

# Breakup study of neutron drip-line nuclei at RIBF

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*ISOLDE WORKSHOP Nov, 2009, CERN, Switzerland*

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1n halo and 2n halo

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

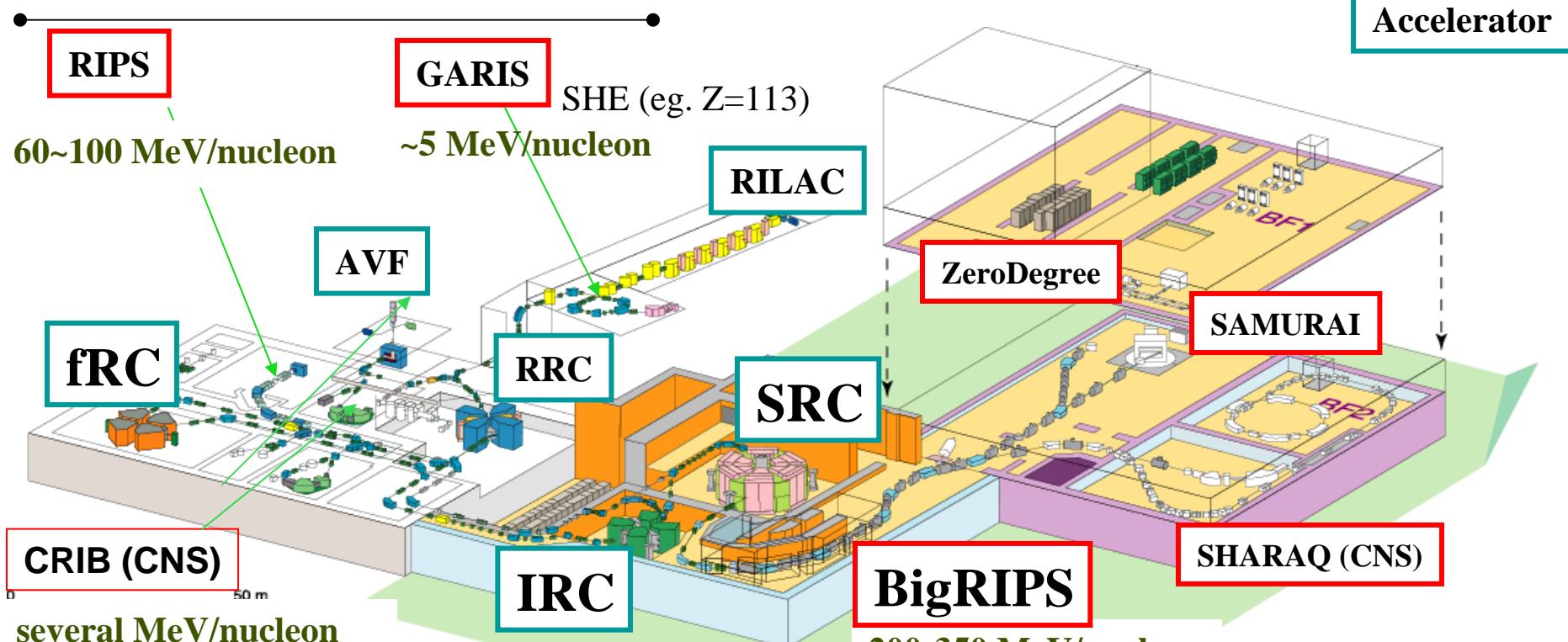
3 Inclusive Coulomb Breakup of  $^{31}\text{Ne}$  and  $^{22}\text{C}$  :  
--- *Day-one experiment at RI Beam Factory, RIKEN*

T. Nakamura, N.Kobayashi, Y.Kondo, et al. submitted to PRL.

4 Summary and Outlook

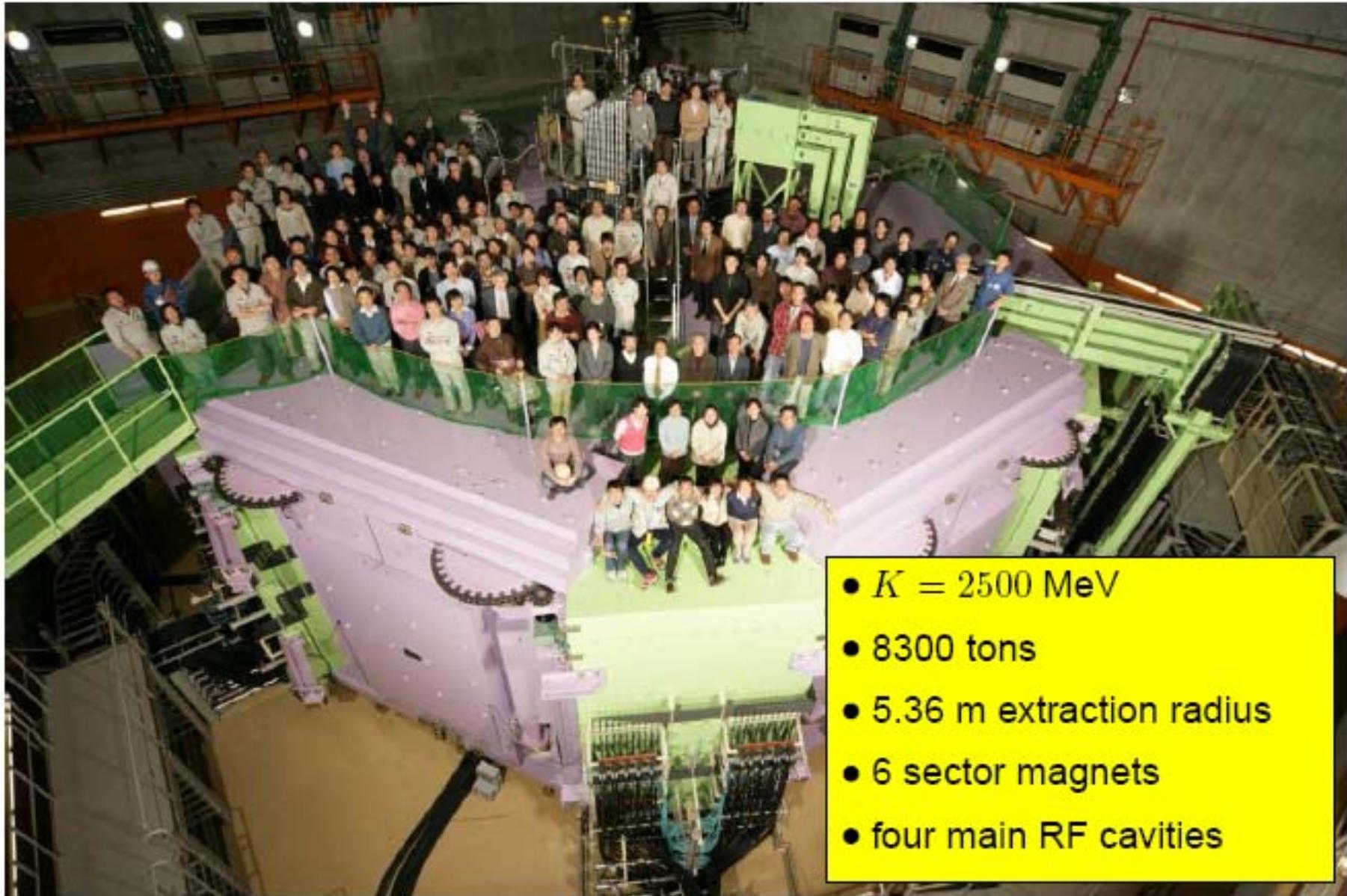
# RIKEN RI Beam Factory (RIBF)

Old facility



New facility

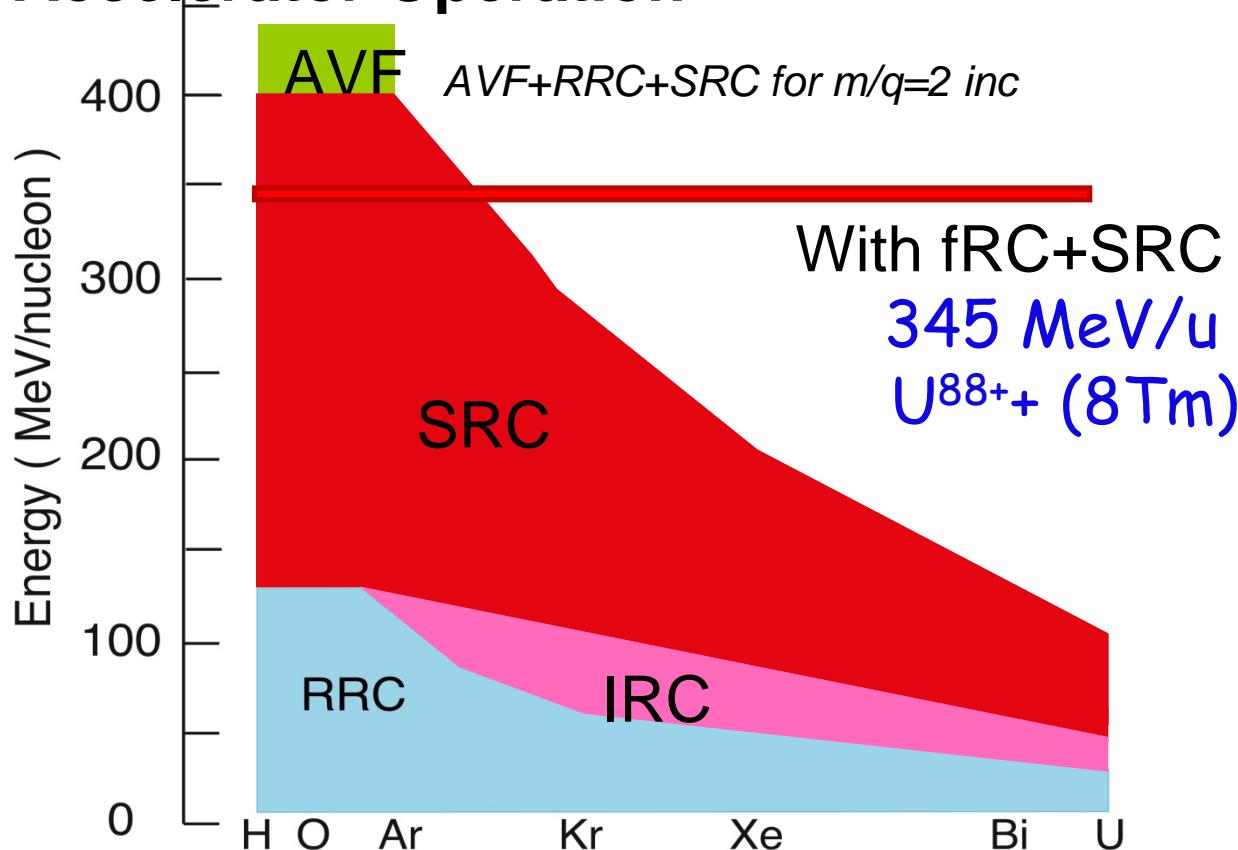
**Intense Heavy Ion beams (up to U) up to 345AMeV at SRC  
Fast RI beams by projectile fragmentation and U-fission at BigRIPS  
Operation since 2007**



- $K = 2500$  MeV
- 8300 tons
- 5.36 m extraction radius
- 6 sector magnets
- four main RF cavities

SRC: World Largest Cyclotron

# RIBF Accelerator Operation



Intensities of 345 MeV/u beams from the SRC:

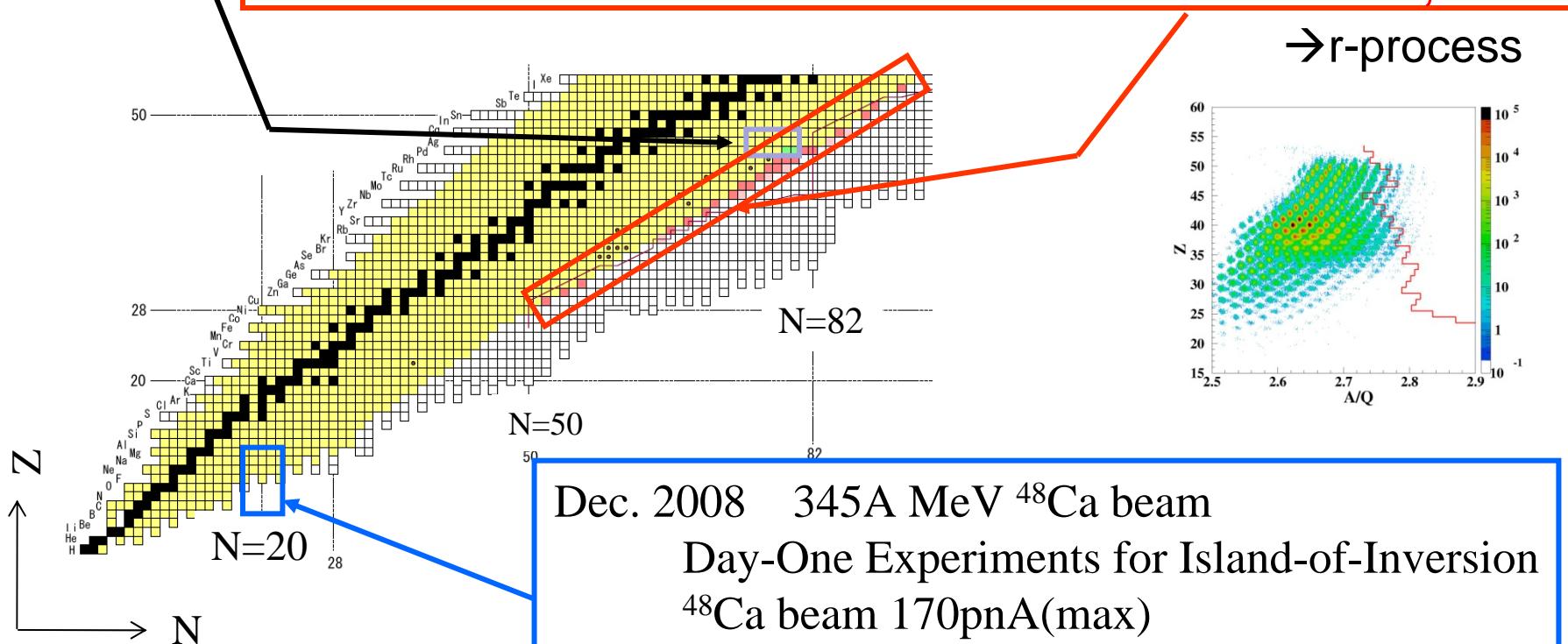
	Ca	Kr	Xe	$^{238}\text{U}$	
	500			1000	final goal (2-3 years)
Intensity (pnA)	200	50	10	5	expected 2009/10
	100	—	10	0.3	measured in 2008
	—	30	—	0.02	measured in 2007

# Programs at BigRIPS in 2007-2008

May 2007 345A MeV  $^{238}\text{U}$  beam 0.02 pnA (max)

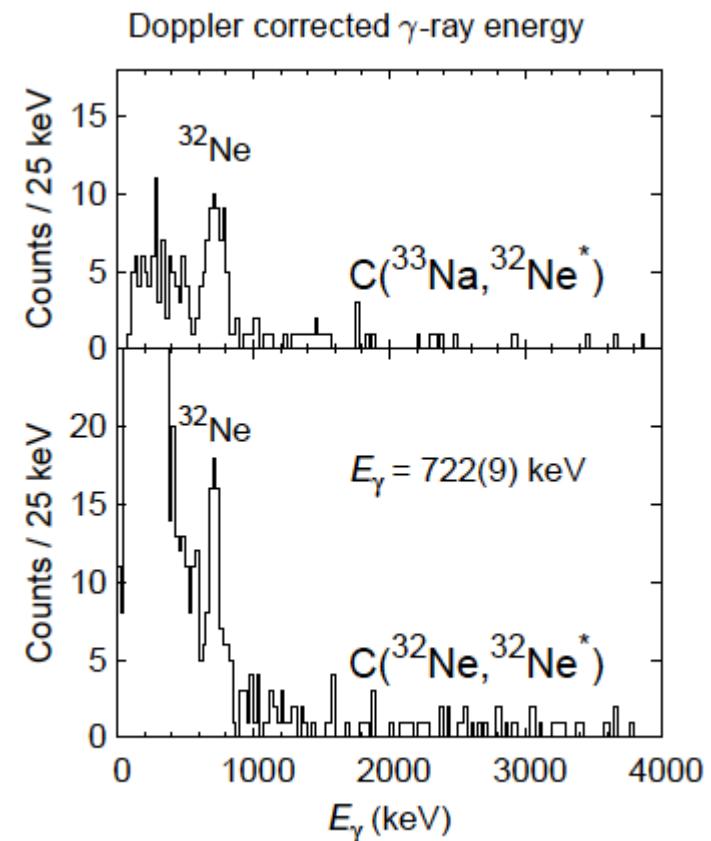
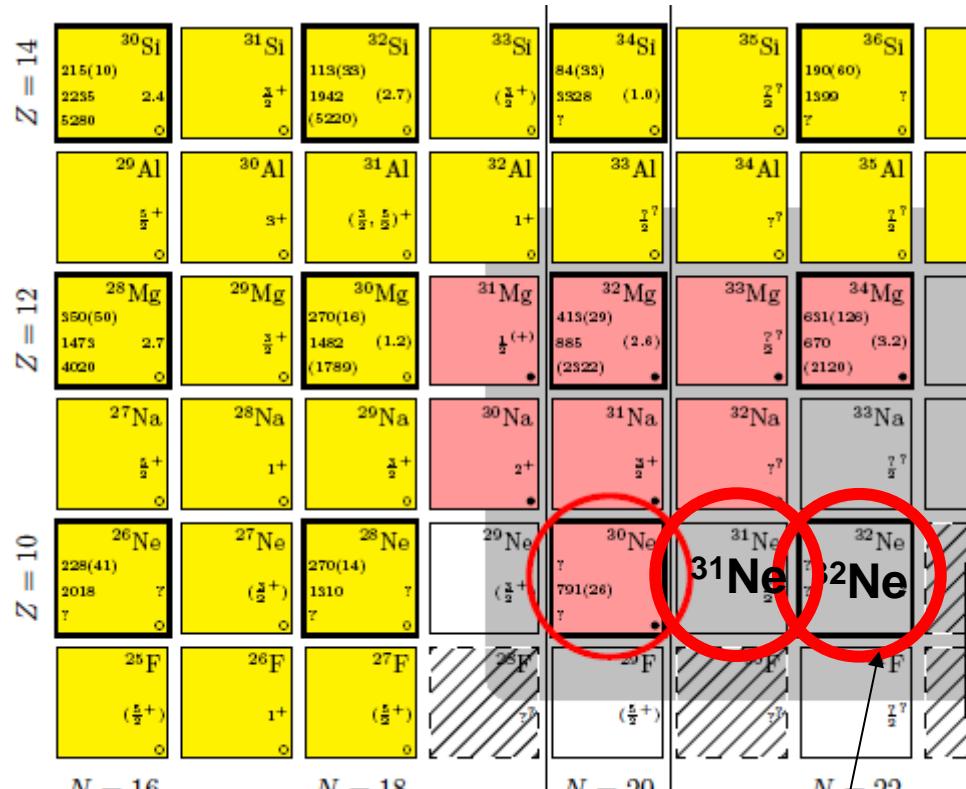
Two new isotopes,  $^{125,126}\text{Pd}$  ( $Z=46$ ), Onishi et al. JPSJ 77 (08) 083201

Nov. 2008 345A MeV  $^{238}\text{U}$  beam 0.4 pnA(max) T.Onishi,T.Kubo et al.  
More than 20 new isotopes Ni( $Z=28$ ) --- I( $Z=53$ ) e.g.  $^{79}\text{Ni}$ ,  $^{138}\text{Sn}$



# In beam $\gamma$ -ray spectroscopy of $^{32}\text{Ne}$

P.Doonenbal, H.Scheit et al.



First  $2^+$  state of  $^{32}\text{Ne}$  was observed at 722(9) keV

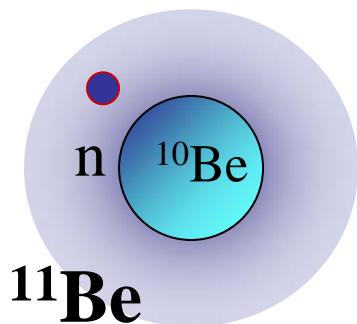
→ $^{32}\text{Ne}$  is confirmed to be inside the island of inversion

About 7hour-data

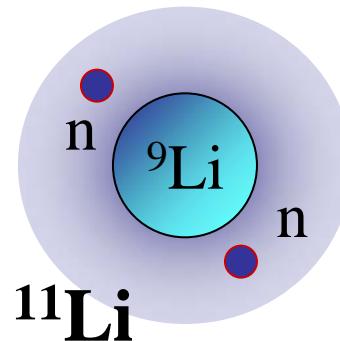
Phys. Rev. Lett. 103, 032501 (2009).

( $^{32}\text{Ne}$  5pps)

# Characteristic Features of Coulomb breakup and E1 Response of halo nuclei



$$S_n = 504 \text{ keV}$$



$$S_{2n} = 300 \text{ keV}$$

N.B. Recent mass measurement

$$S_{2n} = 369.15(65) \text{ keV},$$

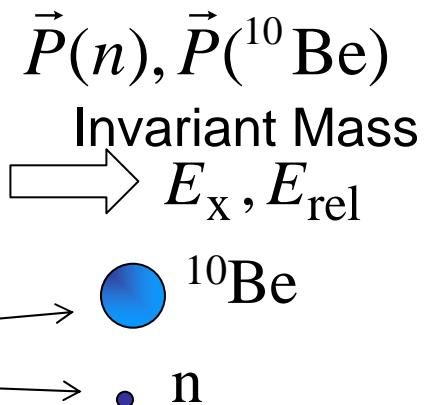
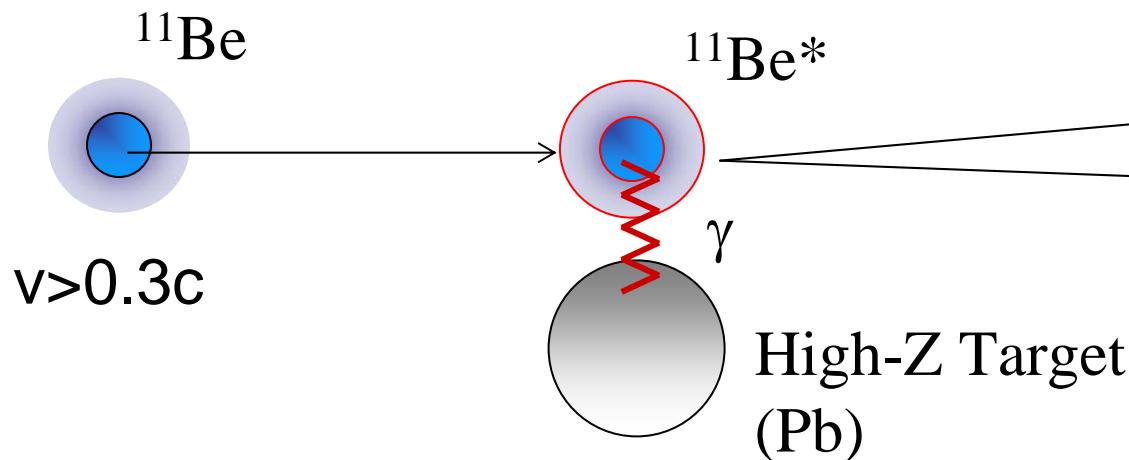
M. Smith et al. PRL 101 (2008) 2501.

$$S_{2n} = 378(5) \text{ keV},$$

C. Bachelet et al. PRL 100 (2008) 182501.

# Coulomb Breakup

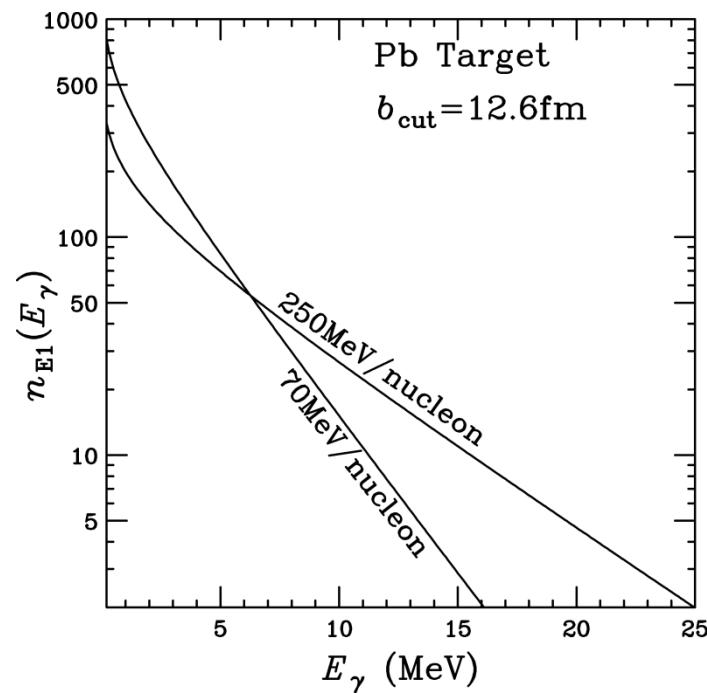
→ Photon absorption of a fast projectile



