Coulomb Breakup and Soft E1 Excitation of Halo Nuclei : Present and Future

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Contents

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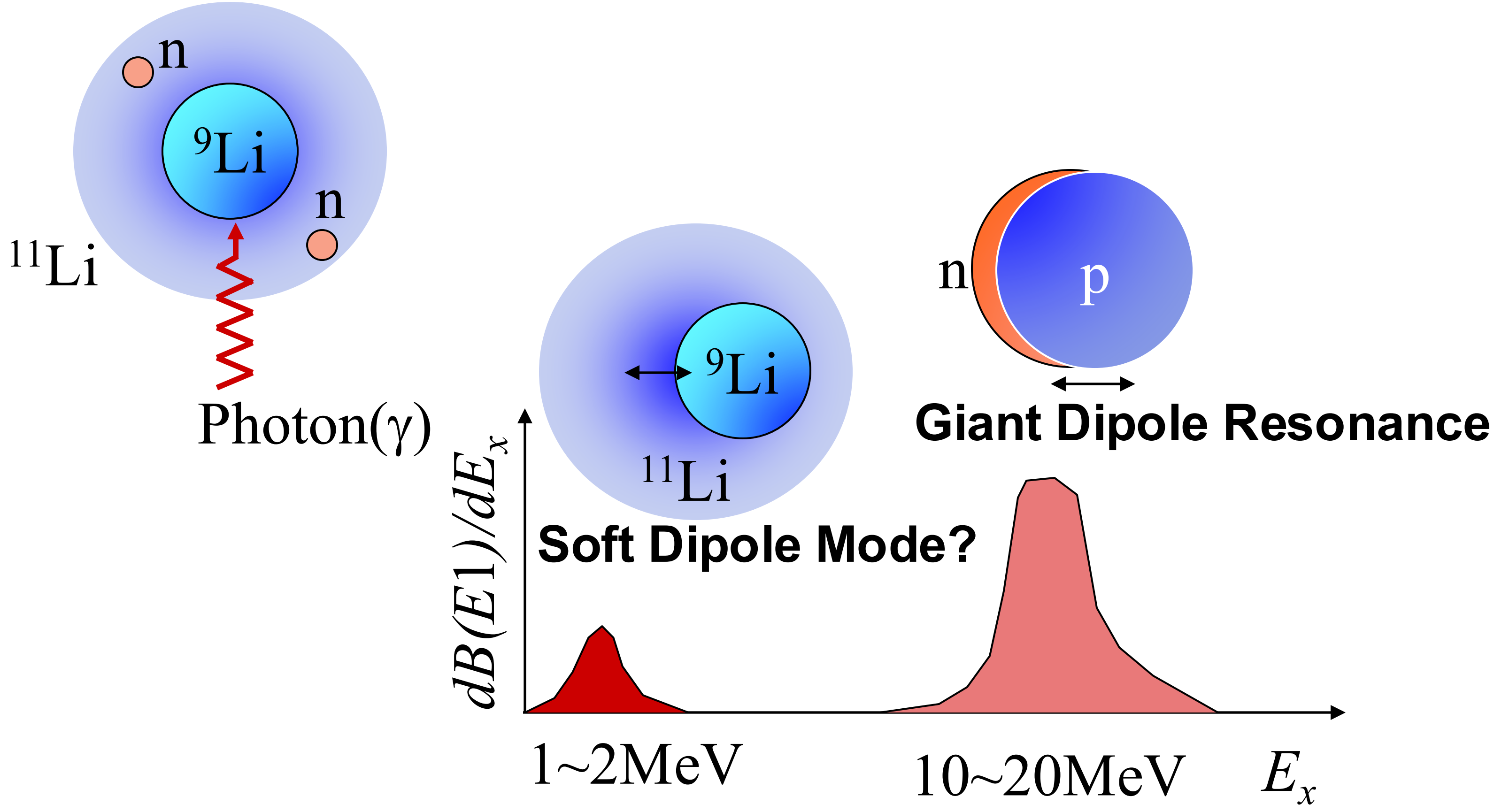
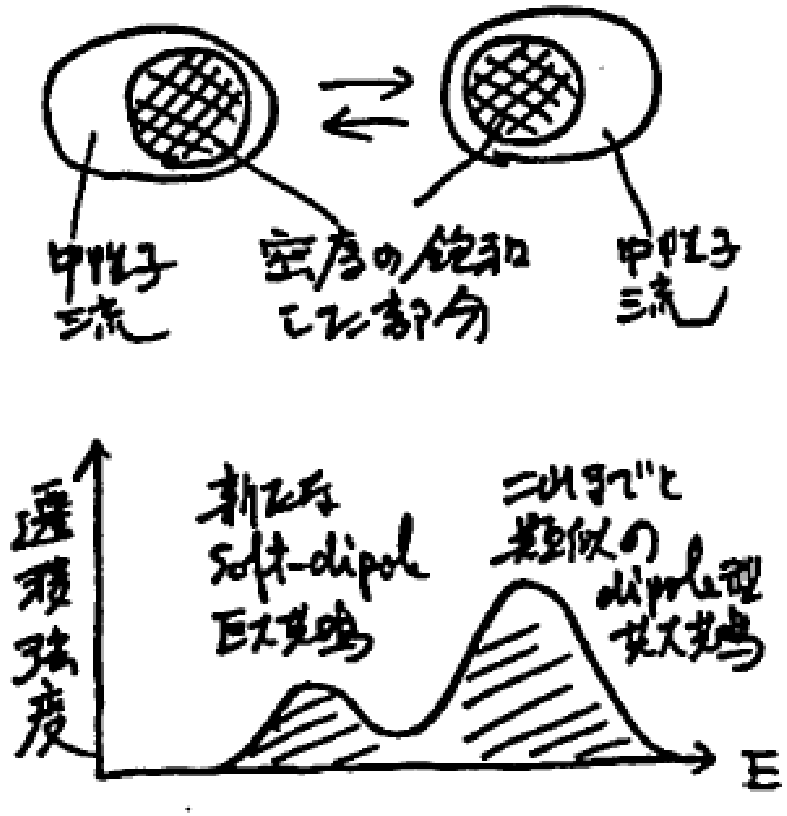
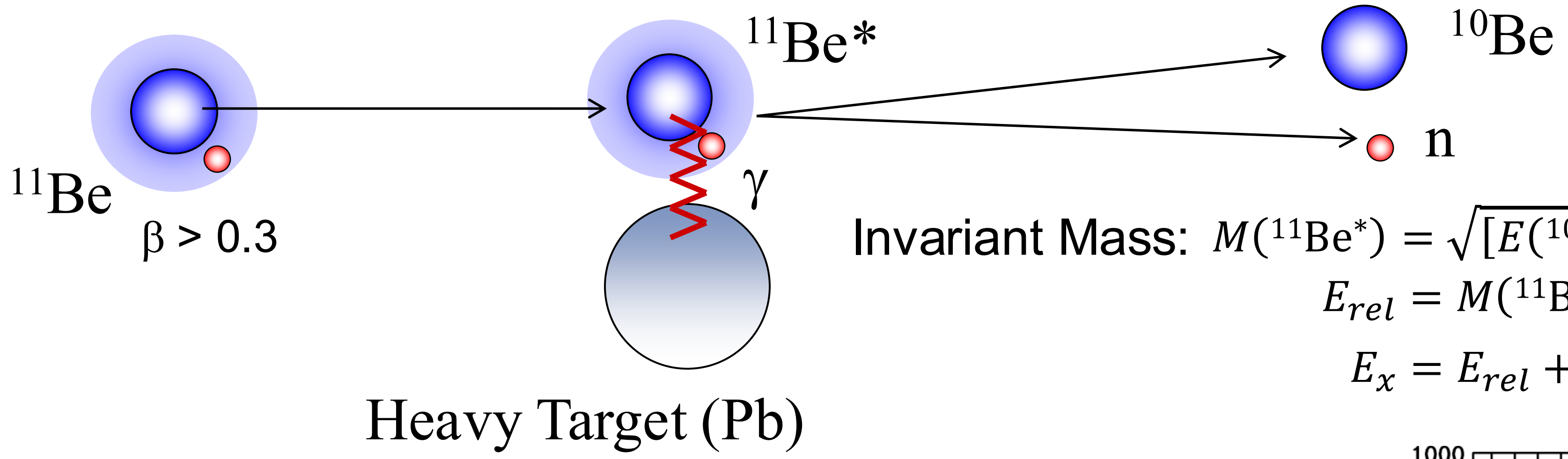
How a halo nucleus responds when it absorbs a photon (E1 Response) ?





