Spectroscopy of *p*-wave neutron halo nuclei via neutron removal reactions

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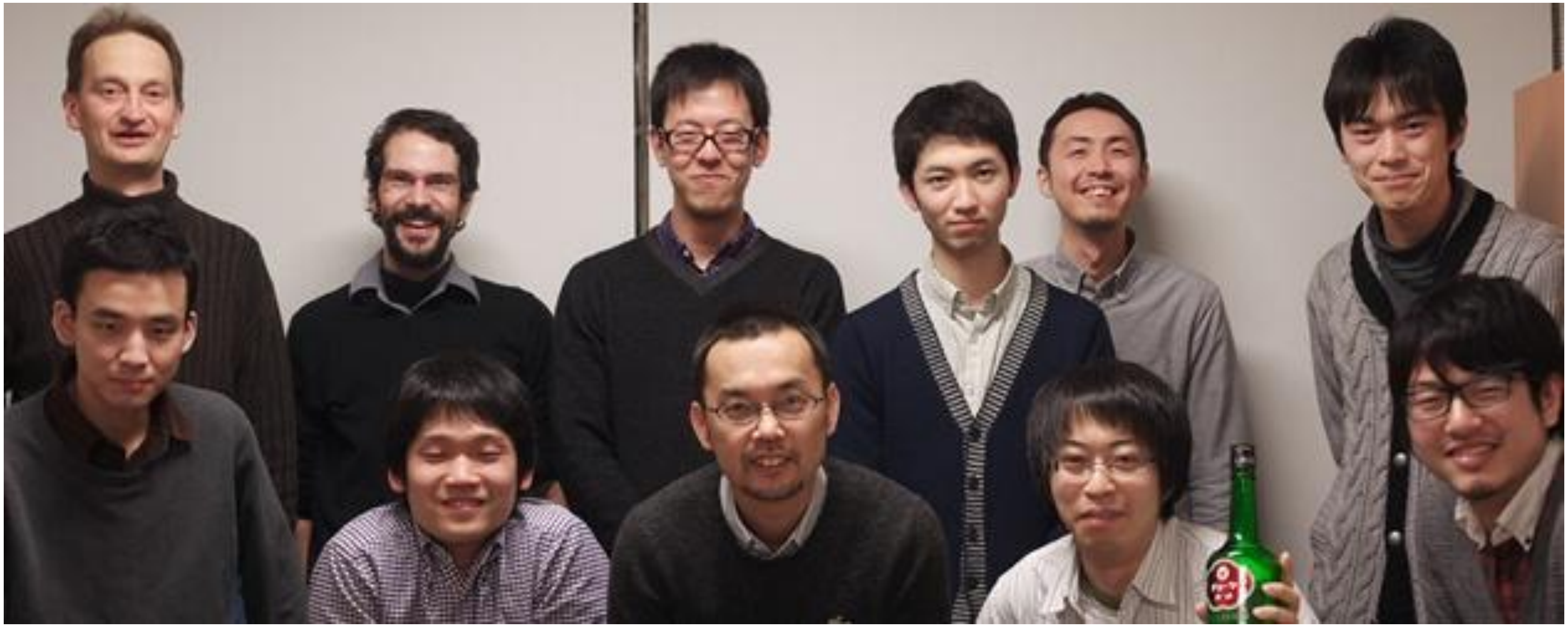
Collaborators

NAKAMURA GRP.

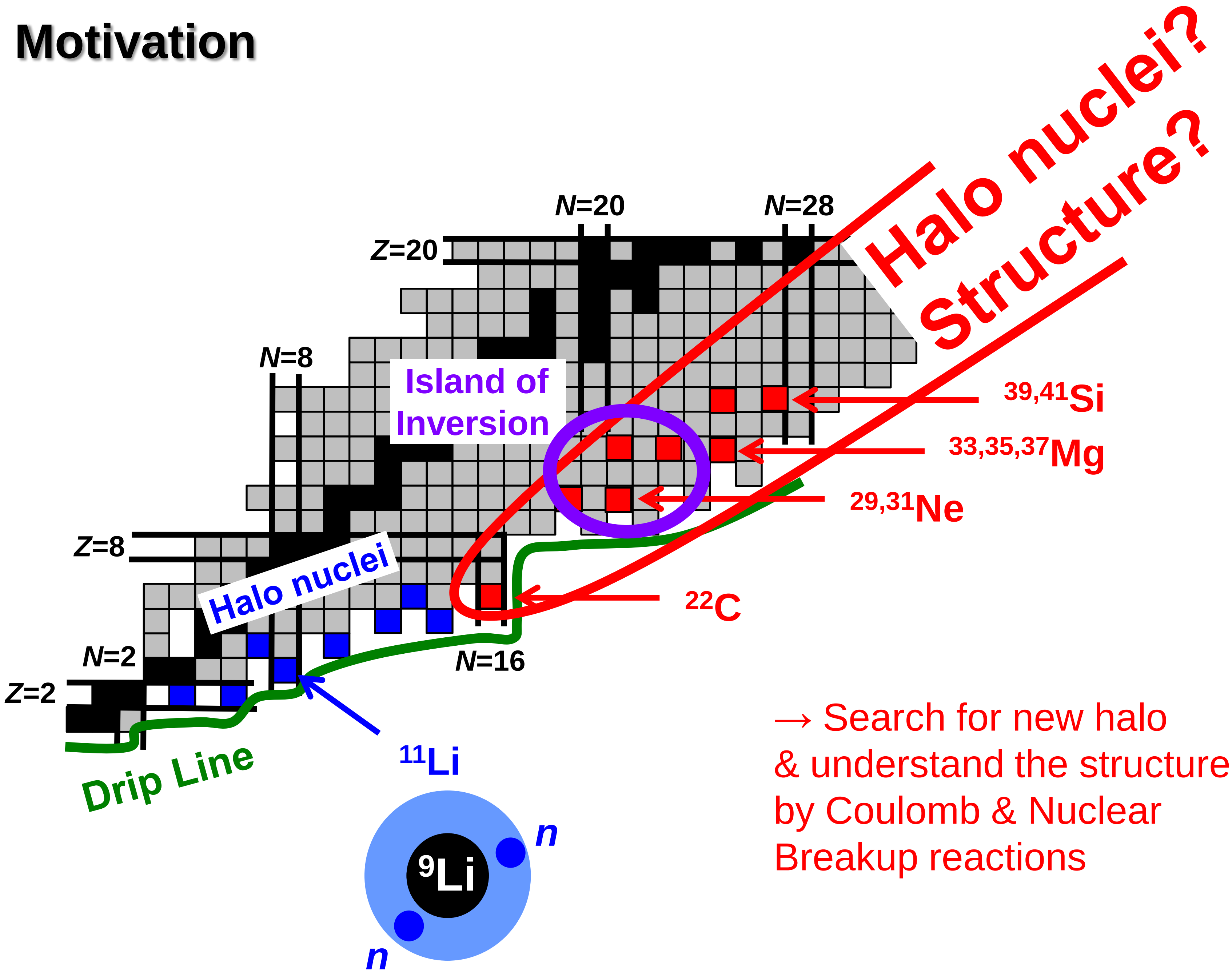


N. Kobayashi, T. Nakamura, Y. Kondo, J.A. Tostevin, N. Aoi, H. Baba, S. Deguchi, N. Fukuda, J. Gibelin, G. S. Lee, H. S. Lee, N. Inabe, M. Ishihara, Y. Kawada, K. Rituparna, T. Kubo, F. Michael, M. Matsushita, T. Motobayashi, T. Onishi, N. A. Orr, H. Otsu, R. Barthelemy, H. Sakurai, E. C. Simpson, S. Kim, T. Sako, T. Sumikama, Y. Satou, K. Takahashi, H. Takeda, M. Takechi, S. Takeuchi, R. Tanaka, N. Tanaka, Y. Togano, K. Yoneda

Outline

- Introduction
  - Motivation
  - Halo nuclei
  - Coulomb breakup reaction
  - Momentum distribution $d\sigma/dP_{//}$
- Experimental setup
  - Targets & detectors
- Results
  - Inclusive breakup cross sections
  - Focus on ^{31}Ne & ^{37}Mg
- Summary

Motivation

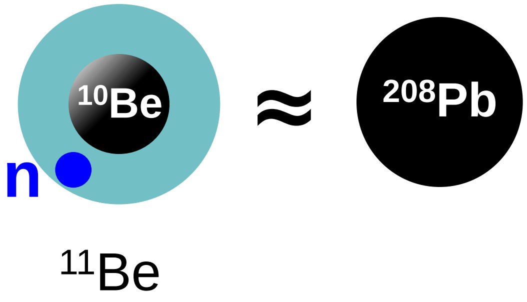


→ Search for new halo & understand the structure by Coulomb & Nuclear Breakup reactions

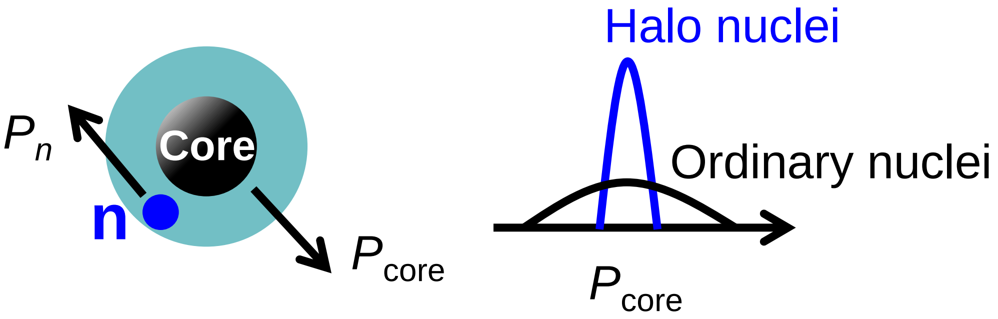
Characteristic features of Halo Nuclei (I)

Large radius

Spatially extended wave function
of a valence neutron
→ Large reaction cross section

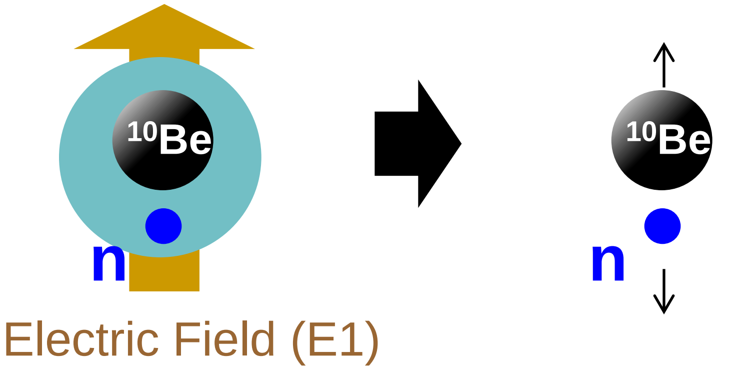


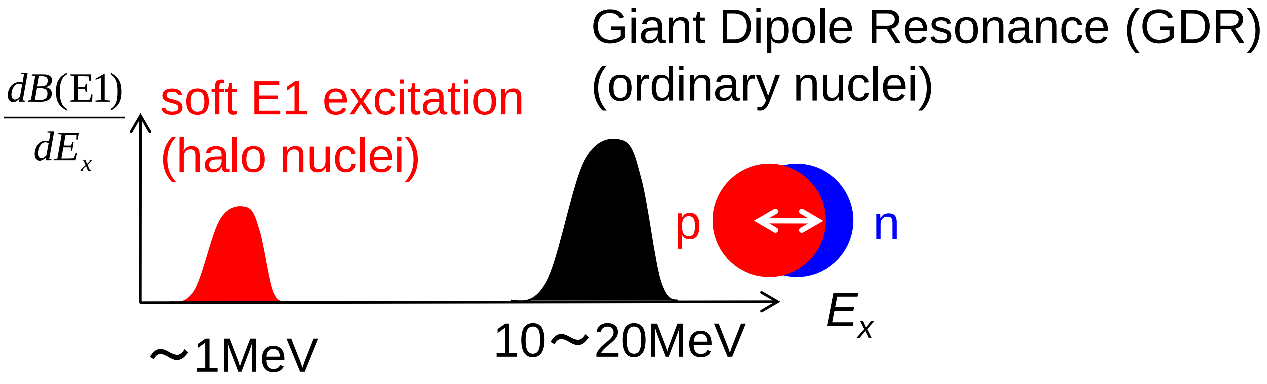
Narrow momentum
distribution of a core



Characteristic features of Halo Nuclei (2)

Large E1 (Electric dipole) strength





Conditions of halo formation

Low separation energy (S_n)

