Extremely neutron-rich nuclei probed by breakup reactions with rare-isotope beams

Takashi Nakamura
Tokyo Institute of Technology

Tokyo Tech

Clusters & Hierarchies

Nuclear Physics School for Young Scientists (NUSYS-2023) @ Fudan University, Shanghai, China, Aug 6-13, 2023

Contents

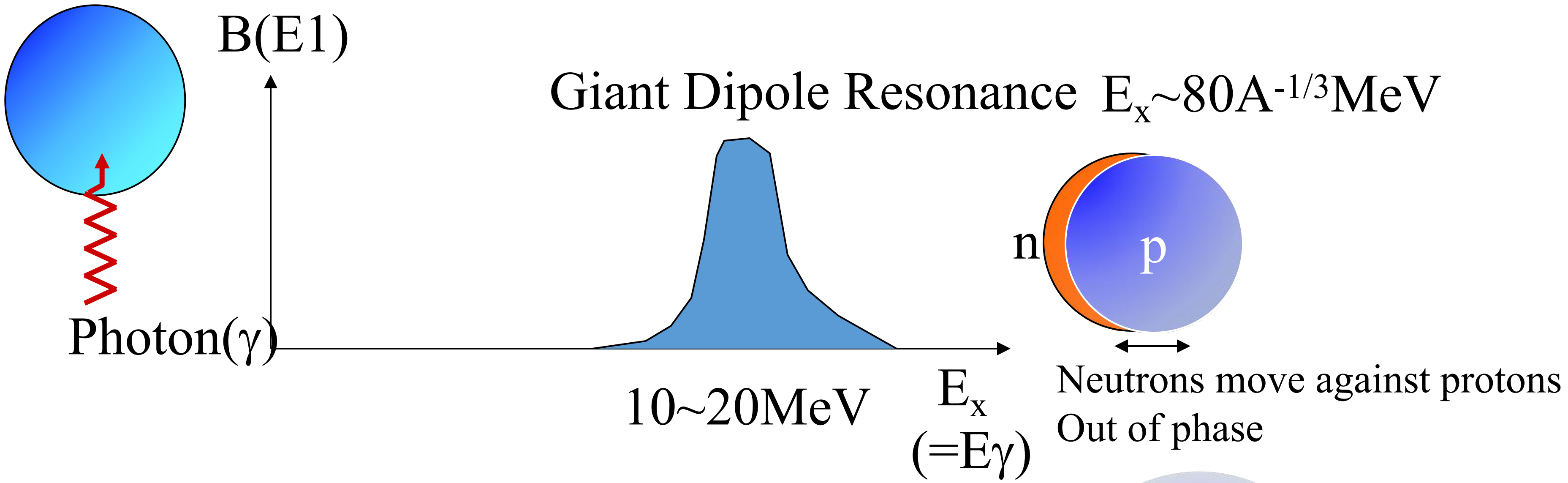
- Lecture-I: Clustering, Hierarchical Structure of Matter, and Nuclear Halo
  - Clusters and Hierarchies of Matter, Semi-hierarchy
  - Clusters near the neutron drip line
  - Neutron Halo nuclei—Basics
  - Three Signals of Neutron Halo
  - Anatomy of Neutron-halo nucleus
- Lecture-II: Coulomb breakup of Neutron Halo Nuclei and Soft E1 Excitation
  - Soft dipole resonance and Soft E1 excitation —Original Idea
  - Coulomb breakup
  - Coulomb breakup of one-neutron halo nuclei → ^{11}Be, ^{19}C, ^{15}C, ^{31}Ne, ^{37}Mg
  - Coulomb breakup of two-neutron halo nuclei → ^{11}Li, ^{19}B, ^{6}He
- Lecture-III: Quasi-free scattering and Multi-neutron states
  - Tetra-neutron
  - ^{28}O: The last canonical doubly magic nucleus?
  - Perspectives: More multi-neutron nuclei

Three Signals of Halo

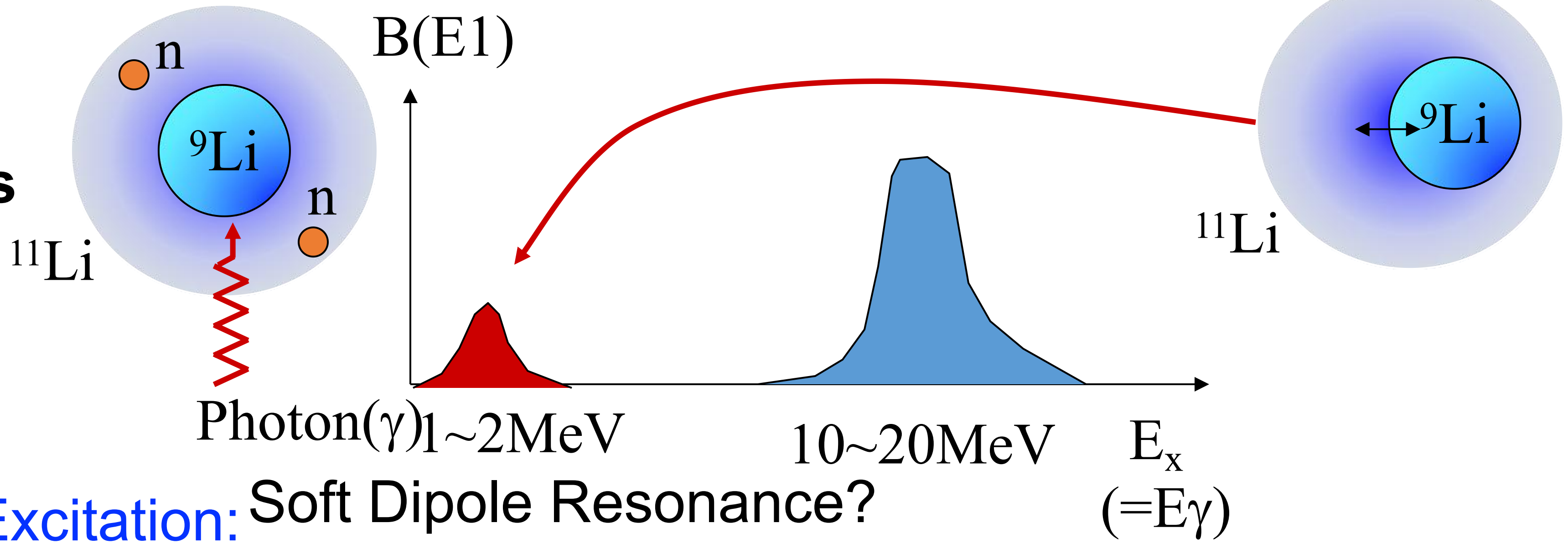
- Large Reaction (Interaction) Cross Section
- Narrow Momentum Distribution of Halo Neutrons
- Soft E1 Excitation: Enhanced Electric-dipole Strength at Low excitation energies → Lecture II

When a nucleus absorbs a photon

Normal Nucleus



Halo Nucleus



Soft E1 Excitation: Soft Dipole Resonance?
Or Non-resonant enhancement?

The story begins by Kiyomi Ikeda

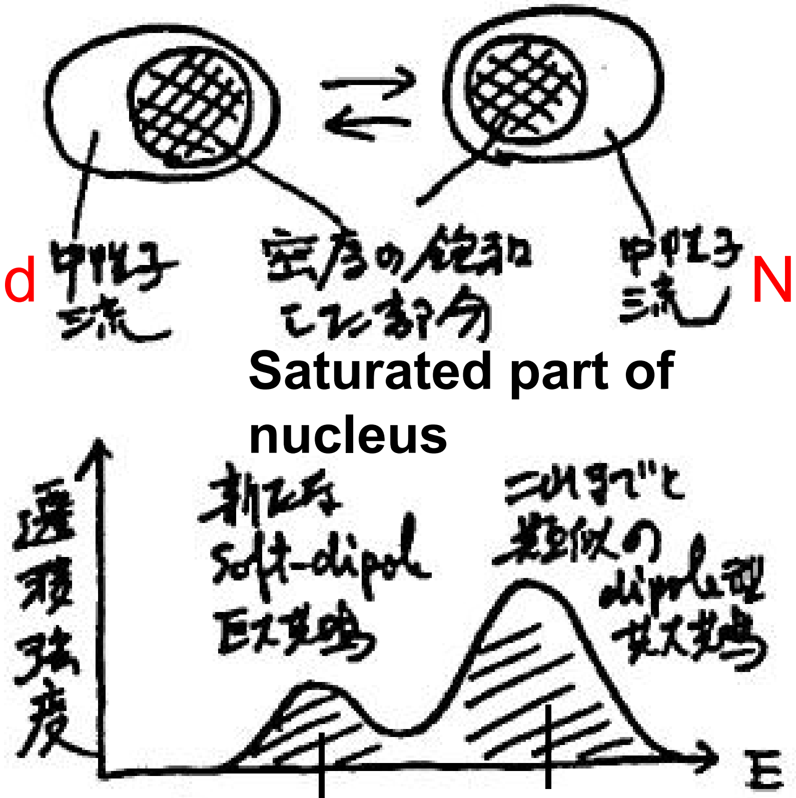
(The same Ikeda-san who made Ikeda Diagram)

Neutron fluid

Neutron fluid

Saturated part of nucleus

Transition Probability (dB(E1)/dE)



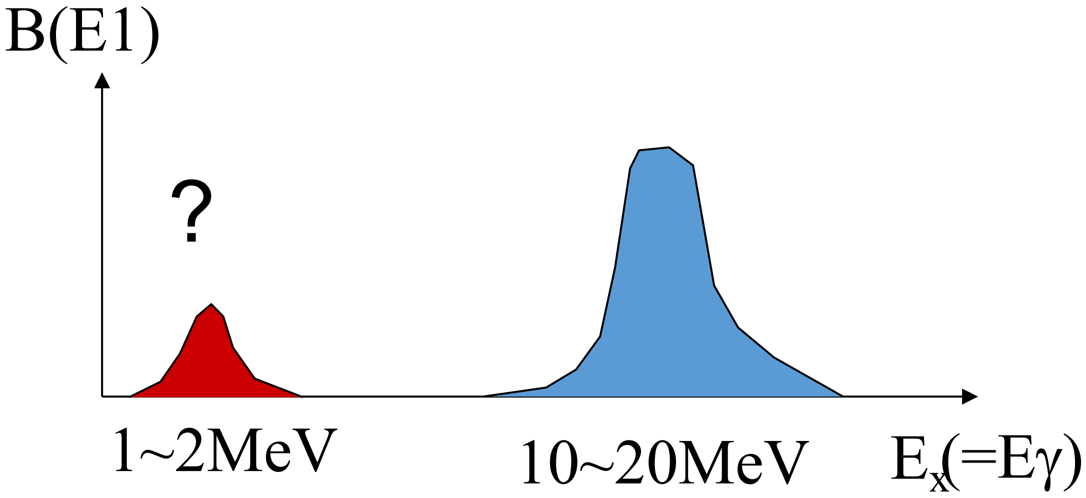
New “Soft-dipole Resonance”

Giant Resoance

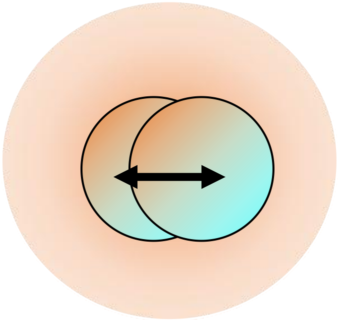
Prediction of Soft Dipole Resonance by Prof.Ikeda
K.Ikeda,INS report JHP-7 (1988) [in Japanese]

5

Resonance or Not ?



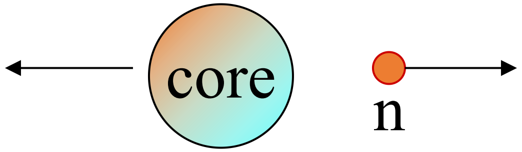
- **Soft Dipole Resonance**



Slow Vibration of core against halo
(Ikeda model)

OR

- **Direct Coulomb Breakup**
(Non-resonant Enhancement)

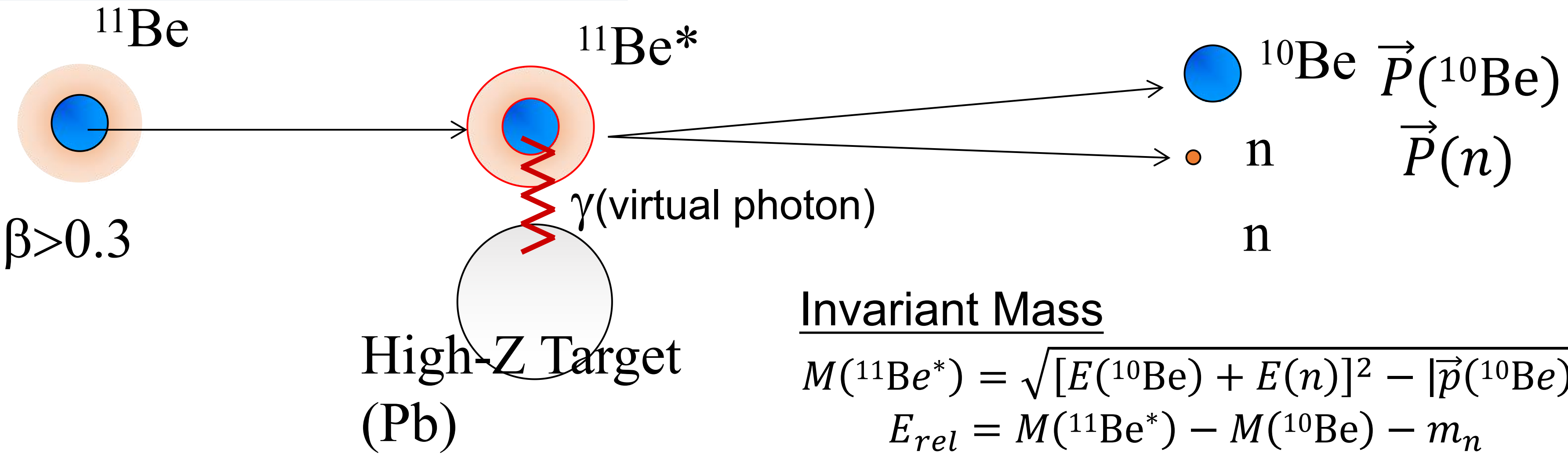


$$\frac{dB(E1)}{dE_x} \propto |\langle \underline{\exp(i\boldsymbol{qr})}|\frac{Z}{A} rY^1{}_m|\Phi_{gs}\rangle|^2$$

$\Downarrow$

Non-Resonant Final States

Coulomb Breakup → Photon absorption of a fast projectile



Invariant Mass

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

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

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

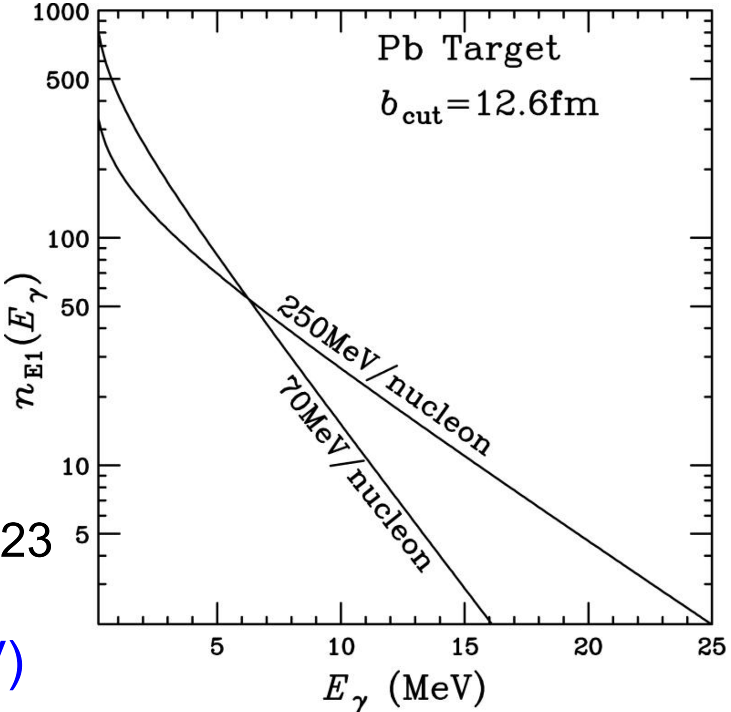
Equivalent Photon Method

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

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

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

1944-June 16, 2023

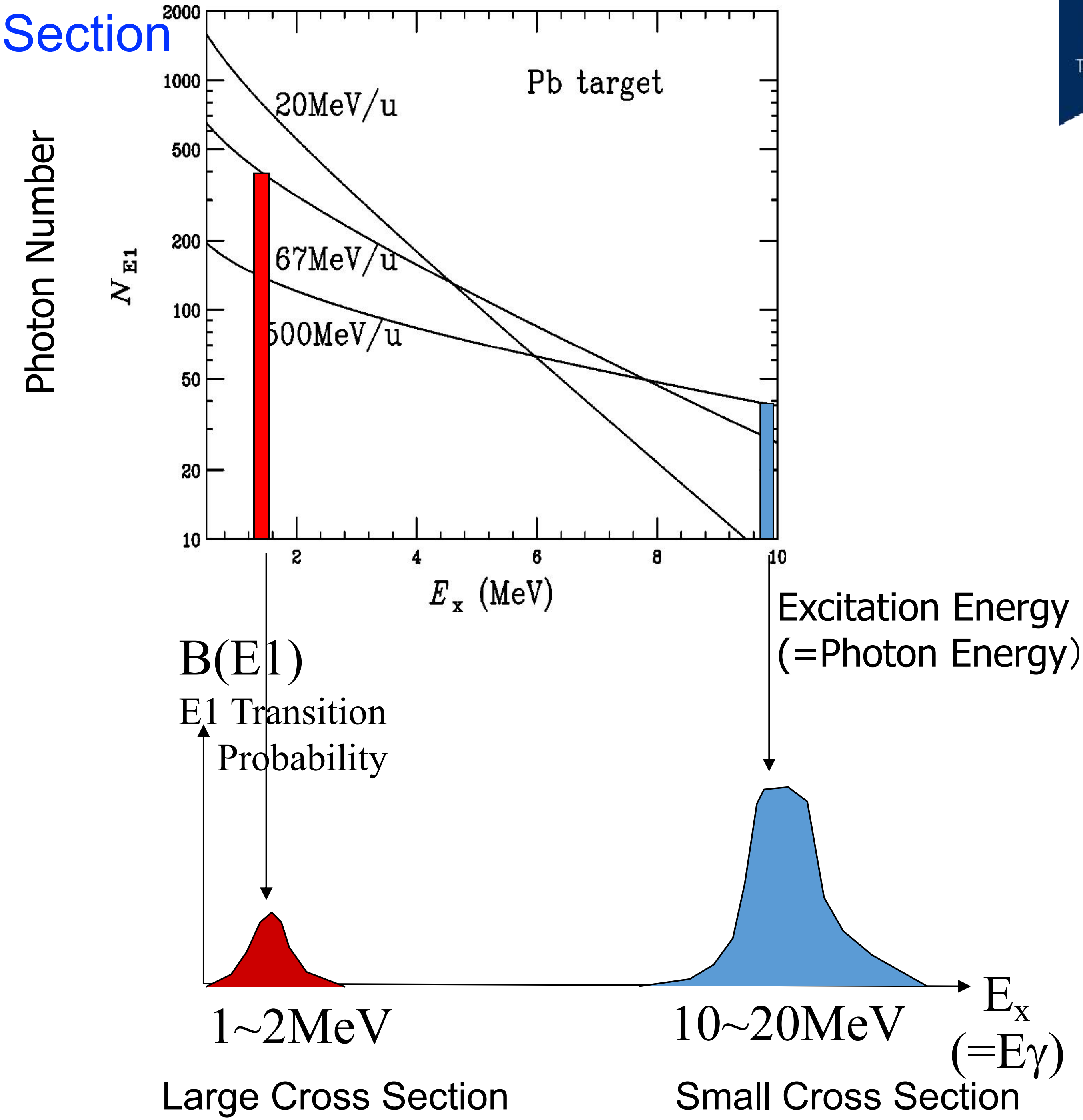


Neutron Halo → Soft E1 Excitation

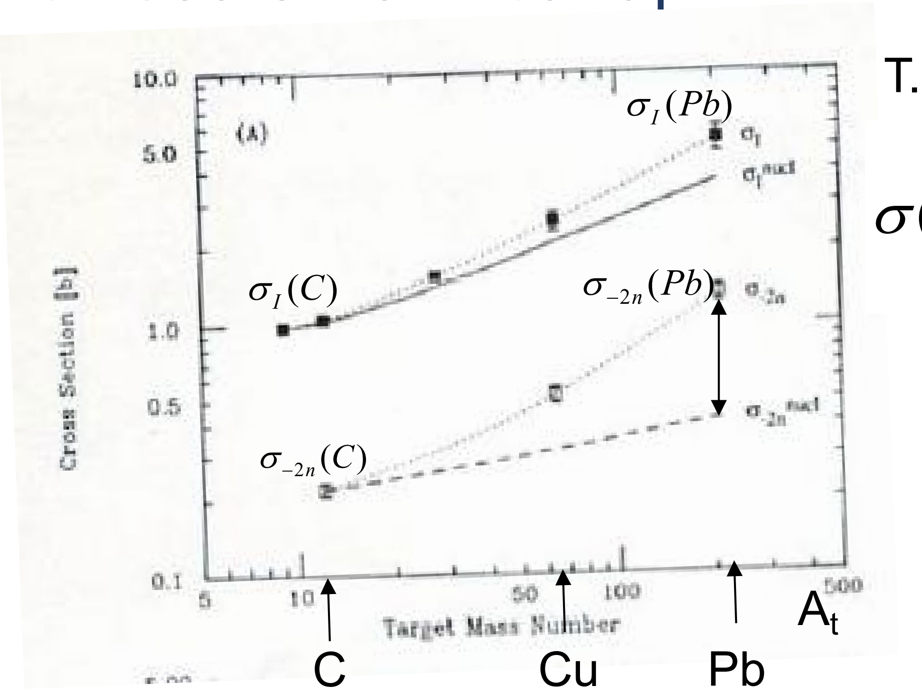
E1 Concentration $E_x < 1\mathrm{MeV}$, c.f. Stable Nuclei: GDR Ex~20 MeV)

"Inclusive" Coulomb Breakup Cross Section --Also Enhanced

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

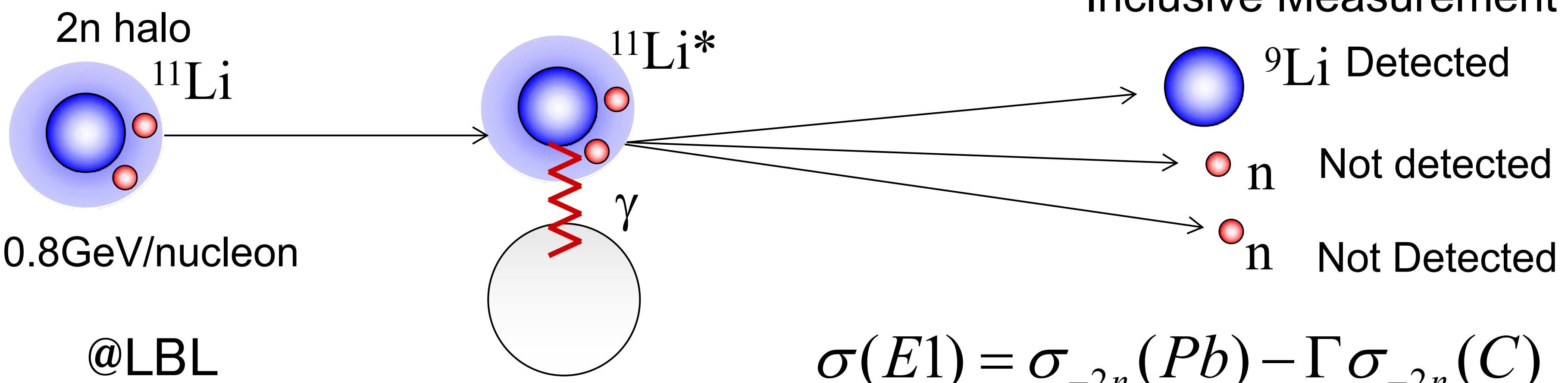


The first experimental indication of Soft E1 —"Inclusive" Coulomb Breakup



T.Kobayashi Phys.Lett.B232, 51 (1989).

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



@LBL

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

0.89(1)b : Large!→Indication of Soft E1 Excitation

Coulomb Breakup of one-neutron halo nuclei

^{11}Be	TN et al., Phys. Lett. B **331**, 296 (1994). N.Fukuda, TN et al., Phys. Rev. C **70**, 054606 (2004). Palit et al., Phys. Rev. C 68, 034318 (2003).	→Mechanism
^{19}C	TN et al., Phys. Rev. Lett. **83**, 1112 (1999).	→Spectroscopy
^{15}C	TN, N.Fukuda et al., Phys. Rev. C **79**, 035805 (2009).	→Astrophycis
^{31}Ne	TN, N.Kobayashi et al., Phys. Rev. Lett. **103**, 262501 (2009). TN, N.Kobayashi et al., Phys. Rev. Lett. **112**, 142501 (2014).	→Spectroscopy of Island-of-Inversion Nuclei
^{37}Mg	N.Kobayashi, TN et al., PRL **112**, 242501 (2014).	

