Coulomb Dissociation of ^{17}B

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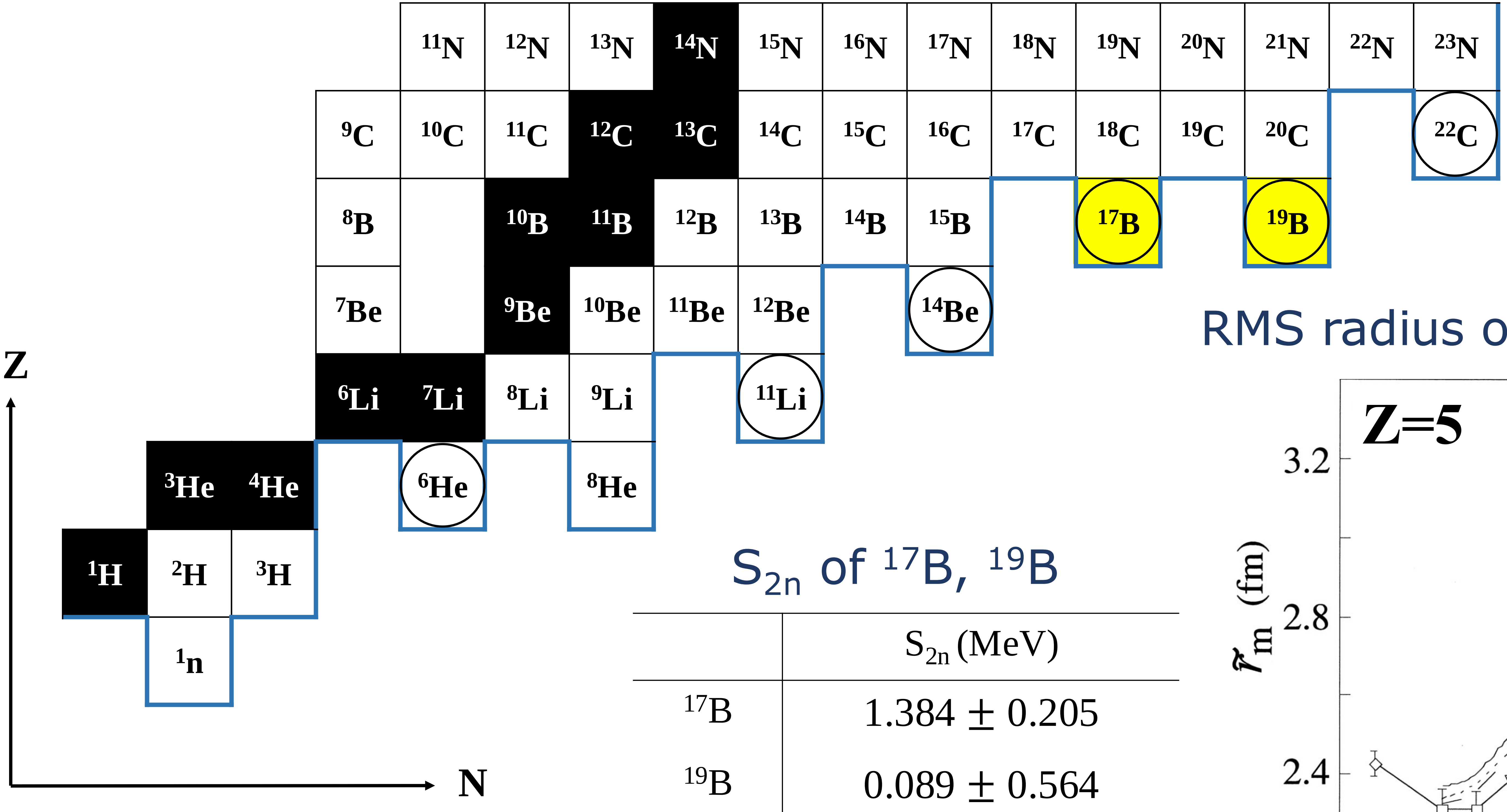
^{17}B: Two-Neutron Halo Nucleus