$S_n \lesssim 1\text{MeV} << 8\text{MeV}$

Ordinary nuclei

Low angular momentum (Low-ℓ) of the valence neutron

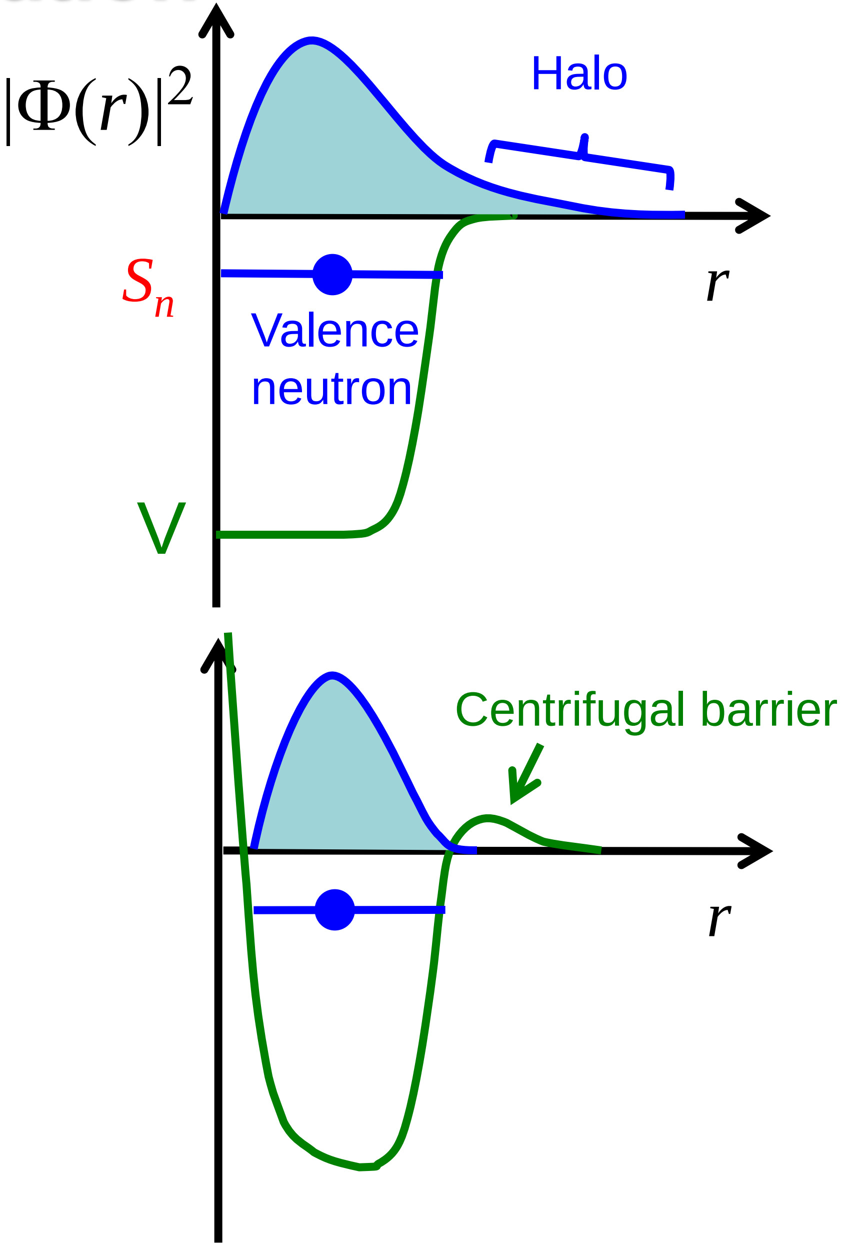
$\ell = 0$: *s*-wave neutron
$\ell = 1$: *p*-wave neutron

Halo

$\ell = 2$: *d*-wave neutron
$\ell = 3$: *f*-wave neutron
$\ell >= 4$

No halo

Determination of ℓ and S_n is crucial



(The r.m.s. radius diverges only for *s- and p*-wave at S_n= 0MeV)

Coulomb breakup -- Method to extract E1 strength

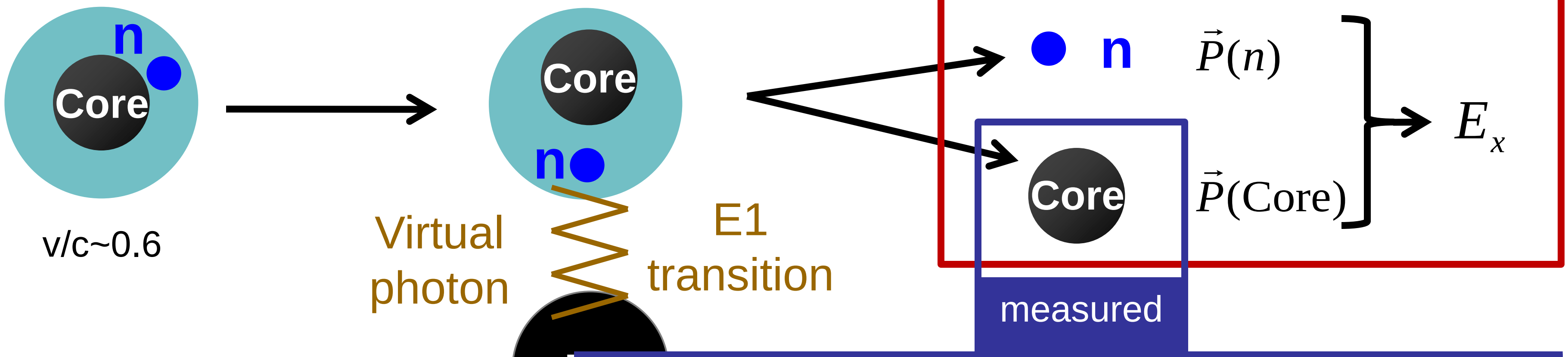
Exclusive Coulomb breakup

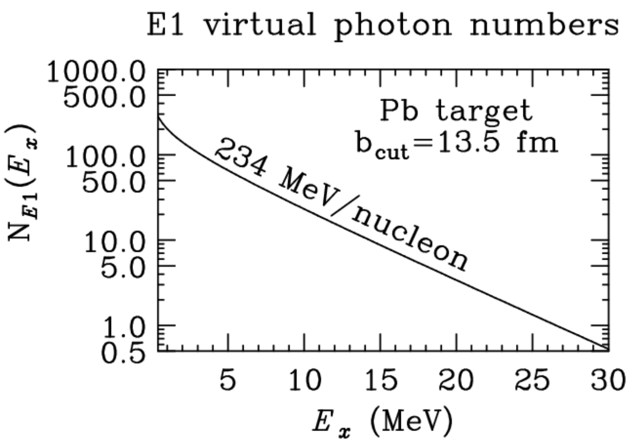
$$\underline{\underline{\frac{d\sigma(E1)}{dE_x}}} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \underline{\underline{\frac{dB(E1)}{dE_x}}}$$

measured ⟶ extracted

Required beam intensity > ~ 100 cps

Invariant mass method





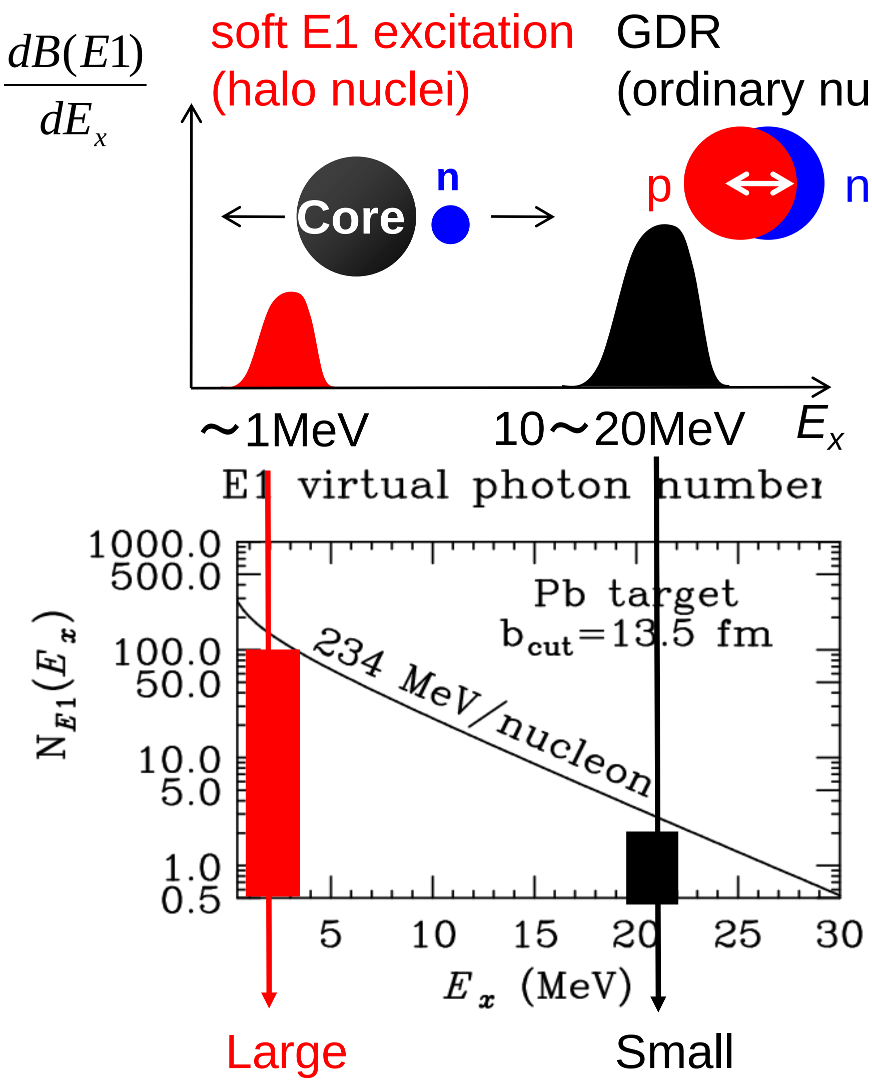
Inclusive Coulomb breakup (this work)

$$\underline{\underline{\sigma_{-1n}(E1)}} = \int_{S_{1n}}^{S_{2n}} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dE_x$$

measured

Feasible even with a few cps

Inclusive σ_{-1n} (*E*1) of halo nuclei



soft E1 excitation
(halo nuclei)

GDR
(ordinary nuclei)

Large

Small

$$N_{E1}(E_x) \times \frac{dB(E1)}{dE_x}$$

Coulomb breakup cross section

$$\sigma_{-1n}(E1) = \int_{S_{1n}}^{S_{2n}} \frac{16\pi^3}{9\hbar c} \underline{N_{E1}(E_x) \frac{dB(E1)}{dE_x}} dE_x$$

halo nuclei ➡ σ_{-1n}(*E*1) is large
($\gtrsim$ 500 mb)

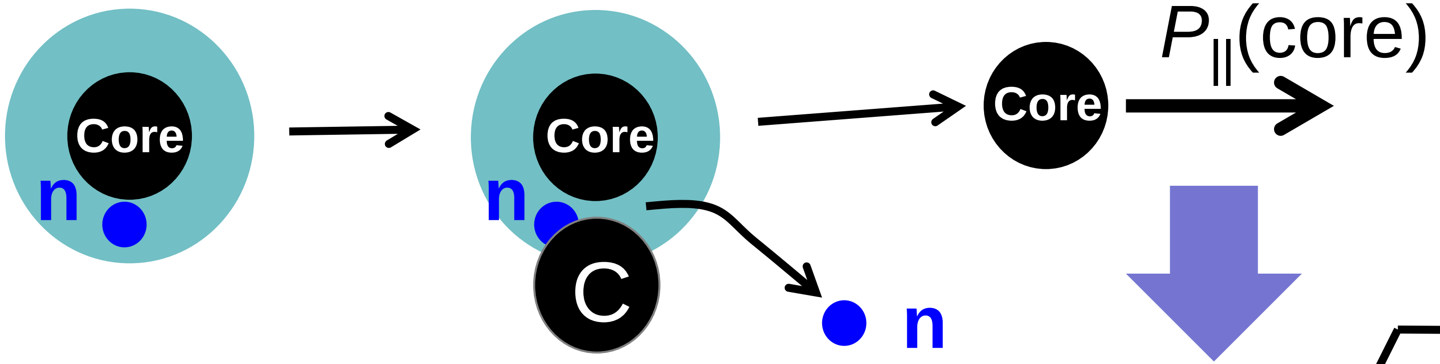
ordinary nuclei ➡ σ_{-1n}(*E*1) is small
(≈ 100 mb)

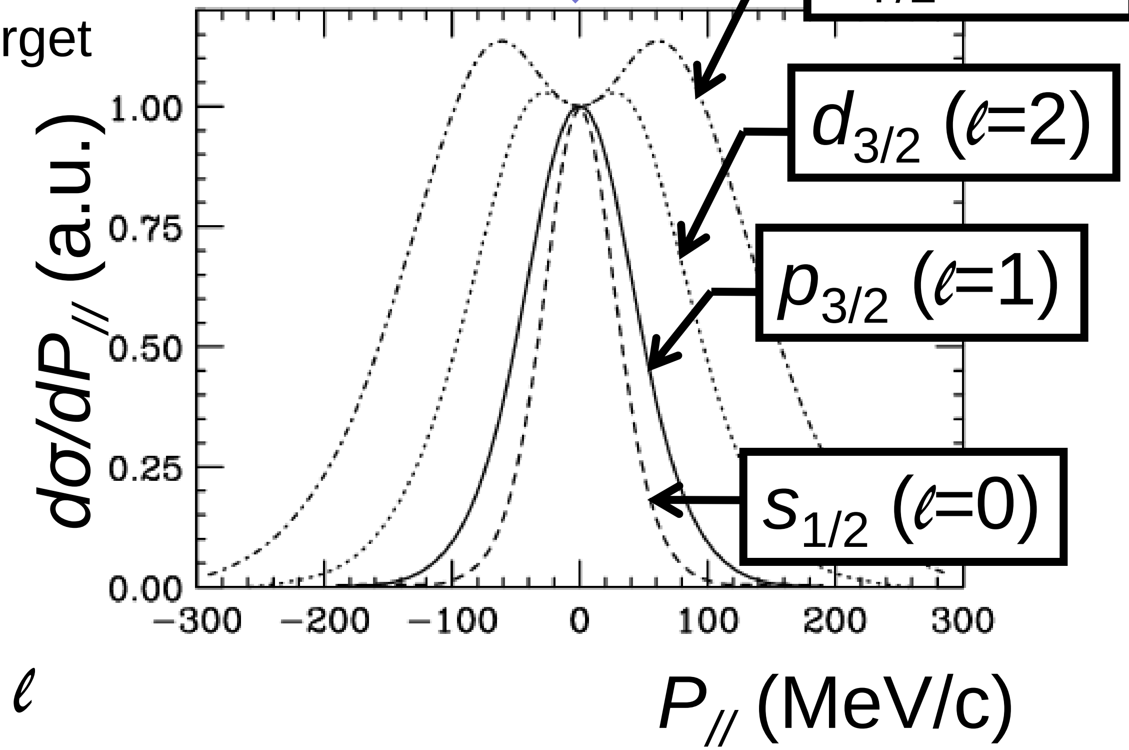
Signature of halo structure from Coulomb breakup

T.Kobayashi *et al.*, PLB **232**, 51 (1989).