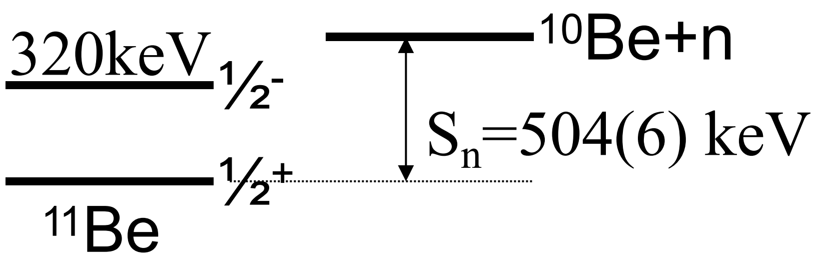
Review

T. Aumann, T. Nakamura, Physica Scripta T152, 014012 (2013).
T. Nakamura, Handbook of Nuclear Physics, https://doi.org/10.1007/978-981-15-8818-1_68-1

Coulomb Breakup of ^{11}Be →Mechanism (Resonance or Not)

^{11}Be

- Well-Known Structure

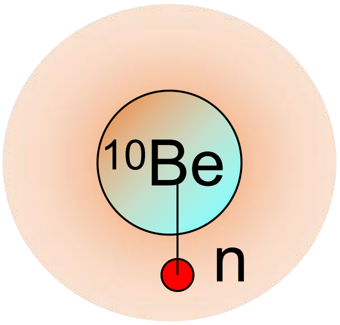


$$^{11}\mathrm{Be(g.s)}=\alpha\left|{}^{10}\mathrm{Be}(0^+)\otimes\nu(2s_{1/2})\right\rangle+\beta\left|{}^{10}\mathrm{Be}(2^+)\otimes\nu(1d_{5/2})\right\rangle$$

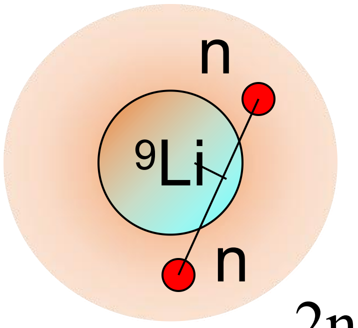
$\alpha^2=0.77$ ^{10}Be(d,p)^{11}Be B.Zwieglinski et al. NPA315,124(1979).

$\alpha^2=0.74$ ^{9}Be(^{11}Be, ^{10}Beγ) X T.Aumann et al. PRL84,35(2000).

- Simple One-neutron Halo Nucleus



^{11}Be



^{11}Li

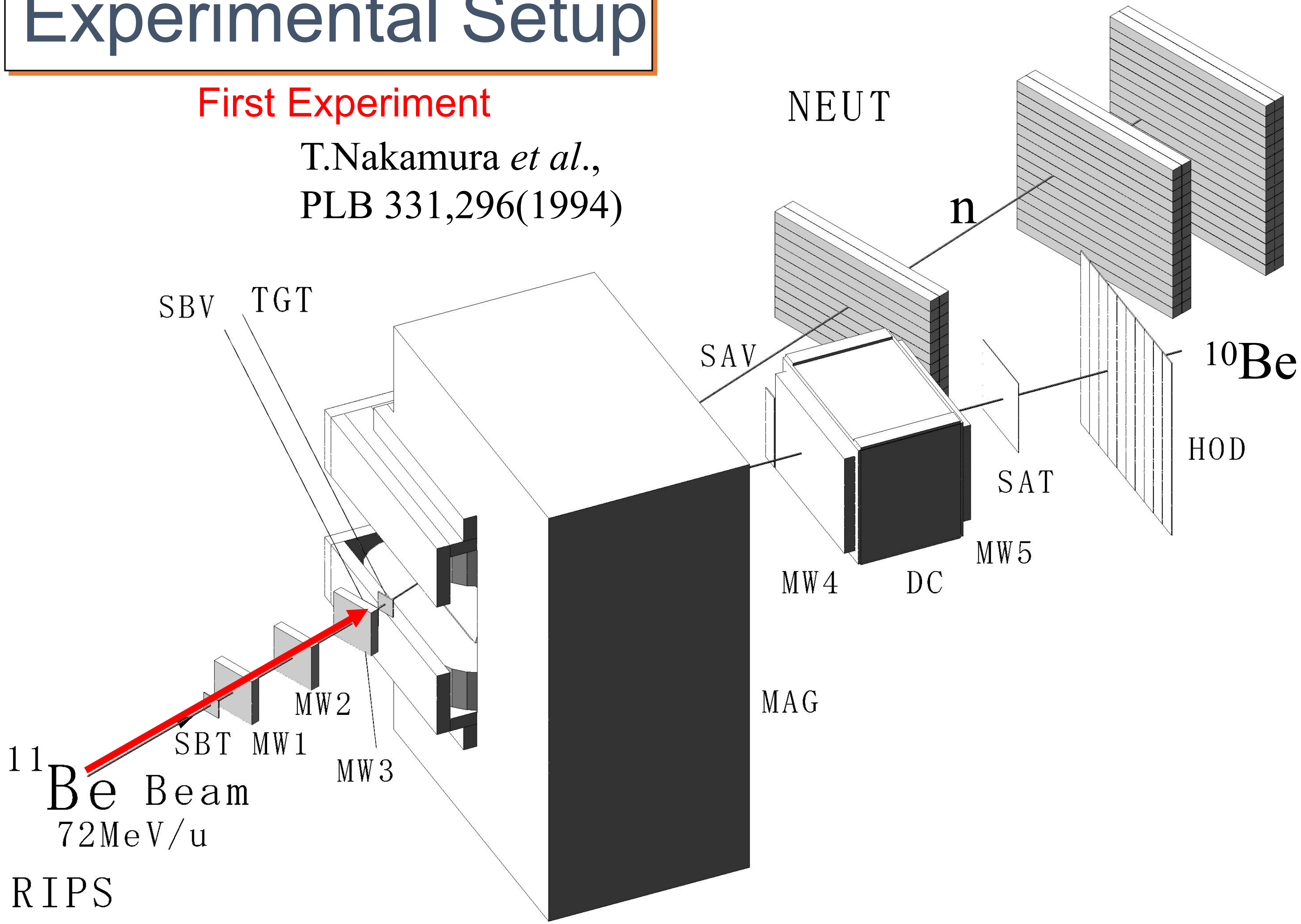
2n correlation?

Coulomb Breakup of ^{11}Be

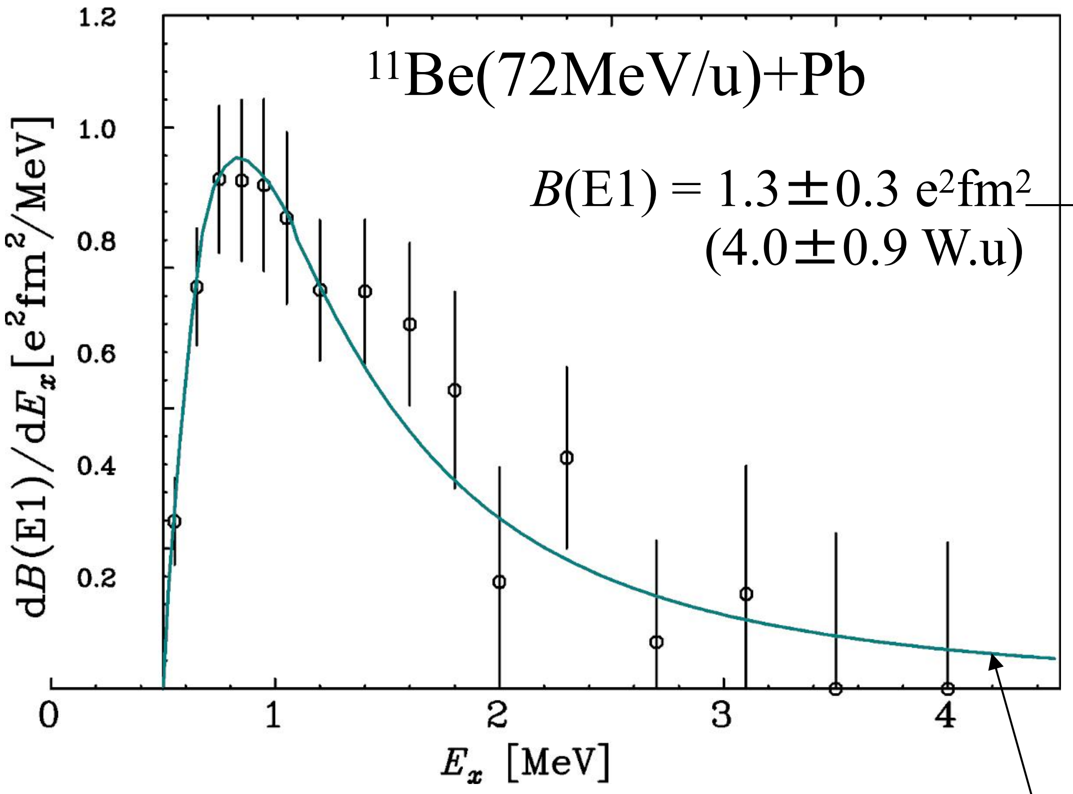
Experimental Setup

First Experiment

T.Nakamura *et al.*,
PLB 331,296(1994)



Low-lying E1 strength of Halo Nuclei



Huge !
(usually B(E1) < 10^{-3})

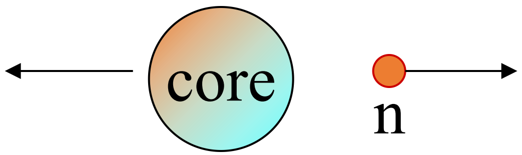
T.Nakamura *et al.*,
PLB 331,296(1994)

Large E1 strength
at low E_x

Direct Breakup

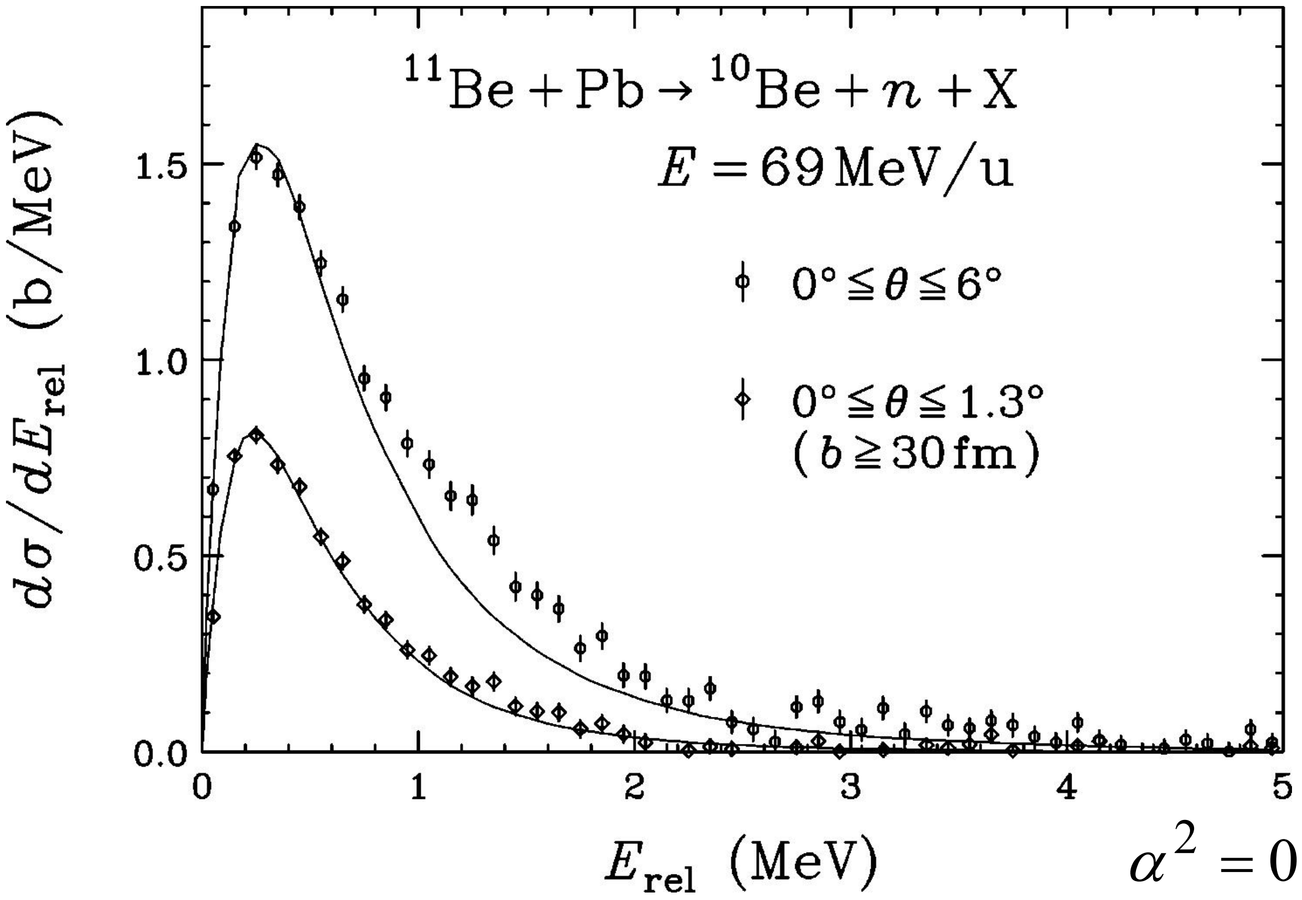
$$\frac{dB(\mathrm{E1})}{dE_x} \propto \left| \langle \exp(i\boldsymbol{q}\boldsymbol{r}) | \frac{Z}{A} r Y^1{}_m | \Phi_{gs} \rangle \right|^2$$

$$\propto \frac{\sqrt{S_n}\,(E_x - S_n)^{3/2}}{E_x{}^4}$$



^{11}Be : 2nd-experiment: Results

N.Fukuda, T.Nakamura et al., PRC 70, 054606 (2004).

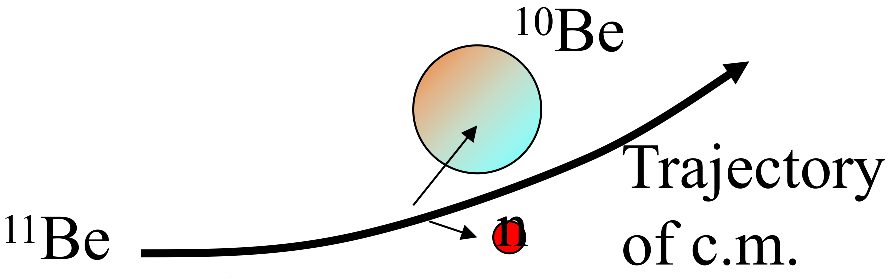


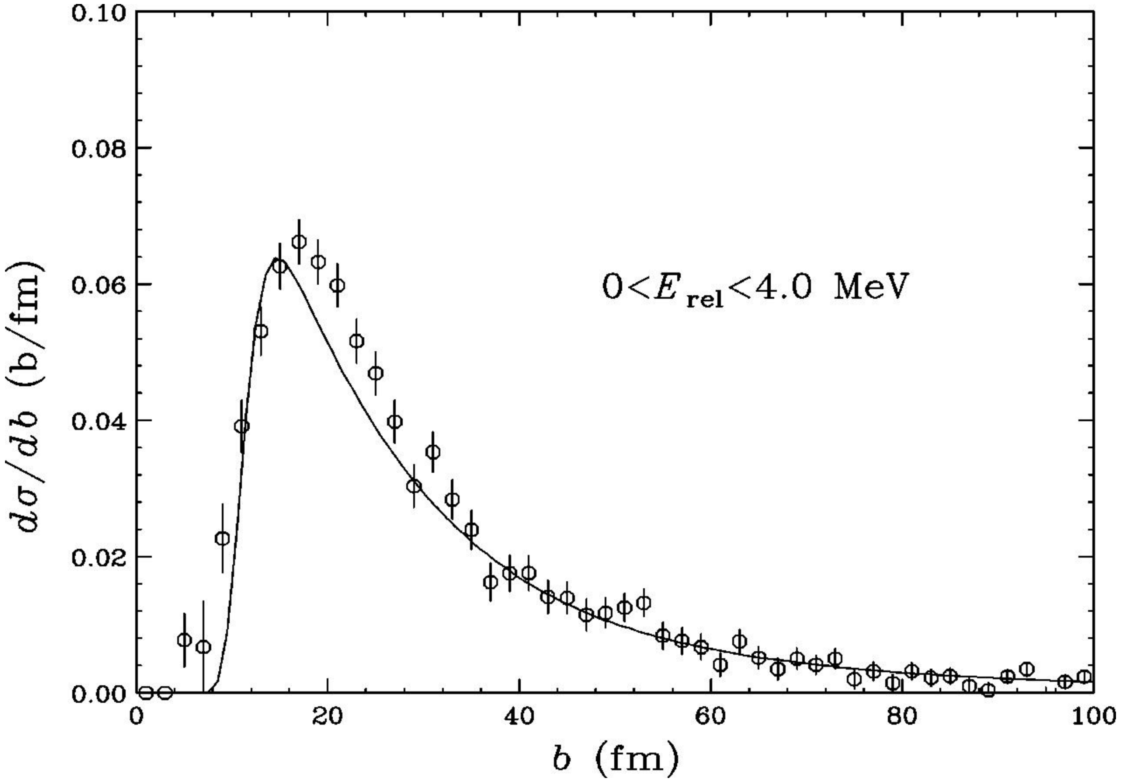
$$\alpha^2 = 0.72 \pm 0.04$$

$$\sigma(\mathrm{Pb}) = 1.79 \pm 0.02\,(\mathrm{b})$$

$$\sigma(\mathrm{Pb;Coul}) = 1.51 \pm 0.02\,(\mathrm{b})$$

Analysis by Impact Parameter

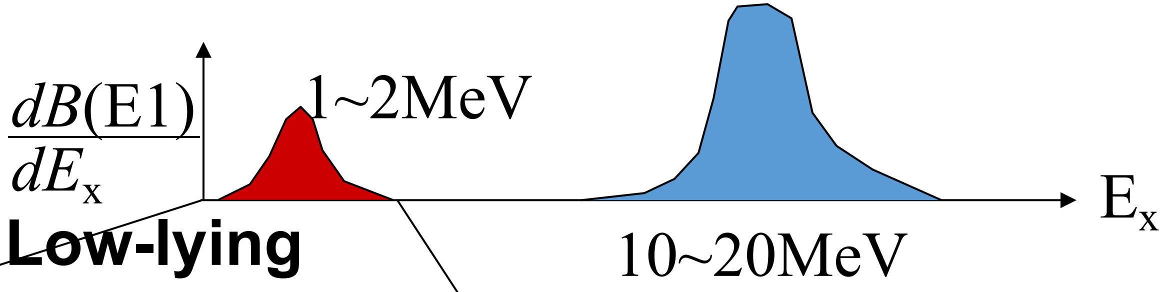




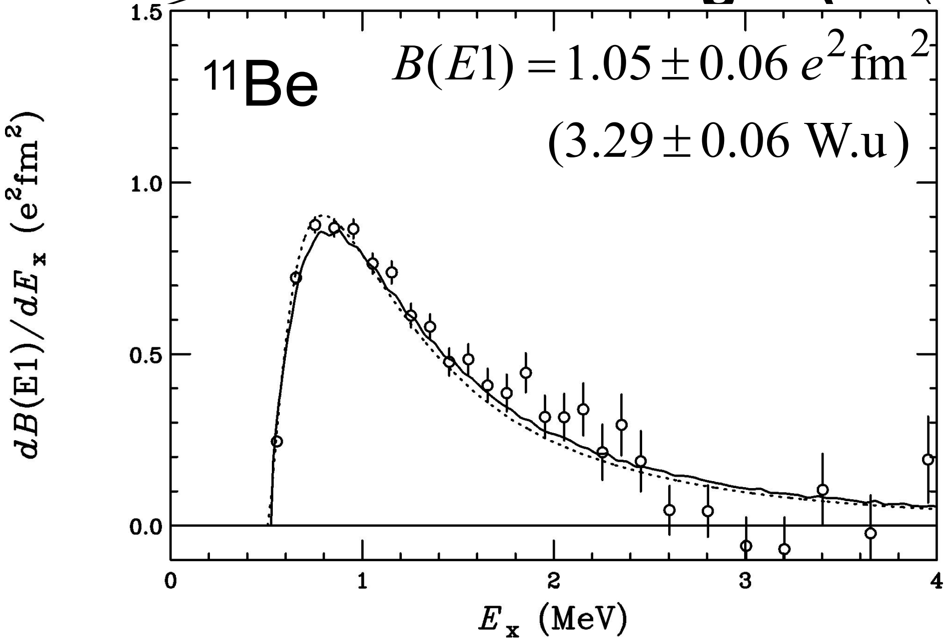
$$b = a\cot(\theta/2)$$

Fukuda TN et al.,PRC2004

E1 Response of ^{11}Be (2nd Experiment, N.Fukuda et al. PRC2004)

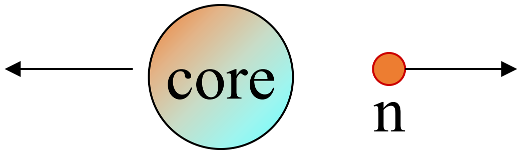


Low-lying E1 Strength (Soft E1 excitation)



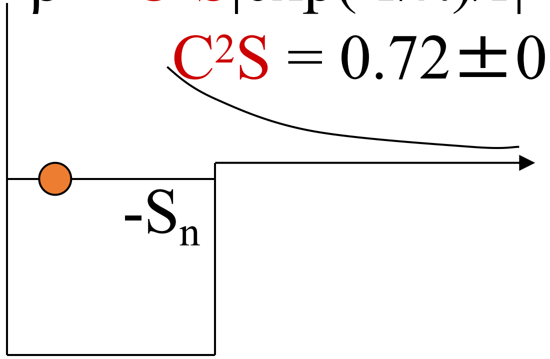
N.Fukuda, TN et al., PRC70, 054606 (2004)
TN *et al.*,PLB 331,296(1994)
Palit et al., PRC68, 034318(2003)

Direct Breakup Mechanism



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

$$C^2S = 0.72 \pm 0.04$$

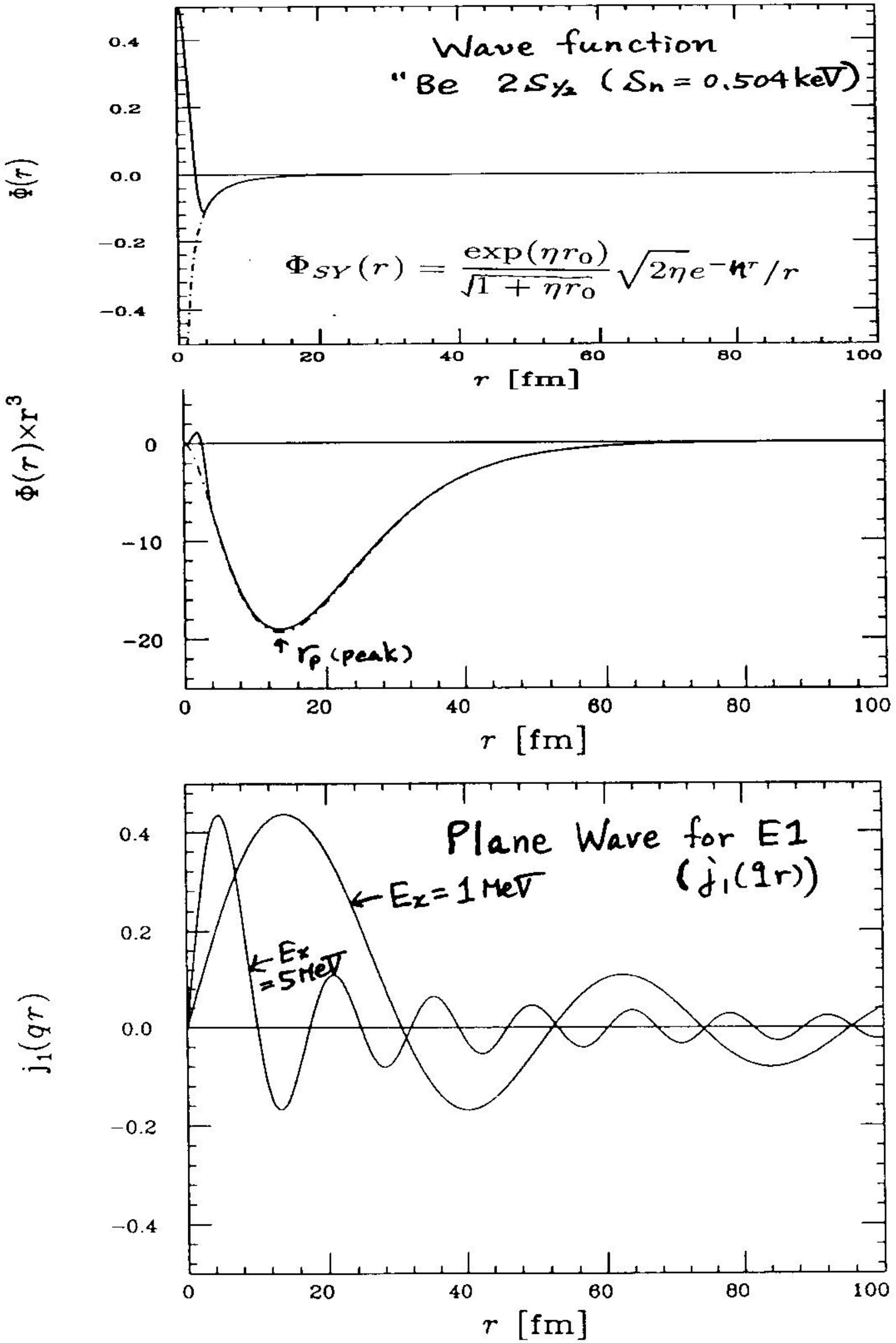


$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1{}_m|\Phi_{gs}\rangle|^2$$
$$\propto C^2S|\langle \exp(i\boldsymbol{qr})|\frac{Z}{A}rY^1{}_m|s_{1/2}\rangle|^2$$

Fourier Transform ⇔

E1 Strength

Halo State



Why Soft E1 is so Sensitve to Halo?

