Weakly-bound and unbound few-body nucleonic systems

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Neutron Star Matter

Outline

1 Introduction----Drip Line and Neutron Halo

RI-Beam Factory at RIKEN (new-generation RIB facility)

2 Probes– Nuclear and Coulomb breakup
(70~200 MeV/nucleon β=0.3~0.6)

3 Coulomb Breakup of ^{11}Li

4 Coulomb and nuclear Breakup of ^{22}C

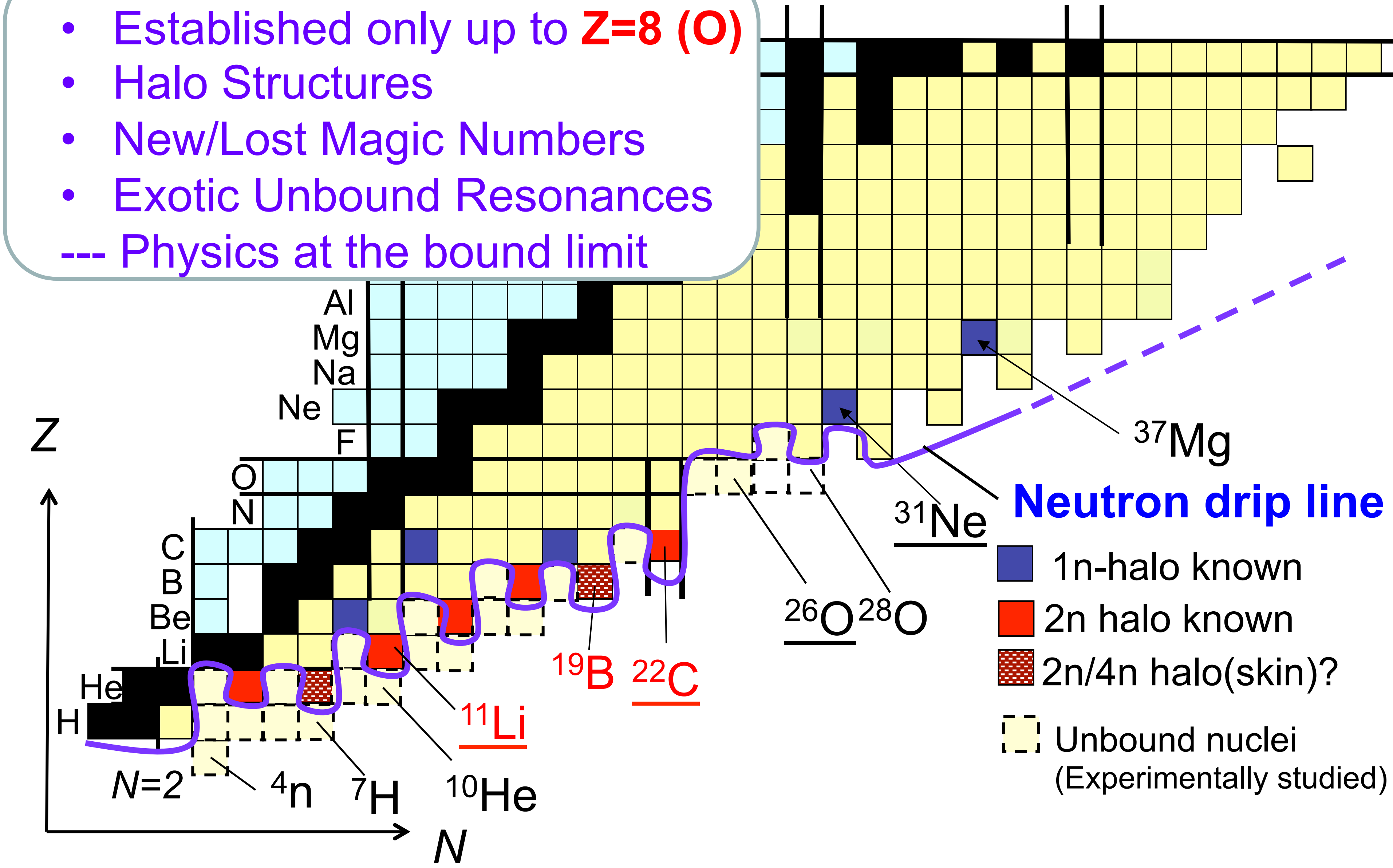
5 Unbound 3-body resonance states ^{26}O

6 Summary and Outlook

Neutron Drip Line– *Boundary of Bound Nuclei*

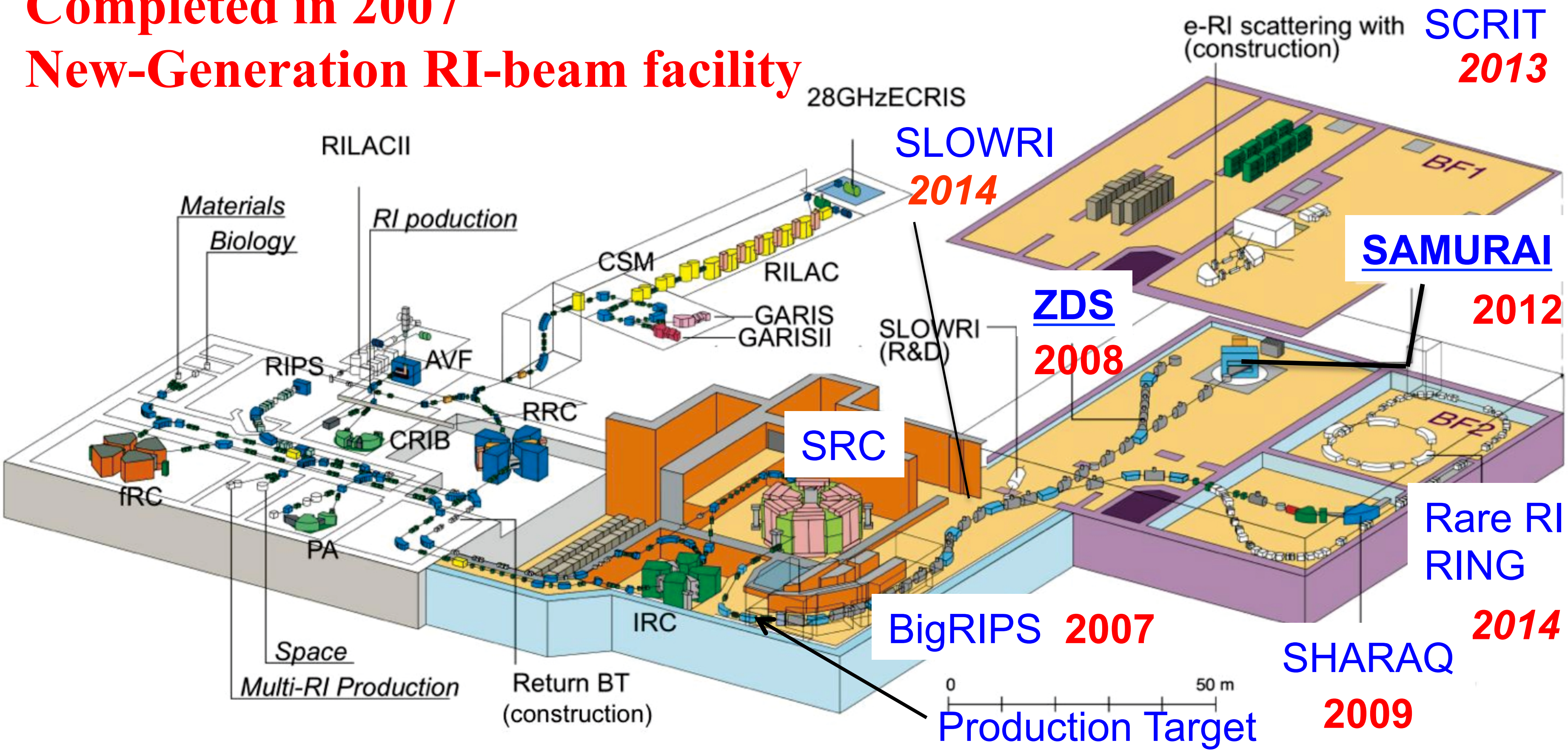
- Established only up to **Z=8 (O)**
- Halo Structures
- New/Lost Magic Numbers
- Exotic Unbound Resonances

--- Physics at the bound limit



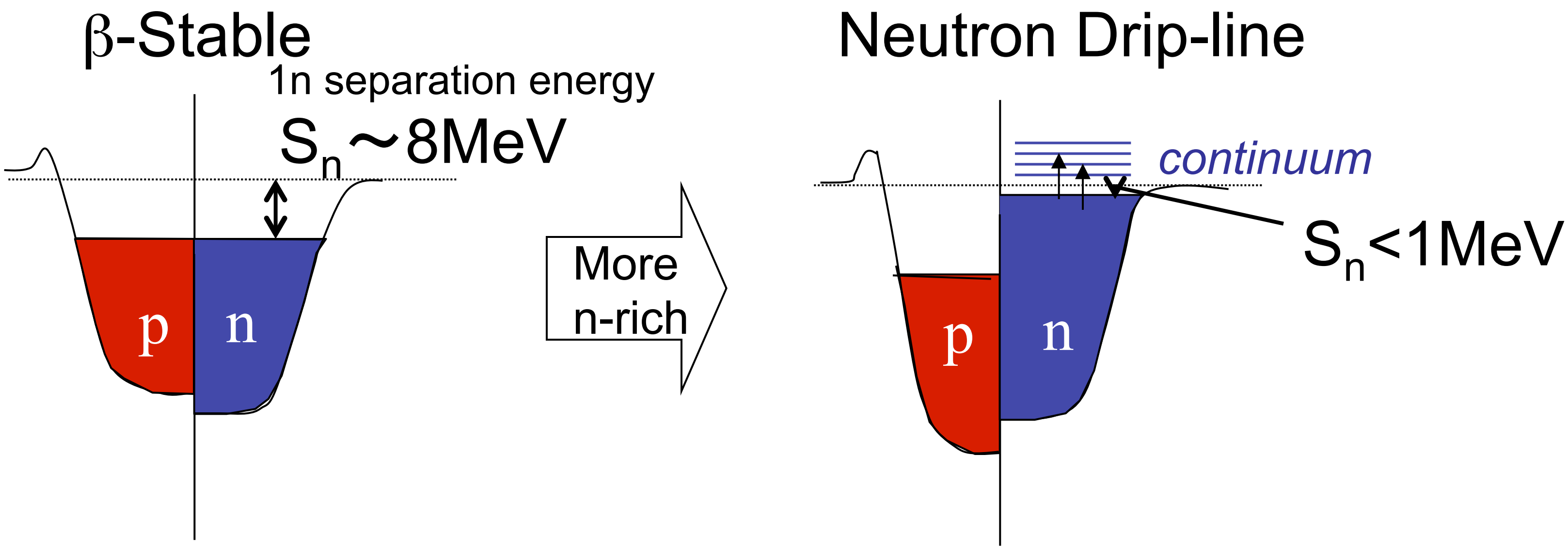
RIKEN RI Beam Factory (RIBF)