Kiyomi Ikeda,
INS report JHP-7 (1988) [in Japanese]

Coulomb Breakup → E1 Response

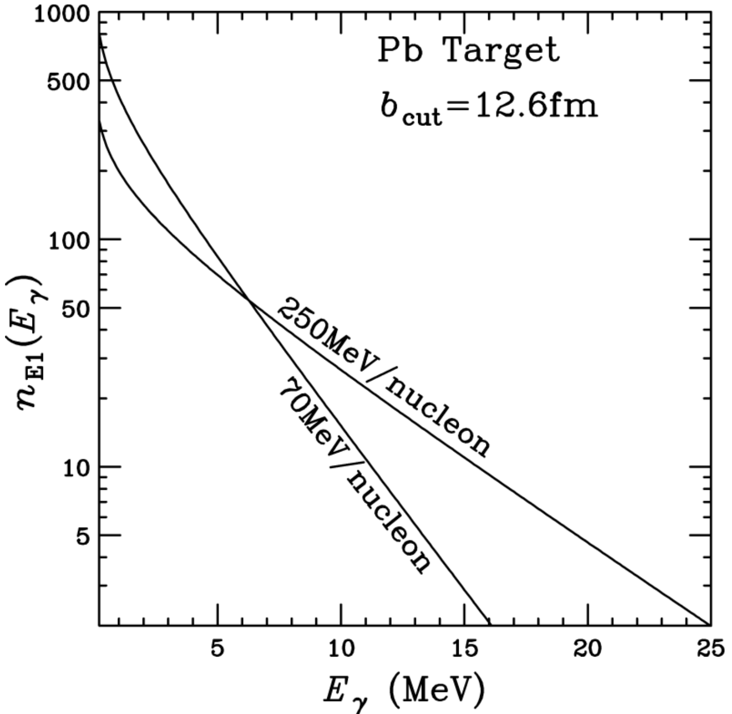


$\vec{P}(n), \vec{P}(^{10}\mathrm{Be})$

Invariant Mass: $M(^{11}\mathrm{Be}^*) = \sqrt{[E(^{10}\mathrm{Be}) + E(n)]^2 - |\vec{p}(^{10}\mathrm{Be}) + \vec{p}(n)|^2}$

$$E_{rel} = M(^{11}\mathrm{Be}^*) - M(^{10}\mathrm{Be}) - m_n$$

$$E_x = E_{rel} + S_n$$



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)×(Transition Probability)

C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).
T. Nakamura, Handbook of Nuclear Physics, pp1-37 (2023).

First Indication of Soft E1 Excitation

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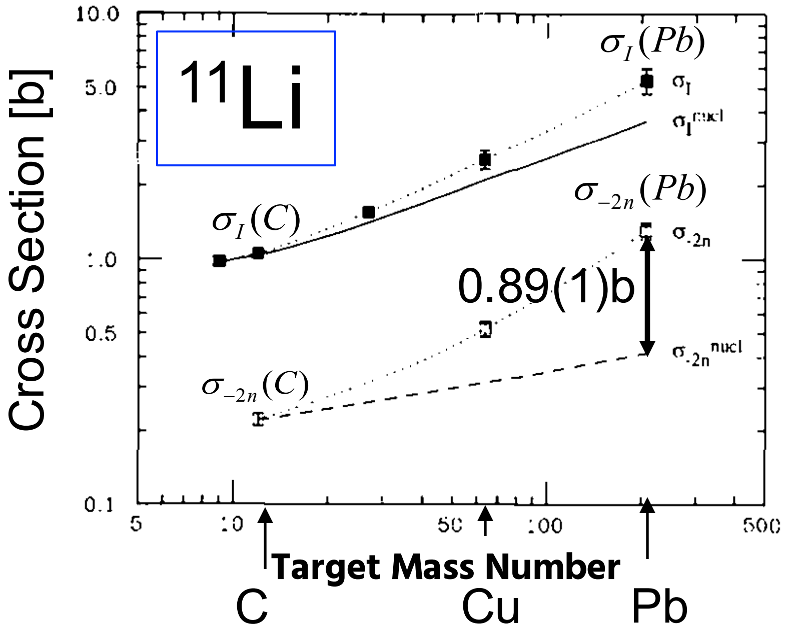


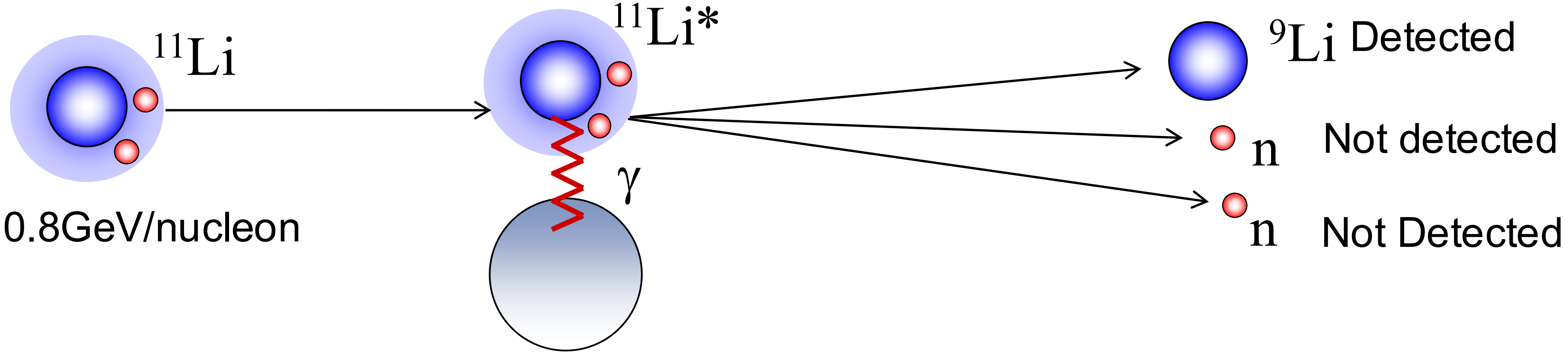
T.Kobayashi et al., Phys.Lett. B**232**, 51 (1989).