B(E1)
Sensitive strongly the Radial
Wave function of the valence neutron

$$B(E1) \propto \left| \left\langle e^{iqr} \left| rY_m^1 \right| \Phi(r) \right\rangle \right|^2$$

$$\left\langle e^{iqr} \left| rY_m^1 \right| \Phi(r) \right\rangle \propto \int e^{iqr} r^3 \Phi(r) dr$$

c.f. T.Otsuka et al., PRC49, R2289 (1994).

B(E1) →Geometry of one-neutron halo nucleus

H.Esbensen et al.,NPA542,310(1992)

Non-energy weighted Sum Rule

$$B(E1) = \int \frac{dB(E1)}{dE} dE = \int \left\langle i \middle| \sqrt{\frac{3}{4\pi}} \frac{Ze}{A} r \middle| f \right\rangle^* \left\langle f \middle| \sqrt{\frac{3}{4\pi}} \frac{Ze}{A} r \middle| i \right\rangle dE$$

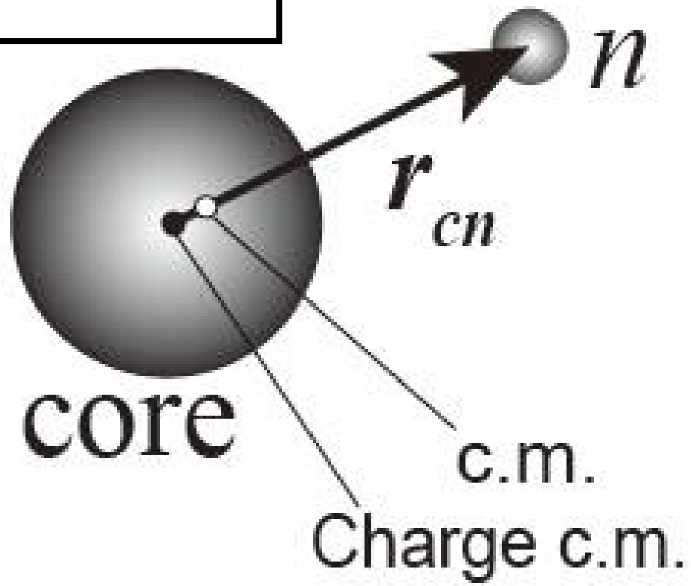
$$= \frac{3}{4\pi} \frac{Ze}{A} \langle i | r^2 | i \rangle = \frac{3}{4\pi} \frac{Ze}{A} \langle r^2 \rangle$$

Experiment: $B(E1) = 1.05 \pm 0.06\ e^2\mathrm{fm}^2 \Rightarrow \sqrt{\langle r^2 \rangle} = 5.77 \pm 0.16\mathrm{fm}$

$$\vec{r} \equiv \overrightarrow{r_{cn}}$$

$$Ze\vec{r}(charge\ c.m) = -\underline{\frac{Ze}{A}}\vec{r}$$

$e_{\mathrm{eff}}^{(E1)}$: E1 Effective Charge

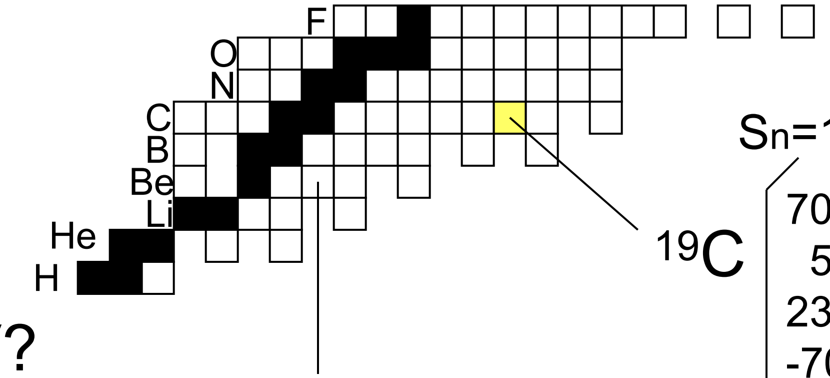


Application: Coulomb Breakup & Soft E1 Excitation for Halo Spectroscopy

T.Nakamura *et al*., Phys. Rev. Lett. **83**, 1112 (1999).

^{19}C

At that time
Controversial
S_n: 0—700keV?
gs: **1/2⁺** or **3/2⁺**, **5/2⁺**?
s or ***d*** dominant?

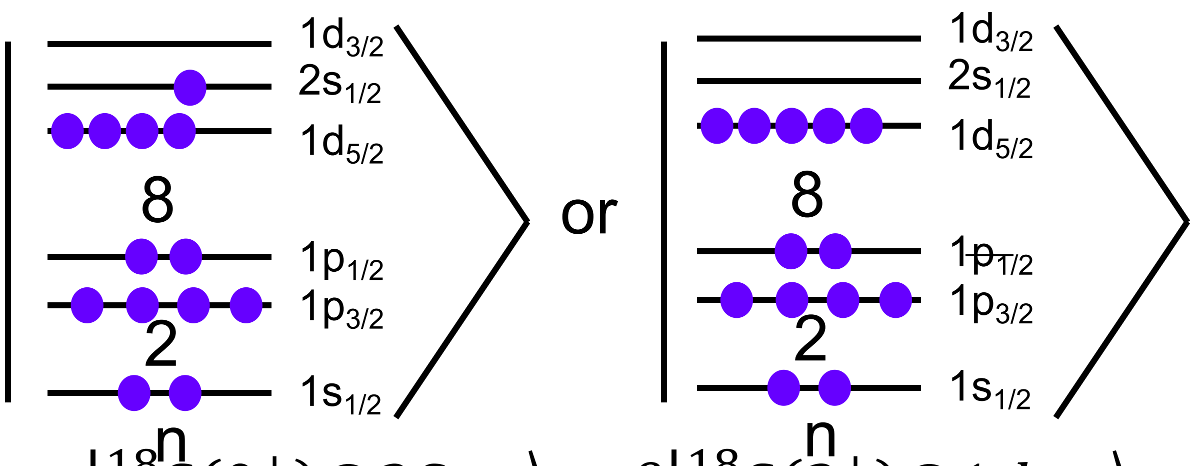


^{11}Be S_n=504±6 keV

S_n=160 ±110 keV (1993 Mass evalulation)

700±240 keV (Vieira et al. PRL57,3253(1986).
50 ±420 keV (Gillbert et al. PLB192,39(1988).
230 ±120 keV (Wouters et al. ZPA331,229(1988).
-70 ± 240 keV (Orr et al. PLB258,29(1991).

$\Psi({}^{19}_{6}C) =$



$$\Psi\left({}^{19}\mathrm{C}\; gs;\; \mathbf{1/2^+}\right) = \alpha\left|{}^{18}\mathrm{C}(0^+)\otimes 2S_{1/2}\right\rangle + \beta\left|{}^{18}\mathrm{C}(2^+)\otimes 1d_{5/2}\right\rangle$$

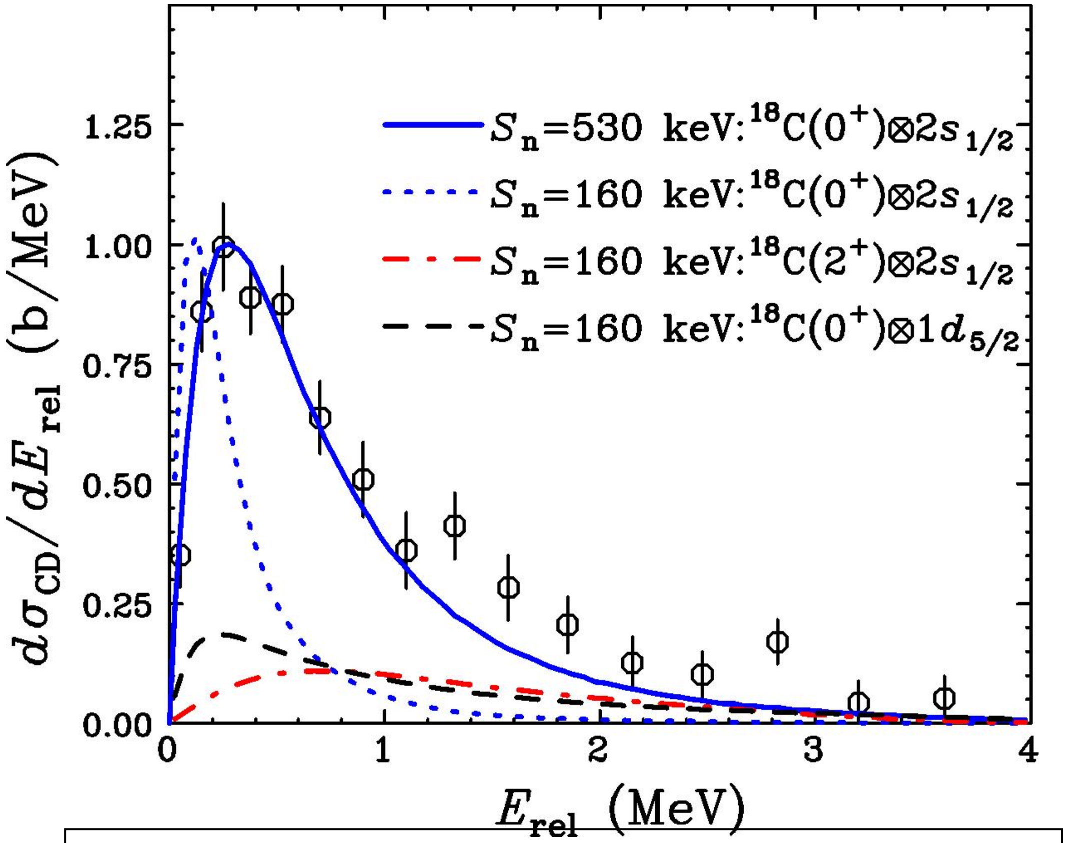
$$\Psi\left({}^{19}\mathrm{C}\; gs;\; \mathbf{5/2^+}\right) = \gamma\left|{}^{18}\mathrm{C}(2^+)\otimes 2S_{1/2}\right\rangle + \delta\left|{}^{18}\mathrm{C}(0^+)\otimes 1d_{5/2}\right\rangle$$

Application of Coulomb Breakup & Soft E1 Excitation for Halo Spectroscopy

T.Nakamura *et al*., Phys. Rev. Lett. **83**, 1112 (1999).

Tokyo Tech

^{19}C



$$\frac{dB(\mathrm{E1})}{dE_x} \propto \left| \langle \exp(i\boldsymbol{qr}) \right| \frac{Z}{A} \mathrm{r} \mathrm{Y}^1{}_{\mathrm{m}} \left| \Phi_{\mathrm{gs}} \rangle \right|^2$$

$$\Psi(^{19}\mathrm{C}\ gs;\ \mathbf{1/2^+}) = \alpha\left|^{18}\mathrm{C}(0^+)\otimes 2S_{1/2}\right\rangle + \beta\left|^{18}\mathrm{C}(2^+)\otimes 1d_{5/2}\right\rangle$$

$$\Psi(^{19}\mathrm{C}\ gs;\ \mathbf{5/2^+}) = \gamma\left|^{18}\mathrm{C}(2^+)\otimes 2S_{1/2}\right\rangle + \delta\left|^{18}\mathrm{C}(0^+)\otimes 1d_{5/2}\right\rangle$$

Conclusion for ^{19}C(g.s)

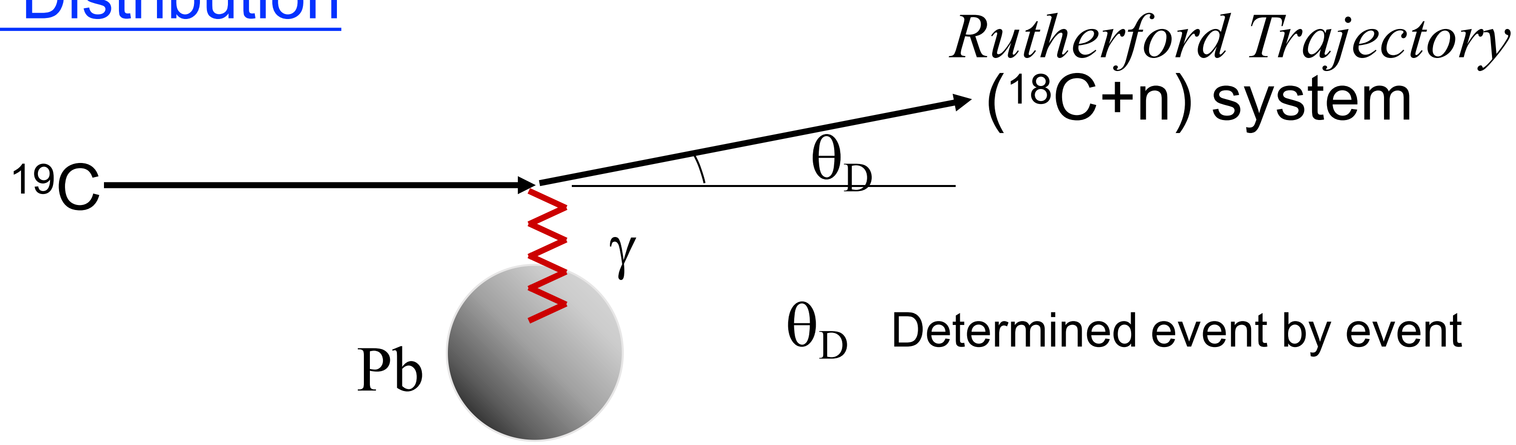
$J^\pi = 1/2^+$

S_n should be larger!

α^2=0.67 for S_n=530keV

B(E1)=0.71(7) e^2fm^2

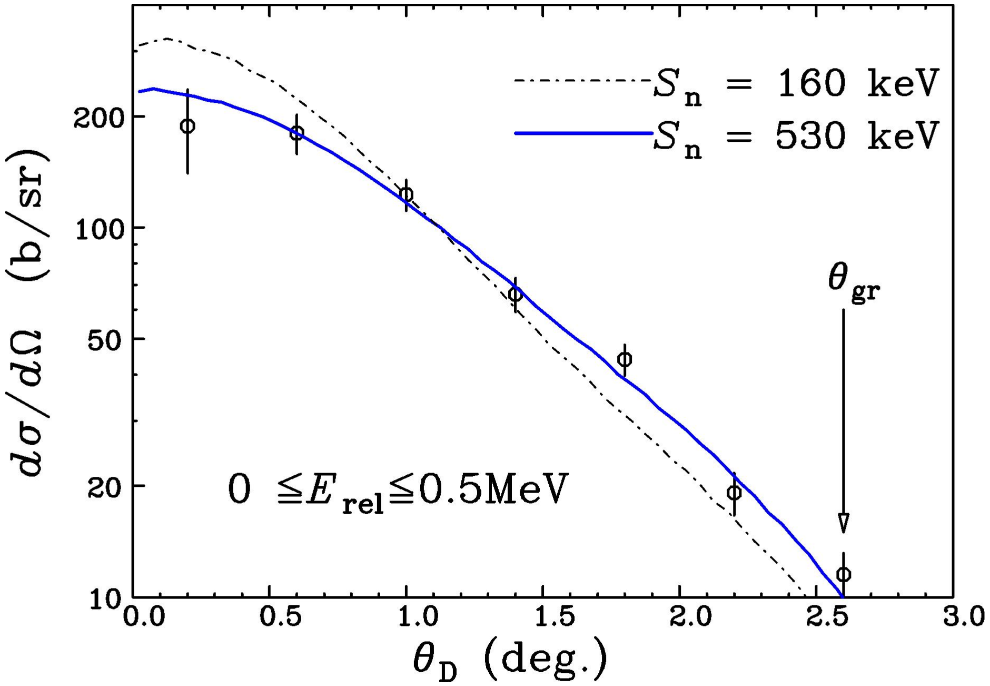
S_n (Mass) by Angular Distribution



θ_D Determined event by event

$$\frac{d\sigma(\theta_D, E_x)}{d\Omega} \propto \frac{dN_{E1}(\theta_D, E_x)}{d\Omega} B(E1; E_x)$$

$$E_x = E_{rel} + \underline{S_n} \longrightarrow S_n$$



$S_n = 530 \pm 130$keV

21

Why $dN/d\Omega$ has Ex dependence?

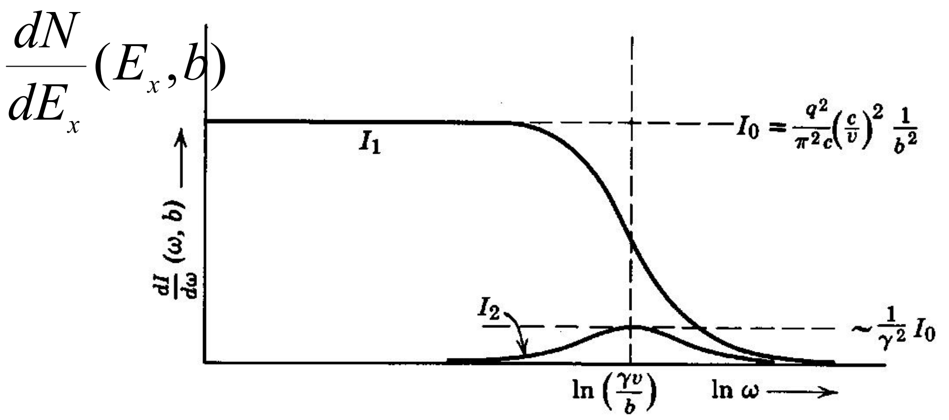
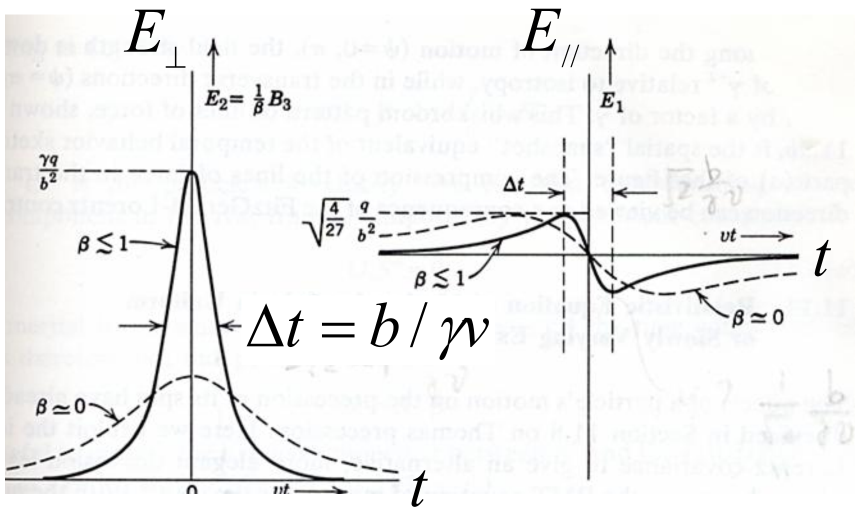


Fig. 15.7 Frequency spectra of the two equivalent pulses of radiation.

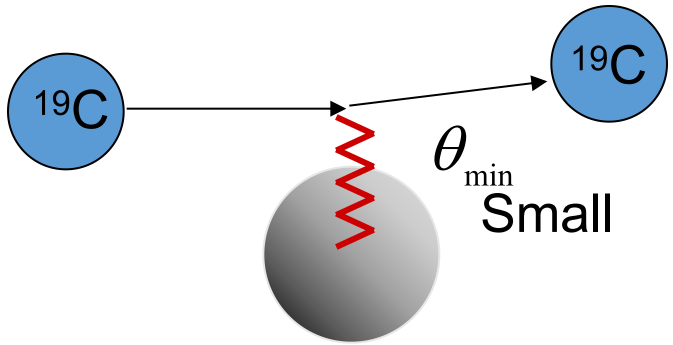
J.D.Jackson Classical Electrodynamics

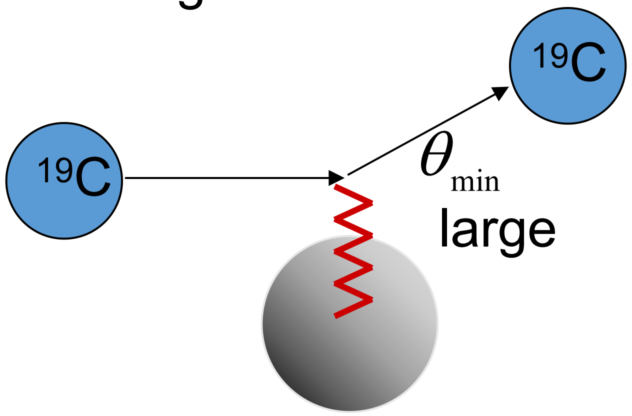


For a given E_{rel}

E_x small ⇨ $b_{max} = \gamma v / E_x$ large

E_x large ⇨ $b_{max} = \gamma v / E_x$ small





Angular distribution -----Independent of the Structure

Soft E1 Excitation → Spectroscopic Tool of 1n Halo nuclei

Tokyo Tech

Coulomb Breakup of ^{19}C

Halo structure of ^{19}C has been established from dB/dE measurement.

Shape & Strength of B(E1) spectrum

⇒ S_n, ℓ, Spectroscopic factor

s, p →Halo, peak at low E_{rel}

Shape & Strength of B(E1) spectrum

Plane-wave approximation

For $\varepsilon_\ell < 0$ $\quad R_{\ell_b}(\varepsilon_b, r) \propto \alpha r h_{\ell b}(\alpha r)$ $\quad$ where $\alpha^2 = -\frac{2m}{\hbar^2}\varepsilon_b$

For $\varepsilon_\ell > 0$ $\quad$ (plane wave approximation)

$$R_{\ell_c}(\varepsilon_c, r) = \sqrt{\frac{2m}{\pi\hbar^2 k}}\, kr j_{\ell_c}(kr) \quad \text{where} \quad k^2 = \frac{2m}{\hbar^2}\varepsilon_c$$

Note $\int_0^\infty dr R_{\ell_c}(E,r) R_{\ell_c}(E',r) = \delta(E-E')$

assumed

Ikuko Hamamoto
–10 Mar, 2023

$\ell_b \to \ell_c$	$\frac{dB(E1)}{dE} \propto \varepsilon_c^{\ell_c+1/2}$ for very small ε_c	$\frac{dB(E1)}{dE}$ is max. at
s → p	$\propto (\varepsilon_c)^{3/2}$	$\varepsilon_c = \frac{3}{5}\varepsilon_b$
p → s	$\propto (\varepsilon_c)^{1/2}$	$\varepsilon_c \approx (0.18)\varepsilon_b$
p → d	$\propto (\varepsilon_c)^{5/2}$	$\varepsilon_c = \frac{5}{3}\varepsilon_b$
d → p	$\propto (\varepsilon_c)^{3/2}$	$\varepsilon_c = \frac{5}{3}\varepsilon_b$

^{15}C

Coulomb breakup of ^{15}C

Extract Radiative neutron capture cross section
Application to Astrophysically-significant Reaction

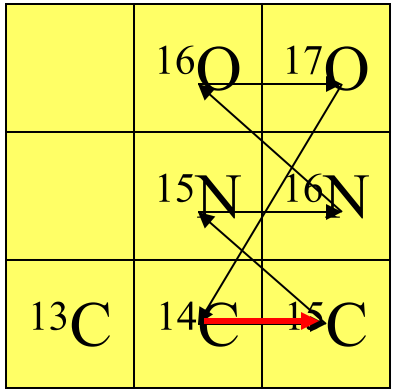
T.Nakamura, N.Fukuda et al.,
Phys. Rev. C 79, 035805 (2009).

Why ^{15}C ?

