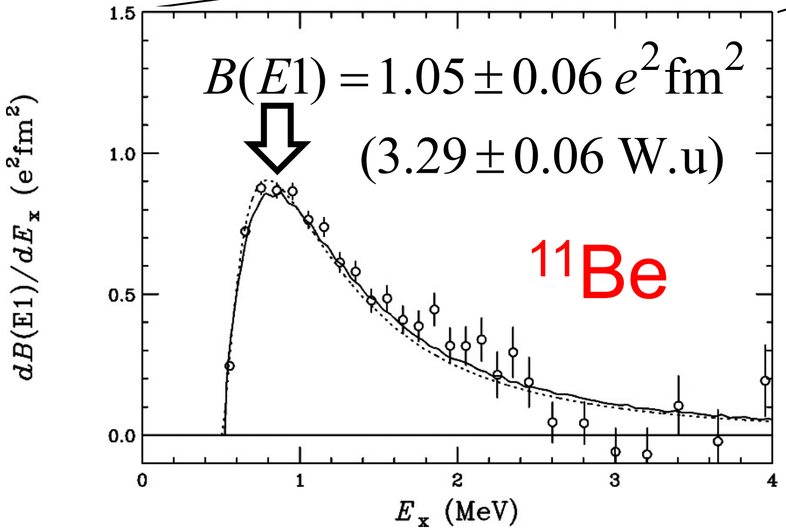
Halo → Soft E1 Excitation

(E1 Concentration at Ex<1MeV)

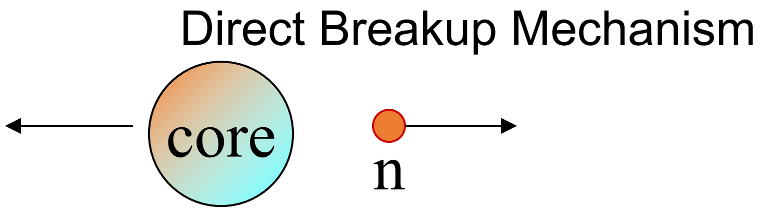
Coulomb Breakup and E1 Response--Case of 1n Halo

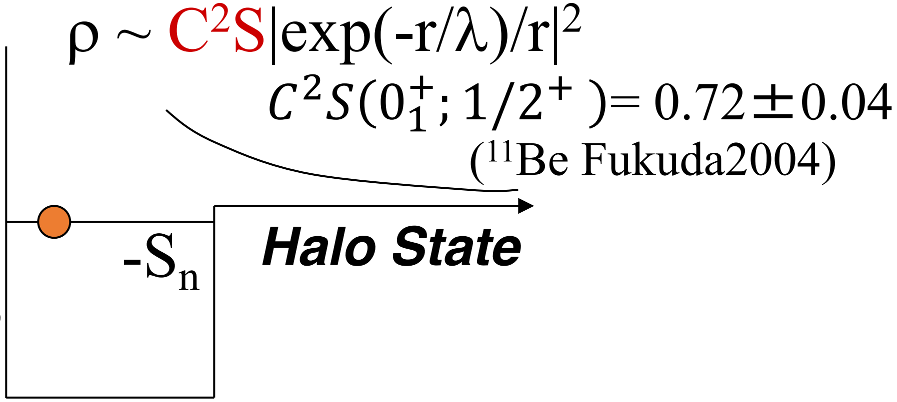
Low-lying E1 Strength (Soft E1 excitation)





N.Fukuda, TN et al., PRC70, 054606 (2004)
TN *et al.*,PLB 331,296(1994)
Palit et al., PRC68, 034318(2003)





E1 Strength

$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1{}_m|\Phi_{gs}\rangle|^2$$
$$\propto C^2S\,|\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1{}_m|s_{1/2}\rangle|^2$$

Fourier Transform

Soft E1 Excitation of 1n halo—Sensitive to S_n, l, C^2S

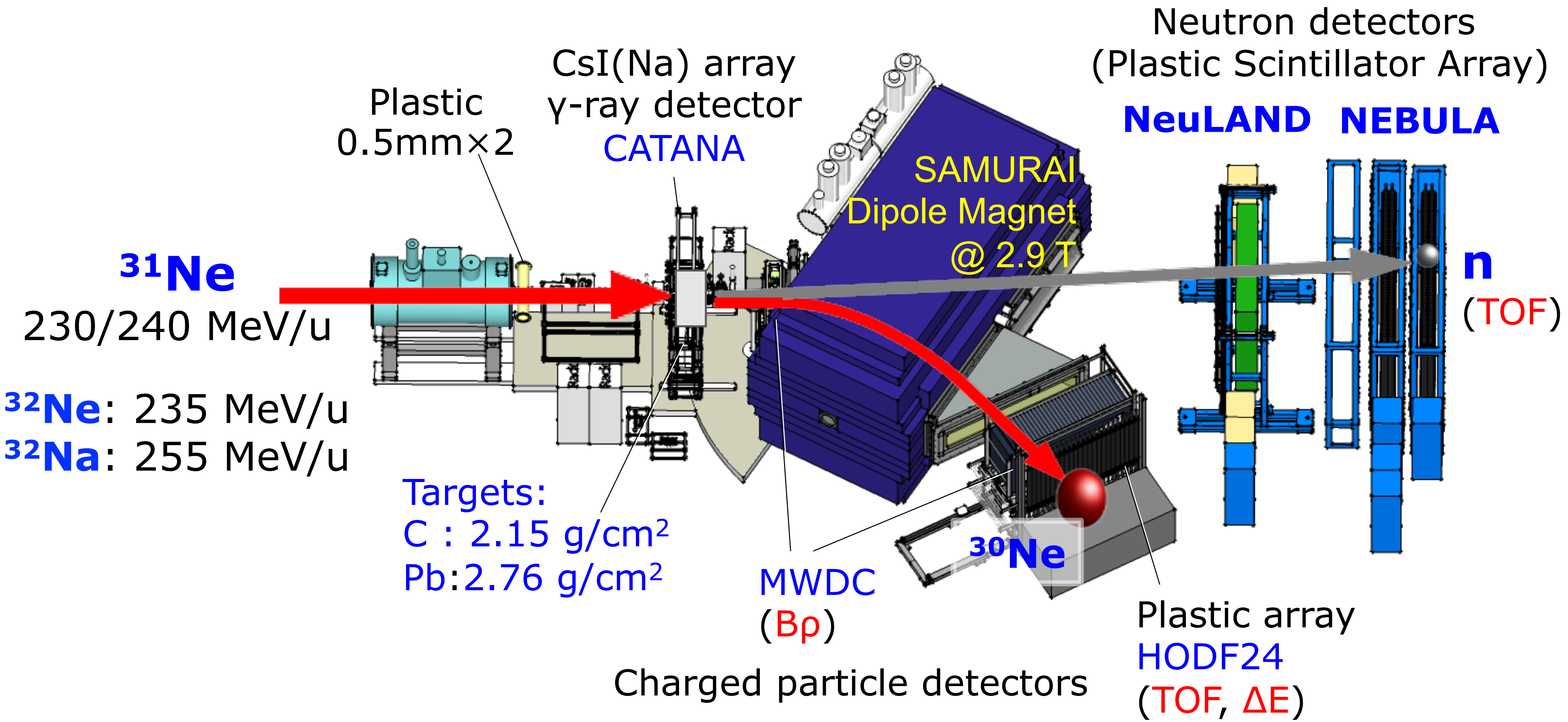
e.g. Peak Energy

s-wave halo: $E_{rel}^{(peak)} \cong \frac{3}{5}S_n$ p-wave halo (p→s): $E_{rel}^{(peak)} \cong 0.18S_n$