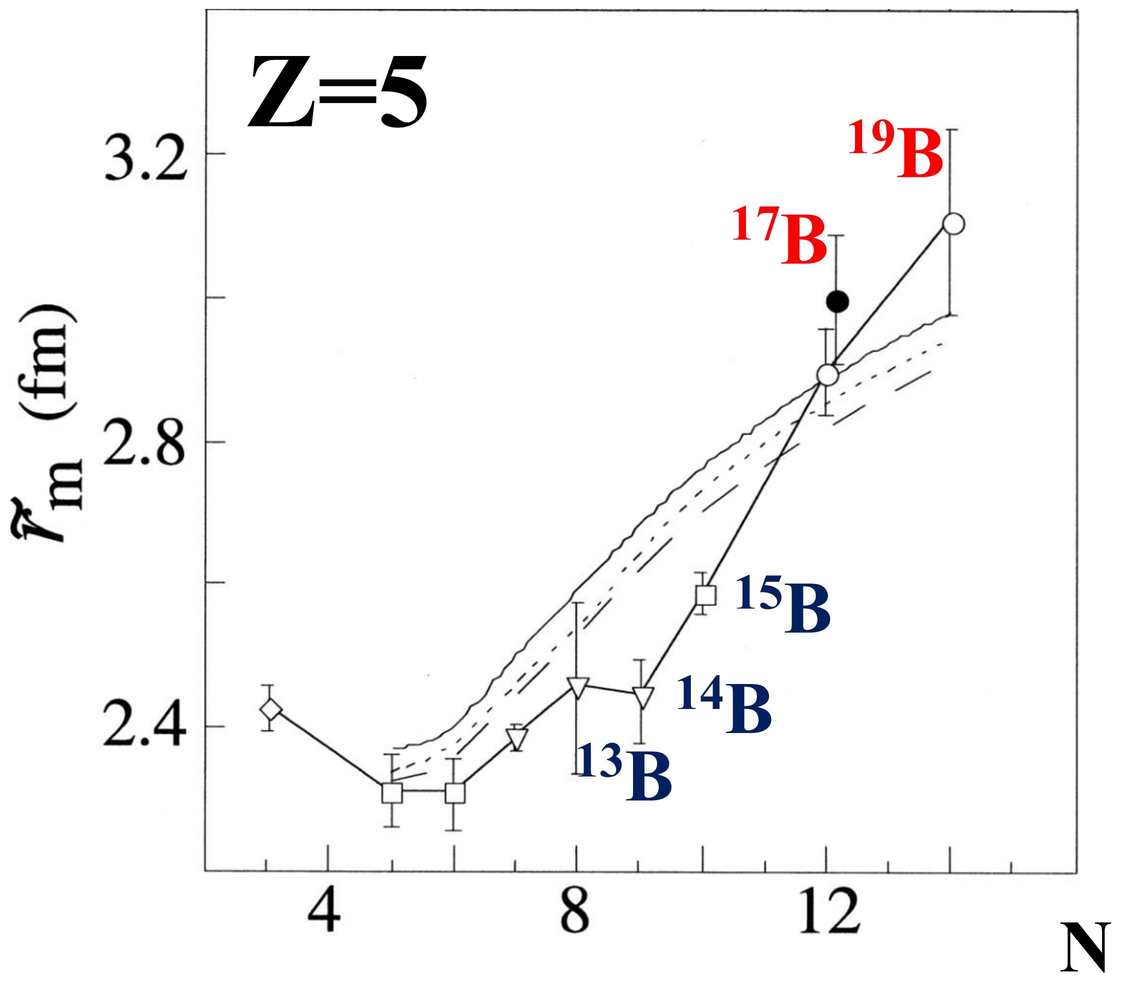


S_{2n} of ^{17}B, ^{19}B

	S_{2n} (MeV)
^{17}B	1.384 ± 0.205
^{19}B	0.089 ± 0.564

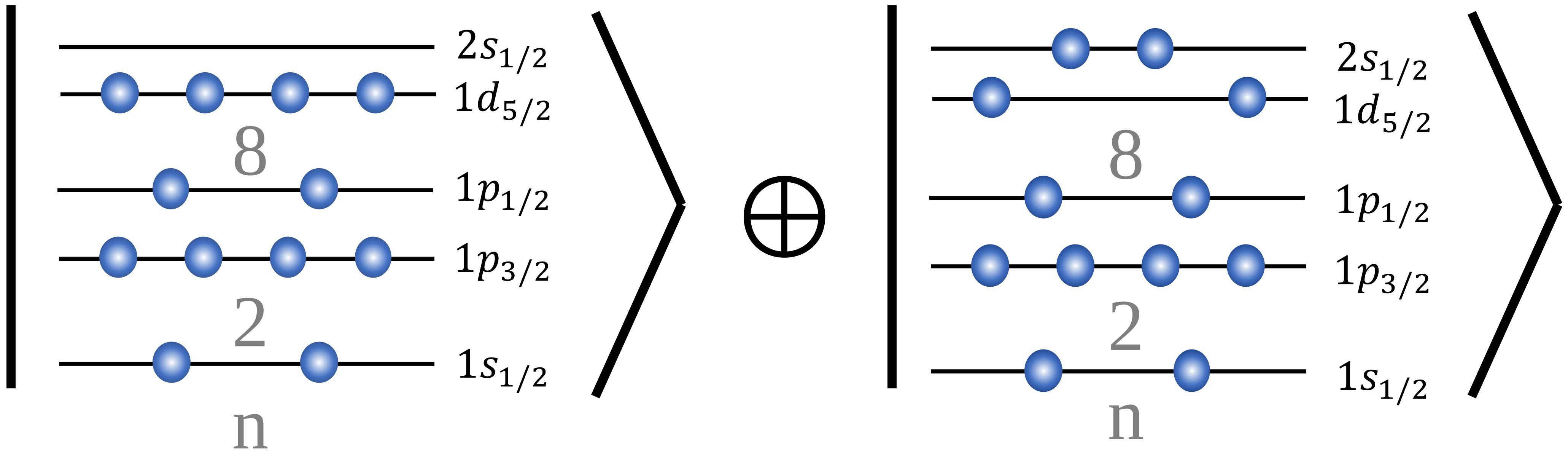
T. Suzuki et al, *Nucl. Phys. A*,658, 313-326 (1999)

RMS radius of boron isotopes



Neutron Orbital Configuration of ^{17}B

$\Psi({}^{17}_{5}B) =$



4n skin-like　　　　2n halo-like

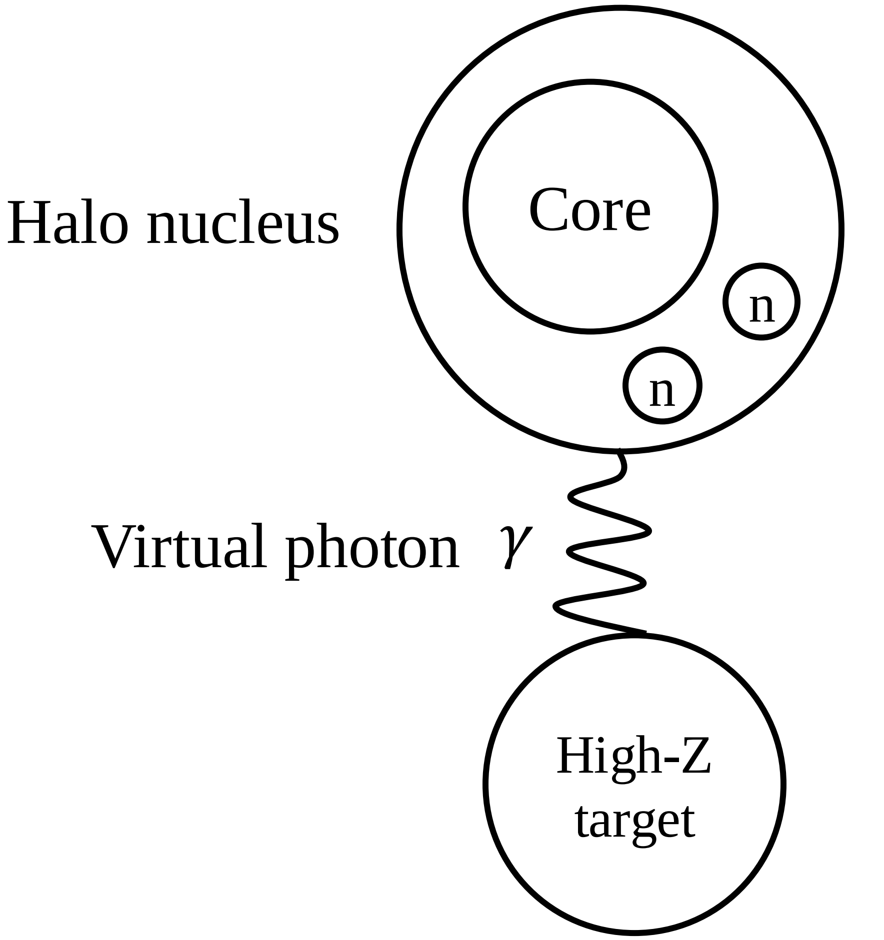
Experimental data of orbital ratio of ^{17}B