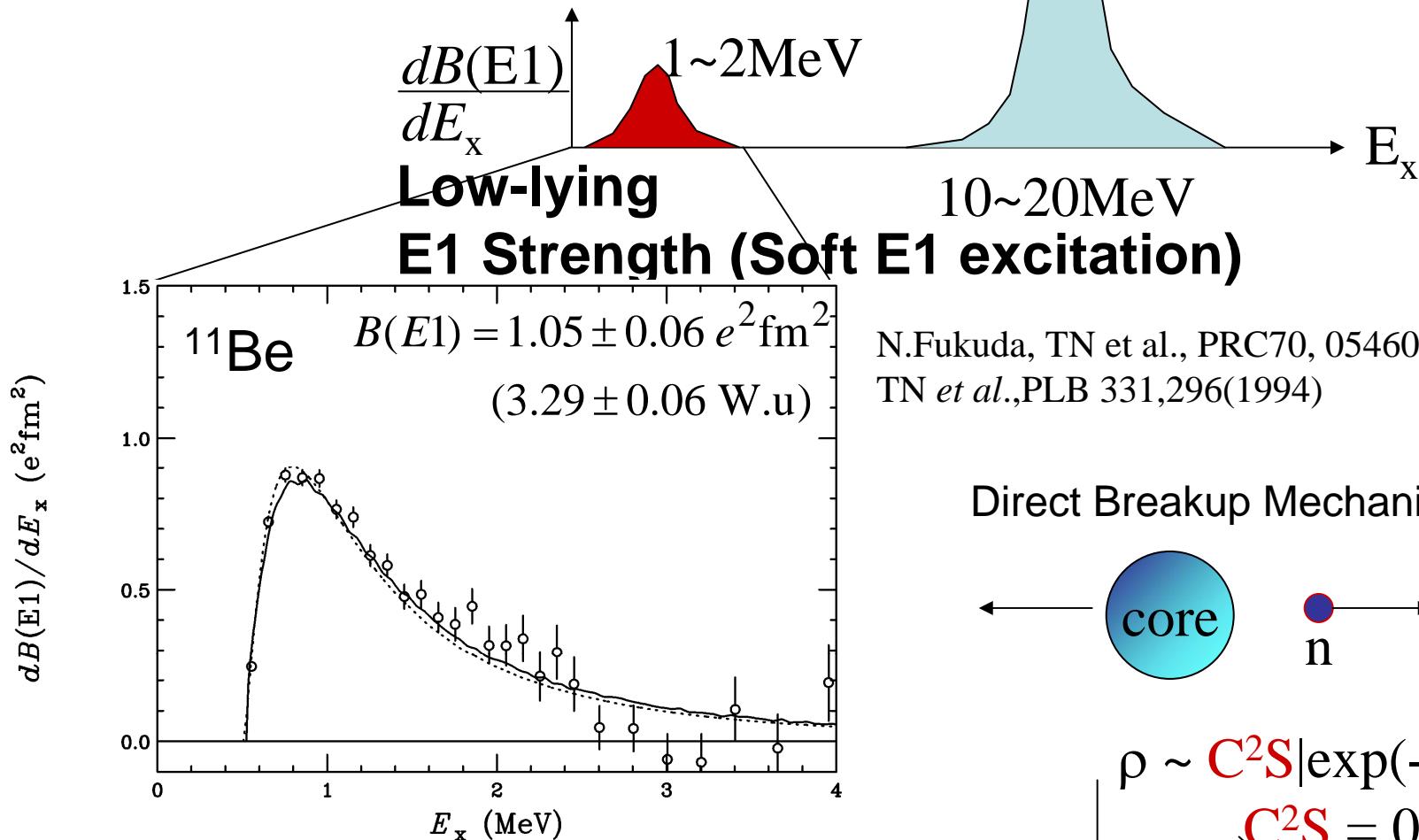
Equivalent Photon Method

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

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



# E1 Response: Case of one-neutron halo



N.Fukuda, TN et al., PRC70, 054606 (2004)  
TN et al., PLB 331,296(1994)

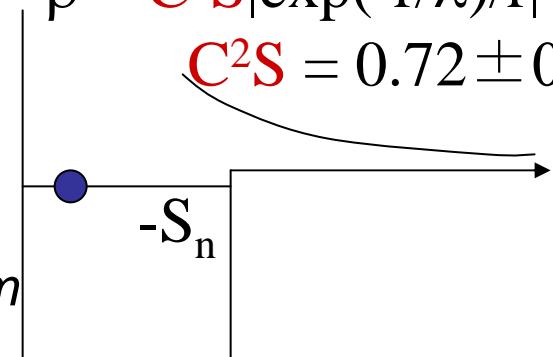
Direct Breakup Mechanism



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

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

$\longleftrightarrow$   
Fourier  
Transform



$$\frac{dB(E1)}{dE_x} \propto | \langle \exp(iqr) | \sum_A r Y_1^1 m | \Phi_{gs} \rangle |^2$$

$$\propto C^2 S | \langle \exp(iqr) | \sum_A r Y_1^1 m | s_{1/2} \rangle |^2$$

E1 Strength

Halo State

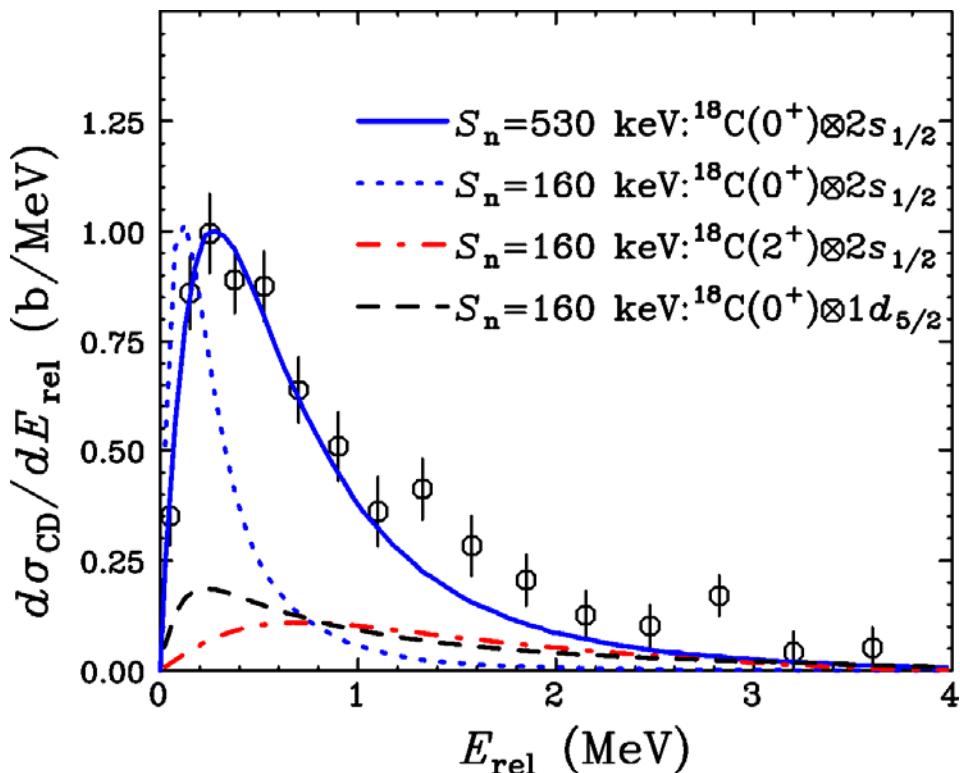
# Coulomb Breakup of (1n+core)-system

## Shape & Strength of $B(E1)$ spectrum

→  $S_n, \ell$ , Spectroscopic factor

$^{19}\text{C}$  Coulomb breakup

s, p → Halo, peak at low  $E_{\text{rel}}$



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

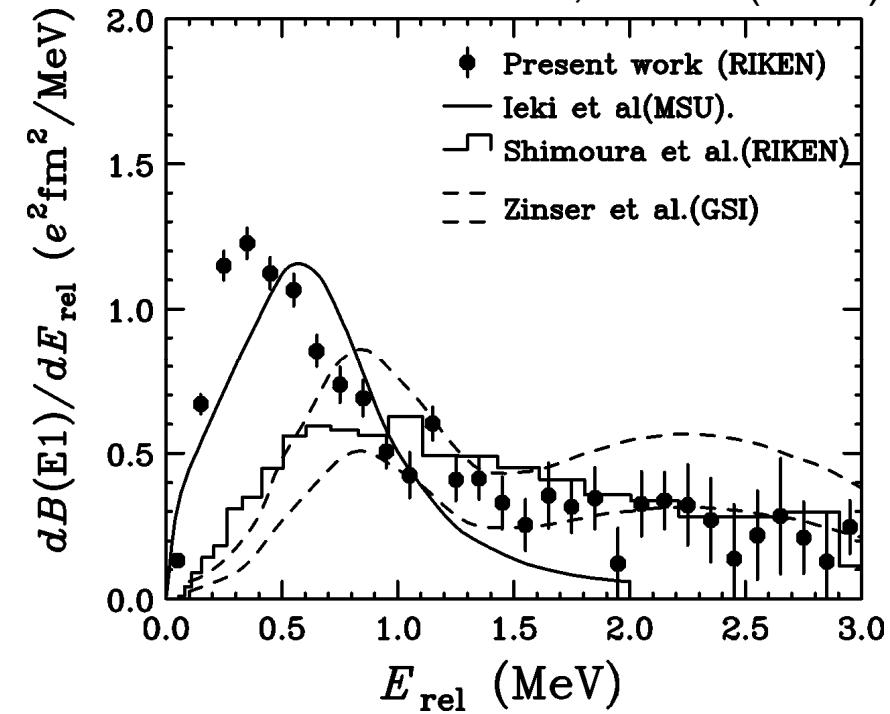
$^{19}\text{C(g.s.)}$

$J^\pi = 1/2^+$   
 $2s_{1/2}$  dominant  
 $C^2S(s_{1/2}) = 0.67$   
 $S_n = 530 \text{ keV}$

# Coulomb breakup and soft E1 excitation of $2n$ halo nuclei

## --- Case of $^{11}\text{Li}$

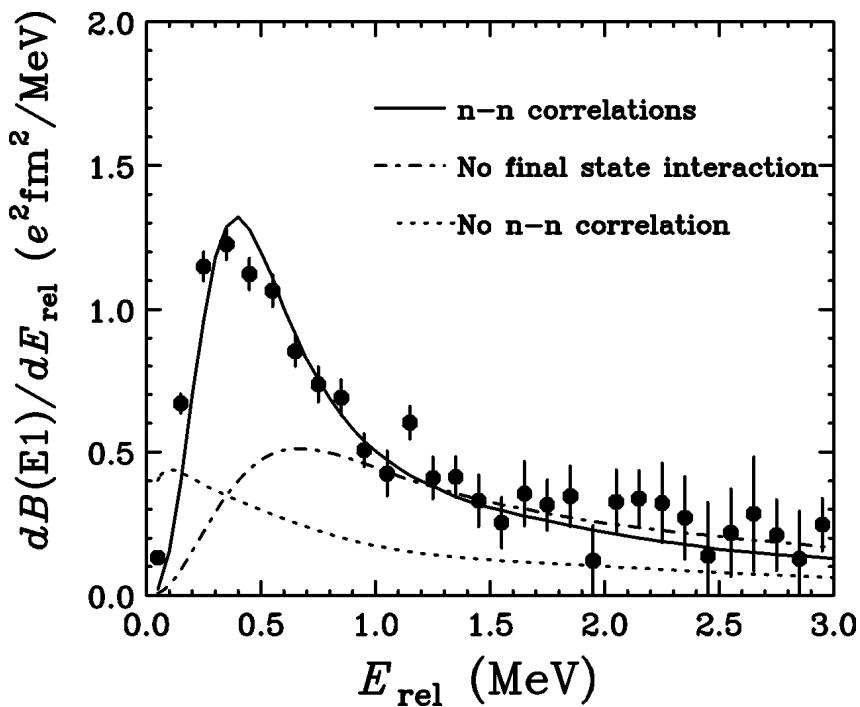
TN et al. PRL96,252502(2006).



$$B(E1) = 1.42 \pm 0.18 \text{ } e^2 \text{ fm}^2 (E_{\text{rel}} \leq 3 \text{ MeV}) \\ = 4.5(6) \text{ W.u}$$

c.f.  $B(E1)=1.05(6)\text{e}^2\text{fm}^2$  for  $^{11}\text{Be}$

## Comparison with 3-body Theory

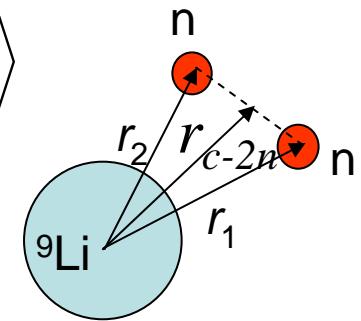


## Calculation

H.Esbensen and G.F. Bertsch  
NPA542,310 (1992).  
H.Esbensen et al.,  
PRC76, 024302 (2007)

# Non-energy weighted E1 Cluster Sum Rule

$$\begin{aligned}
 B(E1) &= \int_0^\infty \frac{dB(E1)}{dE_x} dE_x = \frac{3}{4\pi} \left( \frac{Ze}{A} \right)^2 \left\langle r_1^2 + r_2^2 + 2(\vec{r}_1 \cdot \vec{r}_2) \right\rangle \\
 &= \frac{3}{\pi} \left( \frac{Ze}{A} \right)^2 \left\langle r_{c-2n}^2 \right\rangle
 \end{aligned}$$



Strong E1 Transition

---


$$\begin{aligned}
 B(E1) &= 1.42 \pm 0.18 \text{ } e^2 \text{ fm}^2 (\text{ } E_{\text{rel}} \leq 3 \text{ MeV}) \\
 &\rightarrow 1.78(22) \text{ } e^2 \text{ fm}^2 (\text{Extrapolated value}) \\
 &\rightarrow \sqrt{\left\langle r_{c-2n} \right\rangle^2} = 5.01 \pm 0.32 \text{ fm}
 \end{aligned}$$

~70% larger than non-correlated strength ( $\vec{r}_1 \cdot \vec{r}_2 = 0$ ) 90 deg.

