Island of Inversion studied by Coulomb and Nuclear Breakup

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c.f.
This area is called
中关村

PKU-CUSTIPEN Nuclear Reaction Workshop**"Reactions and Spectroscopy of Unstable Nuclei"**

Contents

- Introduction:
  Physics Motivation
  Probe: Coulomb and Nuclear Breakup

- *Inclusive* Coulomb and Nuclear Breakup of ^{31}Ne and ^{37}Mg
  – Deformation Driven 1n-Halo in the island of inversion
  -- @ ZDS at RIBF at RIKEN

- Summary and Outlook

Evolution Towards the Stability Limit

Where is the neutron drip line?

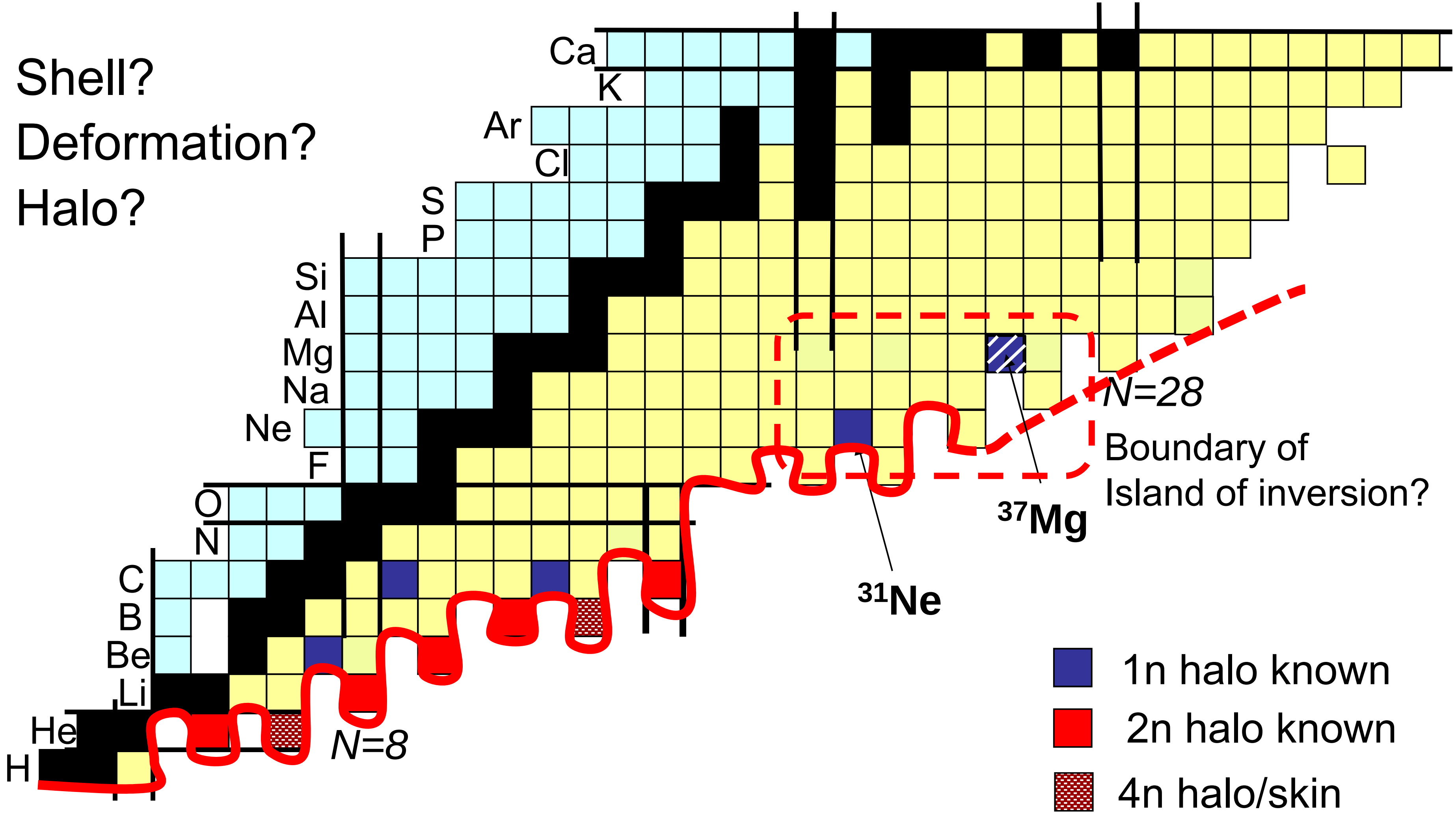
What are characteristic features of drip-line nuclei?

How does nuclear structure evolve towards the drip line?

Shell?

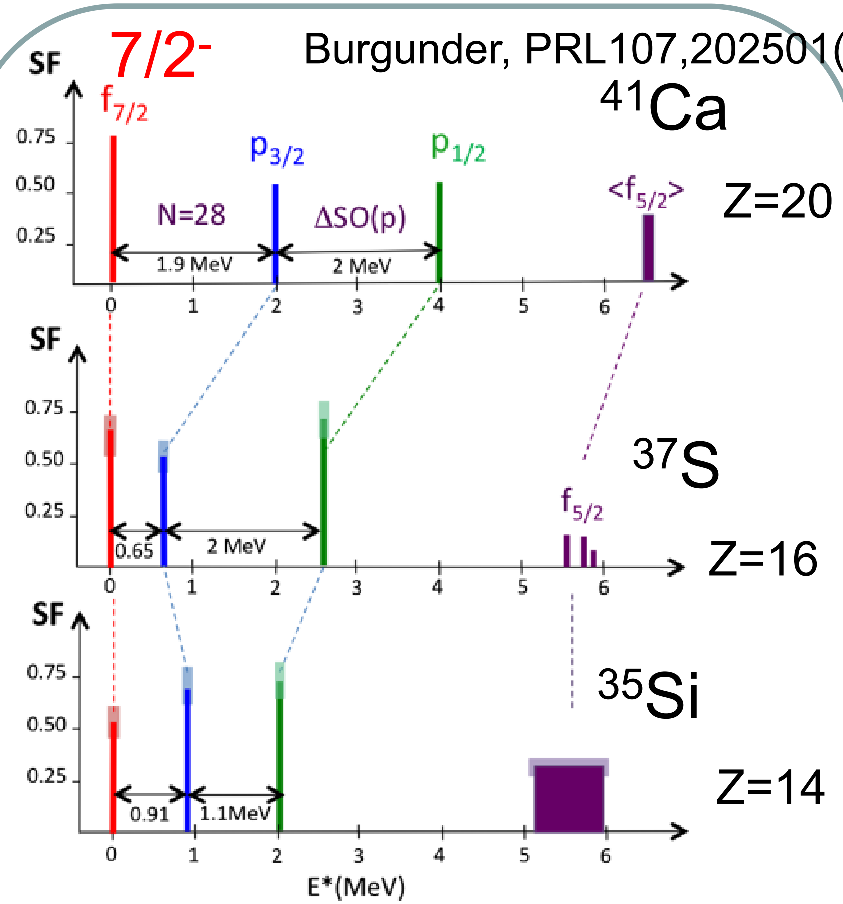
Deformation?

Halo?

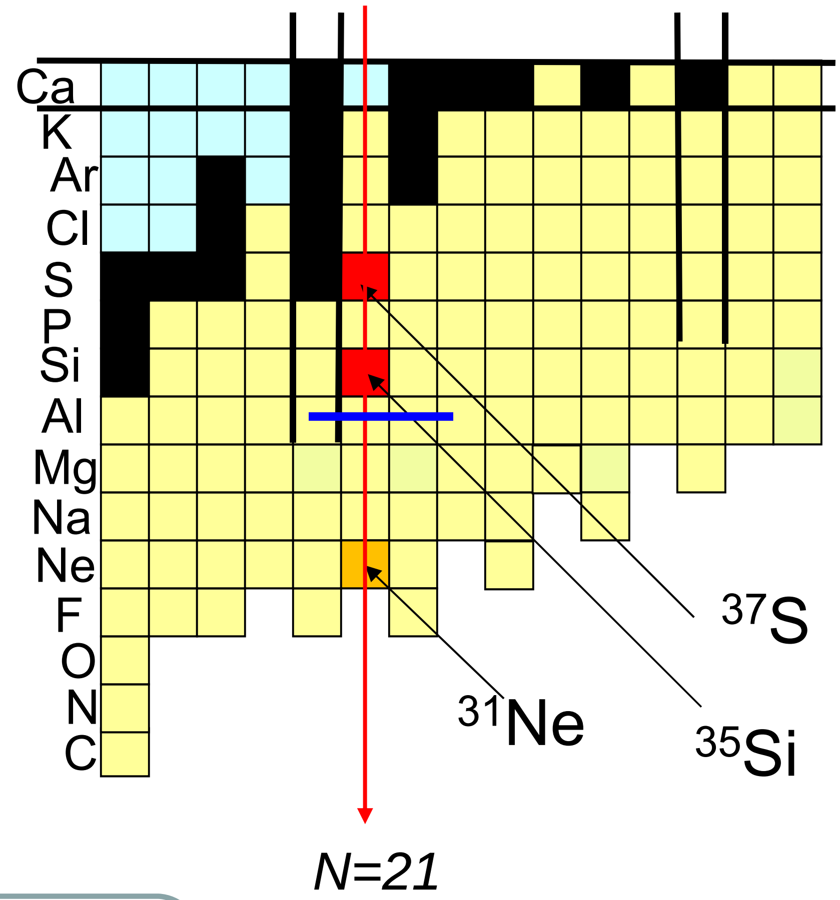


Shell Evolution towards Drip Line in N=21 isotones

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

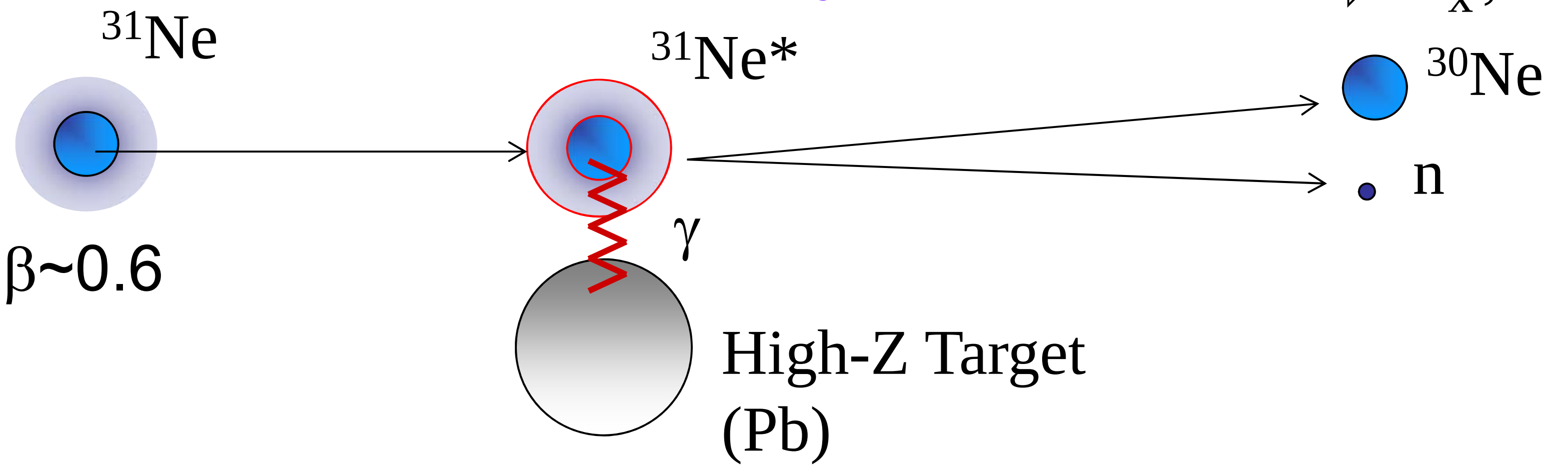
Deformed (gs: 2hω : sd→pf): Island of inversion