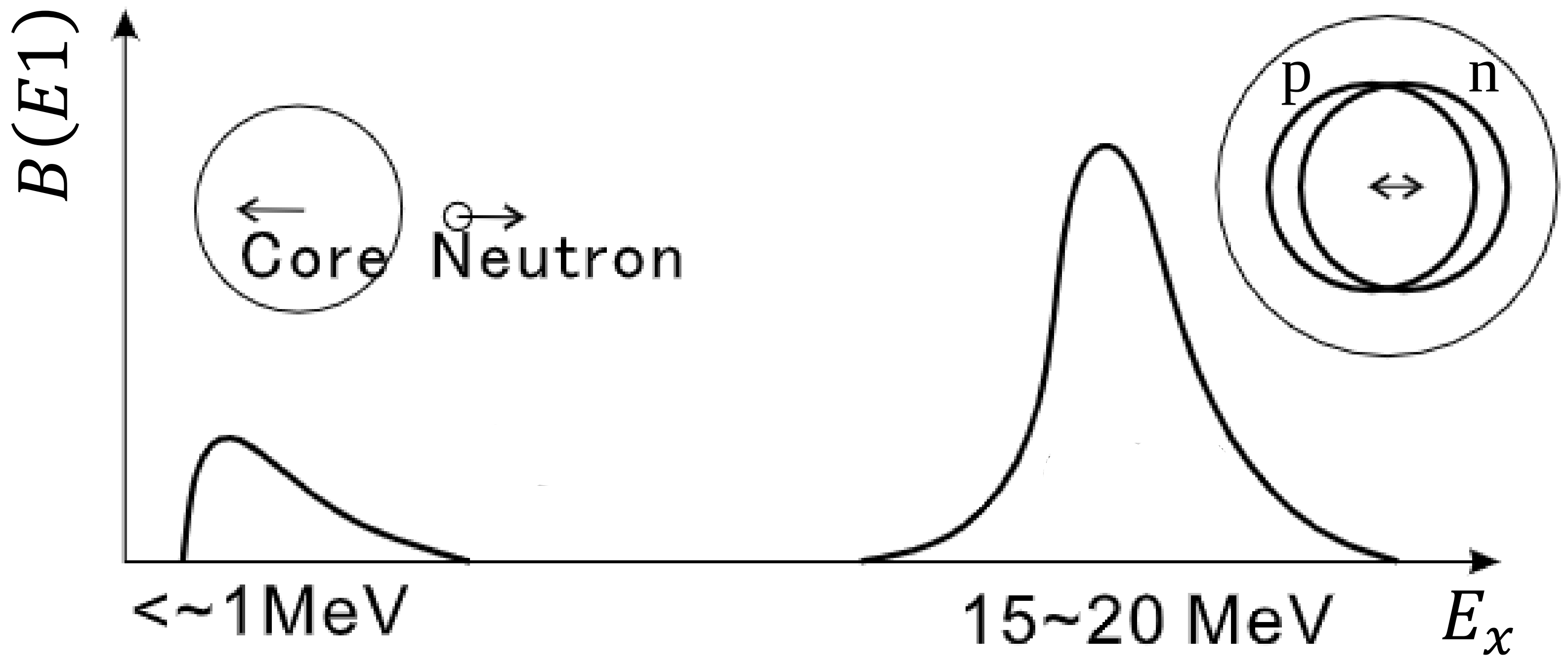
Reference	s-orbital ratio	Method
T. Suzuki (1999)	36(19)%	σ_I with FB model
T. Suzuki (2002)	69(20)%	σ_{-2n} with FB model
Y. Yamaguchi (2004)	50(10)%	σ_R with FB model
Z. H. Yang (2021)	9(2)%	quasifree (p,pn)

Extremely Small s orbital 9(2)% !

Electric Dipole (E1) Response of Halo Nucleus

Coulomb excitaion

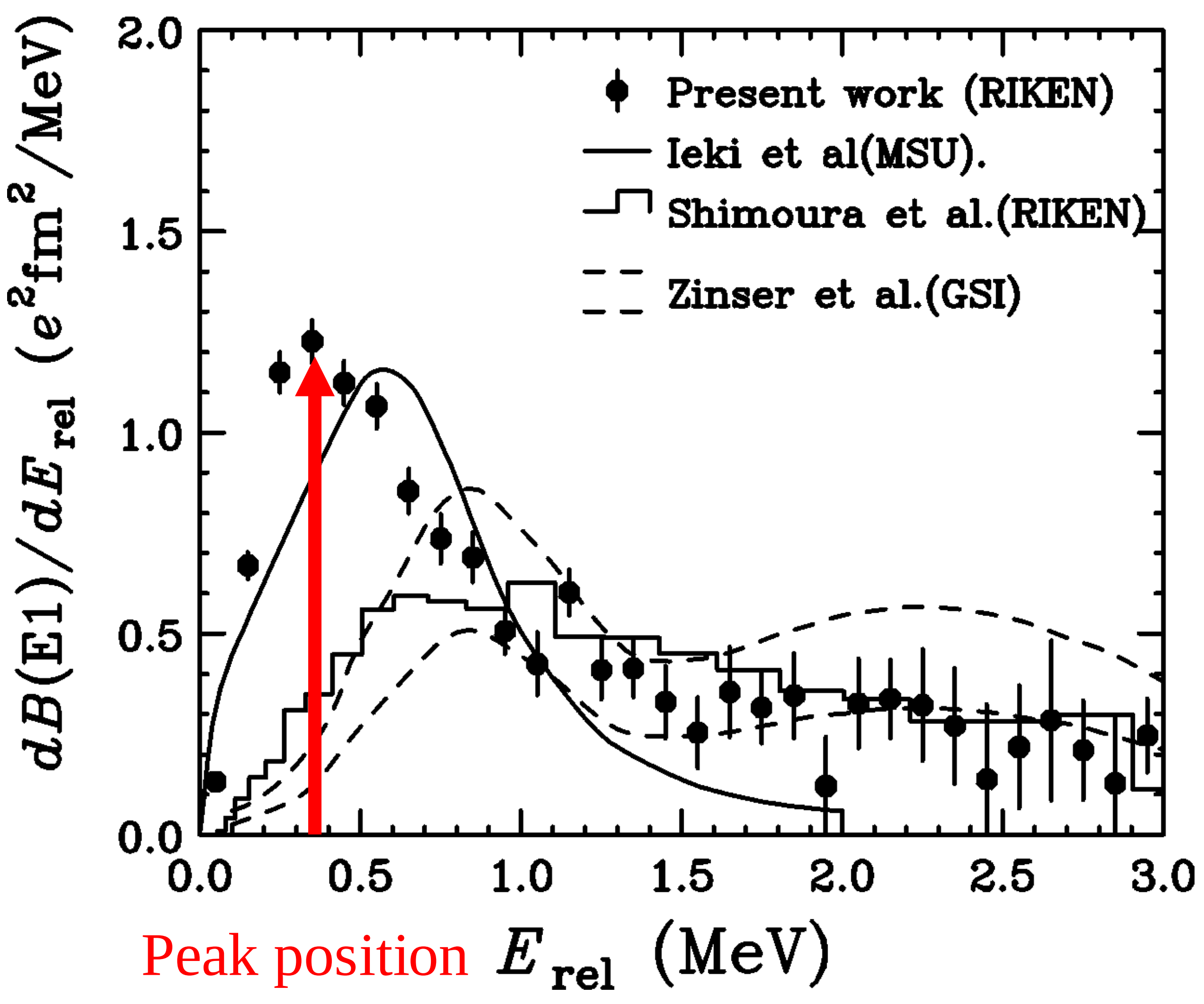




Soft E1 Excitation	**Giant Dipole Resonance**
Polarization between core and neutron(s)	Osillation between proton and neutron

