Probing Neutron Halo Nuclei by Breakup Reactions

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Eg. ^{11}Be, ^{11}Li, ^{14}Be

2 Coulomb/Nuclear Breakup of ^{31}Ne and ^{22}C

at RI Beam Factory, RIKEN

^{31}Ne : T. Nakamura, N.Kobayashi et al., PRL 103, 262501 (2009).

3 Coulomb/Nuclear Breakup of ^{29}Ne,^{33,35,37}Mg, and ^{39,41}Si

at RI Beam Factory, RIKEN

Preliminary

4 Summary and Outlook

Evolution Towards the Stability Limit

Where is the neutron drip line?

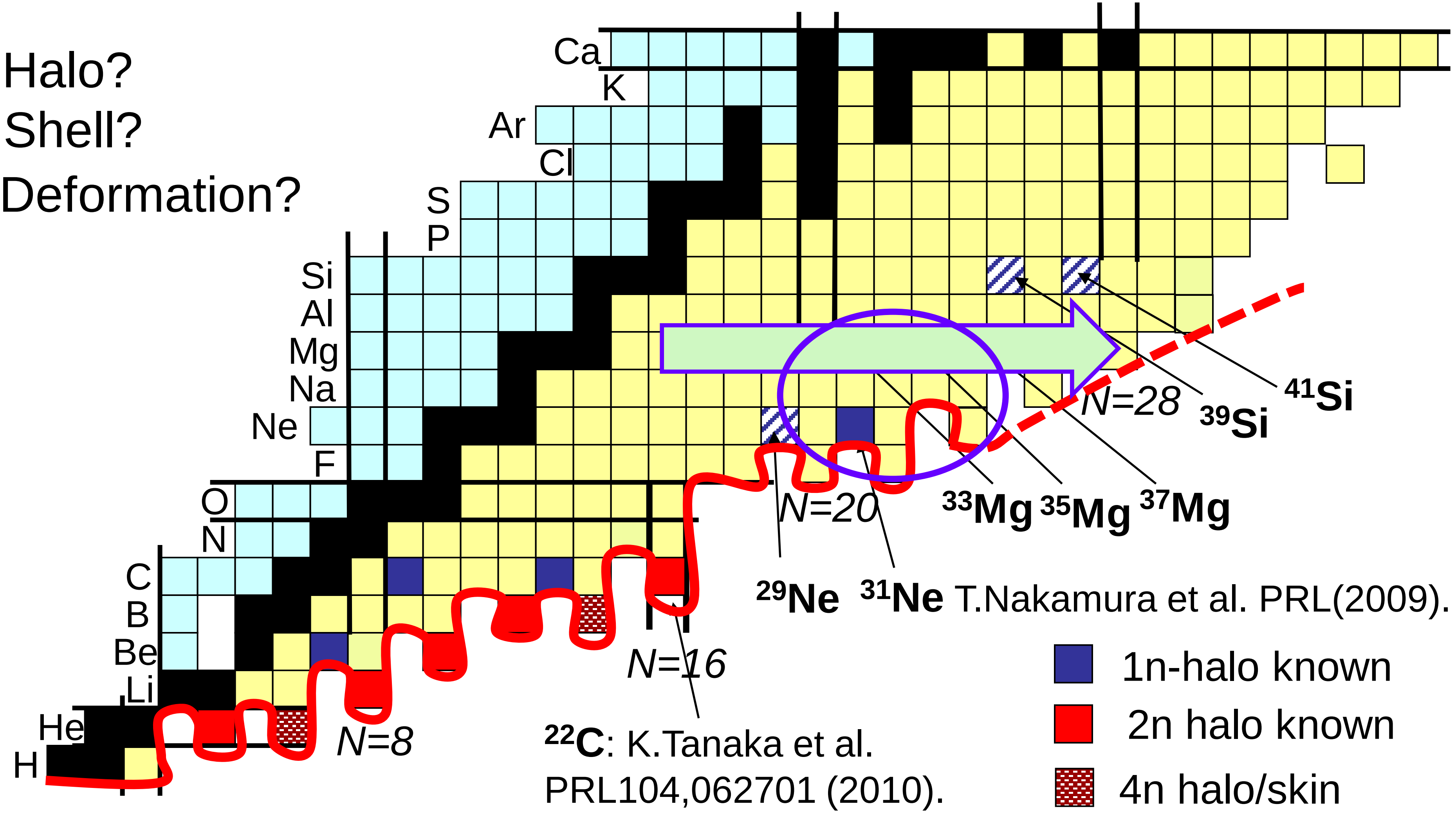
What are characteristic features of drip-line nuclei?

How does nuclear structure evolve towards the drip line?

Halo?

Shell?

Deformation?



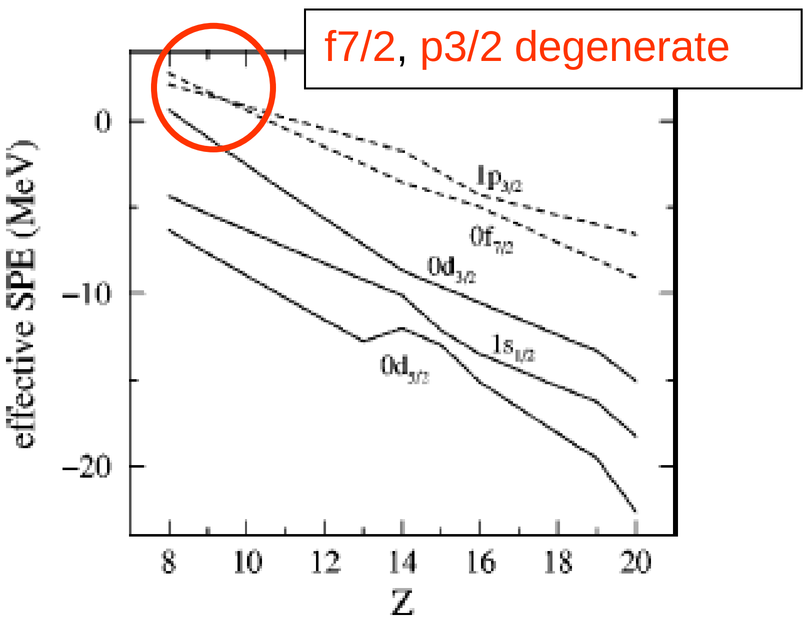
Condition of Halo Formation (1n halo nuclei)

- Low S_n value (<~1MeV)
- Dominance of s or p orbital for the valence neutron

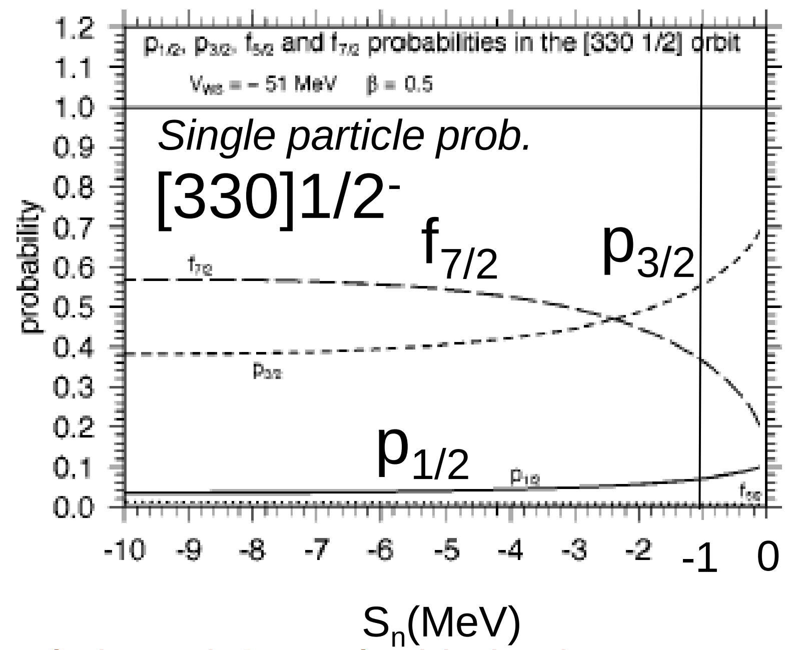
20<N<28→ valence neutron: $f_{7/2}$

Conventional Shell order forbids the formation of halo

Shell-melting, Deformation →Halo formation?



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



Loosely-bound →Low l orbit dominance

I.Hamamoto PRC69, 041306(R)(2004).
Misu et al. NPA614, 44(1997).