Coulomb Breakup of 1n Halo

→Photon absorption of a fast projectile

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

Invariant Mass ⇨ E_x, E_{rel}



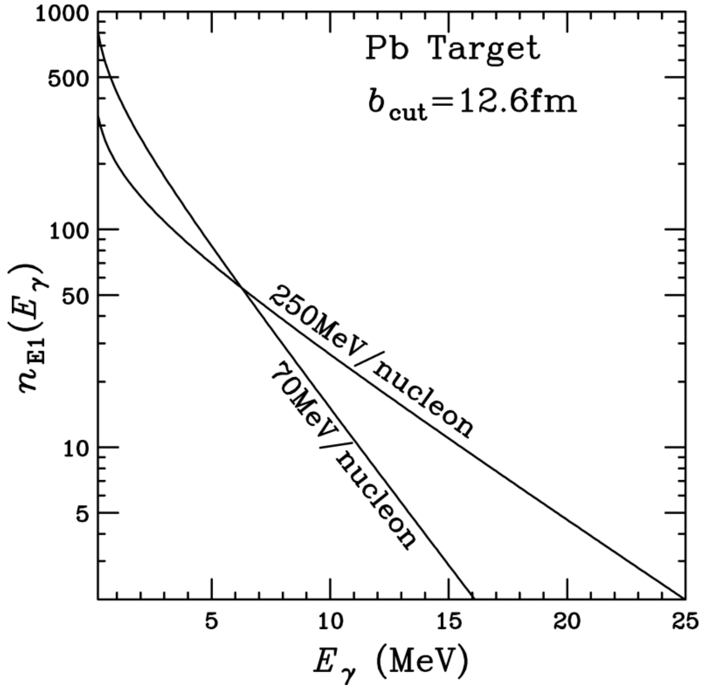
Equivalent Photon Method

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

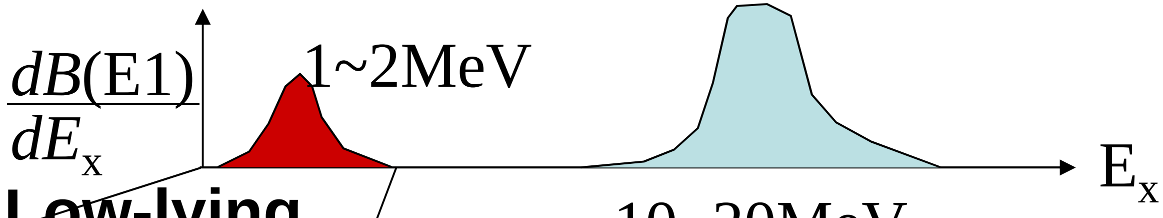
Cross section = (Photon Number)x(Transition Probability)

C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).

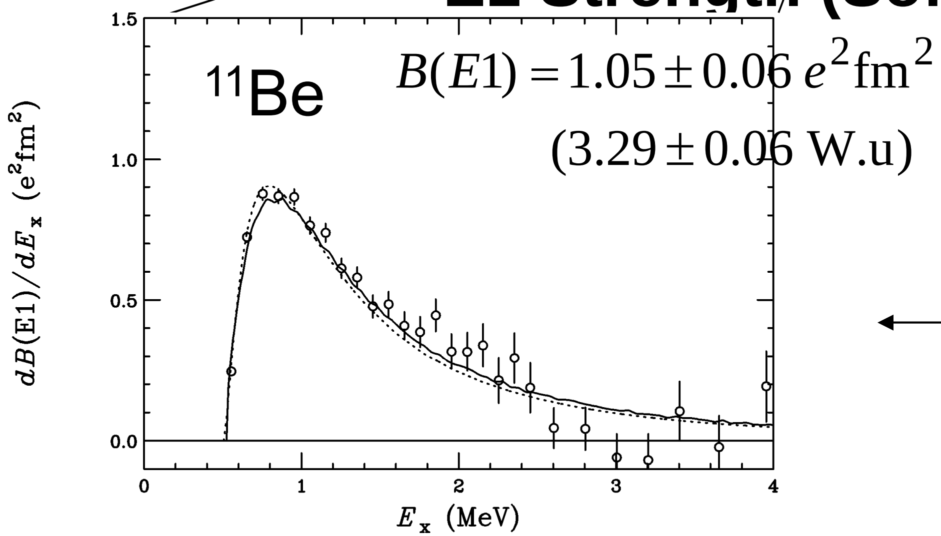
Talk by Motobayashi, Aumann,Yoshida



E1 Response of halo nuclei (Coulomb Breakup of 1n halo)

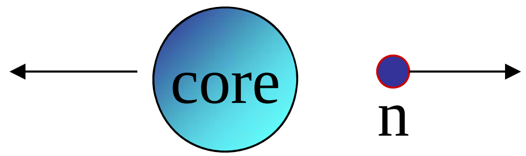


Low-lying
E1 Strength (Soft E1 excitation)



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

Direct Breakup Mechanism



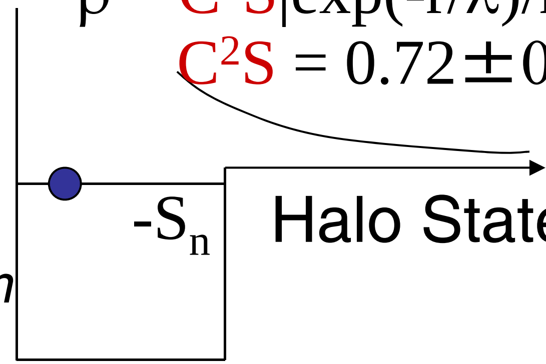
E1 Strength

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

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

Fourier Transform

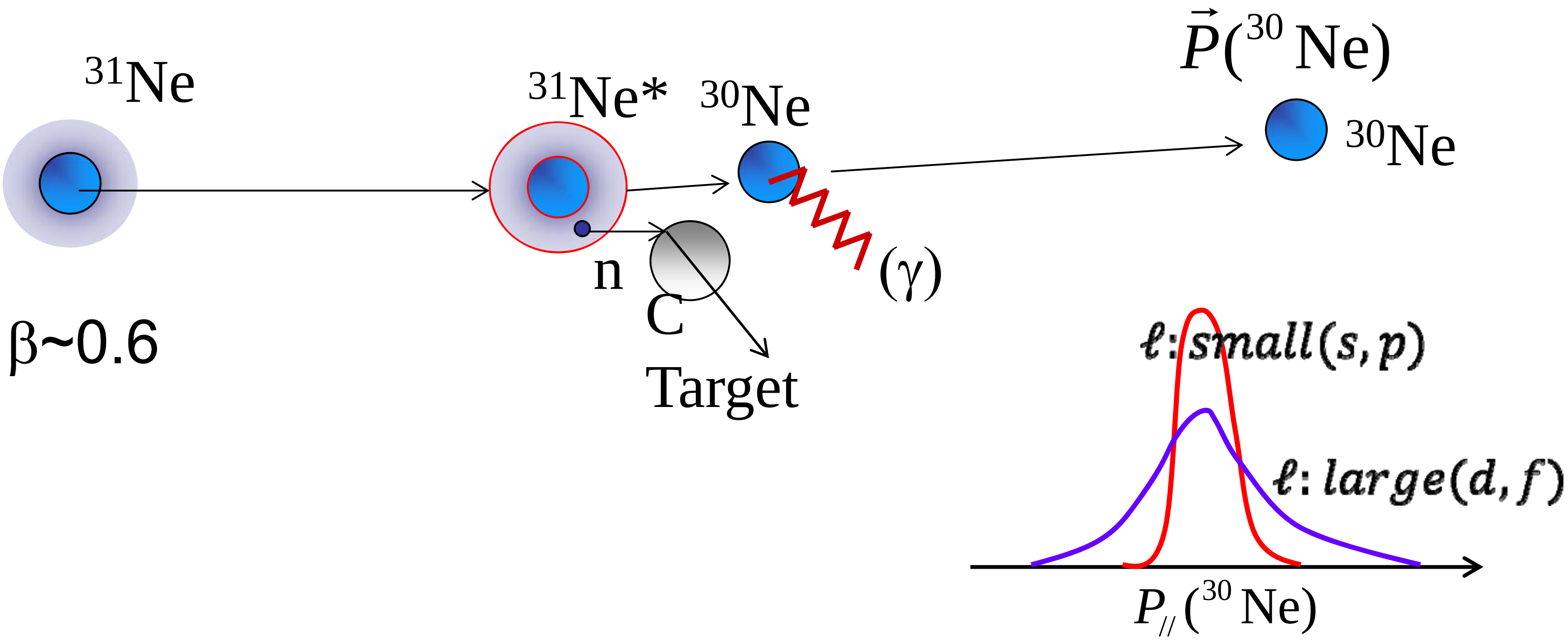
$\rho \sim C^2S|\exp(-r/\lambda)/r|^2$
$C^2S = 0.72 \pm 0.04$



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

Nuclear Breakup of 1n Halo

→e.g. 1n knockout reaction of ^{31}Ne



- γ ray in coincidence → ^{30}Ne(2^+) / ^{30}Ne(0^+) Contribution
- σ_{-1n} and $P_{//}$ distribution → ℓ of valence n, configuration

Theory: Eikonal Approximation

Talk by Bazin

Inclusive Coulomb/Nuclear Breakup of ^{31}Ne and ^{37}Mg

@ ZDS at RIBF, RIKEN

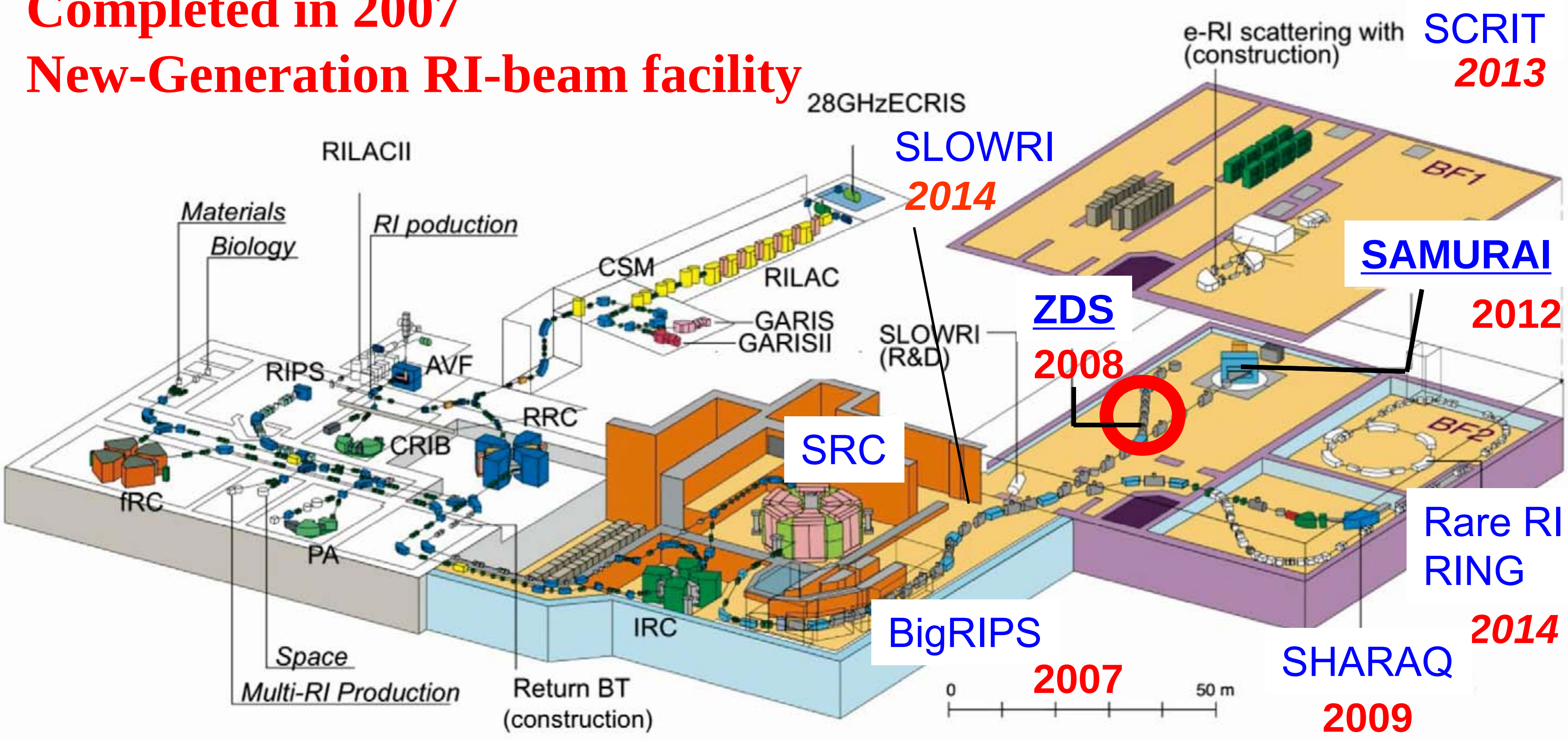
TN, N.Kobayashi et al., PRL 103, 262501 (2009).