Inclusive Coulomb Breakup of ^{11}Li @ LBL

$$\sigma(E1) = \int_{Eth}^{\infty} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dE_x$$

$$\sigma(E1) = \sigma_{-2n}(Pb) - \Gamma \sigma_{-2n}(C)$$

Toshio Kobayashi
- Jul 31 2025



Soft E1 Excitation of *1n* halo nuclei →Halo Wave Function

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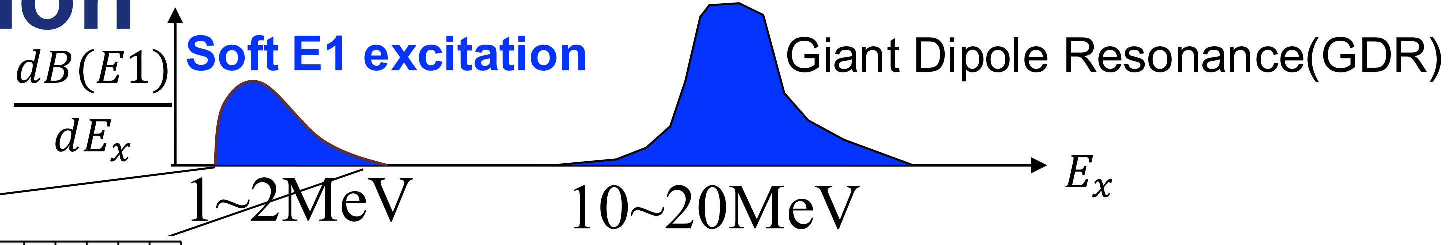
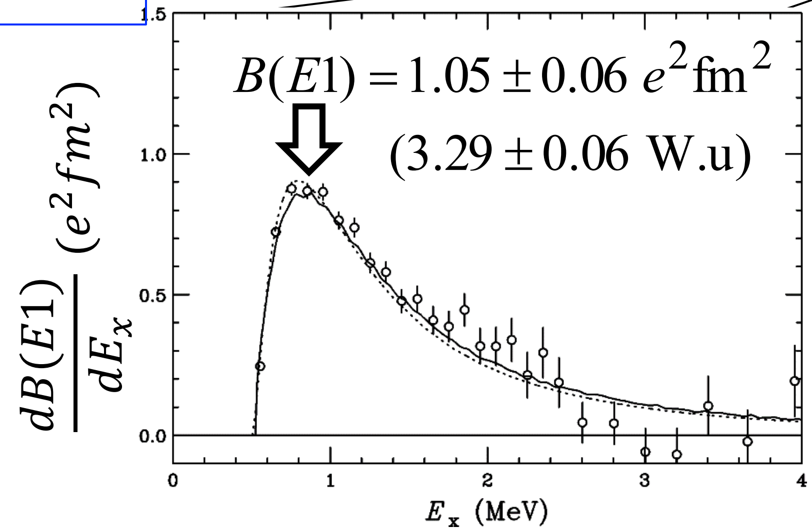
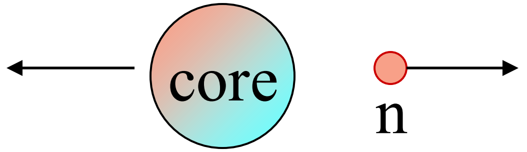


^{11}Be



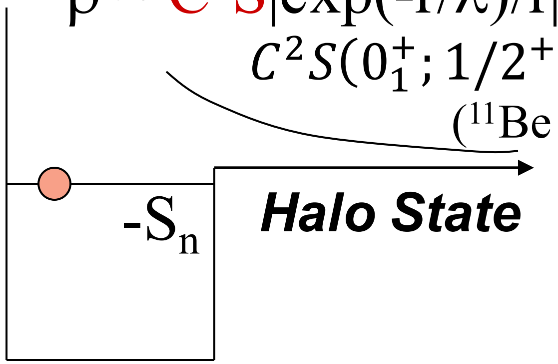
N.Fukuda, TN et al., PRC70, 054606 (2004)
TN *et al.*,PLB 331,296(1994)
Palit et al., PRC68, 034318(2003)

Direct Breakup Mechanism (Not Resonance!)



$\rho \sim C^2S|\exp(-r/\lambda)/r|^2$

$C^2S(0_1^+; 1/2^+) = 0.72 \pm 0.04$ (^{11}Be Fukuda2004)



E1 Strength

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

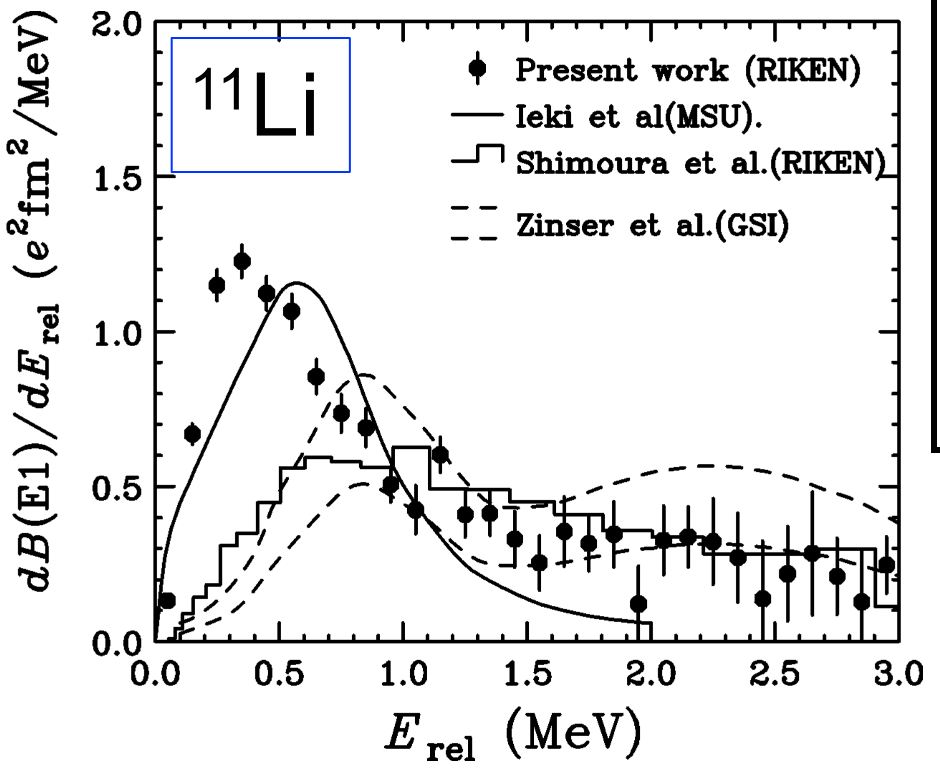
⇔ *Fourier Transform*

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): $E_{rel}^{(peak)} \cong 0.18S_n$

Soft E1 Excitation of *2n* Halo Nuclei → Probe of Dineutron Correlation



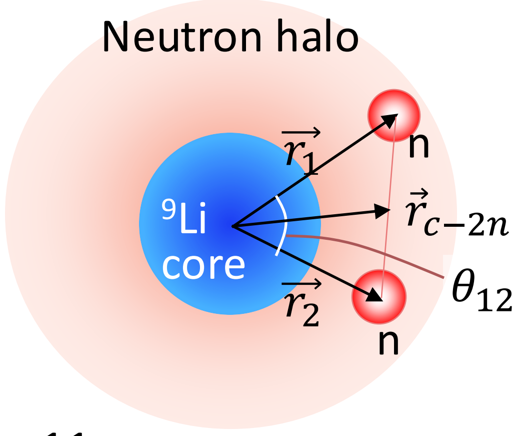
T. Nakamura et al. PRL96,252502(2006).