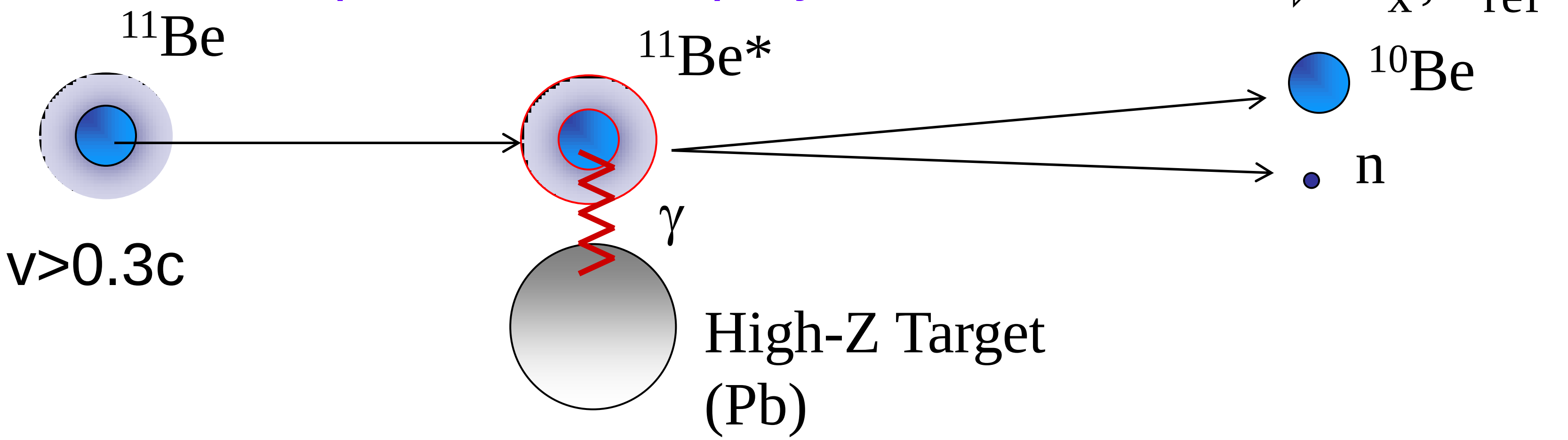
Probe-1: **Coulomb Breakup**

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

Invariant Mass

$\Rightarrow E_x, E_{rel}$

→Photon absorption of a fast projectile

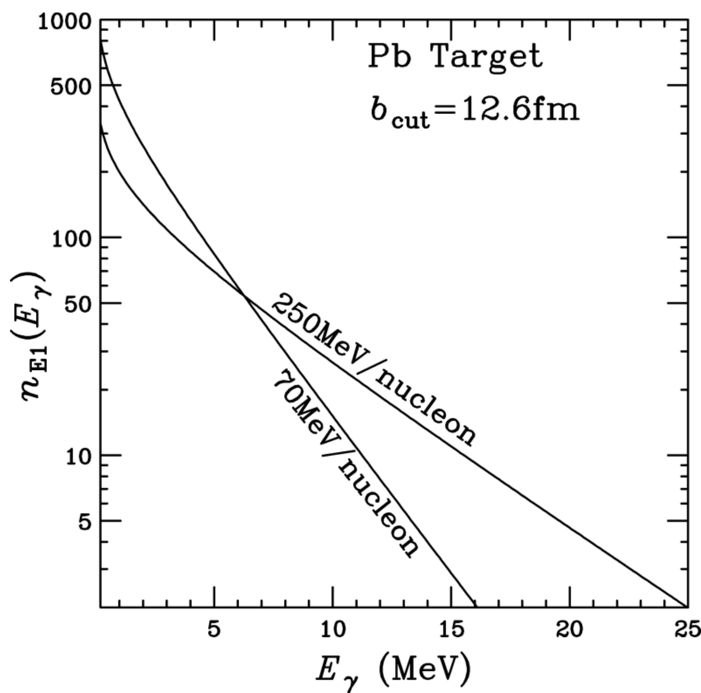


Equivalent Photon Method

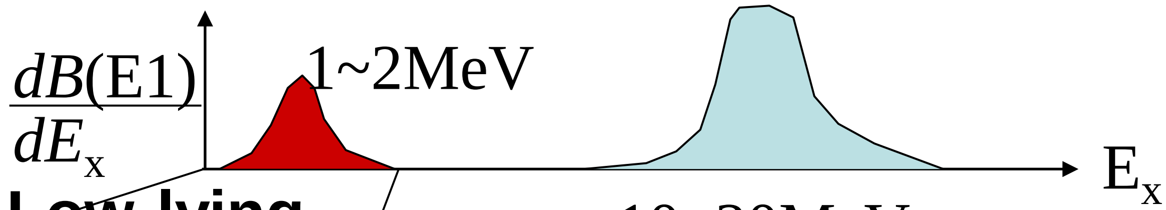
$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(\mathrm{E1})}{dE_x}$$

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

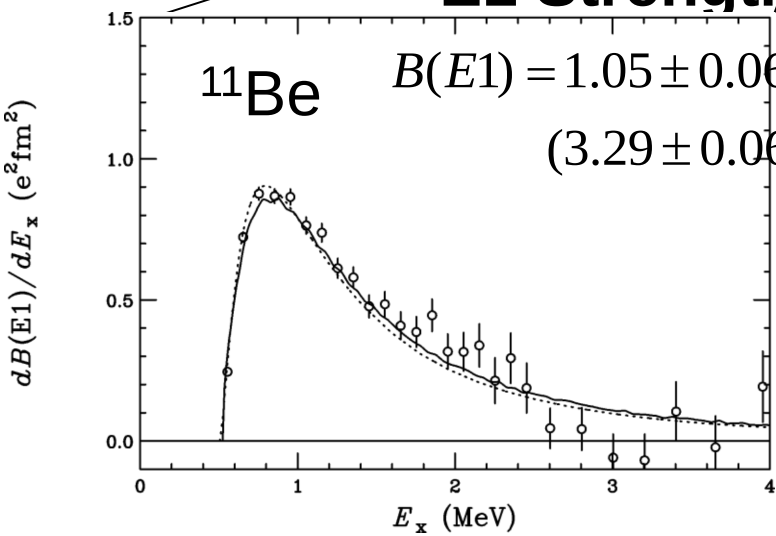
C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).



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



Low-lying
E1 Strength (Soft E1 excitation)

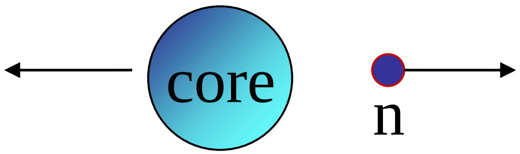


$B(E1) = 1.05 \pm 0.06\ e^2\text{fm}^2$

$(3.29 \pm 0.06\ \text{W.u})$

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

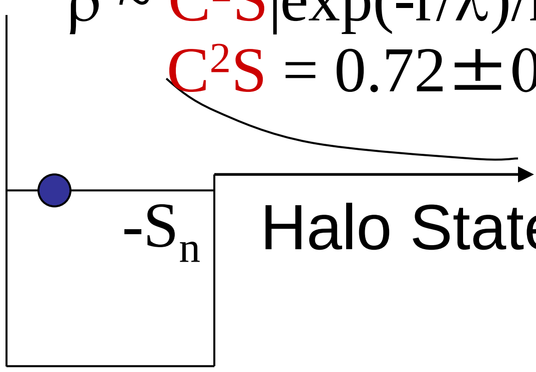
$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} rY^1{}_m|\Phi_{gs}\rangle|^2$$

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

Fourier Transform

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

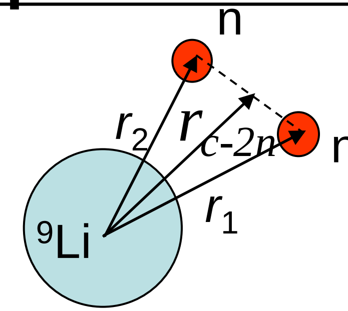
$C^2S = 0.72 \pm 0.04$

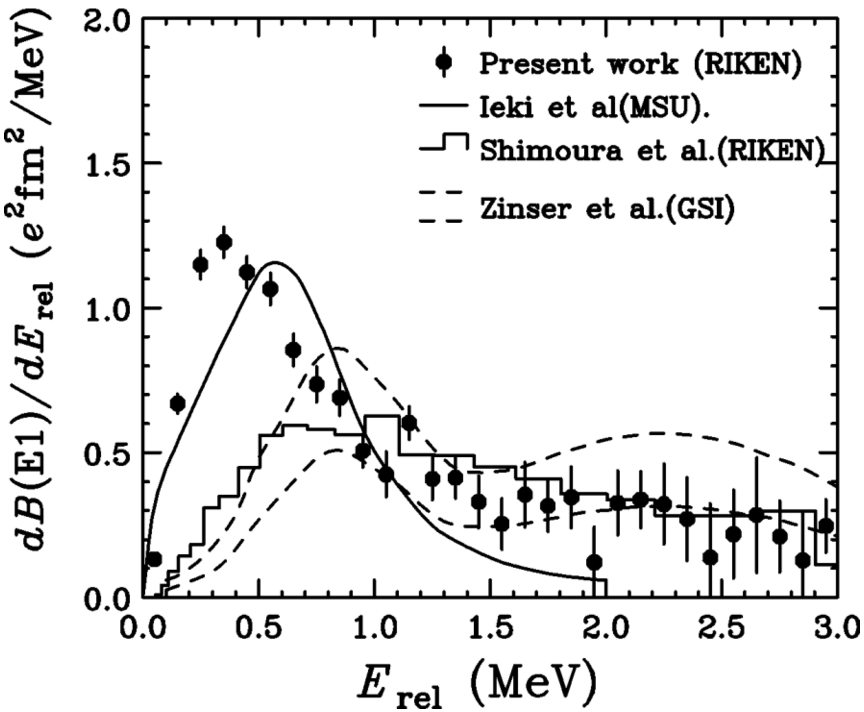


Soft E1 Excitation of 1n halo—Sensitive to S_n, l , C^2S

Dineutron Correlation in ^{11}Li (Coulomb Breakup of 2n halo)

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



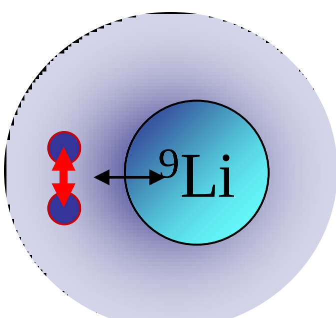


$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x$$

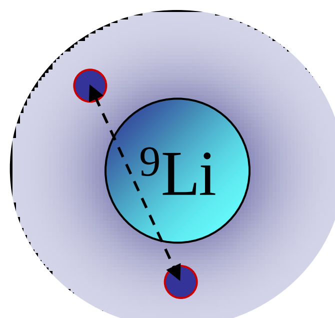
$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\,2} + r_2^{\,2} + 2(\vec{r}_1 \cdot \vec{r}_2)\right\rangle$$

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

$$\rightarrow 1.78(22)\, e^2\, fm^2 \rightarrow \theta_{12} = 48^{+14}_{-18}\,\mathrm{deg}.$$



Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation



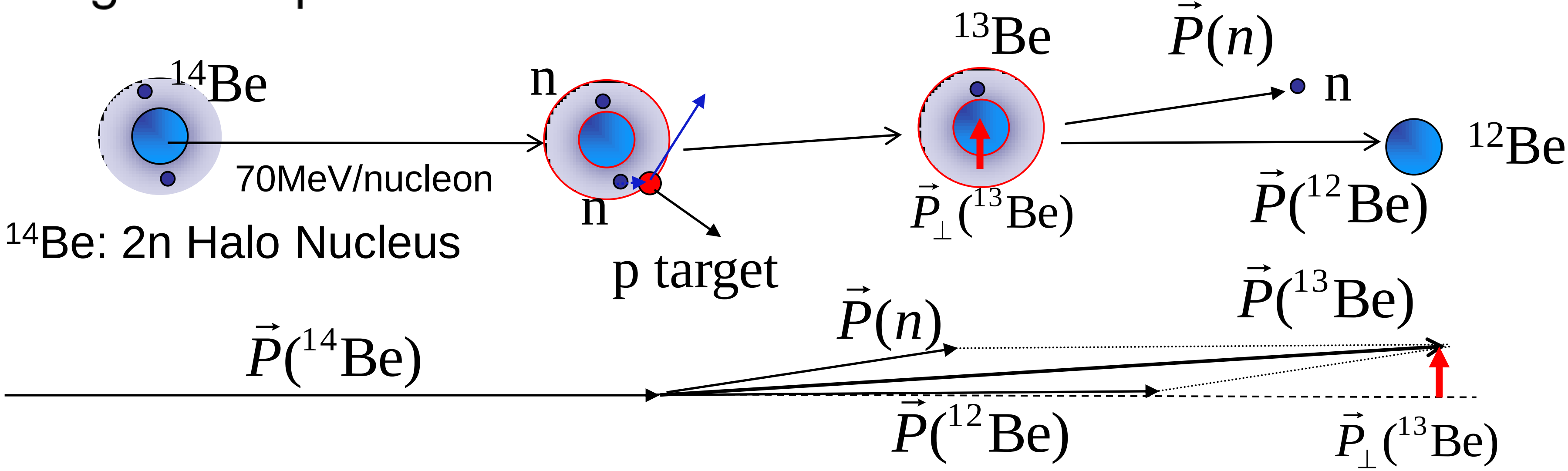
Weak 2n correlation
→Weakly Polarized
→Weak E1 Excitation