$P_{//}$ distribution for nuclear breakup

-- Method to extract the valence neutron orbital ℓ



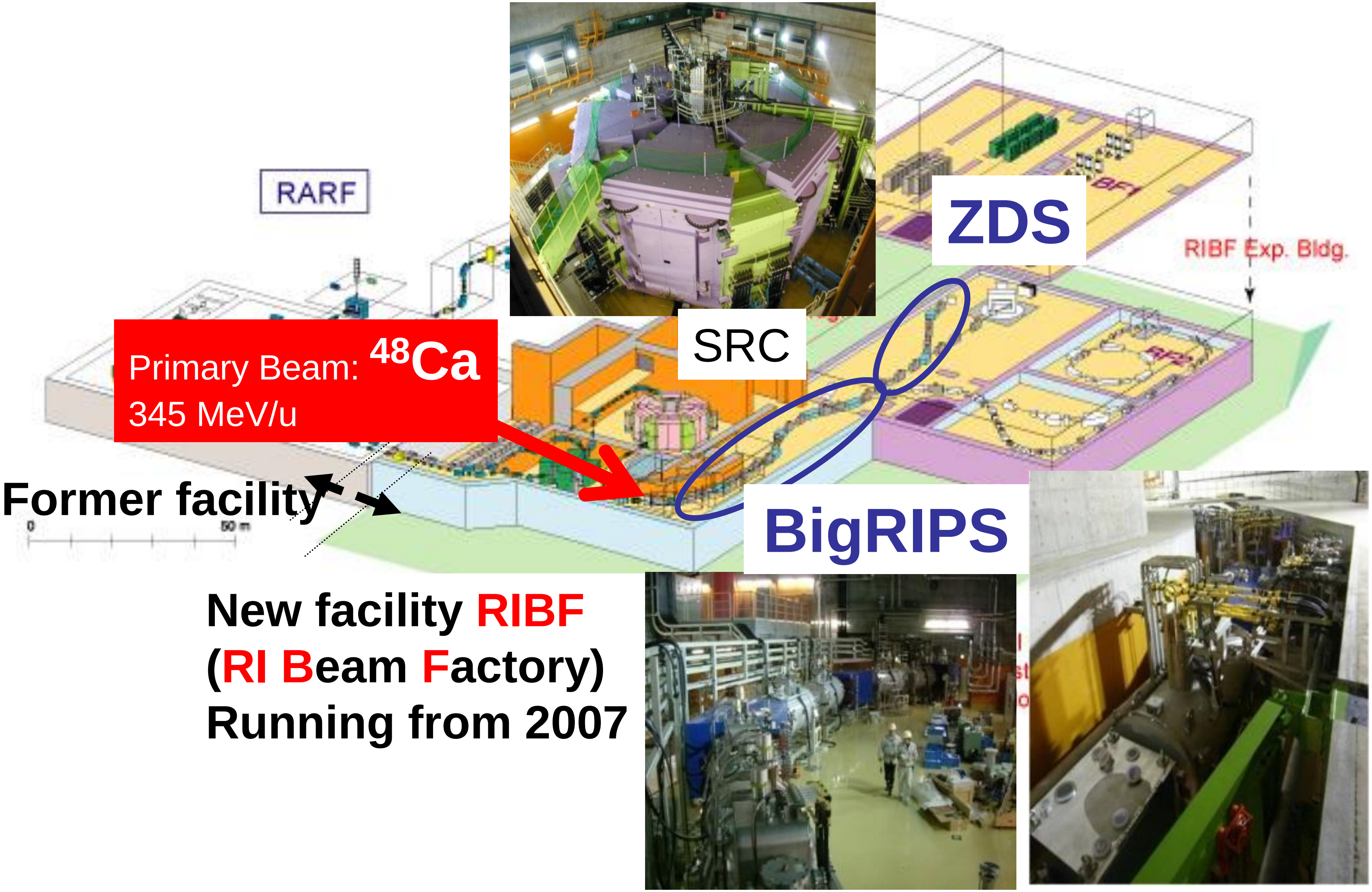


$$|\text{Proj.}\rangle = |\text{Core}\otimes\varphi_{nlj}\rangle$$

$P_{//}$ distribution

→ Angular momentum ℓ
of the valence neutron

RI Beam Factory @ RIKEN



ZDS

SRC

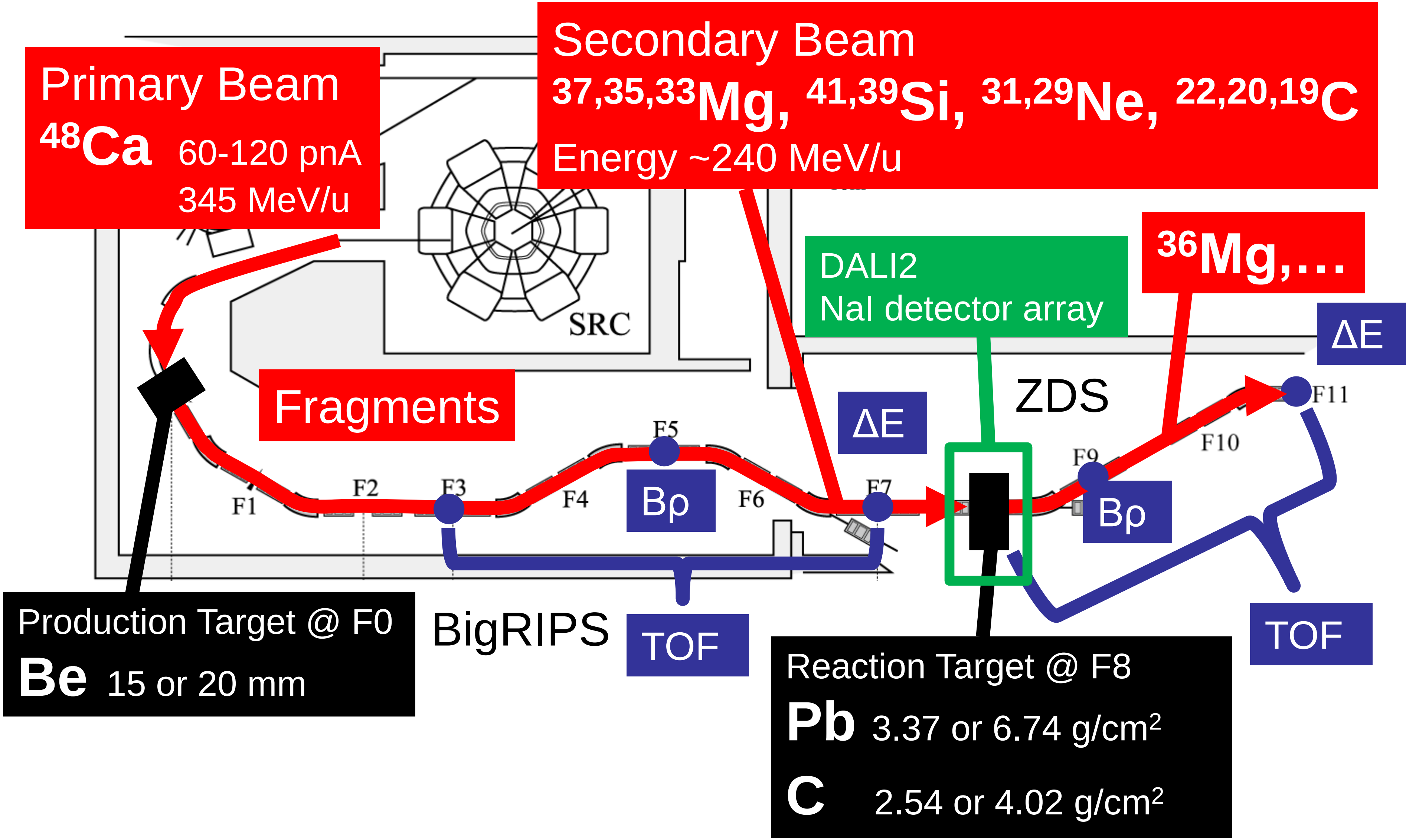
Primary Beam: ^{48}Ca
345 MeV/u

Former facility

BigRIPS

New facility RIBF
(RI Beam Factory)
Running from 2007

Experimental setup



Primary Beam

^{48}Ca 60-120 pnA

345 MeV/u

Secondary Beam

^{37,35,33}Mg, ^{41,39}Si, ^{31,29}Ne, ^{22,20,19}C

Energy ~240 MeV/u

DALI2

NaI detector array

^{36}Mg,…

ΔE

ΔE

ZDS

Fragments

Bρ

Bρ

BigRIPS

TOF

TOF

Production Target @ F0

Be 15 or 20 mm

Reaction Target @ F8

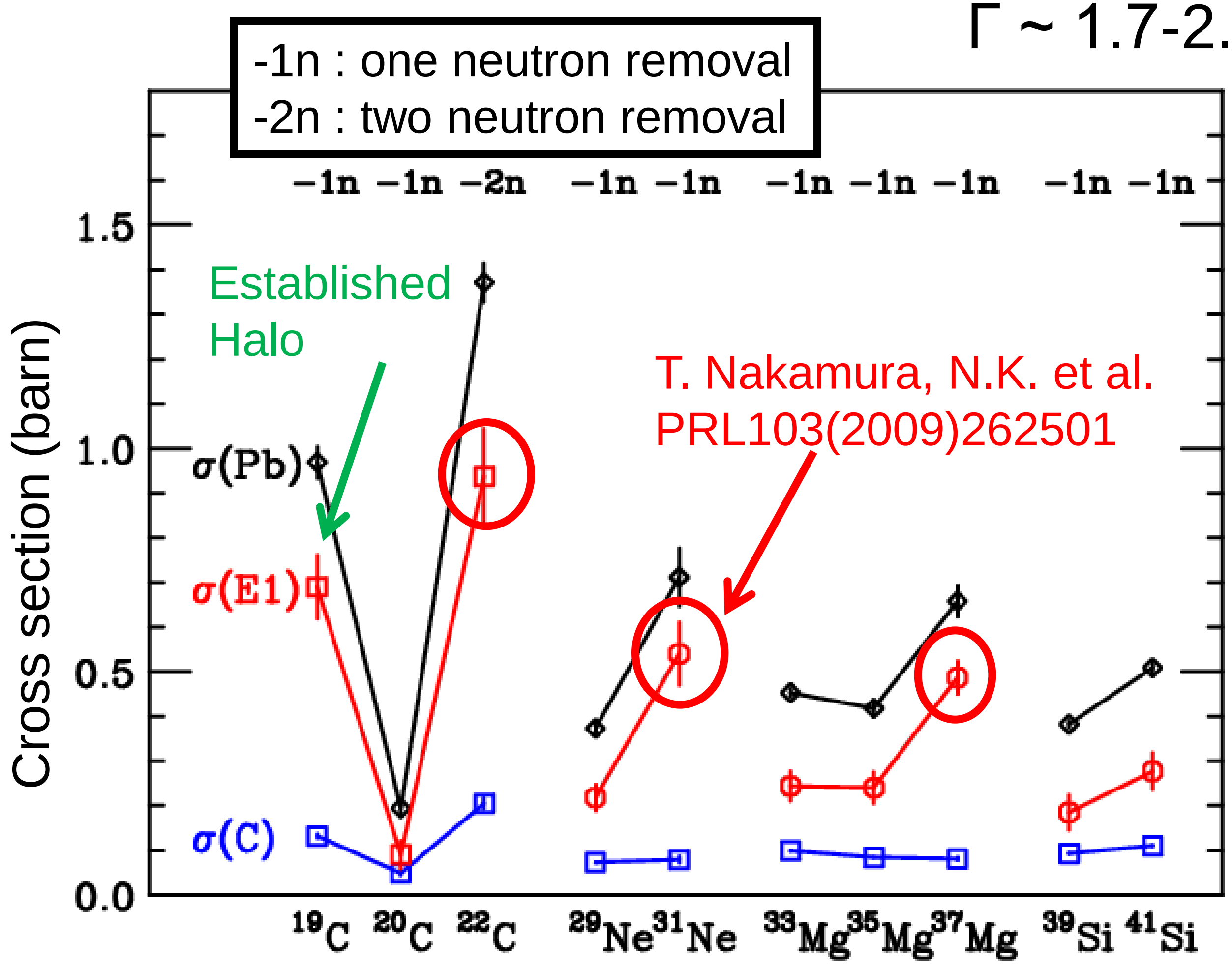
Pb 3.37 or 6.74 g/cm^2

C 2.54 or 4.02 g/cm^2

Results

σ(E1) = σ(Pb) – Γσ(C)

Γ ~ 1.7-2.6


-1n : one neutron removal

-2n : two neutron removal

Established Halo

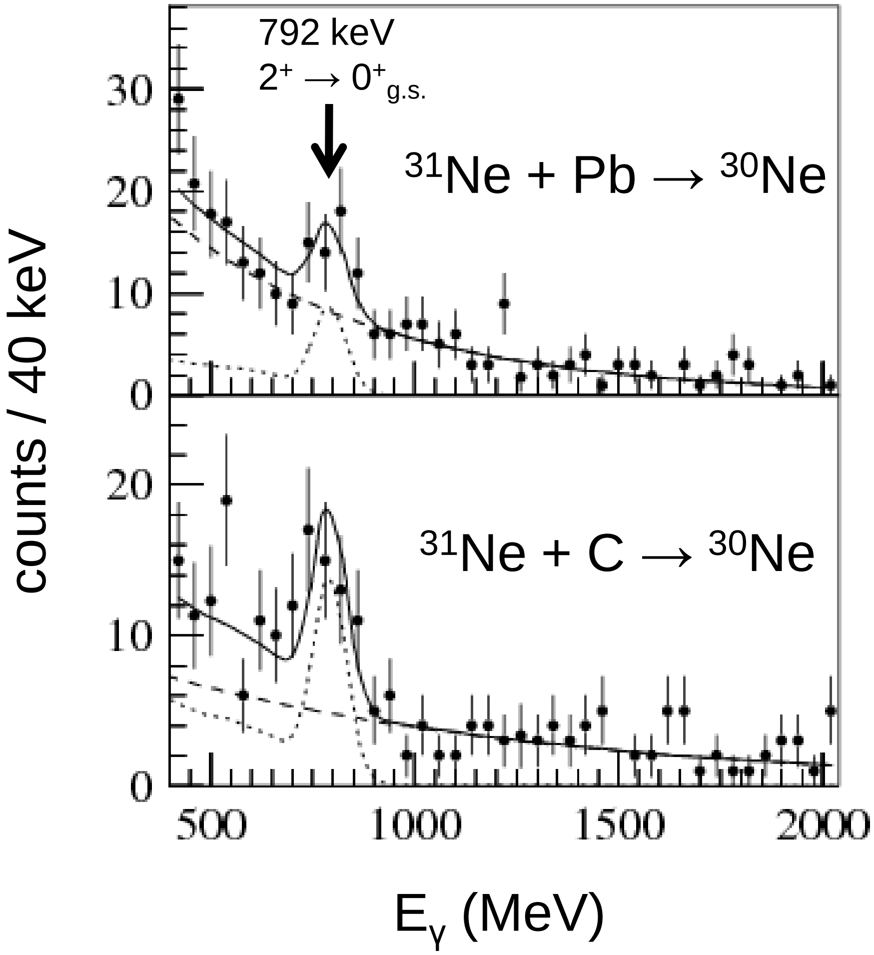
T. Nakamura, N.K. et al. PRL103(2009)262501