—————  $\left\langle \theta_{12} \right\rangle = 48^{+14}_{-18} \text{ deg}$

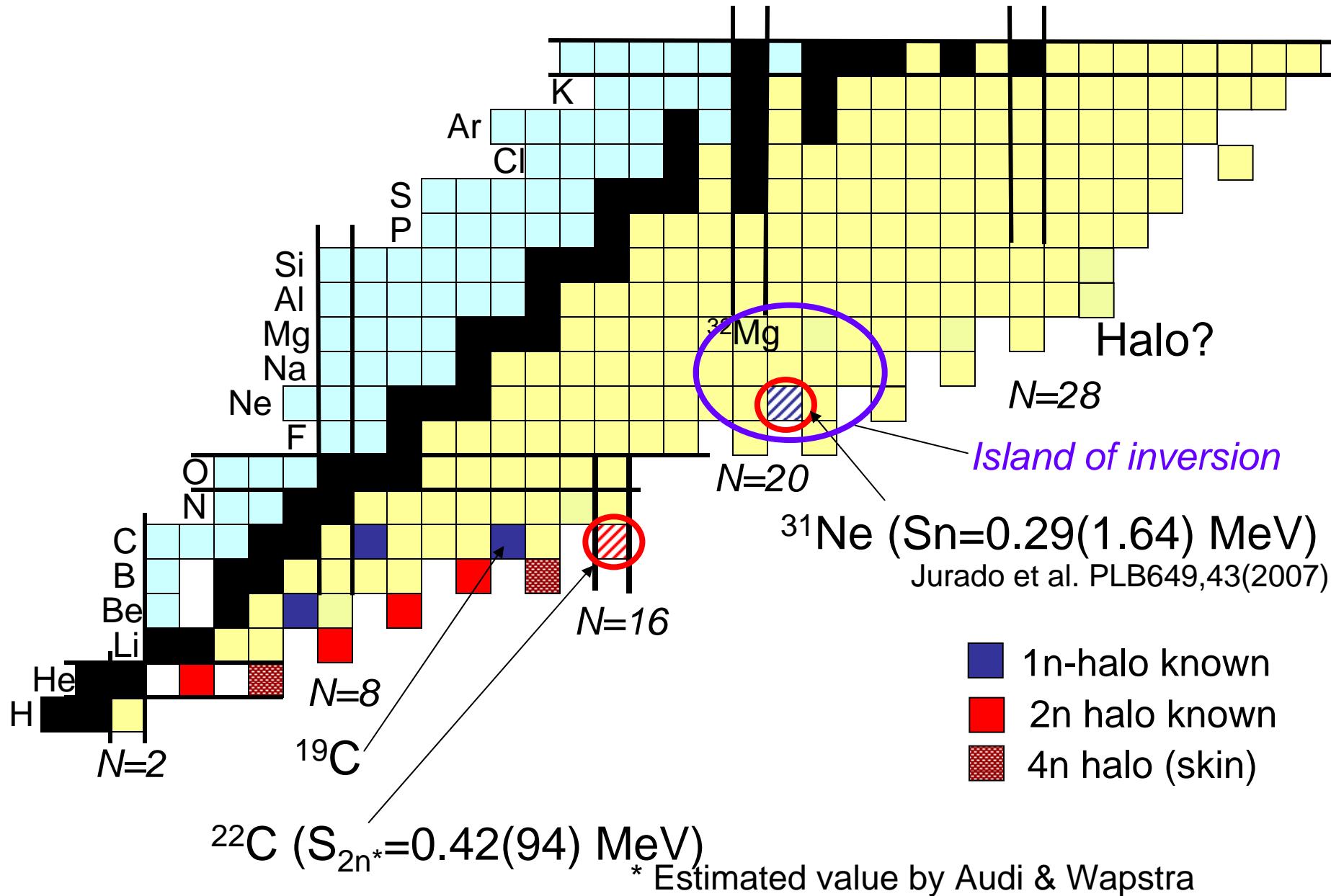
Larger nn correlation  $\rightarrow$  Stronger soft E1 excitation

3

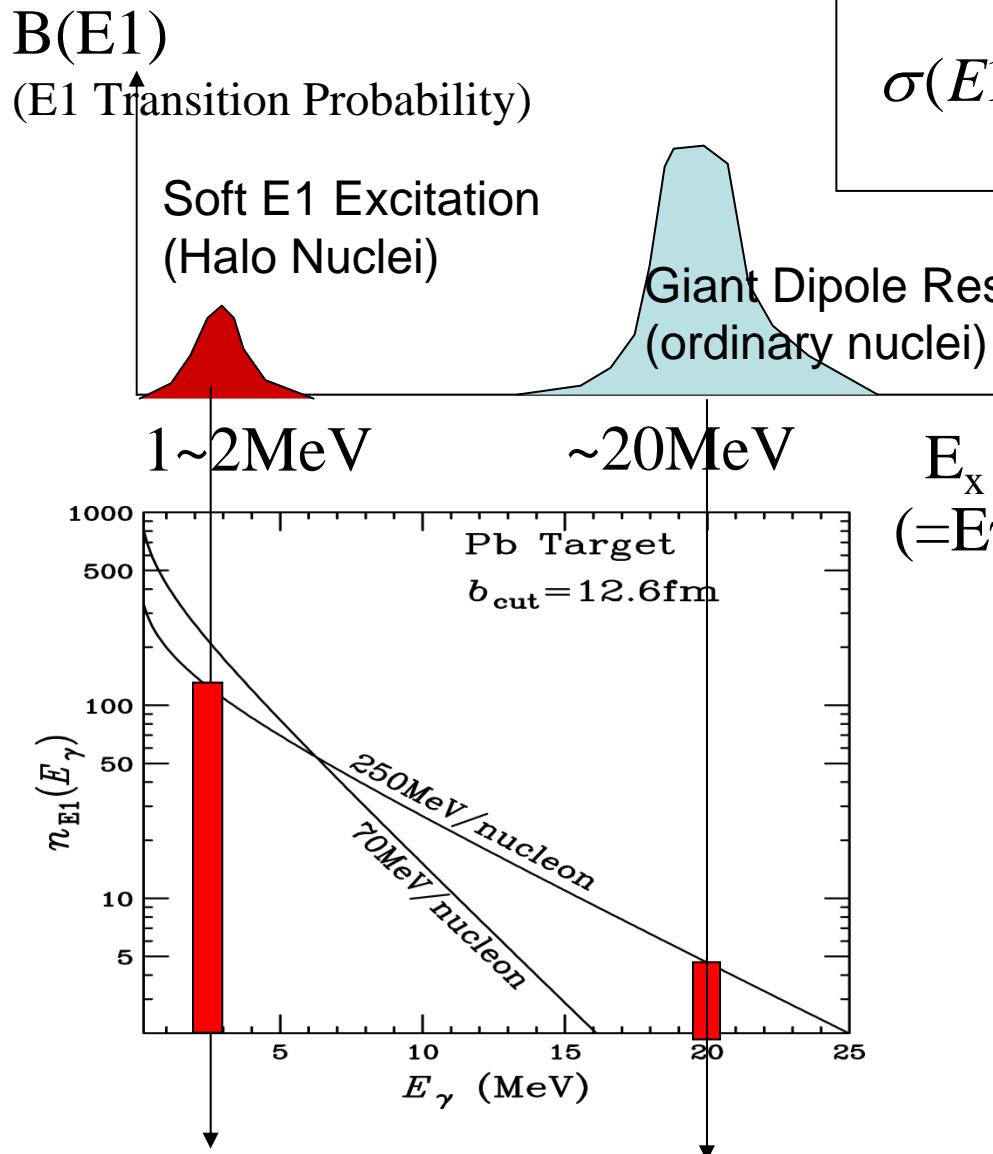
### Inclusive Coulomb Breakup of $^{31}\text{Ne}$ and $^{22}\text{C}$ @ RIKEN RI BEAM FACTORY

As an experiment for  
Day-one  $^{48}\text{Ca}$  beam campaign,  
December 2008

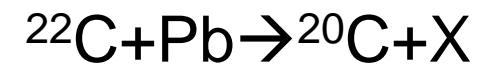
# Neutron Halo's along the drip line?



# Inclusive Coulomb Breakup



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



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

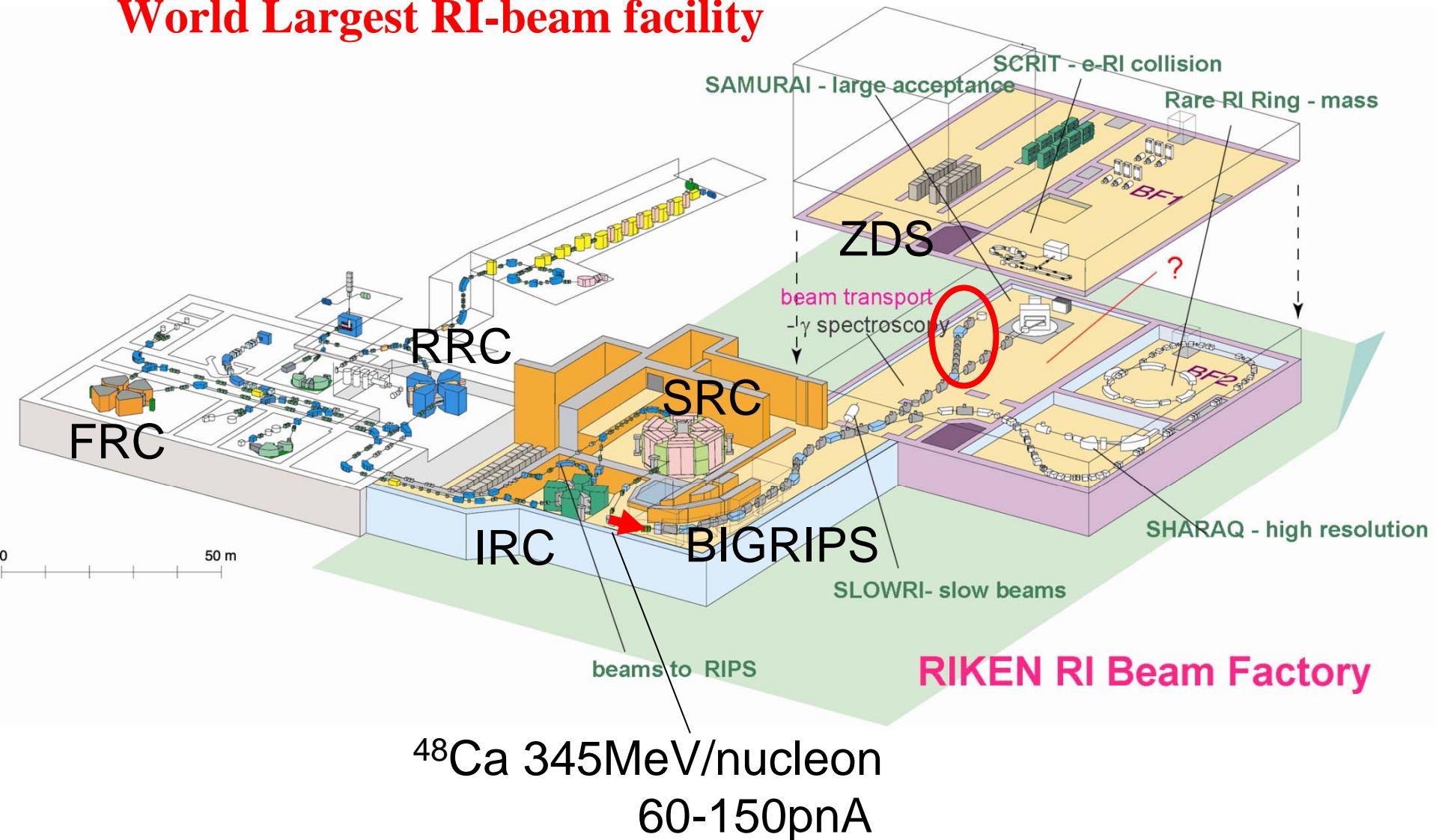
$$\sigma(E1) \sim 0.5\text{--}1 \text{ barn}$$