E1 Non-energy weighted cluster sum rule

$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x$$

$$= \frac{3}{4\pi}\left(Ze\frac{2}{A}\right)^2 \langle r_{c-2n}{}^2 \rangle$$

$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \langle r_1{}^2 + r_2{}^2 + 2(\vec{r_1}\cdot\vec{r_2})\rangle$$



^{11}Li

$$B(E1) = 1.42(18)e^2fm^2 \; (E_{rel} \le 3 \text{ MeV})$$

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

c.f. $\langle\theta_{12}\rangle = 66^{\circ}{}^{+22}_{-18}$ C.A. Bertulani, M.S. Hussein, PRC76, 051602(R)(2007).

$\langle\theta_{12}\rangle = 56.2^{\circ}{}^{+17.8}_{-21.3}$ K. Hagino, H. Sagawa PRC76, 047302 (2007).

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

Soft E1 Excitation of 2n-halo → dineutron correlation

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Coulomb Breakup of ^{31}Ne
-- 1n halo nucleus in the island of inversion

Island of Inversion

<u>**N=21 Isotones**</u>

^{41}Ca, ^{39}Ar, ^{37}S, ^{35}Si

Ground state : $7/2^-$ ($f_{7/2}$)

^{33}Mg:

Ground state: $3/2^-$ ($p_{3/2}$)

D.Bazin, PRC103, 064318(2021)

^{31}Ne:

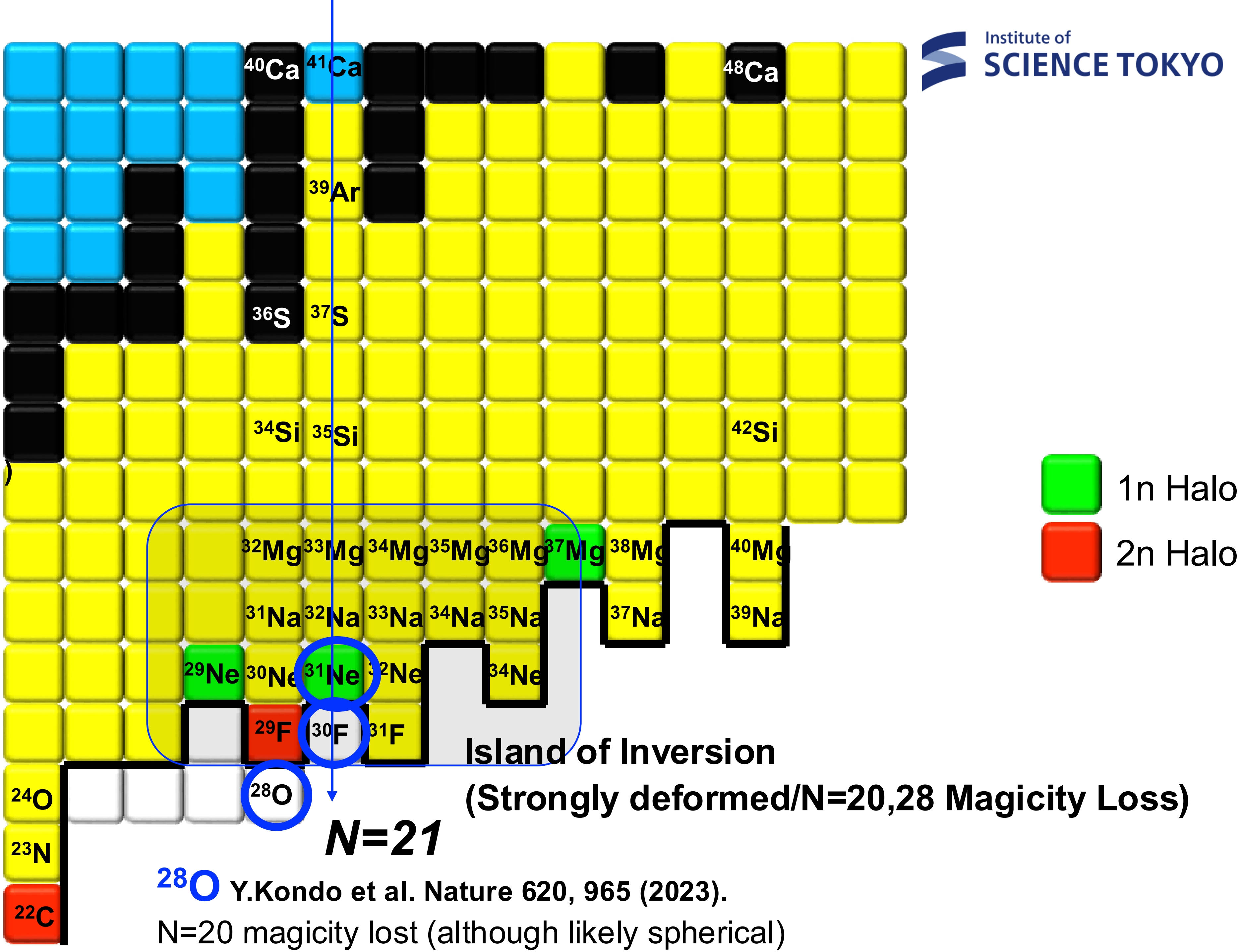
Ground state: $3/2^-$ ($p_{3/2}$)

TN, N.Kobayashi, PRL2009,PRL2014

^{30}F

Ground state: **p-wave resonance**

J.Kahlbow et al. PRL 133, 082501 (2024).



^{28}O Y.Kondo et al. Nature 620, 965 (2023).

N=20 magicity lost (although likely spherical)

Previous Work: "Inclusive" Coulomb/nuclear breakup

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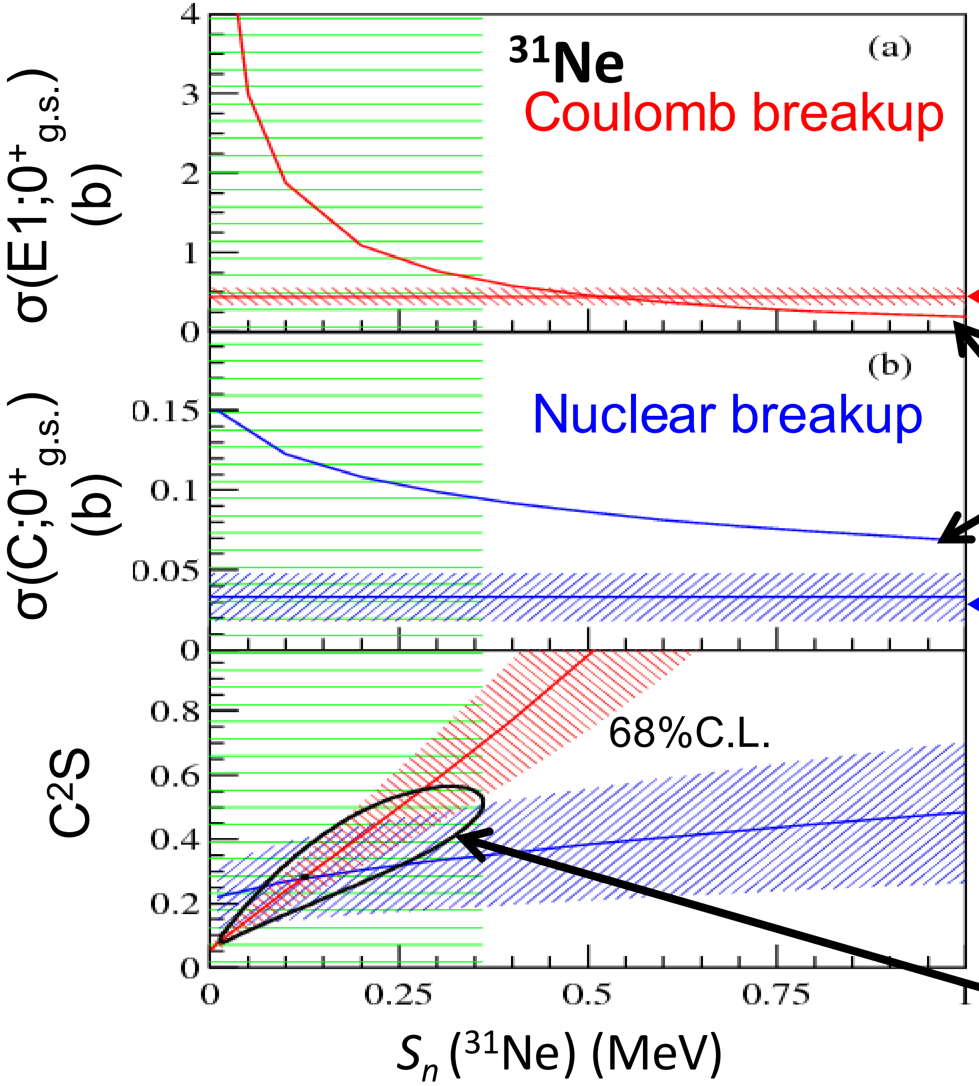
→ Nobu Kobayashi's Talk



