Physics of Unstable Nuclei

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Neutron Star Matter

Contents

Existence of human being depends on a subtle balance of Nature!

人間の存在は自然の絶妙なバランスで決まっている

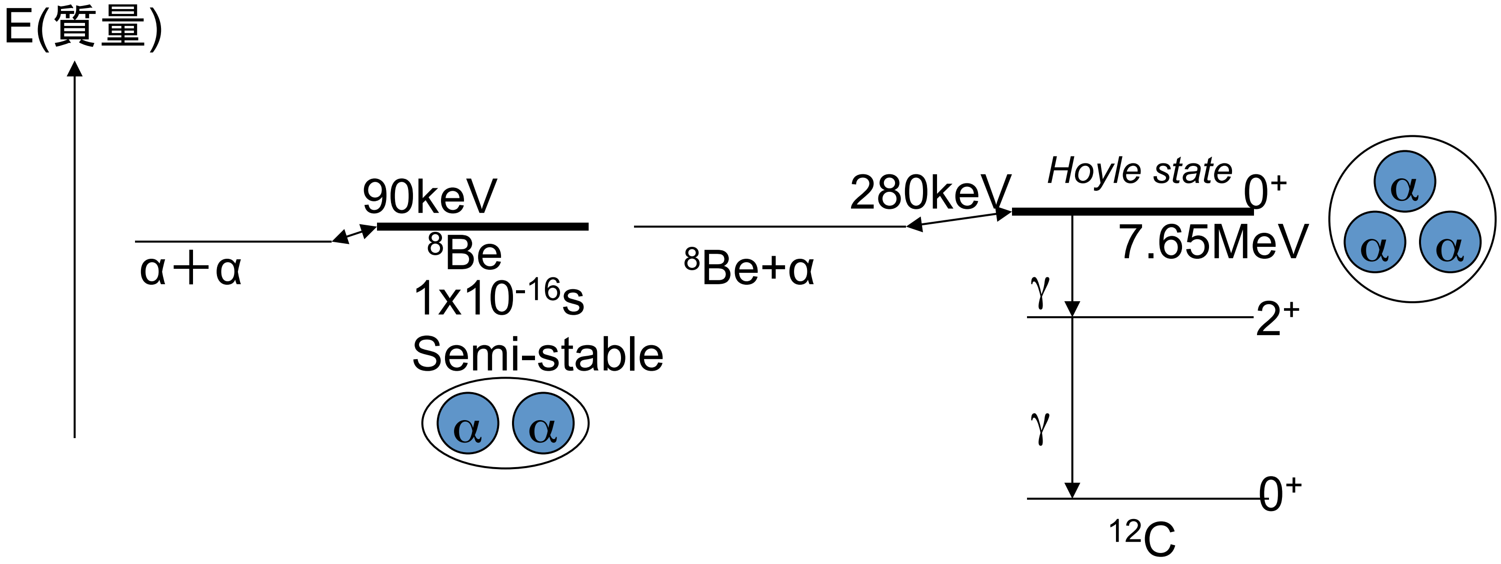
There are no particle-stable A="5" and "8" nuclei in nature

^{1}H,^{2}D, ^{3}He,^{4}He,(5), ^{6}Li, ^{7}Li,(8),^{9}Be,^{10}B,…,^{209}Bi

Big Bang: Mostly H and ^{4}He (Heavier than ^{7}Li were not produced)
→ How are heavier elements synthesized?

Triple alpha Reaction

Triple-alpha: Detour for the synthesis of elements ^{12}C→Heavier elements



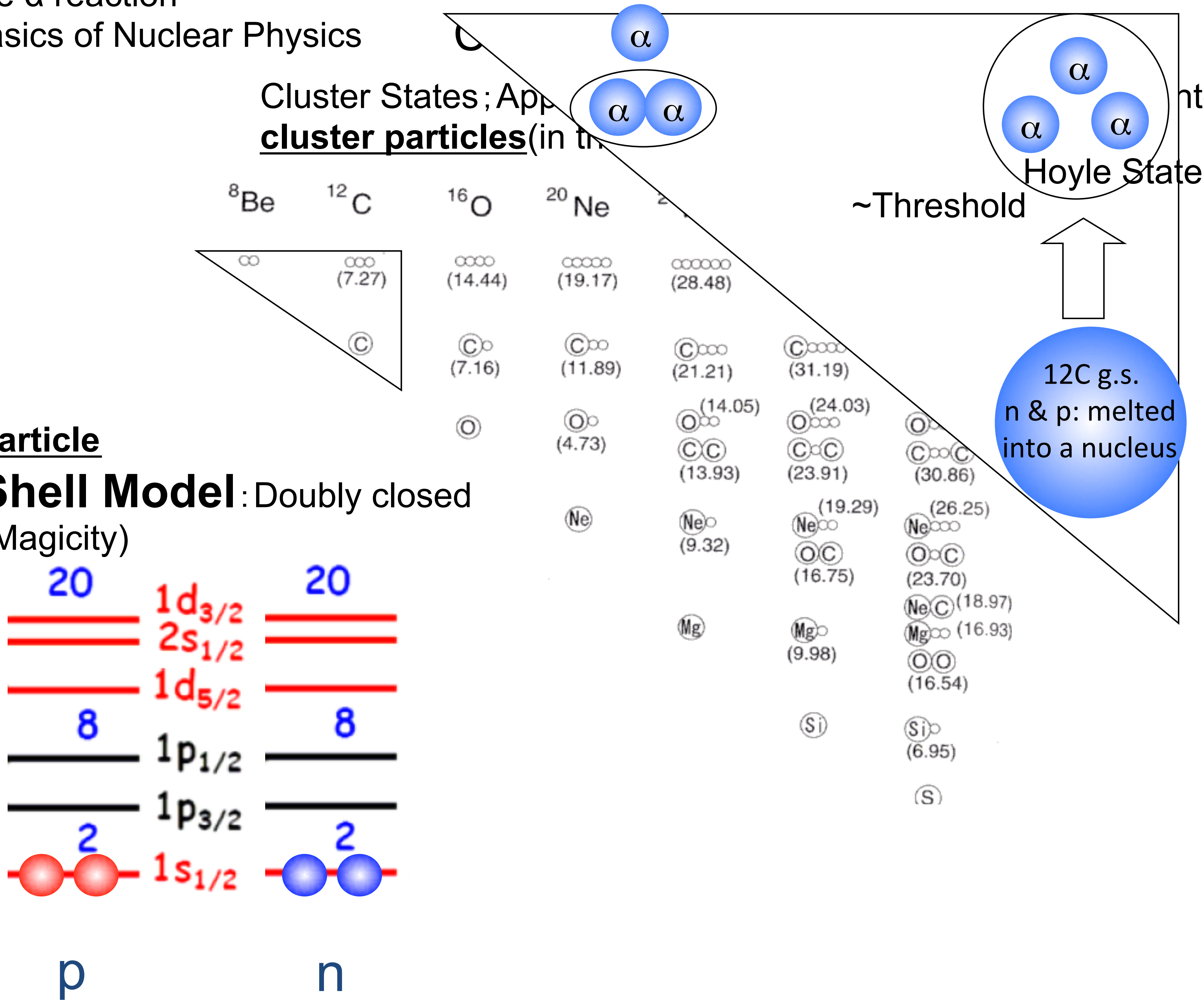
Triple α reaction
-- Basics of Nuclear Physics