$$<0.1 \text{ barn}$$

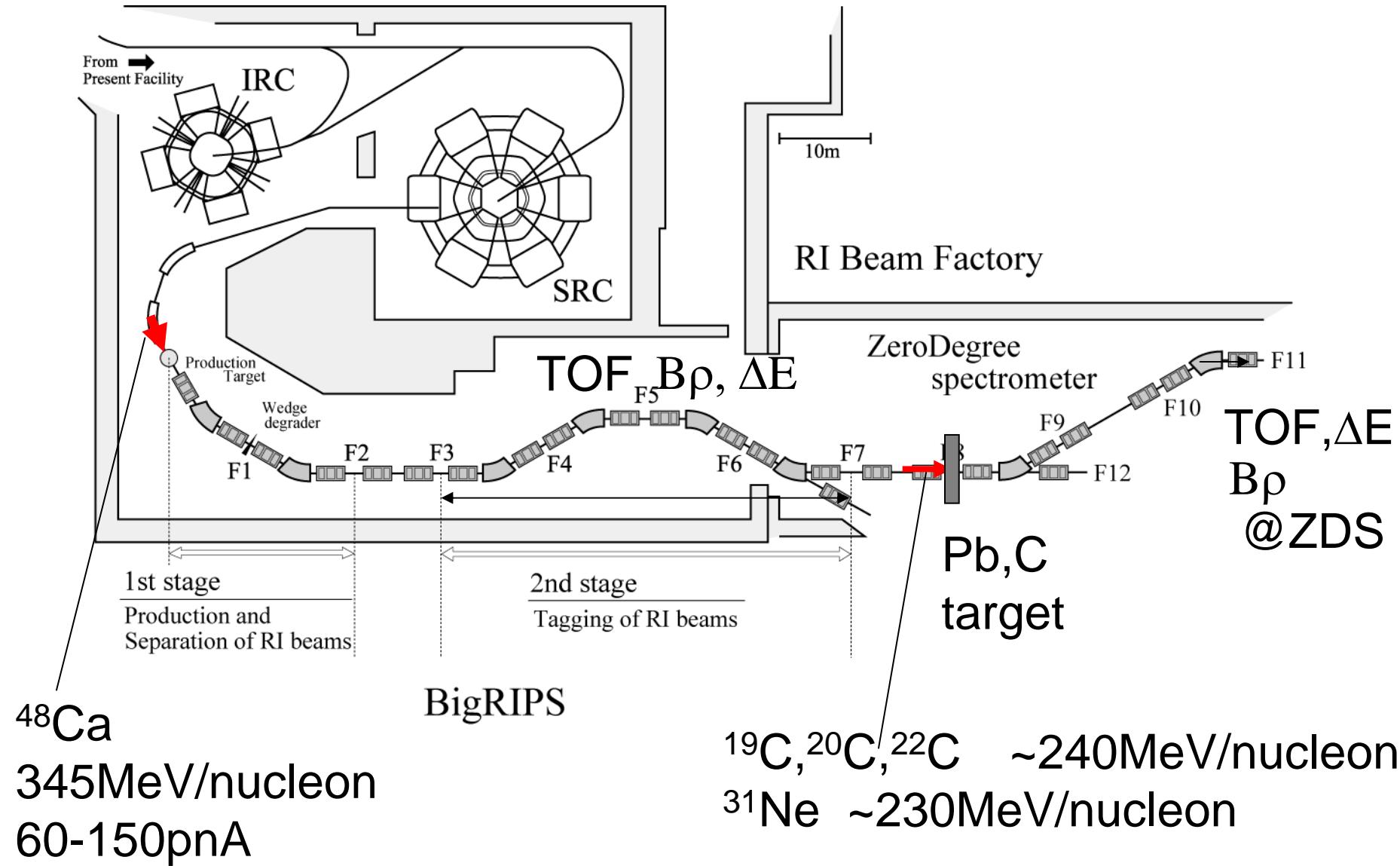
# RIKEN RI Beam Factory (RIBF)