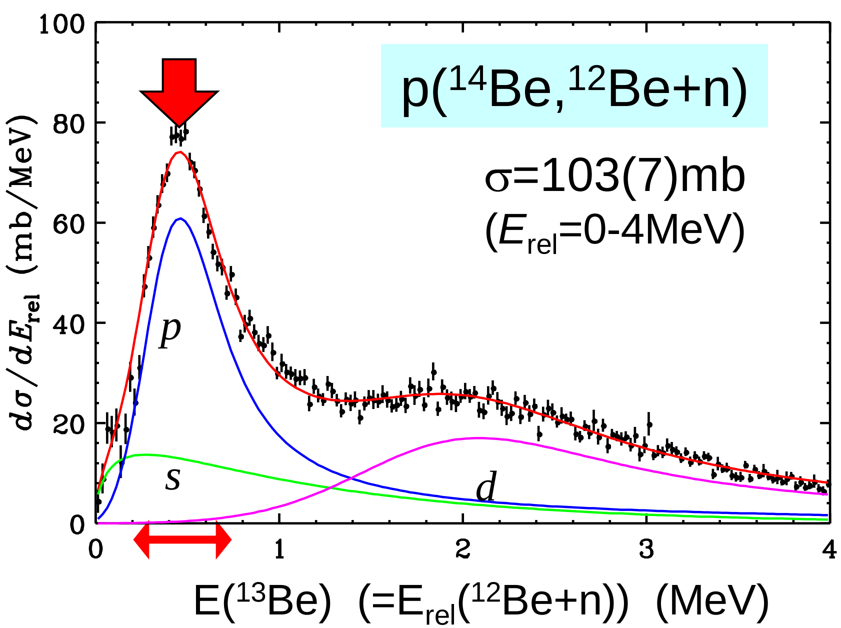
Soft E1 Excitation of 2n-halo—+dineutron-like correlation

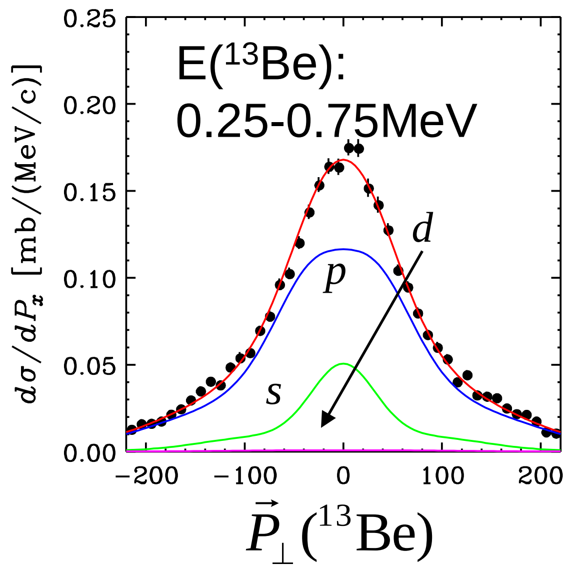
Probe-II: **Nuclear Breakup** (momentum distribution)

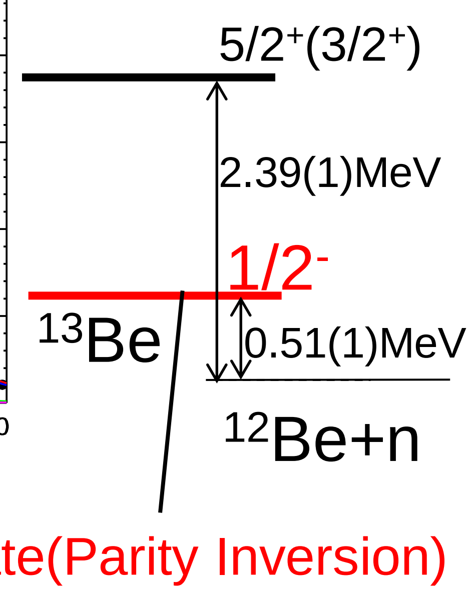
Y.Kondo,TN et al.PLB 690, 245 (2010).

Eg. $^{14}Be+p \rightarrow ^{13}Be+X$









2

Coulomb Breakup of ^{31}Ne and ^{22}C

Nuclear Breakup of ^{31}Ne

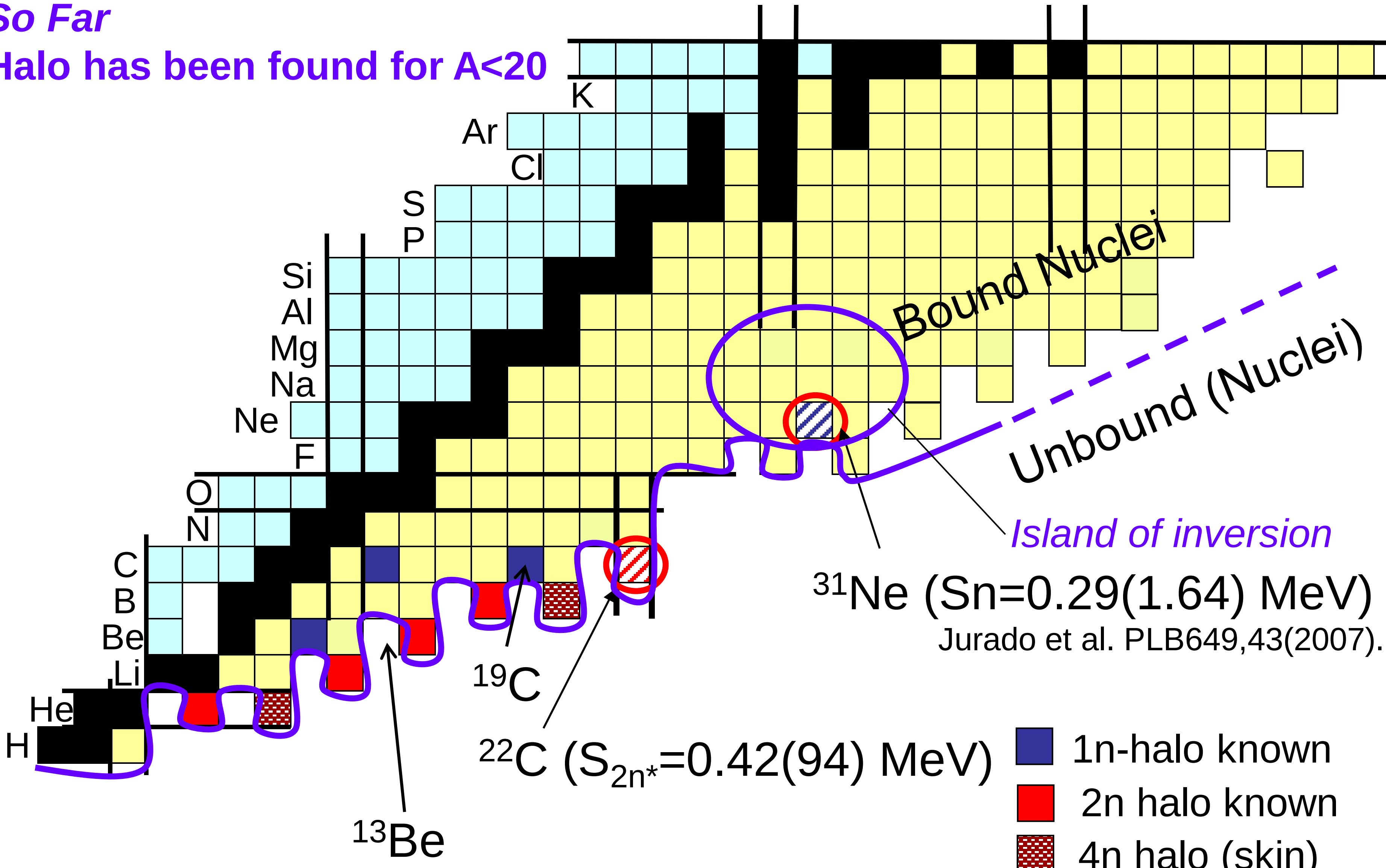
@ RI Beam Factory, RIKEN

^{31}Ne Coulomb Breakup:

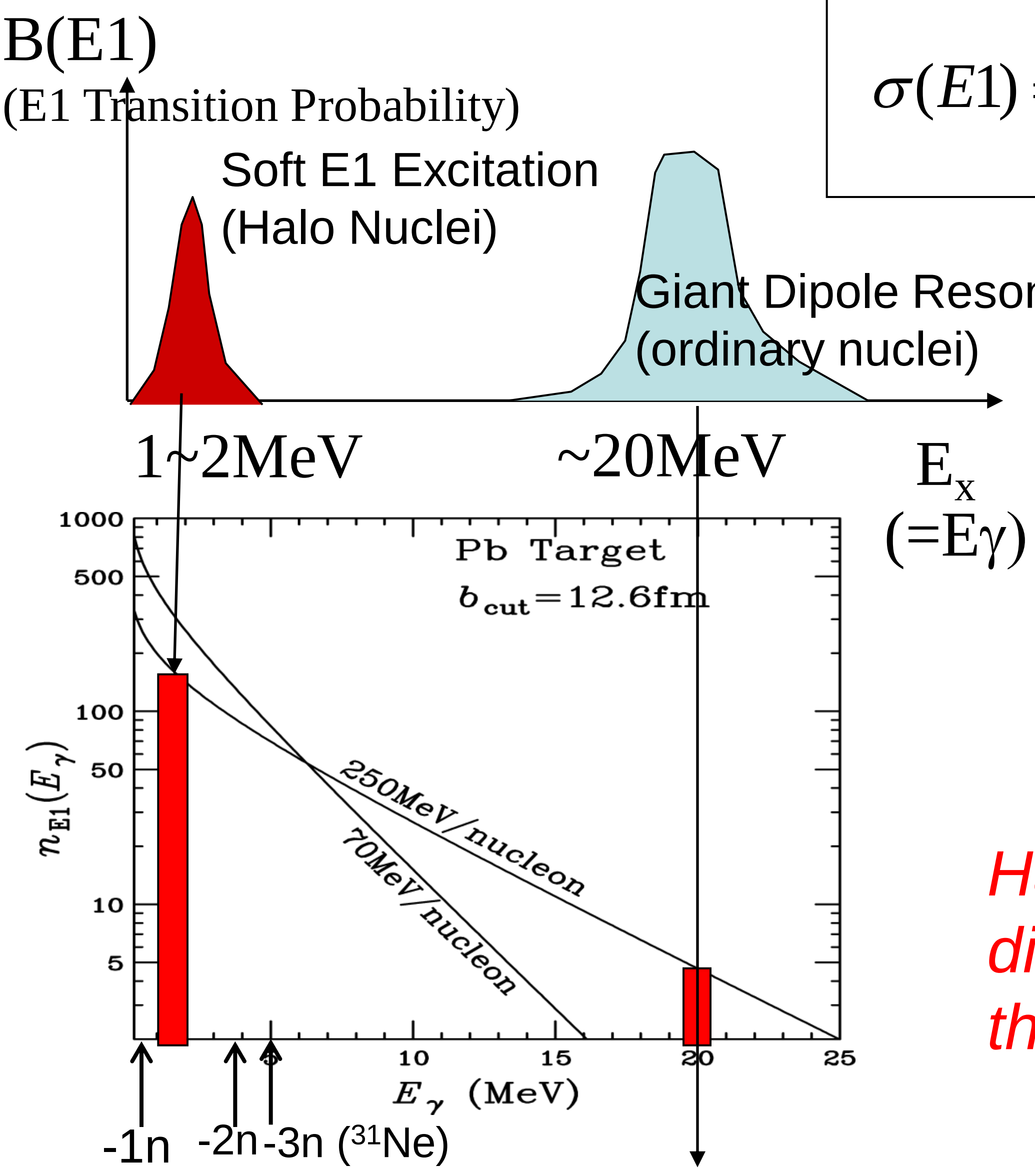
T. Nakamura, N.Kobayashi et al., PRL 103, 262501 (2009).