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) ~10^{12} particles/s
^{238}U beam (345 MeV/nucleon) ~10^{11} particles/s

Characteristic features of neutron-drip line nuclei



β-Stable

1n separation energy

$S_n \sim 8\text{MeV}$

More n-rich

Neutron Drip-line

continuum

$S_n < 1\text{MeV}$

Neutron drip-line nuclei

Fermi levels between n and p—Very Different

→Valence neutron – *Weakly-Bound*

→ ‘Halo’ can be formed (but not always)

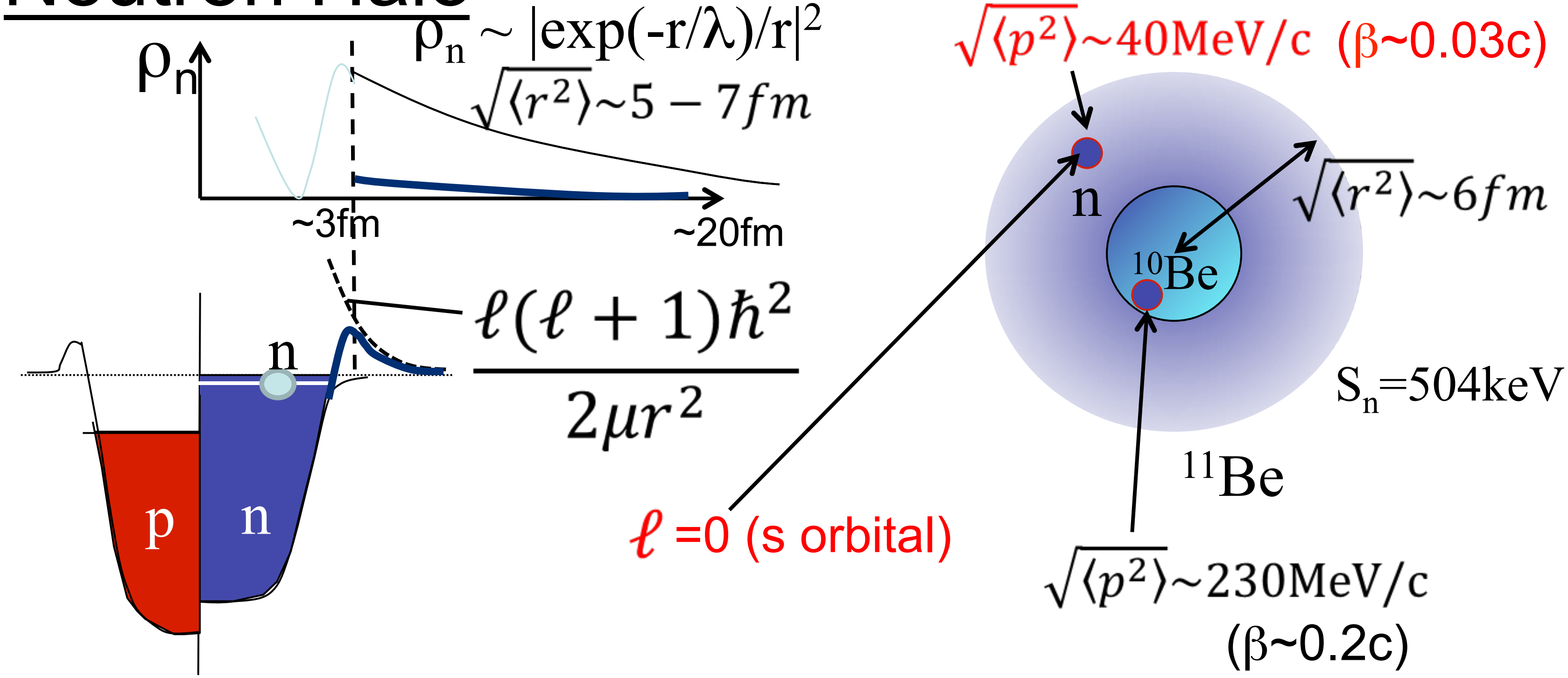
→Excitation/Coupling to the continuum

– More significant

Spectroscopy of Halo Nuclei

→Breakup by 1n/2n emission

Neutron Halo



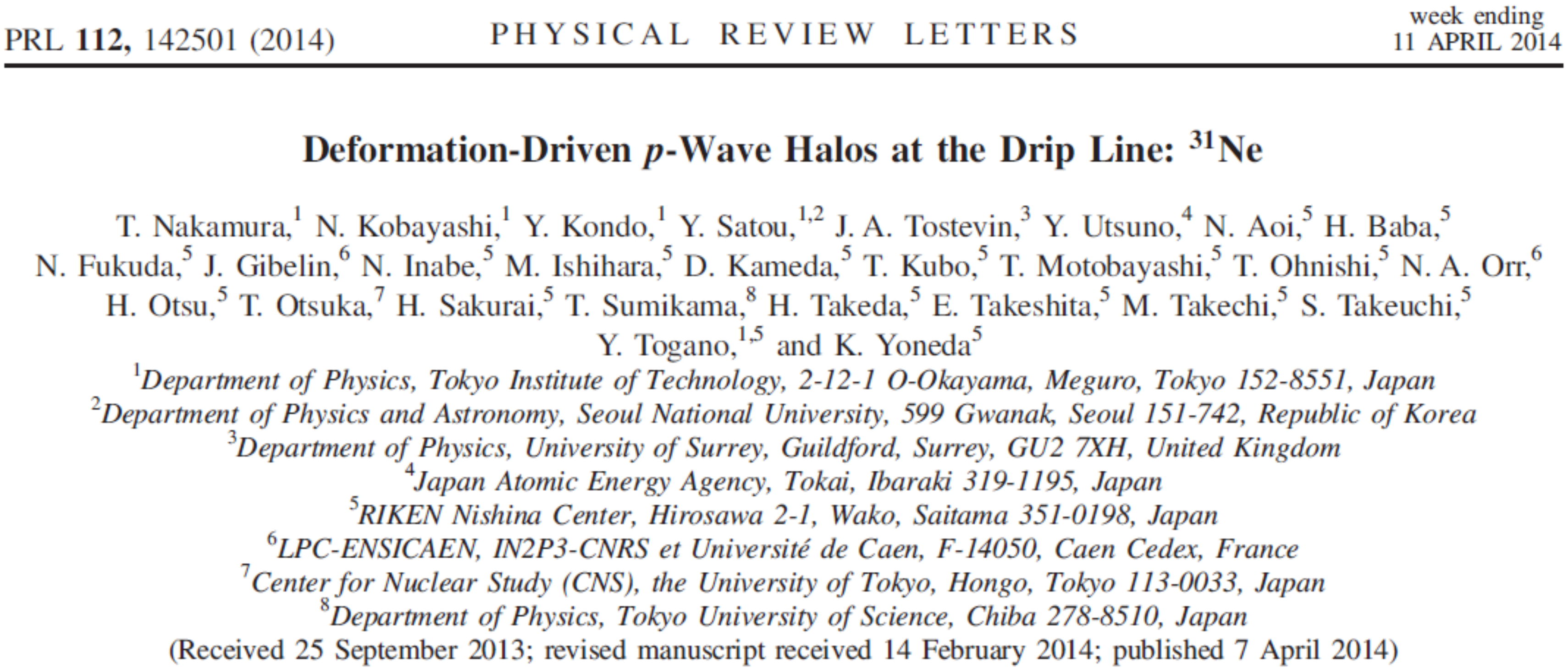
- ✓ Small Separation Energy $S_n < 1MeV << 8MeV$
- ✓ Extended ρ_n Distribution beyond Range of Nuclear Interaction

$$\langle r\rangle \to \infty \quad for\ S_n \to 0 \quad \left(\sqrt{\langle r^2\rangle} \propto 1/S_n\right) \quad \sim 0.1\mathrm{nm}\ for\ S_n = 1\mathrm{meV}$$

- ✓ Small Fermi Momentum → Small Kinetic Energy
- ✓ No (Small) Angular Momentum $\ell = 0,1$ → No (Small) Centrifugal Barrier

⇨ Nuclear Stability At the Limit ←→ Shell Evolution ←→ Halo

Example of 1n Halo:



PRL **112,** 142501 (2014) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2014

Deformation-Driven *p*-Wave Halos at the Drip Line: ^{31}Ne

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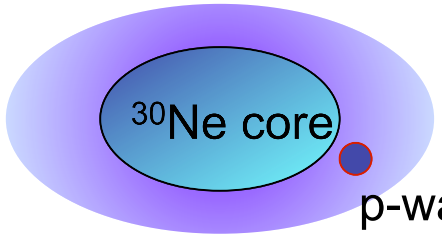
^{31}Ne



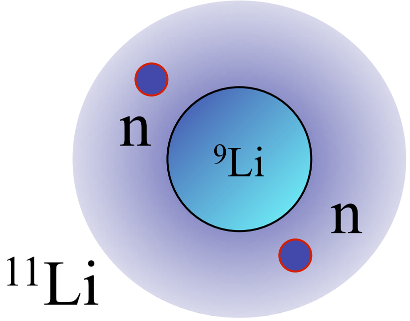
$$S_n = 0.15^{+0.16}_{-0.10}\ \mathrm{MeV}$$

p-wave halo neutron

Deformation β~0.5 (~ 3:2)

Strongly deformed although it is N=21 (close to 20)

Two-neutron Halo



S_{2n}=0.37MeV

^{9}Li + n Barely Unbound

$a = -22.4 \pm 4.8\ fm$

Yu. Aksyustina PLB666,430(2008)

n + n Barely Unbound

$a = -18.9 \pm 0.4\ fm$

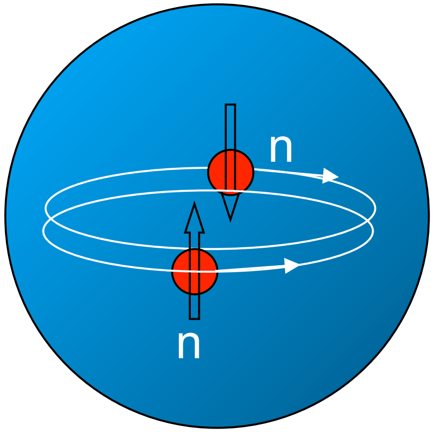
^{9}Li + n+n Bound

S_{2n}=0.369MeV

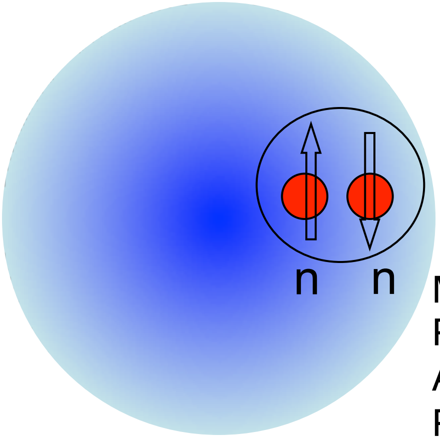
Borromean Ring

Dineutron Correlation?