C

Cluster States；App

cluster particles(in th

nto



α particle

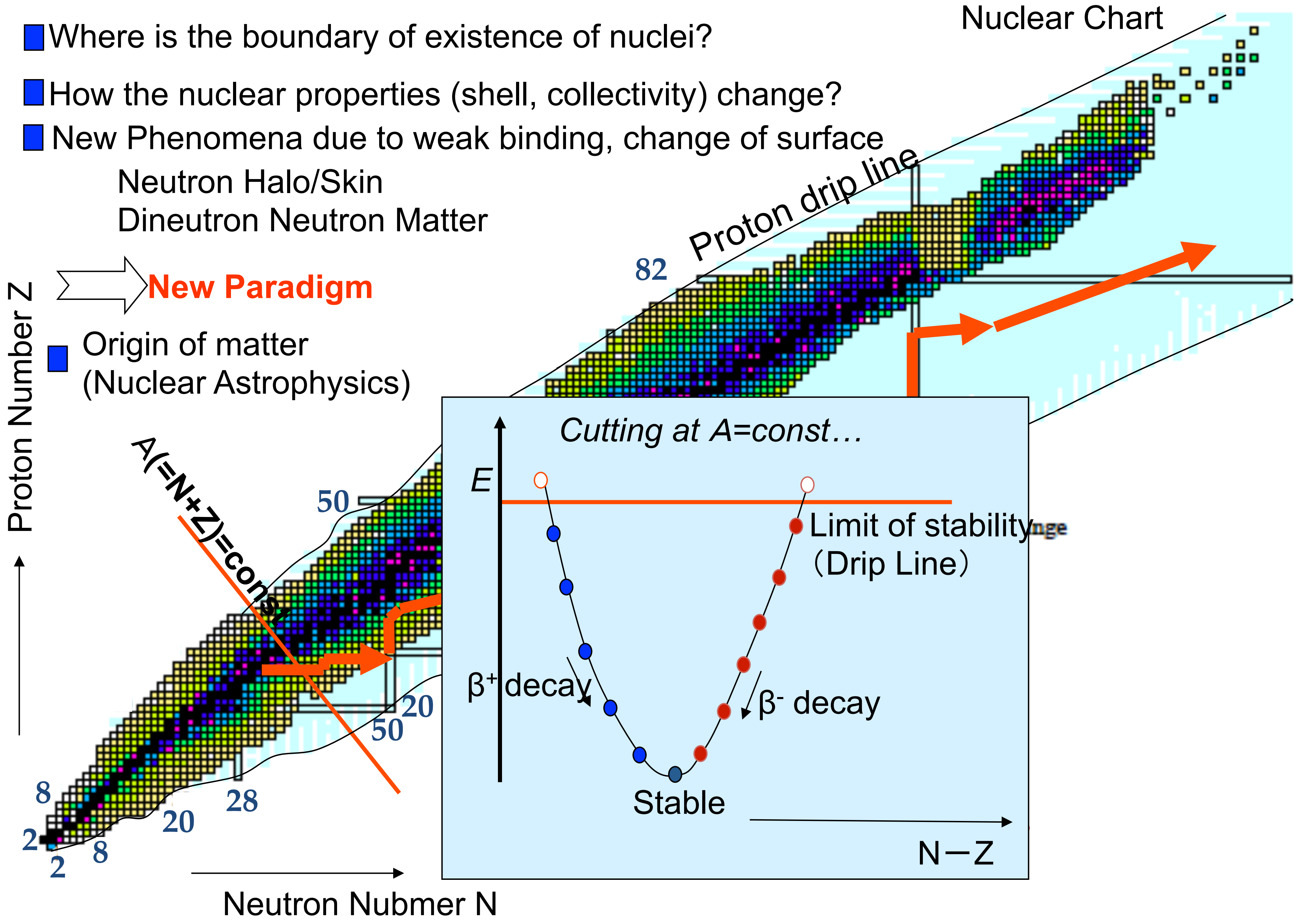
Shell Model：Doubly closed (Magicity)