How Halo is formed in heavy drip-line nuclei?
Halo is abundant?

So Far
Halo has been found for A<20



Inclusive Coulomb Breakup



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

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

$^{22}C+Pb \rightarrow ^{20}C+X$

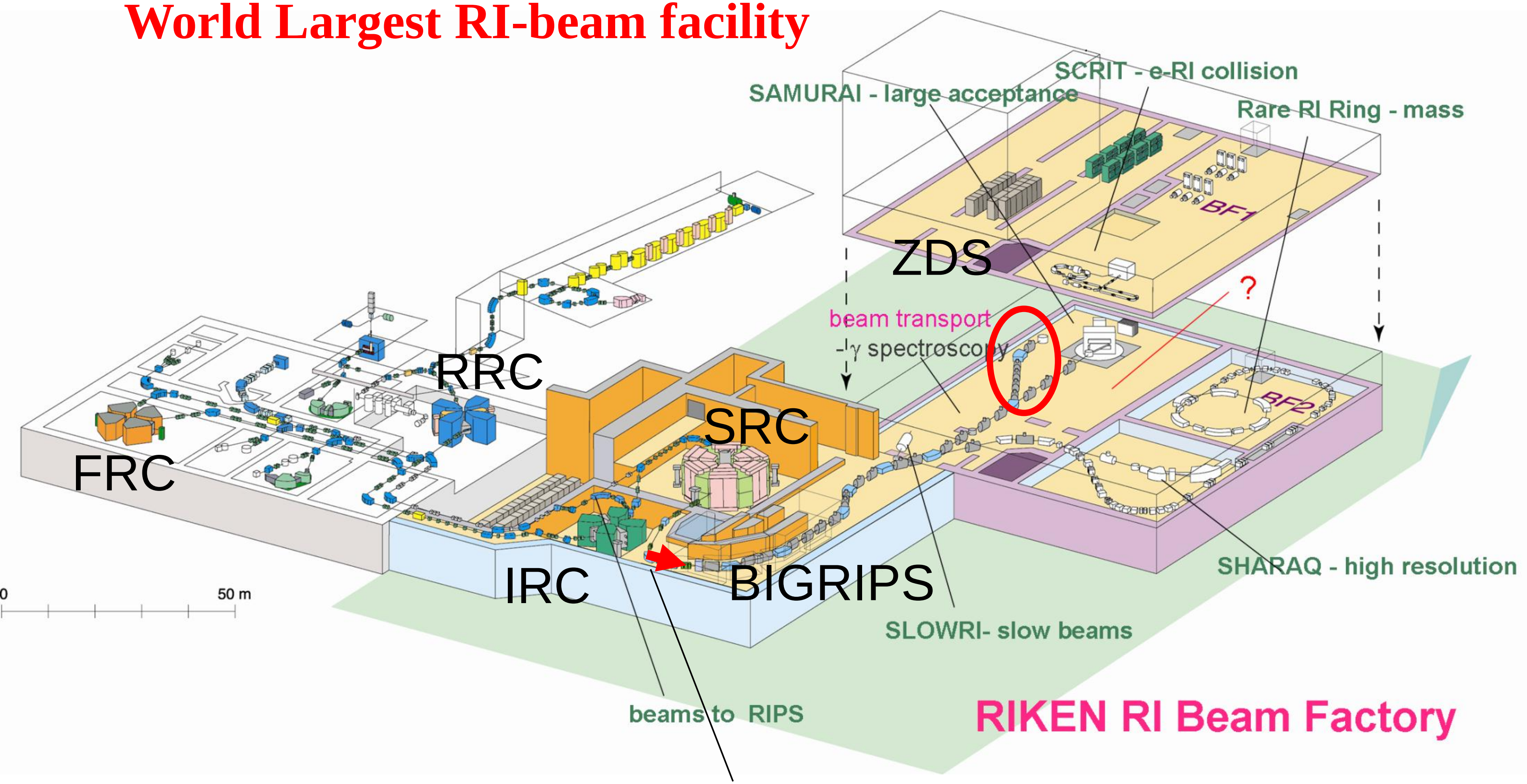
Halo/Non Halo can be distintinguished only from the inclusive cross section !

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

<~0.1b

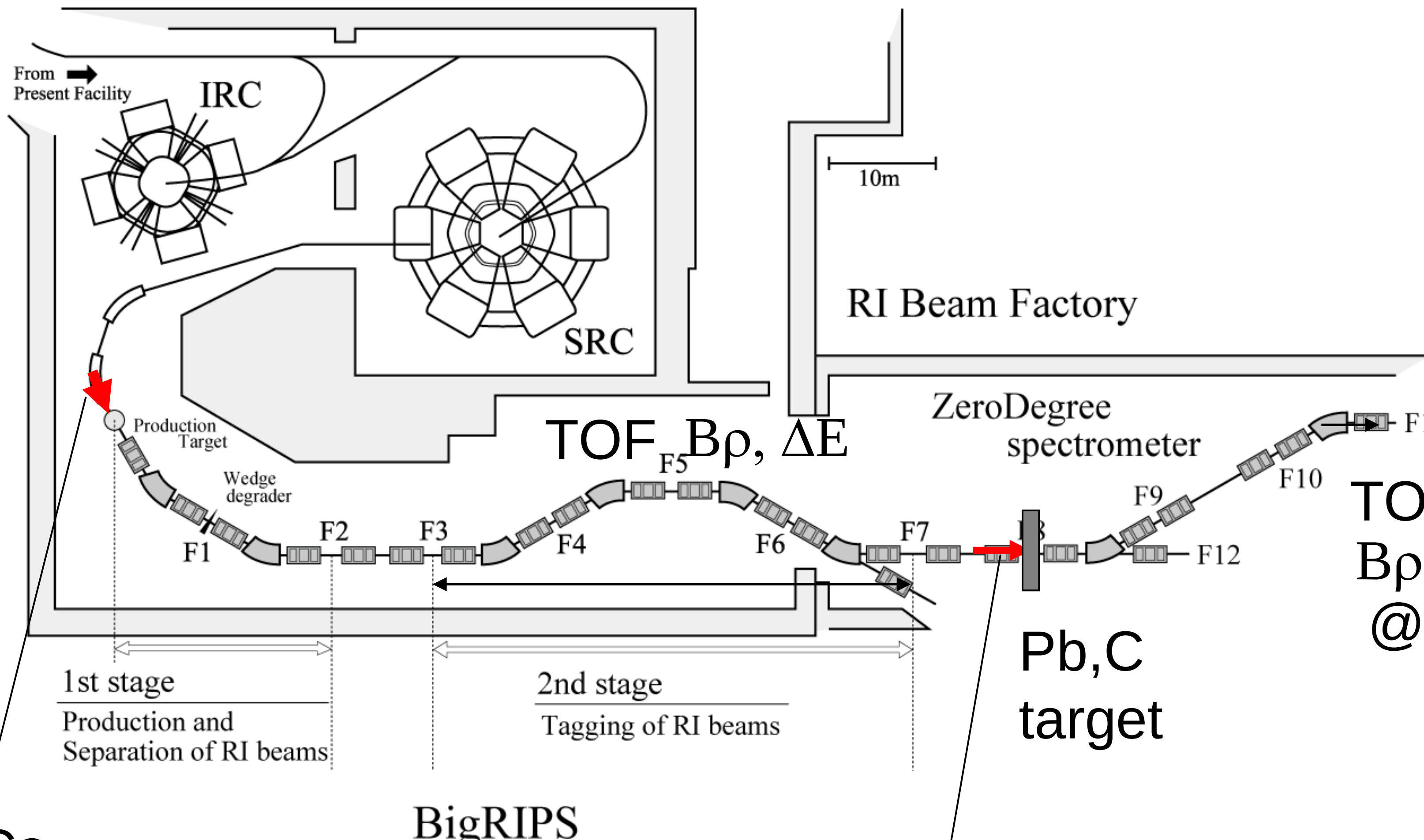
RIKEN RI Beam Factory (RIBF)

Completed in 2007
World Largest RI-beam facility



^{48}Ca 345MeV/nucleon
~60pnA (Typical)