A.B.Migdal predict strong-correlated dineutron system Sov.J.Nucl.Phys.238(1973).



BCS-like Pairing Correlation (long range)



Dineutron correlation
（short-range)
@Weak-binding
Low-density

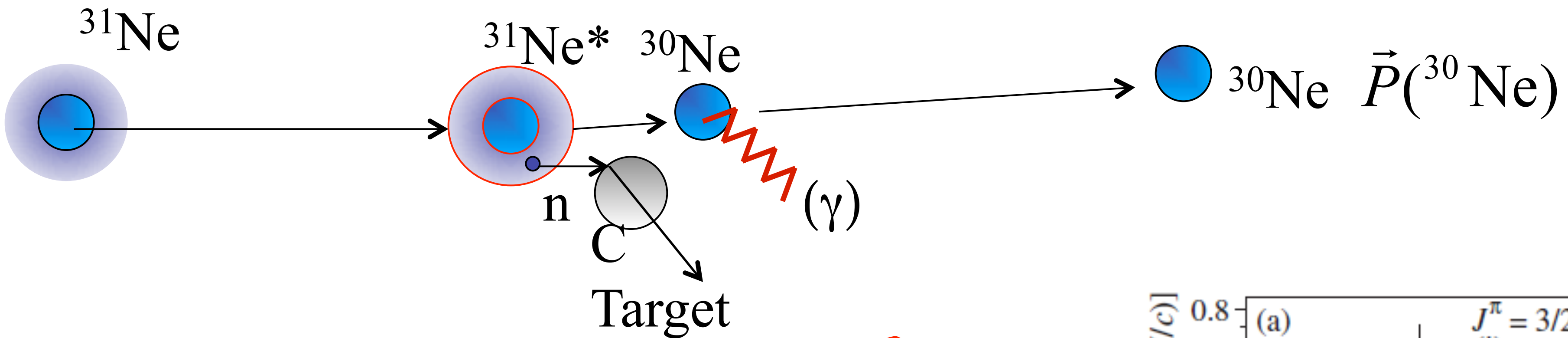
M.Matsuo PRC73,044309(2006).
A.Gezerlis, J.Carlson, PRC81,025803(2010)

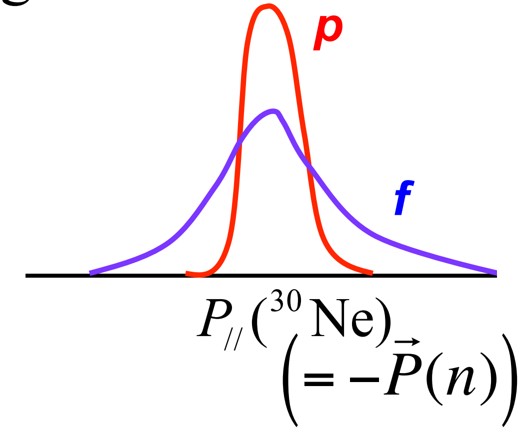
2 Probes– Nuclear and Coulomb breakup

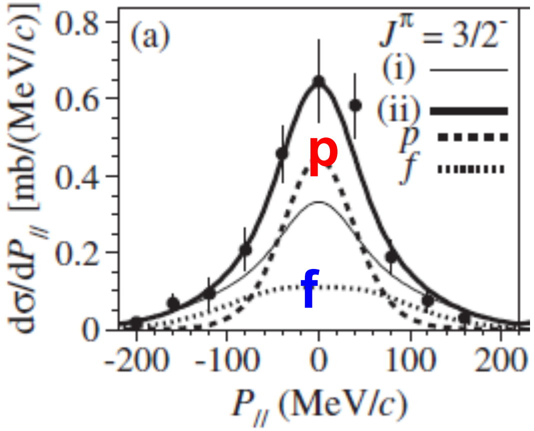
at 70~200 MeV/nucleon (β=0.3~0.6)

Probe-1: **Nuclear Breakup – Case of 1n Halo**

1n knockout reaction of ^{31}Ne (TN et al. , PRL**112**,142501 (2014).)





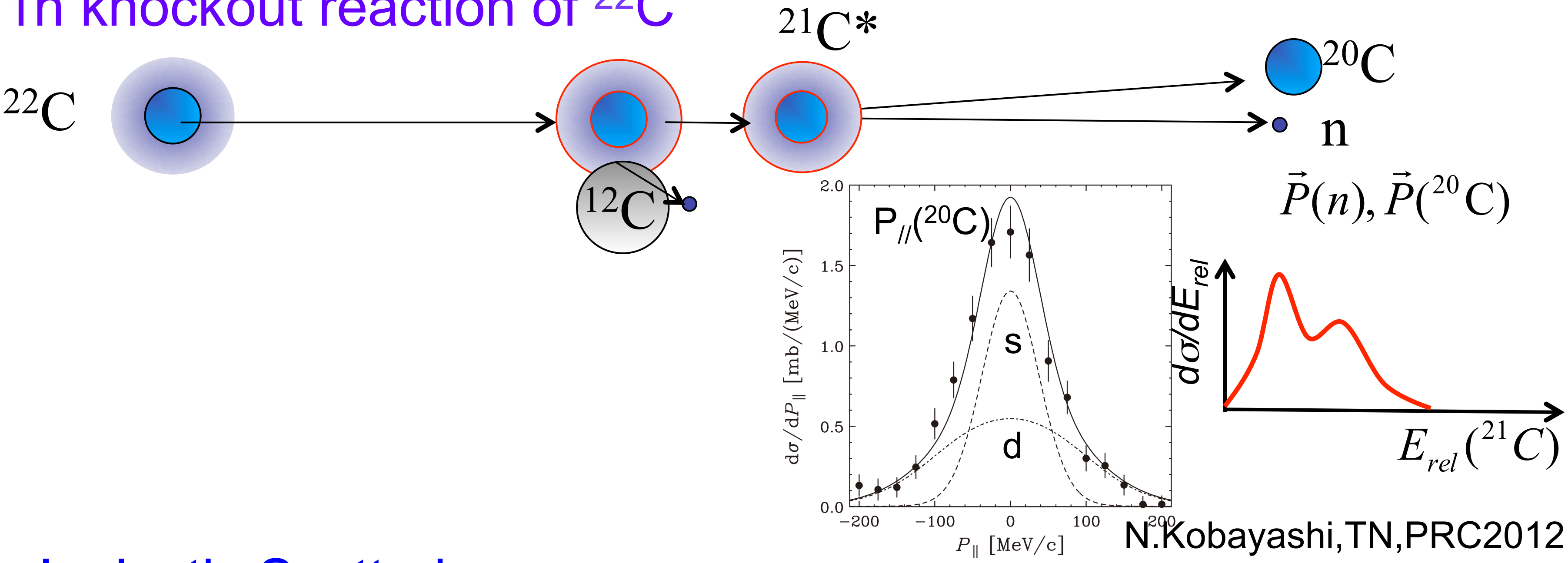


- γ ray in coincidence → ^{30}Ne(2^+) / ^{30}Ne(0^+) Contribution
- σ_{-1n} and $P_{//}$ distribution → ℓ of valence n, configuration