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

N.Kobayashi, TN et al., PRL 112, 252501 (2014).

RIKEN RI Beam Factory (RIBF)

Completed in 2007
New-Generation RI-beam facility



SRC: World Largest Cyclotron (K=2500 MeV)

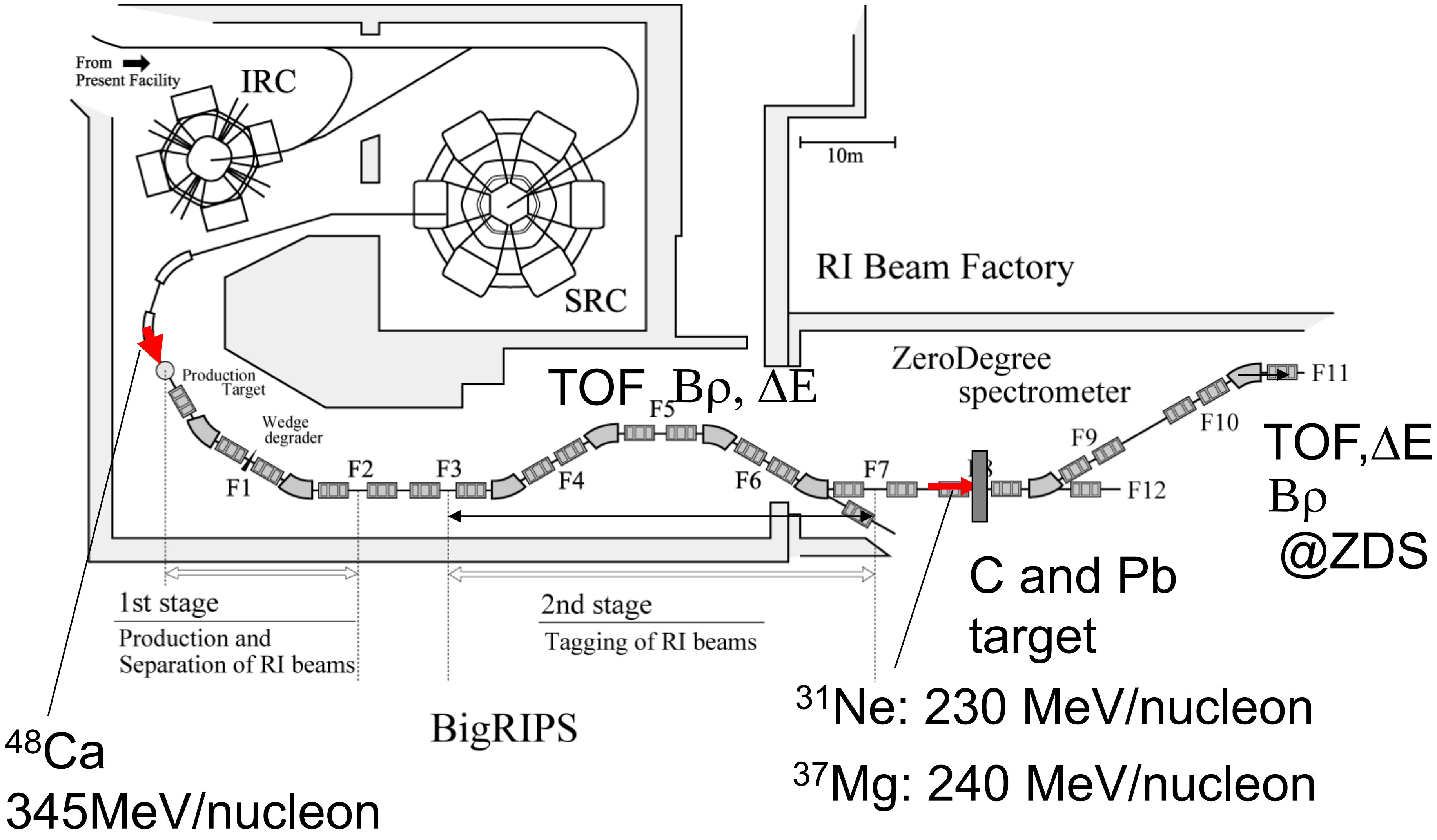
Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)

eg.

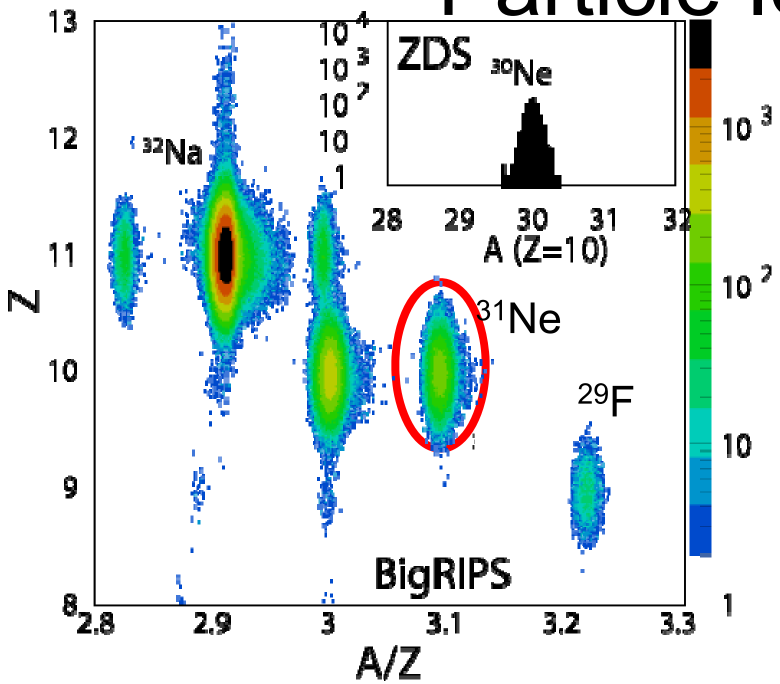
^{48}Ca beam (345 MeV/nucleon) ~200pnA (250pnA max.)

^{238}U beam (345 MeV/nucleon) ~12pnA (15pnA max.)

Experiment at BigRIPS & ZDS at RIBF



Particle Identification



RI beam Intensity @RIBF

~10^3-10^4 times/RIPS

^{48}Ca@60pnA 2008

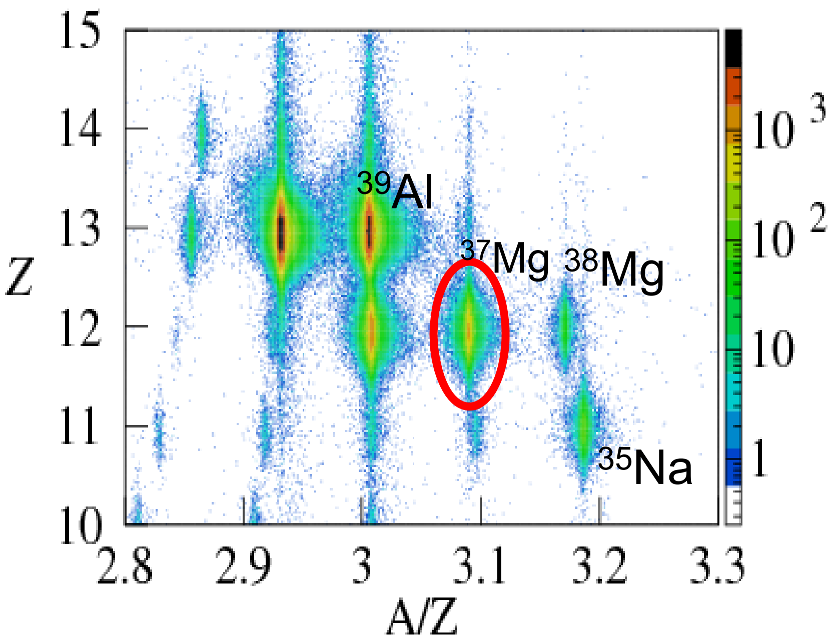
^{31}Ne: 230MeV/nucleon

~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

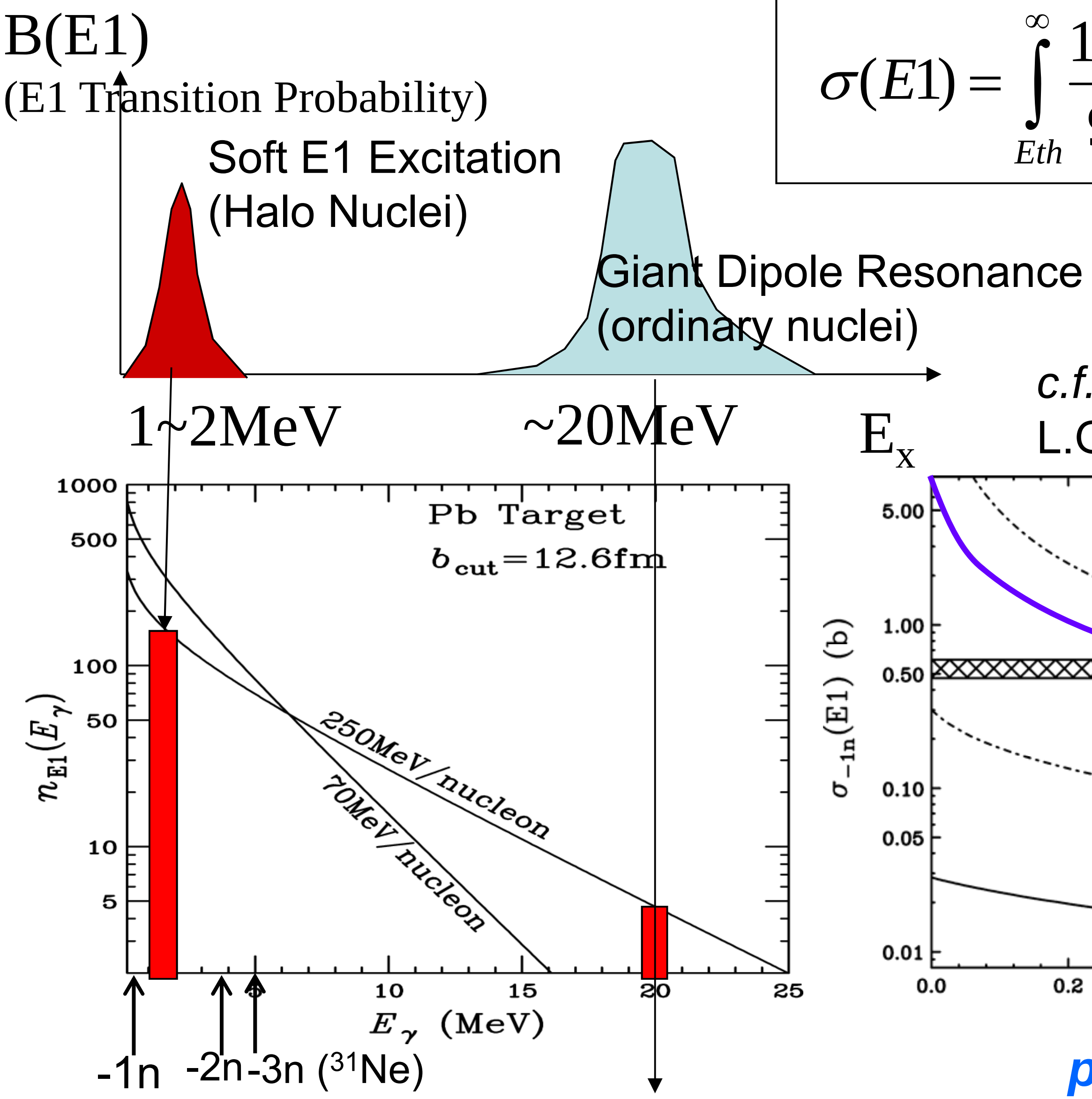
(→200pnA in 2012)