Large σ(E1) of ^{22}C, ^{31}Ne, and ^{37}Mg → halo structure

^{22}C total reaction cross section : K. Tanaka et al. PRL104(2010)062701

^{31}Ne total reaction cross section : M. Takechi et al. PLB707(2012)357

Partial cross sections $^{31}\mathrm{Ne} \rightarrow {}^{30}\mathrm{Ne}(0^{+}_{\mathrm{g.s.}})$



Fitted with a response function (GEANT4)
+ an exponential background

Y. Yanagisawa *et al.*, PLB **232566**, 84 (2003)

Inclusive $\sigma_{-1n}(\mathrm{E1})$ = () mb
$\sigma_{-1n}(\mathrm{E1}; 2^{+}, 4^{+}, \mathrm{etc.})$ = () mb
→ $\sigma_{-1n}(\mathrm{E1}; 0^{+}_{\mathrm{g.s.}})$ = () mb

$0^{+}_{\mathrm{g.s.}}$ / Inclusive = 85%

Inclusive $\sigma_{-1n}(\mathrm{C})$ = () mb
$\sigma_{-1n}(\mathrm{C}; 2^{+}, 4^{+}, \mathrm{etc.})$ = () mb
→ $\sigma_{-1n}(\mathrm{C}; 0^{+}_{\mathrm{g.s.}})$ = () mb

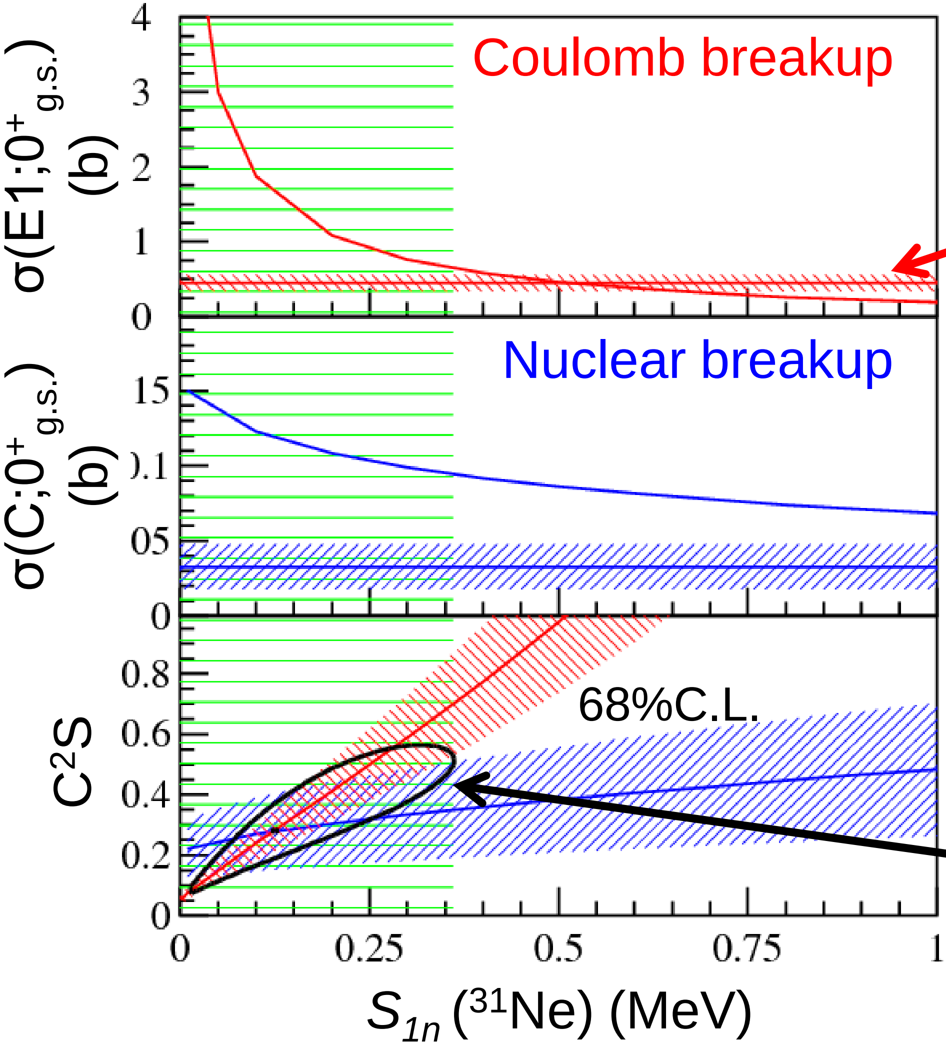
$0^{+}_{\mathrm{g.s.}}$ / Inclusive = 37%

$|{}^{30}\mathrm{Ne}(0^{+}_{\mathrm{g.s.}}) \otimes \varphi_{nlj}\rangle$ in $^{31}\mathrm{Ne}_{\mathrm{g.s.}}$
Only one s. p. oribital can
couple to $^{30}\mathrm{Ne}(0^{+}_{\mathrm{g.s.}})$
theo. & exp. $\sigma_{-1n}(0^{+}_{\mathrm{g.s.}})$
→ $C^{2}S$ of s. p. orbital and S_{n}

Combined analysis
-- Estimation of C^2S & S_{1n} of ^{31}Ne

S_{1n} (^{31}Ne)=-0.06(0.42) MeV

Channel: $^{31}\mathrm{Ne}(3/2^-) \rightarrow {}^{30}\mathrm{Ne}(0^+_{\mathrm{g.s.}}) + 2p_{3/2}$



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

Theoretical calc. for

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

(C^2S = 1)

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

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

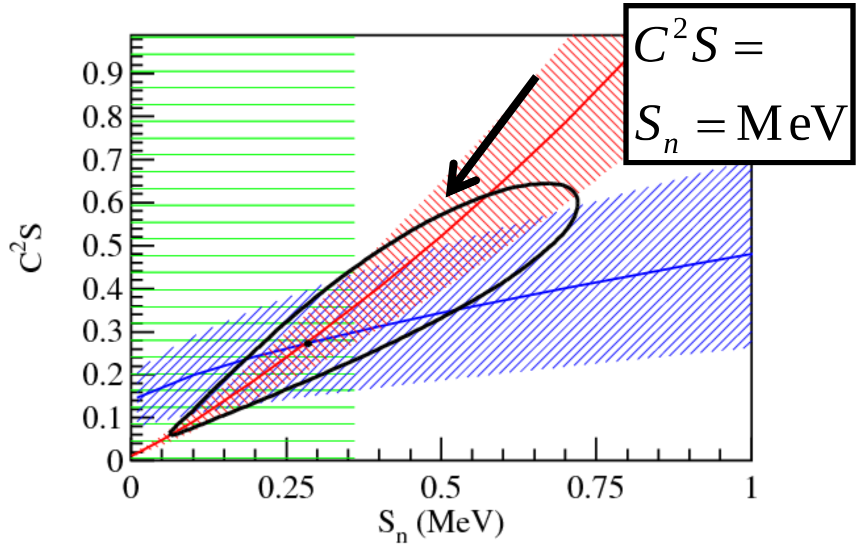
= Exp. / Theo.(C^2S=1)

For $p_{3/2}$

$$\boxed{\begin{array}{l} C^2S = \\ S_{1n} = \mathrm{MeV} \end{array}}$$

All possible configurations

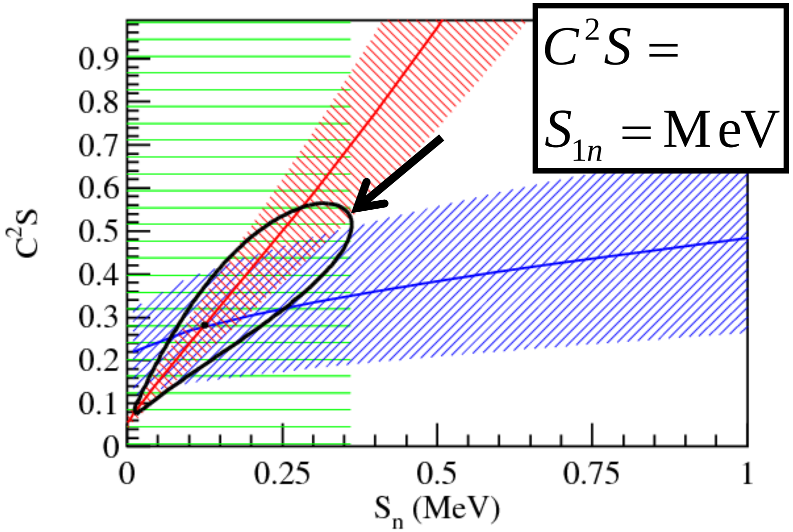
$|^{30}\mathrm{Ne}(0^{+})\otimes 2s_{1/2}\rangle \; J^{\pi} = 1/2^{+}$



$C^{2}S =$

$S_{n} = \mathrm{MeV}$

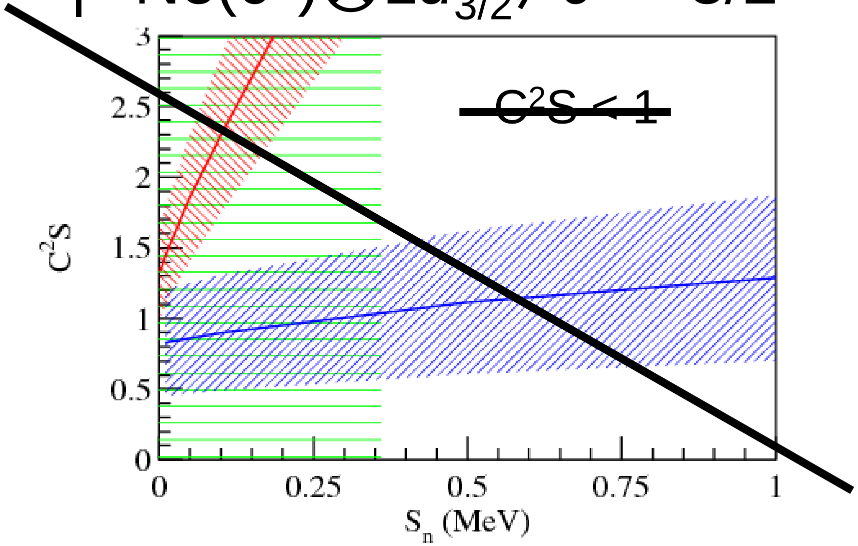
$|^{30}\mathrm{Ne}(0^{+})\otimes 2p_{3/2}\rangle \; J^{\pi} = 3/2^{-}$



$C^{2}S =$

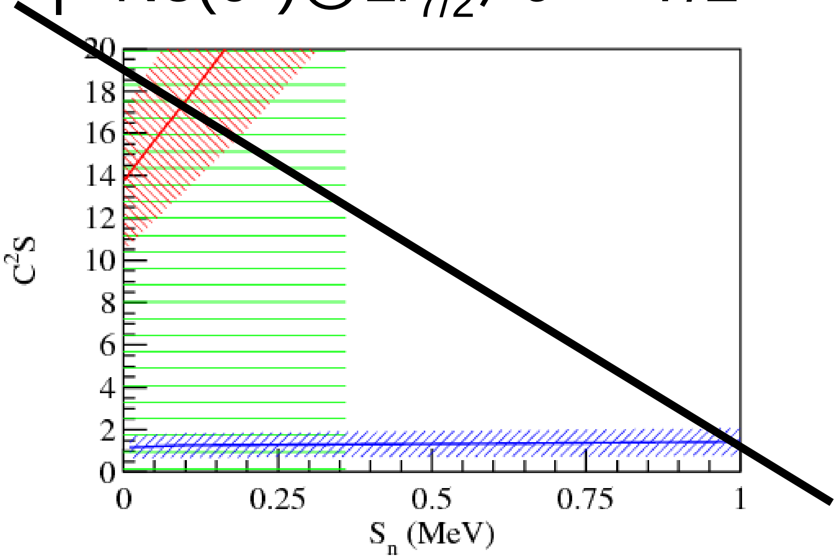
$S_{1n} = \mathrm{MeV}$

$|^{30}\mathrm{Ne}(0^{+})\otimes 1d_{3/2}\rangle \; J^{\pi} = 3/2^{+}$



~~$C^{2}S < 1$~~

$|^{30}\mathrm{Ne}(0^{+})\otimes 1f_{7/2}\rangle \; J^{\pi} = 7/2^{-}$



Inclusive momentum distribution of ^{30}Ne fragment (C target)