$^{14}C(n,\gamma)^{15}C$

Astrophysical Interests

- Burning zone in Low mass Asymptotic Giant Branch(AGB) stars
  Neutrons from $^{13}C(n,\alpha)$ reactions
  $\mathbf{^{14}C(n,\gamma)^{15}C}(\beta^-)^{15}N(n,\gamma)^{16}N(\beta^-)^{16}O(n,\gamma)^{17}O(n,\alpha)^{14}C$ *M.Wiescher et al.*, ApJ, 363,340



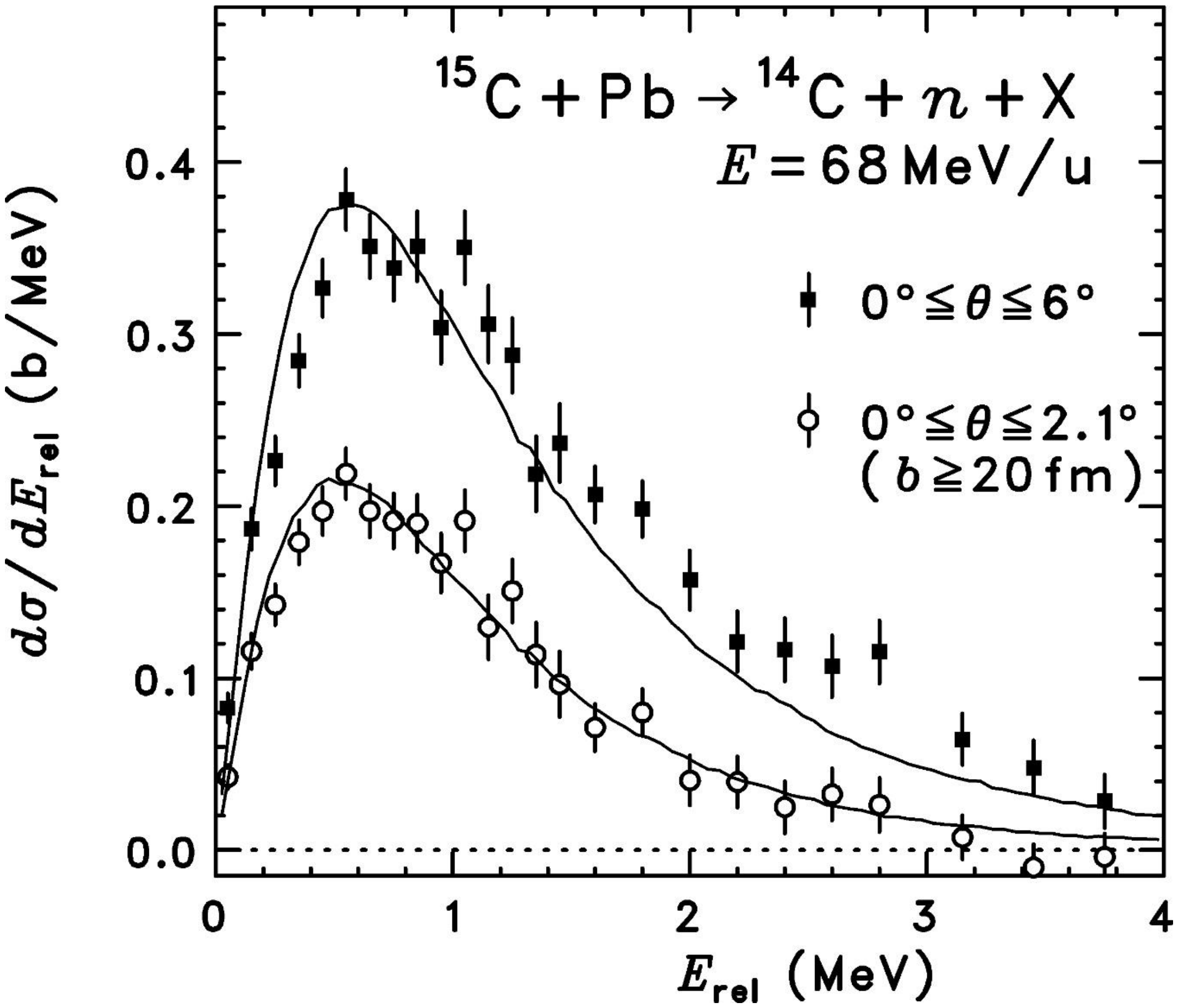
Neutron induced CNO cycle

- Inhomogeneous Big Bang Model
- r-process model Terasawa,Sumiyoshi,Kajino, ApJ562,470(2001).

Results: Coulomb Breakup of ^{15}C

^{15}C: moderate neutron-halo $1/2^+$ gs, S_n=1.27MeV

$$^{15}\mathrm{C(g.s)} = \alpha\left|\,^{14}\mathrm{C}(0^+)\otimes 2s_{1/2}\right\rangle + \beta\left|\,^{14}\mathrm{C}(2^+)\otimes 1d_{5/2}\right\rangle$$



^{15}C+Pb@68MeV/u

α^2=0.75(4)

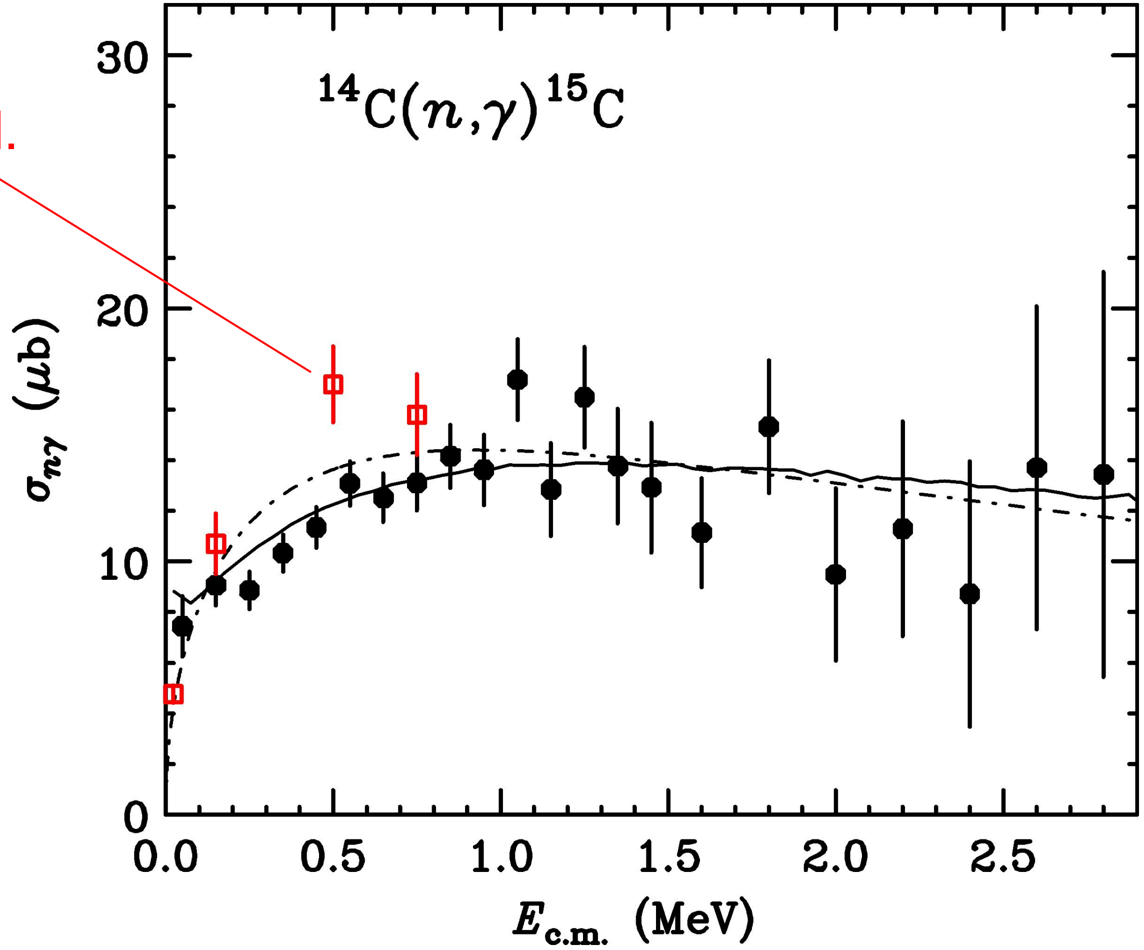
r_0=1.25 fm
a=0.65 fm

Consistent with GSI (α^2=0.73)
(D.Pramanik et al) Data
But not with MSU data

Neutron Capture Cross Section

From the data with b>20fm

R.Reifarth et al.



Consistent with Direct Capture Measurement $^{14}C(n,\gamma)^{15}C$
By R.Reifarth et al., PRC77,015804(2008)

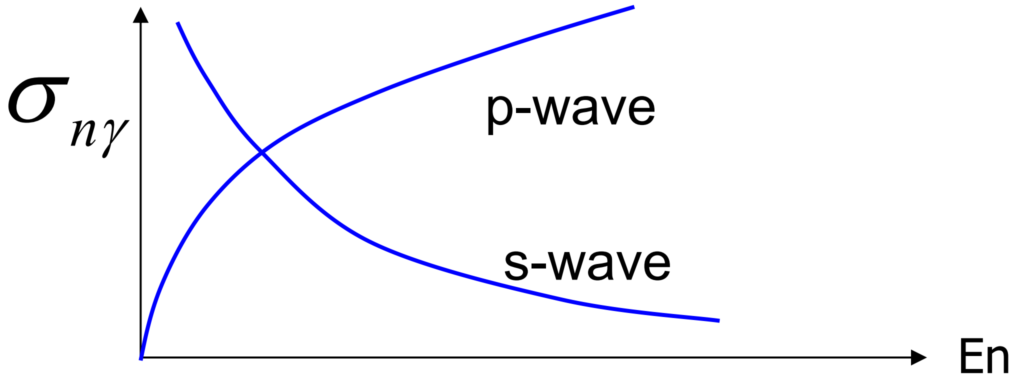
s-wave capture vs. p-wave capture

A(n,γ)B(Normal)

S-wave capture dominant $\sigma_{n\gamma} \propto 1/v \propto 1/\sqrt{E_{rel}}$

A(n,γ)B(Halo)

p-wave capture dominant $\sigma_{n\gamma} \propto \sqrt{E_{rel}}$

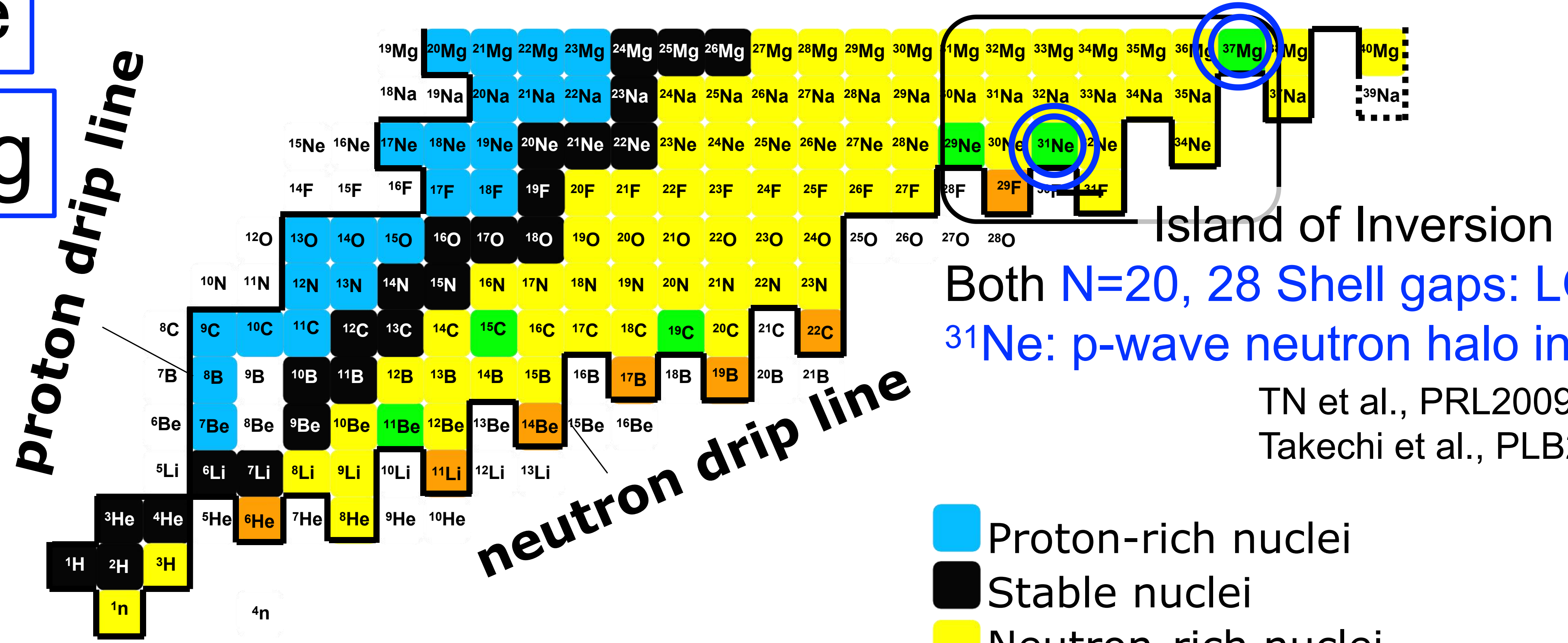


Neutron halo nuclei in the Island of Inversion

Dripline– Boundary between Closed/Open quantum systems
→Clusters/Halos/Shell Evolution

^{31}Ne

^{37}Mg



Both N=20, 28 Shell gaps: LOST

^{31}Ne: p-wave neutron halo in IoI

TN et al., PRL2009, 2014,
Takechi et al., PLB2012

- Proton-rich nuclei
- Stable nuclei
- Neutron-rich nuclei
  - 1n-halo nuclei
  - 2n-halo nuclei
- Driplines
- Unbound nuclei, Observed

Tokyo Tech

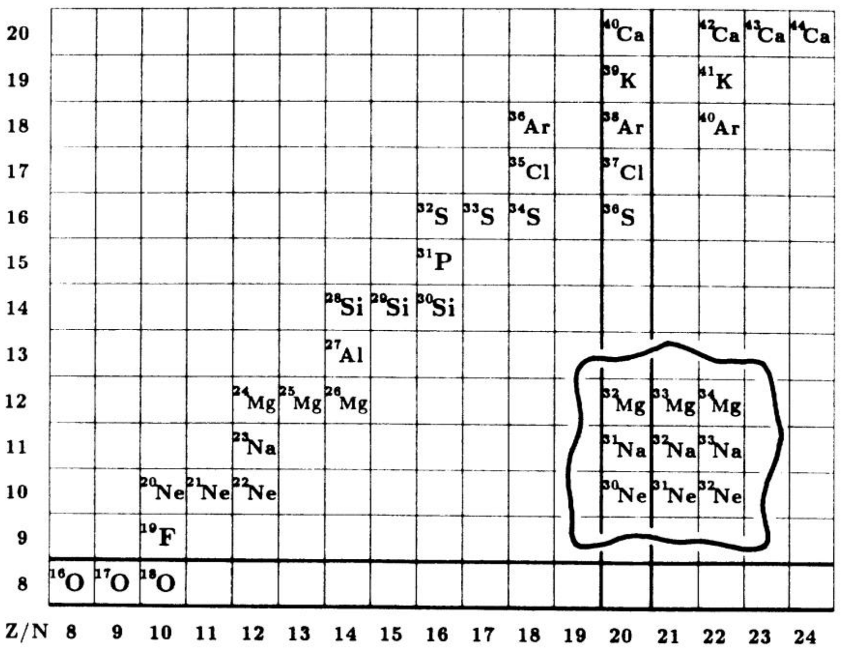
Island of Inversion in a nutshell

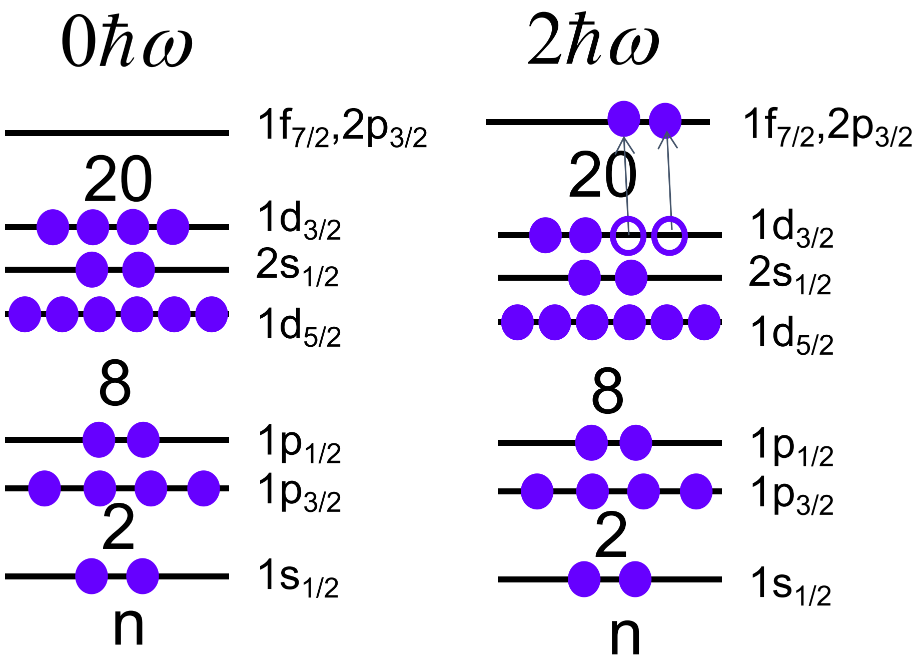
E.K. Warburton, J.A.Becker, B.A.Brown, PRC41, 1147 (1990).

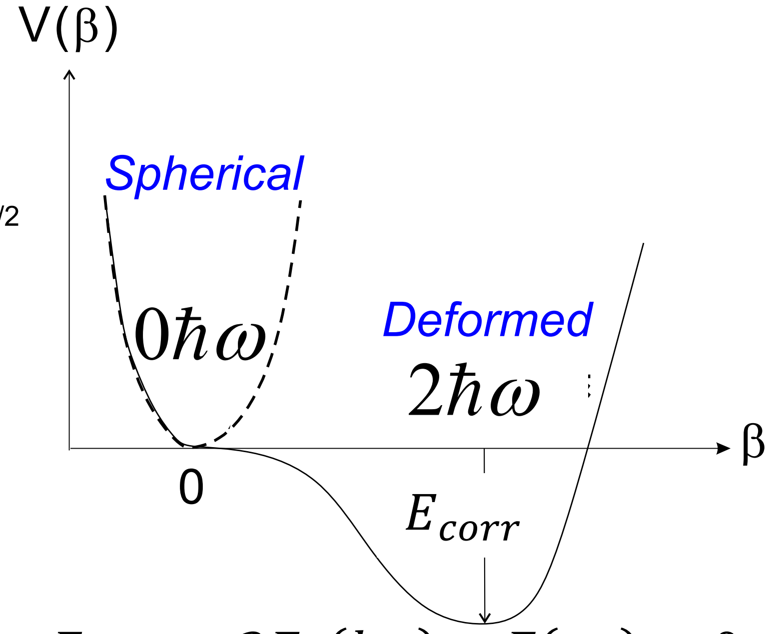
Further evidence for the presence of an anomaly in binding energies for the "island of inversion" centered at $Z = 11$, $N = 21$ is obtained by comparison of shell-model calculations to experiment.

…

It is found that for $Z = 10-12$, $N = 20-22$ (and possibly $N > 22$) nuclei the lowest $2\hbar\omega$ state is more bound than the $0\hbar\omega$ ground state.







$$E_{corr} = 2E_x(\hbar\omega) - E(nn) < 0$$

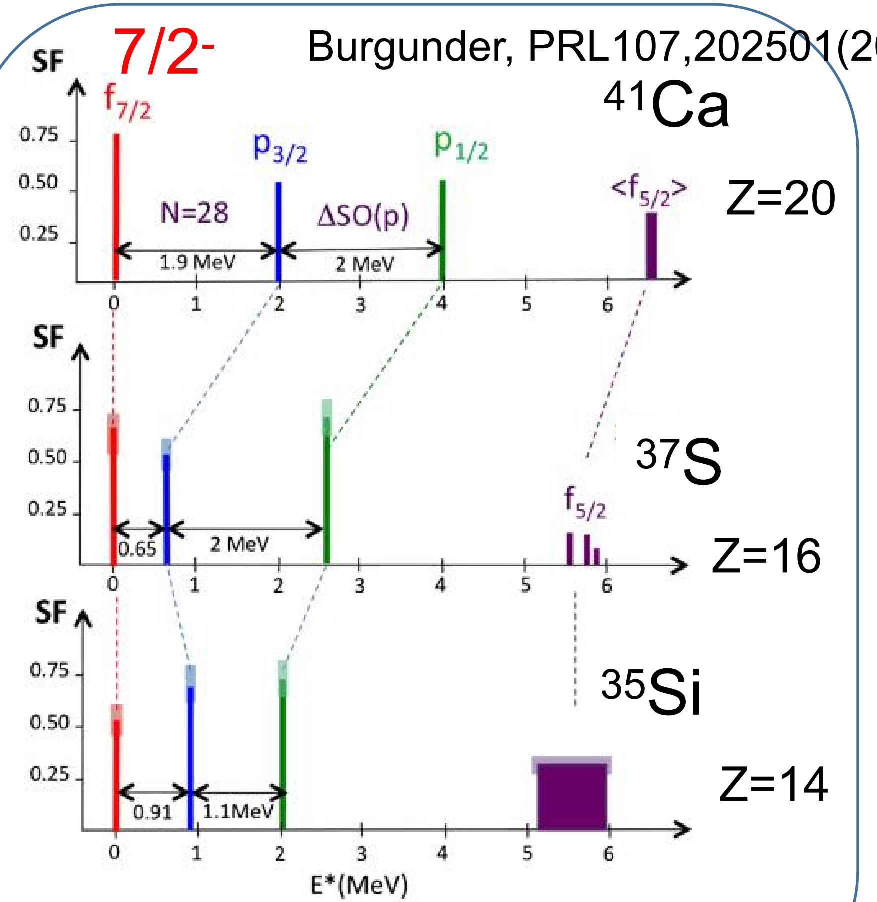
Island of Inversion: $E(0\hbar\omega) > E(2\hbar\omega)$