^{37}Mg: 240MeV/nucleon

~6 counts/s

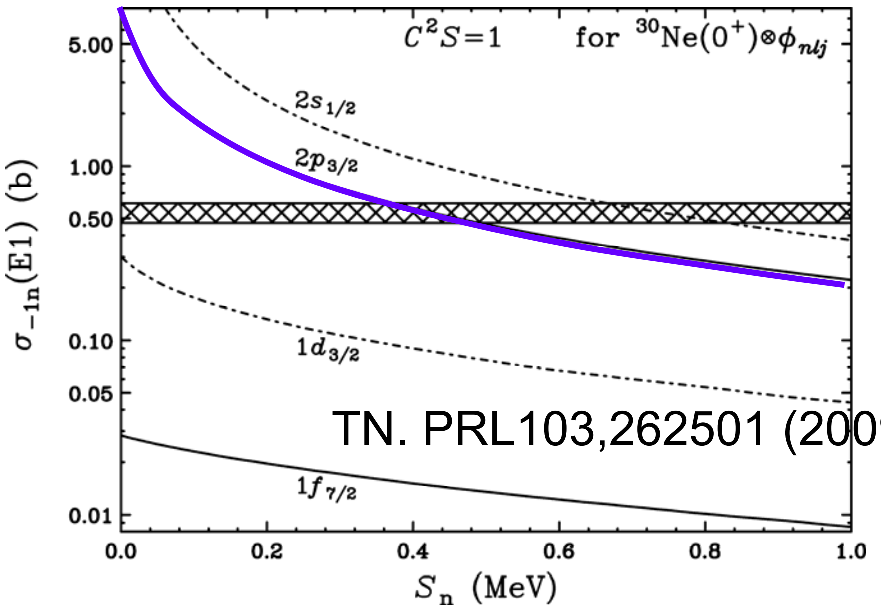
Inclusive Coulomb Breakup

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



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

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



TN. PRL103,262501 (2009))

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

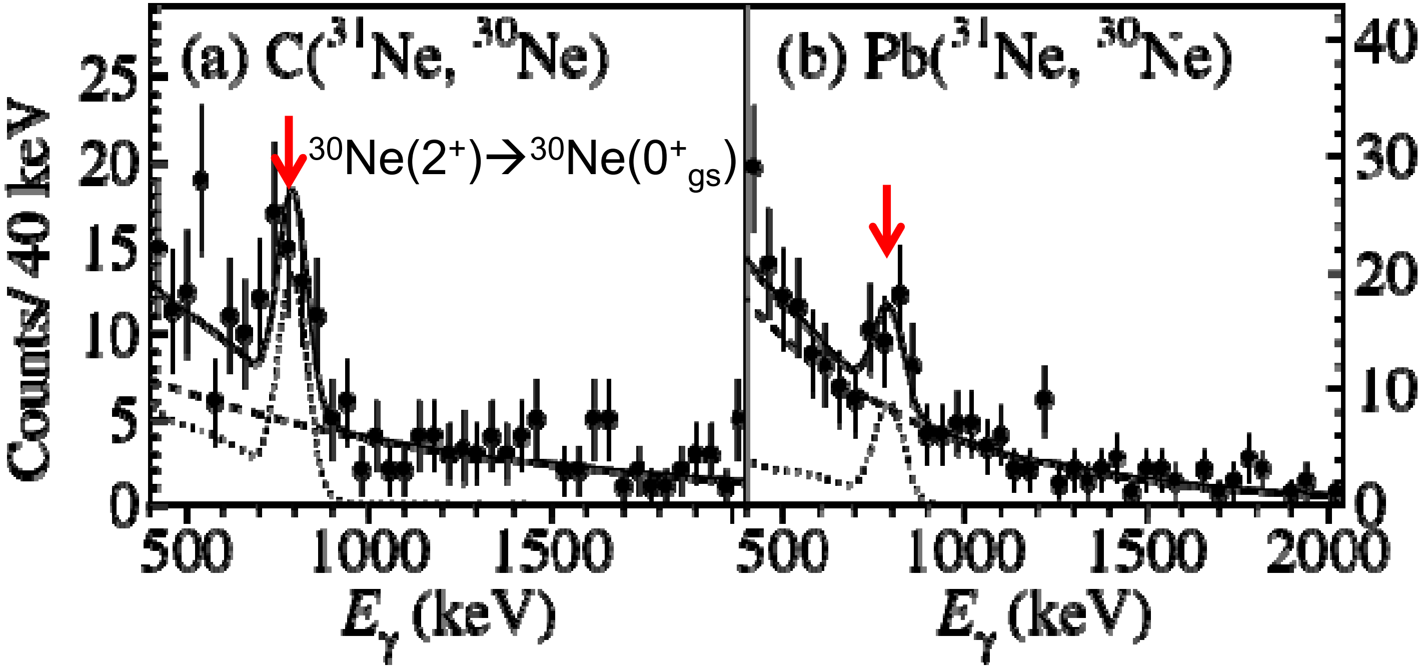
<~0.1b

p or s halo (not f)

C^2S,S_n still unknown

c.f. Takechi et al., PLB707,357 (2012)

Semi-inclusive cross sections $^{31}Ne \rightarrow {}^{30}Ne(0^+_{g.s.})$



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

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

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

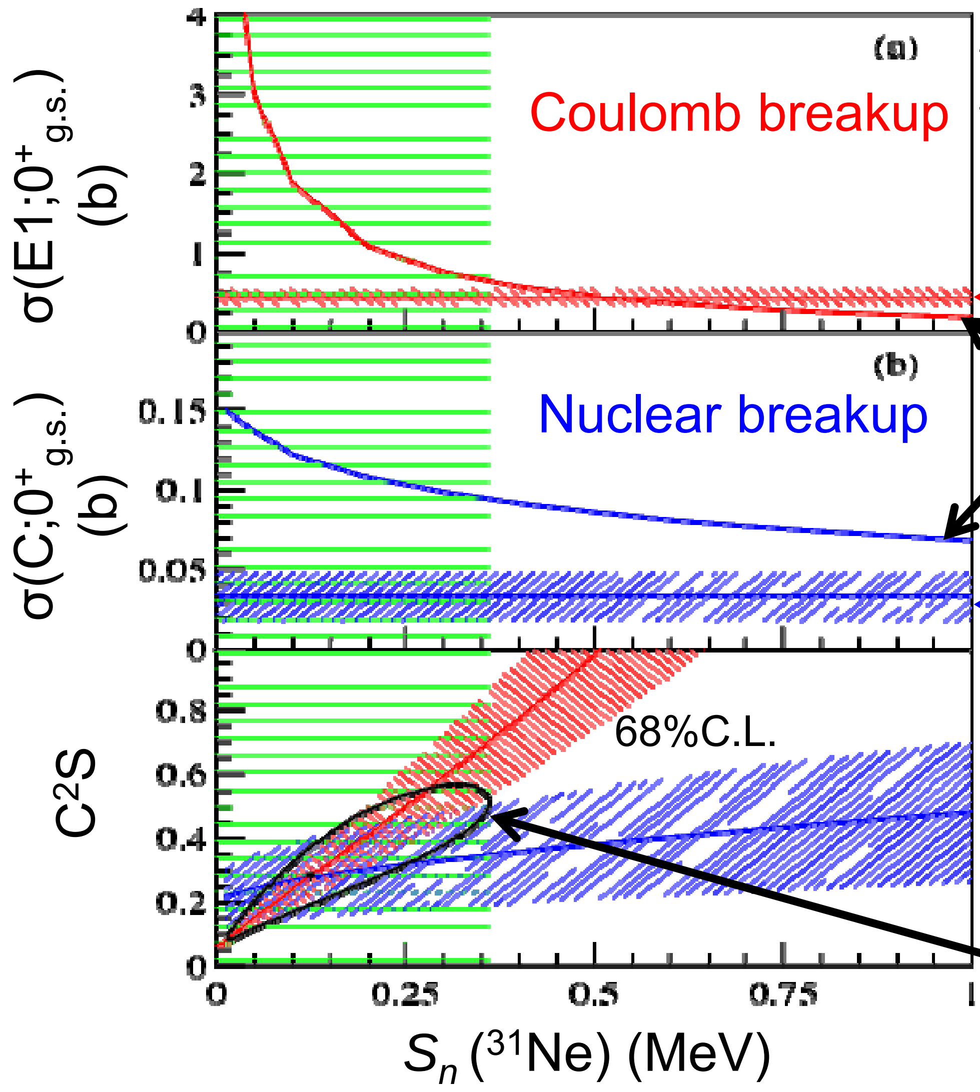
$0^+_{g.s.}$ / Inclusive=85(23)%

Different Sensitivity !

-- Estimation of C^2S & S_n of ^{31}Ne

S_n (^{31}Ne)=-0.06(0.42) MeV
L.Gaudefroy et al.,
PRL109,202503(2012)

^{31}Ne($3/2^-$) : ^{30}Ne(0_1^+) ⊗ $1p_{3/2}$



Only one configuration can couple with 0^+
→ isolate C^2S and S_n

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

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

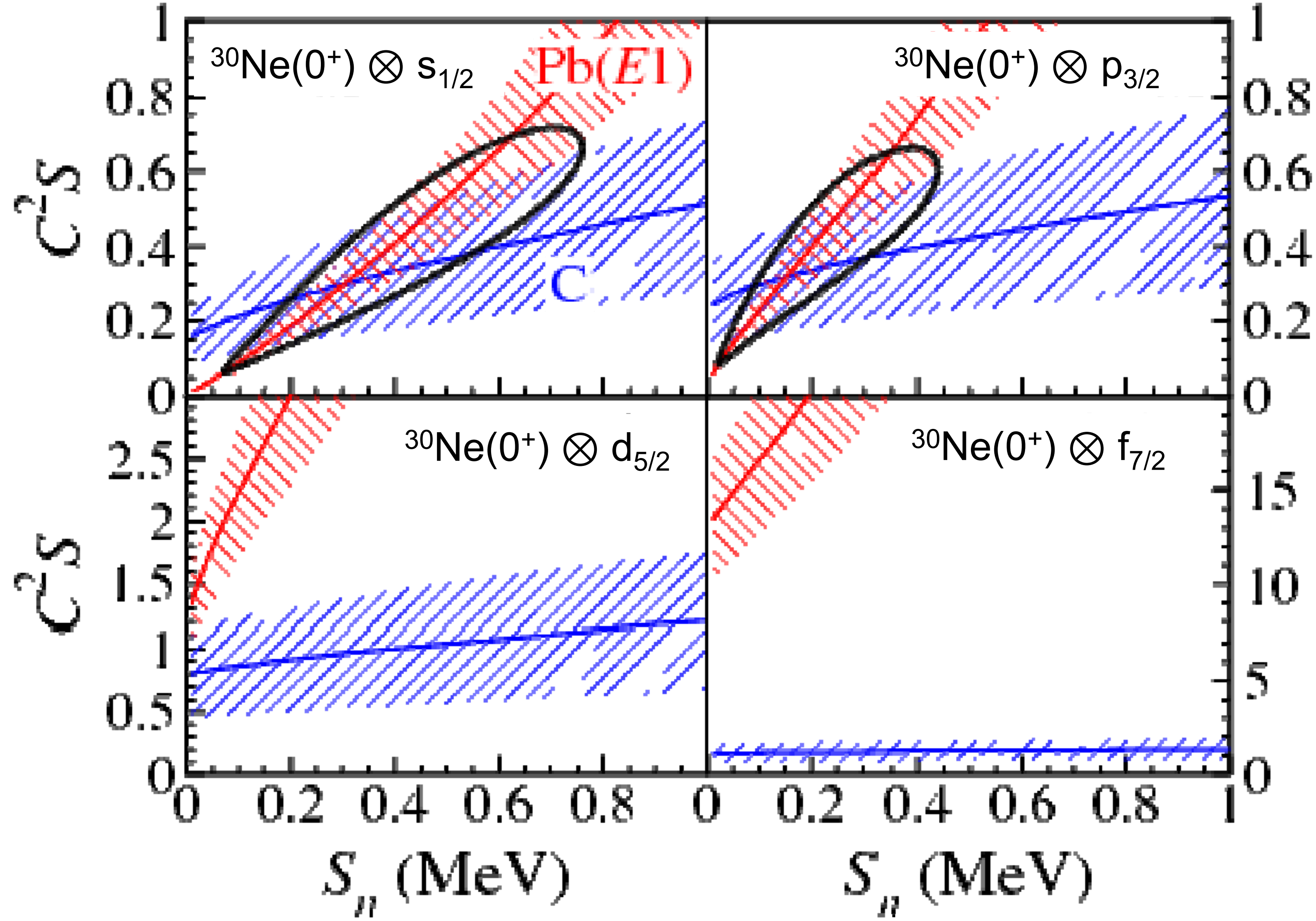
Exp. $\sigma_{-1n}(C;0^+_{g.s.})$ = 33(15) mb