TN, N. Kobayashi et al., PRL **103**, 262501 (2009).

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

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

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

Theoretical calc. for

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

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

^{31}Ne: **3/2$^-$** **p**-wave halo $|^{30}\mathrm{Ne}(0^+_{g.s.}) \otimes p_{3/2}\rangle$

Deformed in spite of **N=21**

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

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

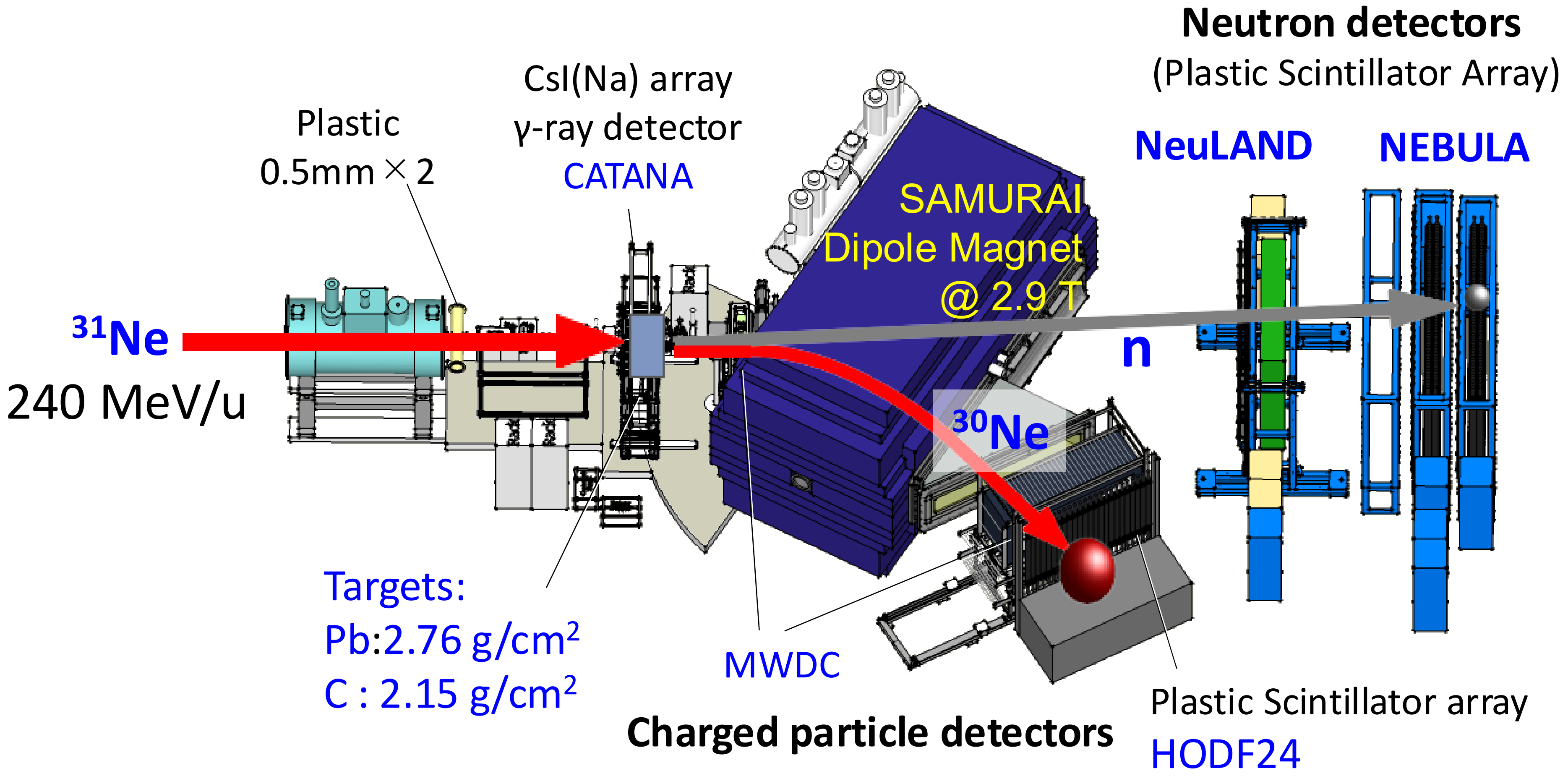
Limited to gs-core config.

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

Experimental Setup:
Coulomb breakup of ^{31}Ne at SAMURAI at RIBF, RIKEN



Coulomb breakup energy spectrum of ^{31}Ne

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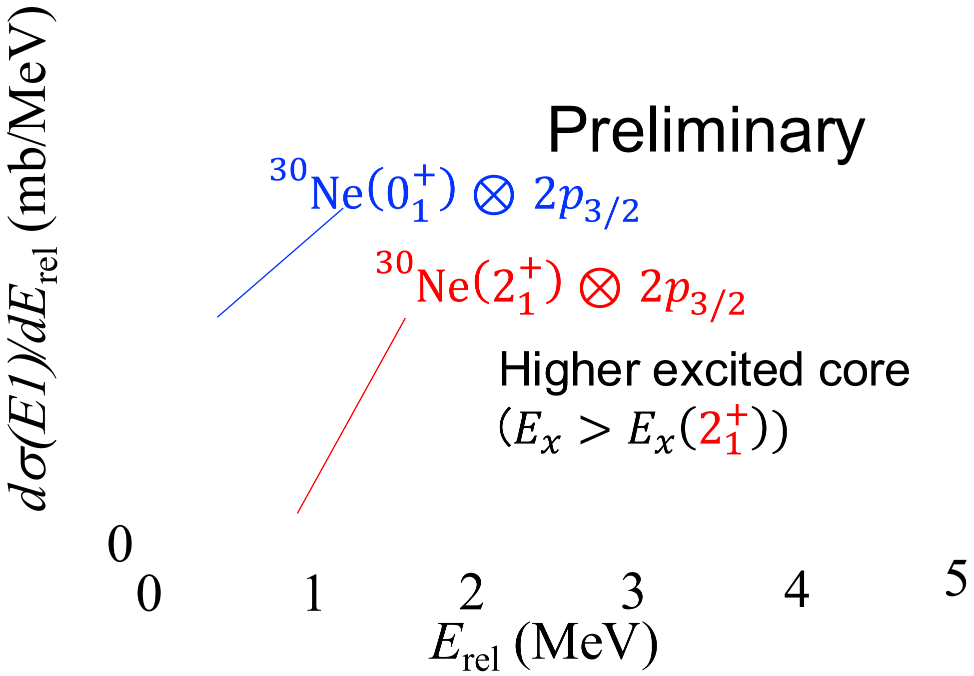
$$\left|{}^{31}\mathrm{Ne}(3/2^-)\right> = \alpha\left|{}^{30}\mathrm{Ne}(0_1^+)\otimes 2p_{3/2}\right> + \beta\left|{}^{30}\mathrm{Ne}(2_1^+)\otimes 2p_{3/2}\right> + \cdots$$