Experiment at BigRIPS & ZDS at RIBF



TOF$_{F5}$ Bρ, ΔE

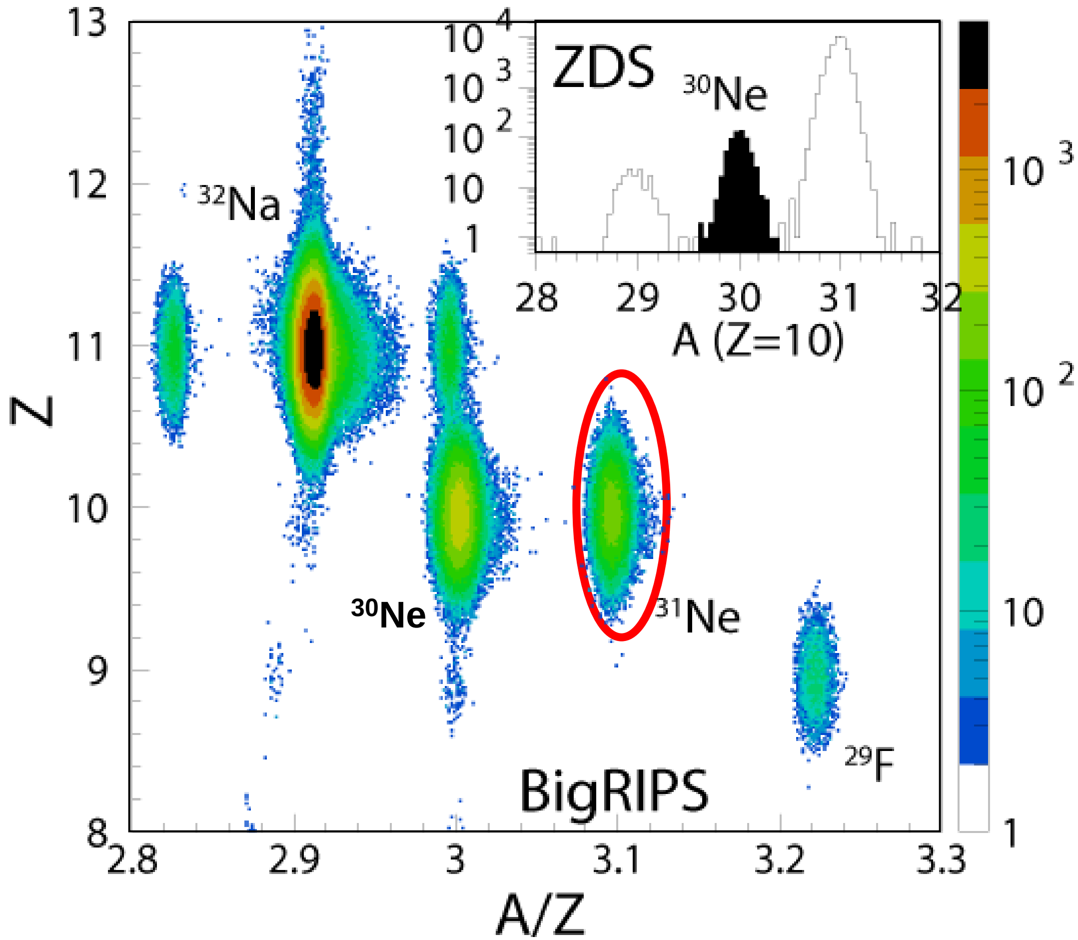
TOF,ΔE
Bρ
@ZDS

Pb,C
target

^{48}Ca
345MeV/nucleon
60-150pnA

^{19}C,^{20}C,^{22}C ~240MeV/nucleon
^{31}Ne ~230MeV/nucleon

Particle Identification: $^{31}Ne \rightarrow ^{30}Ne$



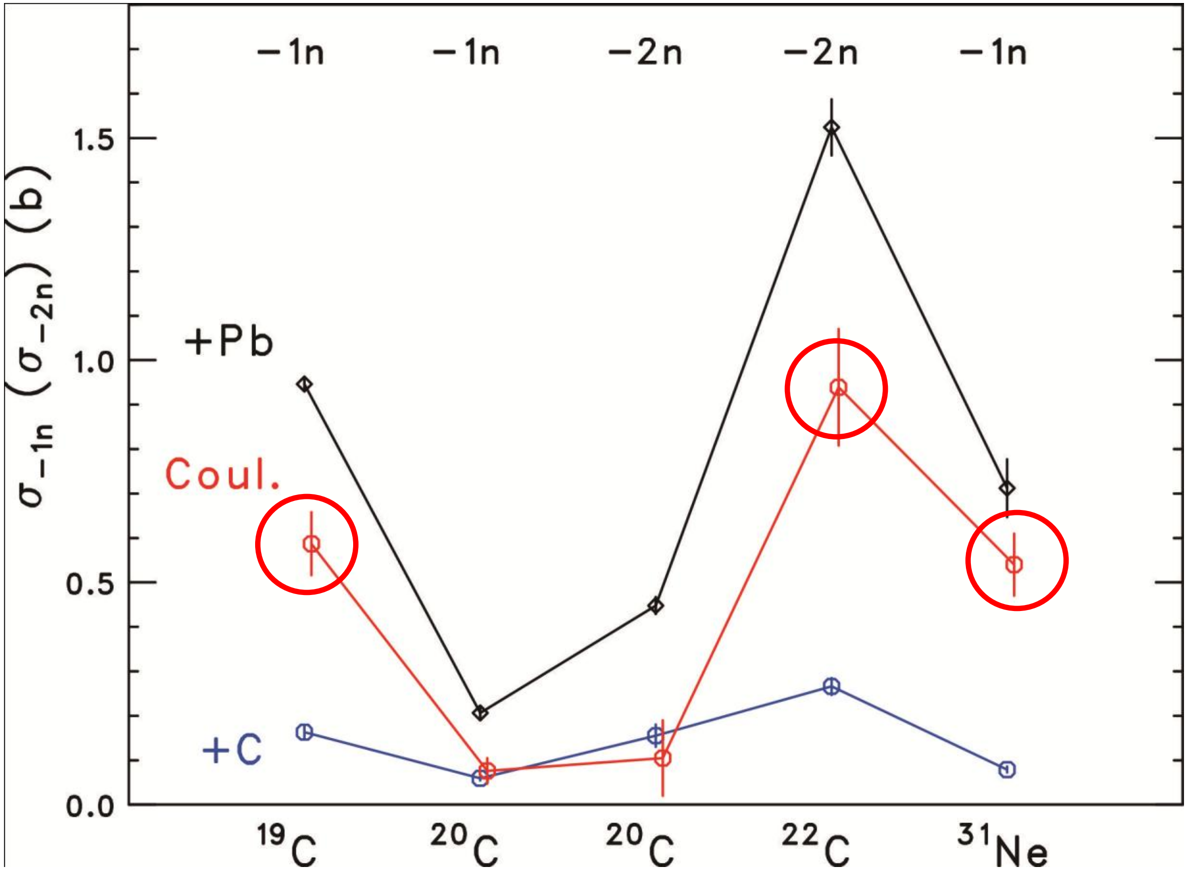
RI beam Intensity @RIBF
~10^3-10^4 times/RIPS

^{31}Ne ~5 counts/s
^{22}C ~ 6 counts/s

c.f. *About 10years ago…*
^{31}Ne -- 4 counts/day @RIPS
H.Sakurai et al., PRC54,2802R(1996).

1n(or 2n) removal cross section

→Coulomb breakup cross section



Evidence for

2n Halo in ^{22}C

1n Halo in ^{31}Ne

c.f. ^{19}C (known halo)

$$\sigma(E1) = \sigma(Pb) - \Gamma\sigma(C)$$

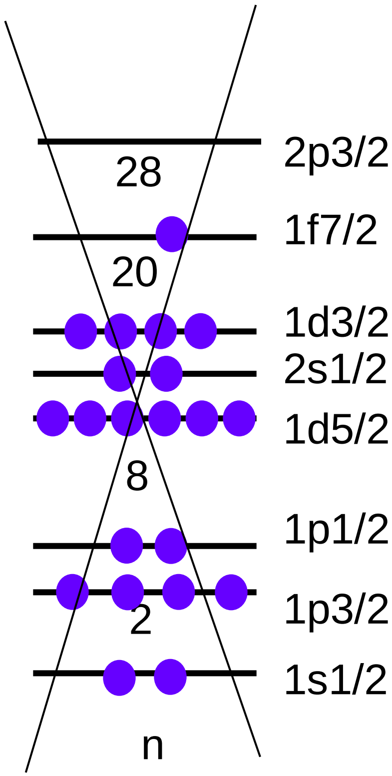
$$\Gamma =\sim 1.7 - 2.6$$

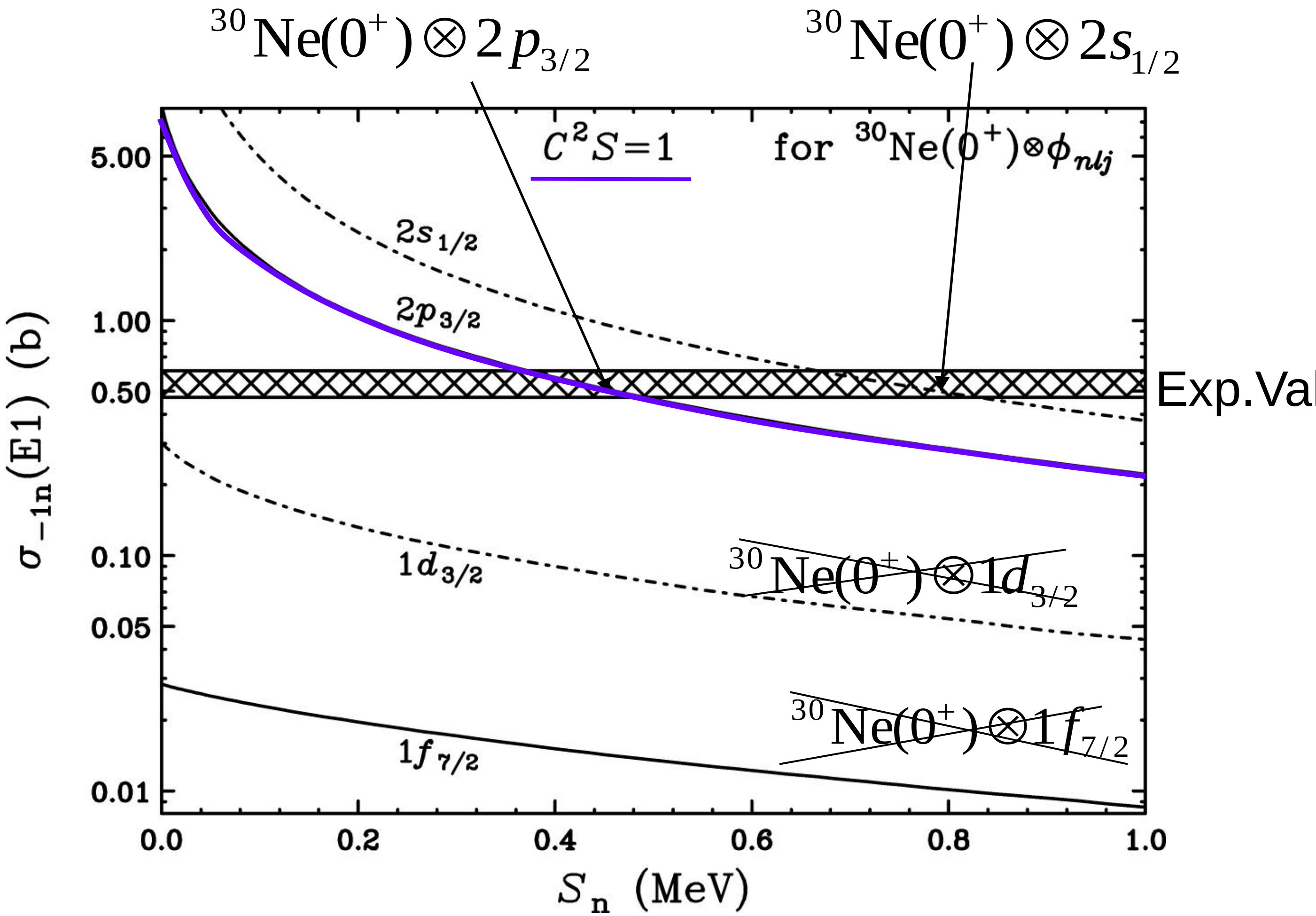
S_n:0.58(9) , 2.93(28), S_{2n}:3.51(24), 0.42(94), S_n:0.29(1.64) in MeV

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

^{31}Ne: Reaction cross section, M. Takechi et al.(2011)