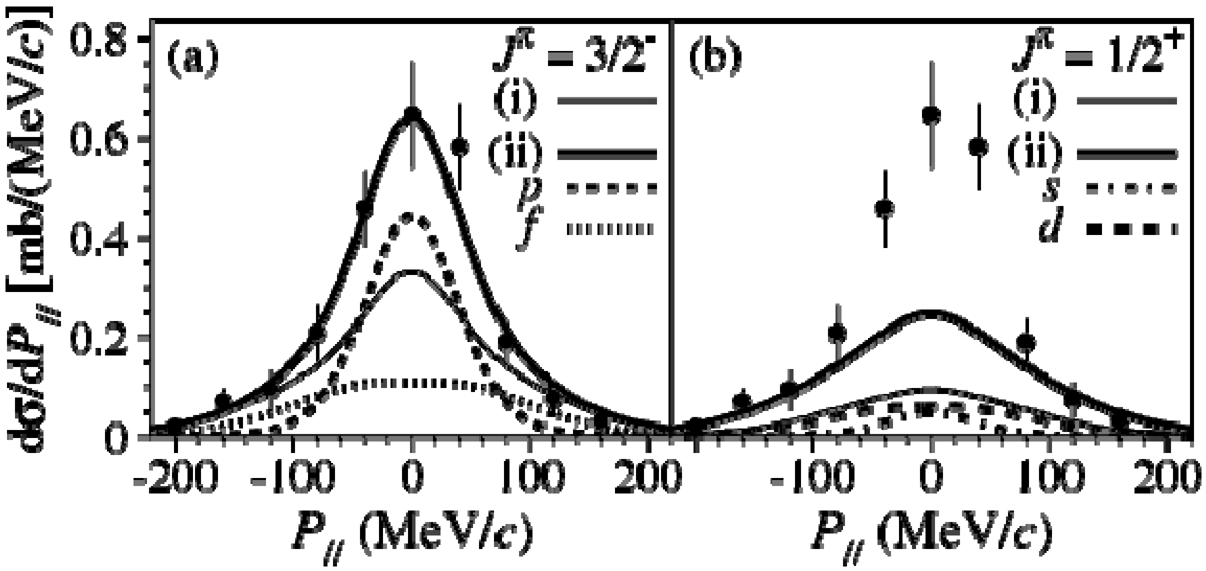
C^2S of $|^{30}Ne(0^+) \otimes p_{3/2}\rangle$ in $|^{31}Ne_{g.s.}\rangle$
= Exp. / Theo.(C^2S=1)

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

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

Possible configurations





Calculation: Eikonal+Large Scale Shell Model(SDPF-M: sd-$p_{3/2}f_{7/2}$ space)

J^π (^{31}Ne)		σ_{-1n}(C)	C^2S	σ_{-1n}^{th}(C)	C^2S^{th}
$3/2^-$	^{30}Ne(0^+_{gs}) ⊗ $2p_{3/2}$	33(15) mb	$0.32^{+0.21}_{-0.17}$	24.3 mb	0.21
	inclusive	90(7) mb		93.3 mb	
$1/2^+$	^{30}Ne(0^+_{gs}) ⊗ $2s_{1/2}$	33(15) mb	$0.30^{+0.25}_{-0.17}$	1.3 mb	0.01
	inclusive	90(7) mb		51.1 mb	

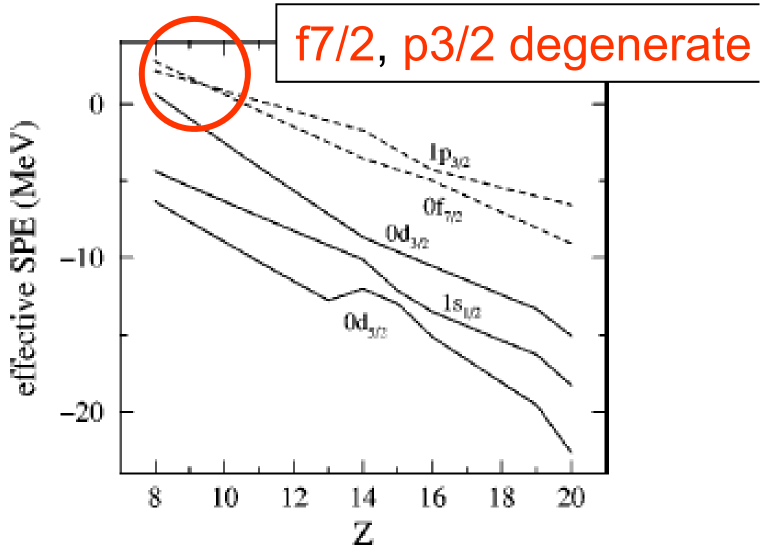
Partial Cross Sections/ Momentum Distribution (compared to Shell Model)

→**^{31}Ne$_{gs}$**: $J^\pi=3/2^-$, ~30% ^{30}Ne(0^+_{gs}) ⊗ $2p_{3/2}$, $S_n=0.15^{+0.16}_{-0.10}$MeV

→Large Configuration Mixing of $p_{3/2}$ and $f_{7/2}$ → **^{31}Ne is deformed**

Theoretical Interpretation

Large Scale Shell Model (SDPF-M)



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

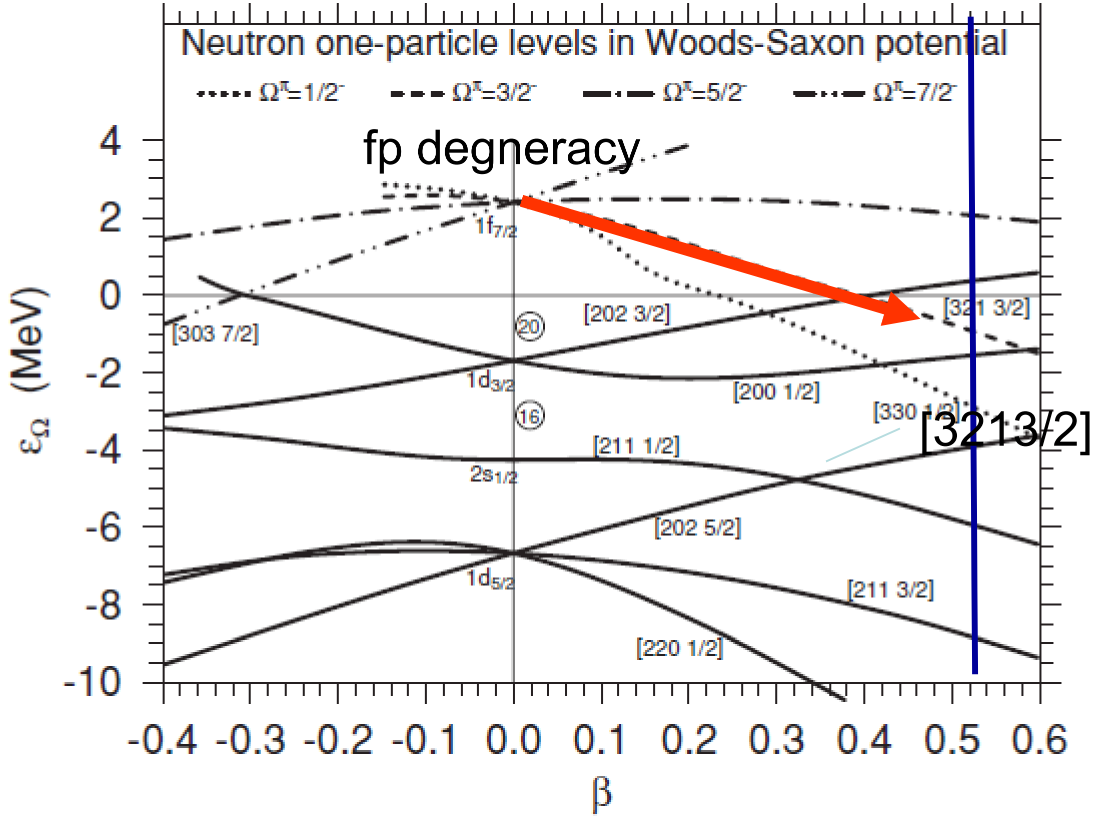
3p-2h dominant

Q_0=60fm^2
B(E2:3/2$^-$→7/2$^-$)=93.2e^{2}fm^2

→ β~0.56

Nilsson Model

Jahn Teller Effect



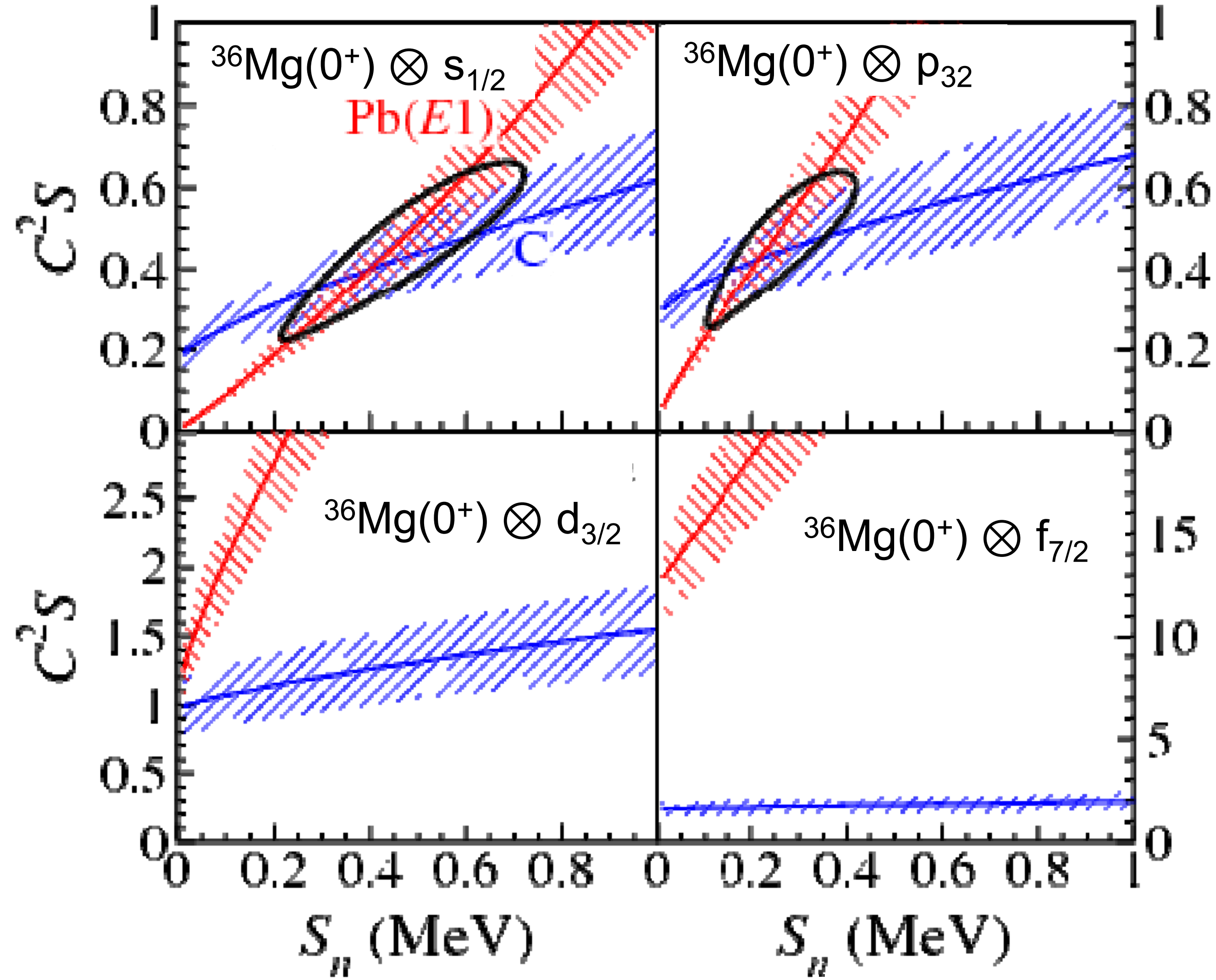
I.Hamamoto PRC 81, 021304(R) (2010)
p becomes more important for smaller s_n
I.Hamamoto PRC 85, 064329 (2012)