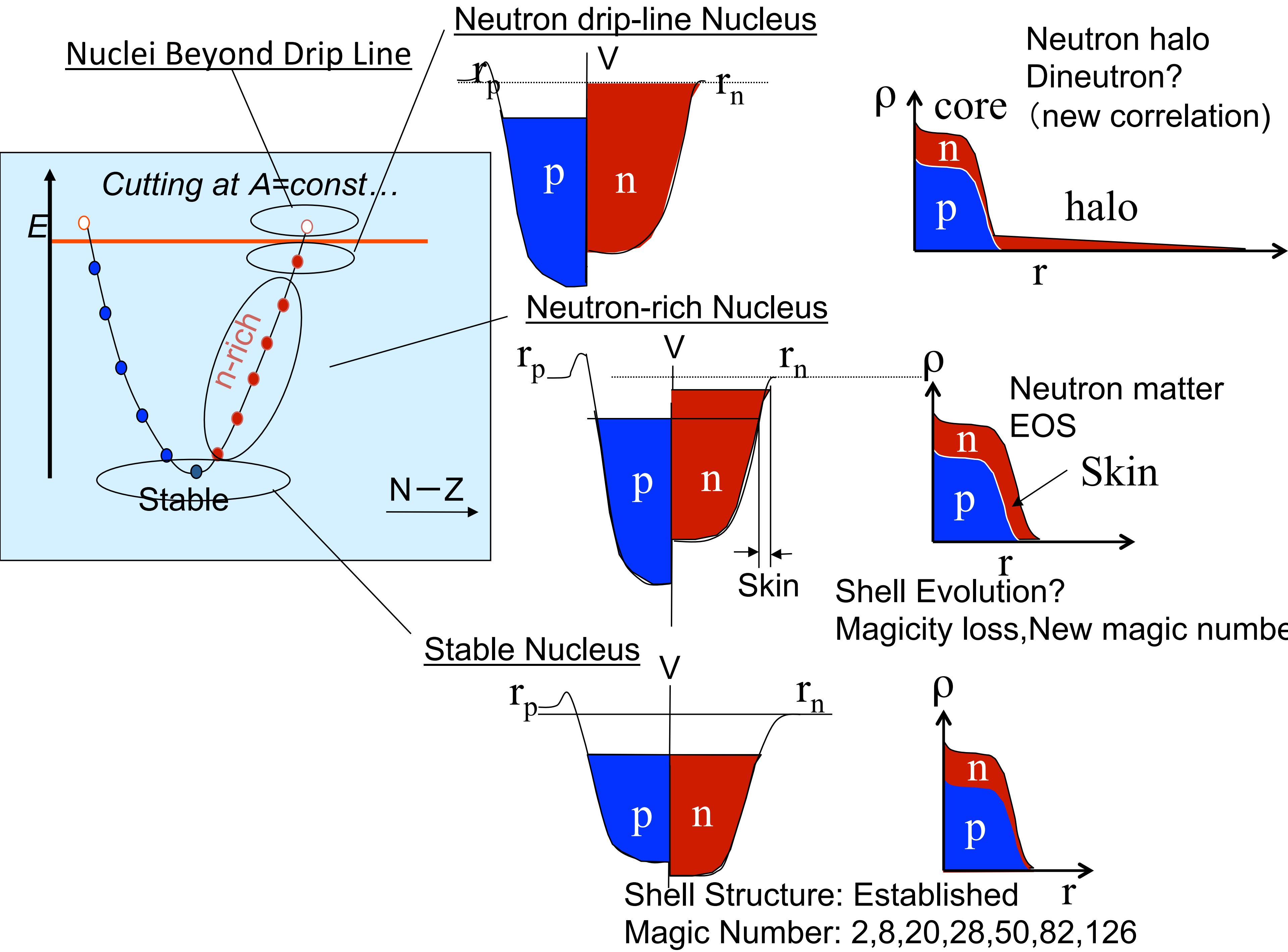
Towards the neutron-rich limit

- Where is the boundary of existence of nuclei?
- How the nuclear properties (shell, collectivity) change?
- New Phenomena due to weak binding, change of surface
  - Neutron Halo/Skin
  - Dineutron Neutron Matter

⇨ **New Paradigm**

- Origin of matter
  (Nuclear Astrophysics)





Neutron halo
Dineutron?
(new correlation)