Theory: Eikonal Approximation

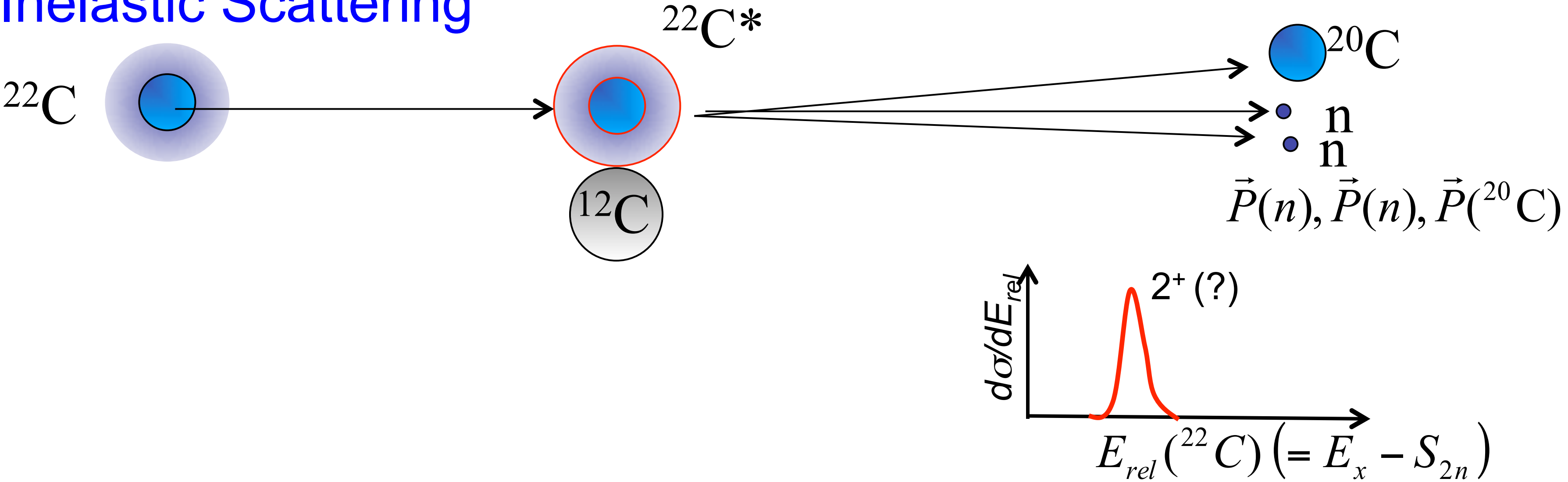
Nuclear Breakup – Case of 2n Halo

1n knockout reaction of ^{22}C



N.Kobayashi,TN,PRC2012

Inelastic Scattering

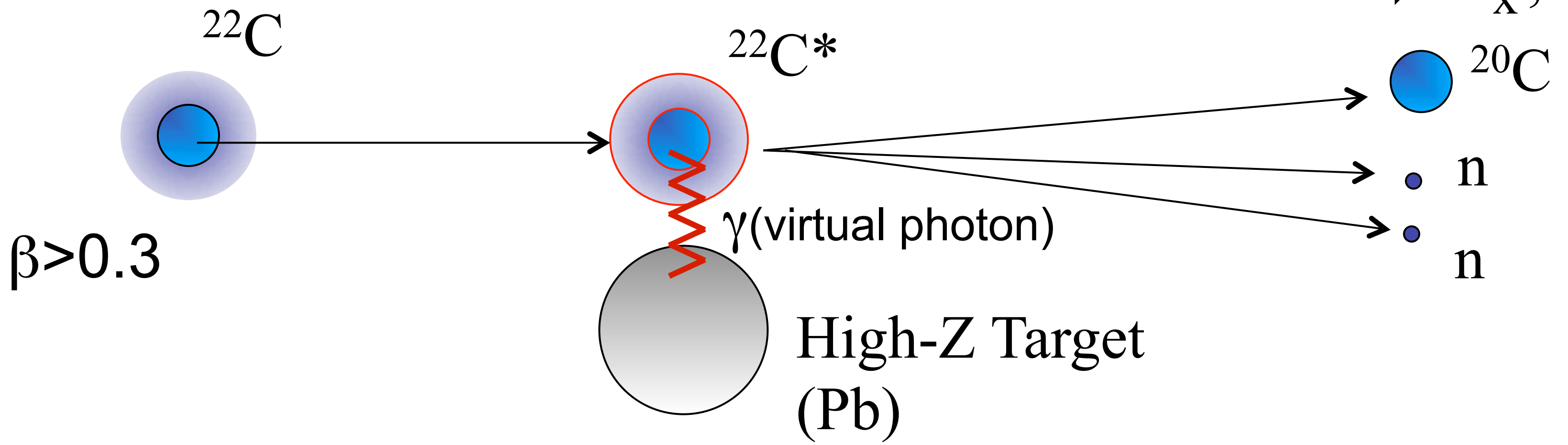


Probe-2: **Coulomb Breakup**

$\vec{P}(n), \vec{P}(n), \vec{P}(^{20}\mathrm{C})$

Invariant Mass ⇒ E_x, E_{rel}

→Photon absorption of a fast projectile

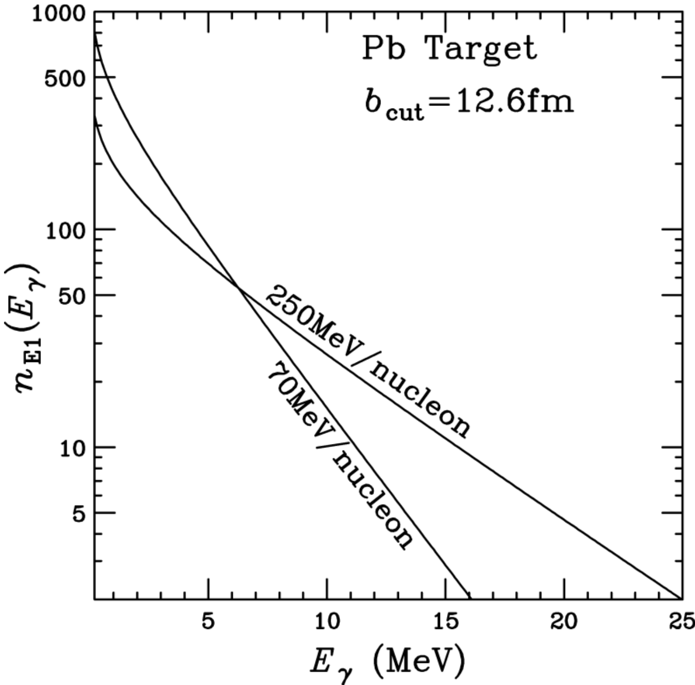


Equivalent Photon Method

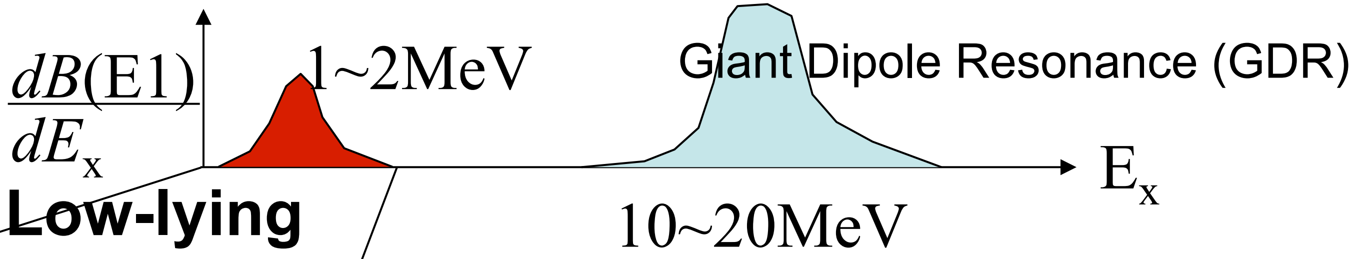
$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x)\frac{dB(E1)}{dE_x}$$

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

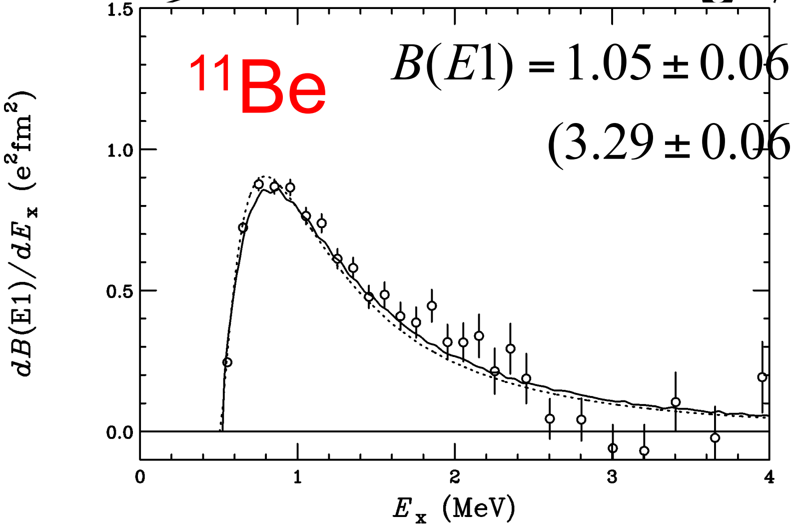
C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).



Coulomb Breakup and E1 Response--Case of 1n Halo



Low-lying
E1 Strength (Soft E1 excitation)