Shell Model w/ SDPF-M for $J^{\pi} = 3/2^{-}_{\mathrm{g.s.}}$

Lines : eikonal model

sum

State	C^2S	σ(mb)
$\lvert {}^{30}\mathrm{Ne}\otimes s\rangle$	0.09	3.0
$\lvert {}^{30}\mathrm{Ne}\otimes p\rangle$	0.55	46
$\lvert {}^{30}\mathrm{Ne}\otimes d\rangle$	1.33	26
$\lvert {}^{30}\mathrm{Ne}\otimes f\rangle$	0.80	19
	total Exp.	93 mb () mb

State	C^2S
$\lvert {}^{30}\mathrm{Ne}(0^{+}_{\mathrm{g.s.}})\otimes 2p_{3/2}\rangle$	0.21
$\lvert {}^{30}\mathrm{Ne}(2^{+}_{1})\otimes 2p_{3/2}\rangle$	0.27

→ Combined analysis:

$^{31}\mathrm{Ne}_{\mathrm{g.s.}}(3/2^{-})$ is supported

Inclusive momentum distribution of ^{30}Ne fragment (C target)

Shell Model w/
SDPF-M for $J^{\pi} = 1/2^{+}$

State	C^2S	σ(mb)
$\lvert {}^{30}\mathrm{Ne}\otimes s\rangle$	0.11	4.9
$\lvert {}^{30}\mathrm{Ne}\otimes p\rangle$	0.25	9.6
$\lvert {}^{30}\mathrm{Ne}\otimes d\rangle$	0.55	13
$\lvert {}^{30}\mathrm{Ne}\otimes f\rangle$	1.1	24

total 51 mb
Exp. () mb

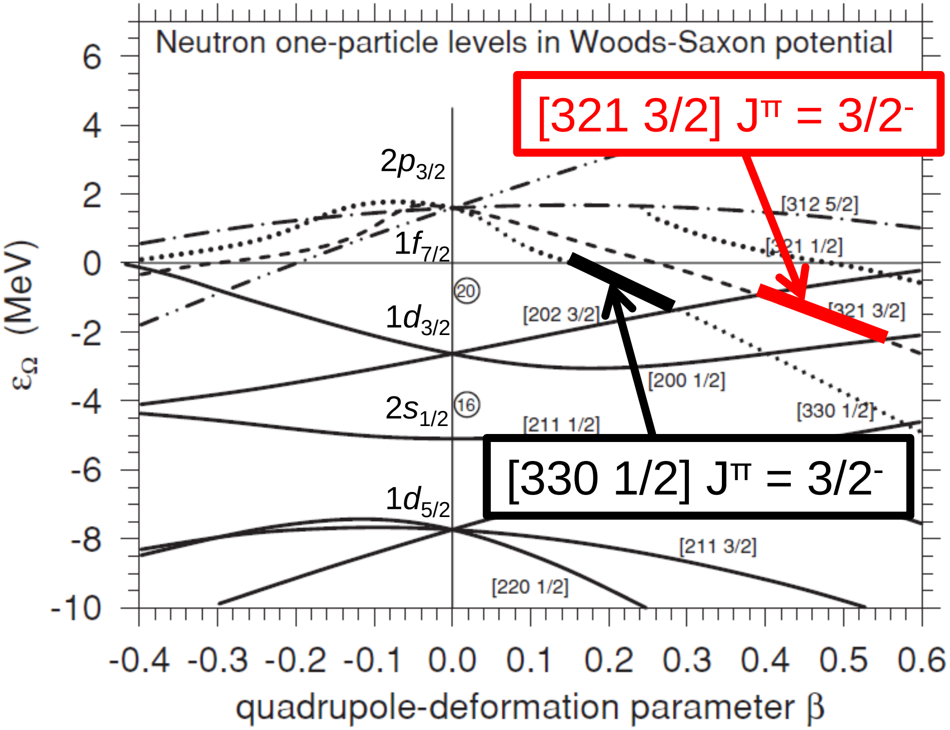
$^{31}\mathrm{Ne}_{\mathrm{g.s.}}(1/2^{+})$ is rejected

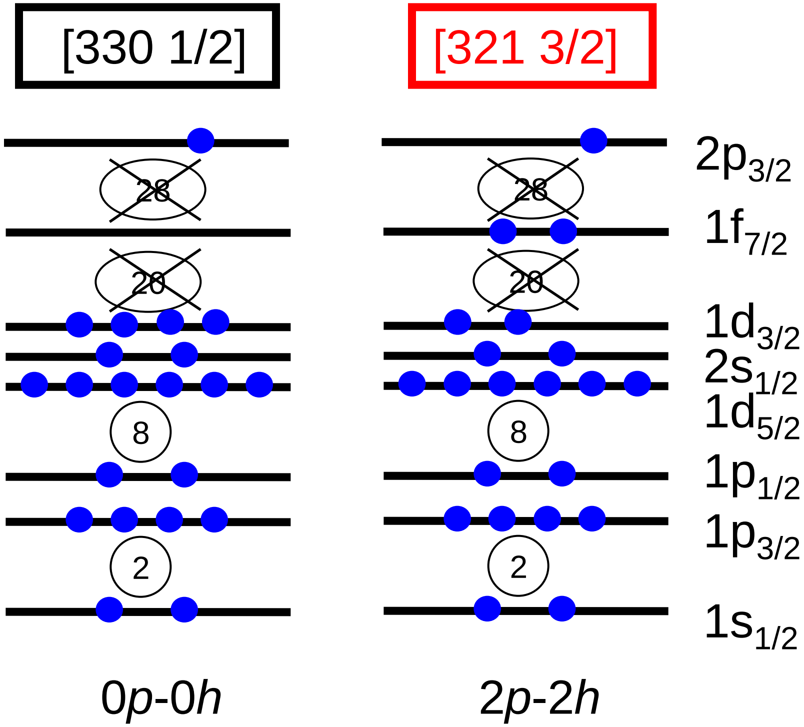
$^{31}\mathrm{Ne}_{\mathrm{g.s.}} \rightarrow J^{\pi} = 3/2^{-}$

Deformation of ^{31}Ne(3/2$^-$)

Nilsson diagram : single particle levels in deformed nucleus

^{31}Ne(3/2$^-$) N = 21





0.16 < β < 0.30 or

0.40 < β < 0.58

Prolate deformation of ^{31}Ne(**3/2**$^-$)

Mixing of *p* and *f* orbitals

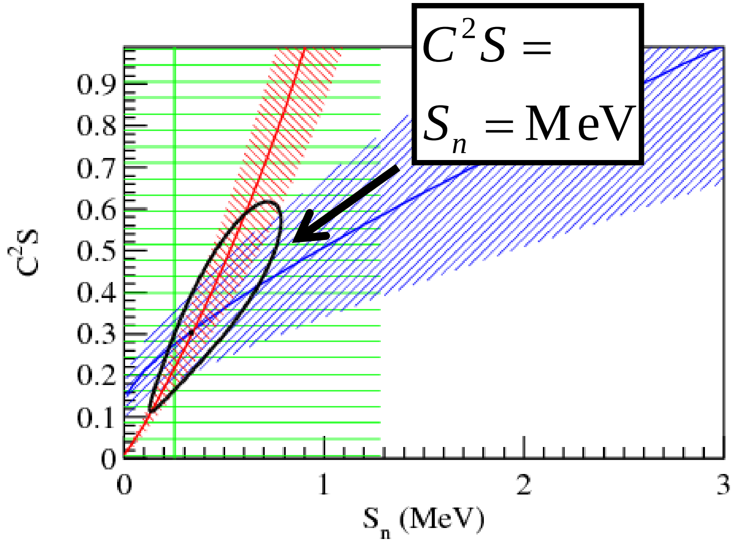
p-wave neutron halo

~~*N* = 20, 28 shell closer~~

I. Hamamoto, PRC**76**(2007)054319.

All possible configurations (^{37}Mg)

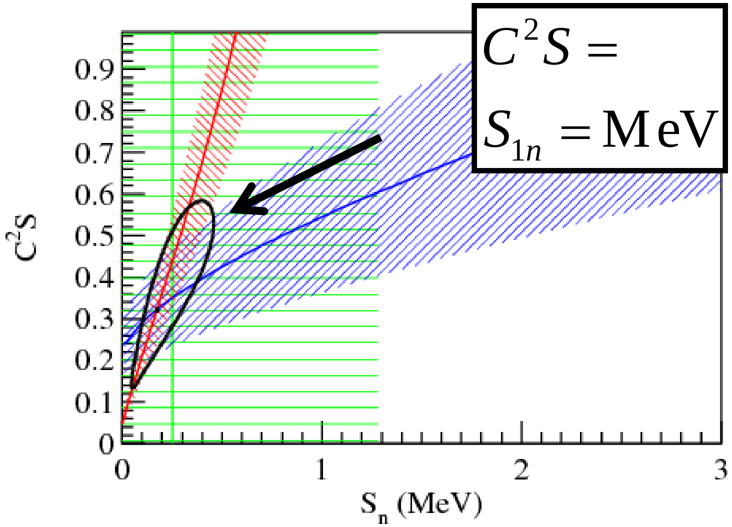
$|{}^{36}\text{Mg}(0^+_{\text{g.s.}}) \otimes 2s_{1/2}\rangle$



$C^2S =$

$S_n = \text{MeV}$

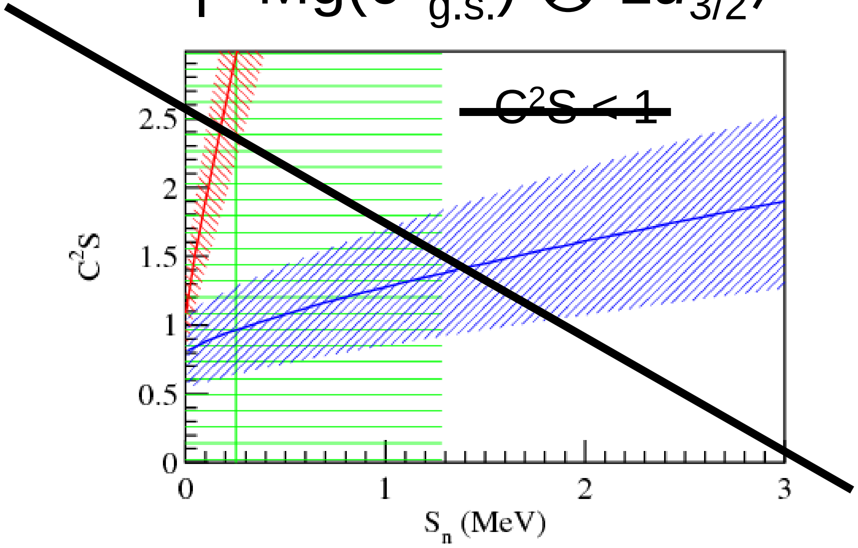
$|{}^{36}\text{Mg}(0^+_{\text{g.s.}}) \otimes 2p_{3/2}\rangle$



$C^2S =$

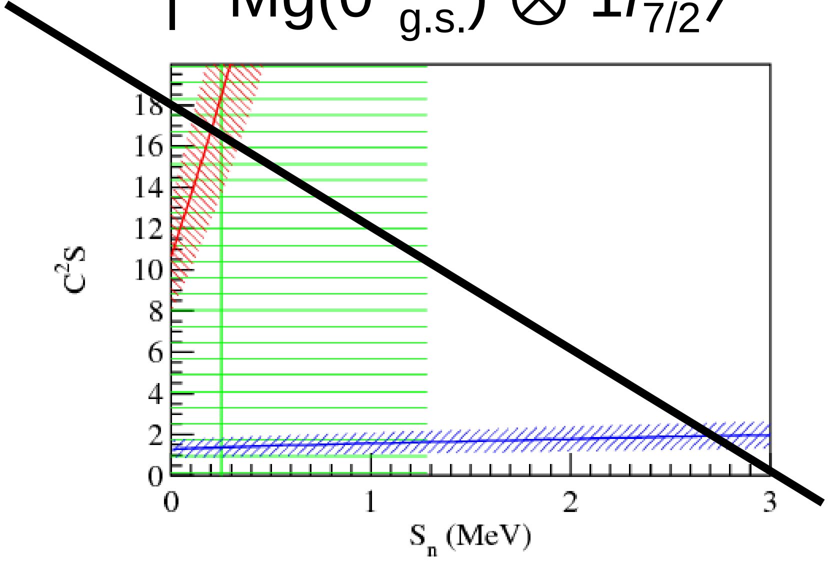
$S_{1n} = \text{MeV}$

$|{}^{36}\text{Mg}(0^+_{\text{g.s.}}) \otimes 1d_{3/2}\rangle$



~~$C^2S < 1$~~

$|{}^{36}\text{Mg}(0^+_{\text{g.s.}}) \otimes 1f_{7/2}\rangle$

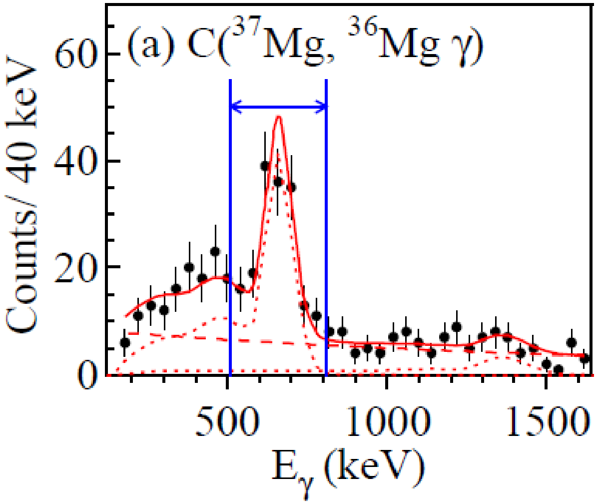


Inclusive momentum distribution of ^{36}Mg fragment (C target)

Shell Model w/ SDPF-M + $p_{1/2}$

large *p*-component
→ *p*-wave neutron halo

$^{37}\mathrm{Mg}_{\mathrm{g.s.}} \rightarrow J^{\pi} = 3/2^{-}$
($1/2^{-}$ is not rejected)