Weakly Bound Effect
Jahn Teller Effect→Deformation
Monopole Migration…

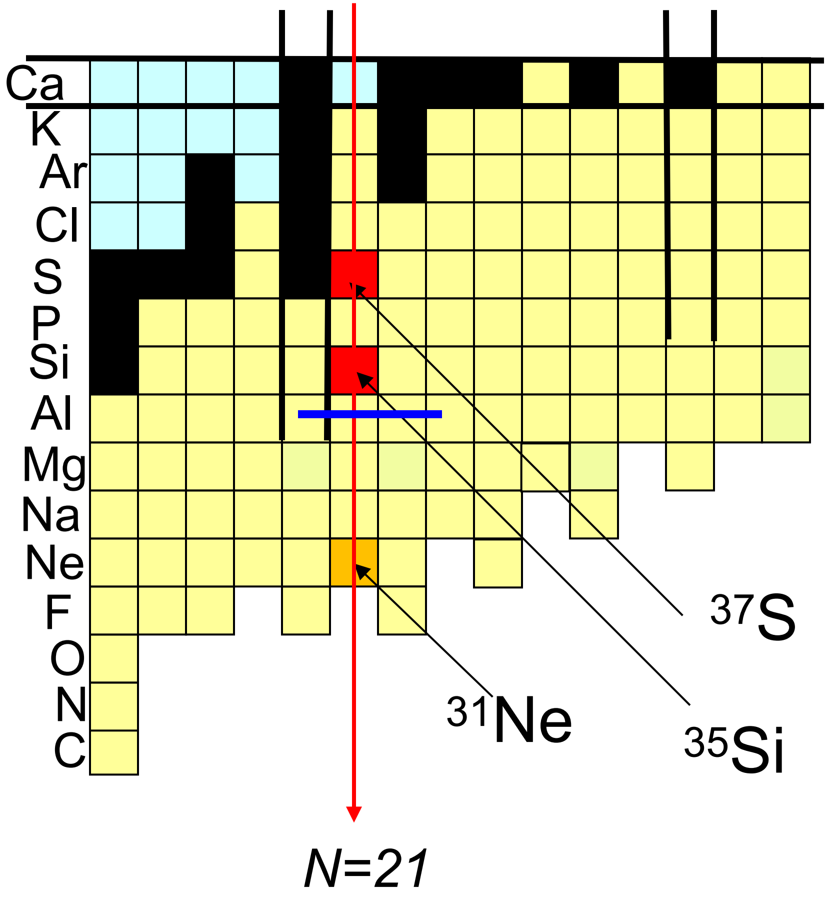
Shell Evolution in nuclei with N=21

^{31}Ne

Burgunder, PRL107,202501(2014). ^{34}Si(d,p)^{35}Si



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

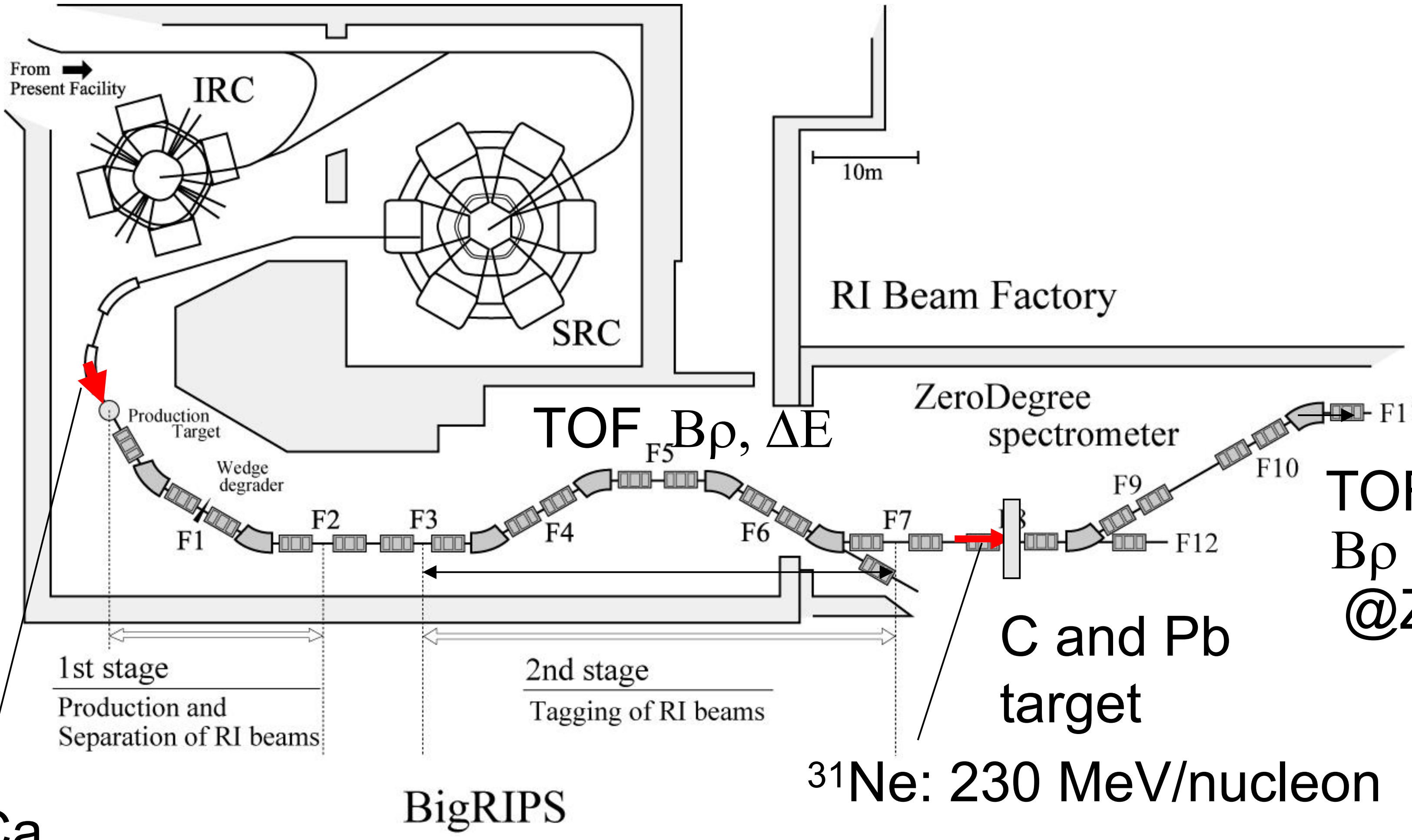


^{33}Mg gs: $3/2^-$ Z=12

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

Deformed: Island of inversion

Experiment at BigRIPS & ZDS at RIBF



TOF, Bρ, ΔE

TOF,ΔE
Bρ
@ZDS

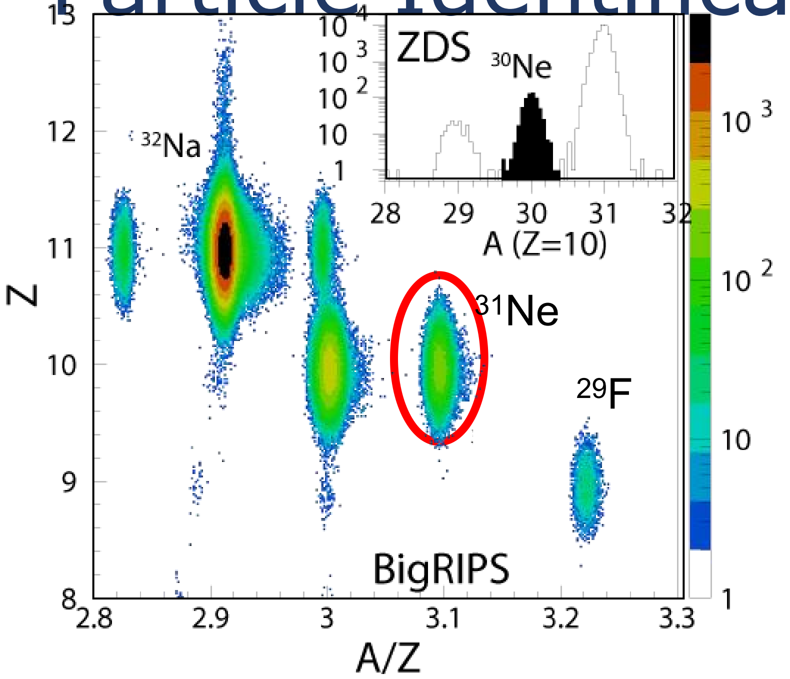
C and Pb
target

^{31}Ne: 230 MeV/nucleon

^{37}Mg: 240 MeV/nucleon

^{48}Ca
345MeV/nucleon

Particle Identification



RI beam Intensity @RIBF

~10^3-10^4 times/RIPS

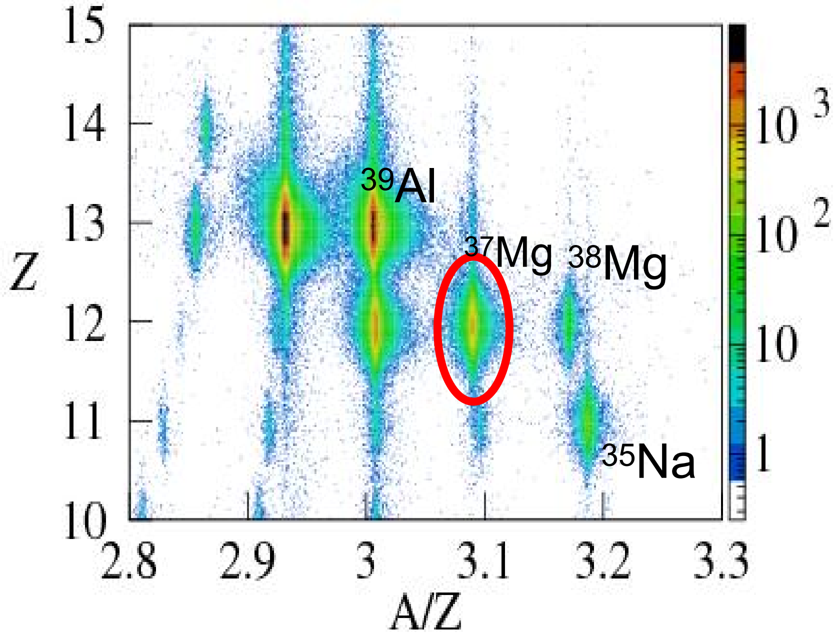
^{48}Ca@60pnA 2008

^{31}Ne: 230MeV/nucleon

~5 counts/s

c.f. ^{31}Ne -- 4 counts/day @RIPS H.Sakurai et al., PRC54,2802R(1996).

^{50}Ti Beam



^{48}Ca@100pnA 2010

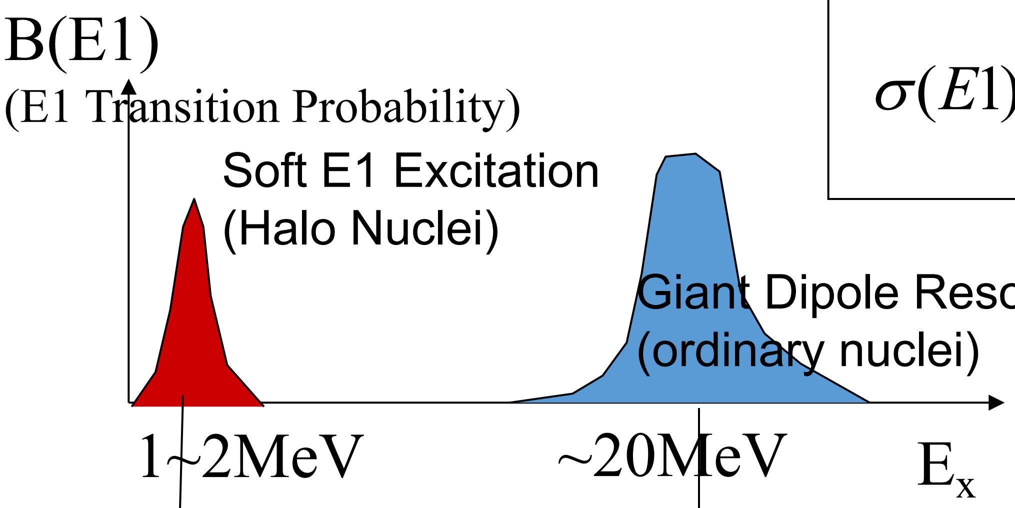
(→200pnA in 2012)

^{37}Mg: 244MeV/nucleon

~6 counts/s

34

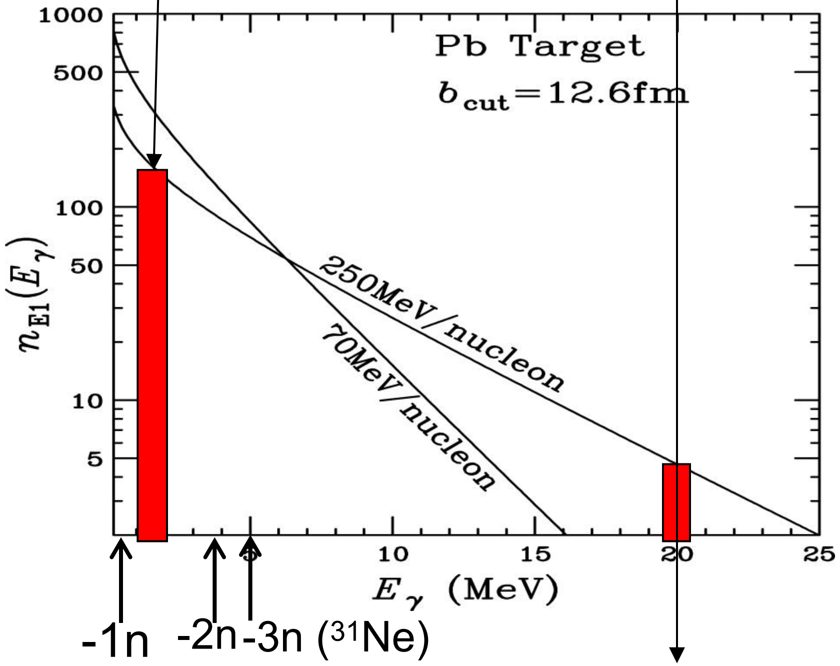
Inclusive Coulomb Breakup

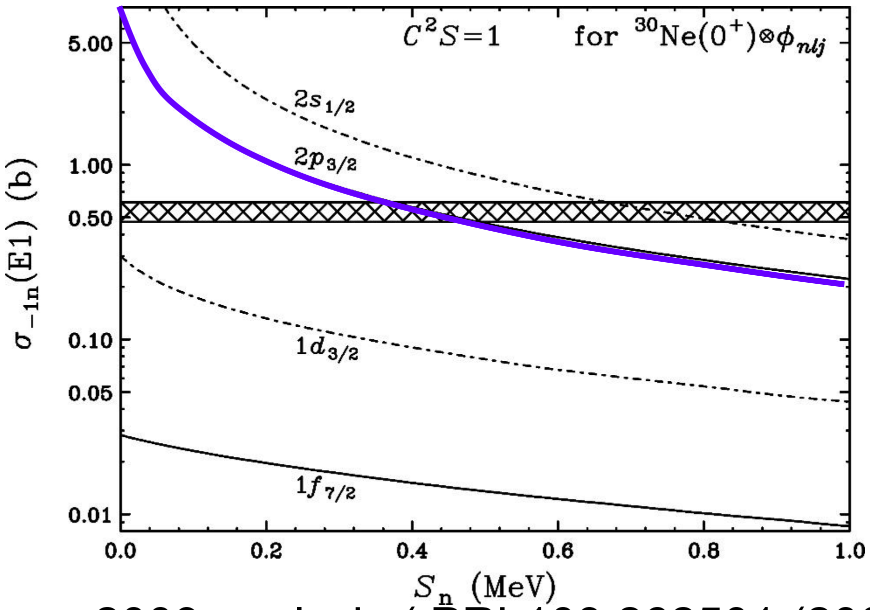


$$\sigma(E1) = \int_{Eth}^{\infty} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dE_x$$

$^{31}Ne+Pb \rightarrow {}^{30}Ne+X$

c.f. S_{1n} (^{31}Ne)=-0.06(0.42) MeV
L.Gaudefroy et al. PRL 2012





-- 2009 analysis (PRL103,262501 (2009))

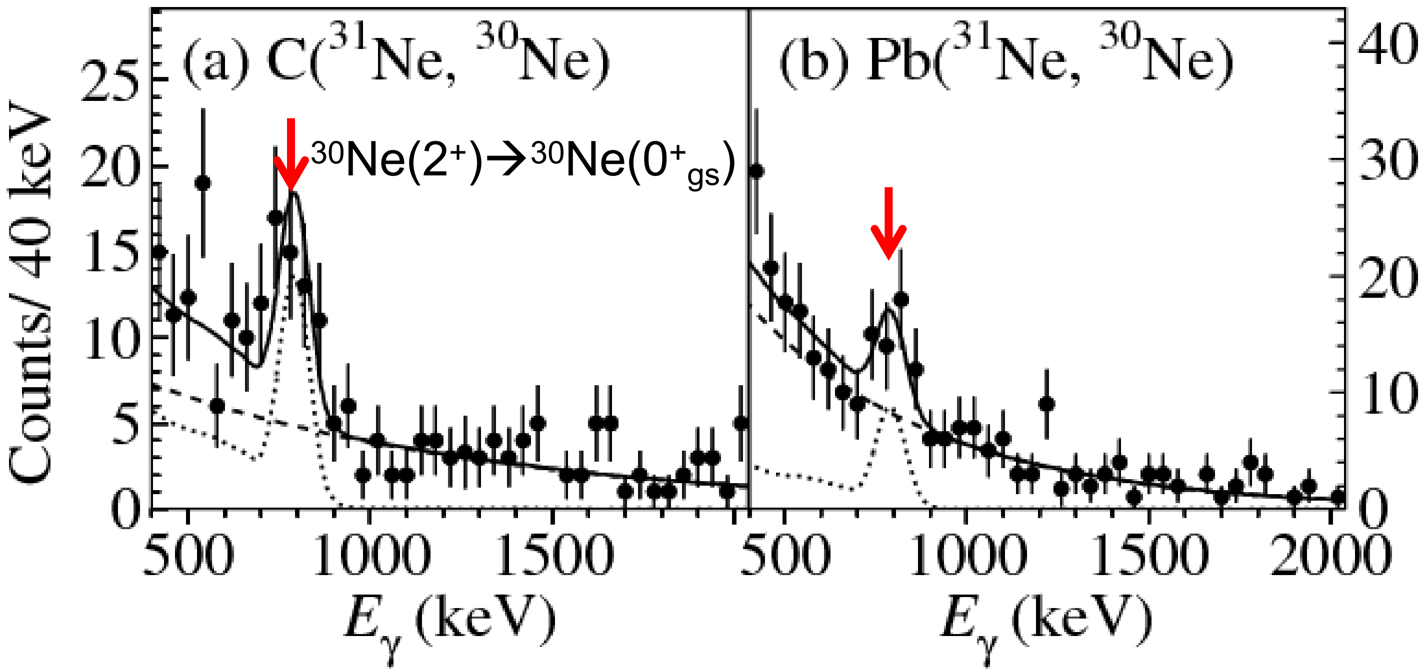
$\sigma(E1)$~0.5--1b

<~0.1b

p or s halo (not f)

C^2S,S_n was still unknown

Partial Cross Section $^{31}Ne \rightarrow ^{30}Ne(0^+_{g.s.})$



Inclusive $\sigma_{-1n}(C)$ = 90(7) mb
$\sigma_{-1n}(C; 2^+, 4^+, etc.)$ = 57(13) mb
→ $\sigma_{-1n}(C; 0^+_{g.s.})$ = 33(15) mb

Inclusive $\sigma_{-1n}(E1)$ = 529(63) mb
$\sigma_{-1n}(E1; 2^+, 4^+, etc.)$ = 81(87) mb
→ $\sigma_{-1n}(E1; 0^+_{g.s.})$ = 448(108) mb

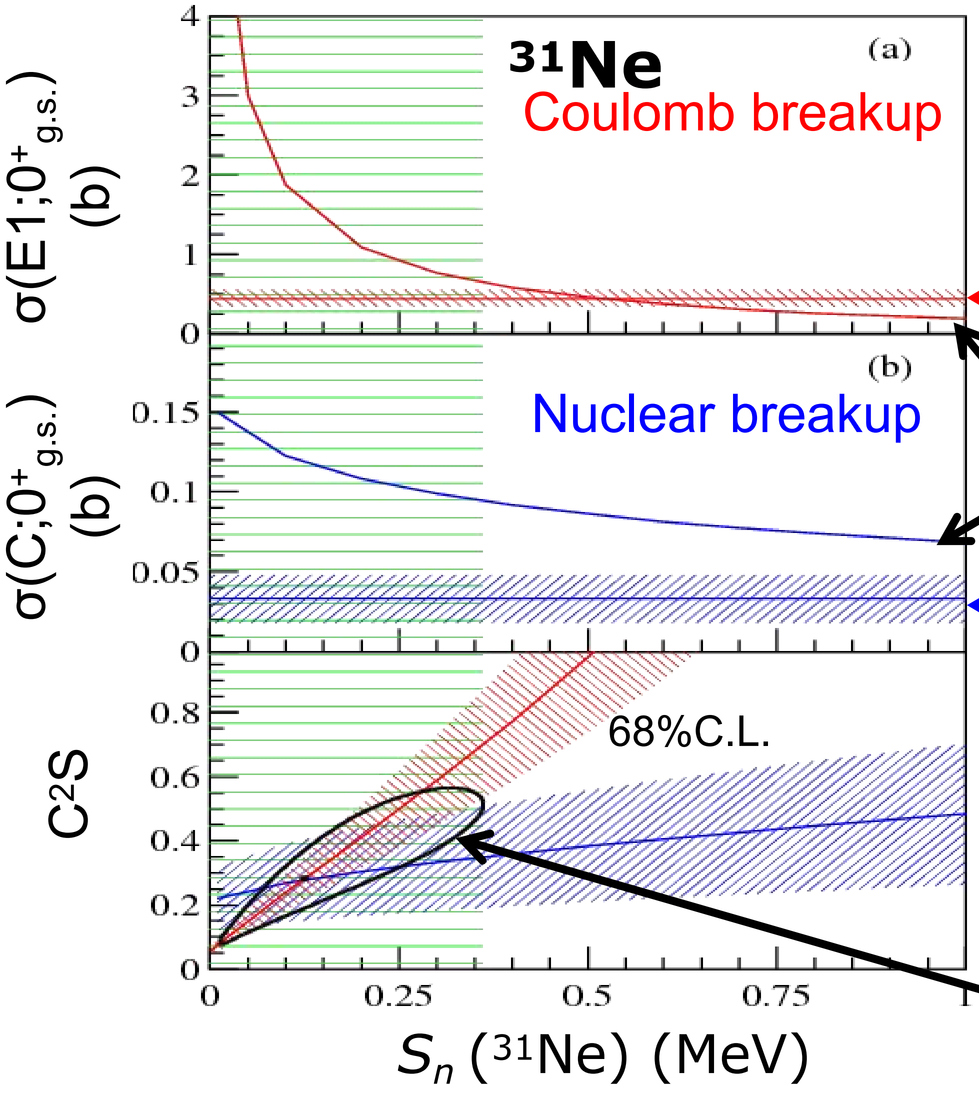
$0^+_{g.s.}$ / Inclusive=37(17)%

$0^+_{g.s.}$ / Inclusive=85(23)%

Different Sensitivity !

Combination of “Inclusive” Coulomb/nuclear breakup of ^{31}Ne $\rightarrow {}^{30}$Ne+X+(γ)

Tokyo Tech



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**

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

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

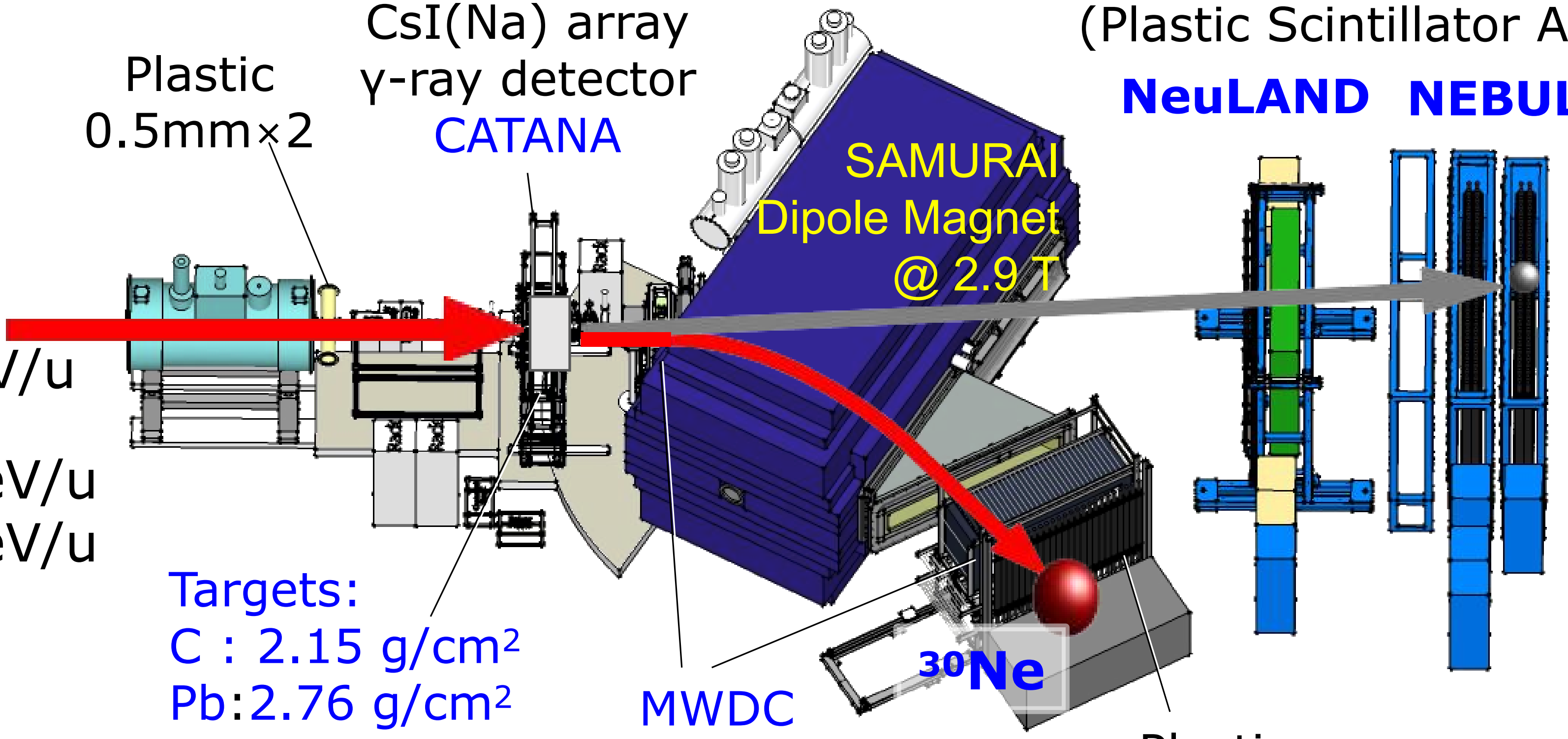
Limited to gs-core config.

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

“Exclusive” Coulomb Breakup of ^{31}Ne at SAMURAI, RIBF

T.Tomai et al.



Interim Summary: One-neutron halo nuclei

✓ Coulomb Breakup of ^{11}Be TN et al., Phys. Lett. B **331**, 296 (1994). N.Fukuda, TN et al., Phys. Rev. C **70**, 054606 (2004).

- Coulomb Breakup → Powerful Method to Probe Soft E1 Excitation
- Soft E1 Excitation: Direct Breakup Mechanism (Not Soft Dipole Resonance)

✓ Coulomb Breakup of ^{19}C TN et al., Phys. Rev. Lett. **83**, 1112 (1999).

- Shape and Amplitude of Coulomb Breakup Spectrum (B(E1)) → Powerful Spectroscopic Method: l, S_n, C^2S

✓ Coulomb Breakup of ^{15}C TN, N.Fukuda et al., Phys. Rev. C **79**, 035805 (2009).

- Application to (n,γ) cross section in stellar reaction→p-wave n capture

✓ Coulomb Breakup of ^{31}Ne, ^{37}Mg TN, N.Kobayashi et al., Phys. Rev. Lett. **103**, 262501 (2009). TN, N.Kobayashi et al., Phys. Rev. Lett. **112**, 142501 (2014). N.Kobayashi, TN et al., PRL **112**, 242501 (2014).