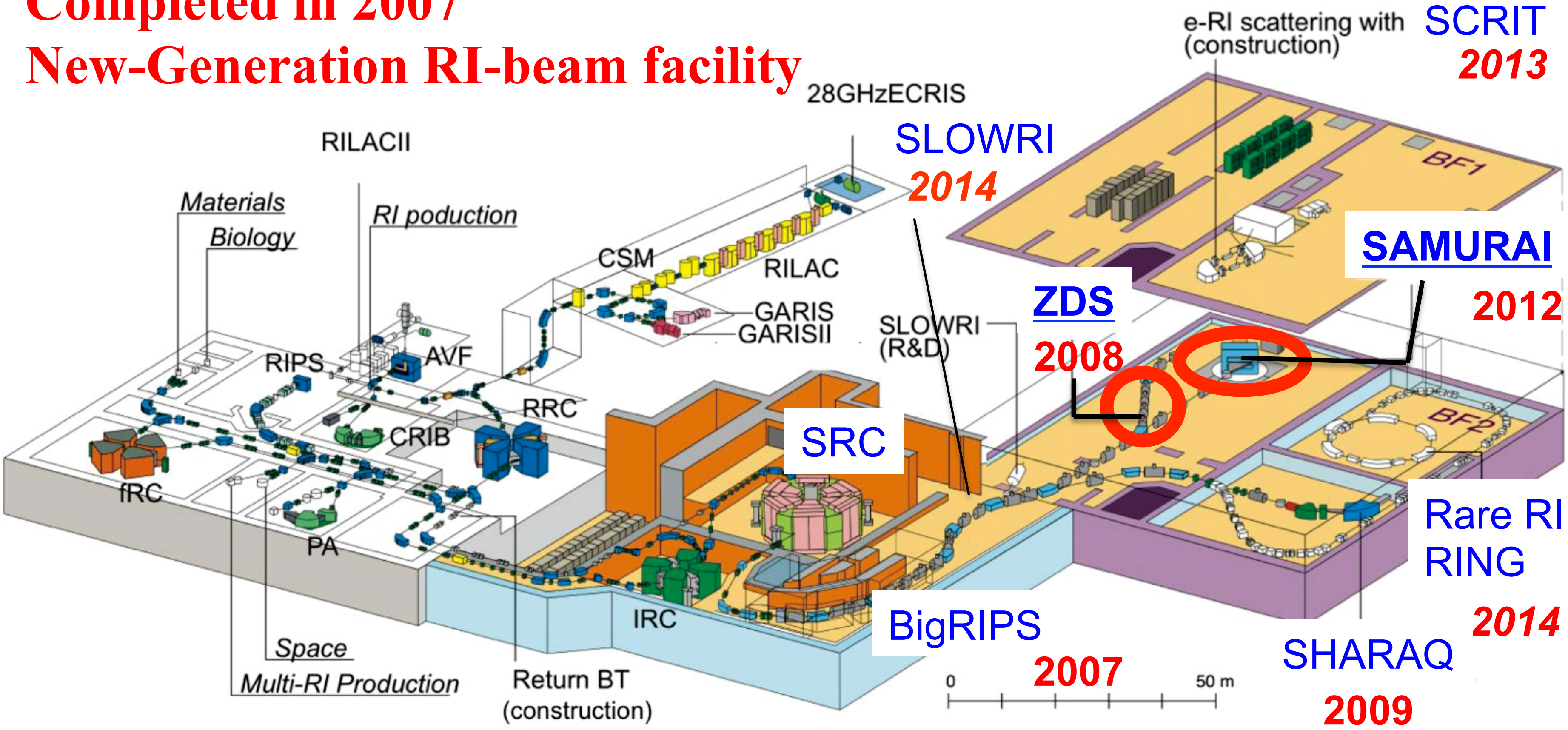
Neutron matter
EOS

Shell Evolution?
Magicity loss,New magic numbe

Shell Structure: Established
Magic Number: 2,8,20,28,50,82,126

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.) **Increasing Year by Year!**

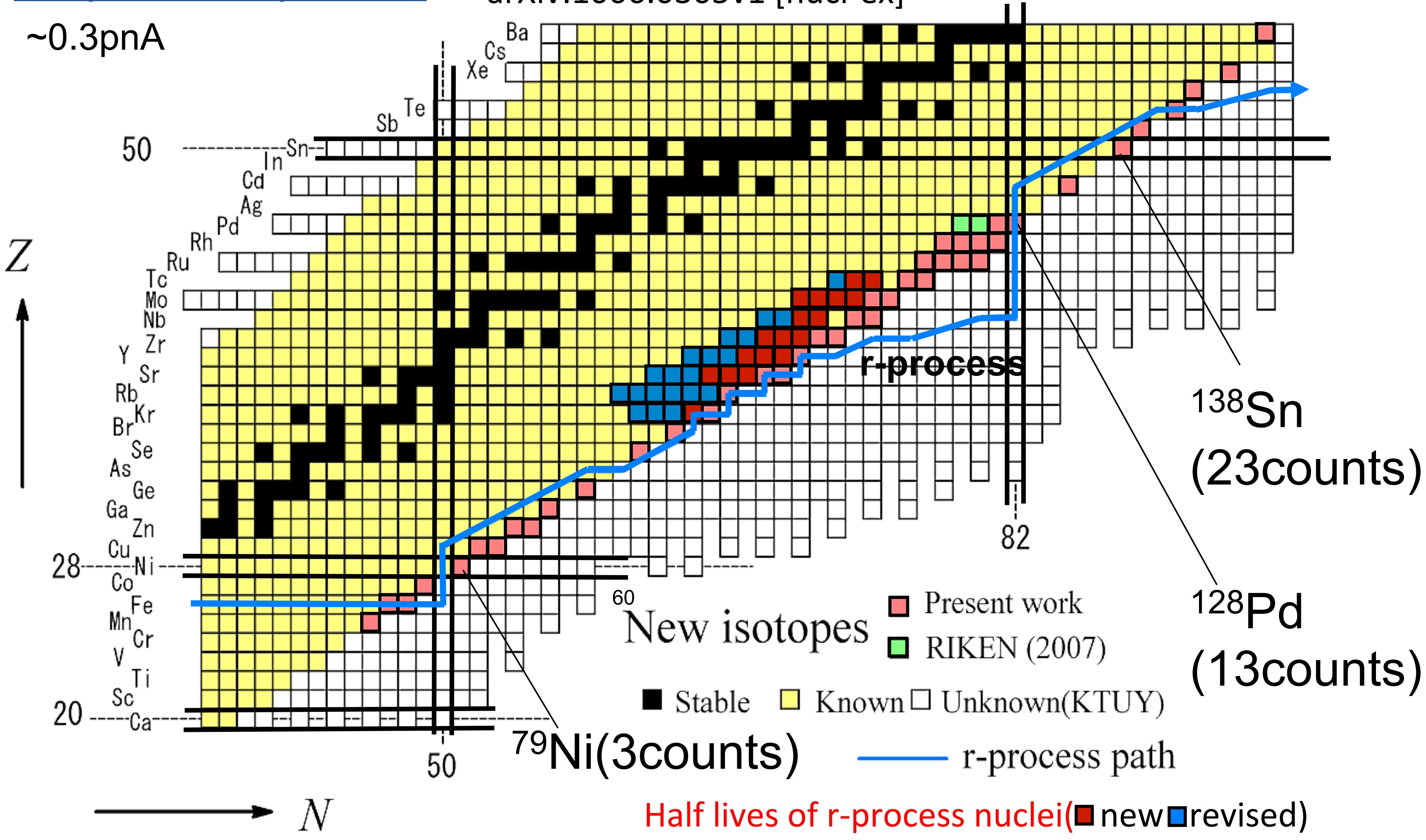
New Isotopes observed at RIBF

(~50 species)