Soft E1 Excitation of 2n Halo Nuclei: ^{11}Li, ^{19}B

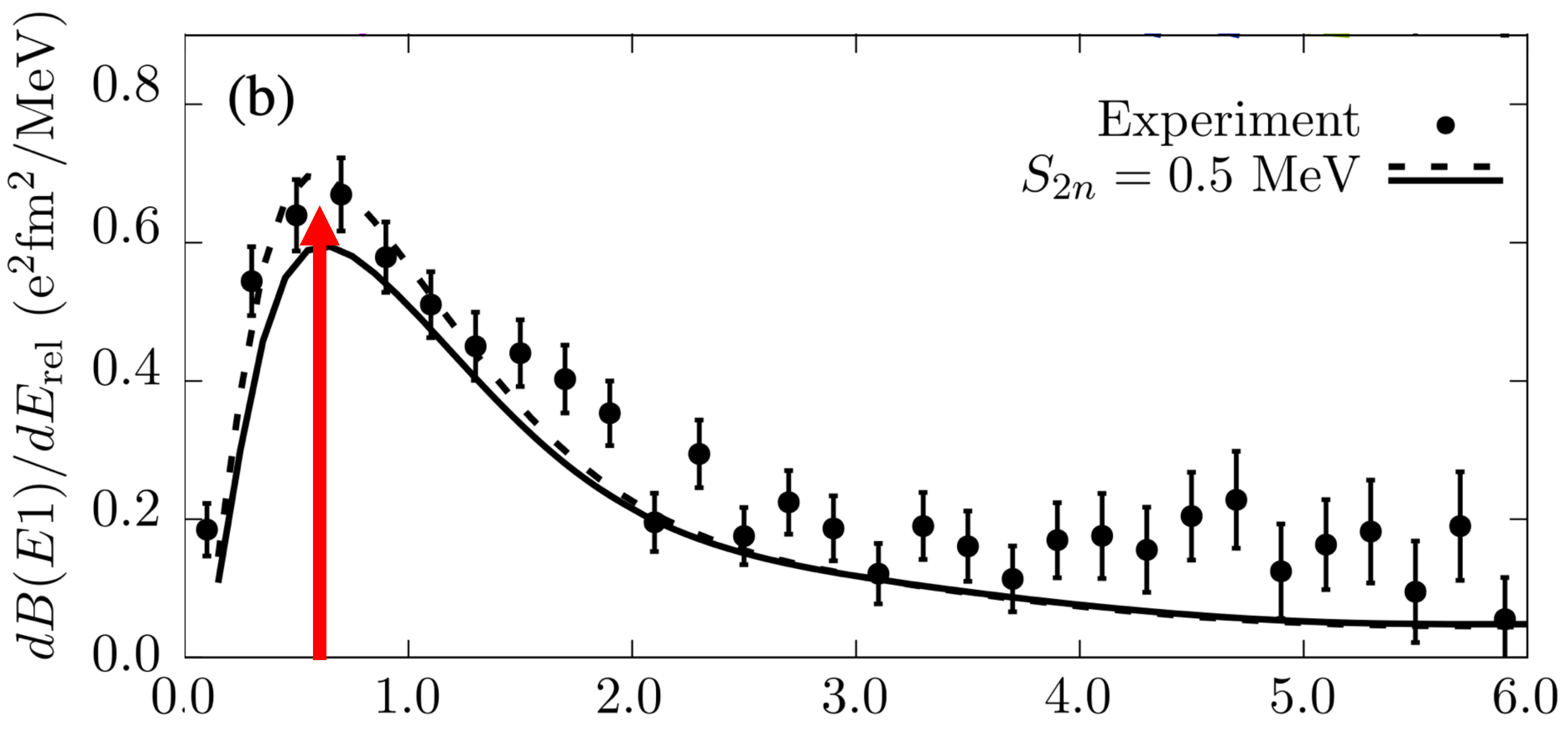
^{11}Li (S_{2n} = 0.369 MeV)



Peak position ~ 0.3 MeV

B(E1)$_{total}$ = 1.42 ± 0.18 [e^2fm^2]

^{19}B (S_{2n} = 0.089 MeV)



Peak position ~ 0.5 MeV

B(E1)$_{total}$ = 1.64 ± 0.06 [e^2fm^2]

T. Nakamura *et al.*, *Phys. Rev. Lett.* **96**, 252502 (2006).

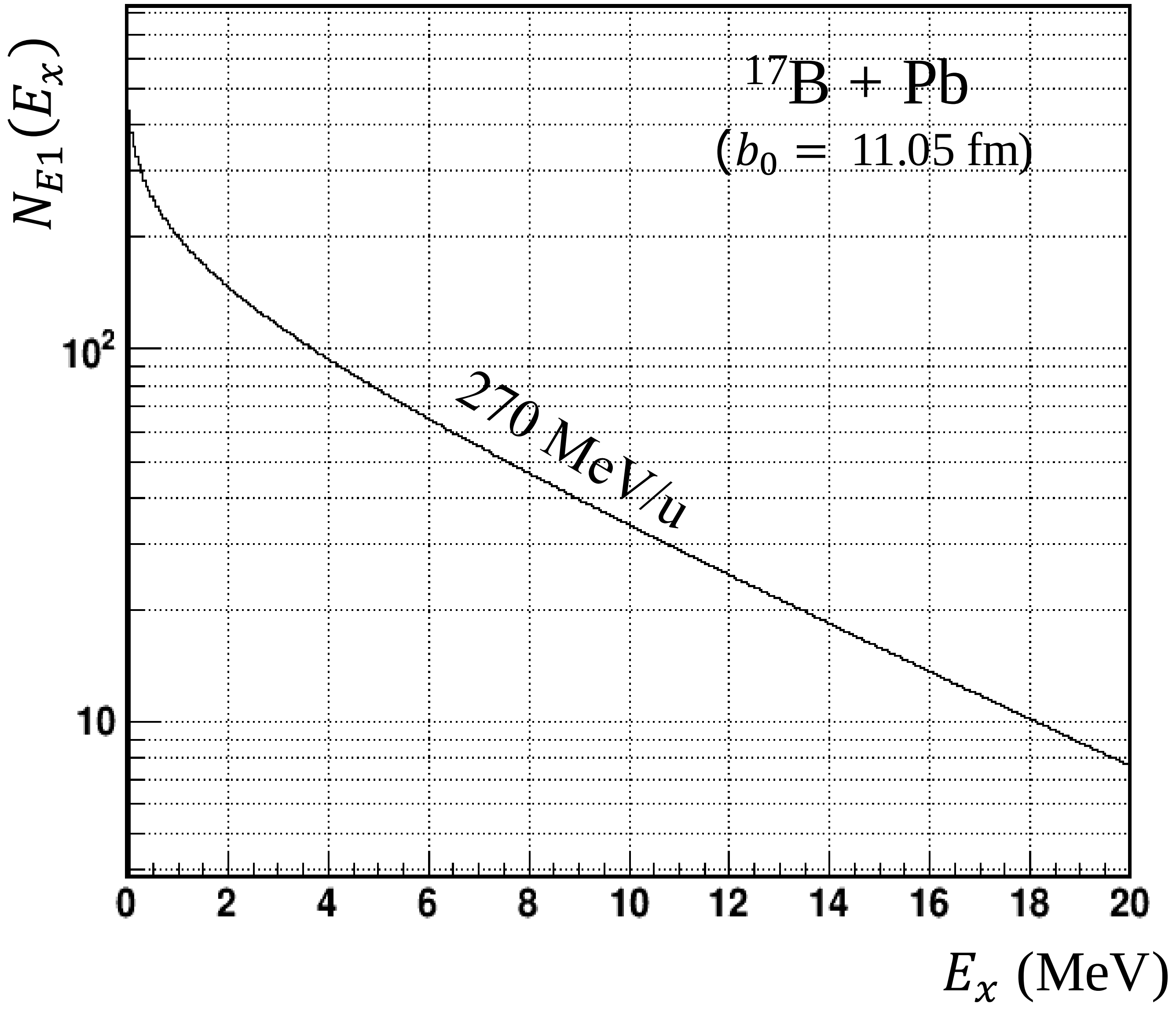
K. J. Cook *et al.*, *Phys. Rev. Lett.*, **124**, 212503 (2020)

Equivalent Photon Method

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

Coulomb dissociation cross section ∝ the number of E1 virtual photons x reduced E1 transition probability