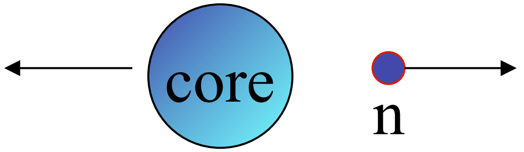


$$B(E1) = 1.05 \pm 0.06\, e^2\mathrm{fm}^2$$

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

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

Direct Breakup Mechanism



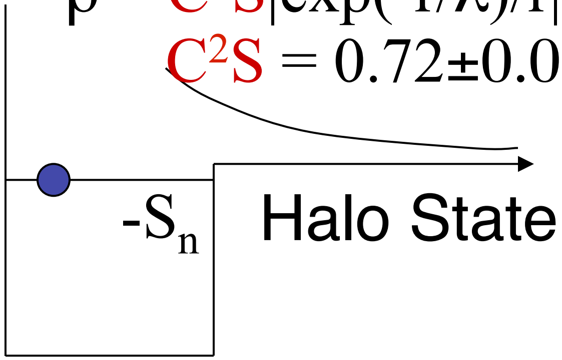
E1 Strength

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

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

Fourier Transform

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



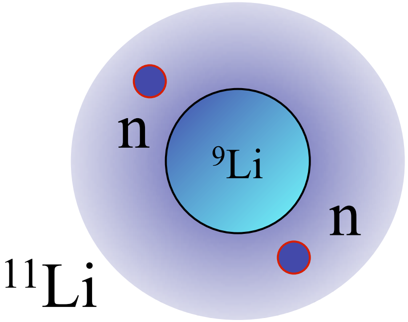
Halo State

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

3 Coulomb Breakup of ^{11}Li

--*Case of 2n Halo*

TN et al. PRL96,252502(2006).
+ Unpublished data



- **Borromean Physics – Binding Mechanism?**

^{10}Li(= ^{9}Li + n) Barely Unbound $a = -22.4 \pm 4.8\ fm$

n + n Barely Unbound $a = -18.9 \pm 0.4\ fm$

^{9}Li + n+n Bound S_{2n}=0.369 MeV

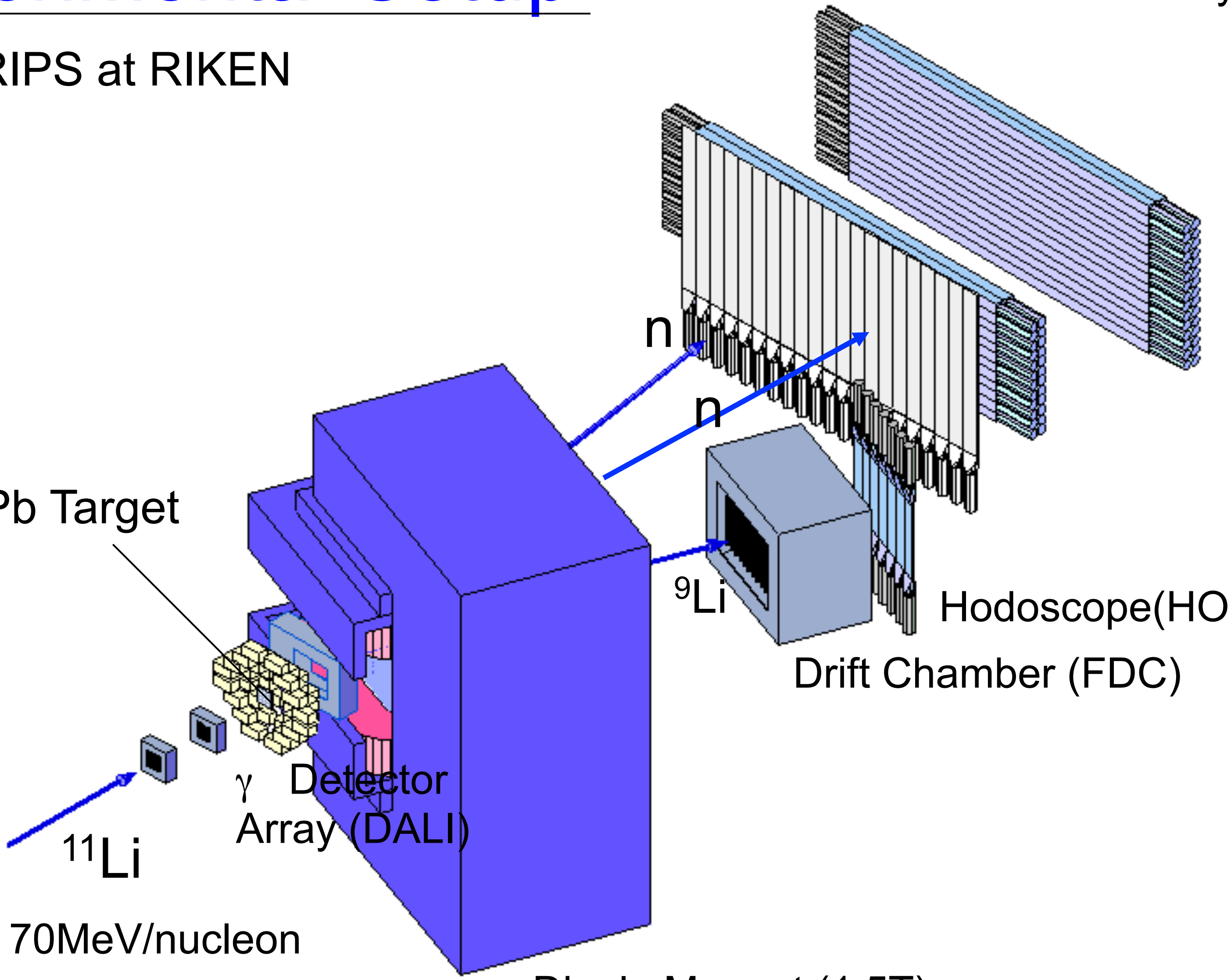
- **Dineutron correlation?**
- **Mixing of 2n with different Parities?**

$$\left|\Phi(^{11}\mathrm{Li}_{gs})\right\rangle = \alpha\left|\Phi(^{9}\mathrm{Li}_{gs})\otimes(s_{1/2})^2\right\rangle + \beta\left|\Phi(^{9}\mathrm{Li}_{gs})\otimes(p_{1/2})^2\right\rangle + \ldots$$

- **Efimov state?** (V.Efimov PLB33,563(1970).)

Experimental Setup

@RIPS at RIKEN



Neutron Detector Array (NEUT)

n

n

Pb Target

^{9}Li

Hodoscope(HOD)

Drift Chamber (FDC)

γ Detector Array (DALI)

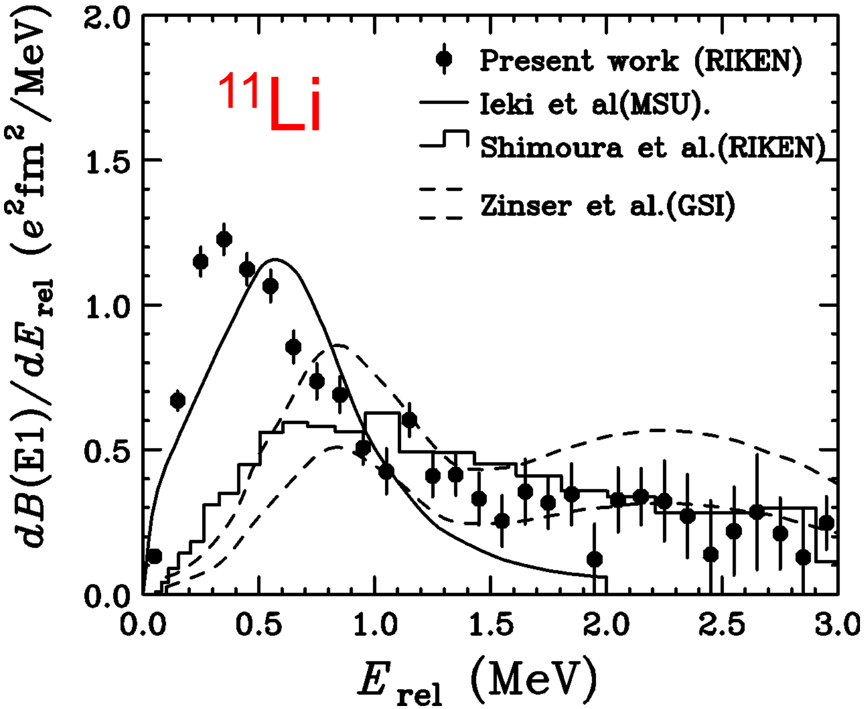
^{11}Li

70MeV/nucleon

Dipole Magnet (1.5T)

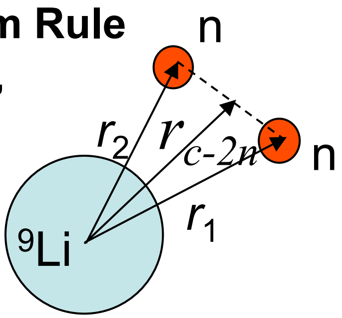
Coulomb Breakup and E1 Response--Case of 2n Halo

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



E1 Non-energy weighted Sum Rule

H. Esbensen and G.F. Bertsch,
Nucl. Phys. **A542**, 310 (1992).

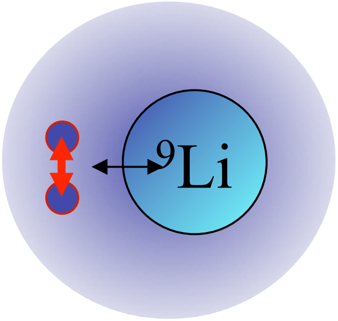


$$B(E1)=\int_{-\infty}^{\infty}\frac{dB(E1)}{dE_x}dE_x$$

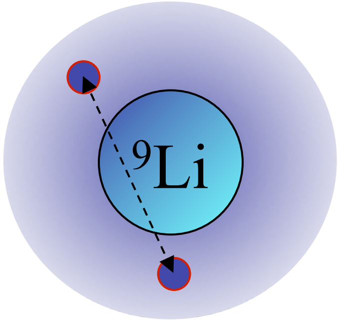
$$=\frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2\left\langle r_1^{\,2}+r_2^{\,2}+2(\vec{r}_1\cdot\vec{r}_2)\right\rangle$$

$$B(E1)=1.42\pm0.18\,e^2\,fm^2\,(E_{\mathrm{rel}}\le 3\mathrm{MeV})$$

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



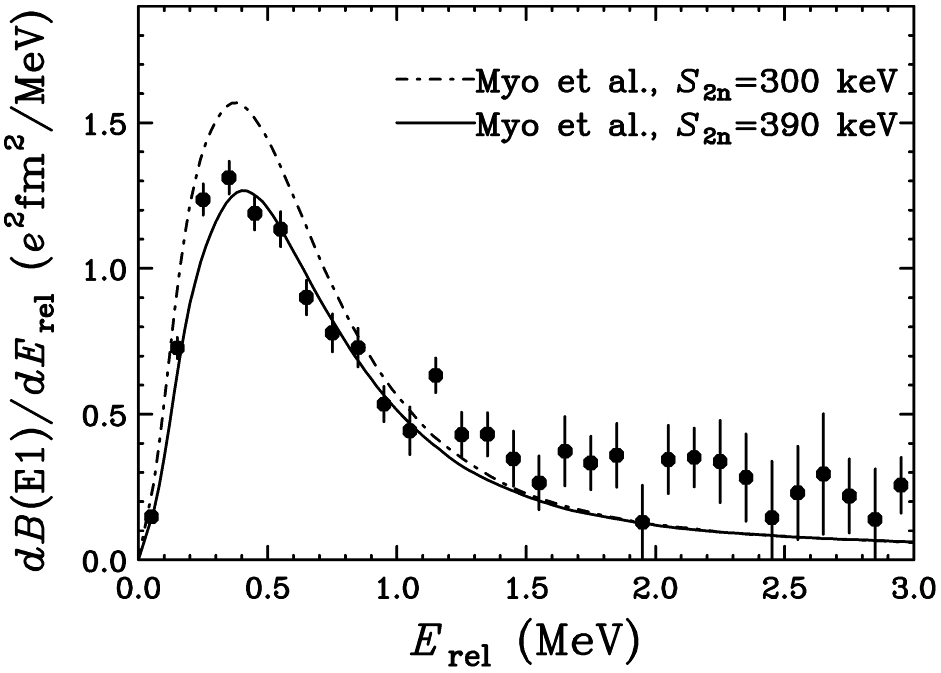
Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation



Weak 2n correlation
→Weakly Polarized
→Weak E1 Excitation

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

Comparison with 3-body theory



Myo et al.,PRC76,024305 (2007).