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



	S_n (MeV)	$C^2S(0_1^+;3/2^-)$ ($^{30}\mathrm{Ne}(0_1^+)\otimes 2p_{3/2}$)	$C^2S(2_1^+;3/2^-)$ ($^{30}\mathrm{Ne}(2_1^+)\otimes 2p_{3/2}$)
This work			
Prev. work*	$0.15^{+0.16}_{-0.10}$	$0.32^{+0.21}_{-0.17}$	-
SM(SDPF-M)		0.212	0.265

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

Double-component Halo: Unique to p-wave halo

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

$$S^{(\mathrm{eff})}{}_n = S_n + E_x(2_1^+) \sim 1.0\mathrm{MeV}$$

p-wave halo

p-wave halo

${}^{30}\mathrm{Ne}(0_1^+)\otimes 2p_{3/2}$
${}^{30}\mathrm{Ne}(2_1^+)\otimes 2p_{3/2}$
Total

$\rho(r)\ (\mathrm{fm}^{-3})$

$r\ (\mathrm{fm})$

Double-Component Halo:

✓ Unique feature of **p-wave halo**

r.m.s radius
for the sum of the two p-wave components

c.f. **Single**-component for **s-wave halo**

$$\left|{}^{11}\mathrm{Be}(1/2^+)\right> = \alpha\left|{}^{10}\mathrm{Be}(0_1^+)\otimes 2s_{1/2}\right> + \beta\left|{}^{10}\mathrm{Be}(2_1^+)\otimes 1d_{5/2}\right>$$

s-wave halo

non-halo

Coulomb Breakup of ^{22}C

^{22}C

Coulomb Breakup of ^{22}C

Nakatsuka, TN, in preparation

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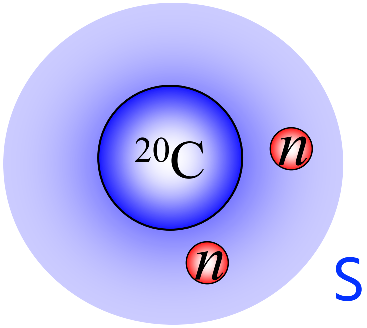
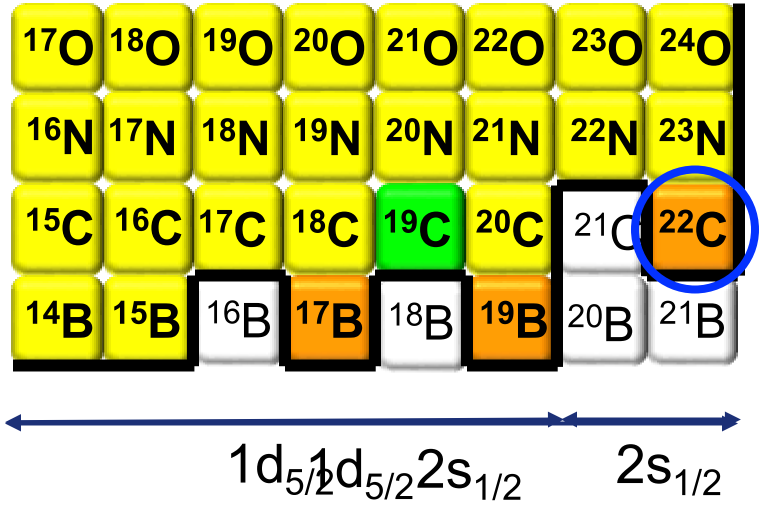
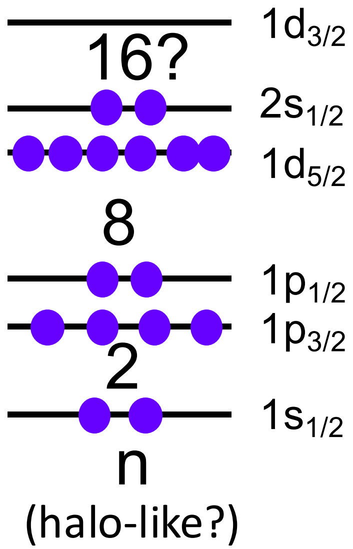
Heaviest s-wave two-neutron halo accessible



S_{2n}: Small but Controversial!

$^{22}C = ^{20}C + 2n$ (halo)?





$S_{2n} = 0.034(20)$ MeV AME2020: Chinese Phys. C45 030003 (2021).

N.Kobayashi, PRC**86**, 054604 (2012).

$S_{2n} = -0.14(46)$ MeV

Direct Mass Measurement: L.Gaudefroy et al. PRL**109**, 202503(2012).

$S_{2n} \sim 0.01$ MeV K. Tanaka et al., PRL**104**, 062701 (2010).

Reaction Cross Section Measurement (^{22}C+p @40A MeV) $r_{rms}(^{22}C) = 5.4(9)\, fm$

$\sim 2\sigma$ deviation

$S_{2n} = 0.56^{+0.27}_{-0.20}$ MeV Y. Togano et al., PLB**761**, 412 (2016).

Reaction Cross Section Measurement (^{22}C+C @235 A MeV) $r_{rms}(^{22}C) = 3.44(8)\, fm$