Completed in 2007

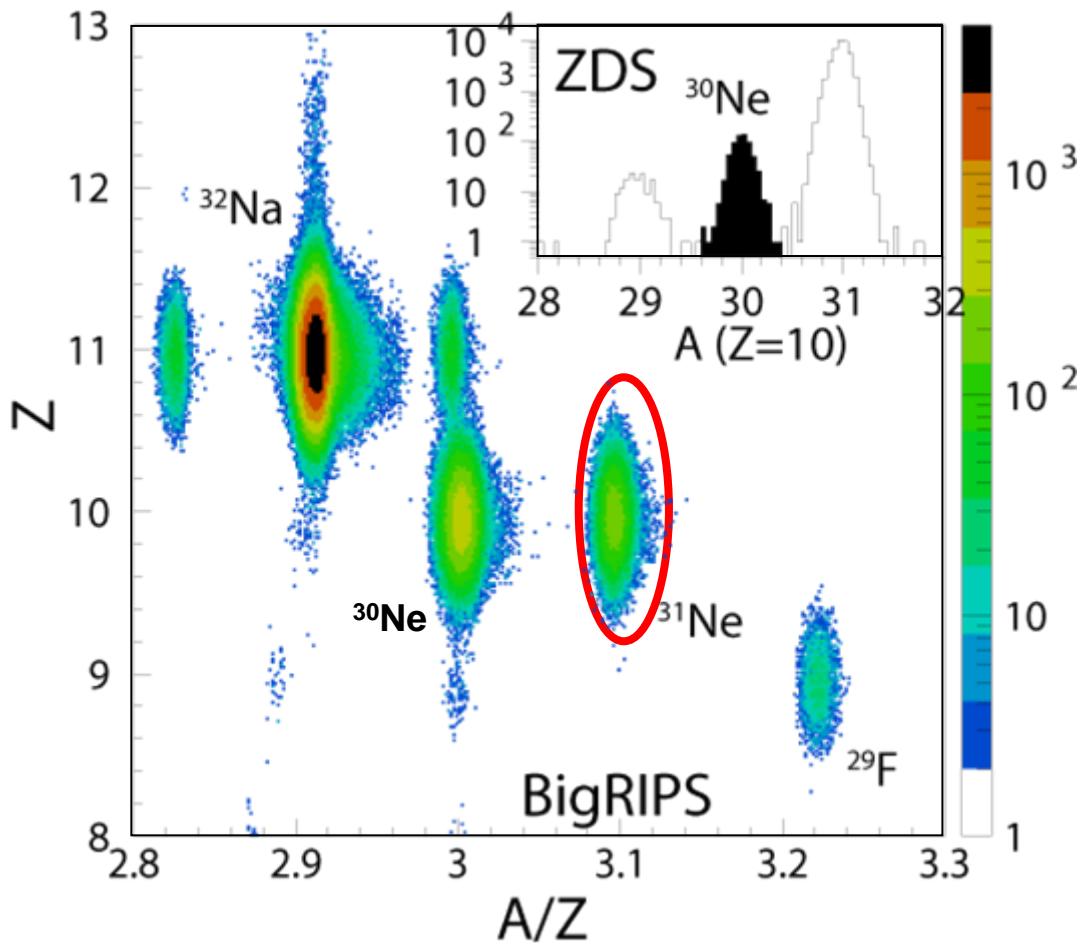
World Largest RI-beam facility



# Experiment at BigRIPS & ZDS at RIBF



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

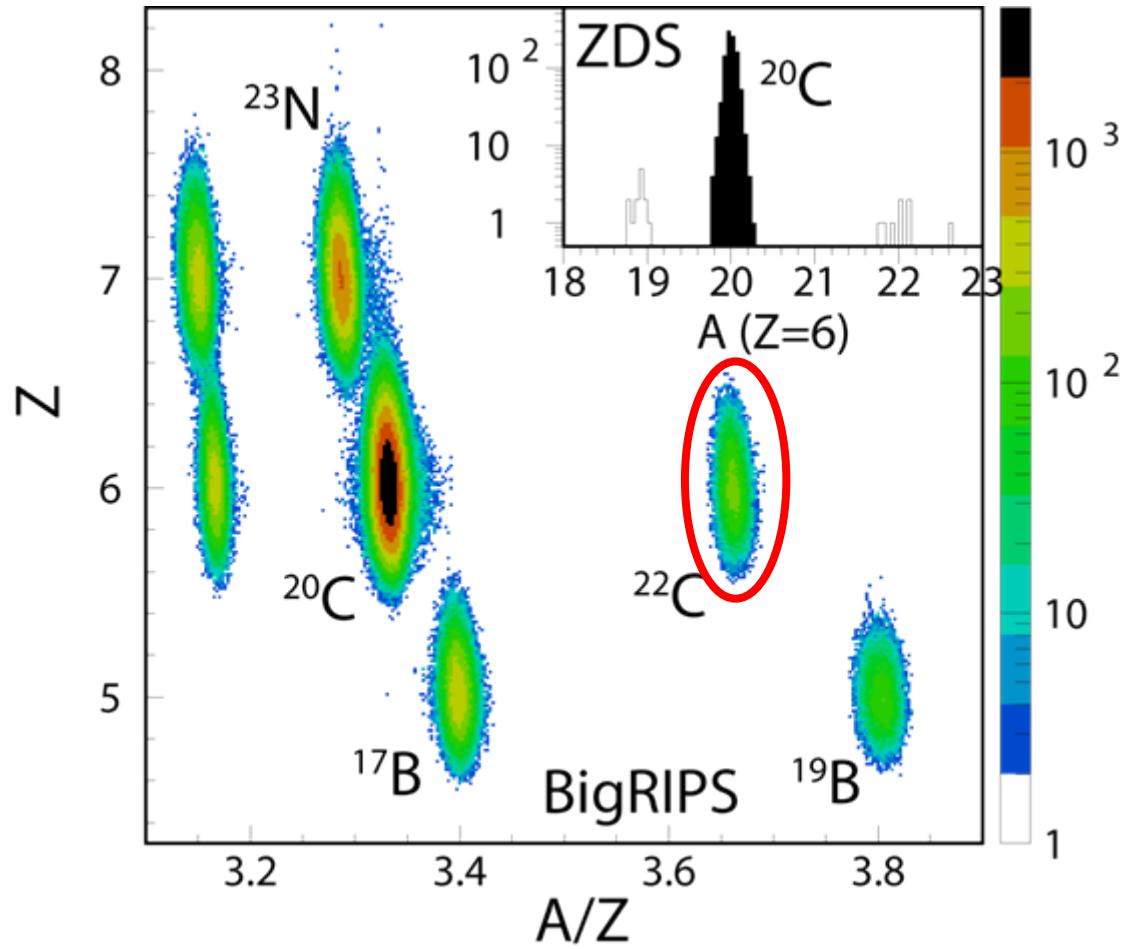


RI beam Intensity  
@RIBF  
 $\sim 10^3\text{-}10^4$  times/RIPS

$^{31}\text{Ne} \sim 5$  counts/s

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

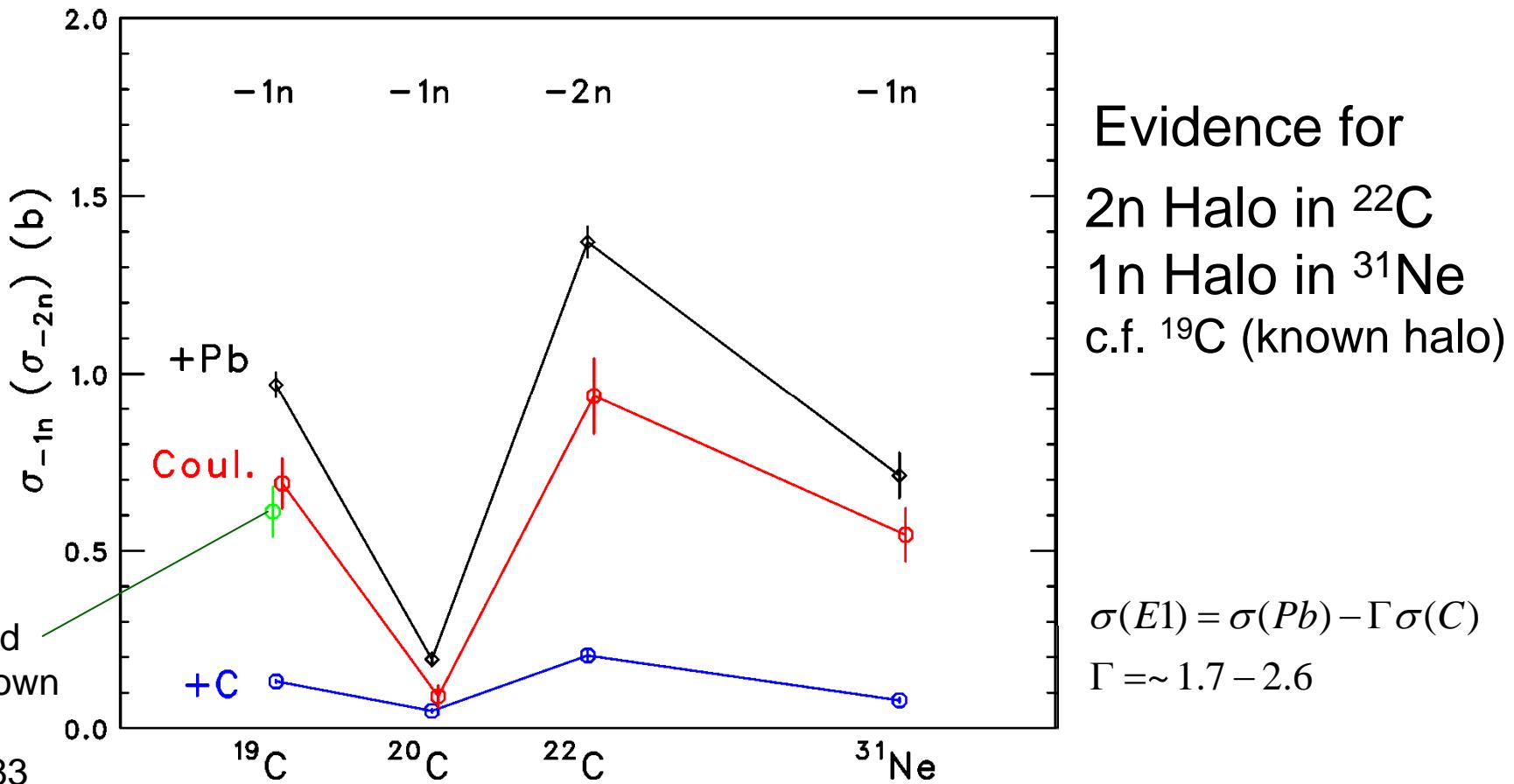
# Particle Identification : $^{22}\text{C} \rightarrow ^{20}\text{C}$



$^{22}\text{C} \sim 6$  counts/s

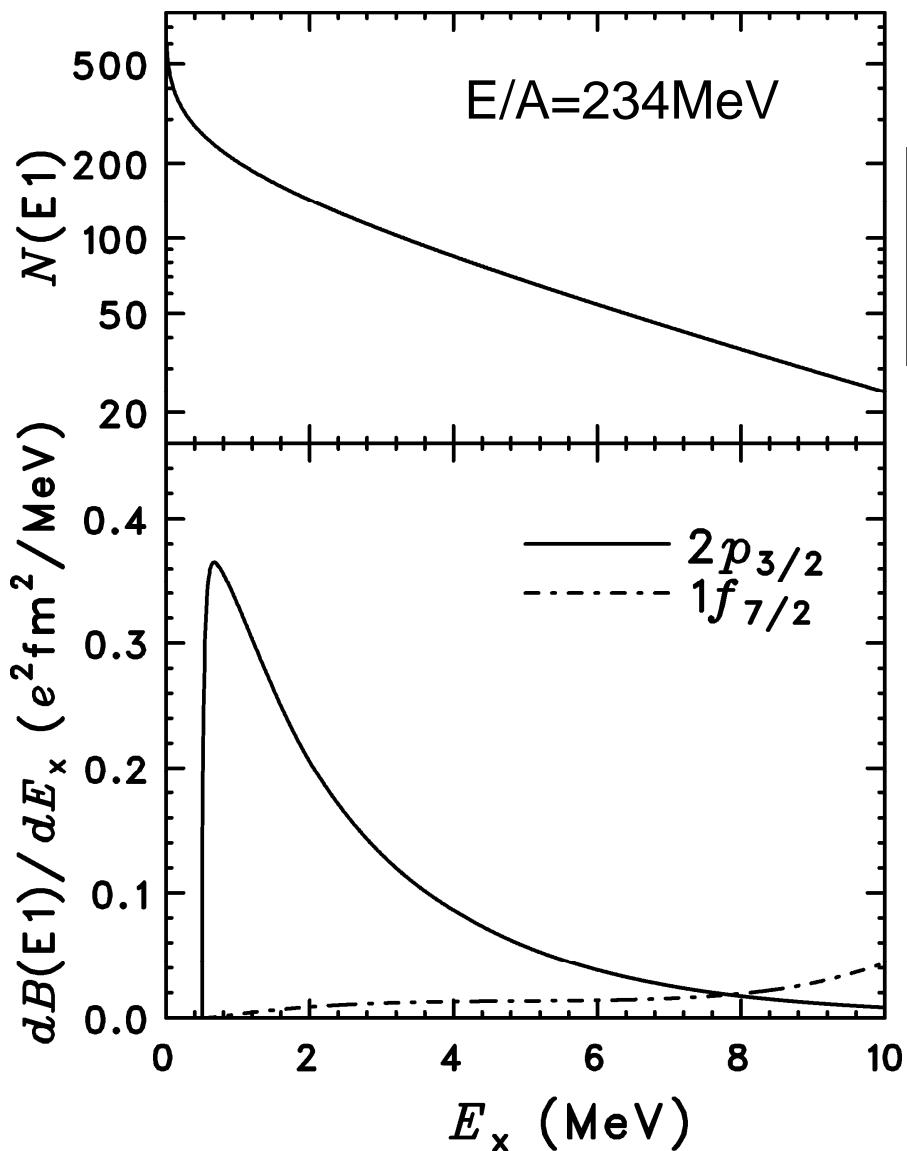
# 1n(or 2n) removal cross section

→Coulomb breakup cross section



$$S_n = 0.58(9) \quad S_n = 2.93(28) \quad S_{2n} = 0.42(94) \quad S_n = 0.29(1.64)$$

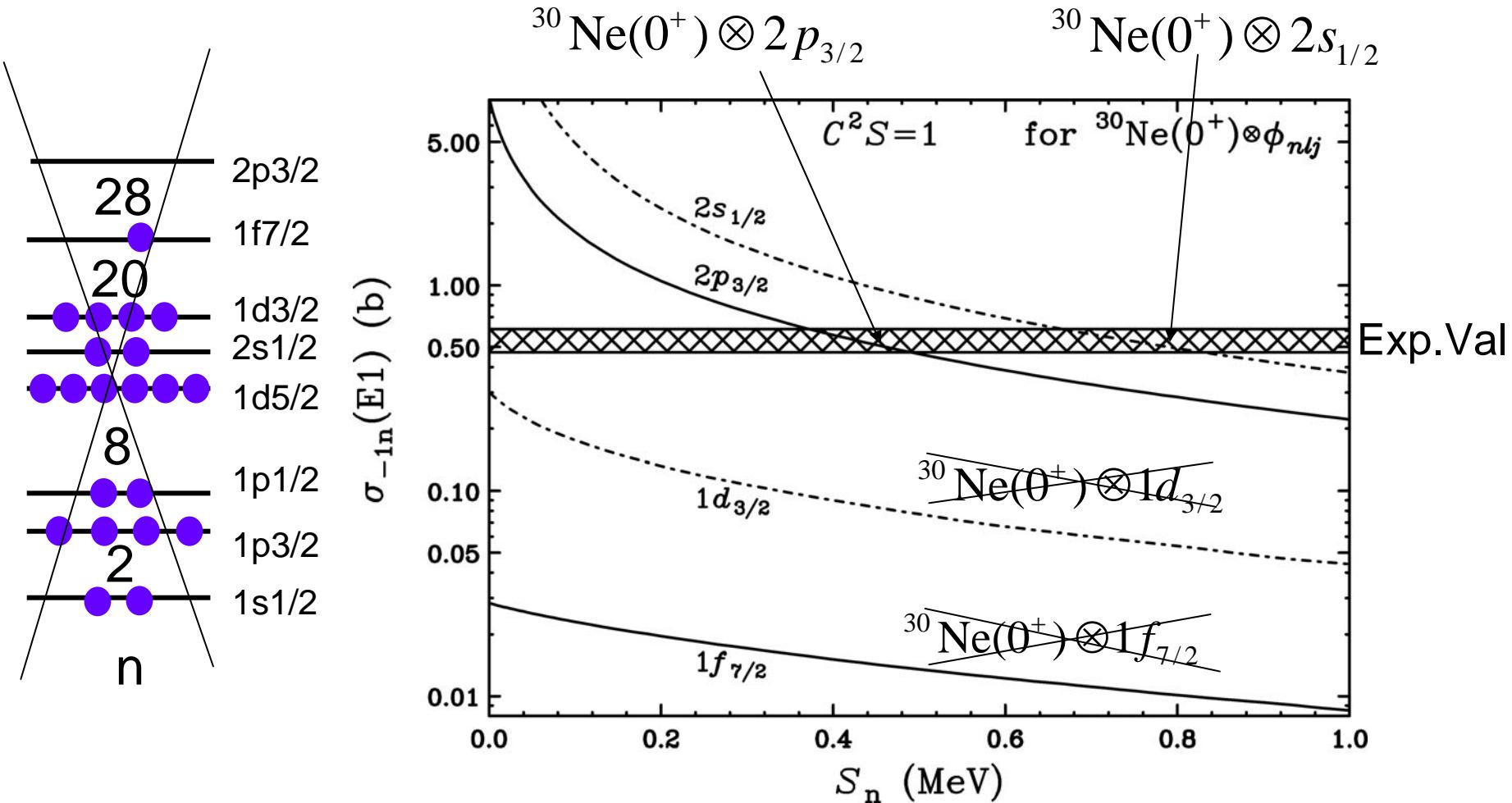
$^{31}\text{Ne}$  (N=21)  $S_n = 0.29(1.64)\text{MeV}$



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

$$\begin{aligned} \frac{dB(E1)}{dE_x} &\propto | \langle q | \frac{Z}{A} r Y_m^1 | \Phi_{gs} \rangle |^2 \\ &= \Sigma C^2 S | \langle \Phi_f | \frac{Z}{A} r Y_m^1 | \phi_{nlj} \rangle |^2 \end{aligned}$$

# $^{31}\text{Ne}$ (N=21)



$2p_{3/2}$  or  $2s_{1/2}$  -- Low-L orbits – 1n-halo structure of  $^{31}\text{Ne}$

$^{30}\text{Ne}(0^+) \otimes 1f_{7/2}$  -- Excluded → Shell Structure is vanishing at  $^{31}\text{Ne}$