Experimental Setup SAMURAI@RIBF

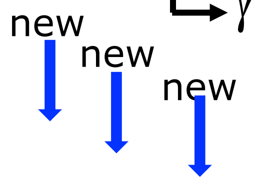
Tokyo Tech

Full Exclusive Coulomb Breakup Measurement of ^{31}Ne **T.Tomai et al.**



γ-ray spectrum : Excited-core component

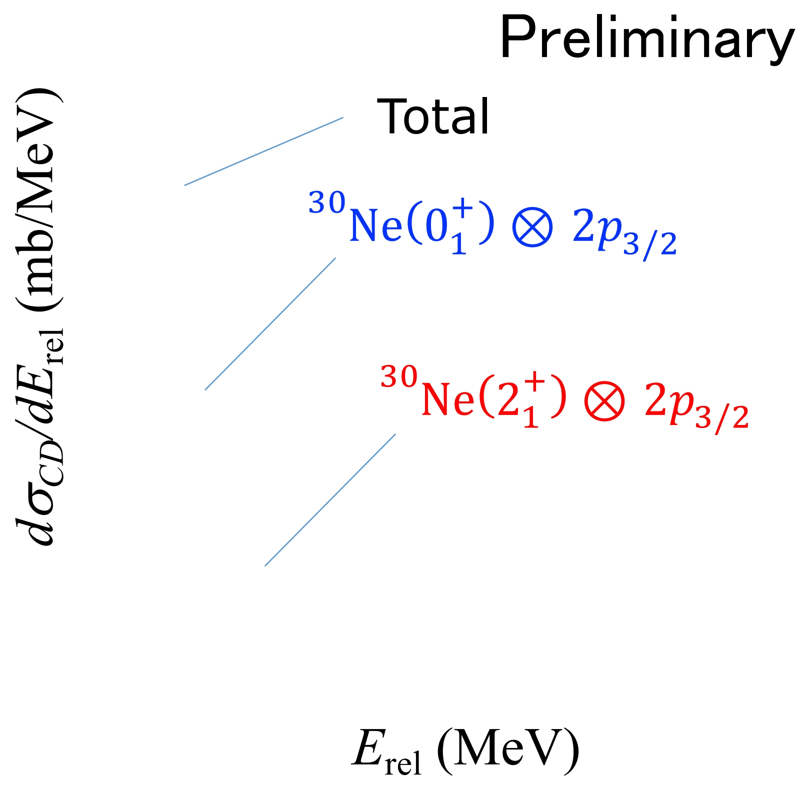
^{31}Ne+C→^{30}Ne*+X
└→γ



$$|^{31}\mathrm{Ne}(3/2^-)> = \alpha|^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2} > +\beta|^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2} > \cdots$$

Coulomb breakup	σ_{CB} (^{30}Ne+n) [mb] Integral E_{rel}=0-5MeV
^{31}Ne→^{30}Ne(total)	
^{31}Ne→^{30}Ne(0$^+$)	
^{31}Ne→^{30}Ne(2$^+$)	
Ratio(0$^+$: 2$^+$)	

Coulomb breakup of ^{31}Ne: **Energy Spectrum**



Preliminary

		$^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}$	$^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}$
	S_n (MeV)	$C^2S(0_1^+;3/2^-)$	$C^2S(2_1^+;3/2^-)$
This work			
Prev. work*	$0.15^{+0.16}_{-0.10}$	$0.32^{+0.21}_{-0.17}$	-
SM(SDPF-M)		0.21	0.34

*TN, N. Kobayashi et al., PRL**112**, 142501 (2014).

$$|^{31}\mathrm{Ne}(3/2^-)> = \alpha\,|^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}> + \beta\,|^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}>$$

$$\alpha^2 = C^2S(0_1^+;3/2^-) \qquad \beta^2 = C^2S(2_1^+;3/2^-)$$

Double−Component Halo

$$|{}^{31}\mathrm{Ne}(3/2^-)> = \alpha|{}^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}> + \beta|{}^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}>$$

$\alpha^2 = 0.22 \pm 0.04$ $\beta^2 = 0.52^{+0.07}_{-0.10}$

Preliminary

Double-Component Halo:

- ✓ Unique feature of p-wave halo

(Single-component for s-wave halo)

- ✓ Coupled to Rotation→Deformed halo

Amplitude ratio of 0^+, 2^+
With Particle Rotor Model (PRM)
→ Quadrupole deformation

$\rightarrow \beta \sim 0.2 - 0.6$

- ➢ PRM Calculation for $S_n = 0.3$ MeV

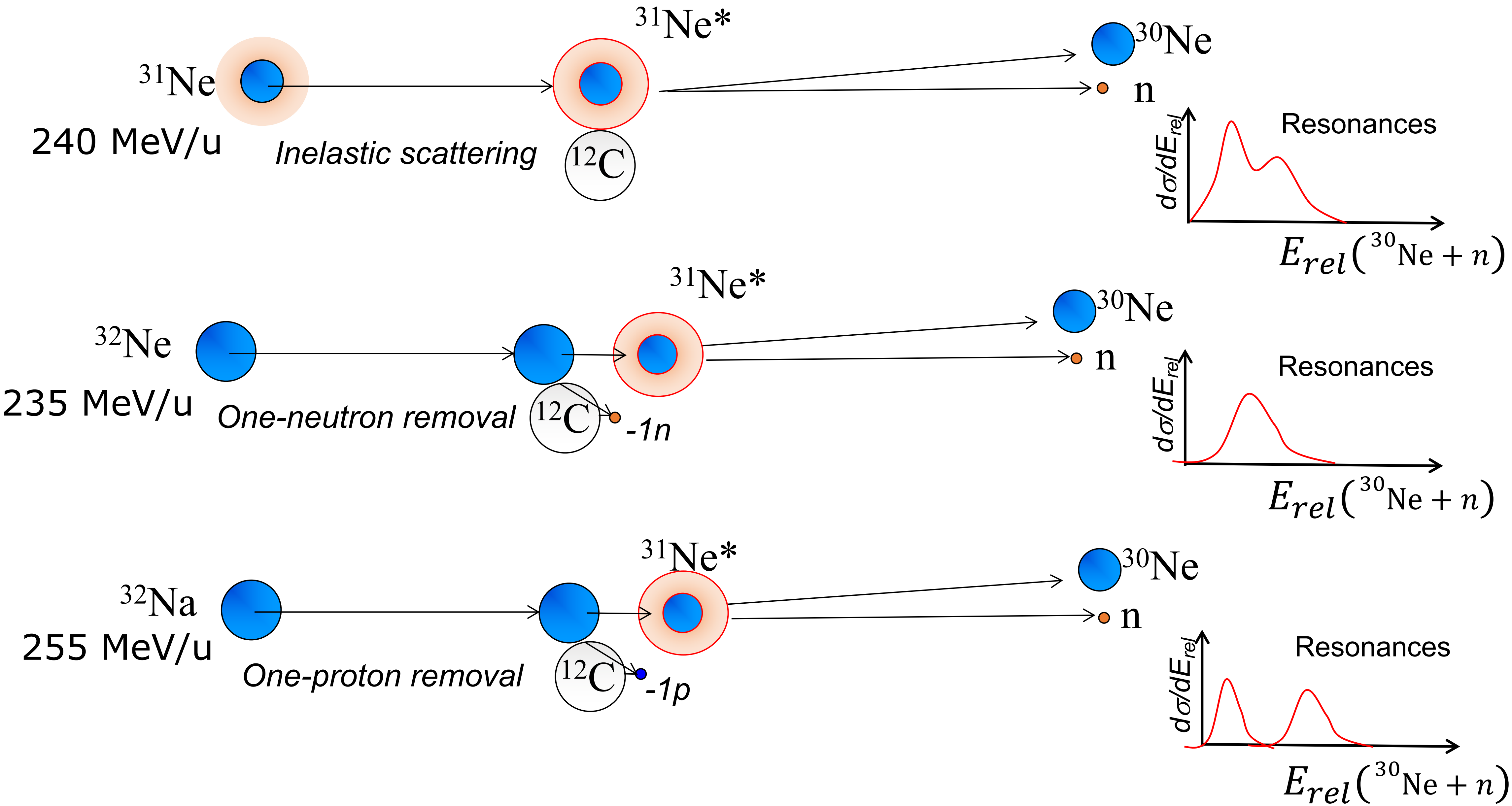
β_2	$[0^+ \otimes p_{3/2}]$	$[2^+ \otimes p_{3/2}]$	$[2^+ \otimes p_{1/2}]$
0.1	0%	6.5%	0%
0.2	44.9%	8.4%	2.0%
0.55	1.9%	29.7%	4.4%

$\sqrt{\langle r^2 \rangle} =$

c.f. ^{11}Be: $\sqrt{\langle r^2 \rangle} = 5.77 \pm 0.16$ fm
N.Fukuda PRC70, 054606 (2004).

Y.Urata, K.Hagino, H.Sagawa, PRC83, 041303(R) (2011).