^{31}Ne (N=21) Shell Configuration





$2p_{3/2}$ or $2s_{1/2}$ <u>Low-L orbits</u> → Large E1 → 1n-halo structure of ^{31}Ne

^{30}Ne(0$^+$)X1$f_{7/2}$ Excluded → Shell gaps(20,28) vanish at ^{31}Ne

→ Island of inversion

Still Unknown: Sn/Configuration Mixing C^2S<1

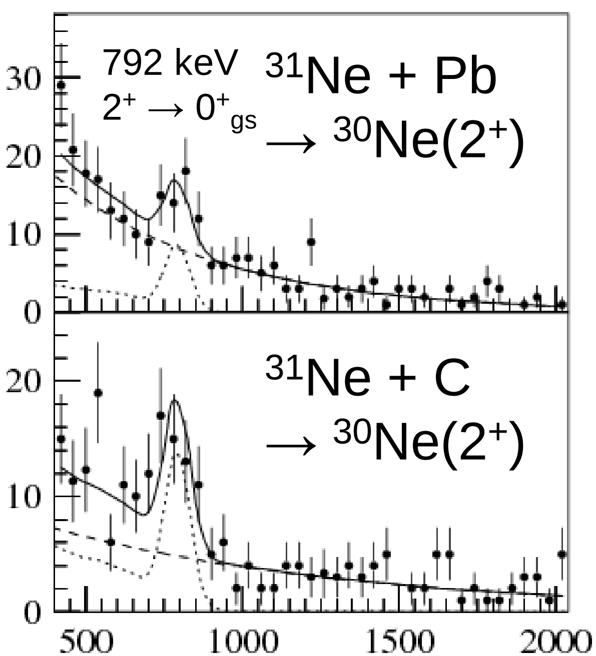
How the ^{31}Ne g.s. is made of ?

→ γ and Nuclear Breakup data

Monte Carlo Shell Model
by Utsuno ,Otsuka
→ 3/2^{-} g.s.

$$^{30}\mathrm{Ne}(0^+)\otimes 2p_{3/2} \quad C^2S = 0.12$$
$$^{30}\mathrm{Ne}(2^+)\otimes 2p_{3/2} \quad C^2S = 0.27$$
$$^{30}\mathrm{Ne}(2^+)\otimes 1f_{7/2} \quad C^2S = 0.25$$

Possible Large Proportion for the ^{30}Ne(2$^+$)x(nlj) Configuration



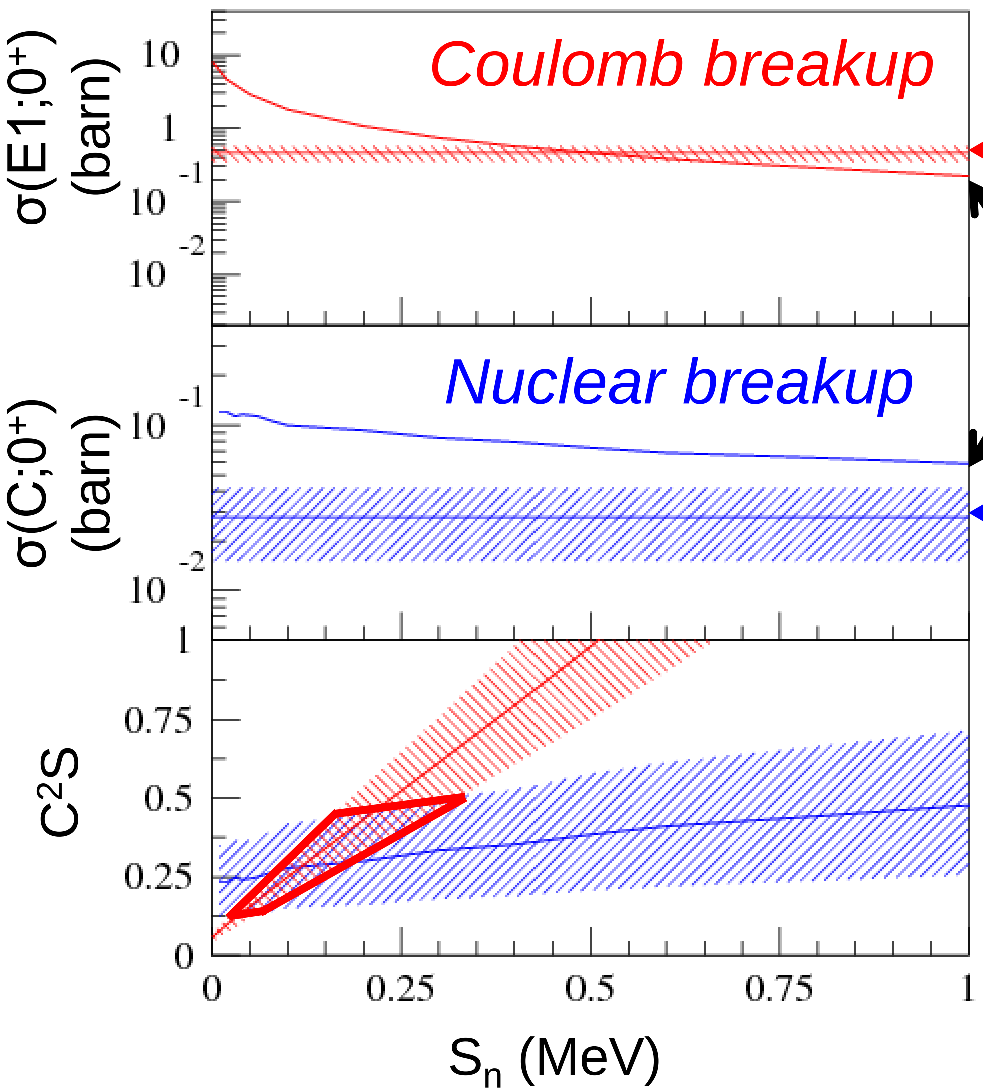
^{31}Ne+Pb→^{30}Ne(0$^+$) : 0.515(103) barn
^{31}Ne+Pb→^{30}Ne(2$^+$) : 0.197(79) barn

→σ(E1;0$^+$) = 0.45(11) barn
(~90% of Total σ(E1)=0.54(7)barn)

^{31}Ne+C→^{30}Ne(0$^+$) : 0.028(13) barn ~35%
^{31}Ne+C→^{30}Ne(2$^+$) : 0.051(12) barn ~65%

Estimation of C^2S & S_n

Channel: $^{31}Ne \rightarrow {}^{30}Ne(0^+)$



Exp. 0.45(11) barn

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

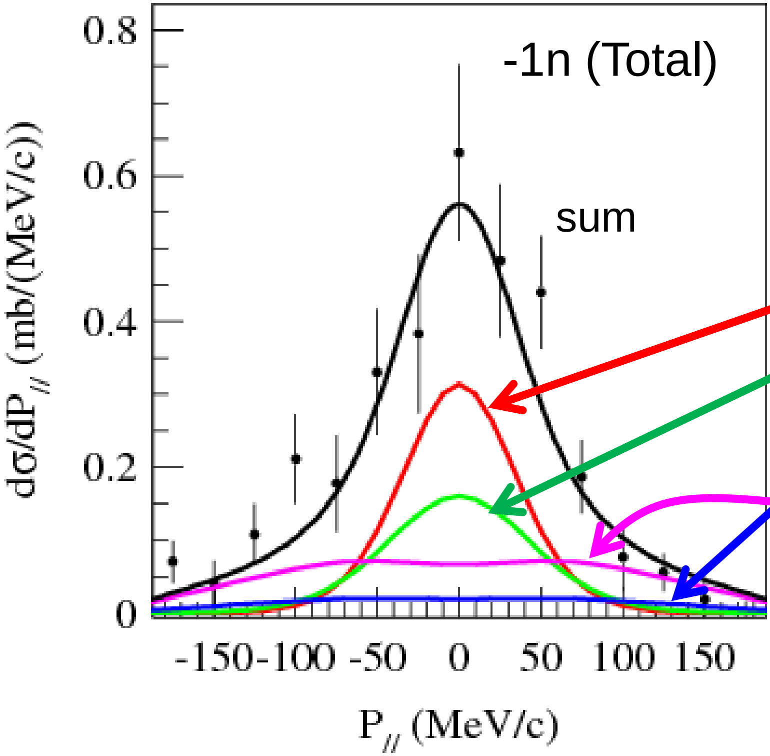
Exp. 0.028(13) barn

$$S_n = 0.12^{+0.21}_{-0.09}\ \mathrm{MeV}$$

$$C^2S = 0.28^{+0.23}_{-0.15}$$

Preliminary

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



Resolution(σ)= 24 MeV/c
Γ (FWHM) =73(11) MeV/c

S_n =0.12 MeV

state	C^2S	σ(barn)
$|^{30}Ne(0^+)\otimes 2p_{3/2}\rangle$	0.28	0.028
$|^{30}Ne(2^+)\otimes 2p_{3/2}\rangle$	0.27	0.018
$|^{30}Ne(2^+)\otimes 1f_{7/2}\rangle$	0.25	0.0058
$|^{30}Ne(4^+)\otimes 1f_{7/2}\rangle$	1.06	0.021
	total	0.073 b

Exp.

(0.079(7)b)

Shell model calculation
by using SDPF-M interaction

Preliminary

"p-wave neutron halo composed of two components"