- Combination of inclusive Coulomb/nuclear breakup →l, S_n, C^2S
- Exclusive data of ^{31}Ne →Better accuracy of S_n, C^2S , Excited core component

T. Aumann, T. Nakamura, Physica Scripta T152, 014012 (2013).
T. Nakamura, Handbook of Nuclear Physics, https://doi.org/10.1007/978-981-15-8818-1_68-1

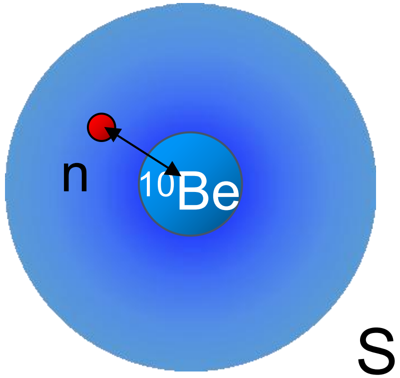
Coulomb Breakup of two-neutron halo nuclei

^{11}Li	TN et al., Phys. Rev. Lett **96**,252502(2006).	→Basics →2n-halo Spectroscopy
^{19}B	K.J. Cook, TN et al., Phys. Rev. Lett. **124**, 212503, 2020	→2n-halo Spectroscopy
^{6}He	Y.L. Sun, TN et al., Phys. Lett. B **814**, 136072 (2021).	→2n-halo Spectroscopy

Review

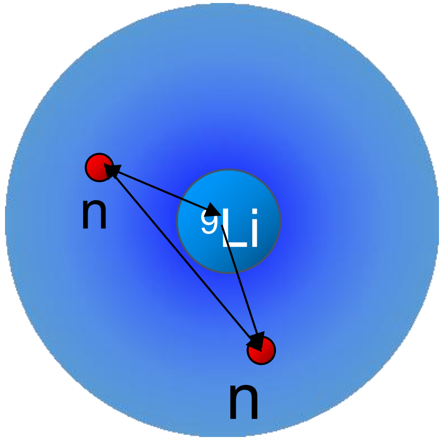
T. Aumann, T. Nakamura, Physica Scripta T152, 014012 (2013).
T. Nakamura, Handbook of Nuclear Physics, https://doi.org/10.1007/978-981-15-8818-1_68-1

One neutron halo nucleus vs. Two neutron halo nucleus



S_n=504 keV

Motion between
core and 1 valence neutron

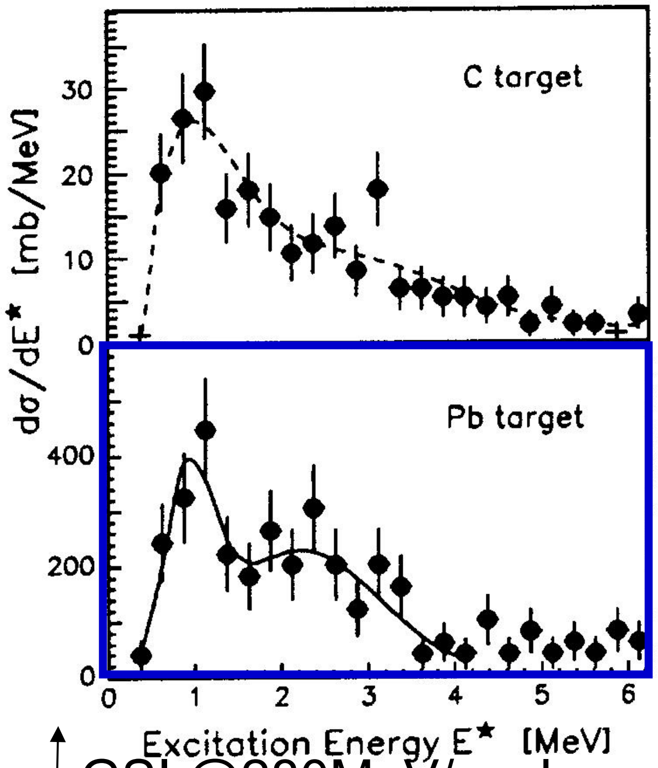


S_{2n}=370 keV

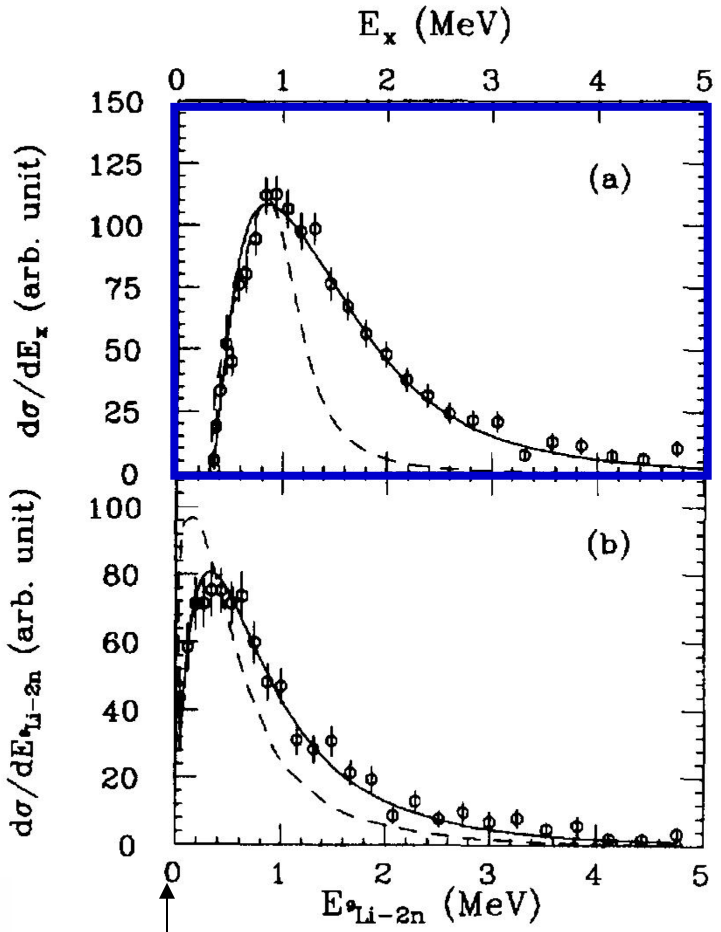
Motion between
1. Core and neutron
2. Core and neutron
3. Two valence neutrons
(neutron-neutron correlations)

Coulomb Breakup of ^{11}Li—Previous

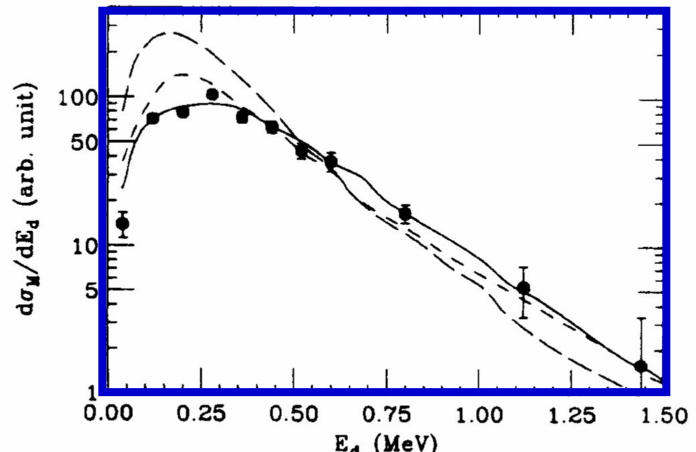
^{11}Li



GSI @280MeV/nucleon
NPA 619 (1997) 151.



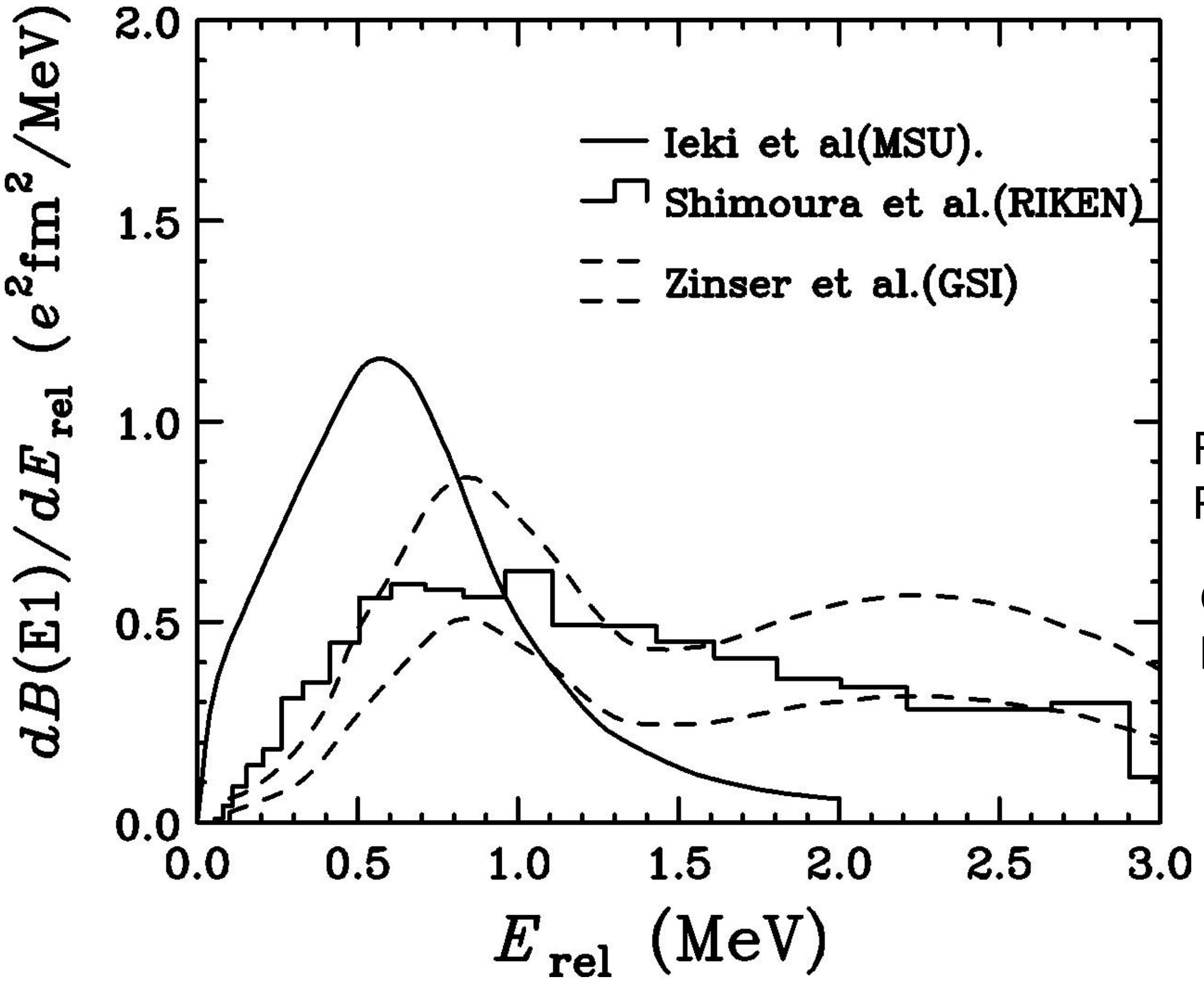
RIKEN @ 43MeV/nucleon
PLB348 (1995) 29.



MSU@ 28MeV/nucleon
PRL 70 (1993) 730.

dB(E1)/dEx Should be Compared !

Coulomb Breakup of ^{11}Li (Summary of Previous Results)



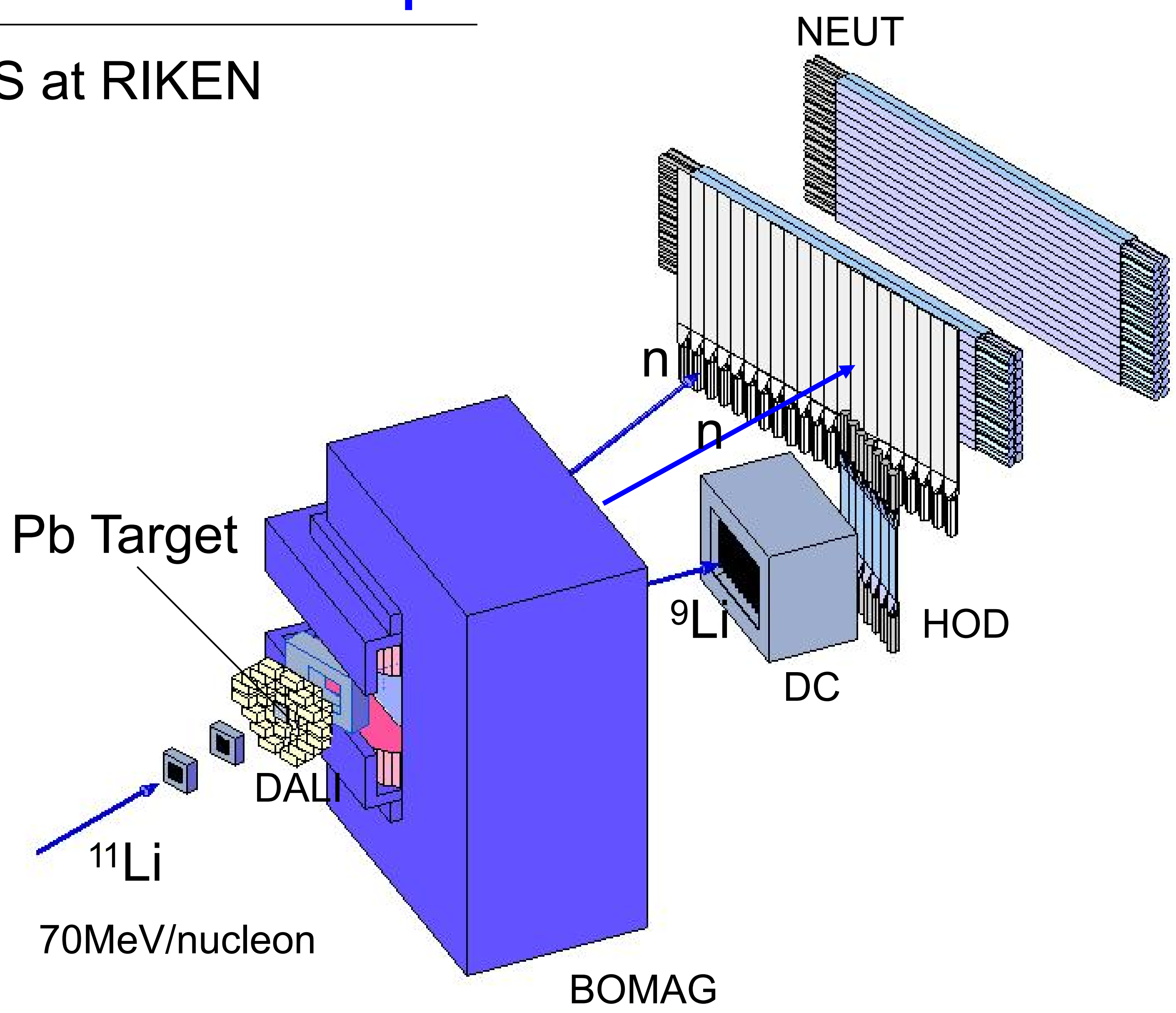
MSU@ 28MeV/nucleon
PRL 70 (1993) 730.
PRC 48(1993) 118.

RIKEN @ 43MeV/nucleon
PLB348 (1995) 29.

GSI @280MeV/nucleon
NPA 619 (1997) 151.

Experimental Setup

@RIPS at RIKEN

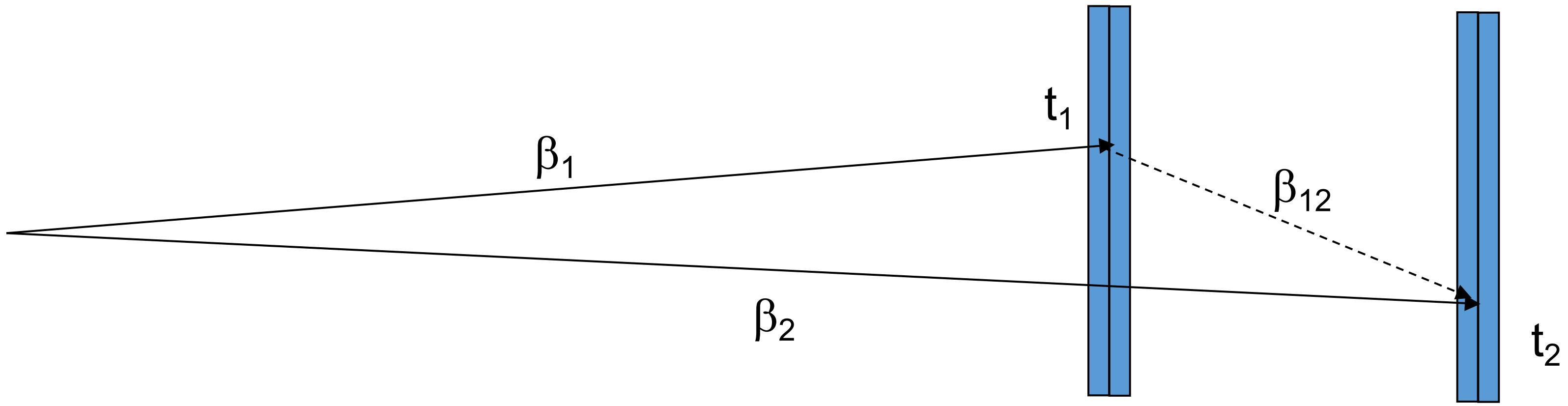


Elimination of Cross-Talk events for 2n+^{9}Li coincidence events

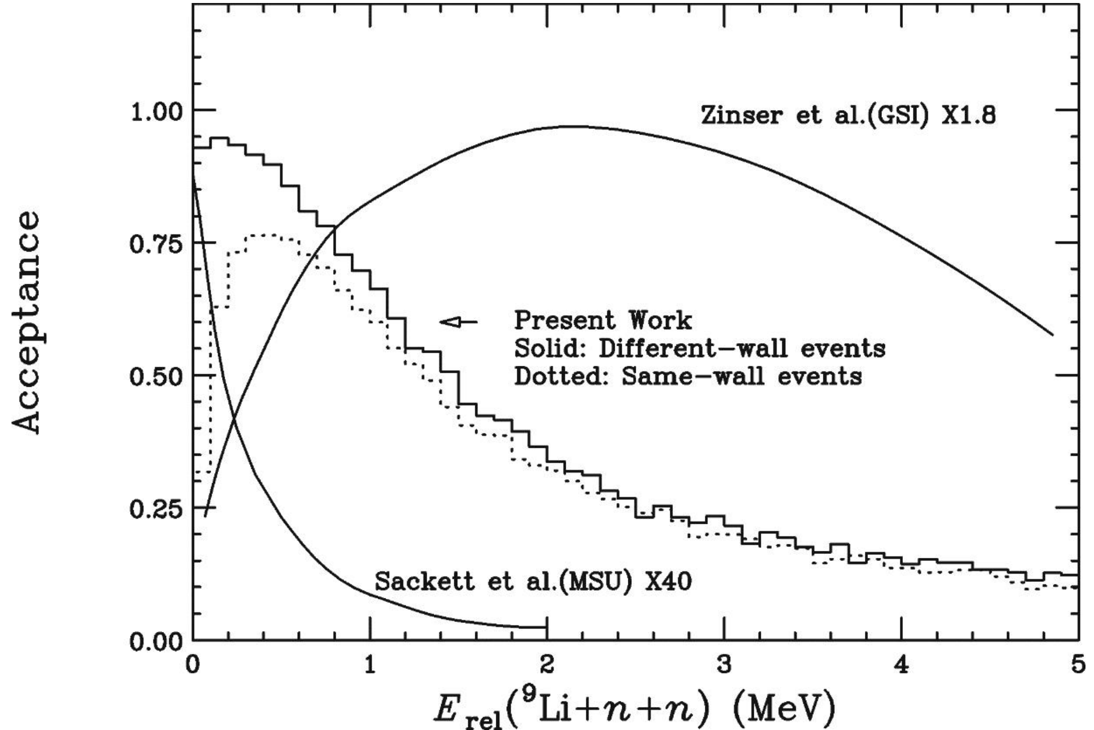
Examine Different Wall Events

Condition: $\beta_1 \leq \beta_{12}$

Almost no bias

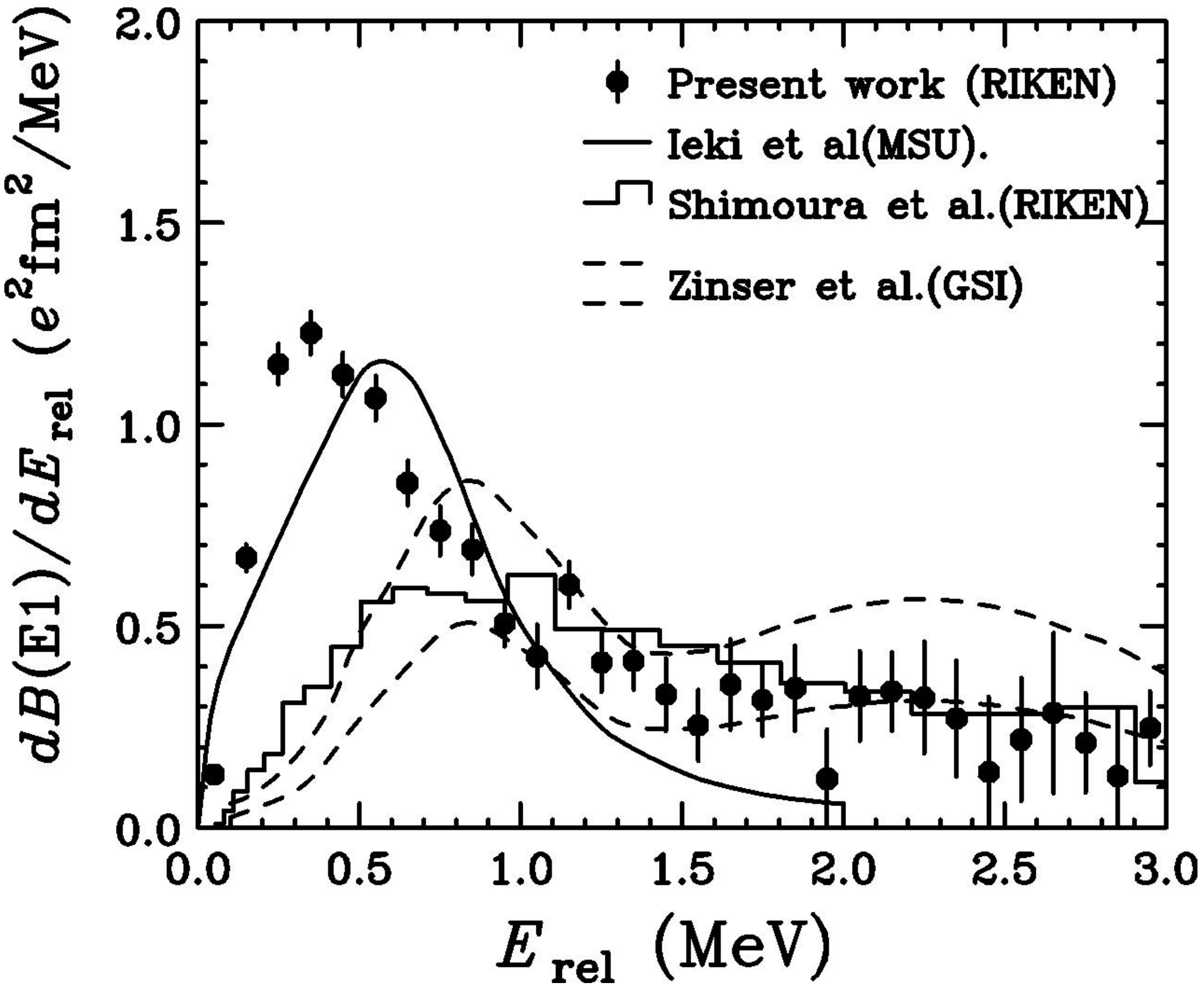


E_{th}=6MeVee to avoid any gamma related events



B(E1) Spectrum of ^{11}Li

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

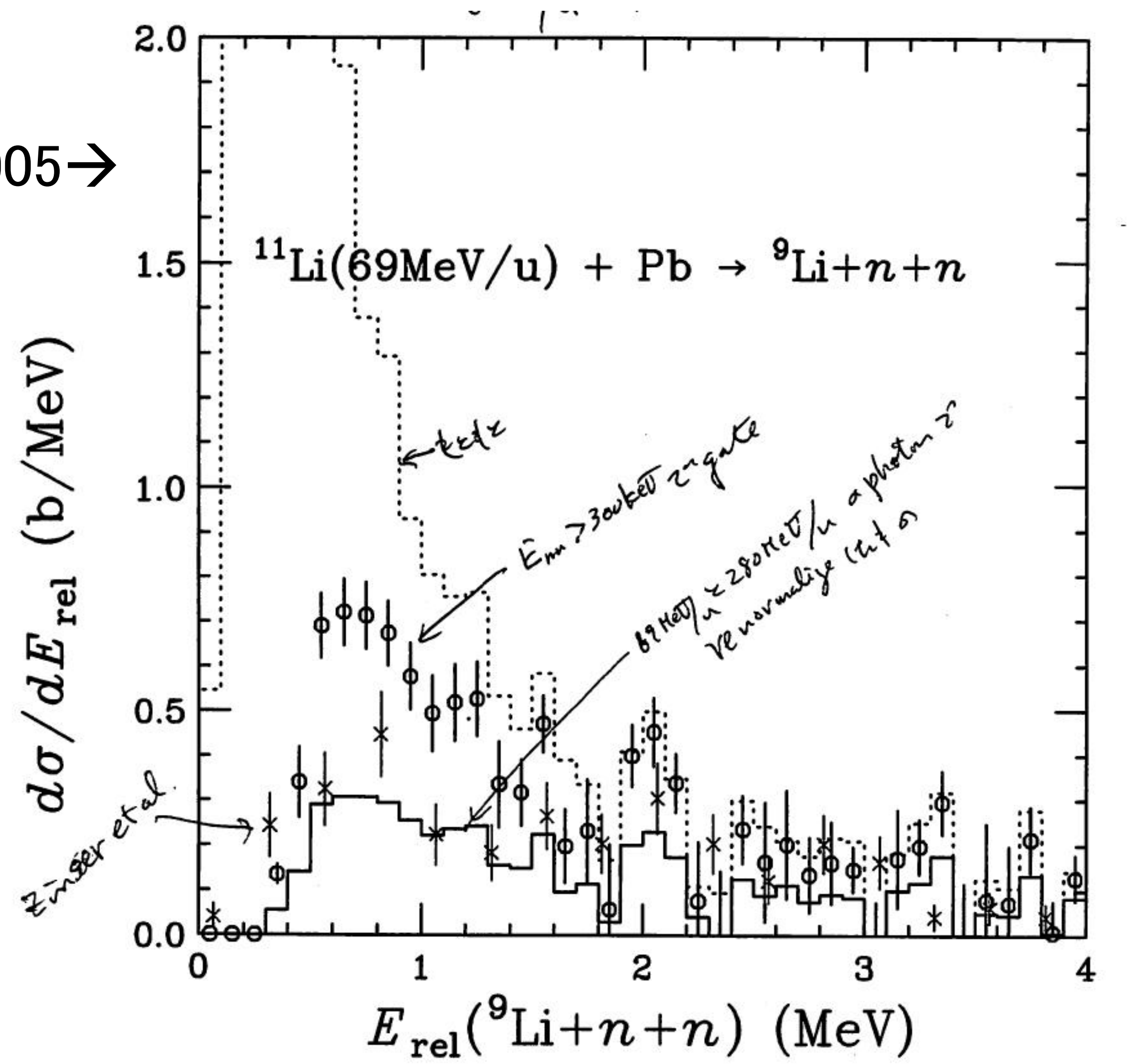


Possible reason for disagreement with the previous results：

Zinser et al., may miss events with small θ_{nn}

→We could reproduce Zinser's data by selecting $E_{nn} > 0.3\,\mathrm{MeV}$ in our data