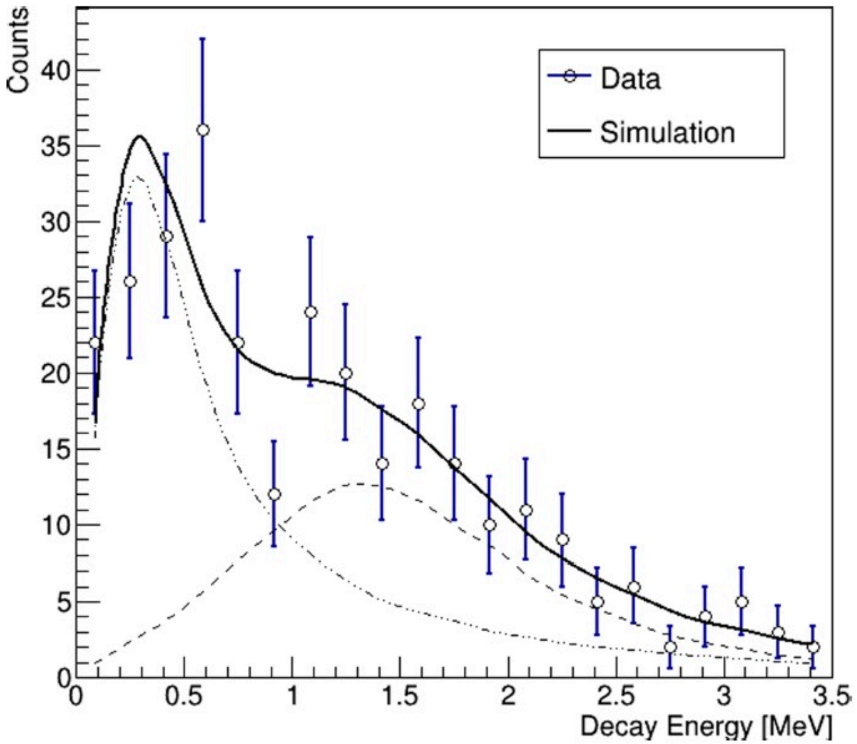
Exclusive Nuclear Breakup



Previous Work: @MSU

D. Chrisman et al., PRC 104, 034313 (2021)

^{33}Mg(-2p)→^{31}Ne*→^{30}Ne+n
89MeV/u



$$E_{rel} = 0.30(17), 1.50(33)\mathrm{MeV}$$

No γ coincidence measurement done

Results

Preliminary

Decay to $^{30}Ne(0_1^+)$

Decay to $^{30}Ne(2_1^+)$
(E_γ=792keV coincidence)

$^{31}Ne+C \rightarrow {}^{31}Ne^* \rightarrow {}^{30}Ne+n$
Inelastic

$^{32}Ne+C \rightarrow {}^{31}Ne^* \rightarrow {}^{30}Ne+n$
-1n

$^{32}Na+C \rightarrow {}^{31}Ne^* \rightarrow {}^{30}Ne+n$
-1p

In addition,
Observed
resonances
decay to $^{30}Ne(4^+)$

^{31}Ne Levels observed by ^{31}Ne, ^{32}Ne, ^{32}Na induced reactions

Preliminary

- ✓ Excited states at observed
- ✓ E(3/2⁻) < E(5/2⁻) < E(7/2⁻) → K=3/2 Rotational Band (Nilsson [321 3/2])
- ✓ $E_x(7/2^-)/E_x(5/2^-)=$ c.f. 2.4← $E_x \propto I(I+1) - I_{gs}(I_{gs}+1)$

3/2⁻

3/2⁻

3/2⁻

Inelastic

^{32}Ne −1n

^{32}Na −1p

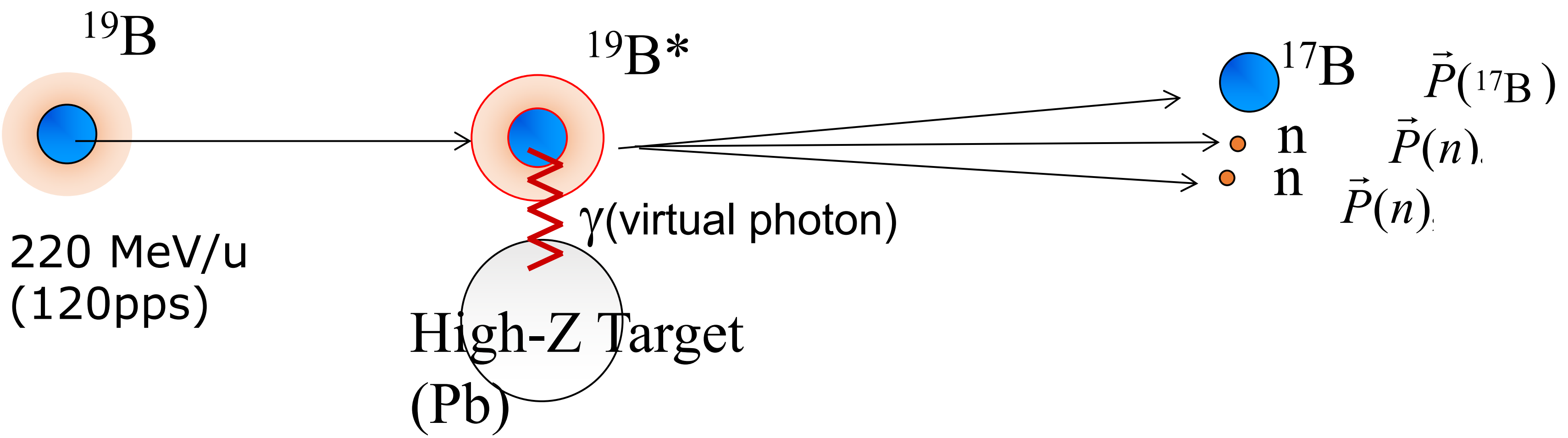
Two-neutron halo—^{19}B/^{22}C

Coulomb breakup of ^{19}B: K.J. Cook et al., PRL2020

Coulomb breakup of ^{22}C: N. Nakatsuka et al., in preparation

Coulomb Breakup of ^{19}B

K. J. Cook, TN et al.PRL124, 212503, 2020



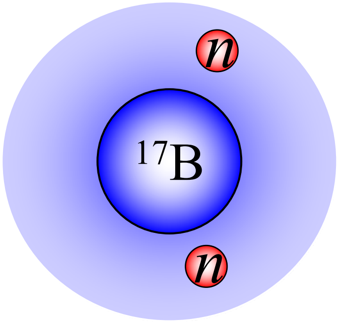
PHYSICAL REVIEW LETTERS **124,** 212503 (2020)

Editors' Suggestion

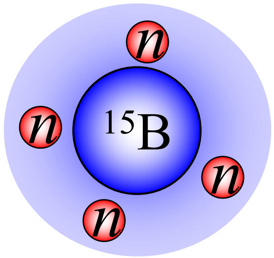
Halo Structure of the Neutron-Dripline Nucleus ^{19}B

K. J. Cook,[1,*] T. Nakamura,[1] Y. Kondo,[1] K. Hagino,[2] K. Ogata,[3,4] A. T. Saito,[1] N. L. Achouri,[5] T. Aumann,[6,7] H. Baba,[8] F. Delaunay,[5] Q. Deshayes,[5] P. Doornenbal,[8] N. Fukuda,[8] J. Gibelin,[5] J. W. Hwang,[9] N. Inabe,[8] T. Isobe,[8] D. Kameda,[8] D. Kanno,[1] S. Kim,[9] N. Kobayashi,[1] T. Kobayashi,[10] T. Kubo,[8] S. Leblond,[5,†] J. Lee,[8,‡] F. M. Marqués,[5] R. Minakata,[1] T. Motobayashi,[8] K. Muto,[10] T. Murakami,[2] D. Murai,[11] T. Nakashima,[1] N. Nakatsuka,[2] A. Navin,[12] S. Nishi,[1] S. Ogoshi,[1] N. A. Orr,[5] H. Otsu,[8] H. Sato,[8] Y. Satou,[9] Y. Shimizu,[8] H. Suzuki,[8] K. Takahashi,[10] H. Takeda,[8] S. Takeuchi,[8,1] R. Tanaka,[1] Y. Togano,[7,11] J. Tsubota,[1] A. G. Tuff,[13] M. Vandebrouck,[14,§] and K. Yoneda[8]

^{19}B: Two-neutron halo or Four neutron skin?



Or?