Experimental Setup: Coulomb breakup of ^{22}C at SAMURAI at RIBF, RIKEN

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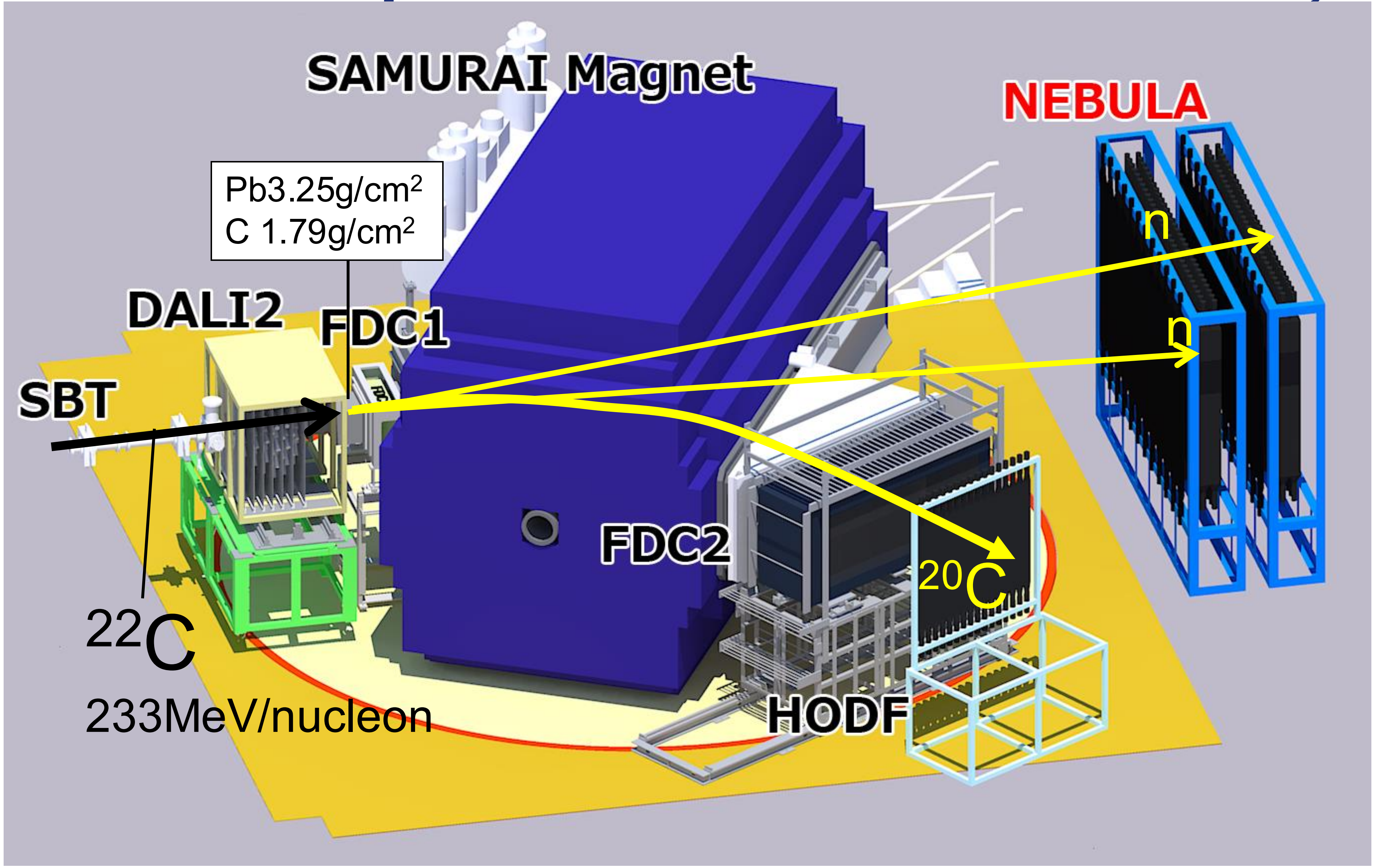

Coulomb Breakup of ^{22}C: *Preliminary Results*

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Nakatsuka, Y.Osawa, TN et al.,

Large Coulomb Breakup Cross Section
→ Soft E1 Excitation

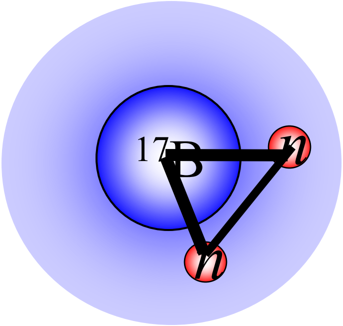
^{22}C+Pb

^{22}C+C(x3.3)

dB(E1)/dE in **^{22}C**:
Peak: **Much broader** and **less pronounced** than **^{19}B**

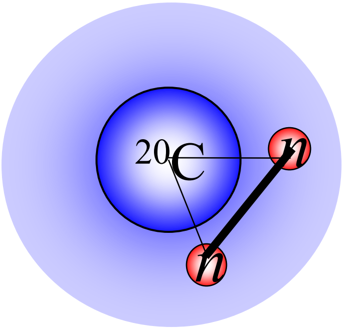
K.J. Cook et al.
PRL**124**, 212503 (2020).

^{19}B



3-body model (Hagino)

^{22}C



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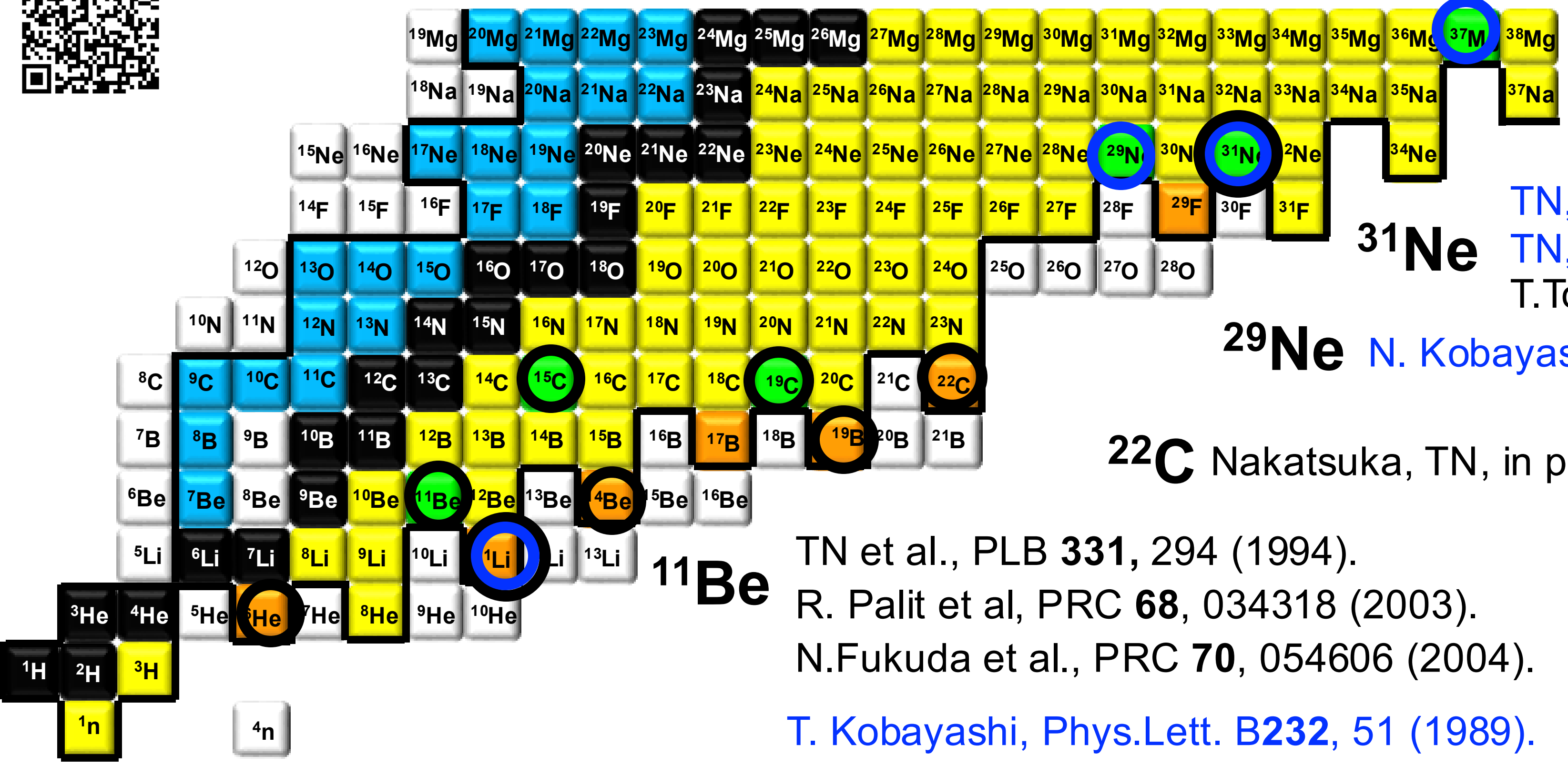
Summary:
Coulomb Breakup of neutron halo nuclei in 36 years

T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).
T. Nakamura, Handbook of Nuclear Physics, pp1-37 (2023).