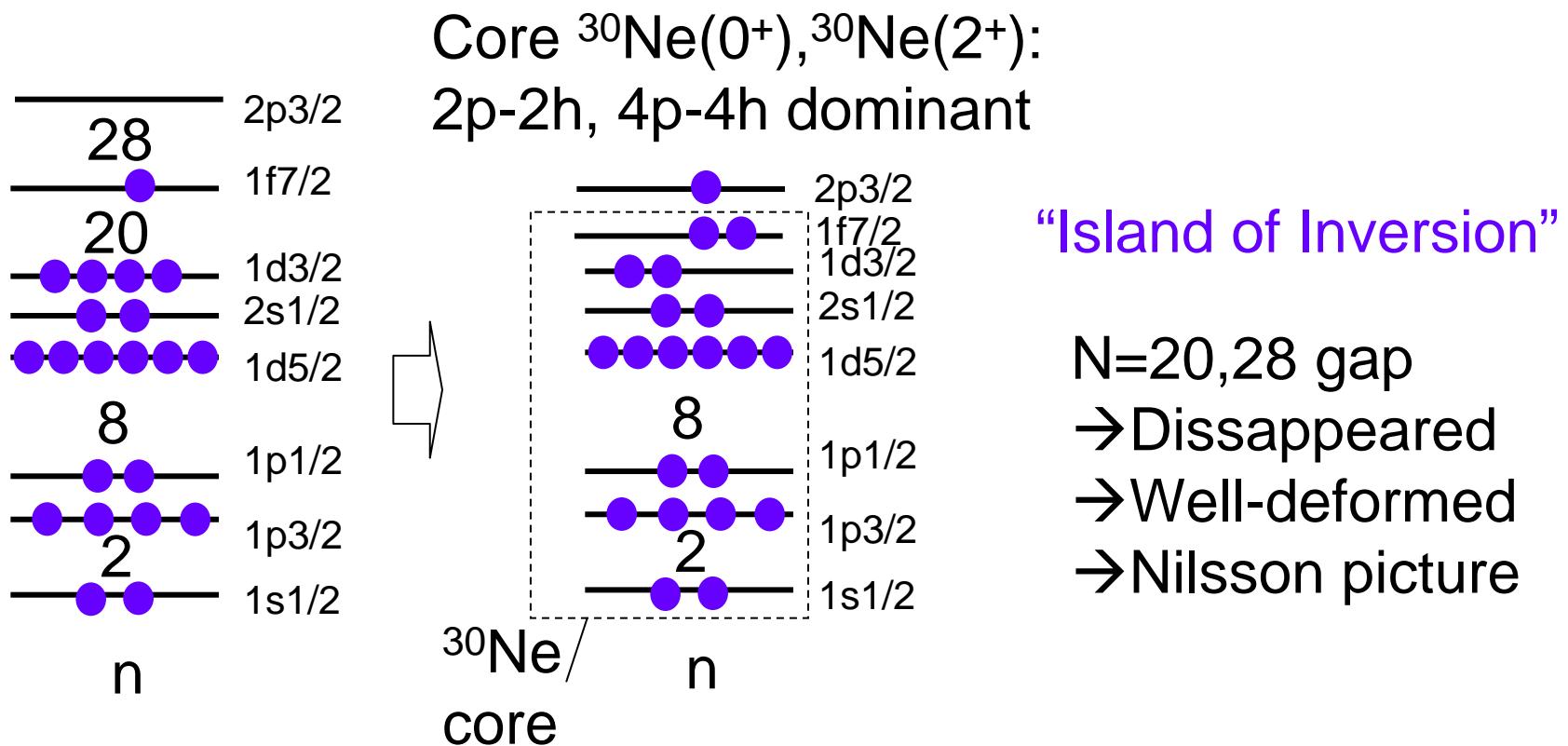
# Theoretical consideration ( $^{31}\text{Ne}$ )

## ● Large Scale Monte Carlo Shell Model

by Y.Utsuno, T.Otsuka (c.f. Y.Utsuno et al. PRC60,054315(1999).)

*Prediction: g.s. of  $^{31}\text{Ne}$ :  $3/2^-$  ( $p$  wave dominance)*

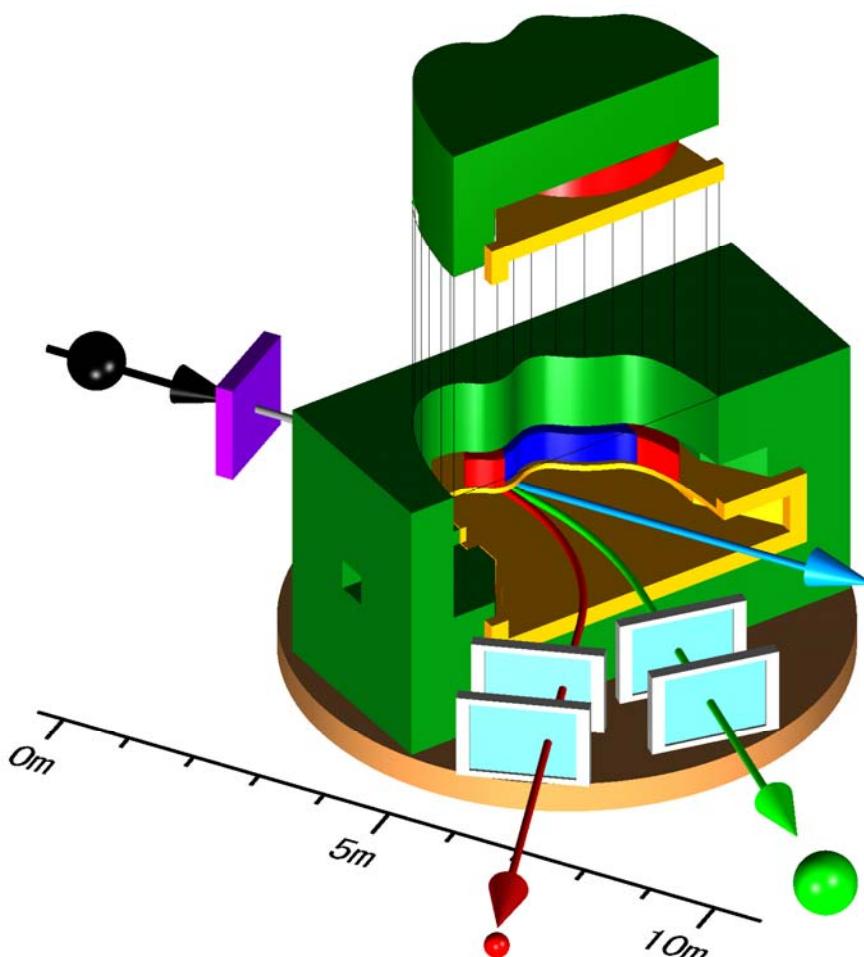
*consistent with experiment (p-wave case)*



# SAMURAI (to be completed in 2011)

Superconducting Analyser for MUlti-particles from RAdio-Isotope Beam

## →Kinematically Complete Measurement of Breakup Reaction

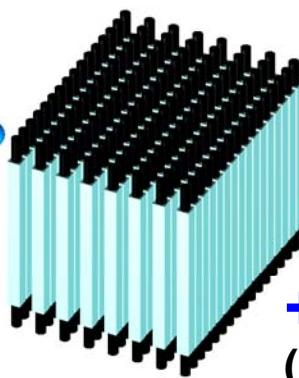


### Superconducting Magnet

To let neutron(s) pass through the gap

Sweep Beam and Charged Fragments

Good Mass Resolution for PID @ A~100



### +NEBULA

(NEutron Detection System for Breakup of Unstable Nuclei with Large Acceptance)

### Bending Power

$BL=7\text{Tm}$  ( $B=3\text{Tesla}$ , 60deg bending)

# Summary

1

Overview of RIKEN RI-Beam Factory

2

Characteristics of Coulomb breakup and Soft E1 Excitation

Soft E1 of one neutron halo

Direct Breakup Mechanism

Spectral-Shape, Strength of  $B(E1)$

---- Sensitive to  $\ell$ , Sn, Spectroscopic factor

Soft E1 of two neutron halo

Strong E1 transition for  $^{11}\text{Li}$

Soft E1 Excitation → Probe dineutron-like correlation

TN et al., PRL96, 252502 (2006).

3

Inclusive Coulomb Breakup of  $^{31}\text{Ne}$  and  $^{22}\text{C}$  :

Observe strong soft E1 excitation at  $^{31}\text{Ne}(\sim 0.5\text{b})$  and  $^{22}\text{C}(\sim 1\text{b})$

→ 1n Halo structure in  $^{31}\text{Ne}$

2n Halo structure in  $^{22}\text{C}$

-----  $^{31}\text{Ne}$  : s or p --- significant role for soft E1 excitation  
conventional shell order vanishing ~~1f7/2~~

--- "island of inversion" → Halo with Deformed Core?

## Acknowledgement

H.Sakurai, T.Kubo, H.Scheit, for slides  
Experimental Group of Day-1 campaign

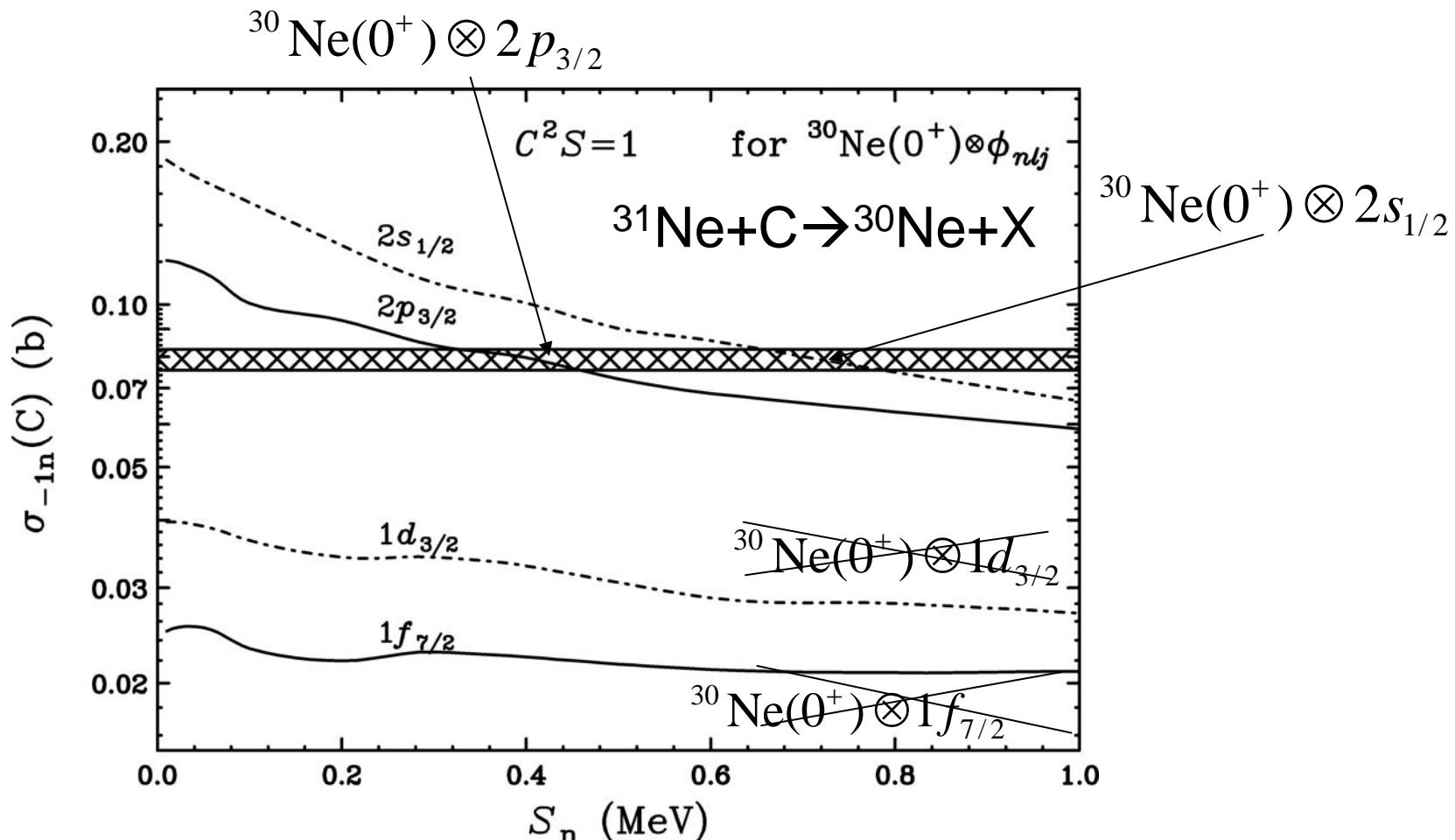
## Coulomb Breakup of $^{11}\text{Li}$ ( PRL96,252502(2006))

T.Nakamura, A.M.Vinodkuar, T.Sugimoto, Y.Kondo, N. Aoi, H. Baba, D. Bazin, N. Fukuda, T. Gomi, H. Hasegawa, N. Imai, M. Ishihara, T.Kobayashi, T. Kubo, M. Miura, T. Motobayashi, H. Otsu, A.Saito, H.Sakurai, S. Shimoura, K. Watanabe, Y.X. Watanabe, T. Yakushiji, Y. Yanagisawa, K. Yoneda

## Inclusive Coulomb Breakup of $^{31}\text{Ne}$ and $^{22}\text{C}$ as an experiment in RIBF DayOne Campaign

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, S.Shimoura, T.Sumikama, H.Takeda, E.Takeshita,M.Takechi, S.Takeuchi, K.Tanaka, K.N.Tanaka, N.Tanaka, Y.Togano, Y.Utsuno,K. Yoneda, A.Yoshida, K.Yoshida,