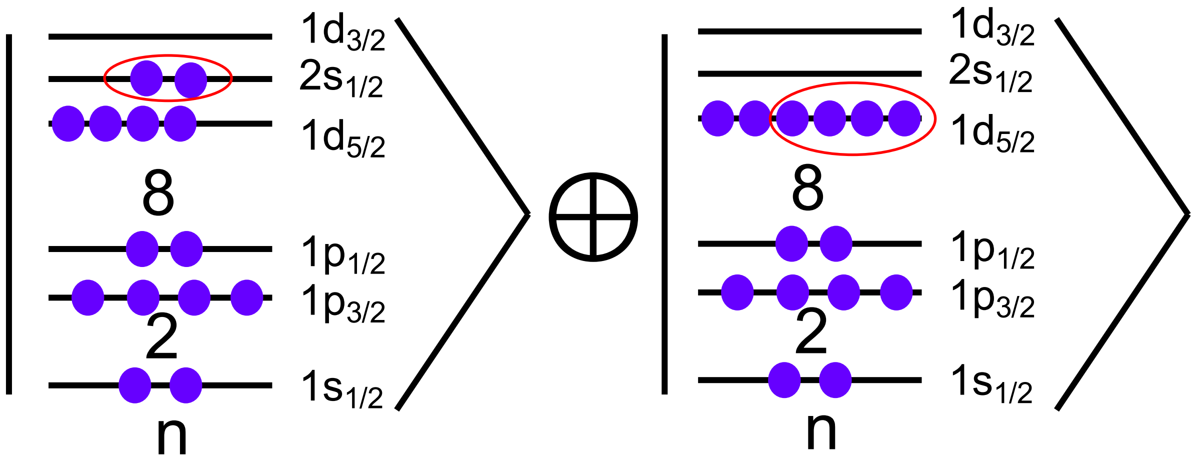
$^{19}B = {}^{17}B + 2n$(halo)?

$S_{2n} = 0.089(560)$ MeV

$^{19}B = {}^{15}B + 4n$(skin)?

$S_{4n} = 1.47(35)$ MeV

$$\Psi({}^{19}_{5}B) = \left| \text{(halo-like)} \right\rangle \oplus \left| \text{(skin-like)} \right\rangle$$

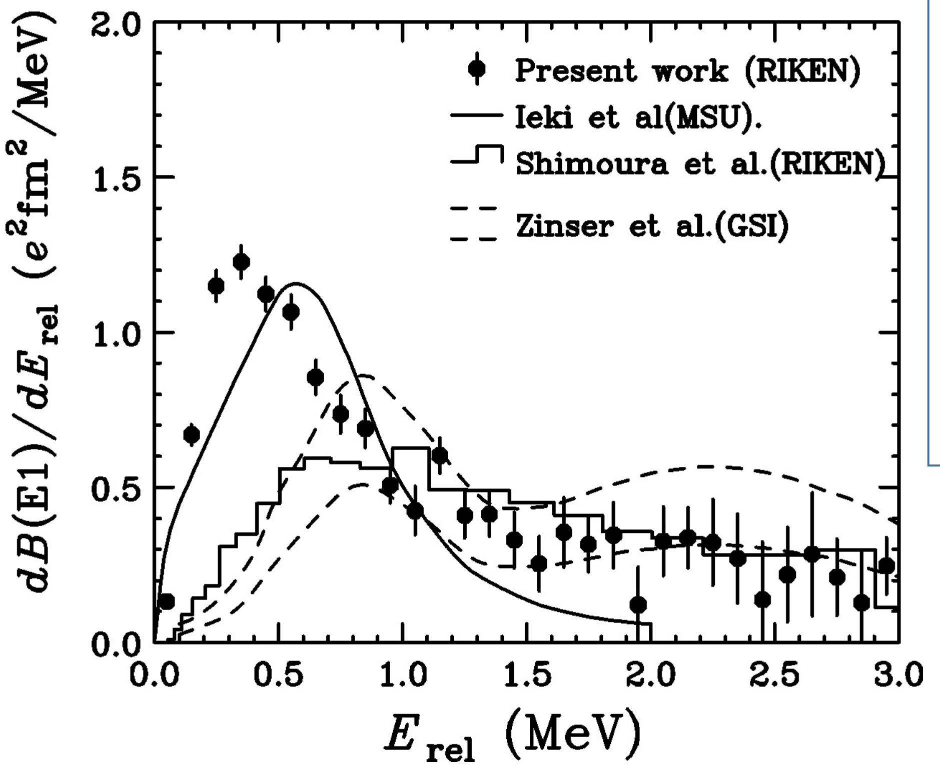


(halo-like)

(skin-like)

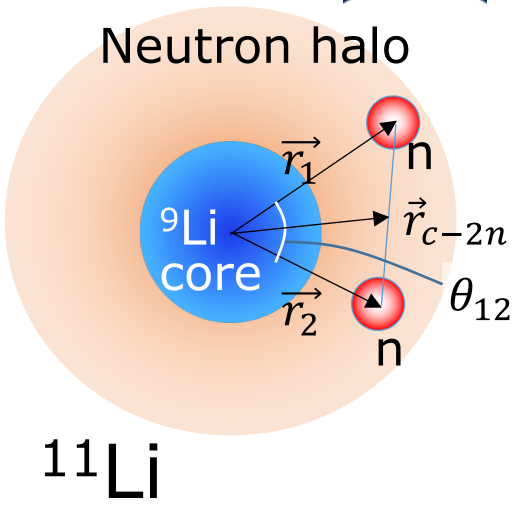
Coulomb Breakup of ^{11}Li → Probe of Dineutron Correlation

T. Nakamura et al. PRL96,252502(2006).



E1 Non-energy weighted cluster sum rule

$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x = \frac{3}{4\pi}\left(Ze\frac{2}{A}\right)^2 \langle r_{c-2n}{}^2 \rangle = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r_1{}^2 + r_2{}^2 + 2(\vec{r_1}\cdot\vec{r_2})\rangle$$



$$B(E1) = 1.42 \pm 0.18\ e^2 fm^2 (E_{rel} \le 3\text{MeV})$$

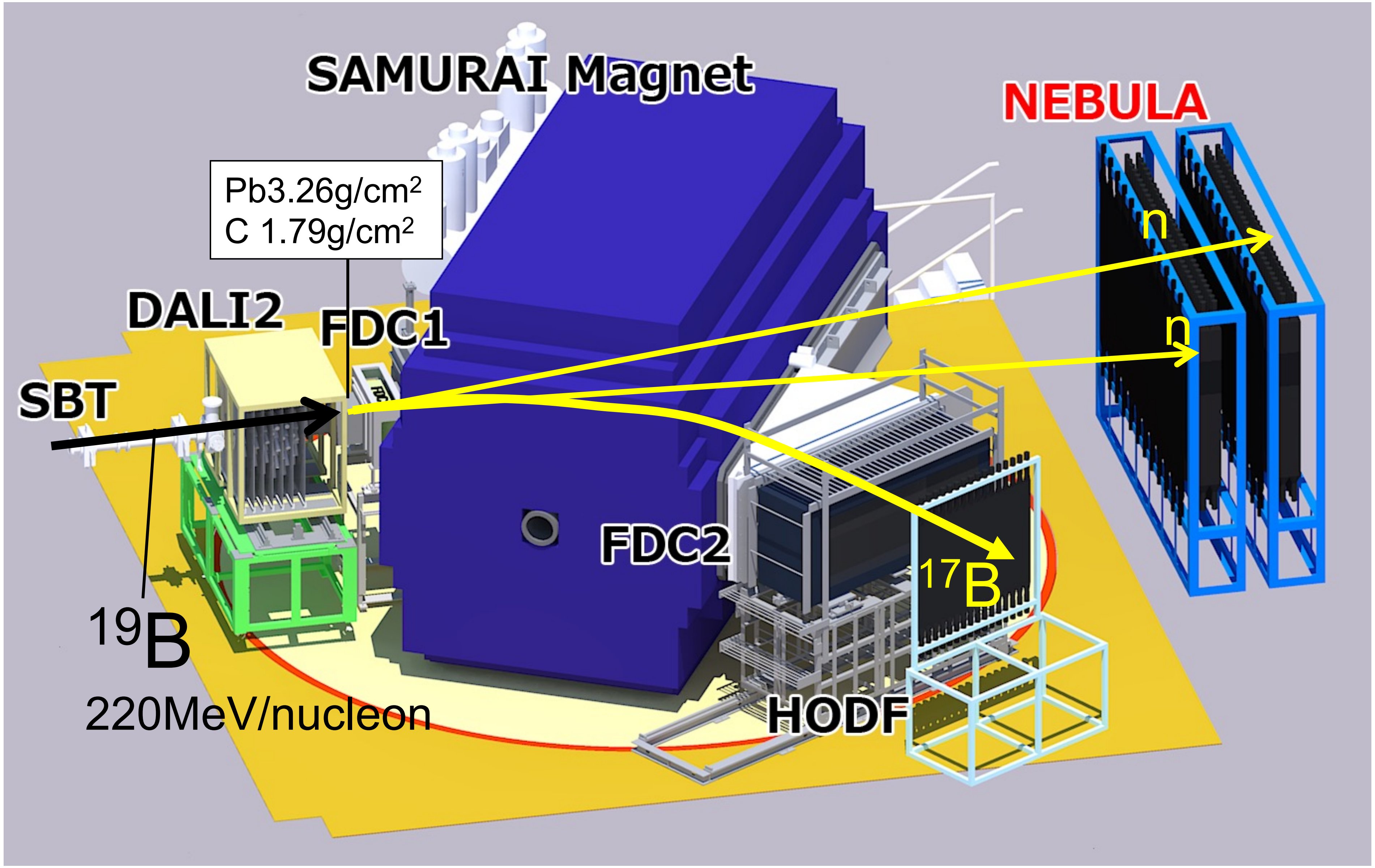
$$\rightarrow 1.78(22)\ e^2 fm^2 \rightarrow \langle \theta_{12} \rangle = 48^{+14}_{-18}\ \text{deg.}$$

Spatial Correlation in the Ground State of ^{11}Li

Soft E1 Excitation of 2n-halo → dineutron correlation

See also ^{11}Li(p,pn) results by Y.Kubota et al., PRL125, 252501 (2020).