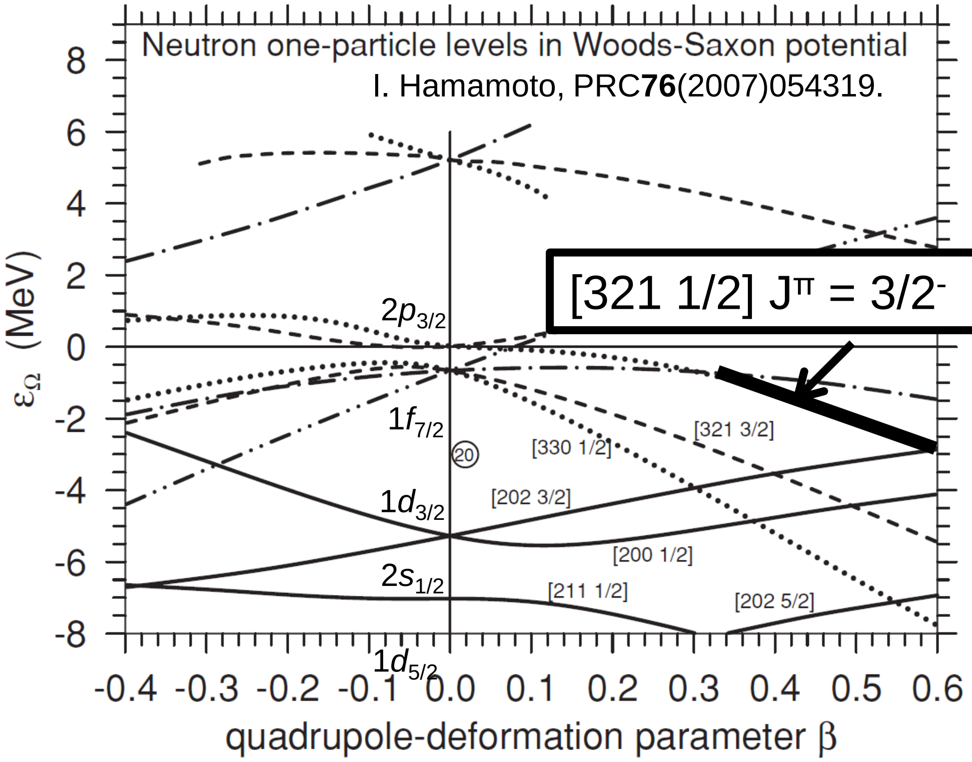


Inclusive

Populating excited states

Deformation of ^{37}Mg(3/2$^-$)

^{37}Mg(**3/2**$^-$) N = 25

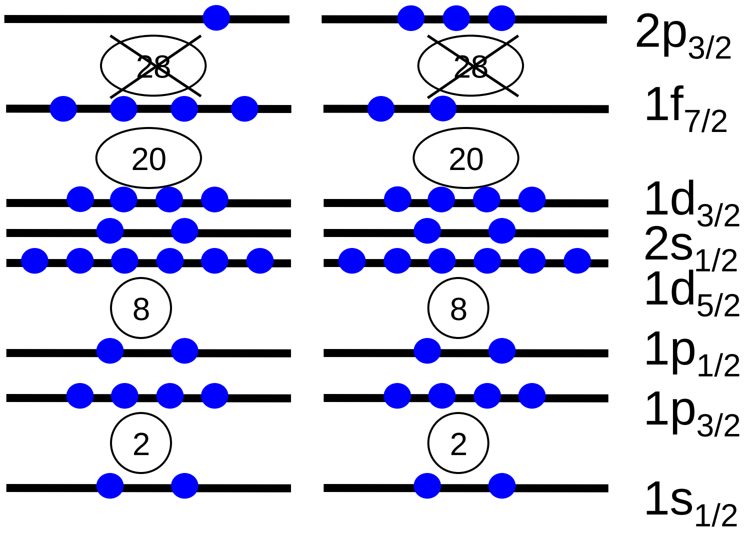


Neutron one-particle levels in Woods-Saxon potential

I. Hamamoto, PRC**76**(2007)054319.

$0.32 < \beta < 0.6$

[321 1/2] J$^\pi$ = 3/2$^-$

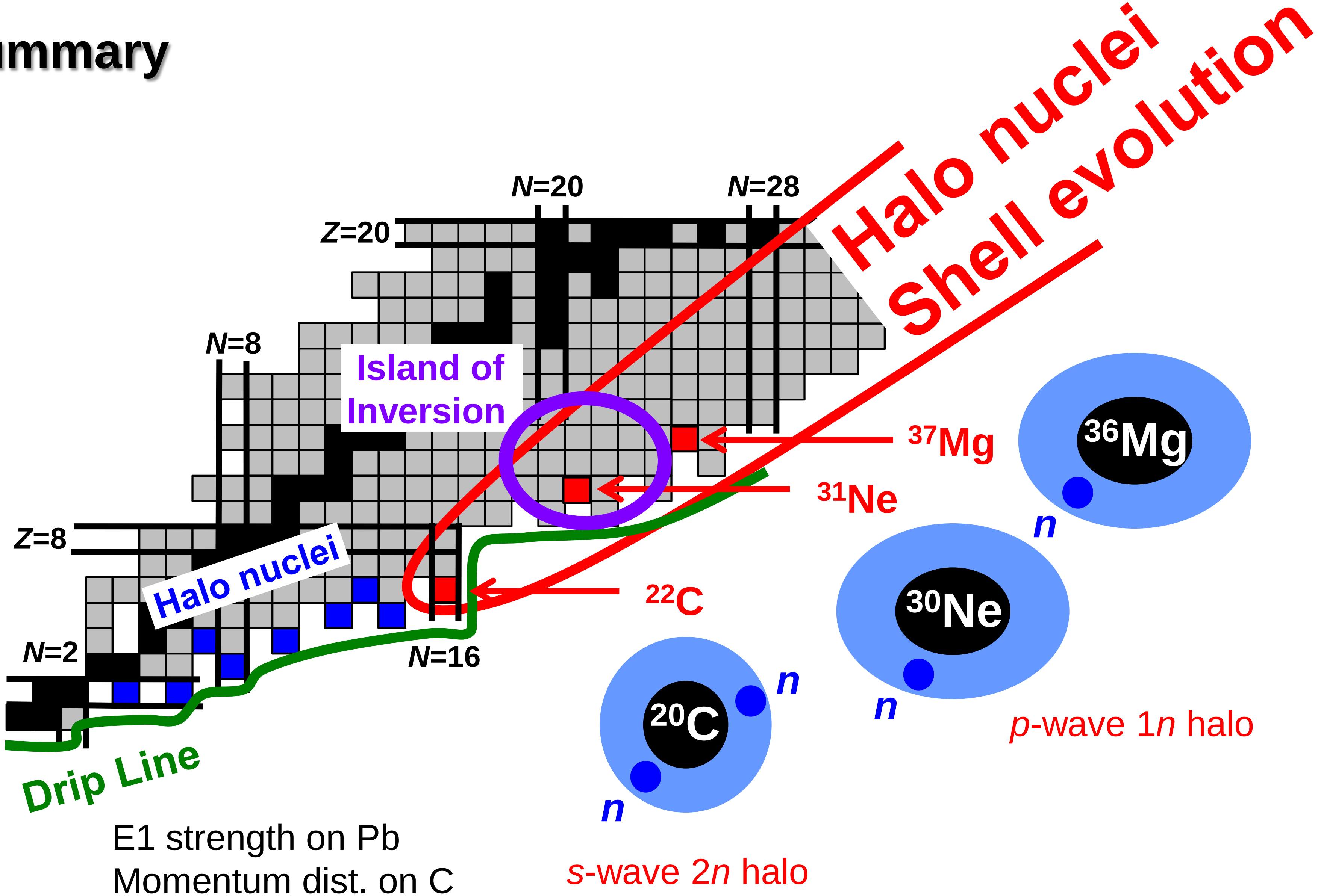


0*p*-0*h*

Prolate deformation in ^{37}Mg(**3/2**$^-$)

~~*N* = 28 shell closer~~ **Deformed *p*-wave halo**

Summary



E1 strength on Pb
Momentum dist. on C
→ S_n, J^π, C^2S
→ *p*-wave neutron (deformed) halo nuclei & their structure
→ Halo nuclei can be common on the drip line

Thank you.

^{37}Mg, N = 25, SDPF-M

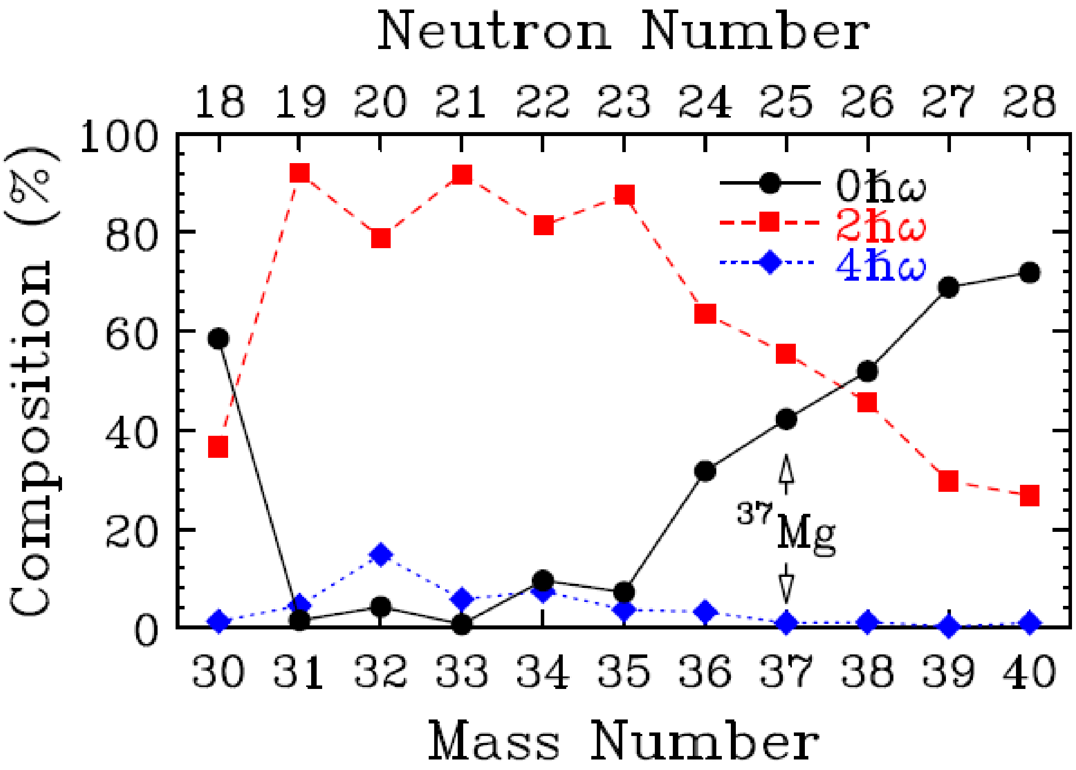
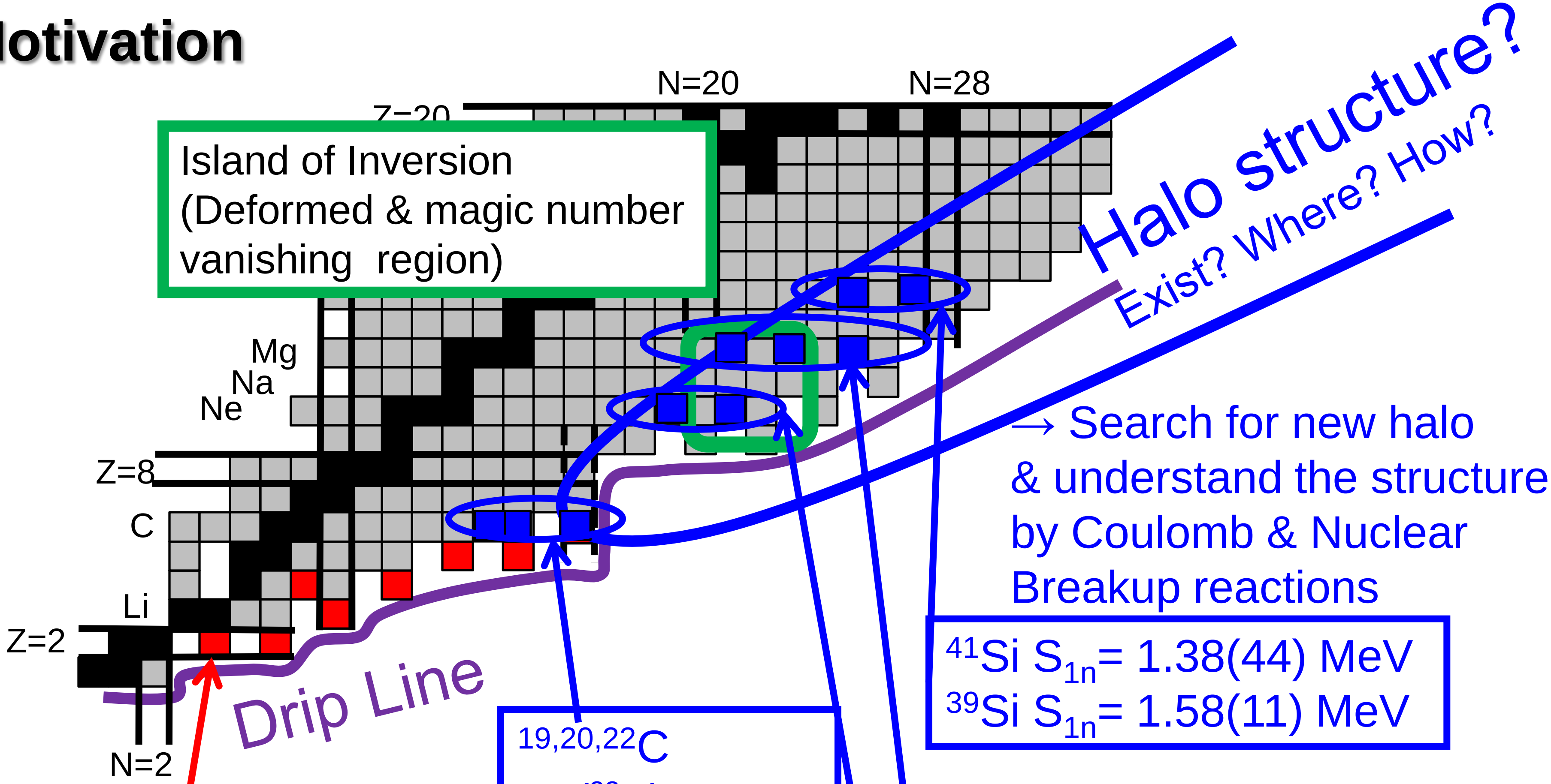


FIG. 4: (color online). Percentage compositions of $0\hbar\omega$ (black circles), $2\hbar\omega$ (red squares), and $4\hbar\omega$ (blue diamonds) configurations in the ground states of the Mg isotopes from large-scale shell-model calculations with the SDPF-M effective interaction [35].