# Nuclear Breakup of $^{31}\text{Ne}$ on C target



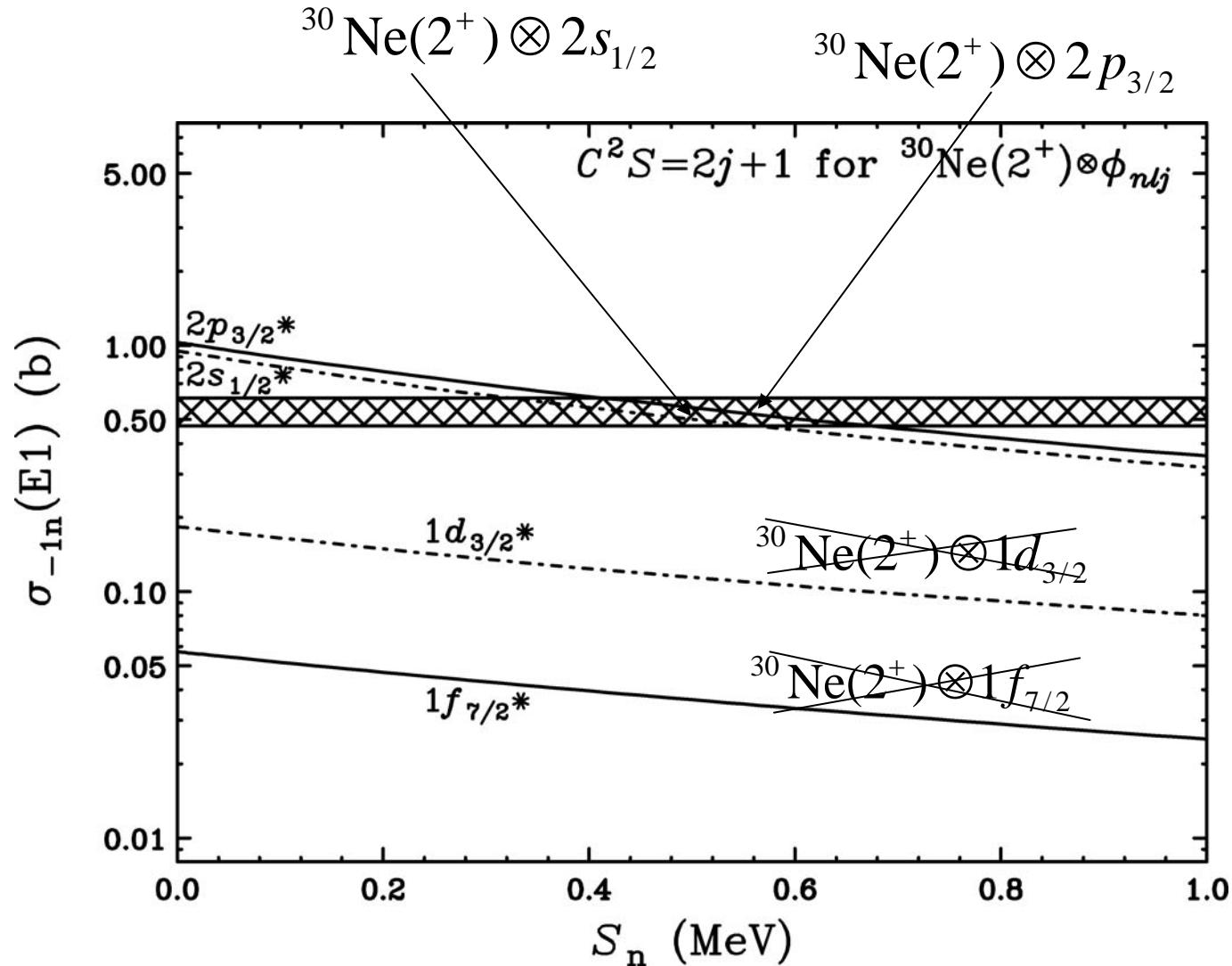
Calculation: Eikonal approximation(Glauber)

B.Abu-Ibrahim,Y.Ogawa,Y.Suzuki,I.Tanihata

Computer Phys.Comm. 151, 369(2003).

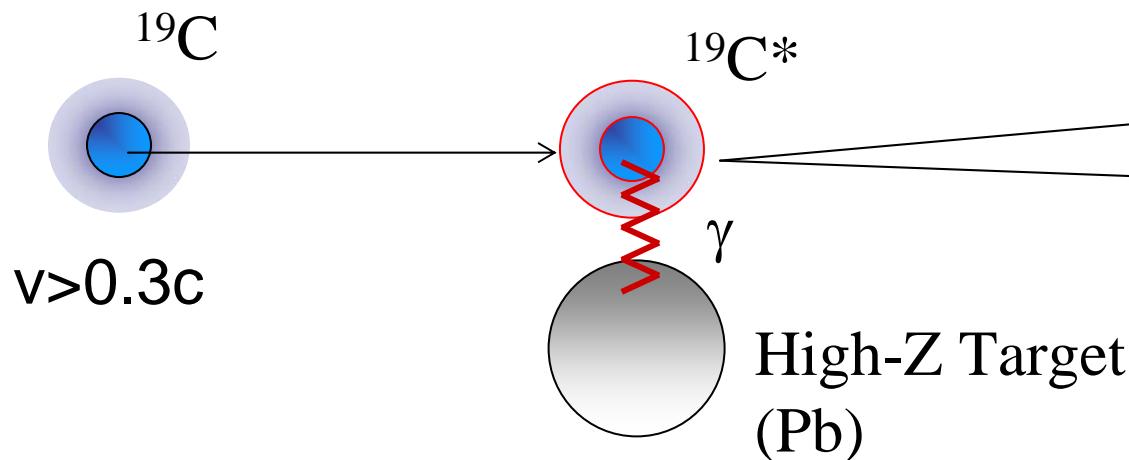
# $^{31}\text{Ne}$ (N=21)

## Comparison with $^{30}\text{Ne}(2^+) \times \phi_{nlj}$



# Coulomb Breakup

→ Photon absorption of a fast projectile

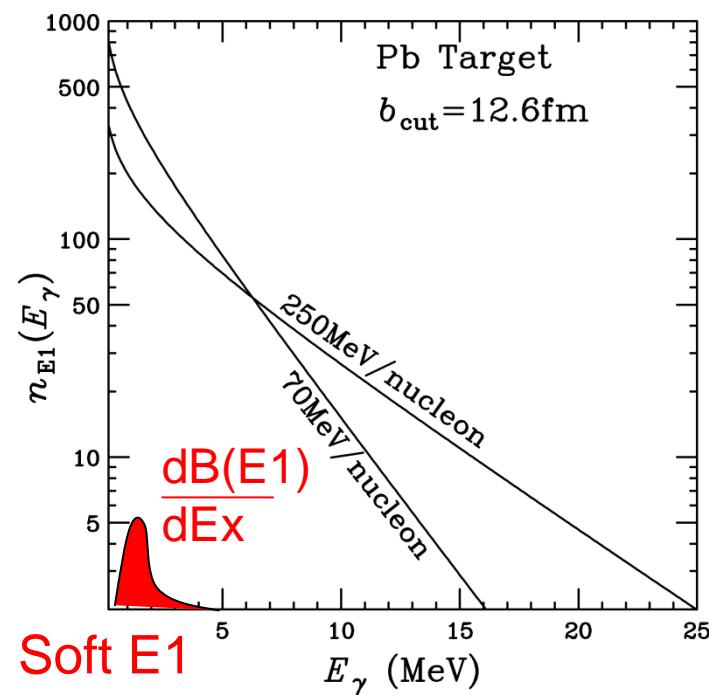


$\vec{P}(n), \vec{P}(^{18}\text{C})$   
 Invariant Mass  
 $E_x, E_{\text{rel}}$   
 $^{18}\text{C}$   
 $n$

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)  $\times$  (Transition Probability)



$$dB(E1; i \rightarrow f) / dE_{rel} \propto |\langle f | r | i \rangle|^2$$

## Plane wave approximation

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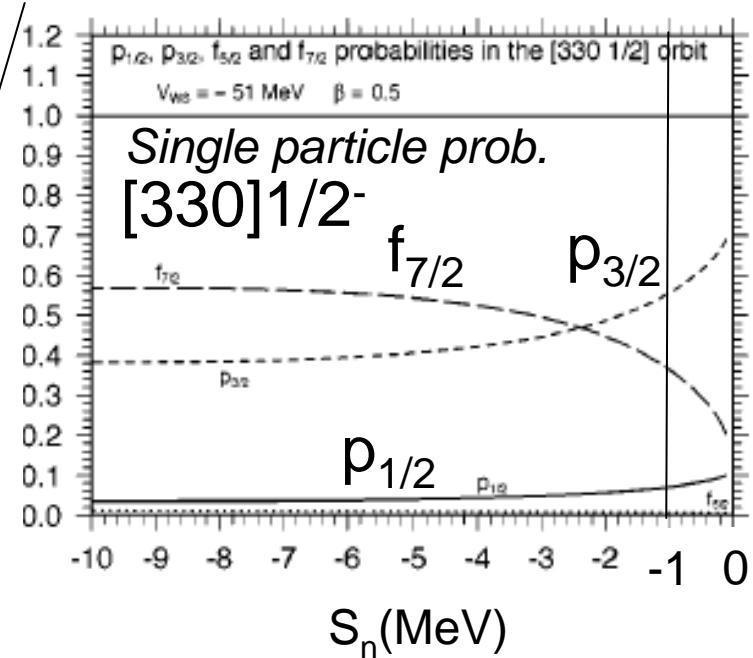
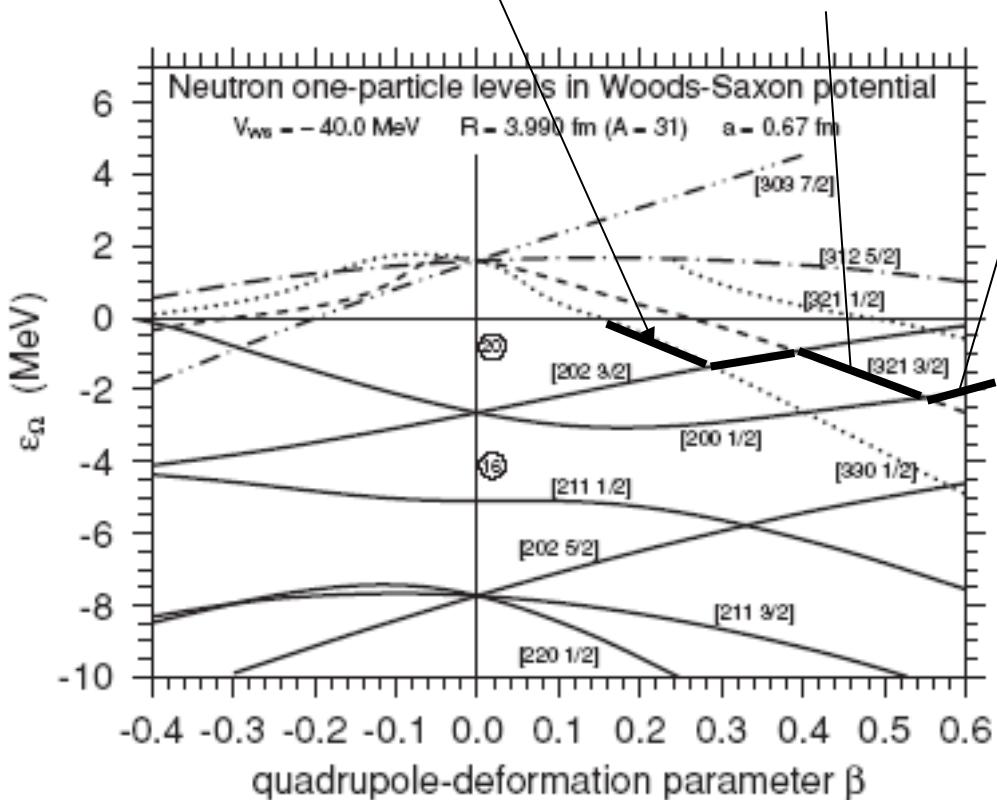
$\ell_i \rightarrow \ell_f$	$dB(E1) / dE \propto E_{rel}^{\ell_c + 1/2}$ ( $E_{rel} \sim 0$ )	$dB(E1) / dE$ _ max at
$s \rightarrow p$	$\propto E_{rel}^{3/2}$	$E_{rel} = 3/5(S_n)$
$p \rightarrow s$	$\propto E_{rel}^{1/2}$	$E_{rel} \approx 0.18 S_n$
$p \rightarrow d$	$\propto E_{rel}^{5/2}$	$E_{rel} = 5/3(S_n)$
$d \rightarrow p$	$\propto E_{rel}^{3/2}$	$E_{rel} = 5/3(S_n)$

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c.f. Lecture at Tokyo Tech by I.Hamamoto  
Mar.2009

# Theoretical consideration-II ( $^{31}\text{Ne}$ )

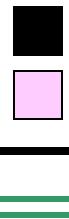
$N=21: [330]1/2^- \quad [321]3/2^- \quad [200]1/2^+$



Loosely-bound  
→ Low I orbit dominance  
Halo with deformed core?

- I.Hamamoto PRC69,041306(R)(2004).
- T.Misu, W.Nazarewicz,S.Aberg.NPA614,44(1997).
- I.Hamamoto.PRC76,054319(2007).

# Exploration of the Limit of Existence



stable nuclei

unstable nuclei observed so far

drip-lines (limit of existence) (theoretical predictions)

~300 nuclei

~2700 nuclei

~6000 nuclei

magic numbers

4000 species to be produced  
(1000 more new isotopes)