T.Ohnishi, T.Kubo et al., JPSJ 77 (2008) 083201.
T.Ohnishi, T.Kubo et al., JPSJ,79 (2010) 073201.
arXiv:1006.0305v1 [nucl-ex]

^{238}U(345MeV/u)+ Be/Pb

~0.3pnA

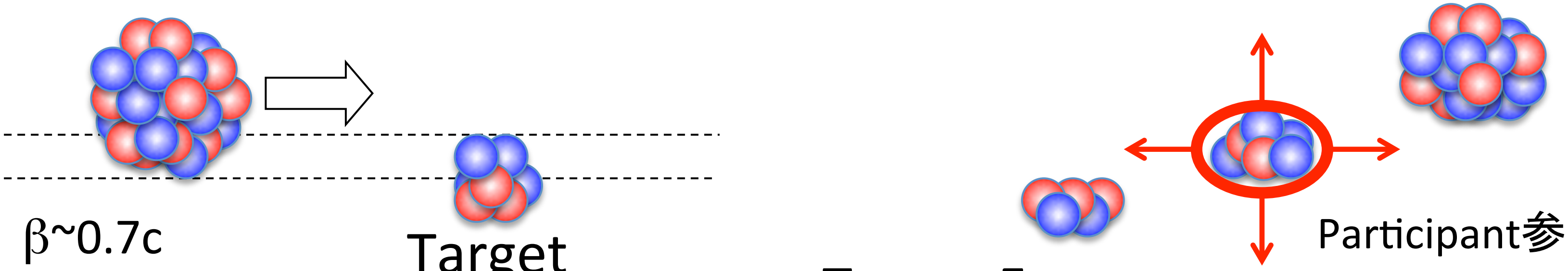


Half lives of r-process nuclei(🟥new🟦revised)

Nishimura et al., PRL106,052502(2011).

How To Produce RI Beam (不安定核生成法）

入射核破砕反応(Projectile Fragmentation)



Projectile(入射核）

e.g. ^{48}Ca

β~0.7c

350 MeV/nucleon

(Typical Energy at RIBF)

Target

(Spectator傍観者)

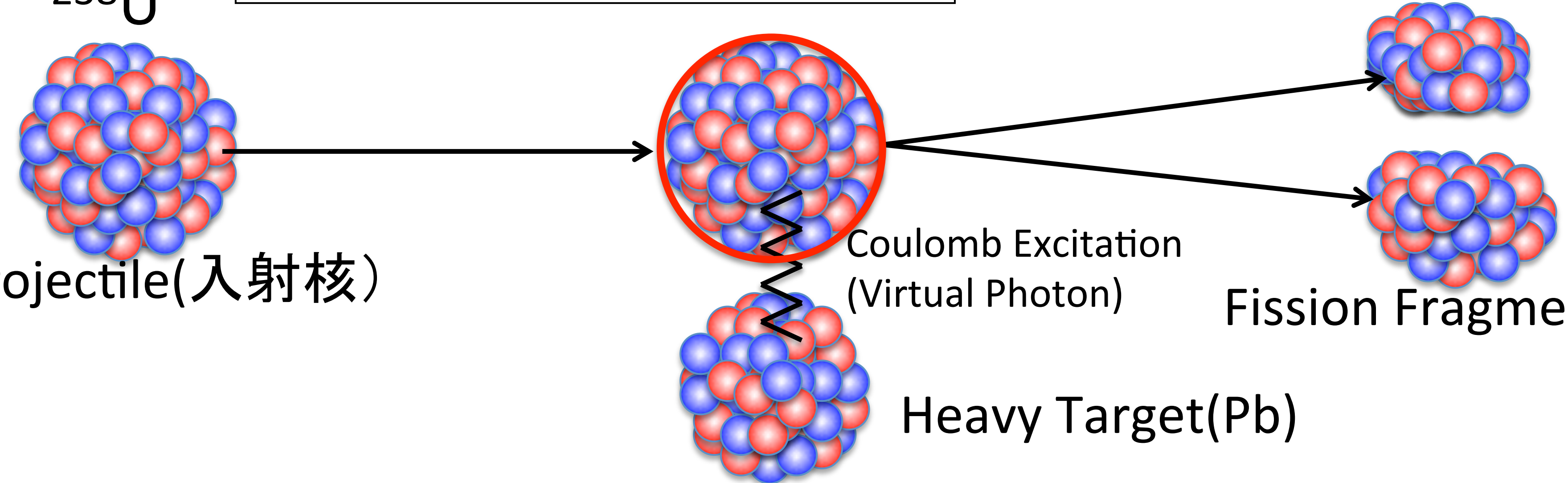
Projectile Fragment

Participant参加者

Target Fragment

(Spectator傍観者)

飛行核分裂 (Infight Fission)



^{238}U

Projectile(入射核）

Coulomb Excitation

(Virtual Photon)