Experimental Setup at SAMURAI at RIBF



Inclusive Cross Sections

K.J Cook, TN et al. PRL2020

	Exclusive $\sigma_{^{17}\mathrm{B}+2n}$ (mb)	Inclusive σ_{-2n} (mb)	Inclusive σ_{-4n} (mb)
$^{19}\mathrm{B}+\mathrm{Pb}$	1160(30)(70)	1800(60)	600(30)
$^{19}\mathrm{B}+\mathrm{C}$	54(3)(3)	251(5)	185(3)
$\sigma_{\mathrm{Pb}}/\sigma_{\mathrm{C}}$	22(1)	7.1(3)	3.3(2)

-2n: $\sigma_{Pb} \gg \sigma_c$ → Coulomb Breakup Dominant in **-2n** channel

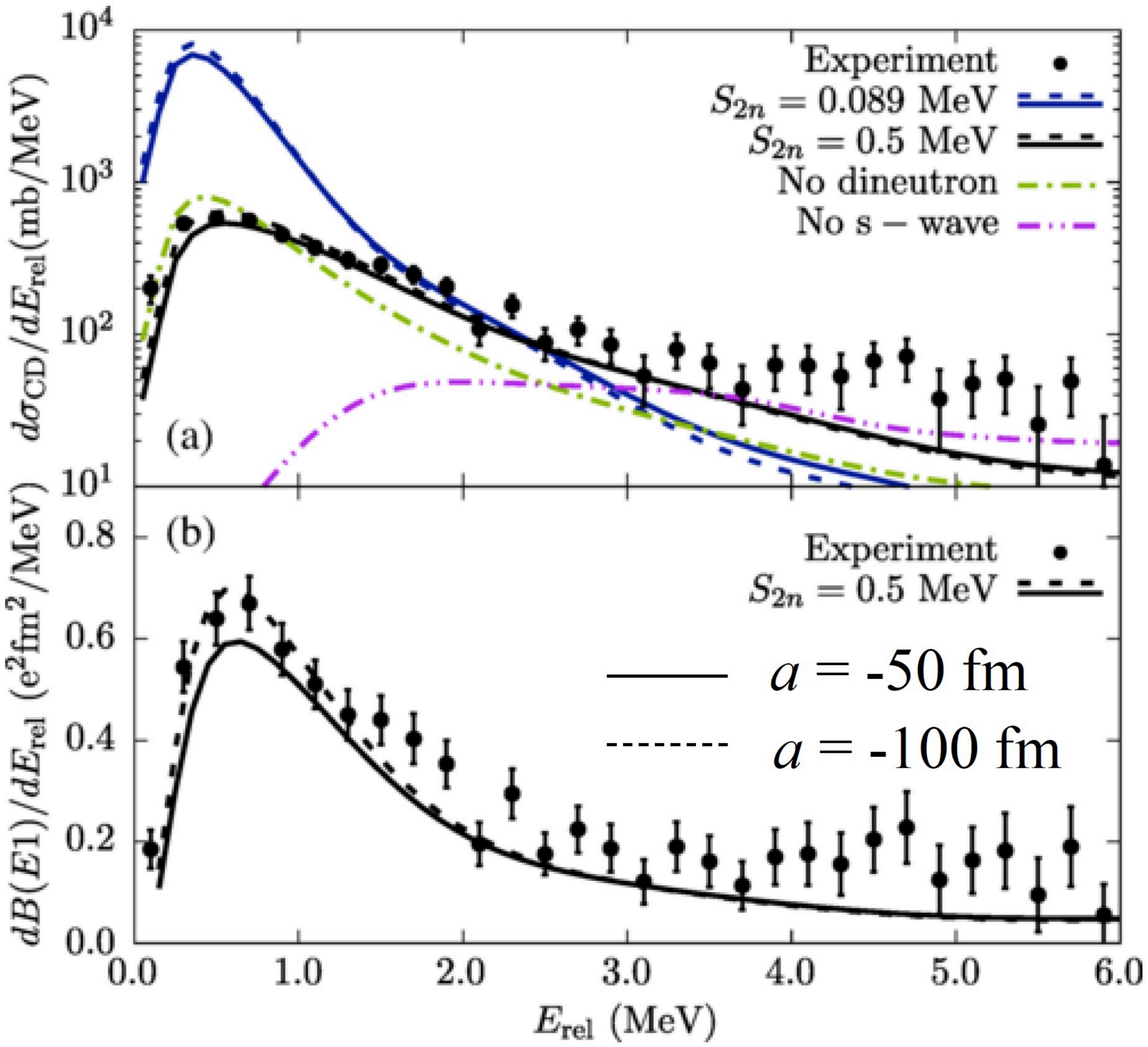
-4n: σ_{Pb} ~$3\sigma_c$ → Nuclear Breakup Dominant in **-4n** channel

^{17}B+2n more likely rather than **^{15}B+4n**

c.f. Z.H. Yang et al., PRL 126, 082501, (2021).
^{17}B(p,pn)^{16}B → Valence neutrons of ^{17}B: d-wave dominant

E1 Response of ^{19}B

K.J Cook, TN et al. PRL2020



- B(E1) = 1.64 ± 0.06 (stat) ± 0.12 (sys) e^{2}fm^2
  →Signature of Halo!

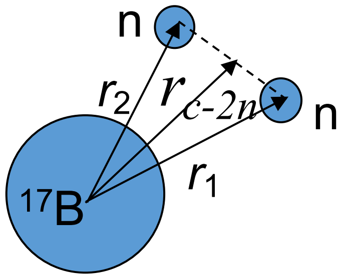
  Similar B(E1) to ^{11}Li, ^{11}Be.

  Core-2n distance (Sum rule)

  $$\sqrt{\langle r^2_{c-2n} \rangle} = 5.75 \pm 0.11(\mathrm{stat}) \pm 0.21(\mathrm{sys})\ \mathrm{fm}$$

- S_{2n} = 0.5 MeV
- substantial s-wave component with a well-developed dineutron correlation.
- Consistent with large scattering length:

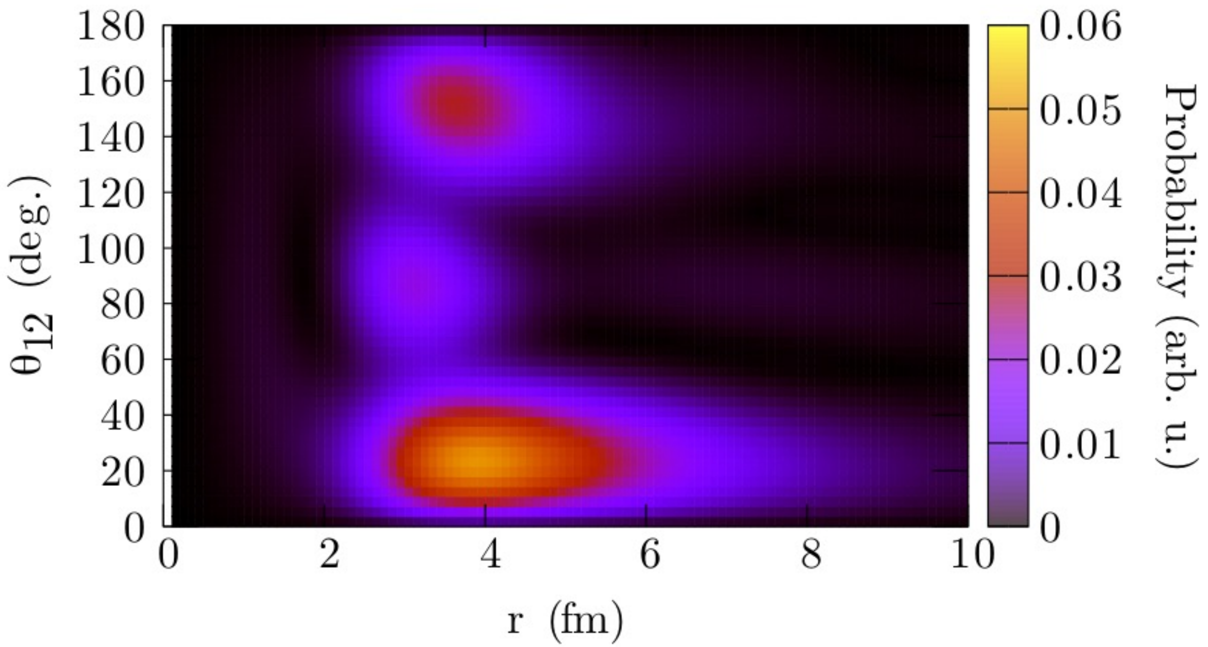
  ^{17}B-n ($a < -50\ fm$)