Core polarization

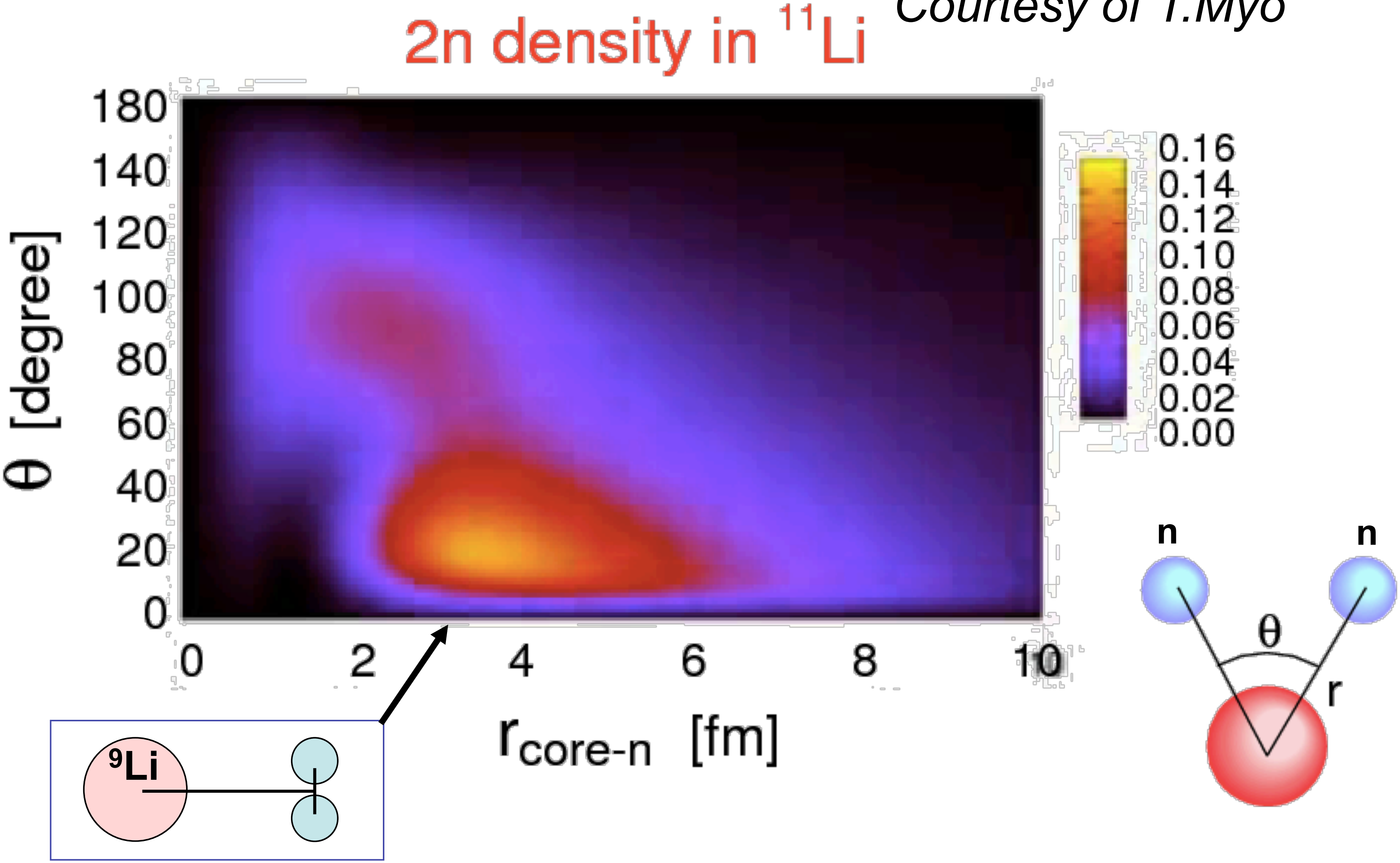
(Tensor correlation+Pauli Principle)

P(S^2)~ 40% $\sqrt{\langle r_{c-2n} \rangle^2} = 5.38\ \mathrm{fm}$ $\langle \theta_{12} \rangle = 65\,\mathrm{deg}$

Both Charge distribution & B(E1) are reproduced.

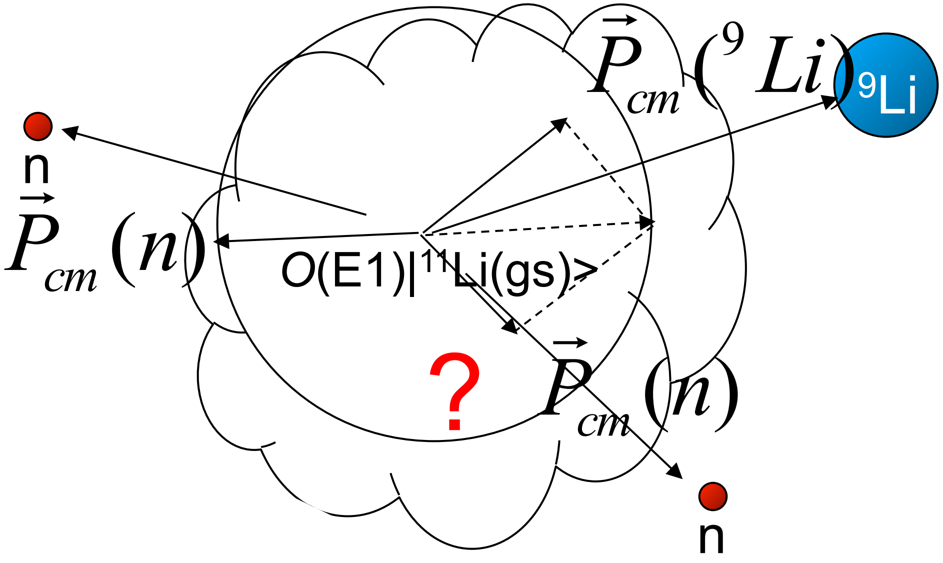
2n correlation density in ^{11}Li

Courtesy of T.Myo



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

Correlations can be studied by three-body decay of ^{11}Li?



--Kinematically complete measurement

4

Coulomb and Nuclear Breakup of ^{22}C

^{22}C (Z=6,N=16)

☐ Prominent 2n-Halo?

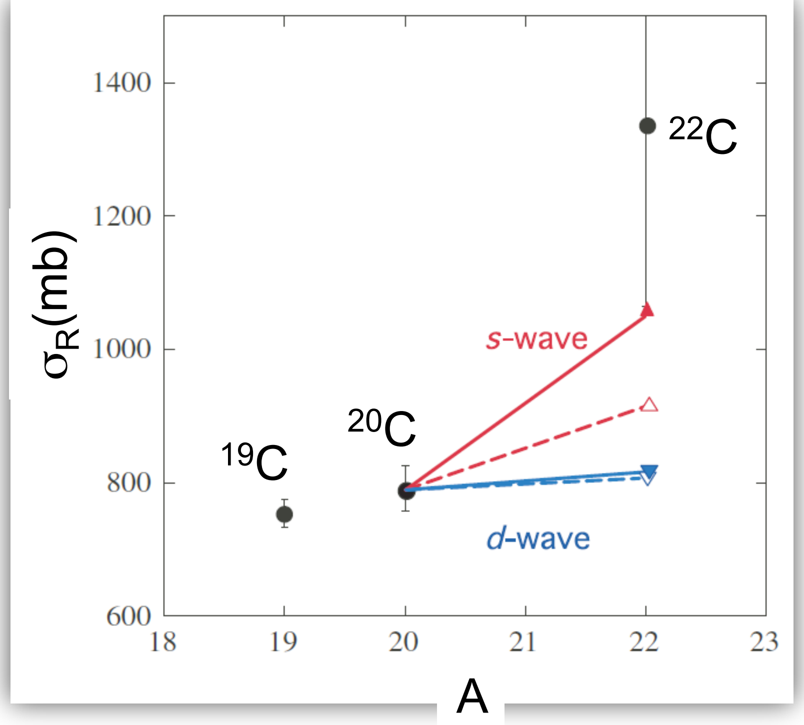
Reaction cross section measurements

$(\langle r_m^2 \rangle)^{1/2}=5.4(9)$ fm c.f. ~3.5 fm ^{11}Li

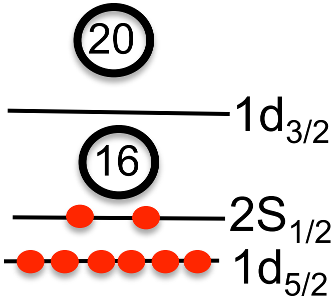
K.Tanaka et al., PRL 104, 062701(2010).

$S_{2n}= -0.14(46)$ MeV

L.Gaudefroy et al. PRL109,202503(2012).



☐ N=16 Magicity?



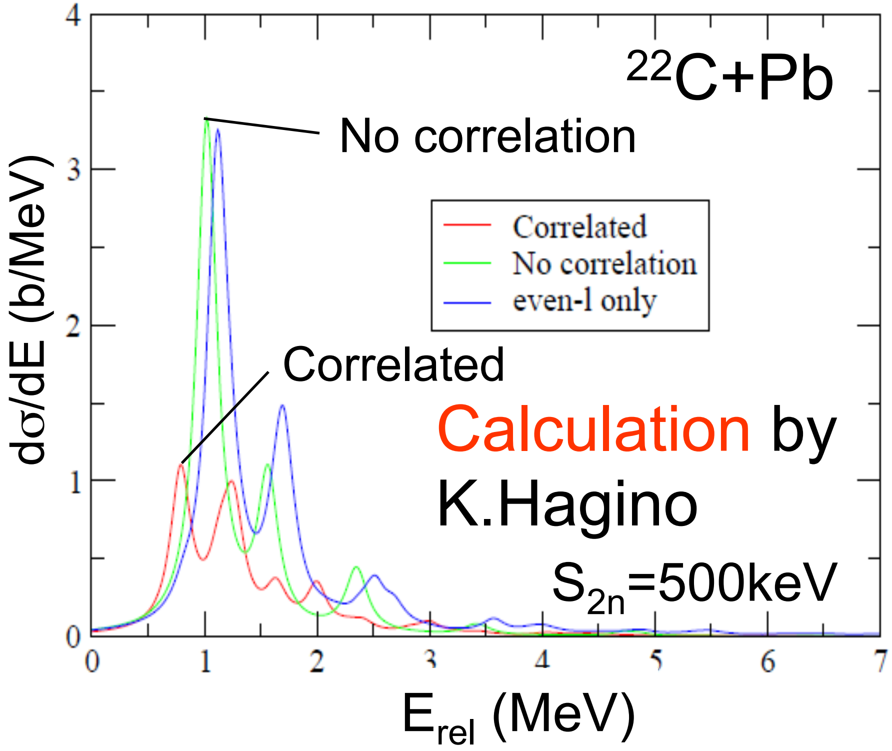
A.Ozawa et al., PRL 84, 5493 (2000).