From My analysis notebook in c.a. 2005→



B(E1) → Geometry of **two-neutron** halo nucleus

Non-energy weighted Sum Rule

H.Esbensen et al.,NPA542,310(1992)

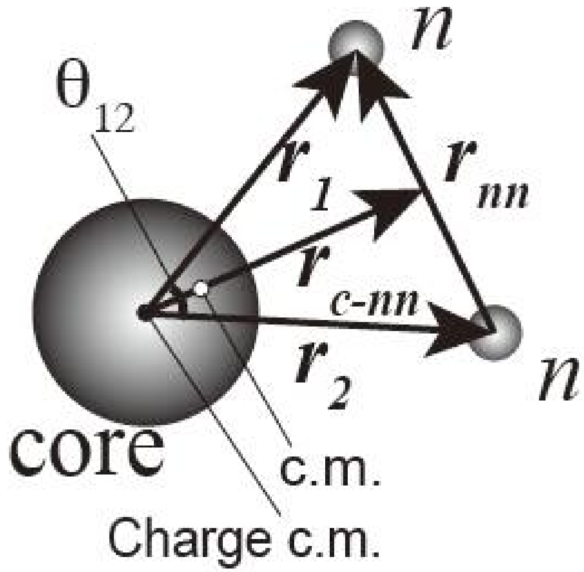
$$B(E1) = \int \frac{dB(E1)}{dE} dE = \int \left\langle i \middle| \sqrt{\frac{3}{4\pi}} \frac{2Ze}{A} \vec{r} \middle| f \right\rangle^* \left\langle f \middle| \sqrt{\frac{3}{4\pi}} \frac{2Ze}{A} \vec{r} \middle| i \right\rangle dE$$

$$= \frac{3}{\pi} \frac{Ze}{A} \langle i|r^2|i\rangle = \frac{3}{\pi} \frac{Ze}{A} \left\langle \frac{(\vec{r}_1 + \vec{r}_1)^2}{2} \right\rangle = \frac{3}{4\pi} \frac{Ze}{A} \langle {r_1}^2 + {r_2}^2 + 2\vec{r_1} \cdot \vec{r_2} \rangle$$

$$\vec{r} \equiv \overrightarrow{r_{c-nn}}$$

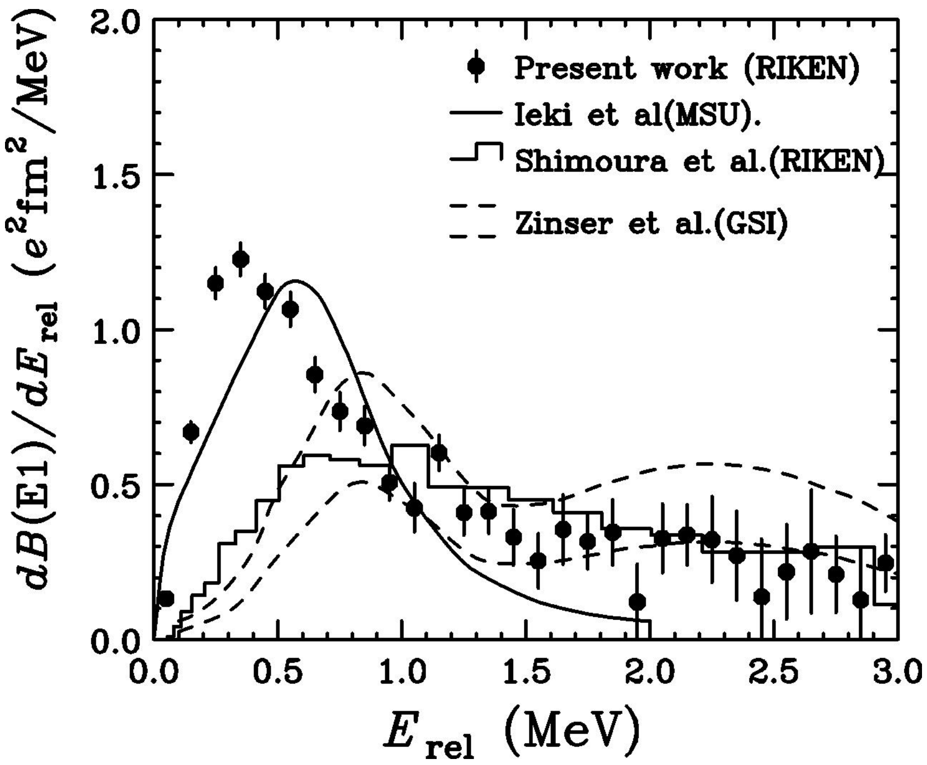
$$Ze\vec{r}(charge\ c.m) = -\frac{2Ze}{\underline{A}} \vec{r}$$

$e_{\mathrm{eff}}{}^{(E1)}$: E1 Effective Charge



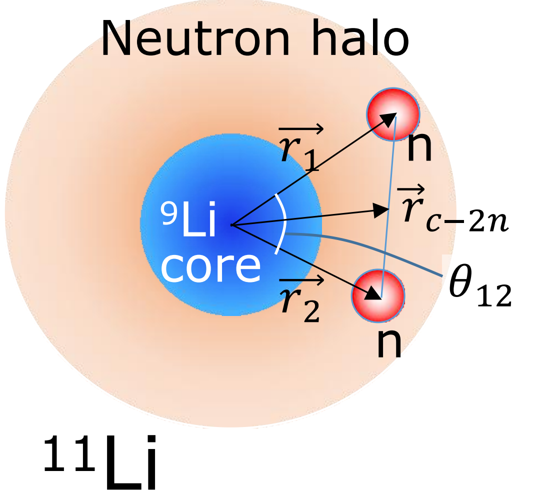
Coulomb Breakup of ^{11}Li
→ Probe of Dineutron Correlation

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



E1 Non-energy weighted cluster sum rule

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



$B(E1) = 1.42(18)e^2fm^2$ $(E_{rel} \leq 3$ 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).

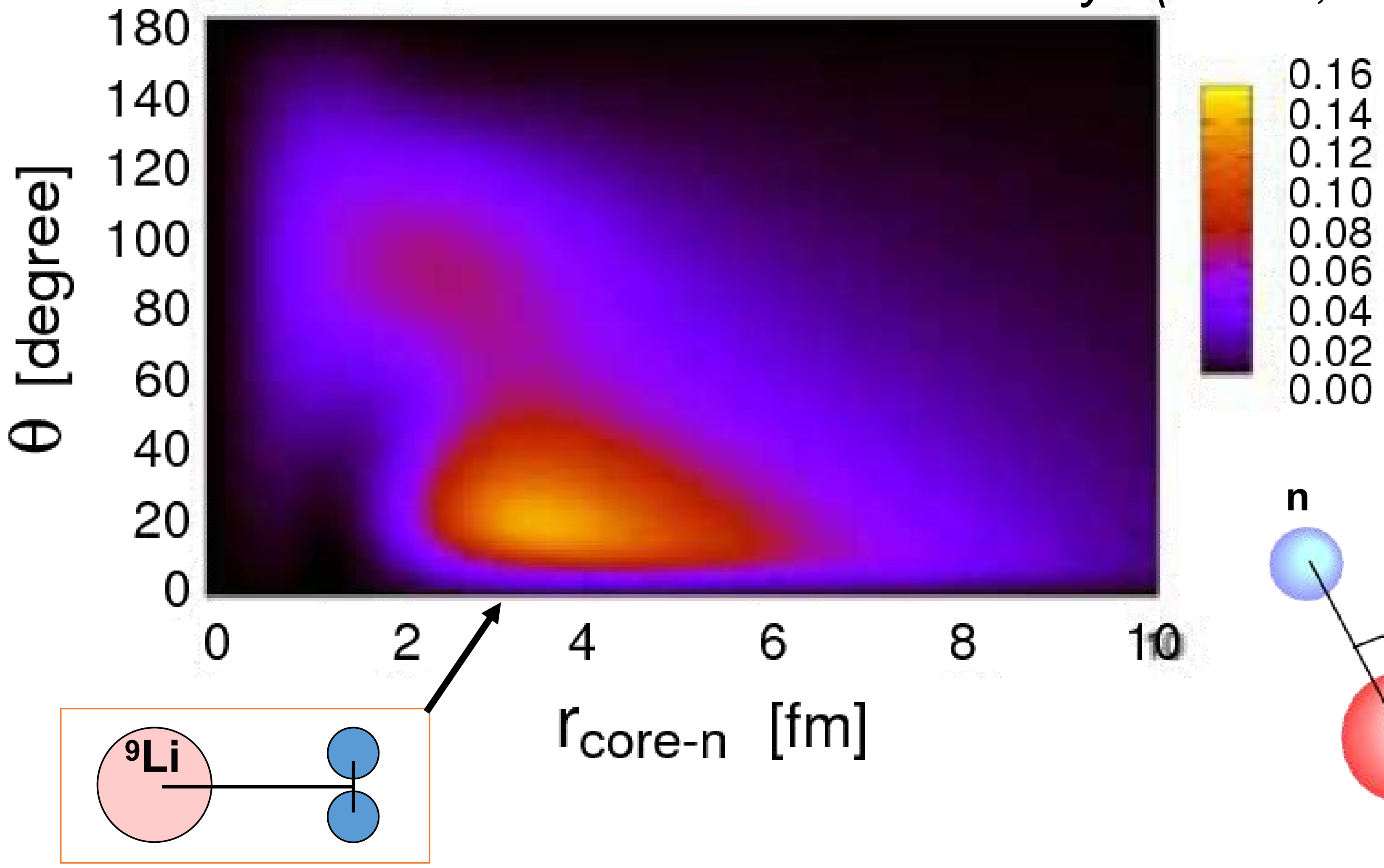
Spatial Correlation in the Ground State of ^{11}Li

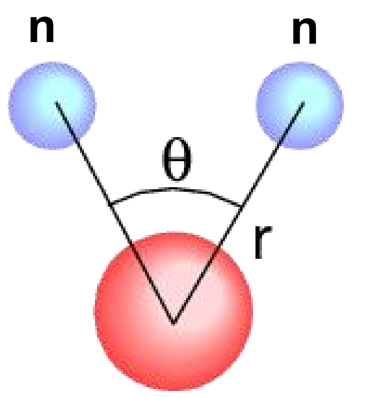
Soft E1 Excitation of 2n-halo → dineutron correlation

2n correlation density in ^{11}Li

Courtesy of T.Myo (RCNP,Osaka U.)

2n density in ^{11}Li

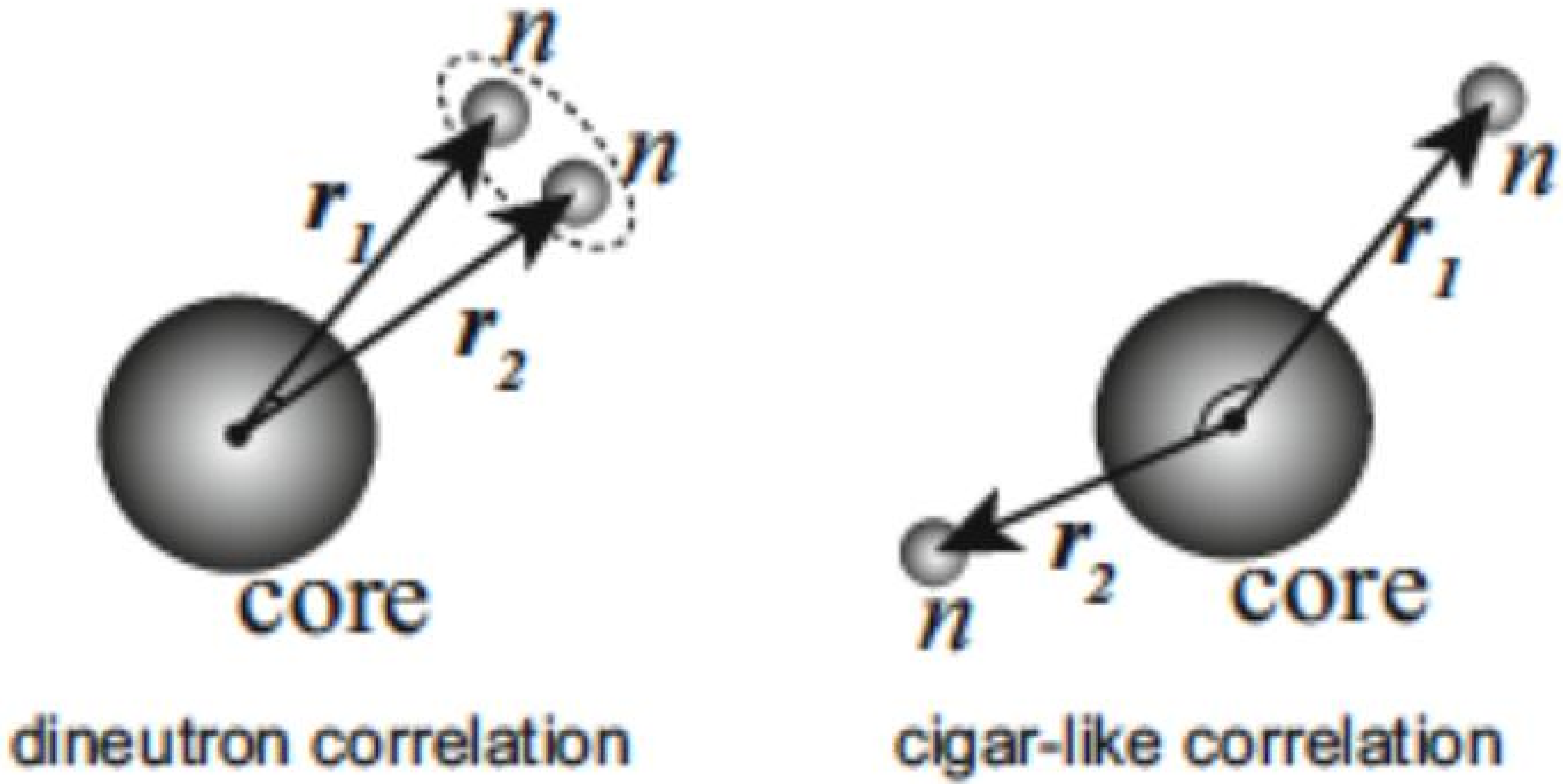




Cf. H.Esbensen and G.F.Bertsch, NPA542(1992)310

50

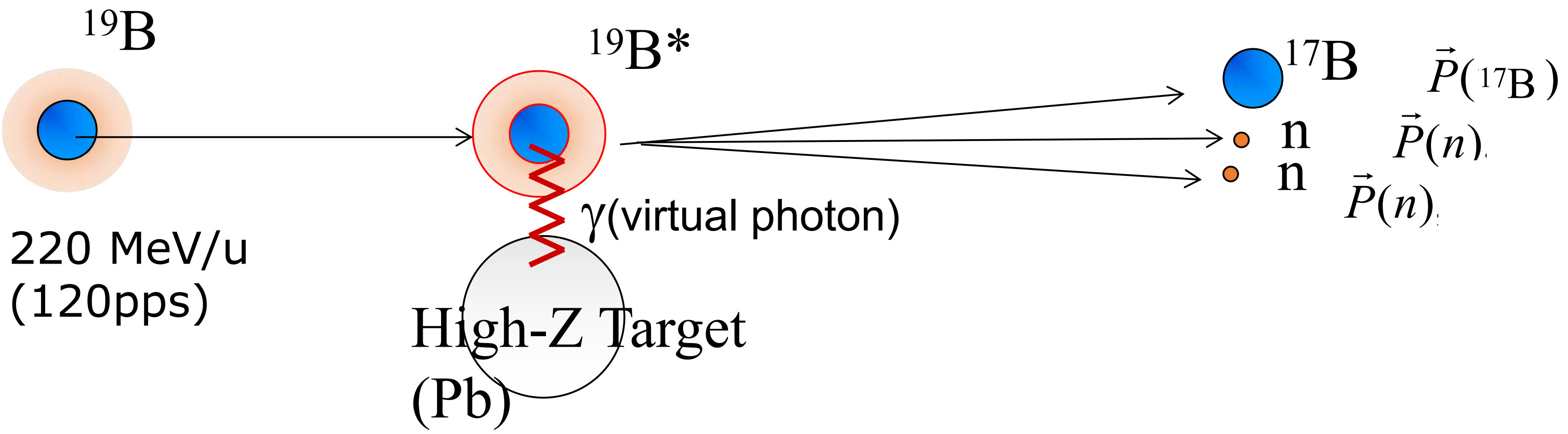
Dineutron & Cigar-like Correlation



T. Nakamura, Handbook of Nuclear Physics, https://doi.org/10.1007/978-981-15-8818-1_68-1

Coulomb Breakup of ^{19}B

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



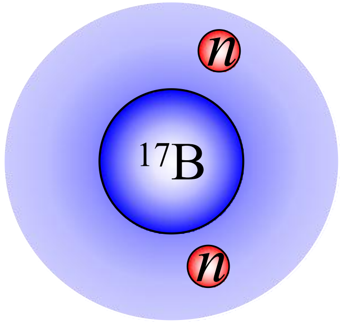
PHYSICAL REVIEW LETTERS **124**, 212503 (2020)

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]

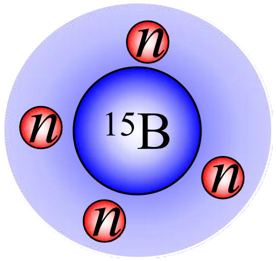
^{19}B: Two-neutron halo or Four neutron skin?



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

S_{2n}=0.089(560) MeV

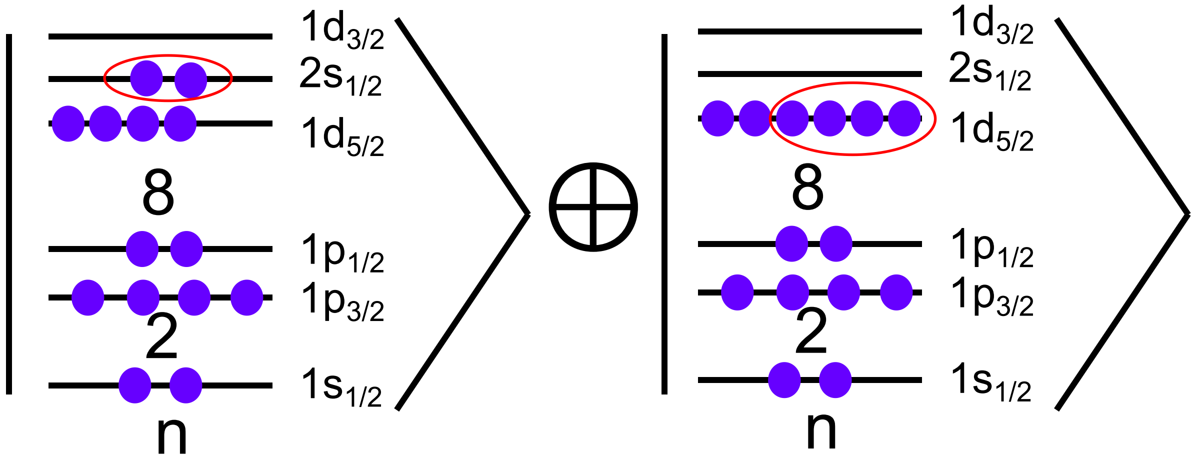
Or?



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

S_{4n}=1.47(35) MeV

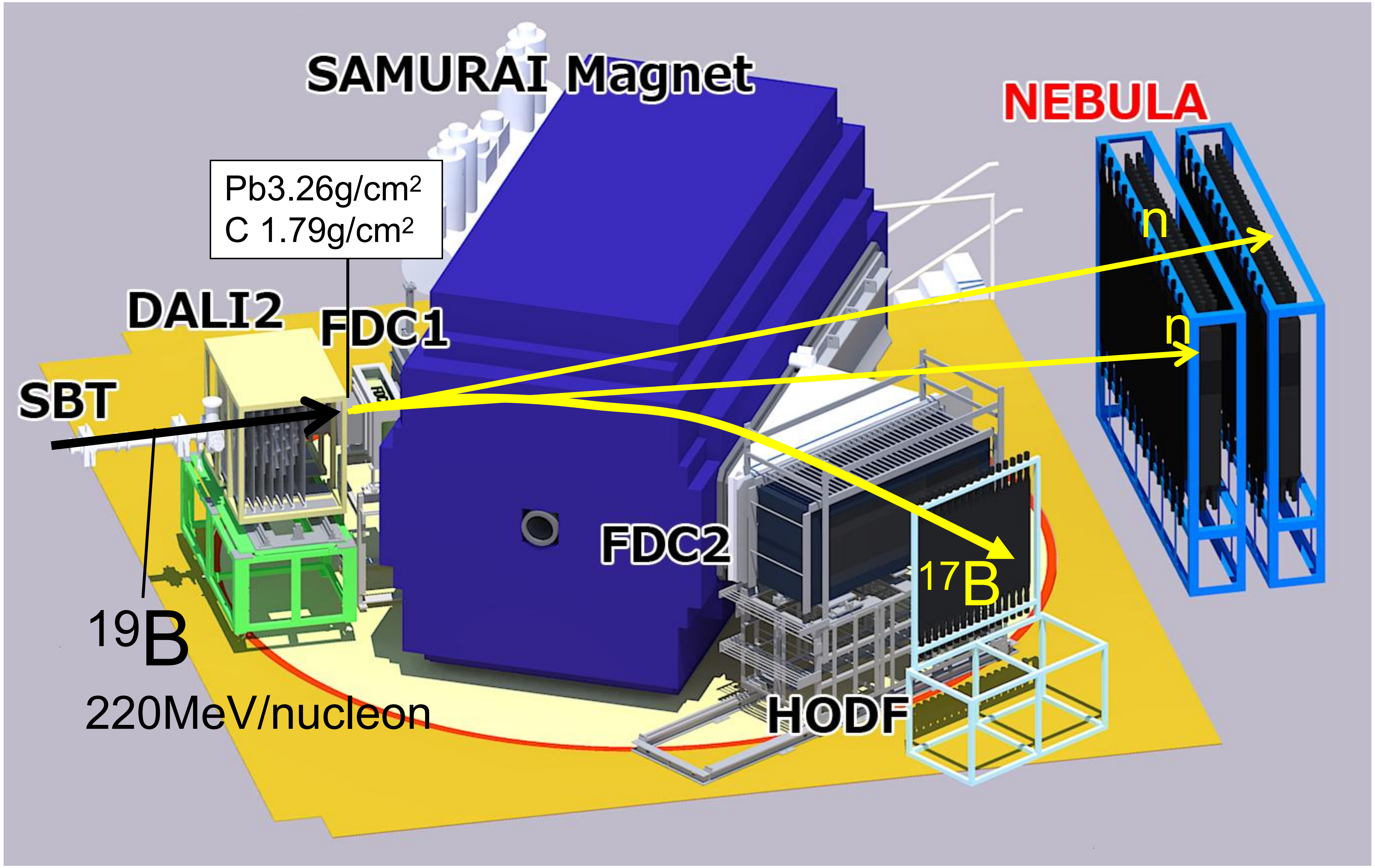
$\Psi({}^{19}_{5}B)=$



(halo-like)

(skin-like)

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

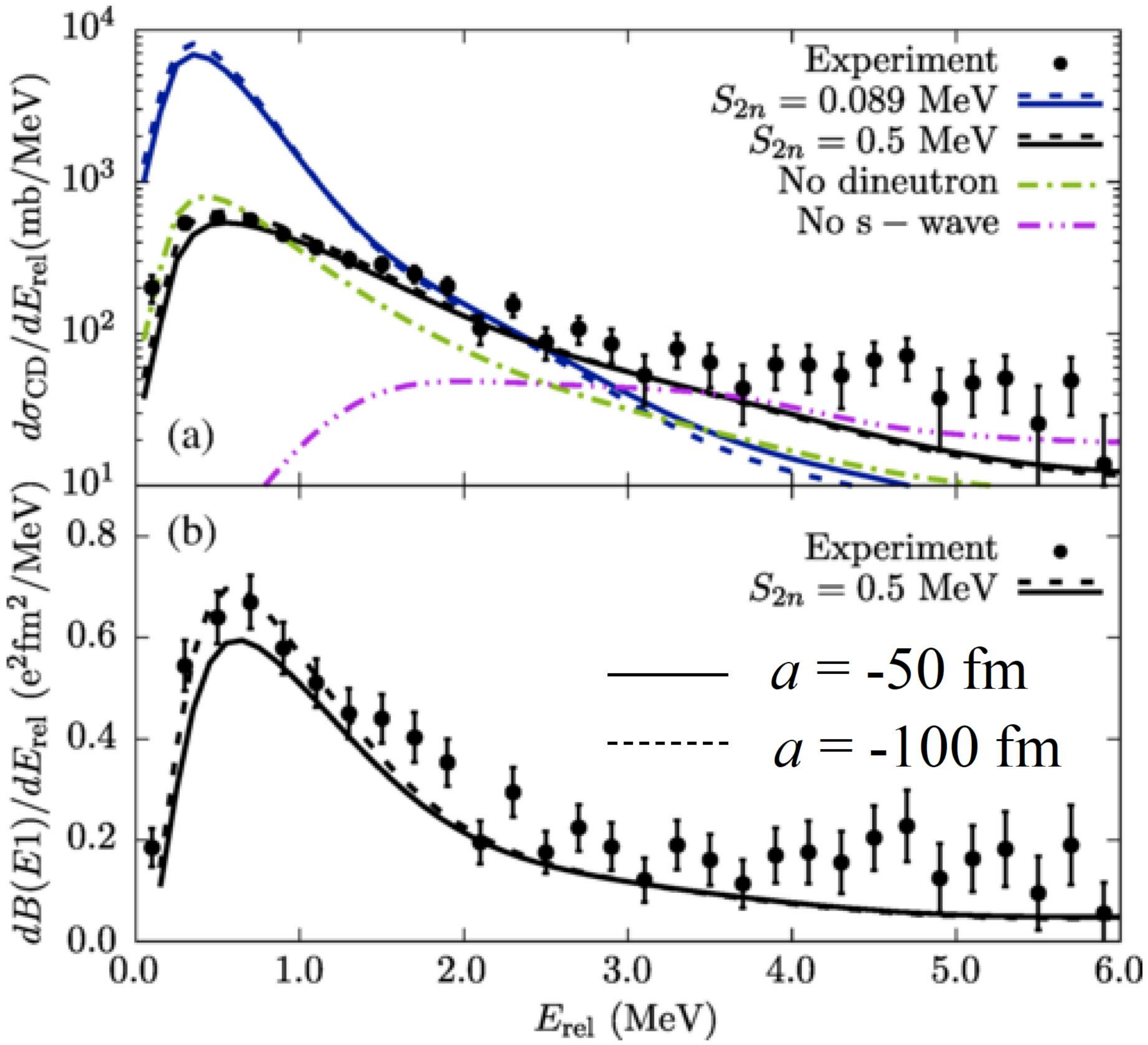
-4n: $\sigma_{Pb} \sim 3\sigma_C$ → Nuclear Breakup Dominant in **-4n** channel

^{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!