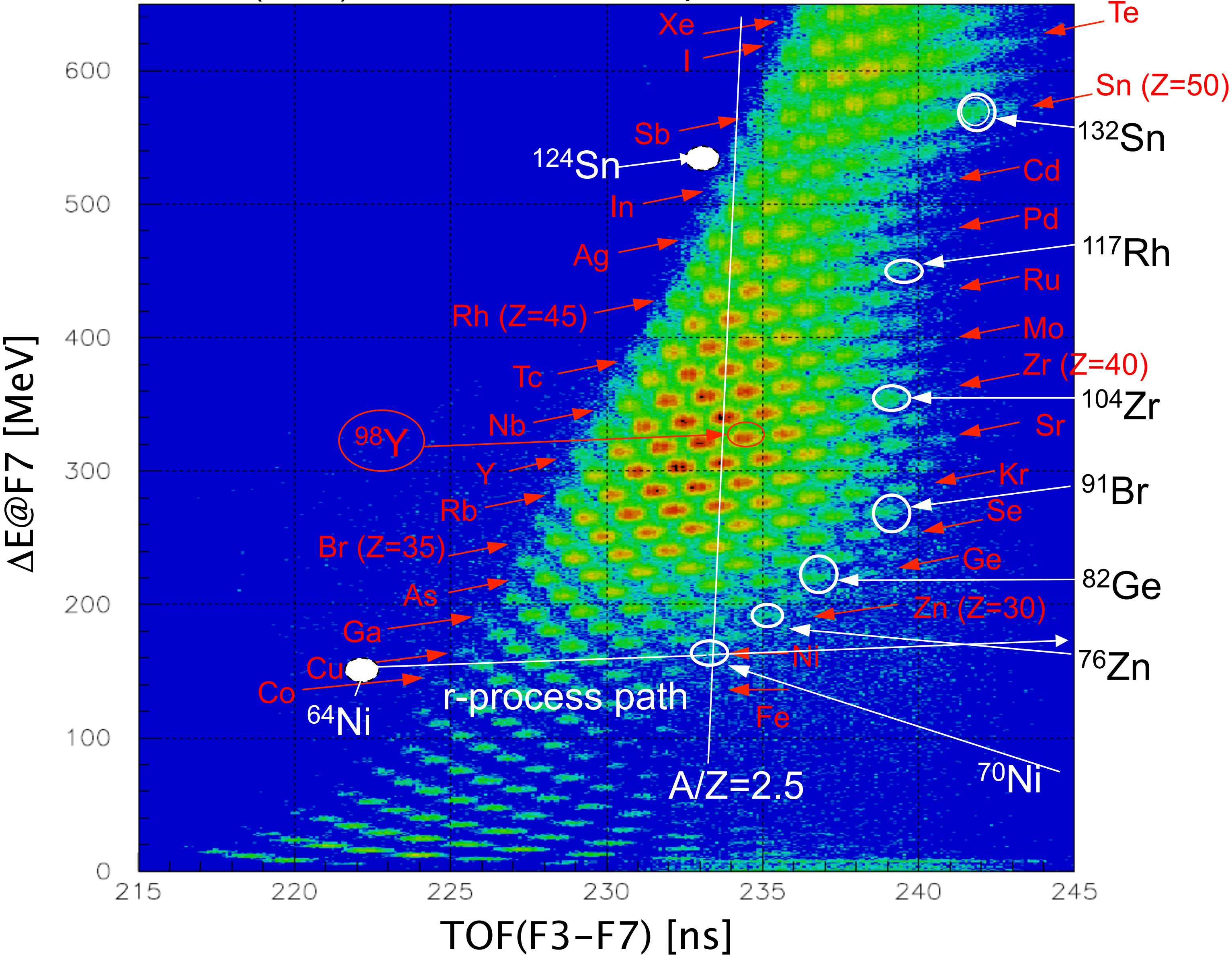
Fission Fragments

Heavy Target(Pb)

Courtesy of T.Kubo

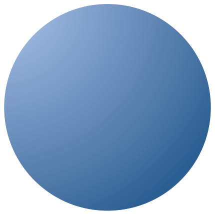
Particle Identification Spectrum

^{238}U + Be(5mm) at 345 MeV/u, Brho optimized for ^{76}Ni



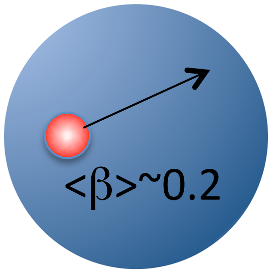
Pictures of Atomic Nuclei

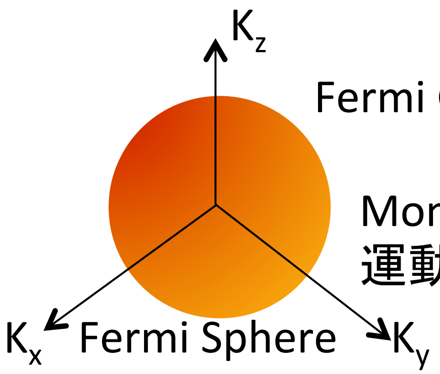
✓ Liquid Drop



- $r = r_0 A^{1/3}$
- Weizsacker-Bethe Mass Formula
- Spherical

✓ Fermi GAS





Fermi Gas @T=0
温度0

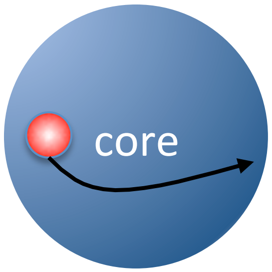
Momentum Space
運動量空間

- Fermi Motion
- N=Z Symmetry
- Neutron star

✓ Simple SHELL Model (single-particle state)

$$\Psi(nucleus) = \left|core\left(0^+\right)\right\rangle \otimes \phi(n\ell j)$$

A(=N+Z)-many-body problem→One-body problem



✓ Correlations

(Large-scale) Shell Model, Deformation, α Cluster, Paring, Di-neutron, Super-fluidity, Halo, Skin,… More

Review

Fermi Gas Model

Free Fermions （n or p) are confined in a volume Ω @T=0

Uncertainty Principle

No.of states

$$n = 2\int d\mathbf{r}\int d\mathbf{p}/h^3 = 2\frac{\Omega}{(2\pi)^3}\int_0^{k_F} 4\pi k^2 dk = 2\frac{\Omega}{(2\pi)^3}\frac{4}{3}\pi k_F{}^3$$