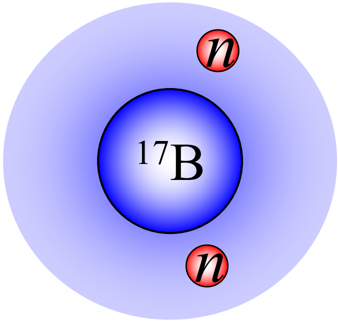


Dineutron correlation in ^{19}B

K.J Cook et al. PRL2020

Three-body model (by K.Hagino) **reproduces dσ/dE_coul very well!**
Valence neutron density distribution for **S_{2n} = 0.5 MeV, a = –50 fm.**





^{19}B=^{17}B+2n(halo)

S_{2n}~0.5 MeV

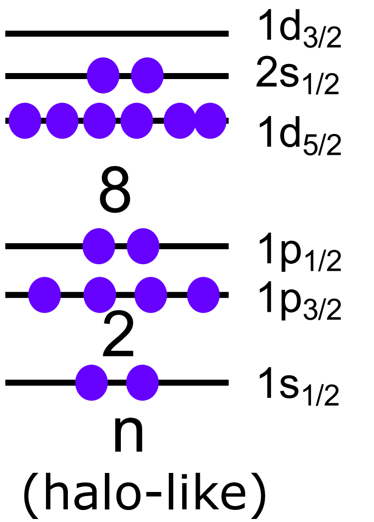
- ✓ Enhanced nn probability at $\theta_{12}\sim 25°$
- ✓ Configuration: Negative:6%, s: 35%, d: 56%
- ✓ Asymmetry: Due to Negative-parity mixture

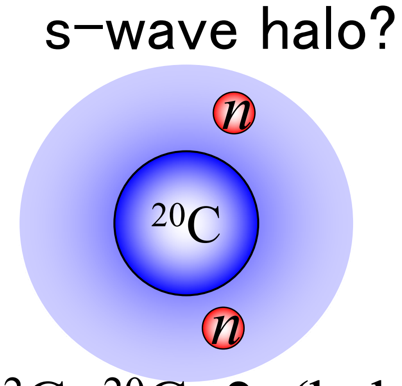
Coulomb breakup of ^{22}C

N. Nakatsuka, TN et al.,

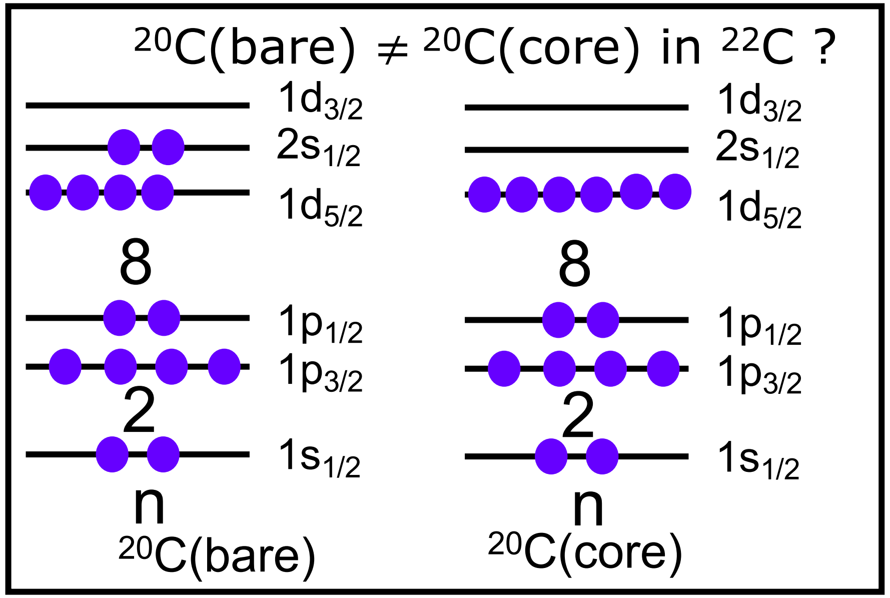
Large Cross Section (typical halo),
but twice broader than ^{19}B
^{22}C: E(peak)~ MeV, FWHM~ MeV
^{19}B: E(peak) ~0.5 MeV, FWHM~1.5 MeV

VERY PRELIMINARY





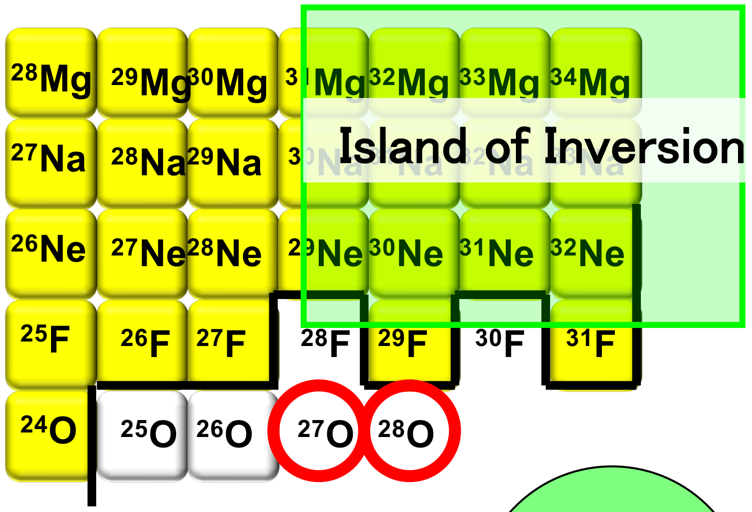
$^{22}C = ^{20}C + 2n$(halo)
$S_{2n} < \sim 0.5$ MeV



c.f. N. Kobayashi PRC2012, $^{20}C + C \rightarrow ^{19}C_{gs}(1/2^+)$ (C^2S~1)

$^{20}C+n+n$: $S_{2n}^{(eff)} = S_{2n} + \Delta$ (T.Suzuki, T.Otsuka PLB753,199(2016)) **or Need $^{20}C+4n$ Description?**