☐ Efimov states?

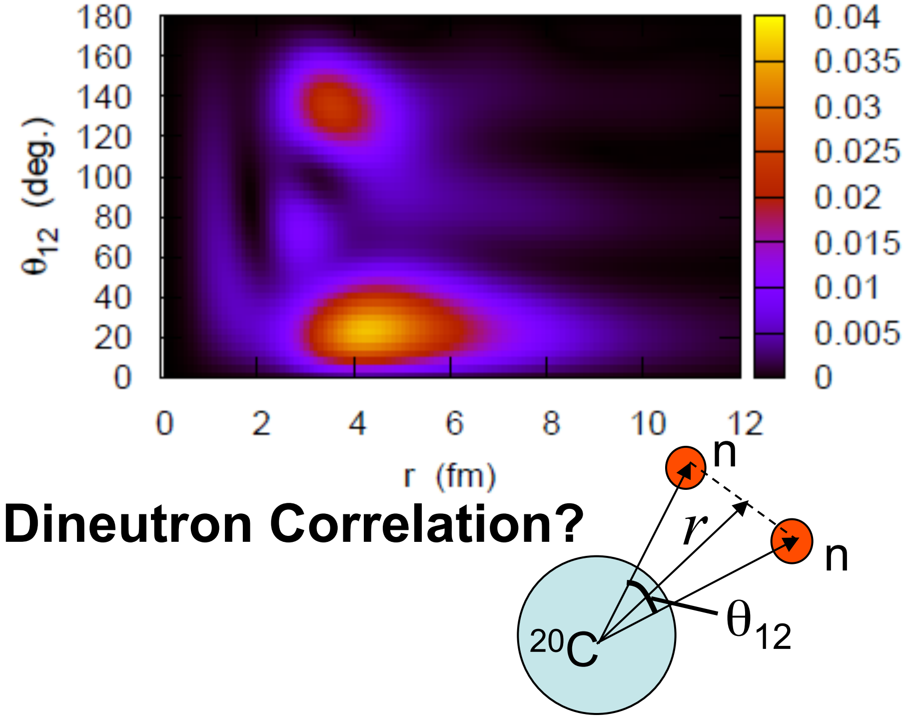
I.Mazumdar et al. PRC61, 051303(R)

If $a_{\text{20C-n}} \sim -100$ fm

Coulomb Breakup of ^{22}C



Calculation by K.Hagino

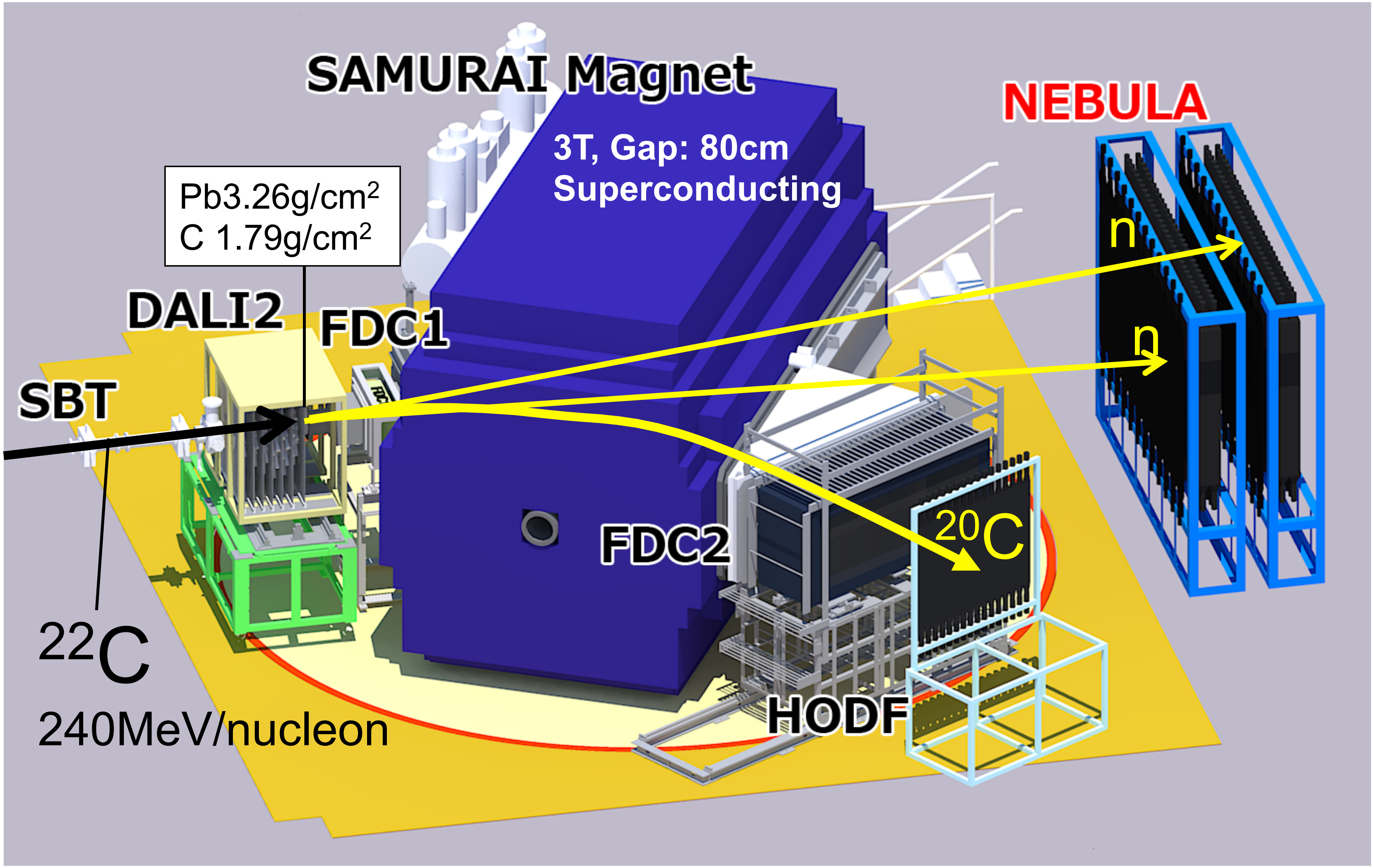


Dineutron Correlation?

Correlated:	$\alpha\vert(2s_{1/2})^2\rangle$	$+\beta\,\vert(1d_{3/2})^2\rangle$	$+\,\gamma\vert(2p_{3/2})^2\rangle$	$+\,\gamma\vert(1f_{7/2})^2\rangle$	….
1.05b	62.5%	24.2%	4.7%	3.8%	
Non-Correlated:	$\vert(2s_{1/2})^2\rangle$				
(s only) 1.66b	100%				

→Kinematically Complete Measurement of Coulomb Breakup

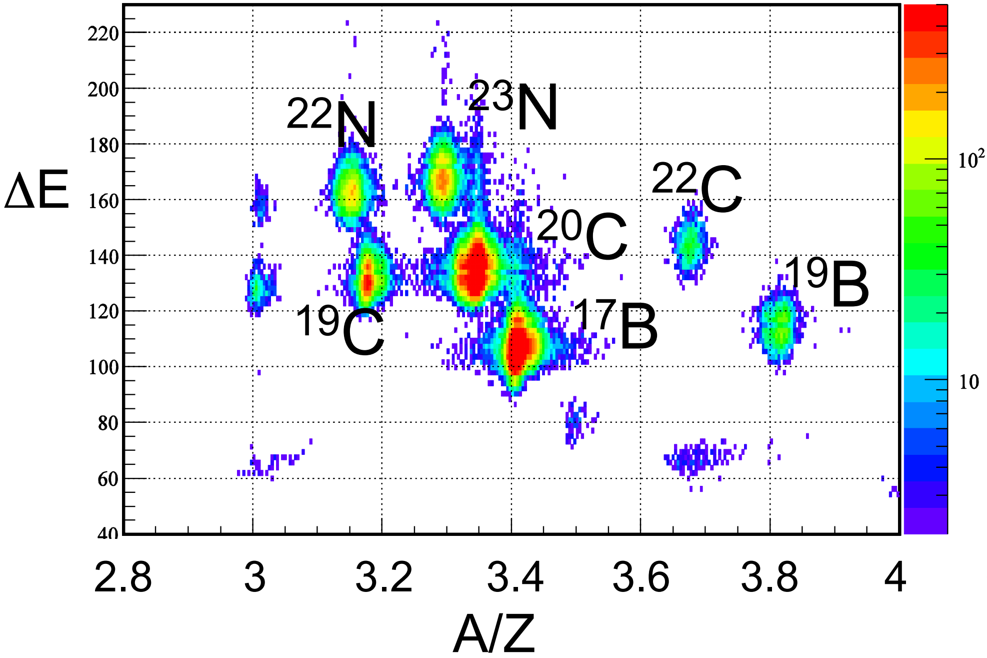
Experimental Setup--Coulomb/Nuclear Breakup of ^{22}C