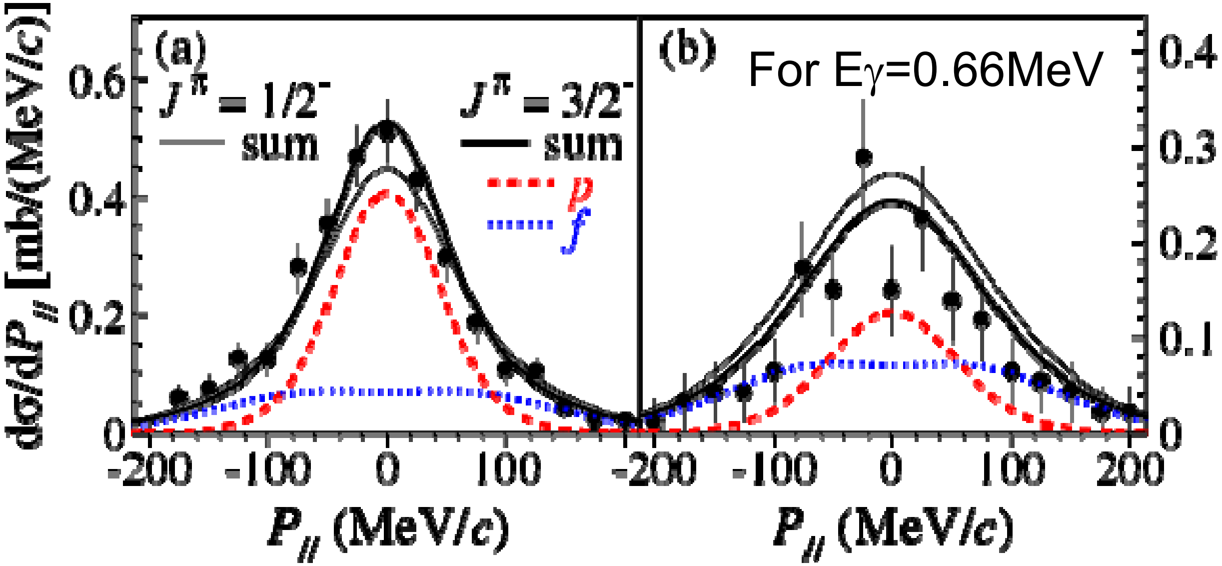
Y. Urata, K. Hagino, and H. Sagawa,
PRC 83, 041303 (R) (2011).
K. Minomo et al, PRL 108, 052503 (2012).

Results and Discussions on ^{37}Mg

N=25

Possible configurations





Calculation: Eikonal+Large Scale Shell Model(SDPF-M: sd-$p_{3/2}f_{7/2}p_{1/2}$ space)

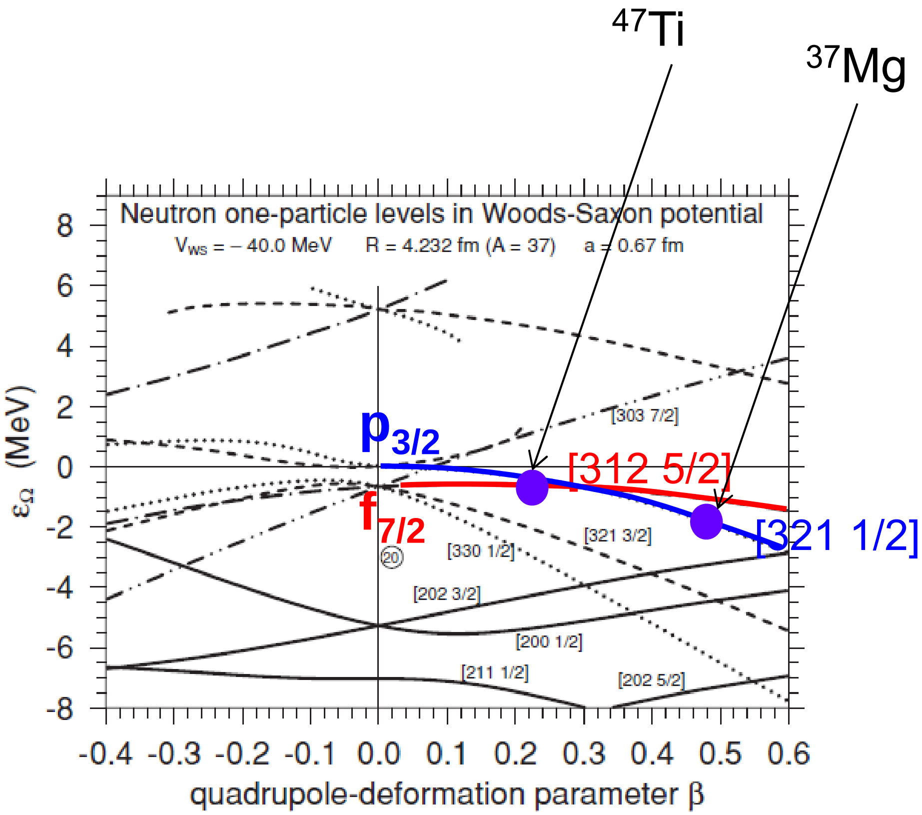
J^{π} (^{37}Mg)		σ_{-1n}(C)	C^2S	σ_{-1n}^{th}(C)	C^2S^{th}
$3/2^-$	^{36}Mg(0^+_{gs}) ⊗ $2p_{3/2}$ inclusive	38(8) mb 80(4) mb	$0.42^{+0.14}_{-0.12}$	30.1 mb 80.6 mb	0.31
$1/2^-$	^{36}Mg(0^+_{gs}) ⊗ $2s_{1/2}$ inclusive	38(8) mb 80(4) mb	$0.40^{+0.16}_{-0.13}$	0.1 mb 37.0 mb	0.001

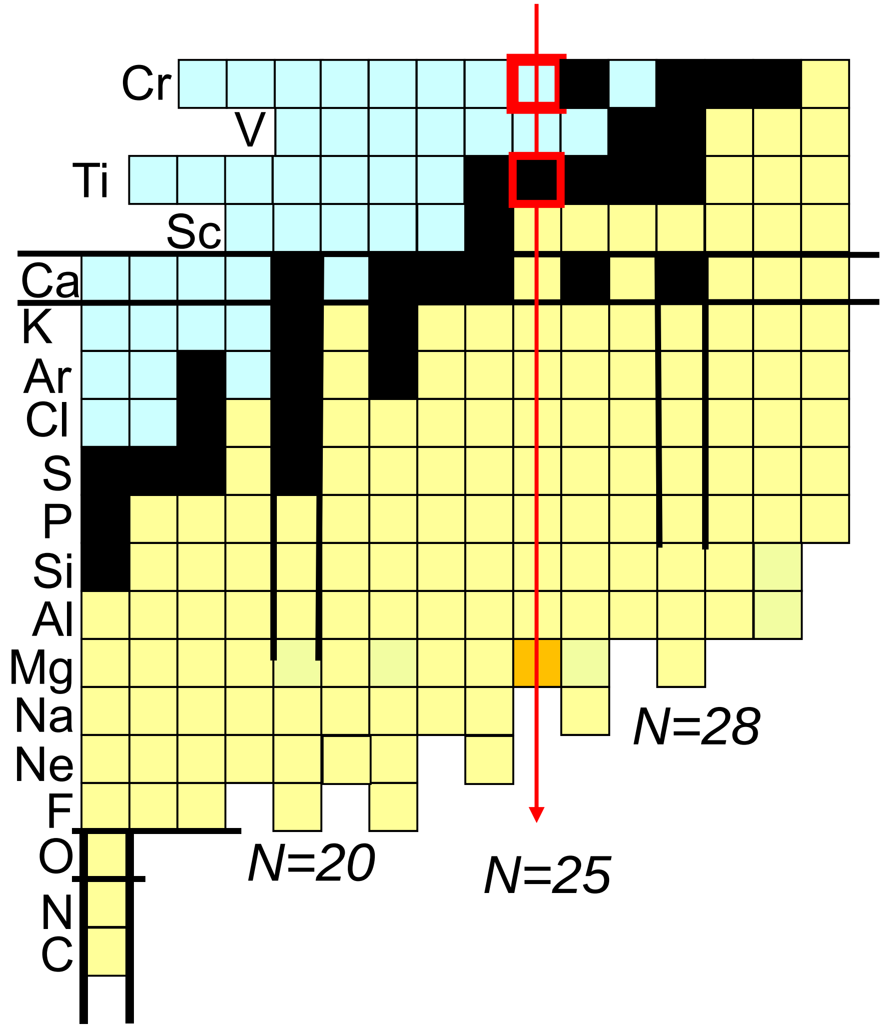
Partial Cross Sections/ Momentum Distribution (compared to Shell Model)

→^{37}**Mg**$_{gs}$: $J^{\pi}=3/2^-$, ~40% ^{36}Mg(0^+_{gs}) ⊗ $2p_{3/2}$, $S_n=0.22^{+0.12}_{-0.09}$MeV
($1/2^-$)

^{37}Mg is also deformed and has a halo configuration !

Shell Evolution in nuclei with N=25





^{49}Cr Z=24 β~0.3
^{47}Ti Z=22 β~0.2
Brandolini, PRC71, 054316(2005).

$p_{3/2}$—$f_{7/2}$ (N=28) gap is larger → [312 5/2] becomes g.s.→ 5/2- (Hamamoto)

^{45}Ca 7/2-, ^{43}Ar(5/2-), ^{41}S (7/2-), ^{39}Si(?), **^{37}Mg(3/2-,1/2-) pf gap is smaller**

Summary and Outlook

Coulomb and Nuclear Breakup around 200 MeV/nucleon
Useful tool to probe halo structures

Inclusive Coulomb and Nuclear Breakup of ^{31}Ne and ^{37}Mg at ZDS

--- Different Sensitivity to the asymptotic wave function
--- Momentum distribution of core fragment in ^{31}Ne+C, ^{37}Mg+C

→^{31}Ne$_{gs}$: $J^{\pi}=3/2^-$, ~30% ^{30}Ne(0^+_{gs}) ⊗ $2p_{3/2}$, $S_n=0.15^{+0.16}_{-0.10}$MeV
→^{37}Mg$_{gs}$: $J^{\pi}=3/2^-$ ($1/2^-$), ~40% ^{36}Mg(0^+_{gs}) ⊗ $2p_{3/2}$, $S_n=0.22^{+0.12}_{-0.09}$MeV

^{37}Mg: Heaviest nucleus with halo so far confirmed
→ Deformed-driven Halo Configuration in ^{31}Ne and ^{37}Mg

Outlook: Inclusive→Exclusive

Invariant mass spectroscopy → Level Structures of ^{31}Ne –rotational band?
→SAMURAI Proposal approved (Spokesperson: N.Kobayashi)

^{22}C, ^{19}B Coulomb Breakup (invariant mass) Done: Analysis is in progress:

Halo Nuclei in heavier drip-line nuclei?

Inclusive Coulomb and Nuclear Breakup of ^{31}Ne and ^{37}Mg

PRL 112, 142501 (2014).

Deformation-driven p-wave Halos at the Drip-line: ^{31}Ne

小林信之

T. Nakamura,[1] N. Kobayashi,[1] Y. Kondo,[1] Y. Satou,[1,2] J.A. Tostevin,[3] Y. Utsuno,[4] N. Aoi,[5] H. Baba,[5] N. Fukuda,[5] J. Gibelin,[6] N. Inabe,[5] M. Ishihara,[5] D. Kameda,[5] T. Kubo,[5] T. Motobayashi,[5] T. Ohnishi,[5] N.A. Orr,[6] H. Otsu,[5] T. Otsuka,[7] H. Sakurai,[5] T. Sumikama,[8] H. Takeda,[5] E. Takeshita,[5] M. Takechi,[5] S. Takeuchi,[5] Y. Togano,[5,1] and K. Yoneda[5]

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[7]*Center for Nuclear Study (CNS), the University of Tokyo, Hongo, Tokyo 113-0033, Japan*
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谢谢！

PRL 112, 252501 (2014).