Fermi Momentum

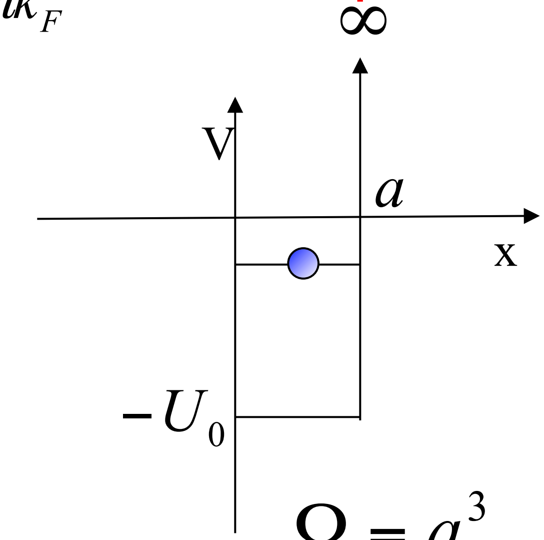
$$k_F = \left(3\pi^2\rho\right)^{1/3}$$ 密度大→フェルミ運動量大→圧力大

$$P_F \sim 280\ \mathrm{MeV/c},\quad \langle P_F\rangle \sim 210\ \mathrm{MeV/c}$$

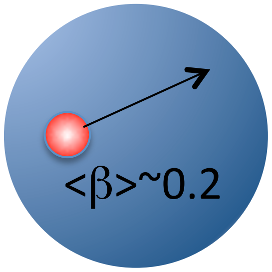
(for N=Z)

Fermi Energy

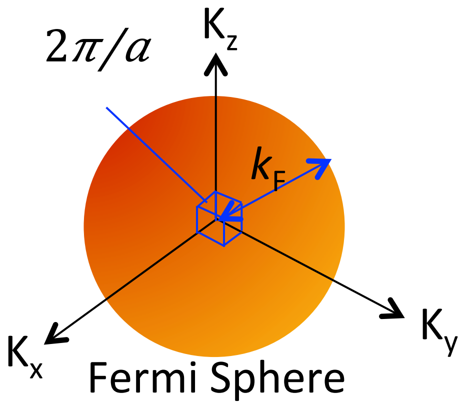
$$\varepsilon_F = \frac{\hbar^2 k_F{}^2}{2m_n} \sim 40\,\mathrm{MeV}$$



$$\Omega = a^3$$



Coordinate Space

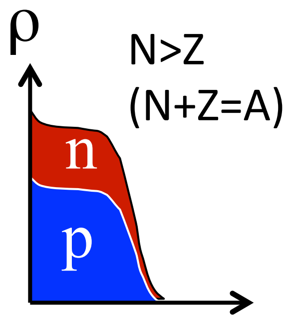


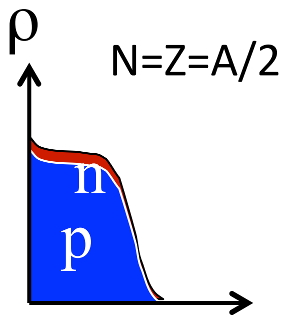
Momentum Space

Symmetry Energy by a Fermi-Gas Model

For a Given A → N=Z is favored Why?

- ✓ |Vnp| > |Vnn|, |Vpp| "np" : More Attractive than "pp","nn"
- ✓ Kinetic Energy is smallest for N=Z





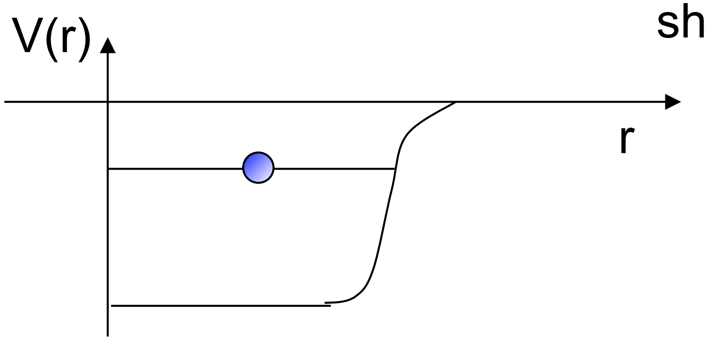
$$k_F = \left(3\pi^2 \rho\right)^{1/3}$$

$$\varepsilon_F = \frac{\hbar}{2m}\left(3\pi^2 \rho\right)^{2/3} = \frac{\hbar}{2m}\left(3\pi^2 \frac{N}{\Omega}\right)^{2/3}$$

$$E_{sym} = T(N,Z) - T\left(N = \frac{A}{2}, Z = \frac{A}{2}\right) = \frac{1}{3}\varepsilon_F \frac{(N-Z)^2}{A}$$

Quiz Extract the radius of a neutron star with 2 solar mass using Fermi-Gas Model