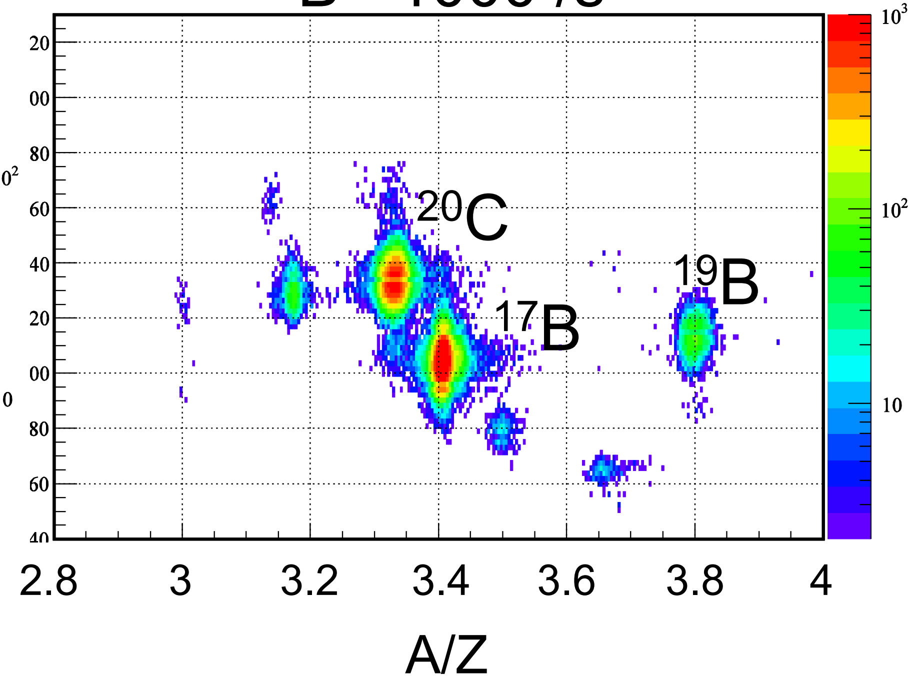
RI Beam Spectra @ SAMURAI May/2012

^{48}Ca 150~200pnA (Max 250pnA)

Tuned for **^{22}C**
(^{22}C+Pb/C→^{20}C+n+n)
^{22}C ~10 /s (@150pnA)
^{23}N ~80 /s



Tuned for **^{19}B**
(^{19}B+Pb/C→^{17}B+n+n)
^{19}B ~50 /s (@200pnA)
^{17}B ~1000 /s



High intense RIBF Beam

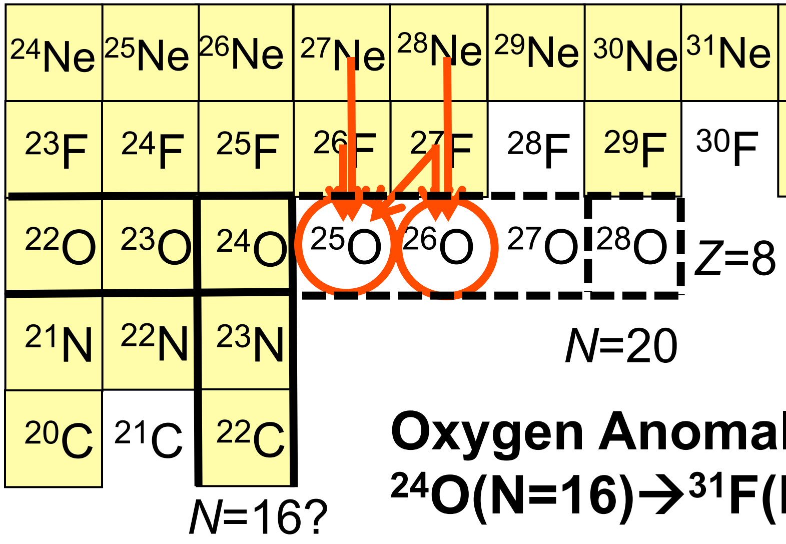
^{22}C: **~10/s** (*c.f. 10/hour K.Tanaka,PRL2010, RIPS@RIKEN*)

Gain of ~3600!

Study of unbound nuclei ^{25}O and ^{26}O

Spokesperson Yosuke Kondo

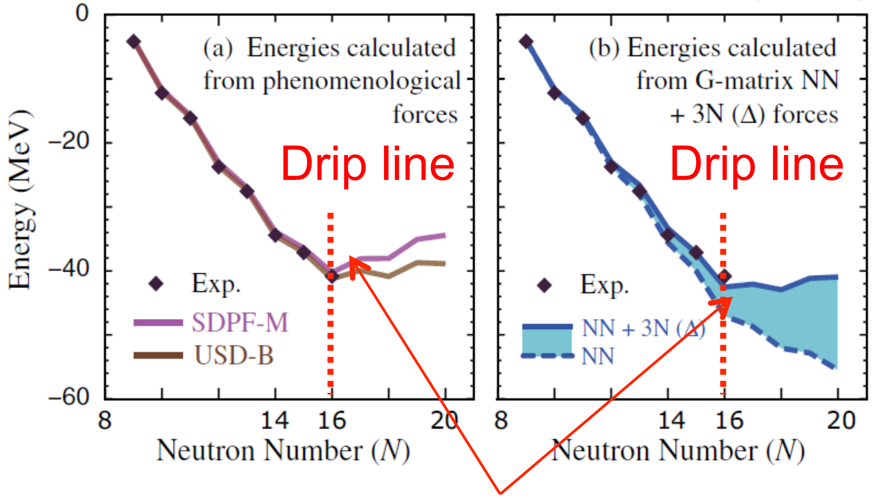
Experimental study of *unbound* oxygen isotopes towards the possible *doubly magic nucleus ^{28}O*



Oxygen Anomaly

^{24}O(N=16)→^{31}F(N=22)

T. Otsuka et al., PRL105, 032501 (2010)



3N effect is large at N>16

Otherwise Oxygen is bound up to ^{28}O

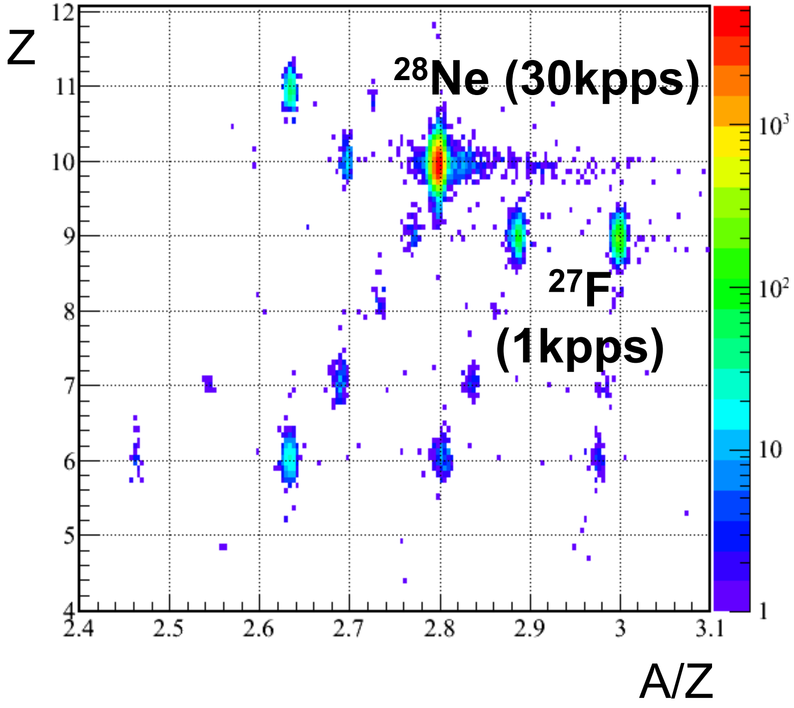
G. Hagen et al., PRL108, 242501(2012).
H. Hergert et al.,, PRL110, 242501(2013).

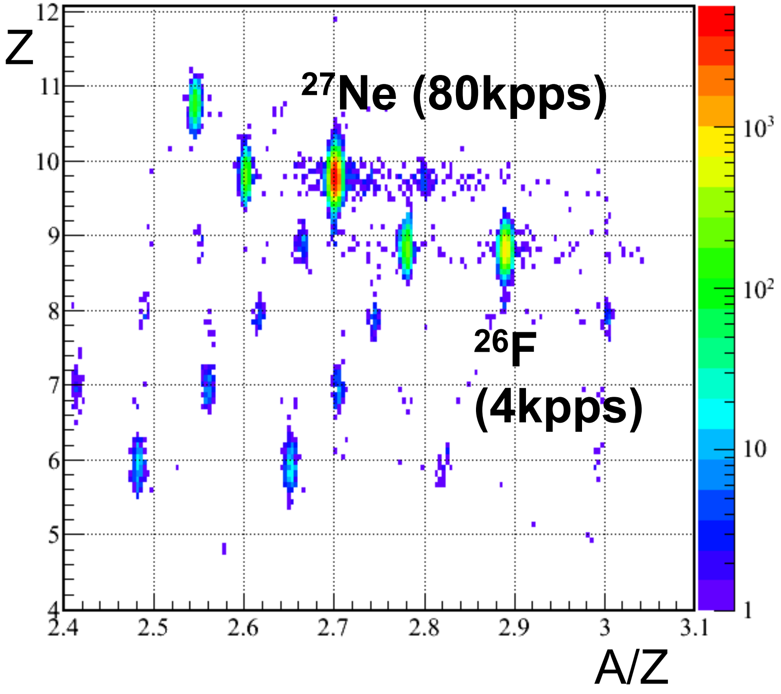
Study of unbound nuclei ^{25,26}O (Spokesperson: Y. Kondo)

One/two-proton removal reactions by using cocktail beams

- ^{27}F(201MeV/u)+C→^{26}O→^{24}O+2n
- ^{28}Ne(229MeV/u)+C→^{26}O→^{24}O+2n

- ^{26}F(201MeV/u)+C →^{25}O→^{24}O+n
- ^{27}Ne(228MeV/u)+C→^{25}O→^{24}O+n





Summary

1 **Nuclear Halo : A weakly-bound nucleonic system**

Diluted Nuclear Matter: Two-fold System, Borromean

Binding Mechanism? Dineutron Correlation?

Configuration Mixing? Three-body Effects?

2 **Nuclear and Coulomb breakup :**

→Powerful probes of weakly bound syatem

3 **Coulomb Breakup of ^{11}Li**

Characteristic E1 Response→ Dineutron Correlation

3 body breakup → ^{9}Li-n,nn correlation, 3-body effect?

4 **Coulomb and nuclear Breakup of ^{22}C**

^{21}C resonance (s and d?), Strong E1 Transition

5 **Unbound 3-body resonance states ^{26}O**

Barely-unbound 3-body state, 1st Excited State: long life time?, 3-body correlation?

Near Future: Variety of unbound states along n-drip line

→ ^{28}O (Possible unbound doubly magic nucleus, →^{24}O+4n)

SAMURAI Dayone Experiment
(May 2012)

First experimental campaign for the 3 physics programs

1. Coulomb breakup of ^{22}C and ^{19}B (T. Nakamura)
2. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B (N. A. Orr)
3. Study of unbound nuclei ^{25}O and ^{26}O (Y. Kondo)

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