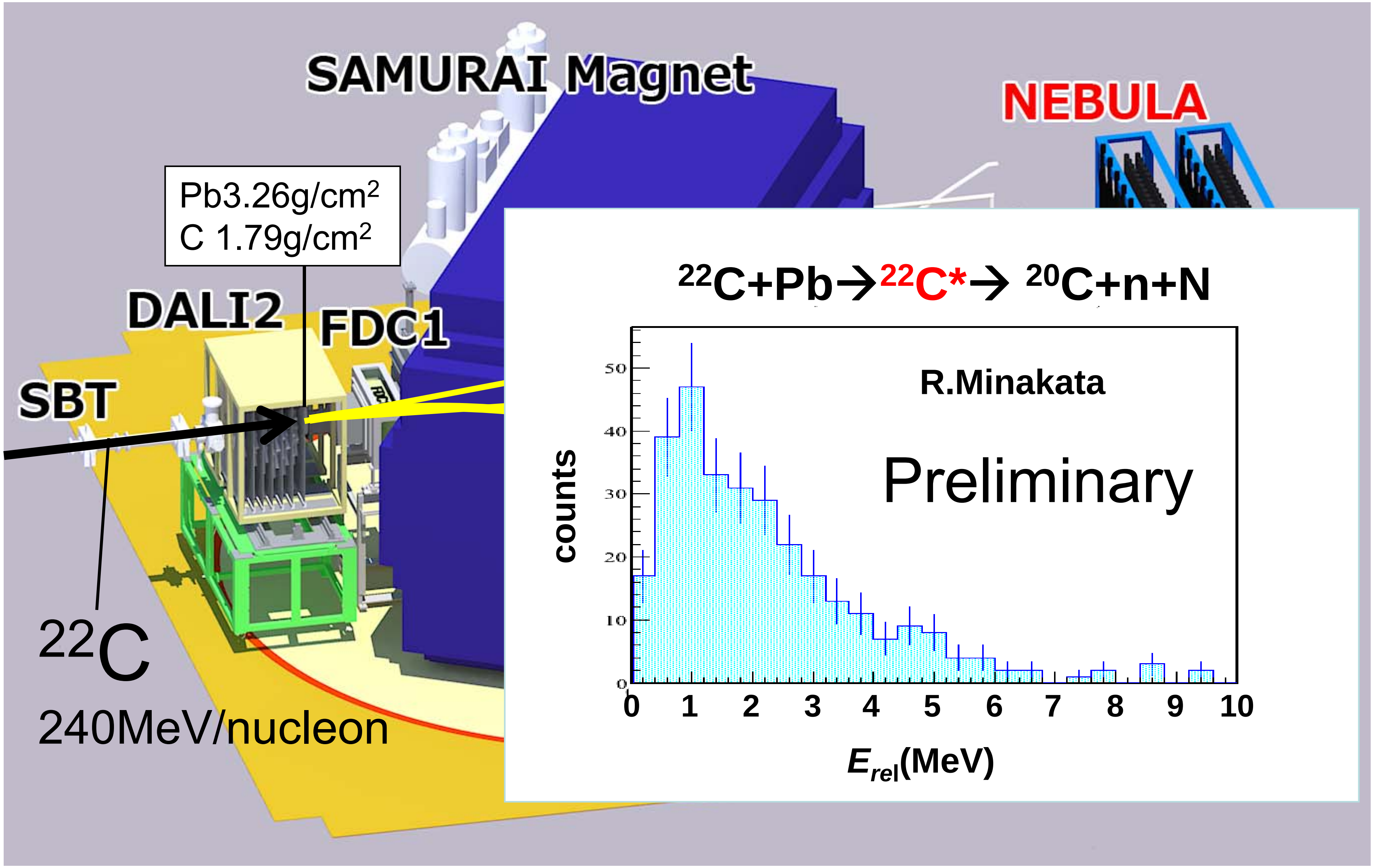
Observation of a p-wave one-neutron halo configuration in ^{37}Mg

N. Kobayashi,[1,*] T. Nakamura,[1] Y. Kondo,[1] J. A. Tostevin,[2,1] Y. Utsuno,[3] N. Aoi,[4,†] H. Baba,[4] R. Barthelemy,[5] M. A. Famiano,[5] N. Fukuda,[4] N. Inabe,[4] M. Ishihara,[4] R. Kanungo,[6] S. Kim,[7] T. Kubo,[4] G. S. Lee,[1] H. S. Lee,[7] M. Matsushita,[4,‡] T. Motobayashi,[4] T. Ohnishi,[4] N. A. Orr,[8] H. Otsu,[4] T. Otsuka,[9] T. Sako,[1] H. Sakurai,[4] Y. Satou,[7] T. Sumikama,[10,§] H. Takeda,[4] S. Takeuchi,[4] R. Tanaka,[1] Y. Togano,[4,¶] and K. Yoneda[4]

Backup

SAMURAI Experiment May/2012

First Full Exclusive Coulomb/Nuclear Breakup Measurement of ^{22}C and ^{19}B



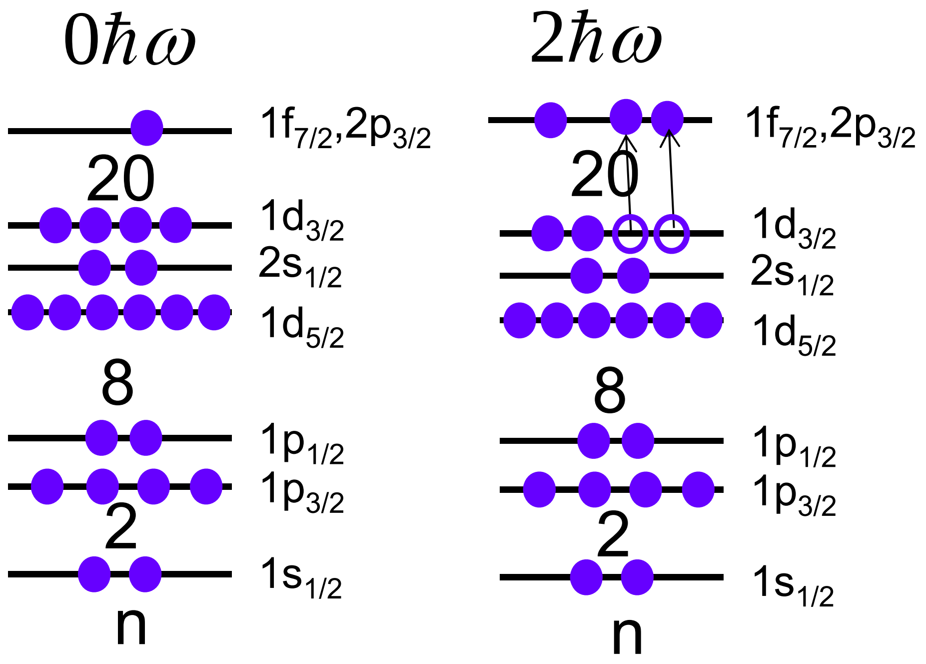
Definition of Island of Inversion

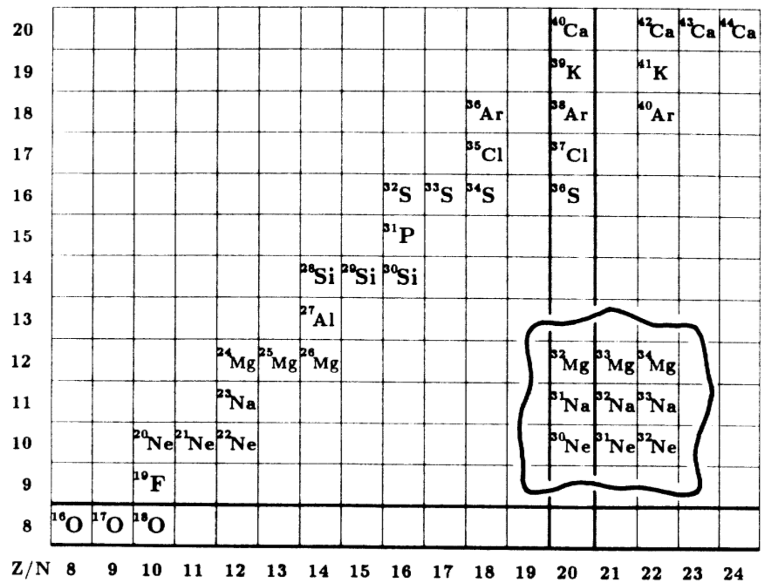
E.K. Warburton, J.A.Becker, B.A.Brown, PRC41, 1147 (1990).

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.





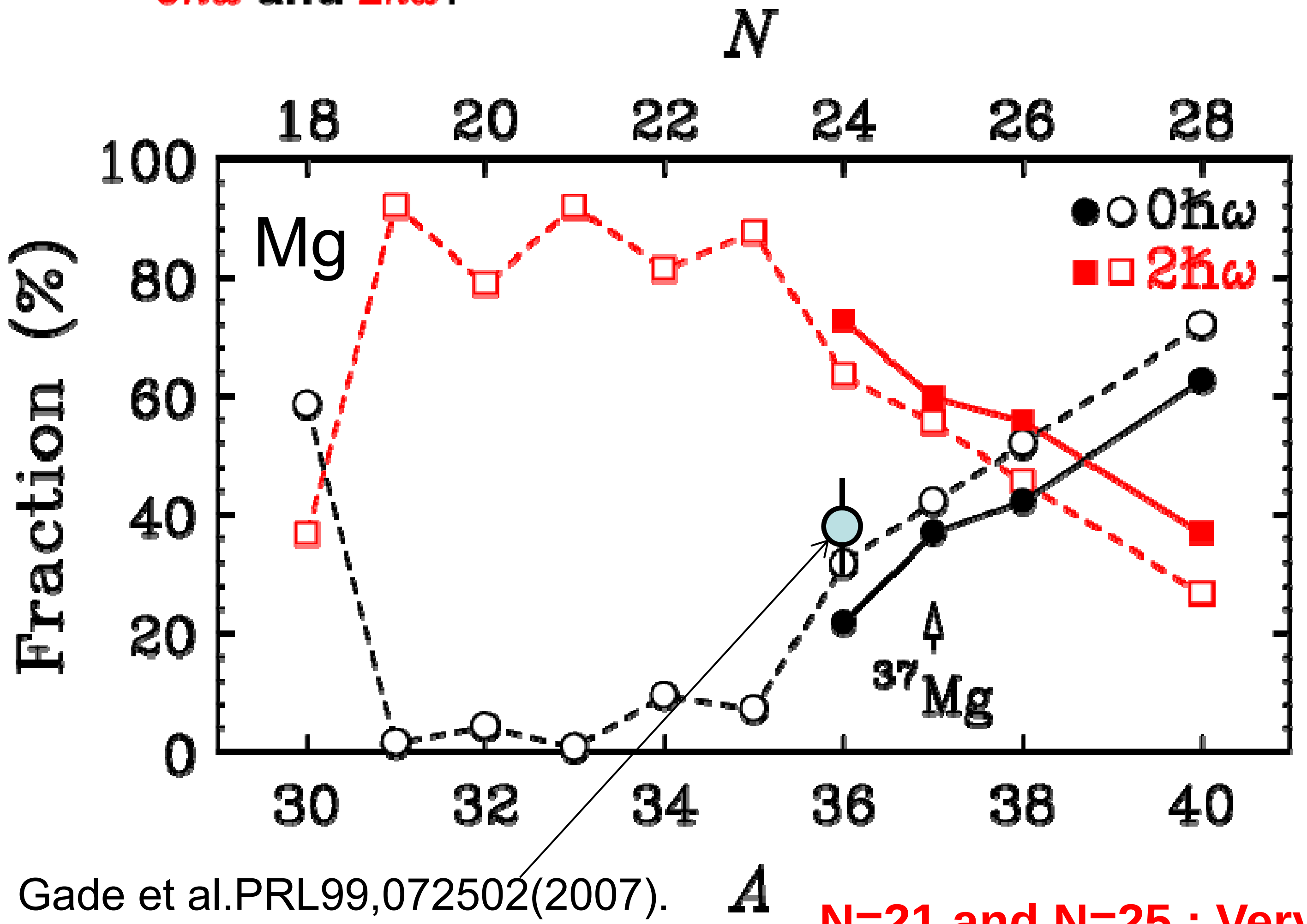
Island of Inversion: $E(0\hbar\omega)>E(2\hbar\omega)$

Naively: $2\hbar\omega + E_{res} < 0$

Shell Evolution in nuclei with Z=12 (Mg isotopes)

Large Scale Shell Model (SDPF-M+$p_{1/2}$)
--- could explain -1n inclusive/partial cross sections/momentum distribution

How this shell model can predict the mixture of $0\hbar\omega$ and $2\hbar\omega$?