Invariant mass spectroscopy of ^{27}O, ^{28}O,

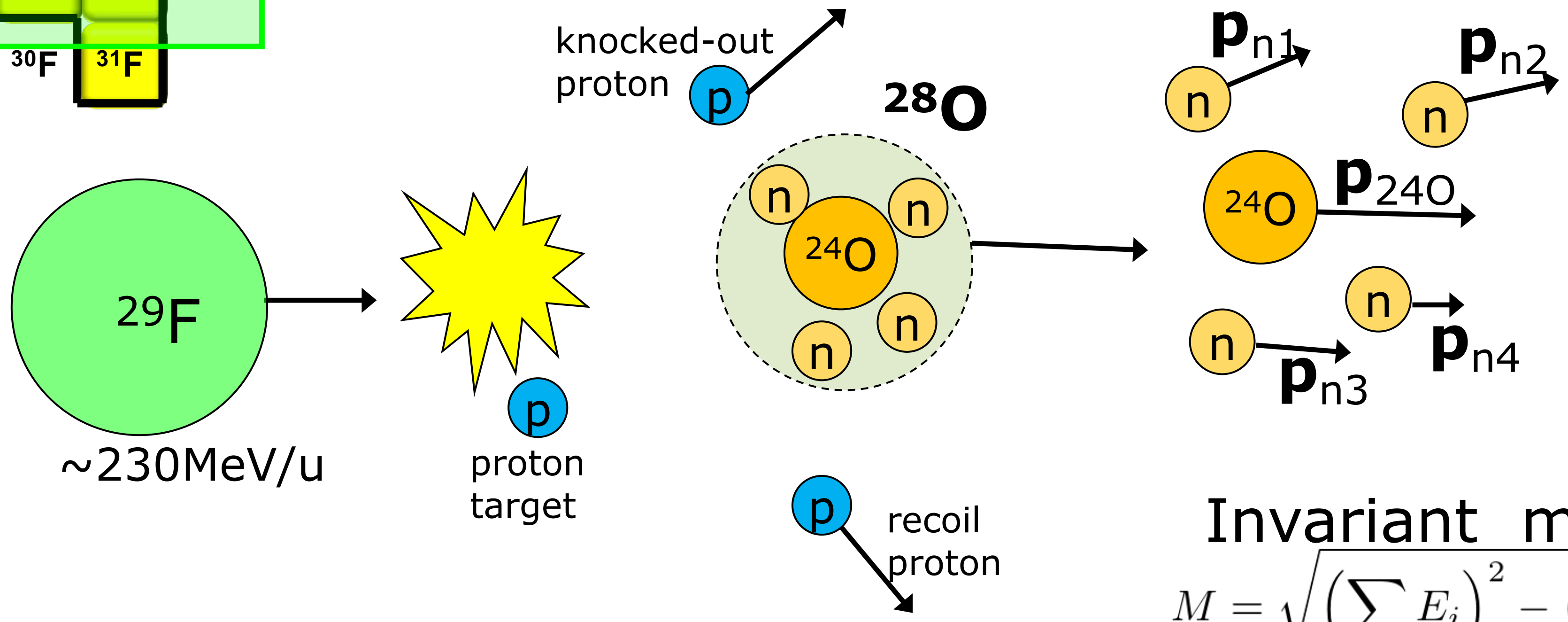


^{28}O(Z=8, N=20)

Candidate Doubly Magic Nucleus

Key for Oxygen anomaly ($^{24}O \rightarrow {}^{31}F$)

Y.Kondo et al.
Paper in preparation



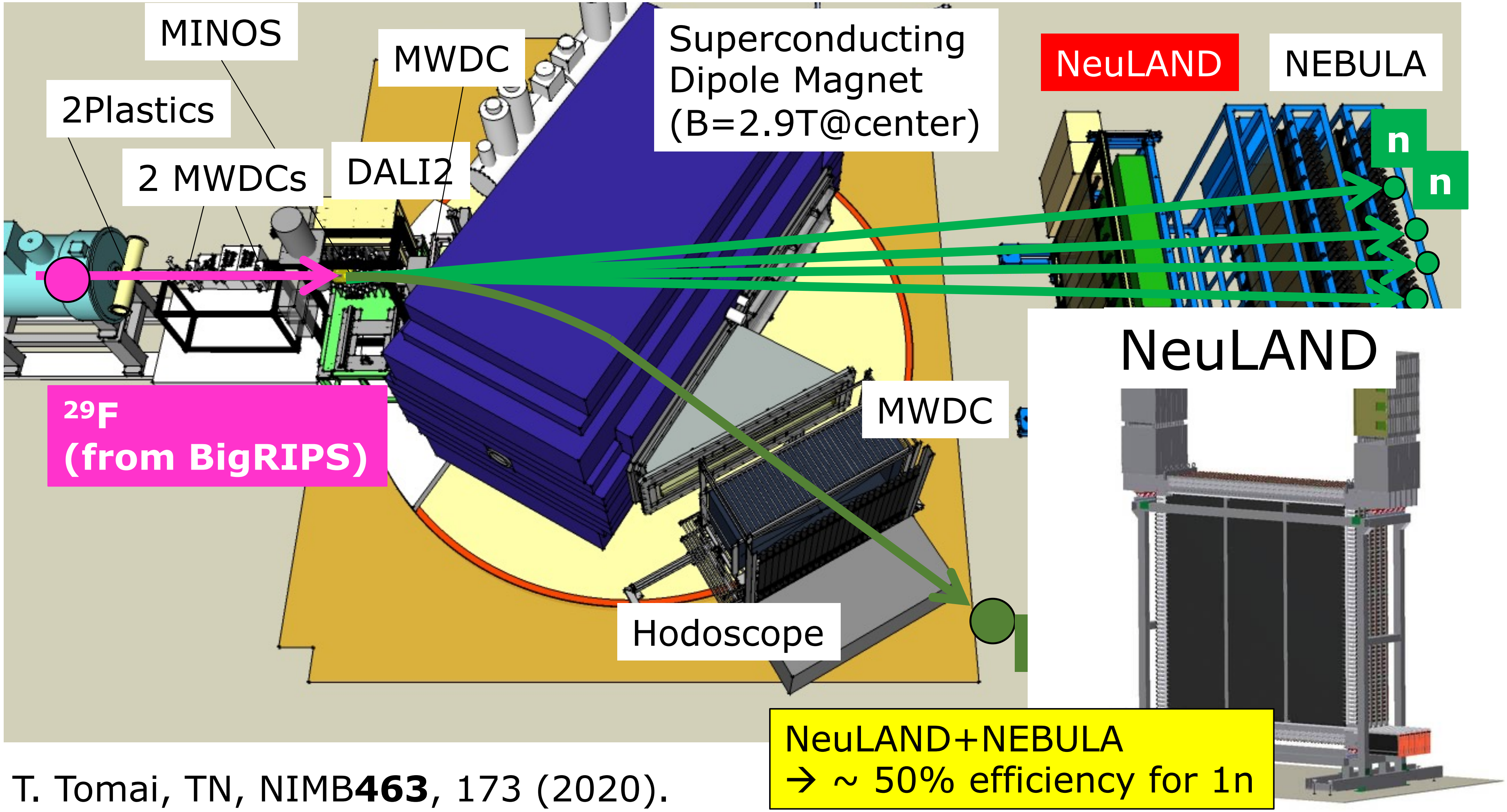
Invariant mass

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \mathbf{p}_i\right)^2}$$

^{28}O: One-proton removal reaction of ^{29}F

→4-neutron coincidence

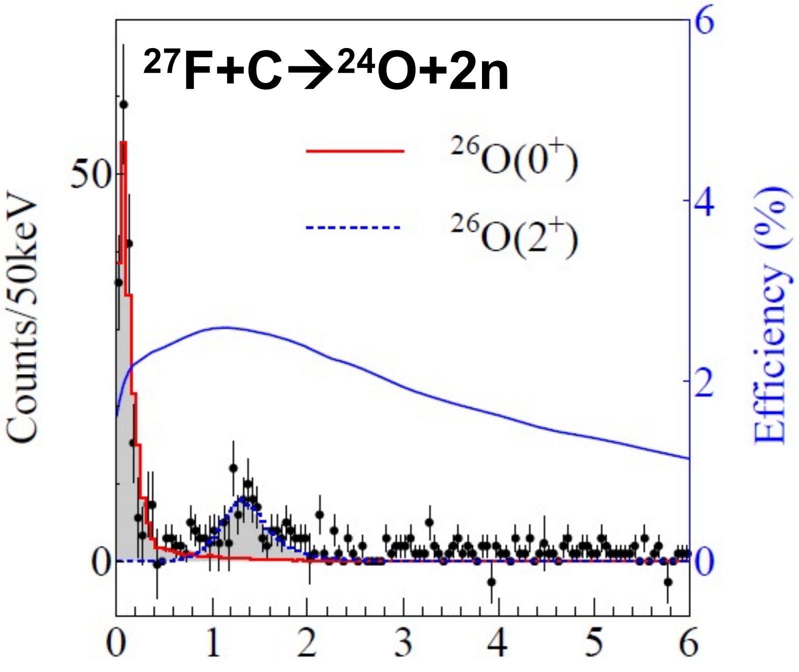
^{28}O measurement @ RIBF-SAMURAI



Y.Kondo, T. Tomai, TN, NIMB**463**, 173 (2020).