Motivation



Island of Inversion
(Deformed & magic number
vanishing region)

→ Search for new halo
& understand the structure
by Coulomb & Nuclear
Breakup reactions

Neutron halo nuclei

$^{19,20,22}C$
$S_{2n}(^{22}C)$
= -0.14(47) MeV

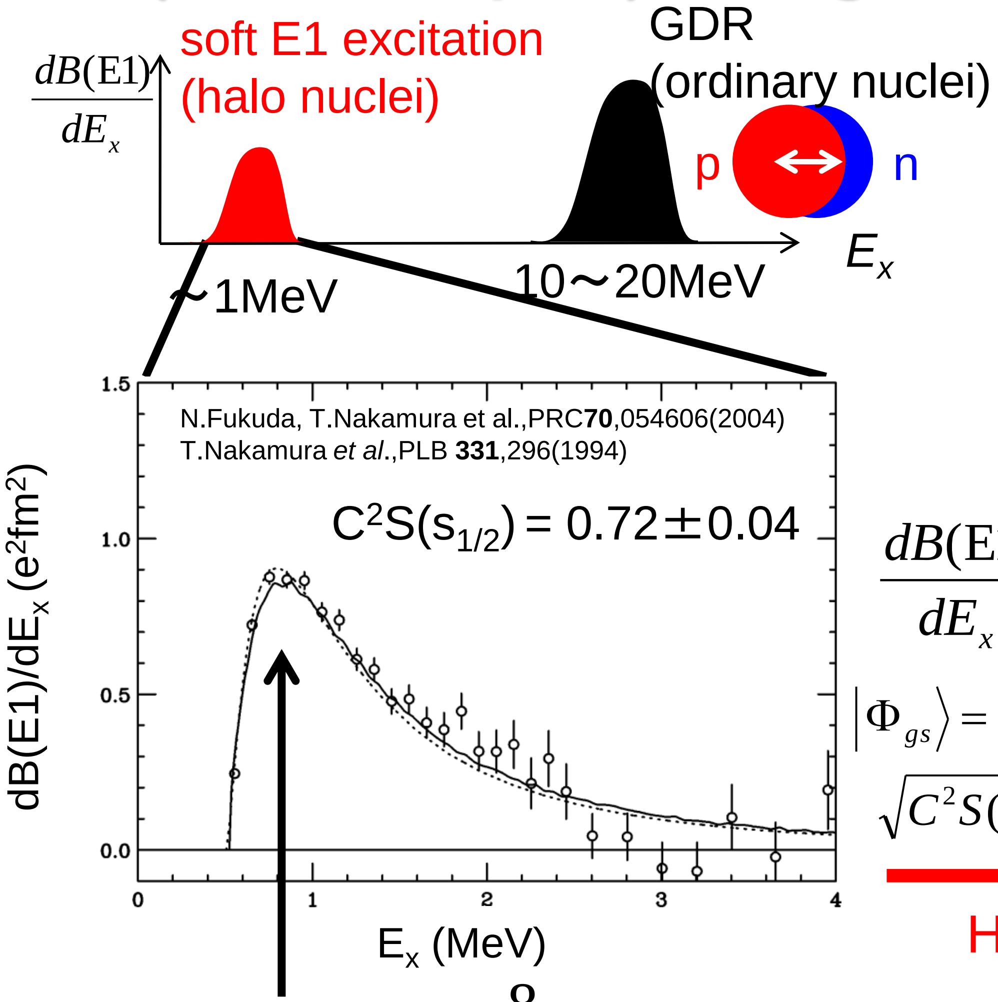
^{41}Si S_{1n}= 1.38(44) MeV
^{39}Si S_{1n}= 1.58(11) MeV

^{37}Mg S_{1n}= 0.25(1.03) MeV
^{35}Mg S_{1n}= 0.99(20) MeV
^{33}Mg S_{1n}= 2.22(3) MeV

^{31}Ne S_{1n}= -0.06(42) MeV
^{29}Ne S_{1n}= 0.95(15) MeV

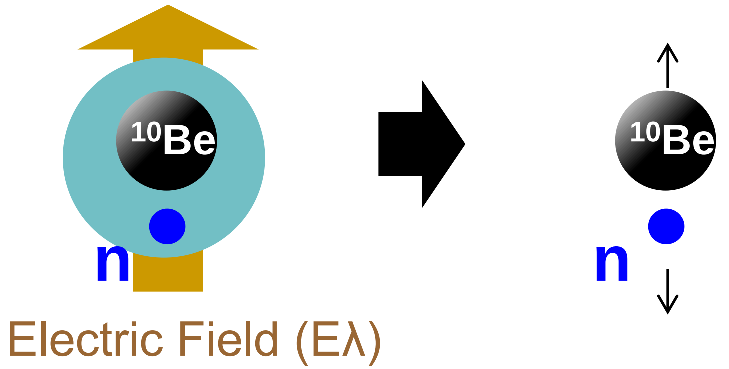
Characteristic features of Halo Nuclei (2)

E1 (Electric dipole) strength of 1*n* halo nucleus (^{11}Be)



N.Fukuda, T.Nakamura et al.,PRC**70**,054606(2004)
T.Nakamura *et al.*,PLB **331**,296(1994)

$C^2S(s_{1/2}) = 0.72 \pm 0.04$



Direct breakup mechanism

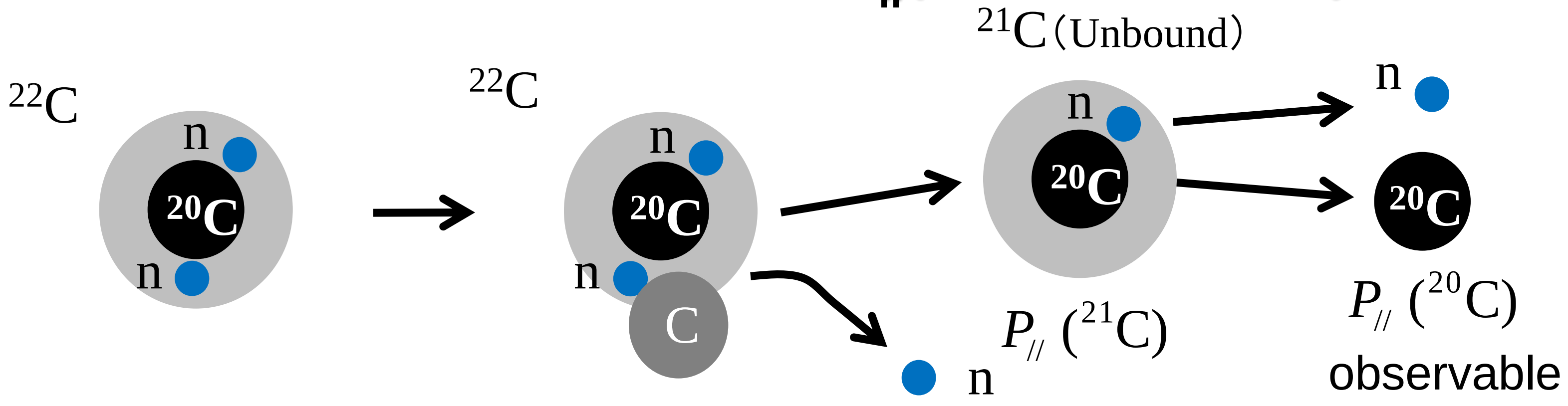
$$\frac{dB(\mathrm{E1})}{dE_x} \propto \left| \left\langle \exp(i\mathbf{qr}) \middle| \frac{Z}{A} r Y_1^m \middle| \Phi_{gs} \right\rangle \right|^2 \propto \boxed{C^2 S(s_{1/2})}$$

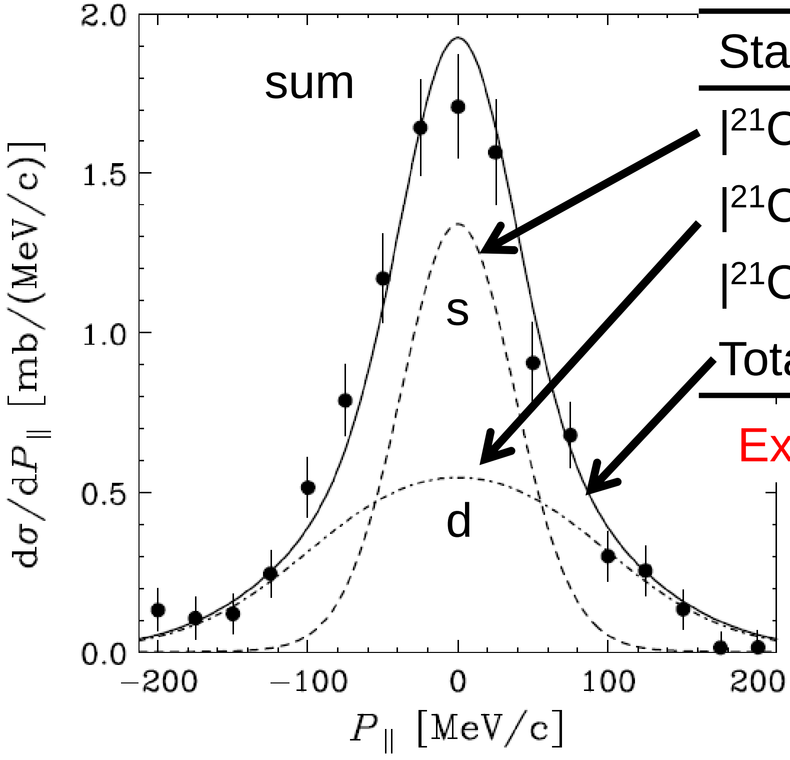
$$\left|\Phi_{gs}\right\rangle = \underbrace{\sqrt{C^2S(s_{1/2})}\left|{}^{10}\mathrm{Be} \otimes s_{1/2}\right\rangle}_{\text{Halo state}} + \sqrt{C^2S(d_{5/2})}\left|{}^{10}\mathrm{Be} \otimes d_{5/2}\right\rangle + \cdots$$

$$E_x(\mathrm{peak}) = \frac{8}{5} S_n \Rightarrow S_n = 504\ \mathrm{keV}$$

Spectroscopic factor (C^2S) & S_n can be extracted

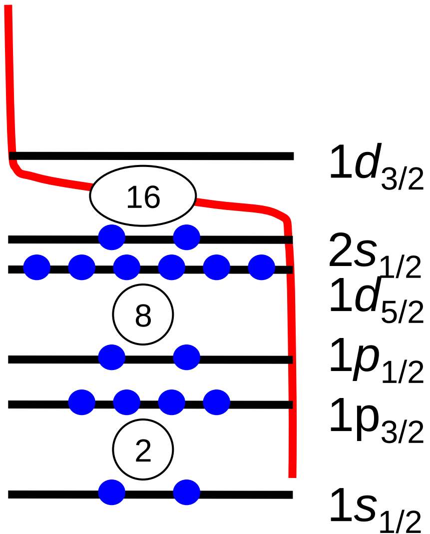
Momentum distribution $d\sigma/dP_{\parallel}(^{22}C + C \rightarrow {}^{20}C)$





State	C^2S	σ(mb)
$\lvert {}^{21}C\otimes 2s_{2/2}\rangle$	1.403	137.55
$\lvert {}^{21}C\otimes 1d_{5/2}\rangle$	4.212	135.87
$\lvert {}^{21}C\otimes 1d_{3/2}\rangle$	0.342	9.55
Total		283.0
Exp. value		266（19）