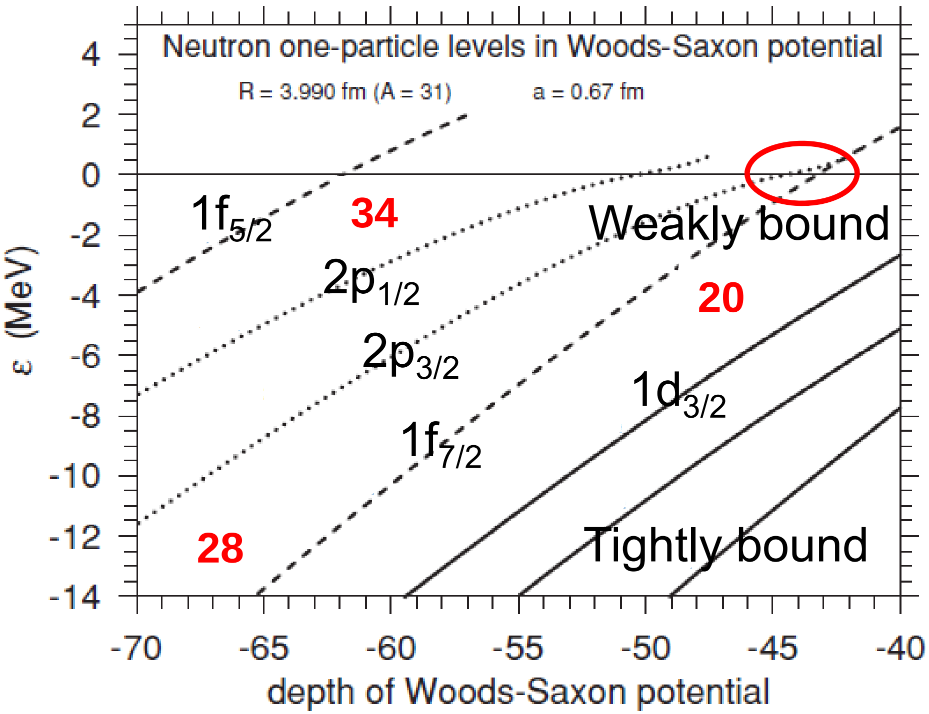
Gade et al.PRL99,072502(2007).
$^{38}Si \rightarrow ^{36}Mg$

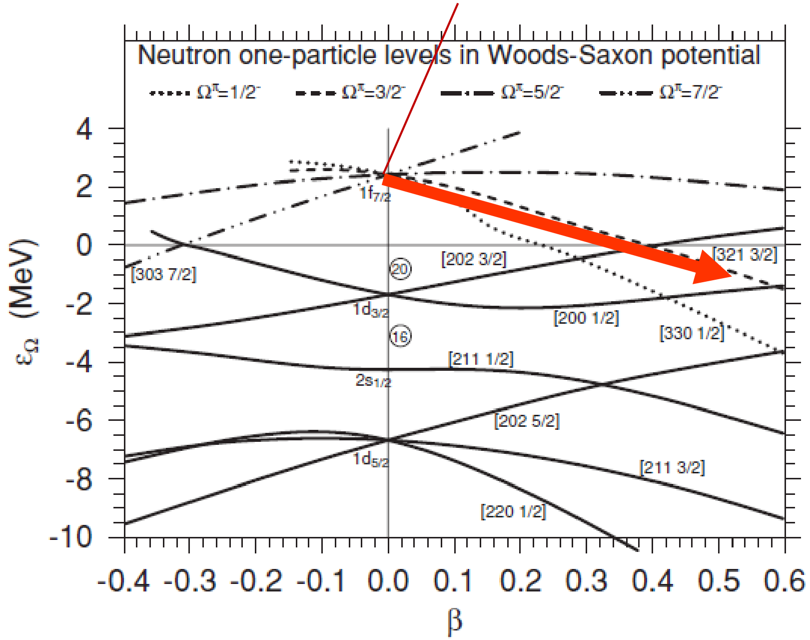
N=21 and N=25 : Very different!

What drives the deformation near Z=10~12, N=20~26?

1. **Weakly bound orbits in mean field**
   → $f_{7/2}$-$p_{3/2}$ degeneracy→Deformation?

$f_{7/2}$-$p_{3/2}$ degeneracy
Jahn-Teller Effect

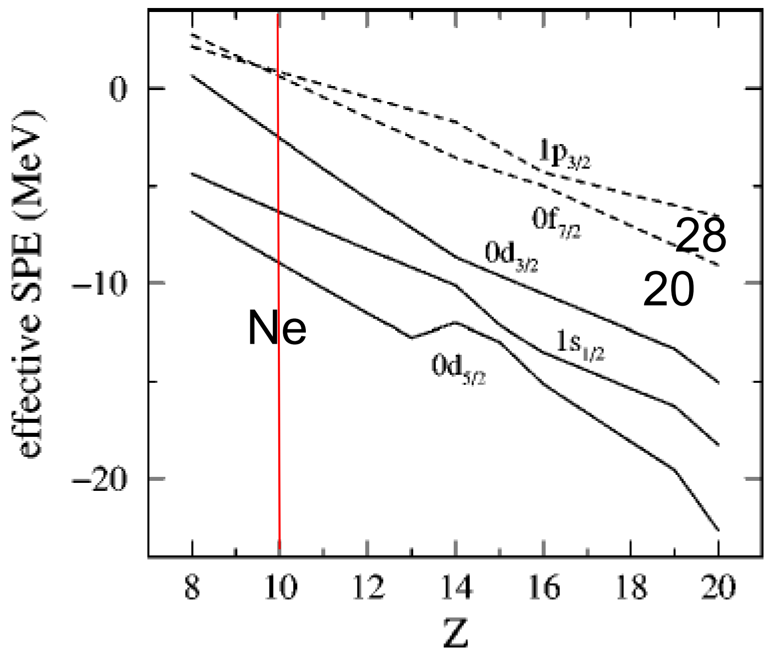




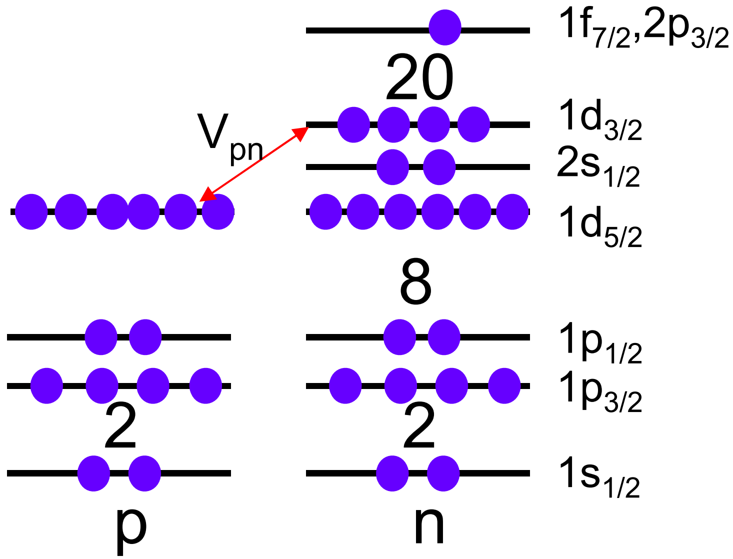
I.Hamamoto PRC76, 054319 (2007).
I.Hamamoto PRC85, 064329 (2012).

What drives the deformation near Z=10~12, N=20~26?

2. **Migration of Effective Single-particle Energy** ←T=0 Monopole interaction
→ **$f_{7/2}p_{3/2}$ degeneracy** (reduced gap of fp-sd)
→ Deformation (for N~20: Equivalent to **$2\hbar\omega$** dominance)

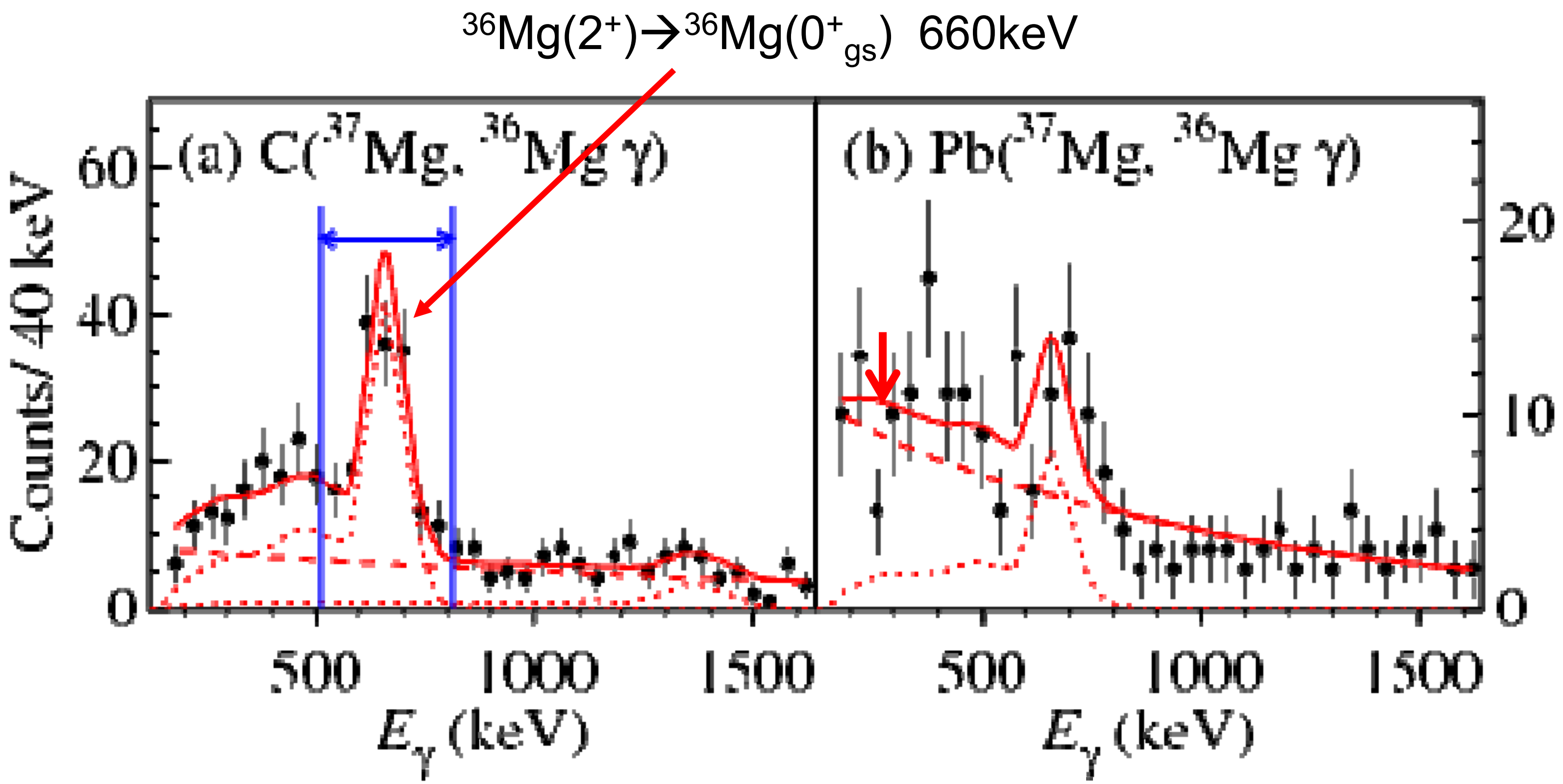


Y. Utsuno et al., PRC60, 054315.



$d_{5/2}$—$d_{3/2}$ ($j_>$--$j_<$)Tensor Force
V_{pn} in the same major shell -- strong

Partial cross section $^{37}Mg \rightarrow {}^{36}Mg(0^+_{g.s.})$



Inclusive σ_{-1n}(C) = 80(4) mb
σ_{-1n}(C; 2^+, 4^+, etc.) = 42(7) mb
→ σ_{-1n}(C; $0^+_{g.s.}$) = 38(8) mb

$0^+_{g.s.}$ / Inclusive=48(10)%

Inclusive σ_{-1n}(E1) = 490(50) mb
σ_{-1n}(E1; 2^+, 4^+, etc.) = 40(60) mb
→ σ_{-1n}(E1; $0^+_{g.s.}$) = 450(80) mb

$0^+_{g.s.}$ / Inclusive=92(19)%