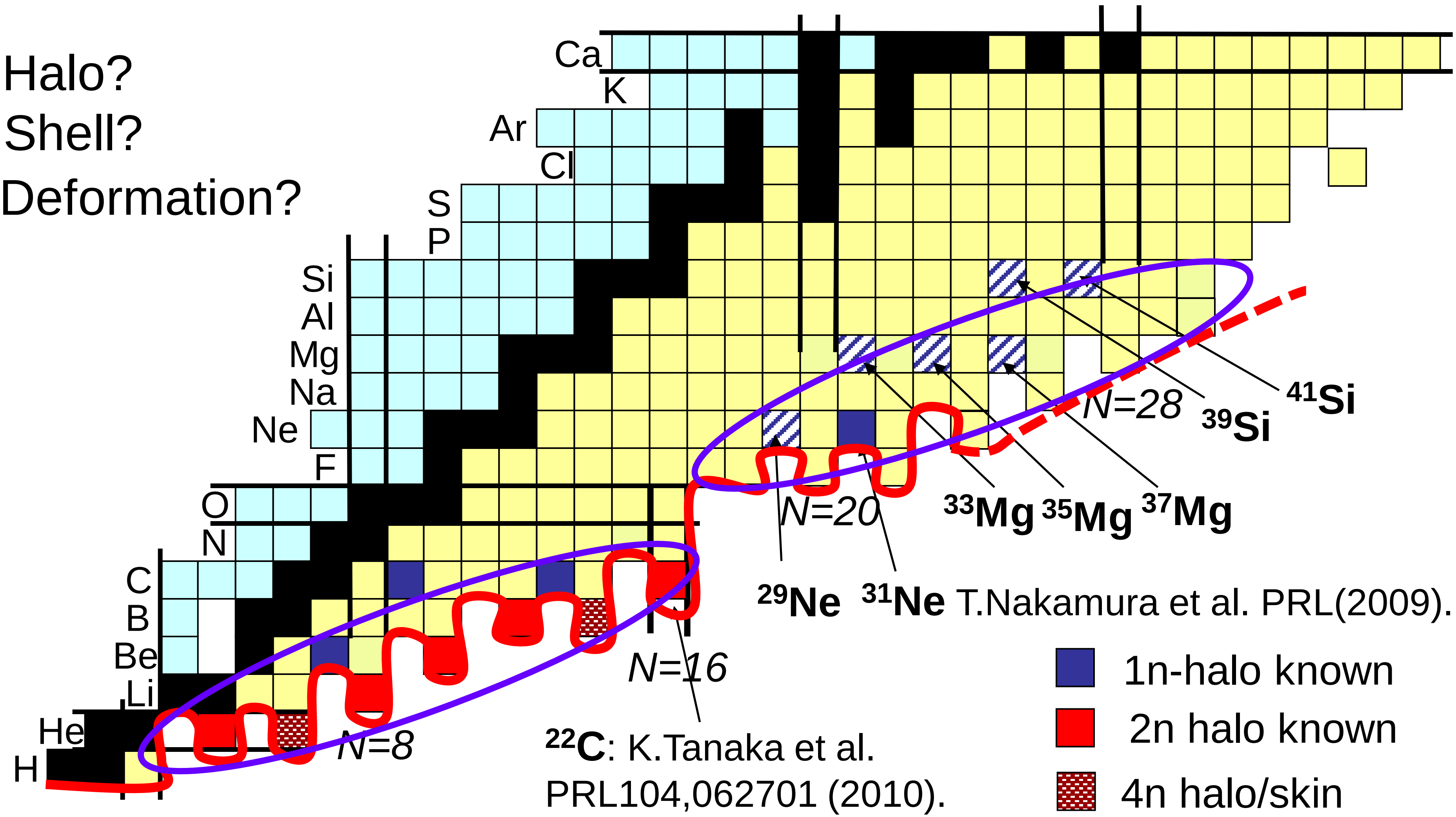
3

Inclusive Coulomb Breakup of ^{29}Ne, ^{33,35,37}Mg, and ^{39,41}Si @ RIKEN RI BEAM FACTORY

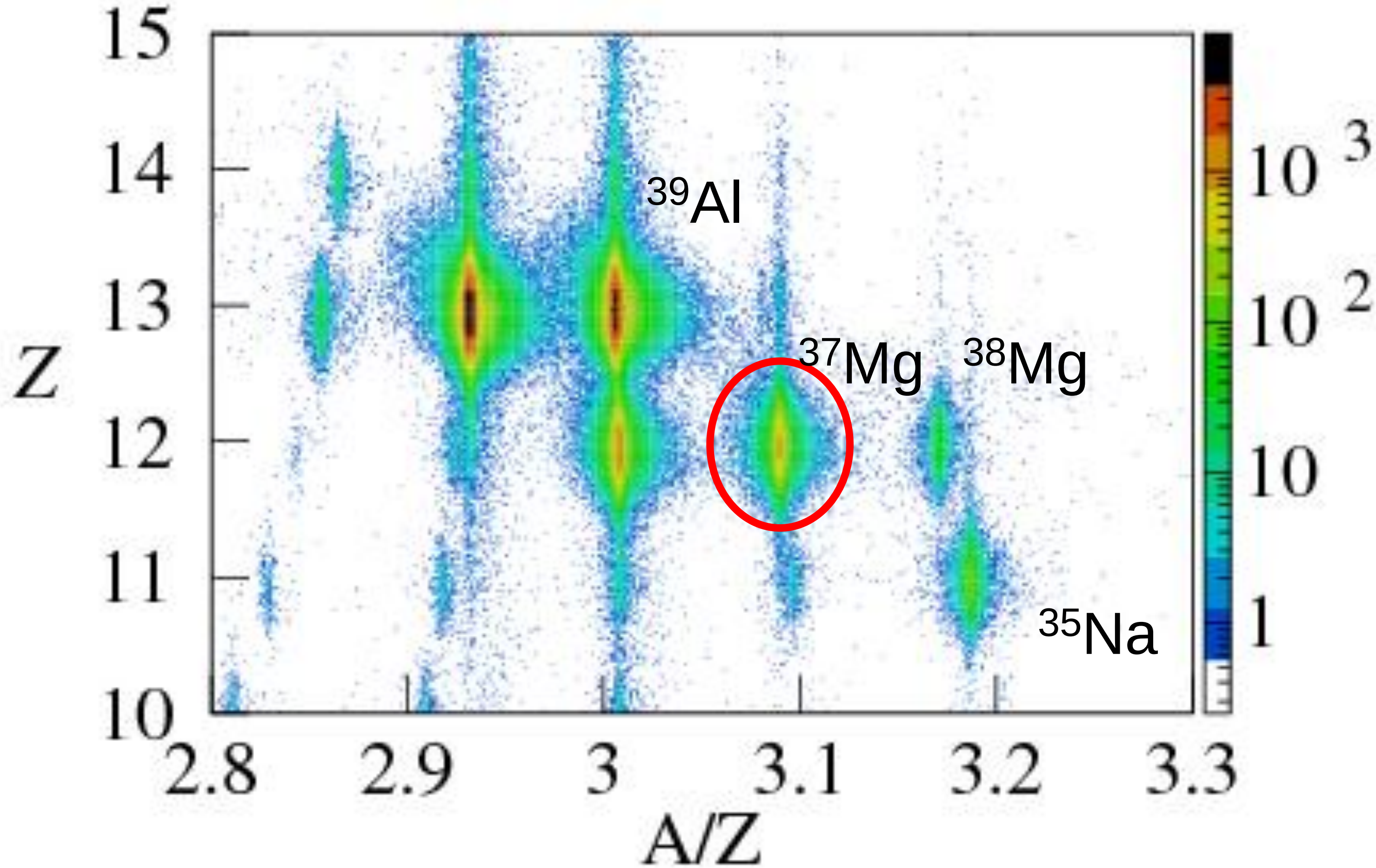
^{48}Ca
345MeV/nucleon
~120pnA
(~Double compared to Day-one exp)

Evolution Towards the Stability Limit
A 30~40 (20<N<28)

Halo?
Shell?
Deformation?