Inclusive Coulomb Breakup Done
Exclusive Coulomb Breakup Done

1n-halo nuclei
2n-halo nuclei



^{37}Mg N.Kobayashi et al., PRL **112**, 242501 (2014).

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

^{29}Ne N. Kobayashi et al., PRC **93**, 014613 (2016).

^{22}C Nakatsuka, TN, in preparation

^{11}Be TN et al., PLB **331,** 294 (1994).
R. Palit et al, PRC **68**, 034318 (2003).
N.Fukuda et al., PRC **70**, 054606 (2004).

^{15}C A. Horvath et al., APJ**570**, 926 (2002).
D. Pramanik et al. PLB **551**, 63 (2002).
TN et al., PRC**79**, 035805 (2009).

^{19}C TN et al., PRL **83**, 1112 (1999).

^{11}Li T. Kobayashi, Phys.Lett. B**232**, 51 (1989).
K.Ieki et al., PRL **70**, 730 (1993).
D. Sackett et al., PRC 48, 118 (1993).
S. Shimoura,TN et al., PLB **348**, 29 (1995).
Zinger et al., NPA **619**, 151(1997).
TN et al., PRL **96**, 252502 (2006).

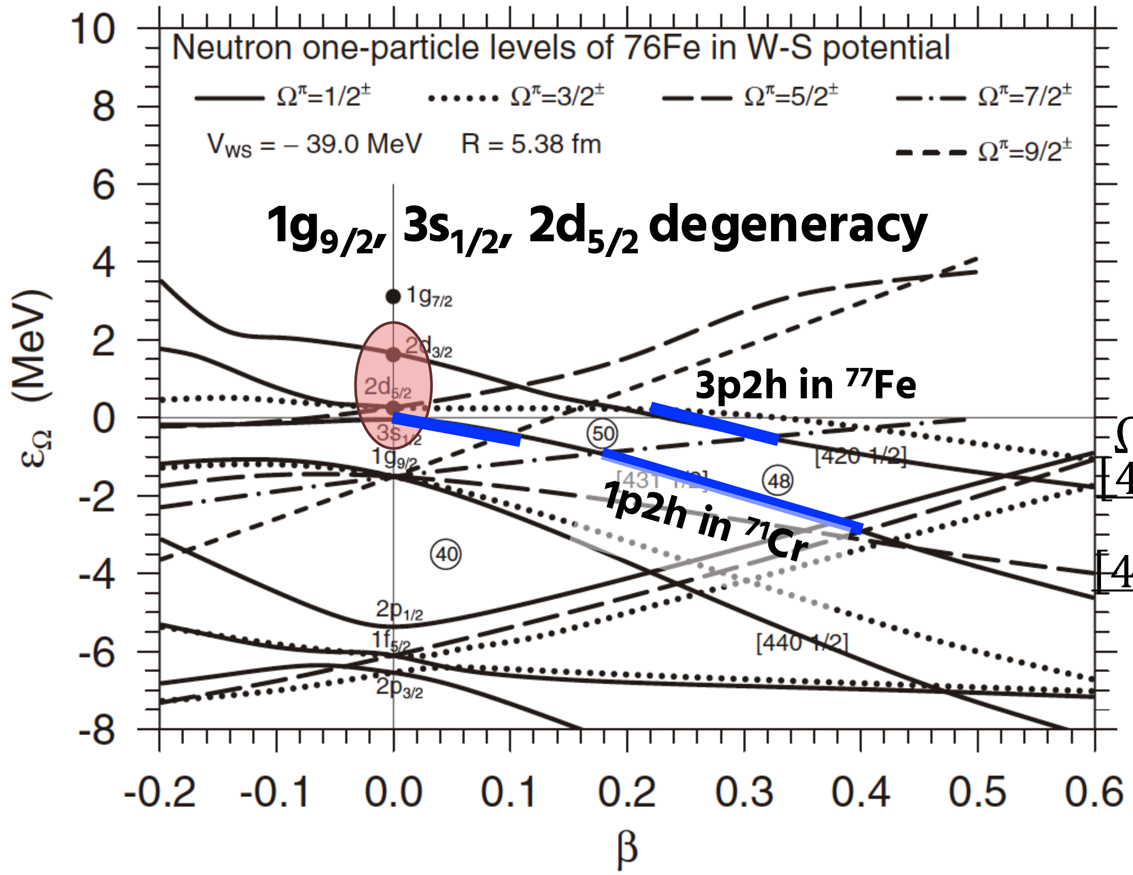
^{19}B K.J. Cook et al. PRL**124**, 212503 (2020).

^{14}Be M. Labiche et al., PRL**86**, 600 (2001).

^{6}He
T.Aumann et al., PRC**59**, 1252 (1999).
Wang et al., PRC**65**, 034306 (2002).
Y.L.Sun,et al., PLB **814**, 136072(2021)

Perspectives

- 3-body Borromean halo:
  - →5-body model & 4n decay experiments provide further insights?
- Halo is universal along the neutron drip line ?
  - → Shell Evolution/Deformation → s-wave, p-wave component always appear at neutron dripline?



$\Omega^\pi = 1/2^+$
[420 1/2]
[431 1/2]

- ➢ Candidate Deformed s-wave halo
  $^{77}_{26}\mathrm{Fe}_{51}$, $^{71}_{24}\mathrm{Cr}_{47}$, $^{73}_{24}\mathrm{Cr}_{49}$, $^{75}_{24}\mathrm{Cr}_{51}$
- ➢ Candidate Deformed s or p-wave halo
  $^{53}_{18}\mathrm{Ar}_{35}$

I. Hamamoto, PRC**95**, 044325 (2017).

- Please measure the mass of halo nuclei directly!

Exclusive Coulomb/nuclear breakup of ^{31}Ne

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T. Tomai, PhD thesis Paper in Preparation

Coulomb Breakup of ^{22}C

N.Nakatsuka, T.Nakamura, Y.Osawa, Y.Kondo, K.Hagino et al., in Preparation

N. Nakatsuka,[1] T. Nakamura,[1] Y. Osawa,[1] Y. Kondo,[1] K. Hagino,[2] A. Navin,[3] K. Ogata,[4,5] S. Ogawa,[4] Jagjit Singh,[6] Y. Satou,[1] T. Inakura,[7] N.L. Achouri,[8] T. Aumann,[9,10] H. Baba,[11] F. Delaunay,[8] Q. Deshayes,[8] P. Doornenbal,[11] N. Fukuda,[11] J. Gibelin,[8] J.W. Hwang,[12] N. Inabe,[11] T. Isobe,[11] D. Kameda,[11] S. Kim,[12] N. Kobayashi,[1] T. Kobayashi,[13] T. Kubo,[11] S. Leblond,[8] J. Lee,[14] M. Ishihara,[11] F. M. Marqués,[8] R. Minakata,[1] T. Motobayashi,[11] T. Murakami,[2] S. Ogoshi,[1] T. Ohnishi,[11] N.A. Orr,[8] H. Otsu,[11] H. Sato,[11] Y. Shimizu,[15] H. Suzuki,[11] H. Takeda,[11] S. Takeuchi,[11] R. Tanaka,[1] Y. Togano,[11] M. Vandebrouck,[16] and K. Yoneda[11]

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