Eikonal calculation
C^2S : Shell Model (WBP)
psd model space
Normalized to 266mb



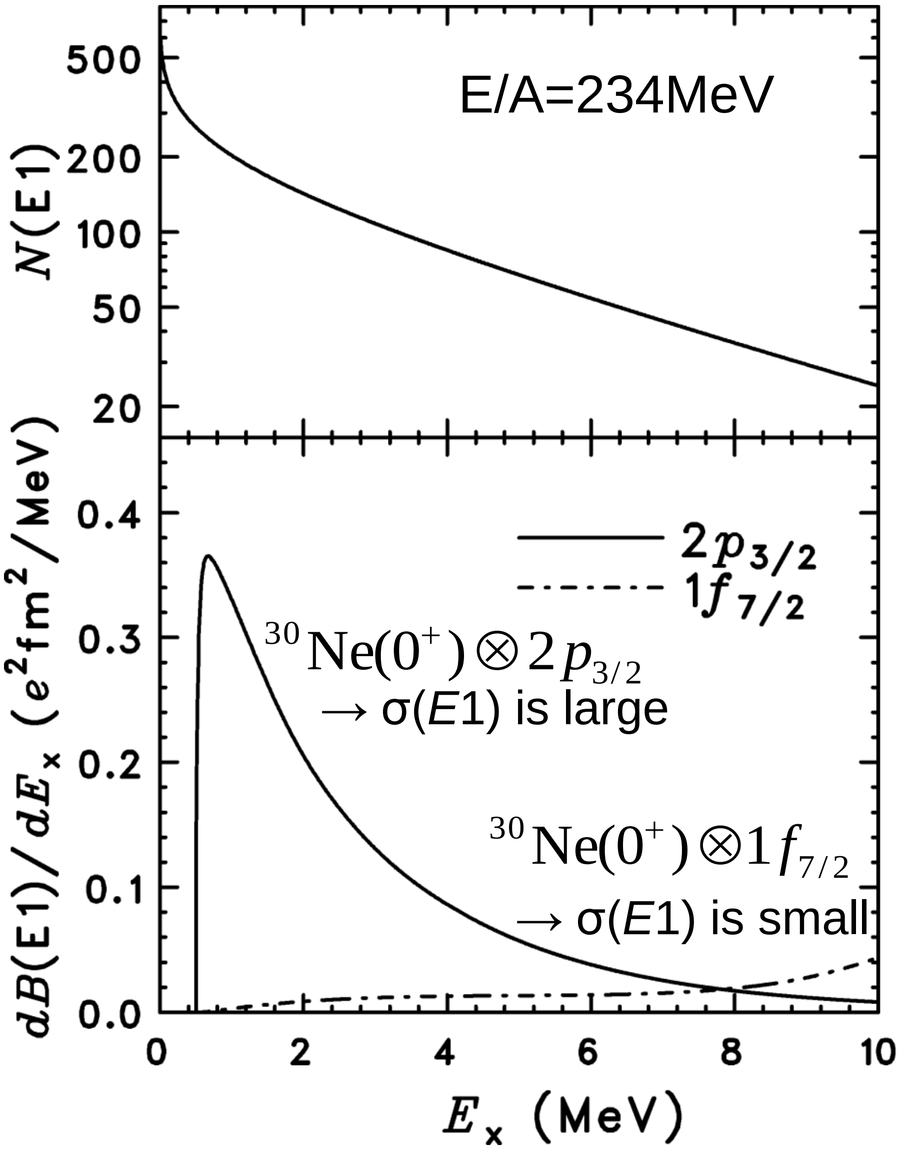
$^{22}C_{g.s.}$ configuration (neutron)

Resolution(1σ) = 27 MeV/c
FWHM = 76(8) MeV/c

Conventional 2n halo

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

Calculation of the cross section for ^{31}Ne



$^{30}\mathrm{Ne}(0^+)\otimes 2p_{3/2}$
→ σ(*E*1) is large

$^{30}\mathrm{Ne}(0^+)\otimes 1f_{7/2}$
→ σ(*E*1) is small

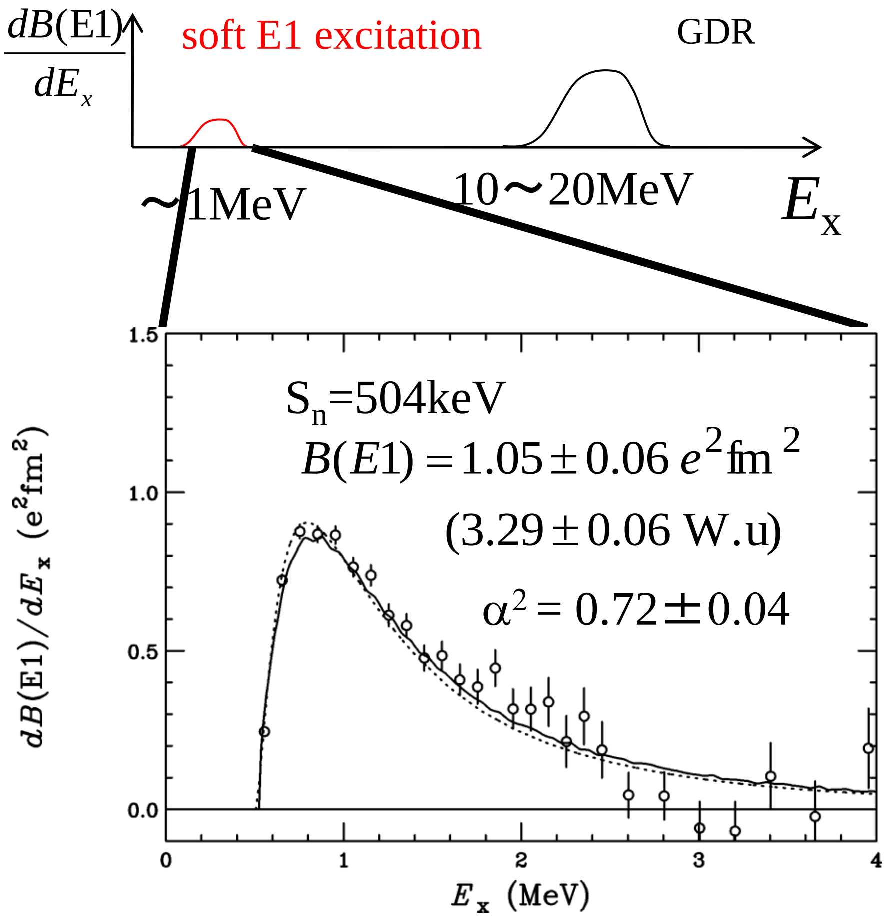
Simple direct breakup mechanism

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

$$\frac{dB(\mathrm{E1})}{dE_x}=\left|\left\langle \mathbf{q}\left|\frac{Ze}{A}rY_1^m\right|\Phi_{gs}\right\rangle\right|^2$$

$$=\Sigma C^2S\left|\left\langle \Phi_f\left|\frac{Ze}{A}rY_1^m\right|\varphi_{nlj}\right\rangle\right|^2$$

Introduction E1 strength of one neutron halo (^{11}Be)



S_n=504keV

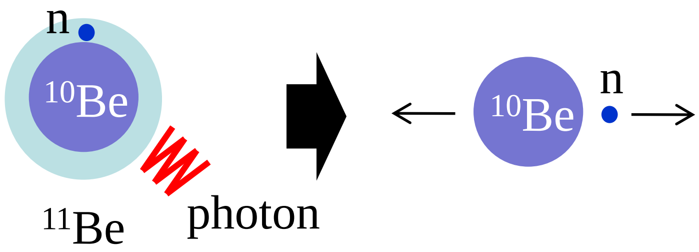
$B(E1) = 1.05 \pm 0.06\ e^2\mathrm{fm}^2$

(3.29 ± 0.06 W.u)

$\alpha^2 = 0.72 \pm 0.04$

N.Fukuda, T.Nakamura et al.,PRC**70**,054606(2004)
T.Nakamura *et al*.,PLB **331**,296(1994)

Direct breakup mechanism



$$\frac{dB(E1)}{dE_x} \propto \left| \left\langle \exp(i\boldsymbol{q}\boldsymbol{r}) \left| \frac{Z}{A} r Y_1^m \right| \Phi_{gs} \right\rangle \right|^2$$

$$|\Phi_{gs}\rangle = \alpha \left|{}^{10}\mathrm{Be} \otimes \nu 2\mathrm{s}_{1/2}\right\rangle + \beta \left|{}^{10}\mathrm{Be} \otimes \nu 1\mathrm{d}_{5/2}\right\rangle + \cdots$$

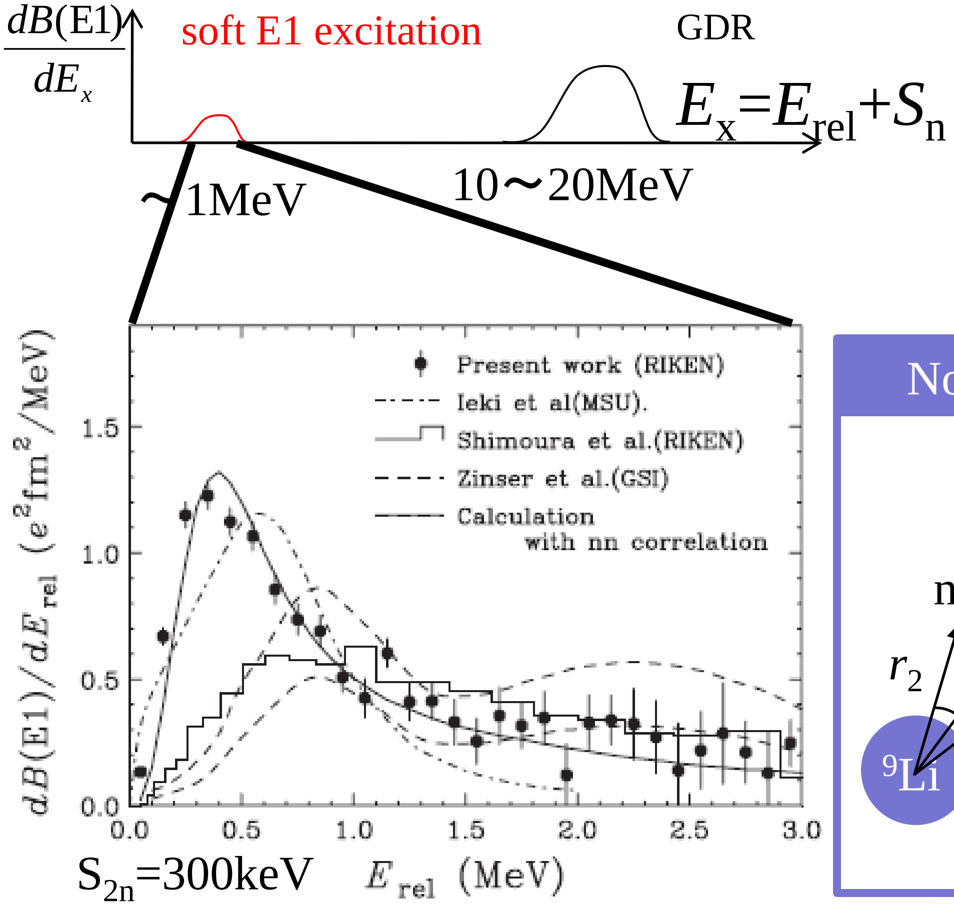
➡ $J^\pi = 1/2^+$

$$E_x(peak) = \frac{8}{5} S_n \quad (s \to p)$$

➡ S_n= 504 keV

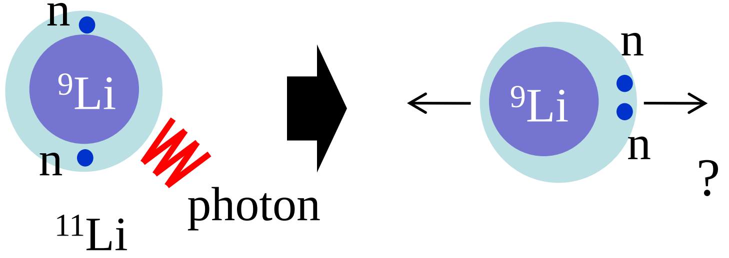
configuration & S_n of $|\Phi_{gs}\rangle$ can be extracted

Introduction E1 strength of two neutron halo (^{11}Li)



S_{2n}=300keV

Mechanism : not established



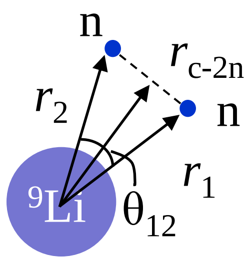
$$B(E1) = 1.42 \pm 0.18\, e^2 fm^2 (E_{rel} \leq 3\text{MeV})$$

$$= 4.5(6)\ \text{W.u}$$

T.Nakamura *et al.*,PRL**96**,252502(2006)

Non-energy-weighted E1 Cluster Sum Rule

$$B(E1) = \int_0^{\infty} \frac{dB(E1)}{dE_x} dE_x$$



$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^2 + r_2^2 + 2r_1r_2\cos\theta_{12}\right\rangle$$

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

H. Esbensen et al., Nucl. Phys. A **542**, 310 (1992).

$$\rightarrow \sqrt{\left\langle r_{c-2n} \right\rangle^2} = 5.01 \pm 0.32\ \text{fm}$$

$$\left\langle \theta_{12} \right\rangle = 48^{+14}_{-18}\ \text{deg}\ \ (\text{noncorrelation}: 90\ \text{deg})$$

$\sqrt{\left\langle r_{c-2n} \right\rangle^2}$ & $\left\langle \theta_{12} \right\rangle$ can be extracted

Calculation of Gamma factor

(basically, ratio of radius of lead nucleus to that of carbon nucleus)

$$R \propto A^{1/3}$$

$$R(\mathrm{Pb}) \ : \ \text{radius of lead nucleus}$$

$$\Gamma_{\max} = \frac{R(\mathrm{Pb})}{R(\mathrm{C})} = 2.6$$

$$\Gamma_{\min} = \frac{R(\mathrm{Pb}) + R({}^{37}\mathrm{Mg})}{R(\mathrm{C}) + R({}^{37}\mathrm{Mg})} = 1.7$$

$$\Gamma = \frac{\Gamma_{\max} + \Gamma_{\min}}{2} = \frac{2.6 + 1.7}{2} = 2.2$$

Extraction of one-neutron removal cross sections σ_{-1n}

$$\sigma^{\exp}_{-1n} = \frac{\boxed{N_{\mathrm{fragment}}}}{\boxed{N_{\mathrm{projectile}}}} \frac{1}{N_t} \longrightarrow \sigma^{\exp}_{-1n} = \frac{\boxed{N_{\mathrm{fragment}}}}{\boxed{N_{\mathrm{projectile}}}} \left(\frac{\boxed{\sigma_R} - \boxed{\sigma'_R}}{e^{-\underline{\sigma'_R} N_t} - e^{-\underline{\sigma_R} N_t}} \right)$$

Reaction loss
in the target

$N_{\mathrm{projectile}}$: the number of projectile
N_{fragment} : the number of fragments
N_t : the number of target nuclei per unit area
σ_R : reaction cross section of projectiles
σ'_R : reaction cross section of fragments

Previous thesis
σ_R : experimental values by this experiment
(large systematic & statistical errors)

This thesis
σ_R of Ne isotopes: M. Takechi et al., PLB707(2012)357.
σ_R of C, Mg, Si isotopes: eikonal model and Skyrme Hartree-Fock calculations.

10% deviation of σ_R → 1% deviation of σ_{-1n}

Change of $\sigma_{-1n} < 3\%$