Particle Identification: ^{37}Mg



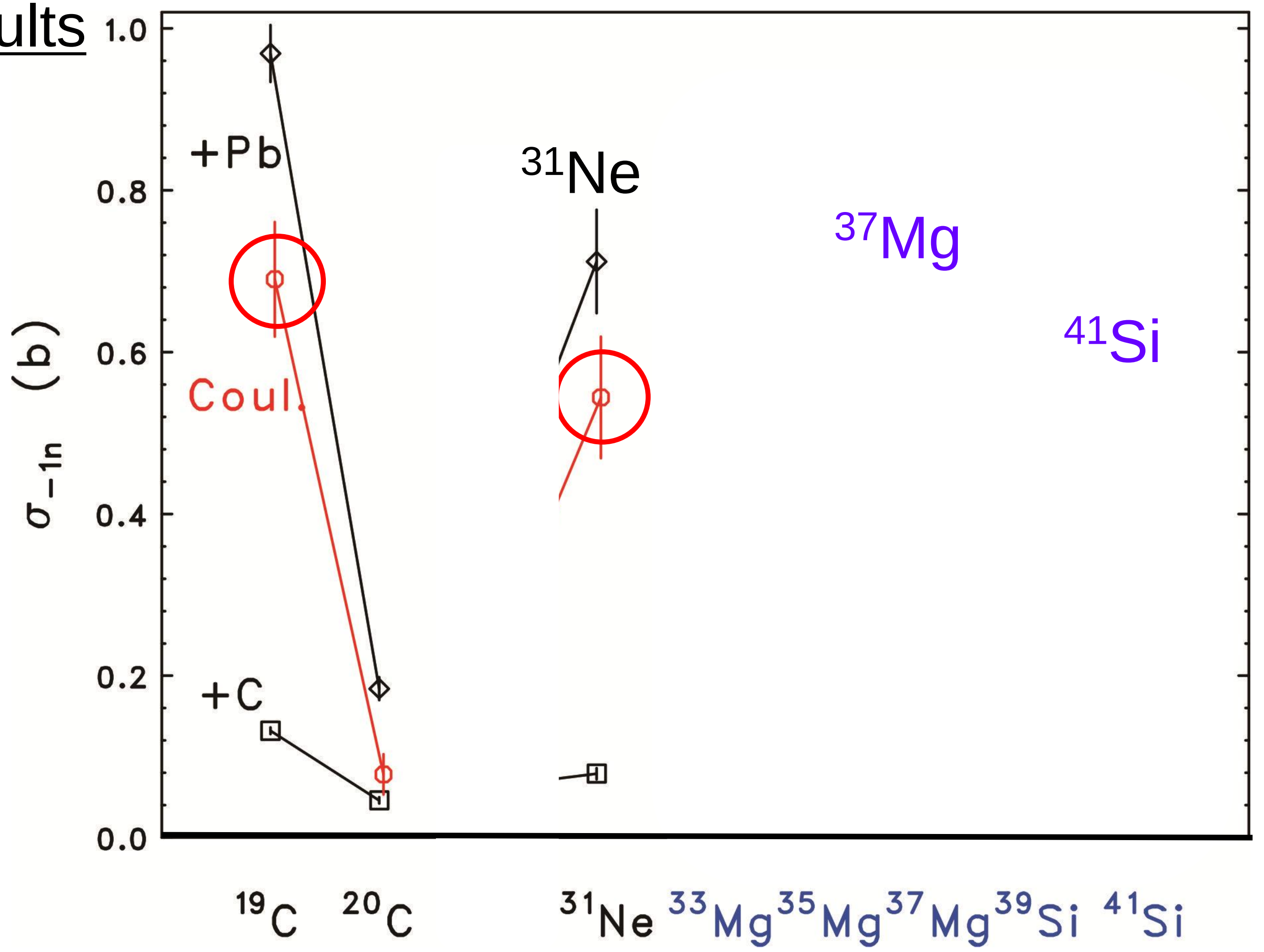
^{37}Mg: 244MeV/nucleon

~6 cps

^{35}Mg: 245MeVnucleon ~100cps

^{41}Si: 229 MeV/nucleon ~ 230cps

Results



^{37}Mg: σ(E1)=500(50) mb *(preliminary)*

→ *^{37}Mg: Possible 1n-Halo State*

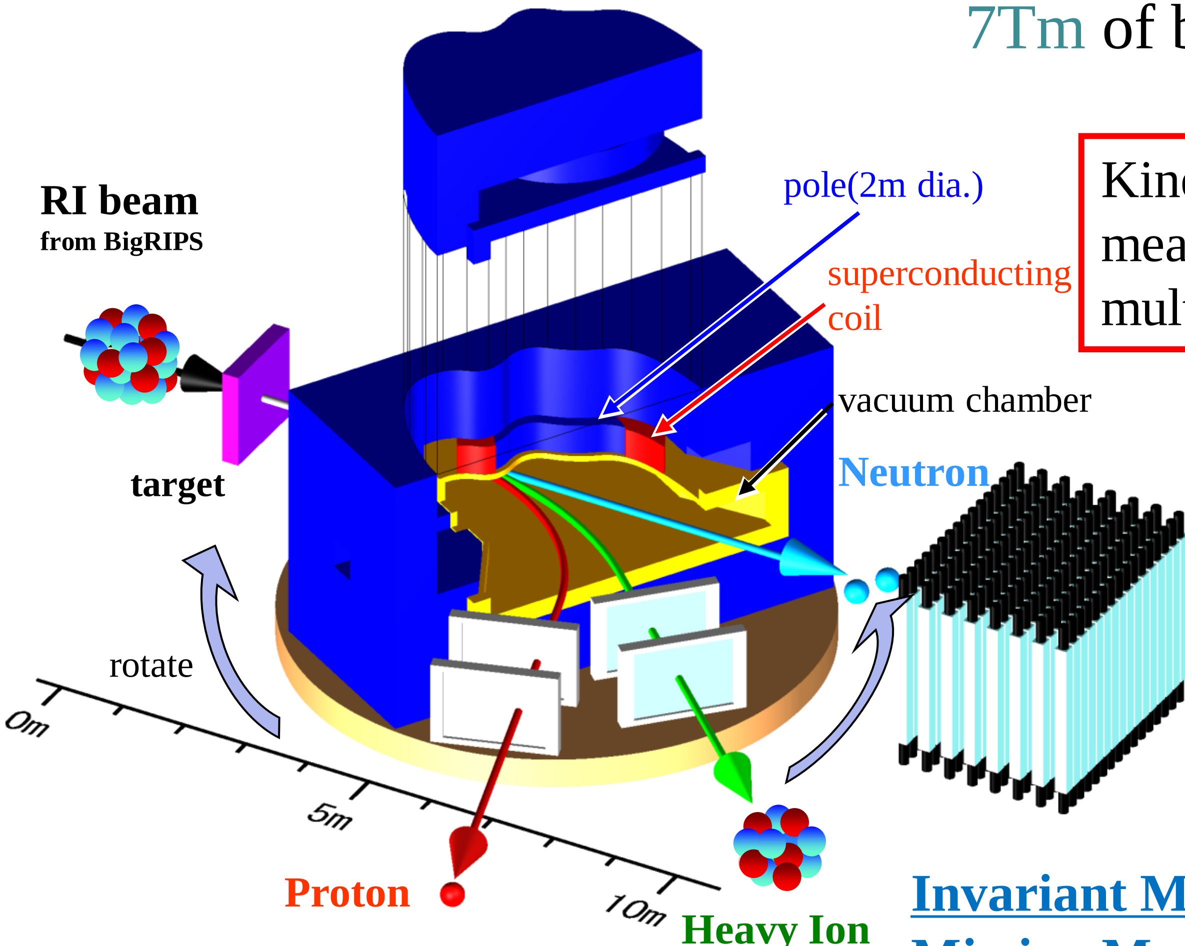
c.f. ^{31}Ne σ(E1)=540(70) mb

^{29}Ne, ^{33,35}Mg, ^{39}Si σ(E1)~200mb ^{41}Si σ(E1)~300mb

SAMURAI

-- new spectrometer in RIBF --

<u>S</u>uperconducting **<u>A</u>**nalyzer for **<u>MU</u>**lti-particle from **<u>RA</u>**dio **<u>I</u>**sotope Beam with 7Tm of bending power



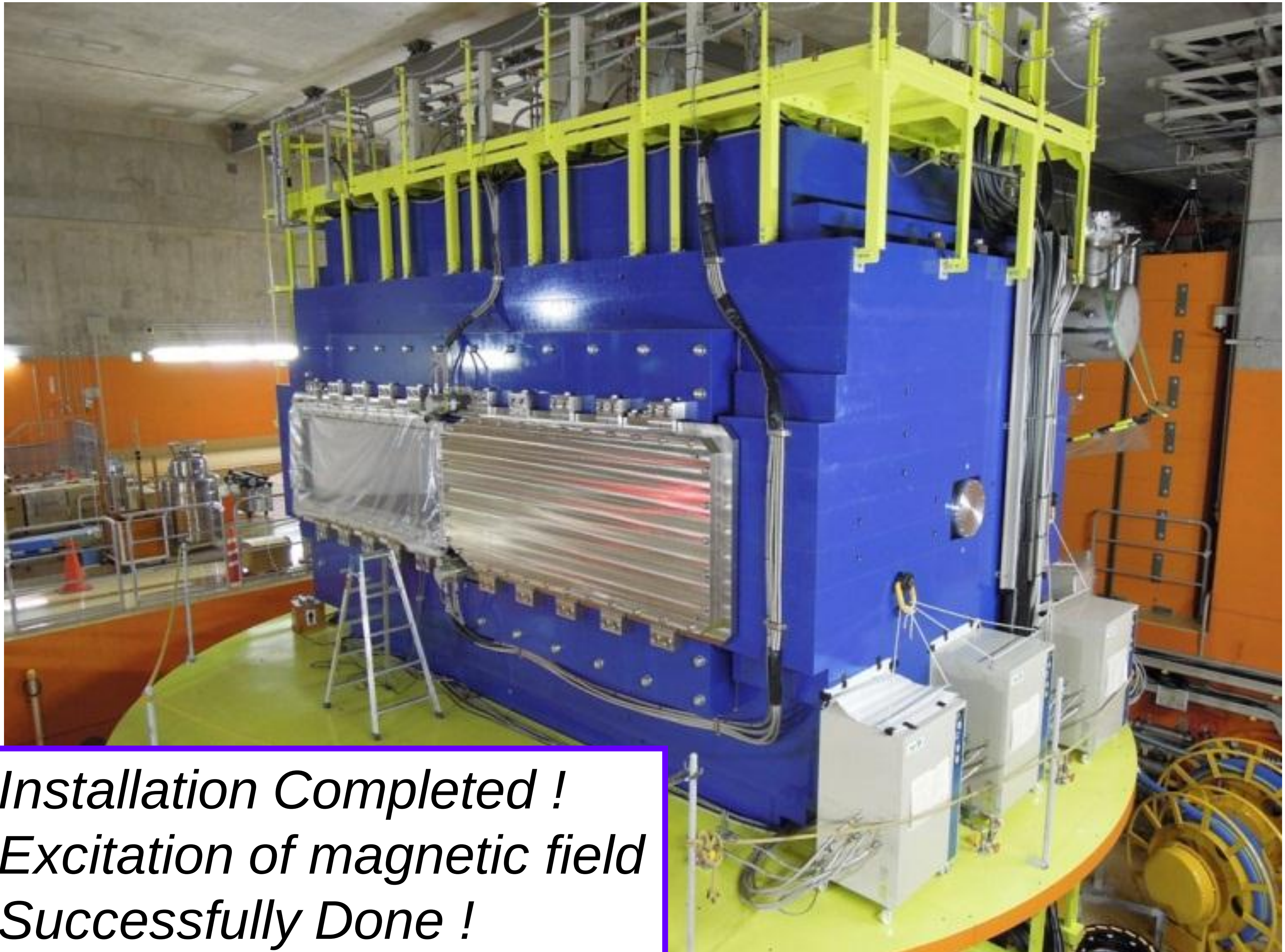
Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

<u>Invariant Mass Measurement</u>

<u>Missing Mass Measurement</u>

Slide: K. Yoneda



Installation Completed !
Excitation of magnetic field
Successfully Done !

Summary

1 Introduction (Coulomb and Nuclear Breakup)

Coulomb breakup → Soft E1 excitation of halo nuclei

Spectral-Shape, Strength of B(E1) ---- Sensitive to ℓ ,S_n,C^2S

(Exclusive Measurement) +di-neutron like correlation

Nuclear breakup (Momentum distribution)

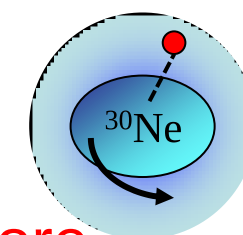
---Probe of single particle state

2 Coulomb/Nuclear Breakup of ^{31}Ne and ^{22}C (inclusive)

Strong soft E1 excitation at ^{31}Ne(~0.5b) and ^{22}C(~1b)

→ 1n Halo structure in ^{31}Ne , 2n Halo structure in ^{22}C

^{31}Ne conventional shell order vanishing ~~1f7/2~~



---"Island of inversion"→Halo with Deformed Core

3 Coulomb/Nuclear Breakup of ^{29}Ne, ^{33,35,37}Mg and ^{39,41}Si :

Strong Soft E1 excitation for ^{37}Mg(~0.5b) – New halo nucleus?

Moderately strong E1 excitations for others (0.2—0.3b)

Evolution of Halo towards the drip line

Collaborators

Inclusive Coulomb Breakup of ^{31}Ne and ^{22}C
(^{31}Ne Coulomb BU: PRL103,262501(2009)
^{22}C Coulomb BU/Nuclear BU: In preparation)

T.Nakamura, **N.Kobayashi**, Y.Kondo, Y.Satou, N.Aoi, H.Baba, S.Deguchi, N.Fukuda, J.Gibelin, N.Inabe, M.Ishihara, D.Kameda, Y.Kawada, T.Kubo, K.Kusaka, A.Mengoni, T.Motobayashi, T.Ohnishi, M.Ohtake, N.A.Orr, H.Otsu, T.Otsuka, A.Saito, H.Sakurai, E. Simpson, S.Shimoura, T.Sumikama, H.Takeda, E.Takeshita,M.Takechi, S.Takeuchi, K.Tanaka, K.N.Tanaka, N.Tanaka, Y.Togano, J.A. Tostevin, Y.Utsuno,K. Yoneda, A.Yoshida, K.Yoshida,

Inclusive Coulomb Breakup of ^{29}Ne, ^{33,35,37}Mg, ^{39,41}Si

T.Nakamura, **N.Kobayashi**, Y.Kondo, Y.Satou, N.Aoi, H.Baba, R. Barthelemy, S.Deguchi, M. Famiano, N.Fukuda, J.Gibelin, Lee Giseung, N.Inabe, M.Ishihara, D.Kameda, R.Kanungo, Y.Kawada, T.Kubo, M. Matsushita, T. Motobayashi, T.Ohnishi, K. Nikolski, N.A.Orr, H.Otsu, T. Otsuka, T. Sako, H.Sakurai, Lee H. Sang, T.Sumikama, K. Sunji, H.Takeda, K. Takahashi, S.Takeuchi, N.Tanaka, R. Tanaka, Y.Togano, Y. Utsuno, K. Yoneda

Tokyo Tech, RIKEN, U. of Tokyo, Seoul U., Tokyo U. of Science, LPC Caen, Rikkyo U., West MI U, St.Mary’s U, JAEA, U. of Surrey