Virtual photon number $N_{E1}(E_x)$



C. A. Bertulani, G. Baur, *Phys. Rep.*, 163, 299 (1988)
T. Aumann, T. Nakamura, *Phys. Scr.*, T152, 014012 (2012)

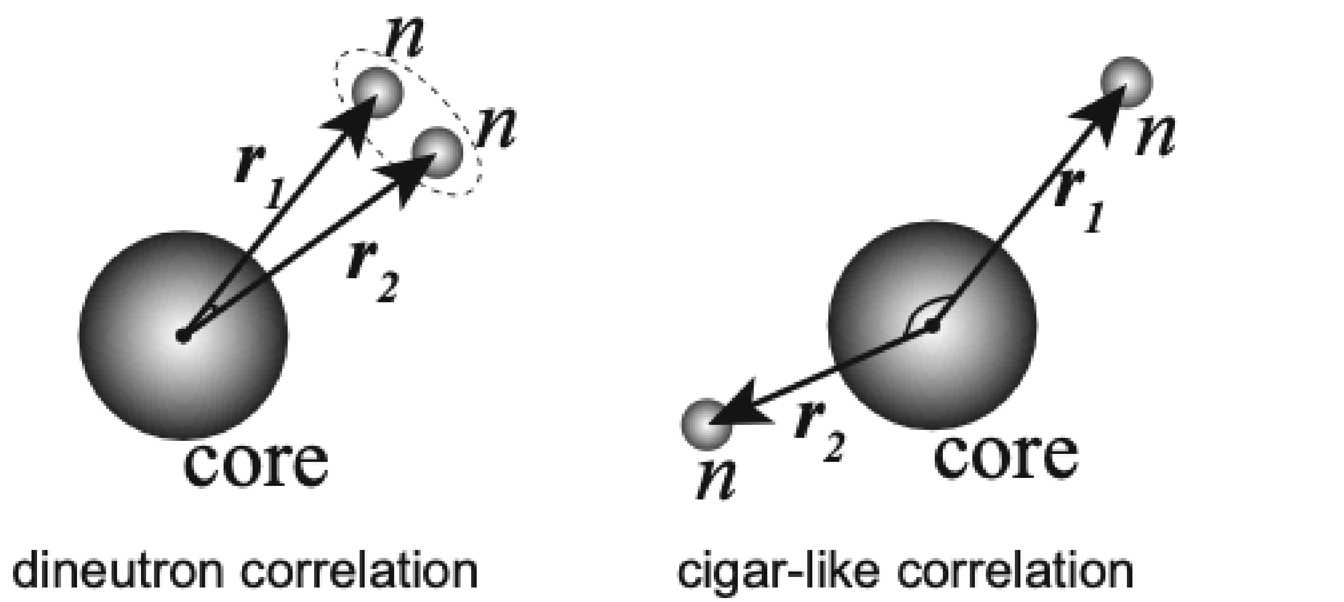
Dineutron Correlation in Two-Neutron Halo

n-n correlation

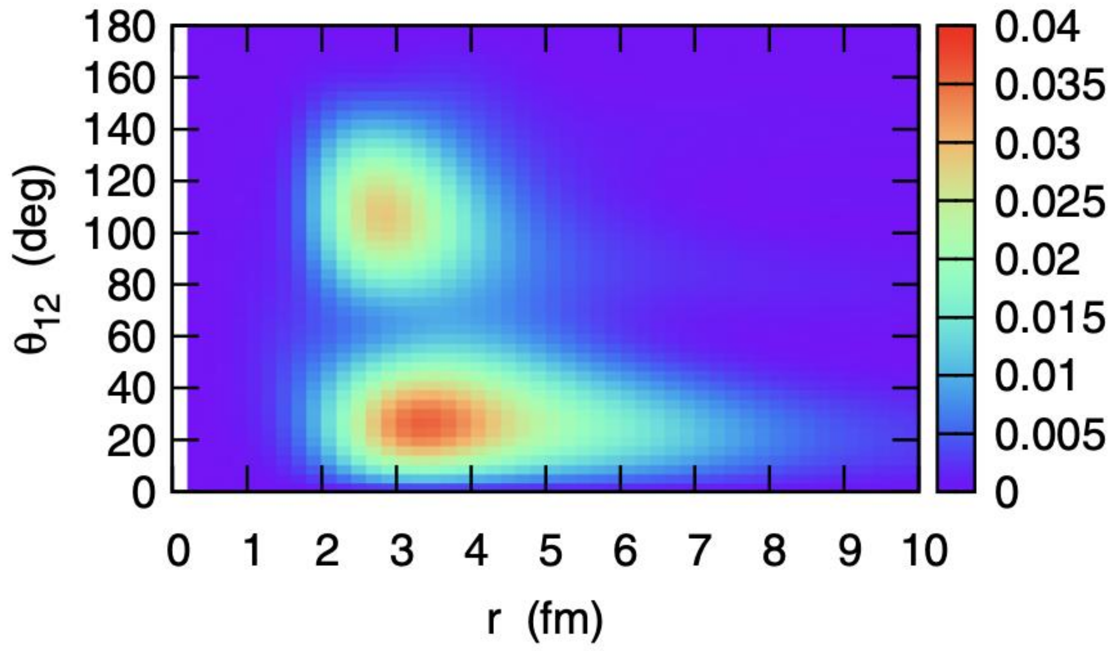
$\theta_{12} > 90°$: cigar-like correlation