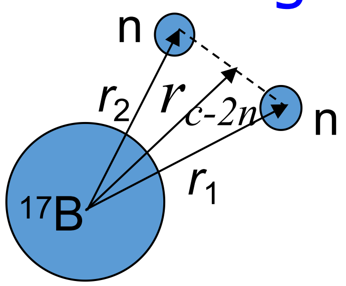
  Similar B(E1) to ^{11}Li, ^{11}Be.

  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:

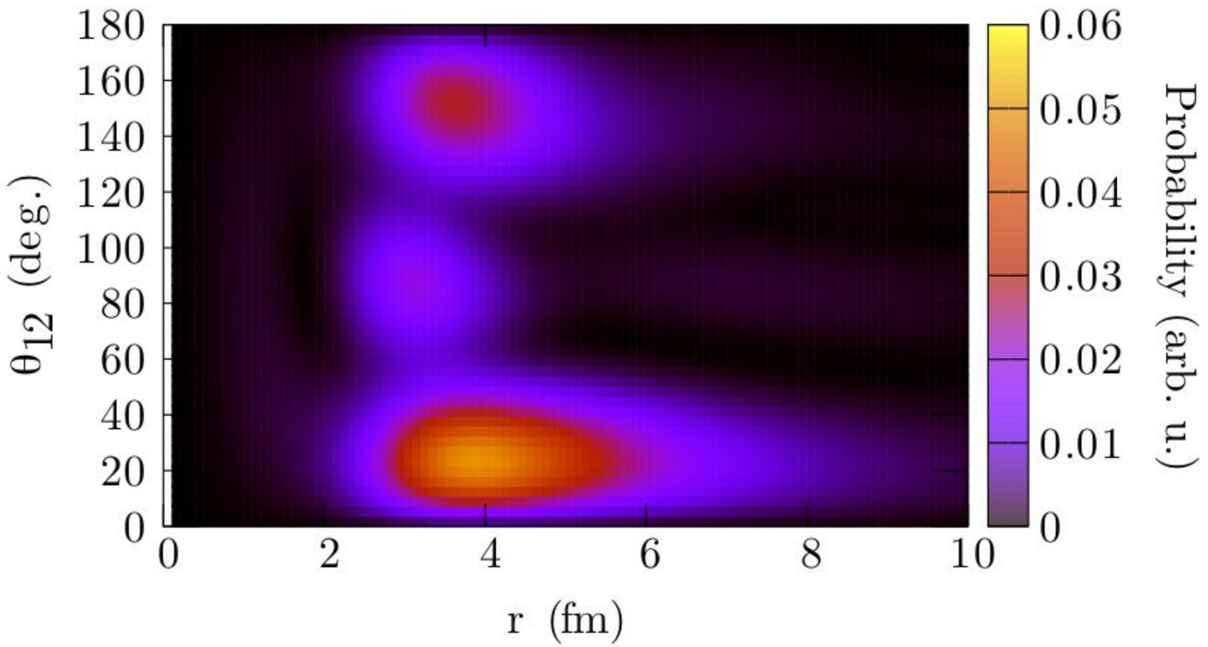
  ^{17}B-n ($a < -50\ fm$)

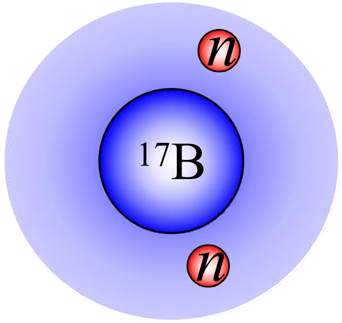


Dineutron correlation in ^{19}B

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)

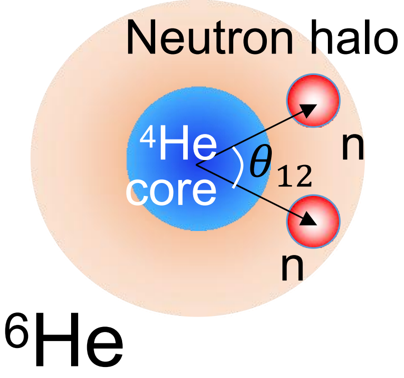
$S_{2n} \sim 0.5$ MeV

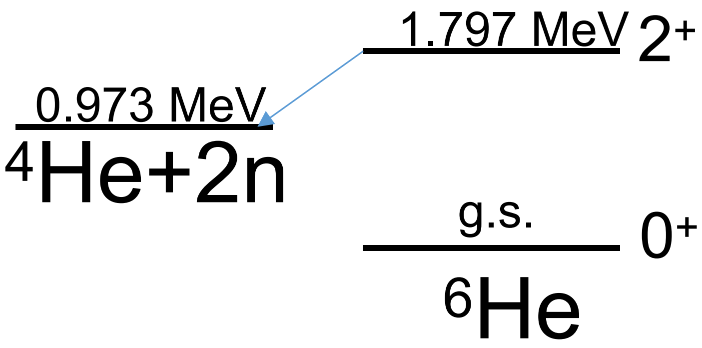
- ✓ Enhanced nn probability at $\theta_{12} \sim 25°$
- ✓ Configuration: Negative:6%, s: 35%, d: 56%
- ✓ Asymmetry: Due to Negative-parity mixture

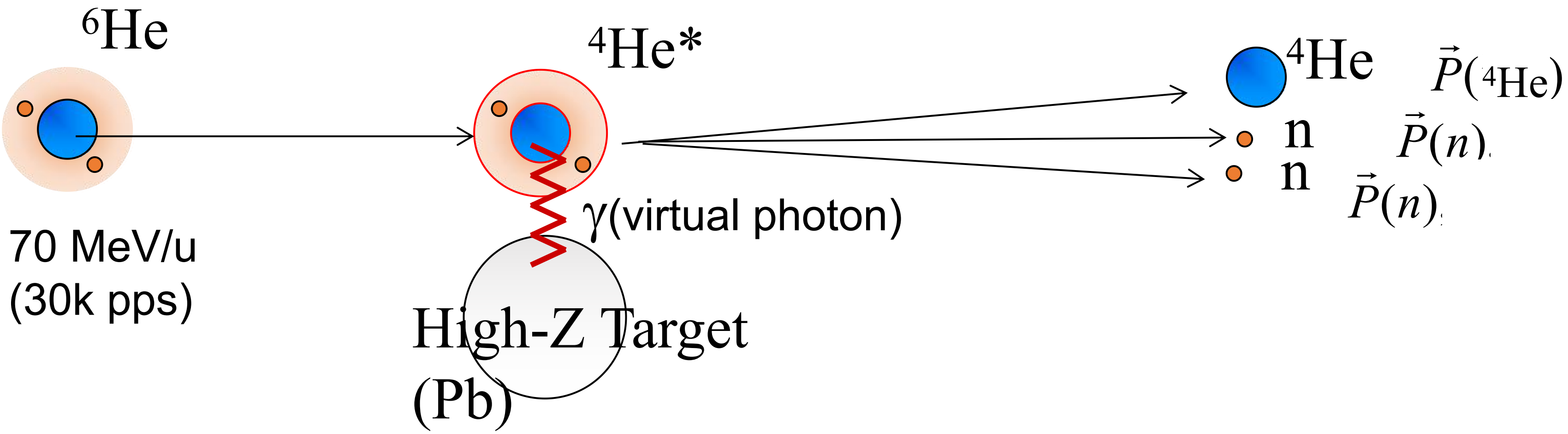
Coulomb/nuclear breakup of ^{6}He at 70 MeV/nucleon at RIPS

^{6}He

Y.L. Sun, TN et al., PLB 814, 136072 (2021).

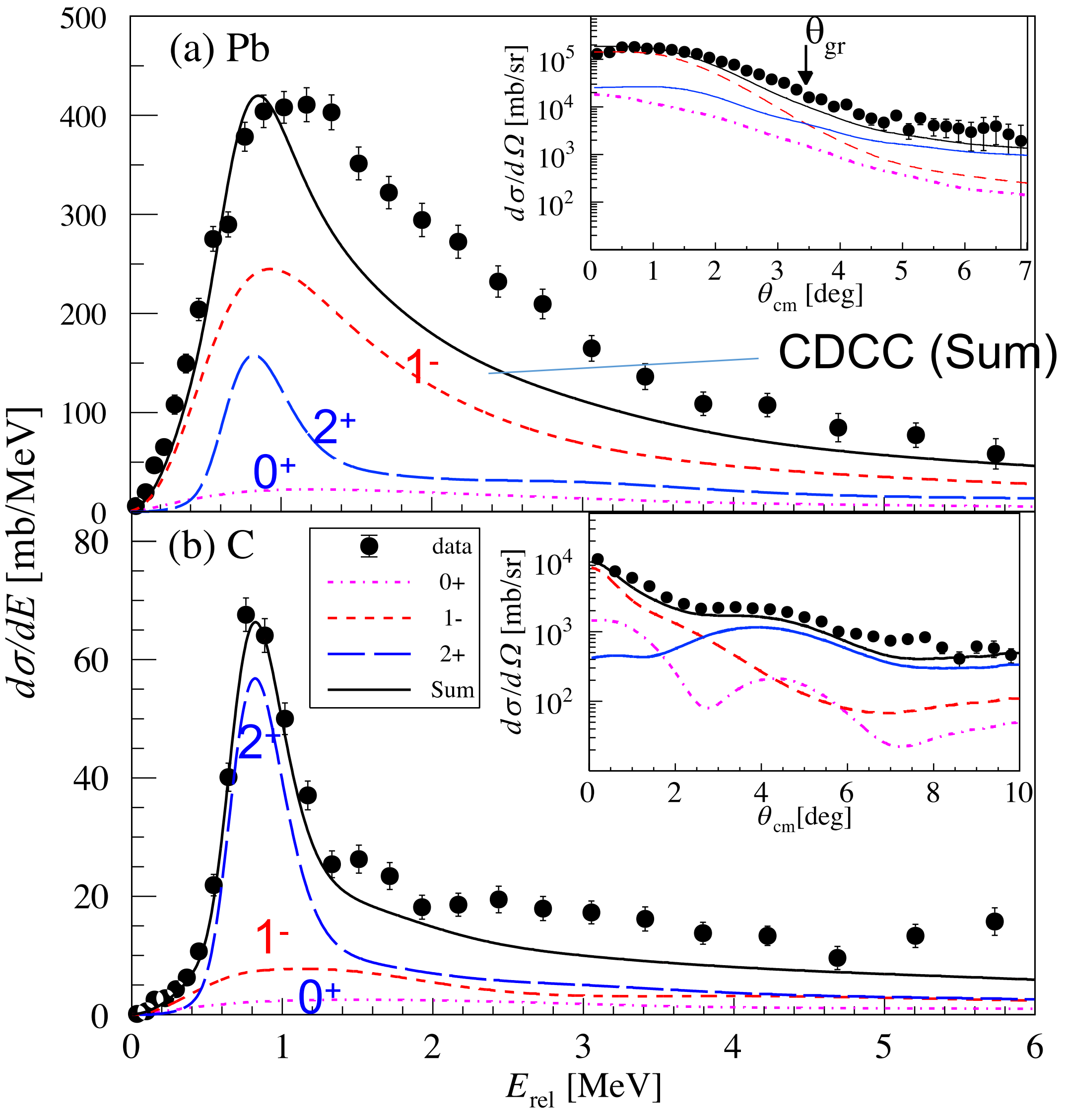






Energy Spectra and Angular Distributions: ^{6}He+Pb, ^{6}He+C

Y.L. Sun et al., PLB2021



Pb target :

- **Enhanced cross section (~1barn) for E_{rel}<6 MeV**

→Soft E1 Excitation : Typical of Halo Nuclei

Comparison with CDCC + 3-body model :

- reproduce the data up to E_{rel}~1MeV
- 1^- (Coulomb) **dominant**
- 2^+ contribution at the known 1st excited state (E_x=1.8MeV)
- Underestimate ~1 MeV<E_{rel}→ Target excitation?

C target :

- **Narrow peak for the 2_1^+ state (1st excited state)**

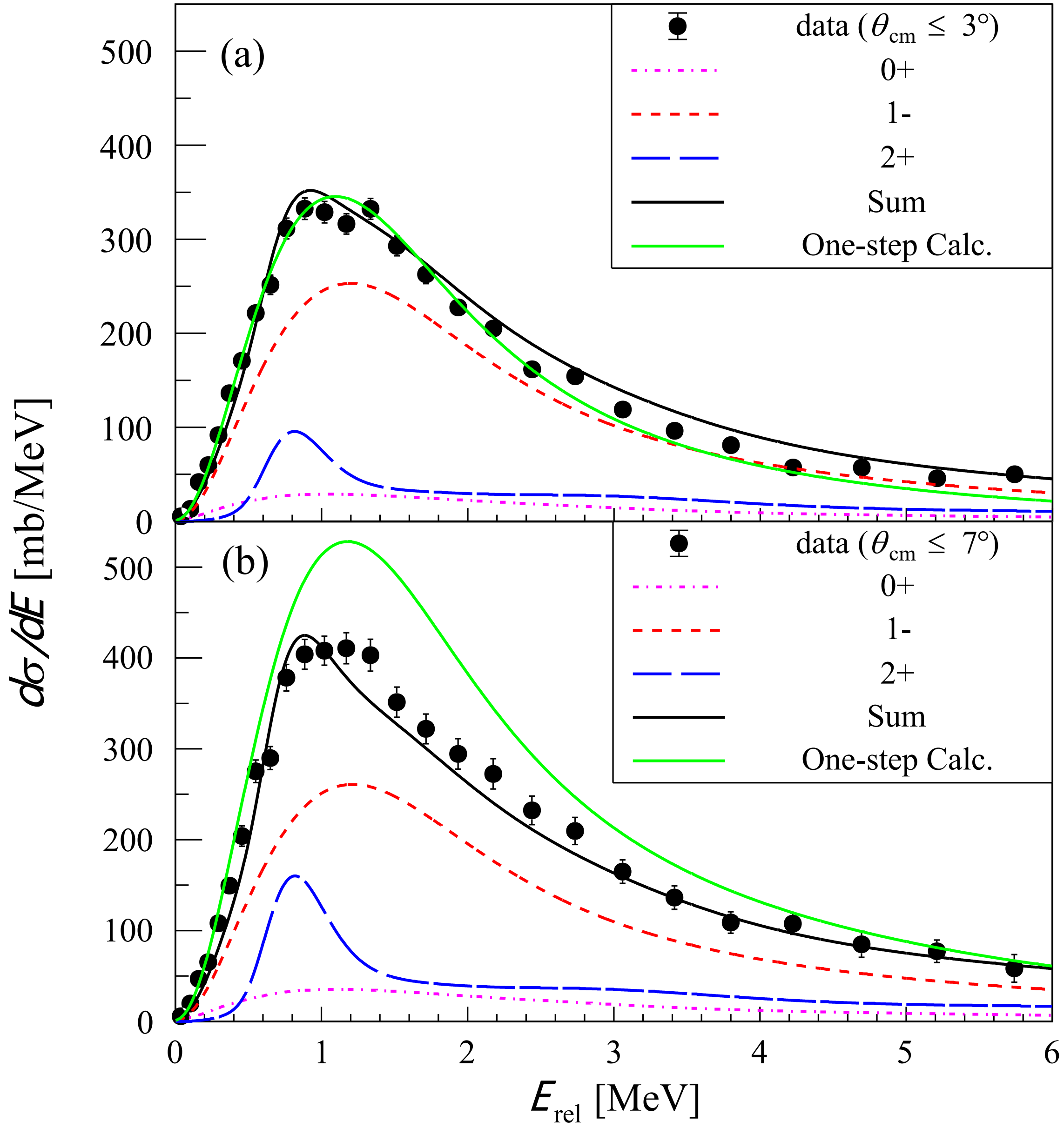
(E_x=1.8 MeV)

Comparison with CDCC + 3-body model :

- reproduce the data up to Erel~1MeV
- 2+ dominant **dominant (nuclear dominant)**
- Underestimate ~1MeV <E_{rel} → Target excitation?

Energy Spectra of ^{6}He+Pb at 70 MeV/nucleon: Comparison with **Modified CDCC**

Y.L. Sun et al., PLB2021



Modified CDCC + 3body model

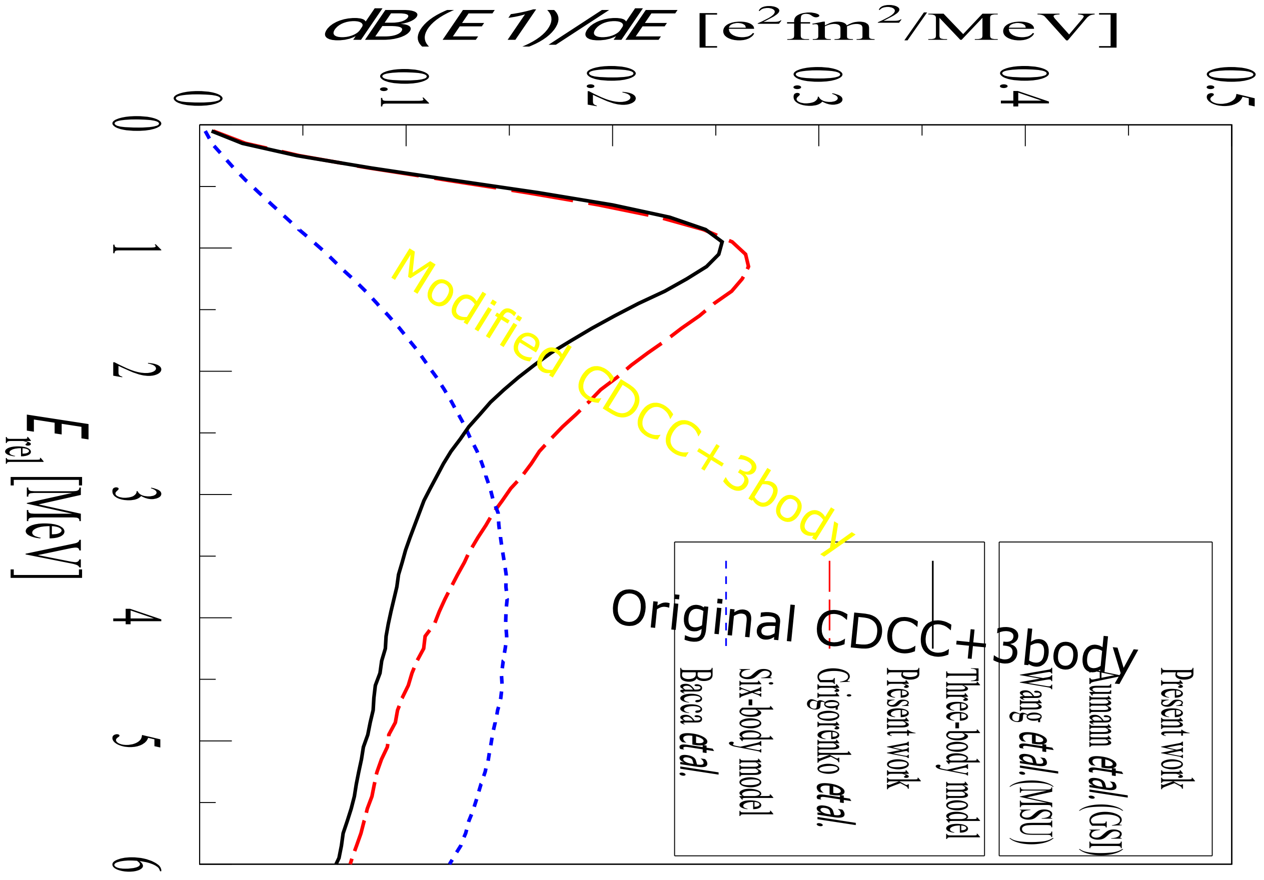
- No Target Excitation is assumed
- α-n interaction (Originally KKNN): modified
- Coupling between 1^- and 0^+ : modified

To reproduce data

Energy differential cross sections: Reproduced for a wide range of θ_{cm}

B(E1) and Dineutron correlation

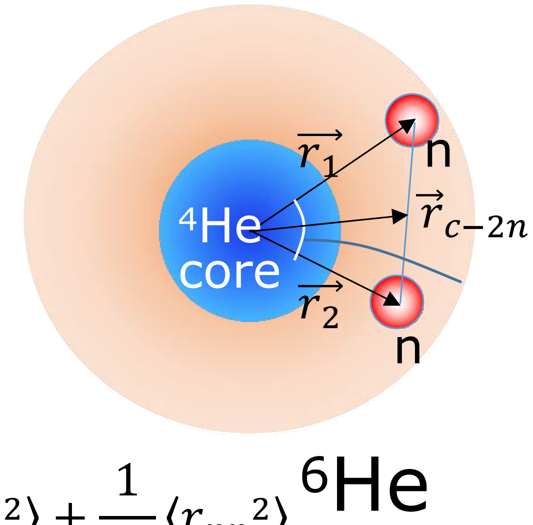
Y.L. Sun et al., PLB2021



Modified CDCC:

$$B(E1) = 1.6(2)\ e^2\mathrm{fm}^2$$

$$\sqrt{\langle r_{c-2n}{}^2\rangle} = 3.9(2)\ \mathrm{fm}$$



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

$$\sqrt{\langle r_{nn}{}^2\rangle} = 4.1(7)\ \mathrm{fm}$$

$$\langle\theta_{12}\rangle = 56^{+9}_{-10}\mathrm{deg.}$$

Original CDCC+Exact 3body model

$$B(E1) = 1.3\ e^2\mathrm{fm}^2$$

$$\langle\theta_{12}\rangle = 68\ \mathrm{deg.}$$

$\langle\theta_{12}\rangle < 90°$ → Dineutron correlation shown for ^{6}He(g.s.)

Interim Summary: Two-neutron halo nuclei

✓ Coulomb Breakup of ^{11}Li TN et al., Phys. Rev. Lett **96**,252502(2006).

- Coulomb Breakup of 2n halo nuclei → Need to Exclude Cross Talk in 2n detections
- B(E1)→ Three-body geometry of halo nucleus (gs)→$\langle r_{c-nn}{}^2\rangle$→$\langle\theta_{12}\rangle$ →dineutron

✓ Coulomb Breakup of ^{19}B K. J. Cook, TN et al.PRL124, 212503, 2020.

- B(E1) strength close to that of ^{11}Li→ Soft E1 Excitation → 2n halo nucleus
- Shape and Amplitude of B(E1) → $S_n \sim 0.5\mathrm{MeV}$, significant s-wave, dineutron

✓ Coulomb Breakup of ^{6}He Y.L. Sun, TN et al., PLB 814, 136072 (2021).

- Soft E1 Excitation→ Typical of Halo nucleus
- Analysis by full microscopic calculations (CDCC)
- B(E1)→Three-body geometry of ^{6}He → dineutron

T. Aumann, T. Nakamura, Physica Scripta T152, 014012 (2013).
T. Nakamura, Handbook of Nuclear Physics, https://doi.org/10.1007/978-981-15-8818-1_68-1

Some remarks on Soft E1 Excitation

- Soft Dipole Resonance or Direct Breakup (Non-resonant)?
  - ✓ 1n Halo Nuclei: **Direct Breakup**
  - ✓ 2n Halo Nuclei: **Most-Likely Direct Breakup** Affected by Strong Final State Interactions

    (For 2n Halo nuclei: **Resonance possibility is not fully excluded)**
- Soft Resonance?
  - ✓ **Low-lying Resonance-like Structure:** observed for ^{11}Li by (p,p') (d,d') reactions

^{11}Li (p,p') J. Tanaka et al., Phys. Lett. B 774, 268–272 (2017).
^{11}LI(d,d') R.Kanungo et al., Phys. Rev. Lett. 114, 192502 (2015).

Summary of E1 Response-Normal/N-skin/N-Halo nuclei