Decay energy spectrum

^{26}O



E(^{24}O+n+n) (MeV)

gs (0^+): 18±3(stat)±4(syst)keV
1st excited state (2^+) :$1.28^{+0.11}_{-0.08}$MeV

Y. Kondo et al., PRL116, 102503, (2016).

^{27}O

^{29}F+^{1}H→^{24}O+3n
E(^{24}O+2n$_{<}$)<0.08 MeV
→ Select decay via $^{26}O_{gs}$

^{27}O events

E(^{24}O+n+n+n) (MeV)

^{28}O

^{29}F+^{1}H→^{24}O+4n

E(^{24}O+n+n+n+n) (MeV)

Theoretical predictions towards ^{28}O

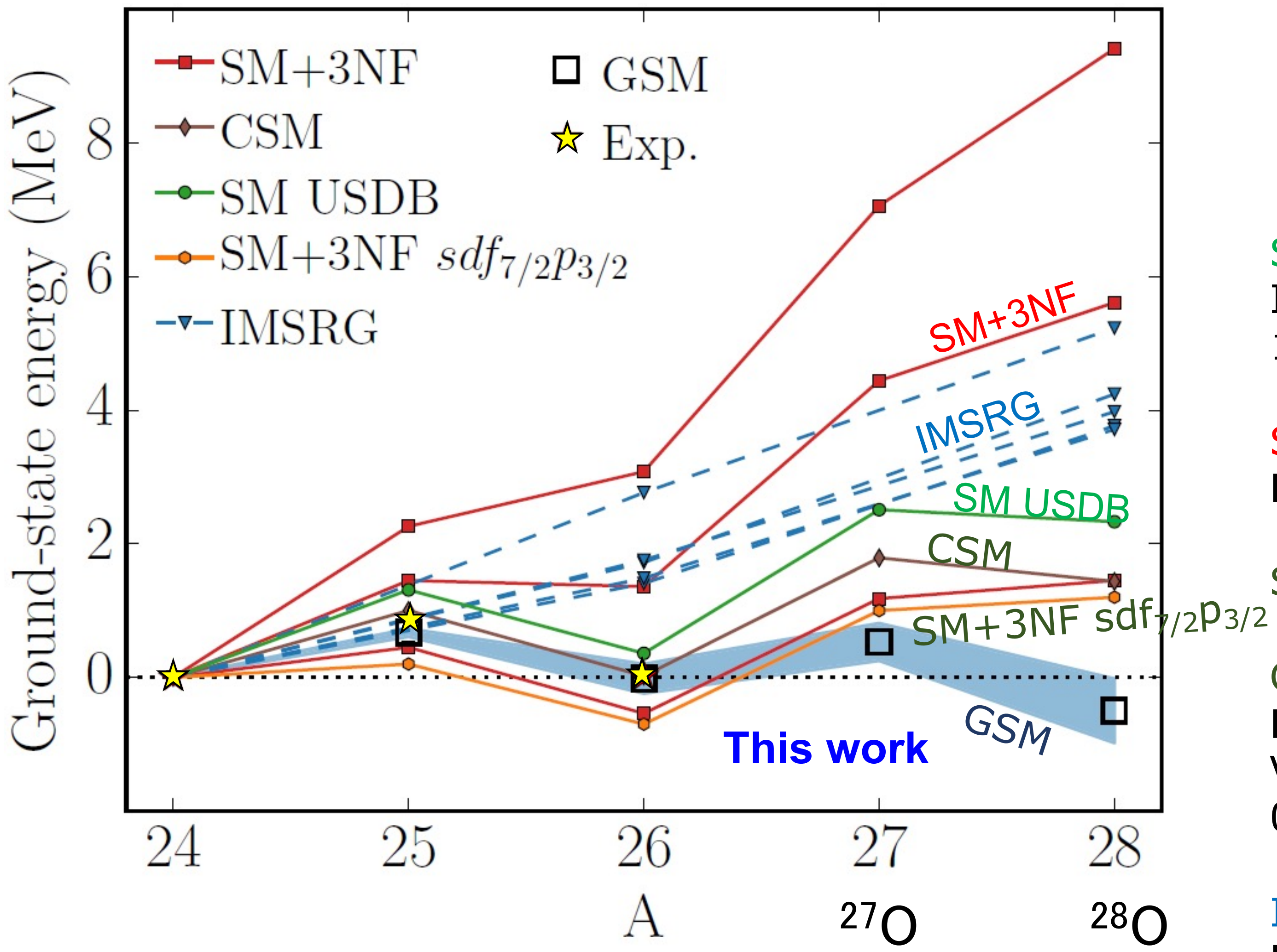


Fig. from K. Fossez et al., PRC 96, 024308 (2017) (GSM)

SM USDB: B. A. Brown, Int. J. Mod. Phys. E26, 1740003 (2017)

SM+3NF: T. Otsuka et al., PRL105, 032501 (2010)

SM+3NF $sdf_{7/2}p_{3/2}$:

CSM: A. Volya et al., PRL94, 052501 (2005), A. Volya et al., PRC74, 064314, (2006)

IMSRG: V. Lapoux et al., PRL117, 052501, (2016), H. Hergert

Summary

- ✓ Neutron dripline =Edge:
  Boundary of Open/Closed Quantum Systems→Clusters/Halo/Shell Evolution
- ✓ Halo-Shell Interplay: ^{31}Ne
  - ➢ Coulomb Breakup of ^{31}Ne : Soft E1 Excitation ← Doubly-halo components
    $^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}$ $^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}$
  - ➢ Nuclear Breakup (^{31}Ne→$^{31}Ne^*$, ^{32}Ne(-1n)→^{31}Ne, ^{32}Na(-1p)→^{31}Ne)
    11 New Excited States Observed; $5/2^-$,$7/2^-$:Rotational Band on K=3/2
    T. Tomai et al., paper in preparation
- ✓ Two-neutron halo
  - ➢ Coulomb Breakup of ^{19}B :
    Strong Soft E1 Excitation, Consistent with dineutron picture S_{2n}~0.5 MeV
    K.J. Cook et al., PRL**124**, 212503, 2020.
  - ➢ Coulomb Breakup of ^{22}C:
    Soft E1 Excitation, but broader peak → Core is different from Bare ^{20}C?
- ✓ Beyond dripline
  - ➢ Discovery of $^{27,28}O$ Y.Kondo, paper in preparation
    → Sringent Constraints on nuclear models/interactions at the Edge

Perspectives

More exotic neutron states → Nuclear interactions/Many-body effects at the Edge

Exclusive Coulomb/nuclear breakup of ^{31}Ne

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Coulomb breakup of ^{19}B

K.J. Cook et al., Physical Review Letters 124, 212503 (2020).

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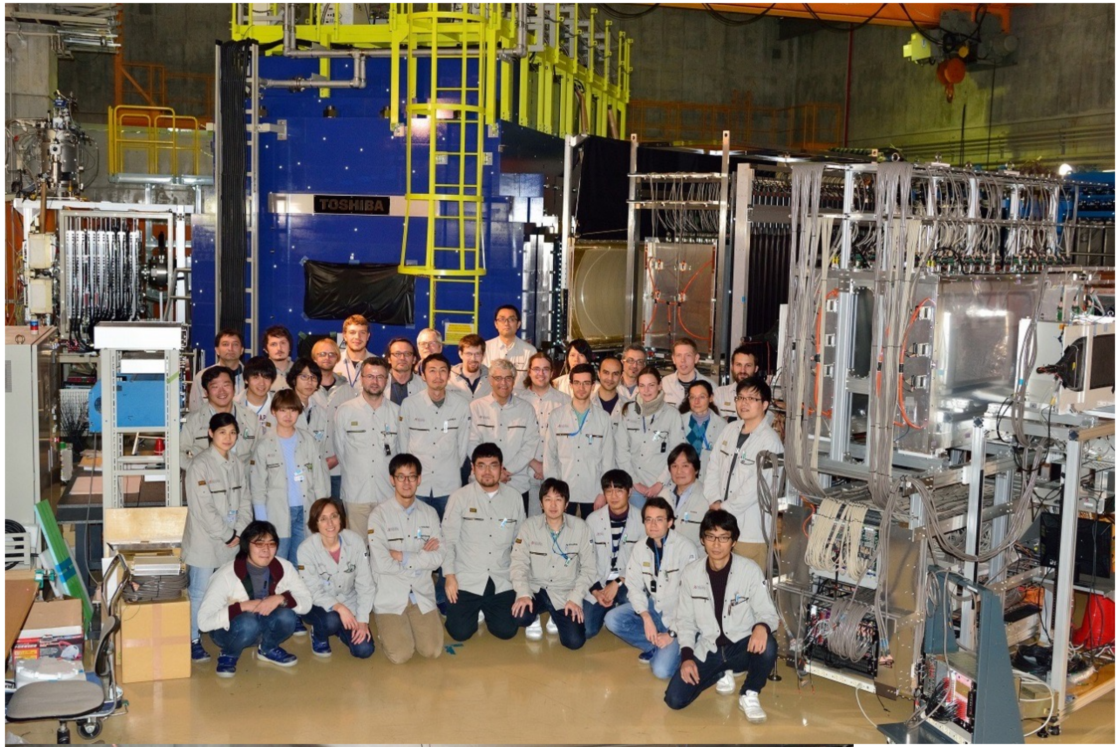
SAMURAI21 collaboration—$^{27,28}O$



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88 Participants (+few analysis)

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