$\theta_{12} < 90°$: dineutron correlation

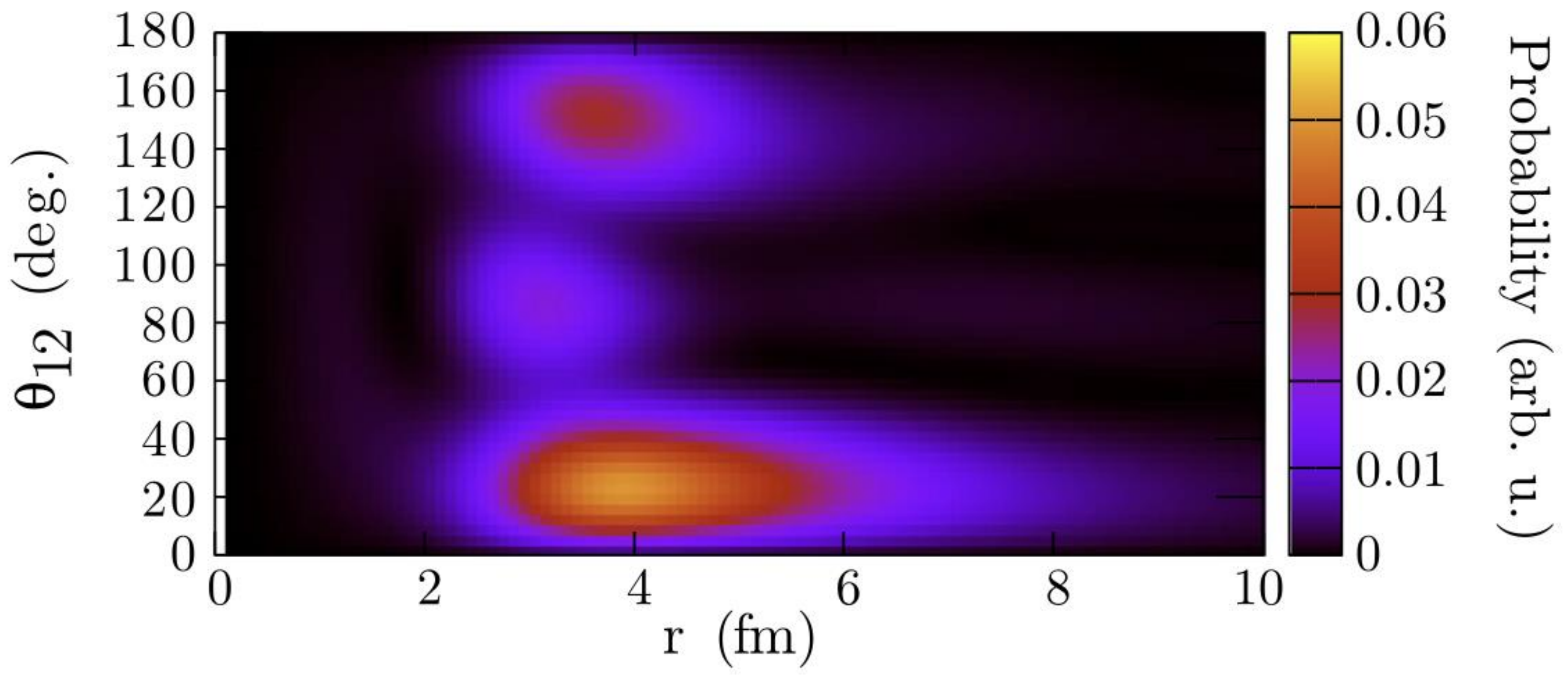
$\theta_{12} = 90°$: no correlation



Dineutron correlation in 11Li

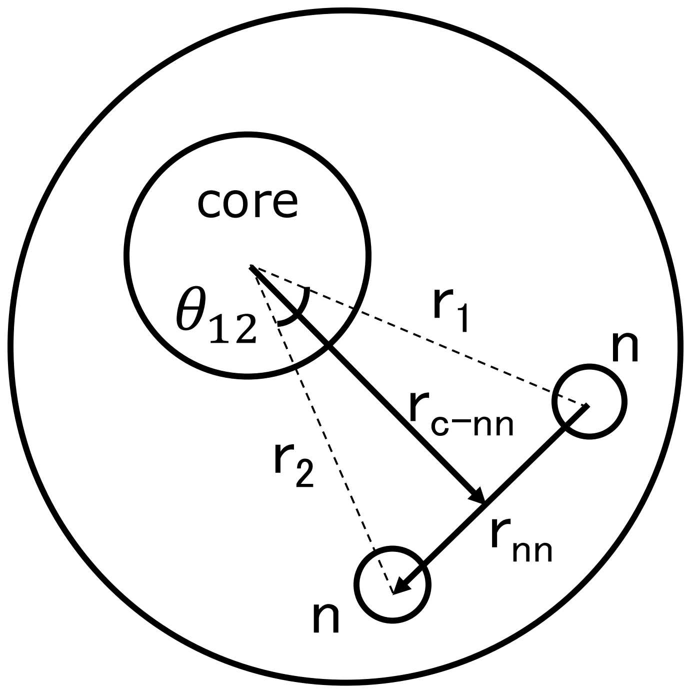


Dineutron correlation in 19B



K. Hagino and H. Sagawa, *Phys. Rev. C.* **72**, 044321 (2005).

Dineutron Correlation in Two-Neutron Halo



Opening angle of two valance neutron

$\langle r_{c-nn}^2 \rangle \leftarrow$ B(E1)

$\langle r_{nn}^2 \rangle \leftarrow$ Matter radius

$$\langle \theta_{12} \rangle = 2\cos^{-1}\left(\frac{\sqrt{\langle r_{c-nn}^2 \rangle}}{\sqrt{\langle r_{c-nn}^2 \rangle + \frac{\langle r_{nn}^2 \rangle}{4}}} \right)$$

K. Hagino and H. Sagawa, *Phys. Rev. C.* **76**, 047302 (2007).

Non-energy-weighted cluster sum rule

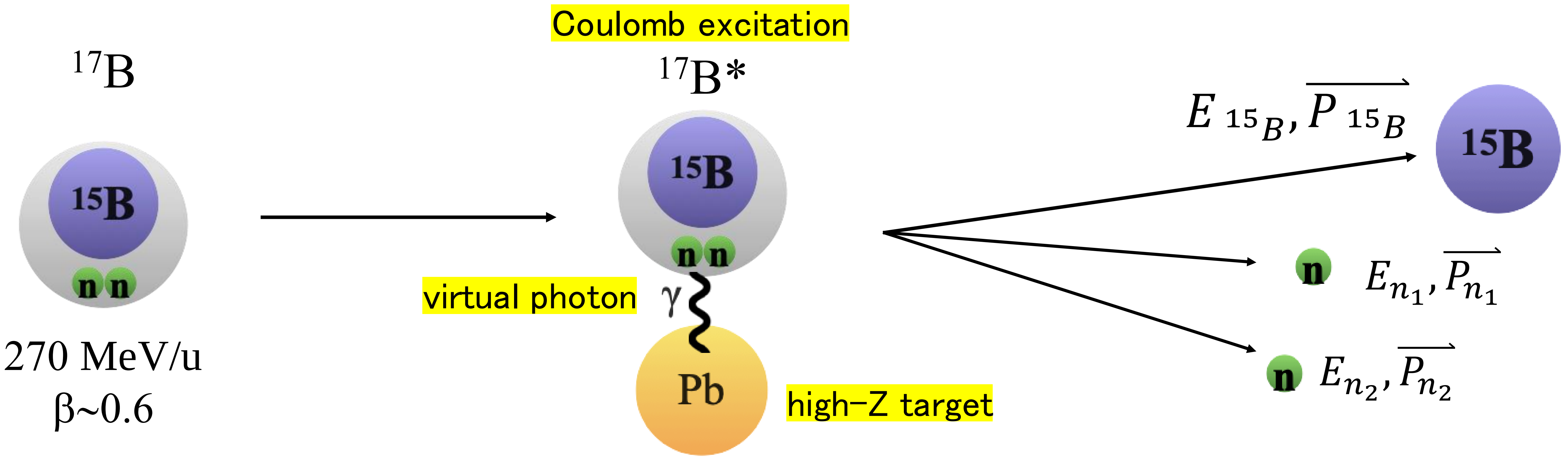
$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x = \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \langle r_{c-nn}^2 \rangle$$

Matter radius of halo nuclei in three-body model

$$\langle r_m^2 \rangle = \frac{A_c}{A}\langle r_m^2 \rangle_c + \frac{2A_c}{A^2}\langle r_{c-nn}^2 \rangle + \frac{1}{2A}\langle r_{nn}^2 \rangle$$

Method

Coulomb Dissociation of ^{17}B @ RIBF, RIKEN

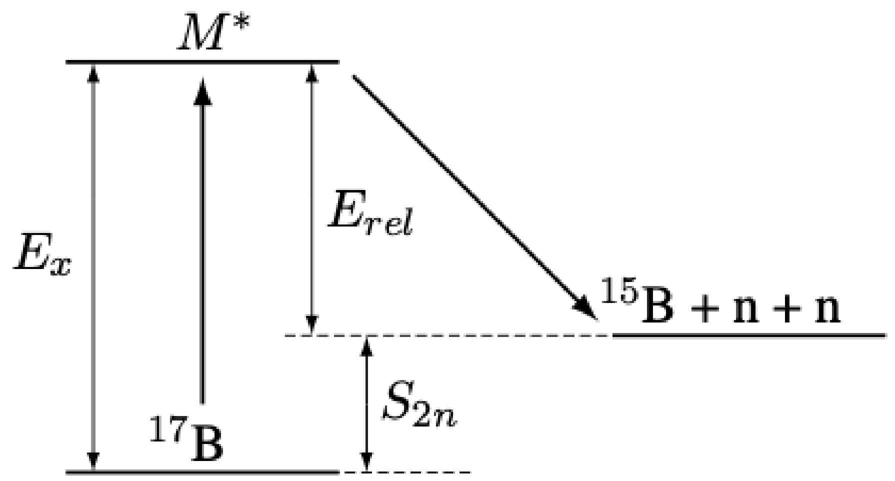


Invariant Mass Method

$$M(^{17}\mathrm{B}^*) = \sqrt{[E(^{15}\mathrm{B}) + E(n_1) + E(n_2)]^2 - |\vec{p}(^{15}\mathrm{B}) + \vec{p}(n_1) + \vec{p}(n_2)|^2}$$

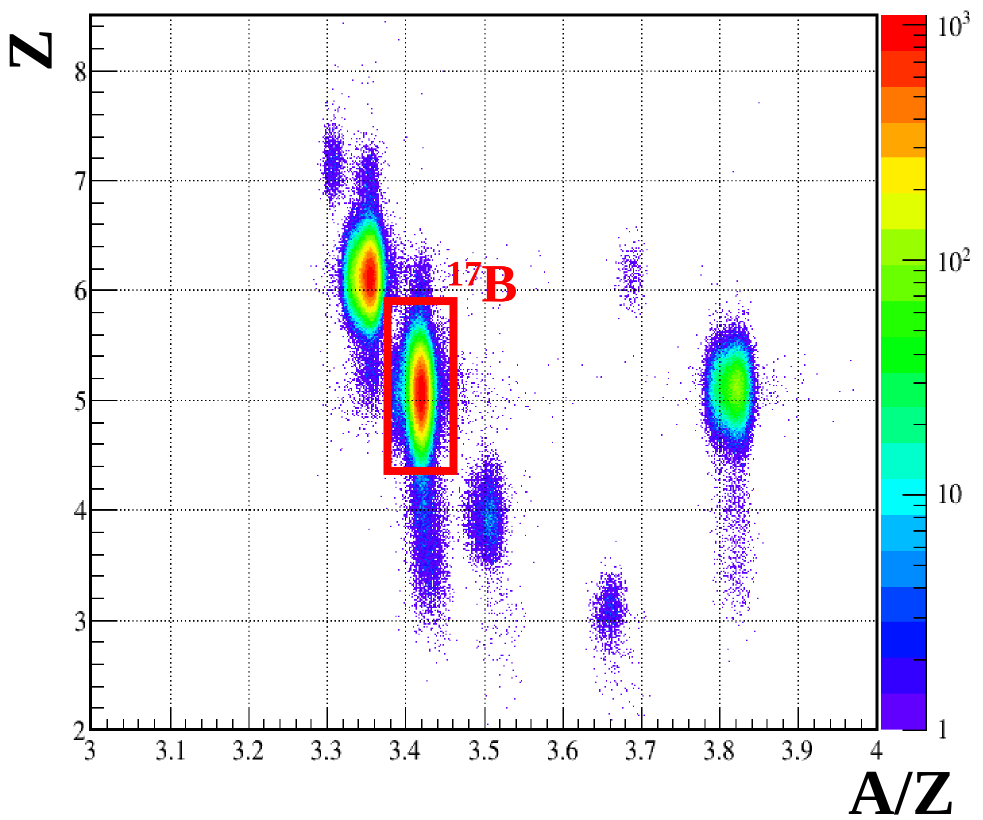
$$E_{rel} = M(^{17}\mathrm{B}^*) - m(^{15}\mathrm{B}) - 2m_n$$

$$E_x = E_{rel} + S_{2n}$$

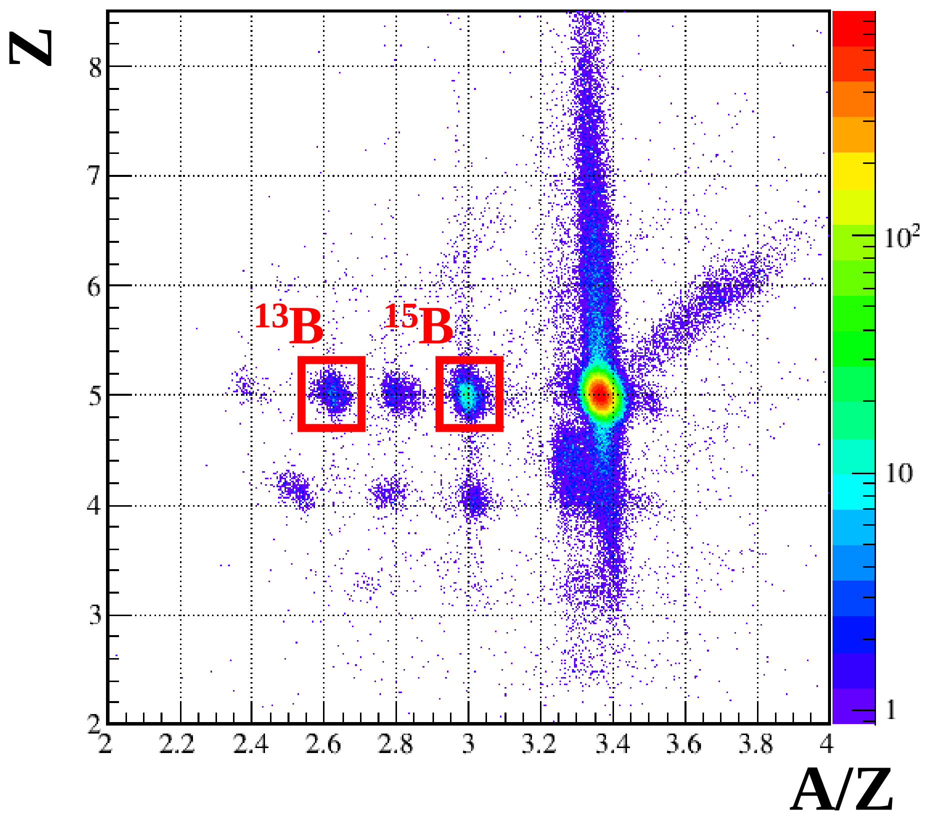


Particle Identification and Inclusive Cross section

Secondary ^{17}B beam PID



Fragment PID from ^{17}B beam



Inclusive Cross Section of ^{17}B and ^{19}B

K. J. Cook *et al.* (2020) — This work

	σ_{-2n} (mb)	σ_{-4n} (mb)		σ_{-2n} (mb)	σ_{-4n} (mb)
^{19}B + Pb	1800 (60)	600 (30)	^{17}B + Pb	617 (21)	154 (11)
^{19}B + C	251 (5)	185 (3)	^{17}B + C	159 (3)	63 (2)
σ_{Pb}/σ_C	7.1	3.3	σ_{Pb}/σ_C	3.9	2.5

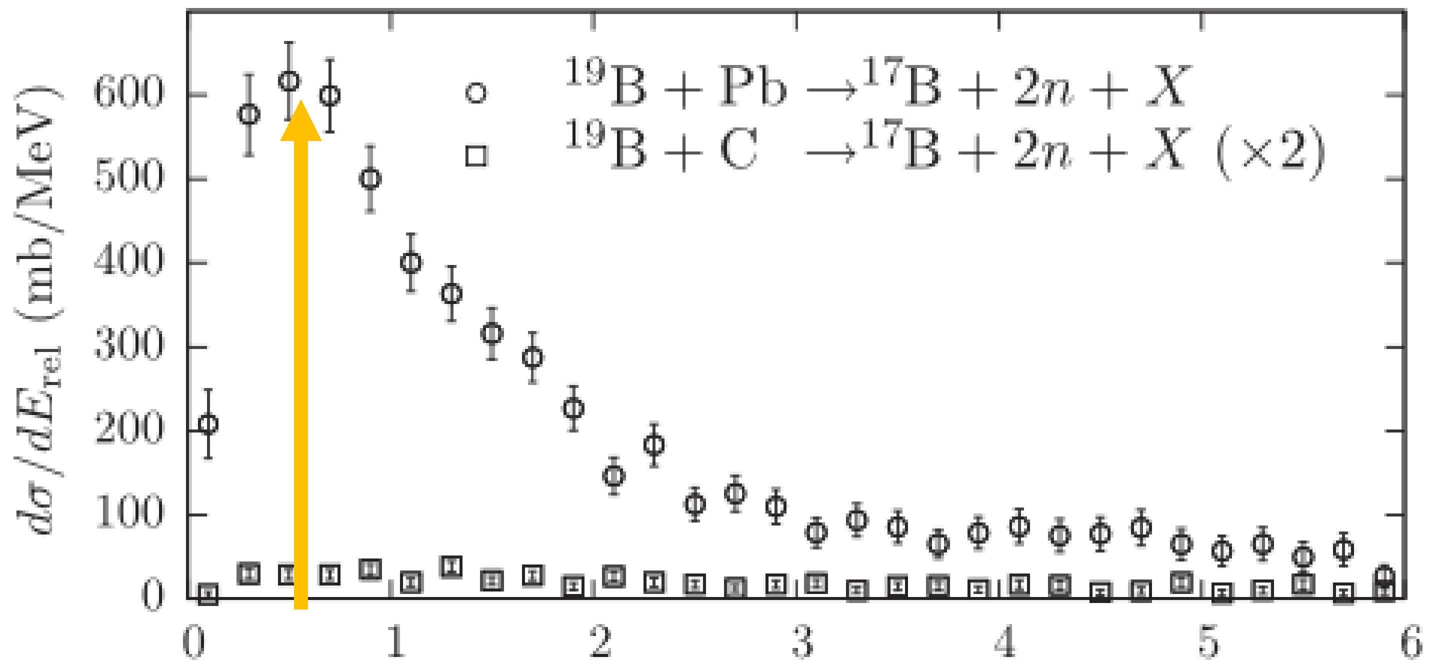
Coulomb Dissociation Cross Section

● $^{17}B + Pb \rightarrow {}^{15}B + 2n + X$
● $^{17}B + C \rightarrow {}^{15}B + 2n + X \; (\times \Gamma)$

$d\sigma/dE_{rel}$ [mb/MeV]

Preliminary

E_{rel} [MeV]



$$\frac{d\sigma_{CD}}{dE_{rel}} = \frac{d\sigma_{inel}(Pb)}{dE_{rel}} - \Gamma \frac{d\sigma_{inel}(C)}{dE_{rel}}$$

Integrated cross section

	This work		K. J. Cook *et al.* (2020)
	^{17}B ($\Gamma = 2.835$)		^{19}B ($\Gamma = 2.8$)
	$E_{rel} < 6$ MeV	$E_{rel} < 7$ MeV	$E_{rel} < 6$ MeV
σ_{inel}(Pb)	300(7) mb	327(8) mb	1160(30) mb
σ_{inel}(C)	20(1) mb	23(1) mb	54(3) mb
σ_{CD}	242(8) mb	261(8) mb	1009(31) mb

	^{17}B	^{19}B
Peak position	~ 2.5 MeV	~ 0.5 MeV
σ_{CD} (< 6 MeV)	242(8) mb	1009(31) mb

Weak Halo

Halo Feature of ^{17}B

Isotope*	S_{2n} [MeV]	σ_{CD_-2n} [mb]	$\sigma_{CD\_^{15}B+2n}$ [mb]	E_{peak} at $\frac{d\sigma_{CD}}{dE_{rel}}$
^{17}B	1.384 ± 0.205	168 ± 22	242 ± 8 ($\leq$ 6 MeV)	~ 2.5 MeV
^{19}B	0.089 ± 0.564	1097 ± 62	1009 ± 31 ($\leq$ 6 MeV)	~ 0.5 MeV
^{11}Li	0.369 ± 0.001	-	2340 ± 50 ($\leq$ 3 MeV)	~ 0.3 MeV

* The beam energy is 270 MeV/u, 220 MeV/u, 70 MeV/u for ^{17}B, ^{19}B and ^{11}Li

About ^{17}B,
It definitely has halo features (small S_{2n} and large r_{rms}).
But according to the significantly small CD cross section and high peak position, it might be better to consider as <u>a weak halo</u> or <u>4-neutron skin nucleus</u>.

Summary

- ^{17}B dissociation into ^{15}B + 2*n* in reactions with Pb and C at 270 MeV/u @ RIBF, RIKEN
- Extract inclusive cross section, relative energy spectrum and CD cross section

  Large peak position: $E_{peak}(^{17}B) \sim 2.5$ MeV (>> $E_{peak}(^{19}B) \sim 0.5$ MeV)

  Small Coulomb dissociation cross section: $\sigma_{CD}(^{17}B) \sim 1/4\ \sigma_{CD}(^{19}B)$

  → weak halo features

Future Plan

- Discussing Γ factor for subtracting nuclear dissociation.
- Extract $B(E1)/dE_{rel}$ spectrum and dineutron correlation.
- Theoretical three-body calculation will be great support on this research.

Collaborators

Tokyo Tech

H. Lee [A], T. Nakamura [A], N. Nakatsuka [B A], Y. Kondo [A], Y. Satou [A] , K. J. Cook [A], S. Ogoshi [A], A. T. Saito [A], N. L. Achouri [C], T. Aumann [D E], H. Baba [F], F. Delaunay [C], Q. Deshayes [C], P. Doornenbal [F], N. Fukuda [F], J. Gibelin [C], J. W. Hwang [G], N. Inabe [F], T. Isobe [F], D. Kameda [F], D. Kanno [A], S. Kim [G], N. Kobayashi [A], T. Kobayashi [H], T. Kubo [F], S. Leblond [C], J. Lee [F], F. M. Marques [C], R. Minakata [A], T. Motobayashi [F], K. Muto [H], T. Murakami [B], D. Murai [I], T. Nakashima [A], A. Navin [J], S. Nishi [A], N. A. Orr [C], H. Otsu [F], H. Sato [F], Y. Shimizu [F], H. Suzuki [F], K. Takahashi [H], H. Takeda [F], S. Takeuchi [F A], R. Tanaka [A], Y. Togano [E I], J. Tsubota [A], A. G. Tuff [K], M. Vandebrouck [L], and K. Yoneda [F]

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Thank you very much for your attention!