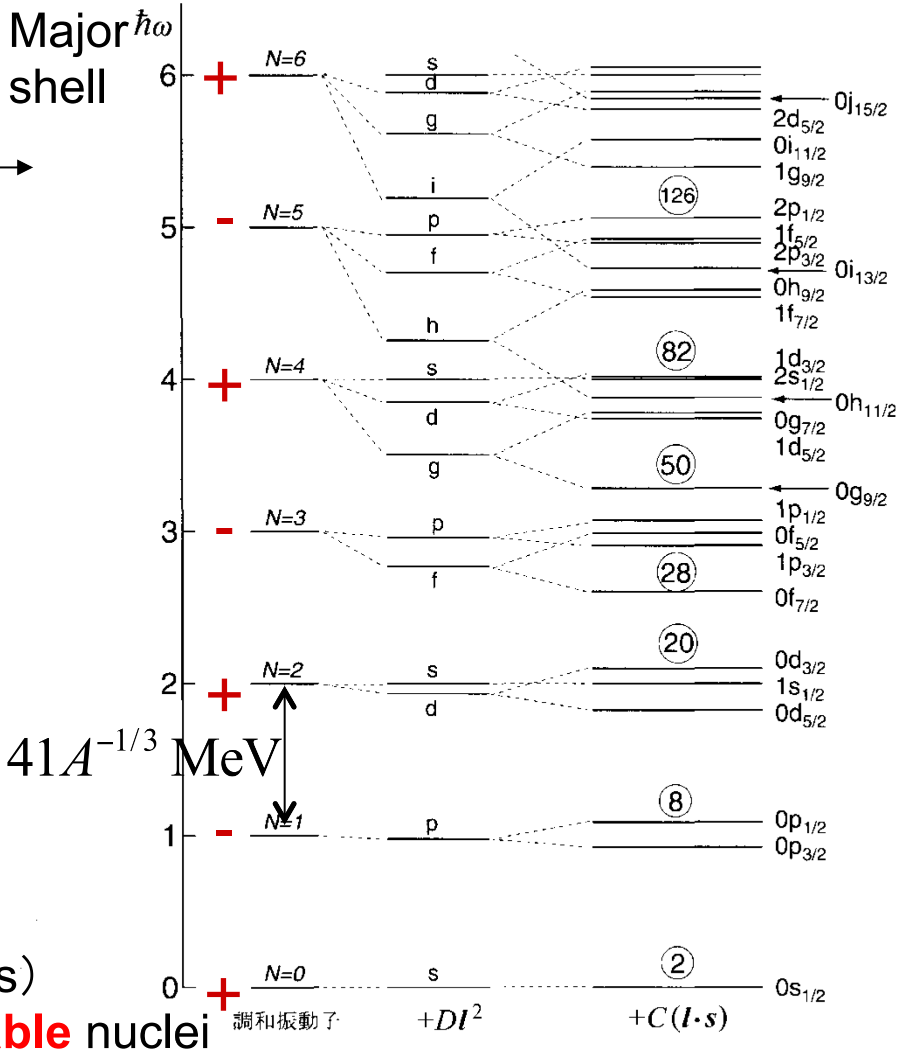
Shell Model



1 nucleon moves independently in a mean-field potential

$$V(r) = \frac{1}{2} m\omega^2 r^2 + V_{ls}(\mathbf{l}\cdot\mathbf{s}) + D\mathbf{l}^2$$

H.O.   Spin-orbit



$$\hbar\omega \approx 41 A^{-1/3}\ \mathrm{MeV}$$

- Same Parities within Major Shell
  →Different Parity（Intruder States）
  appear at high energies in **stable** nuclei

- Energy Gap between Major Shells: ~const. for stable nuclei
  Different from Atomic Shells！

Unstable Nuclei → Shell Structure Evolves →New Magic Numbers, 6,16,32,34 !

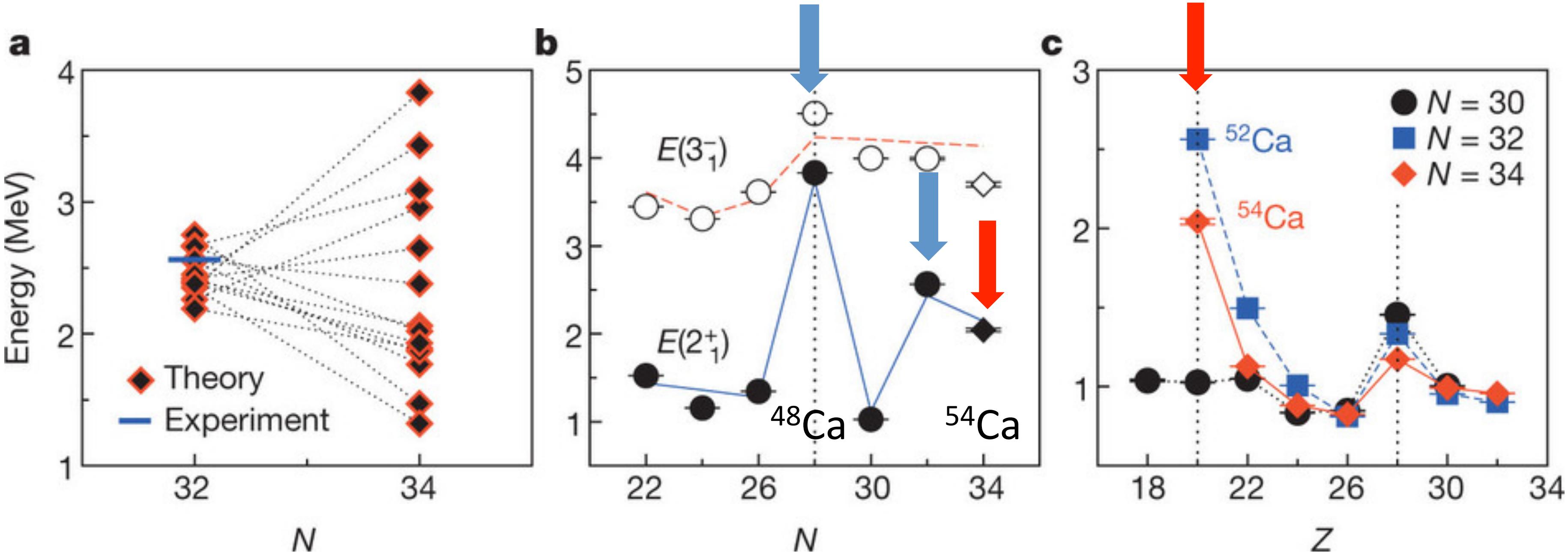
Evidence for a new nuclear ‘magic number’ from the level structure of **^{54}Ca**

D.Steppenbeck, S.Takeuchi et al.

Nature 502, 207 (2013).

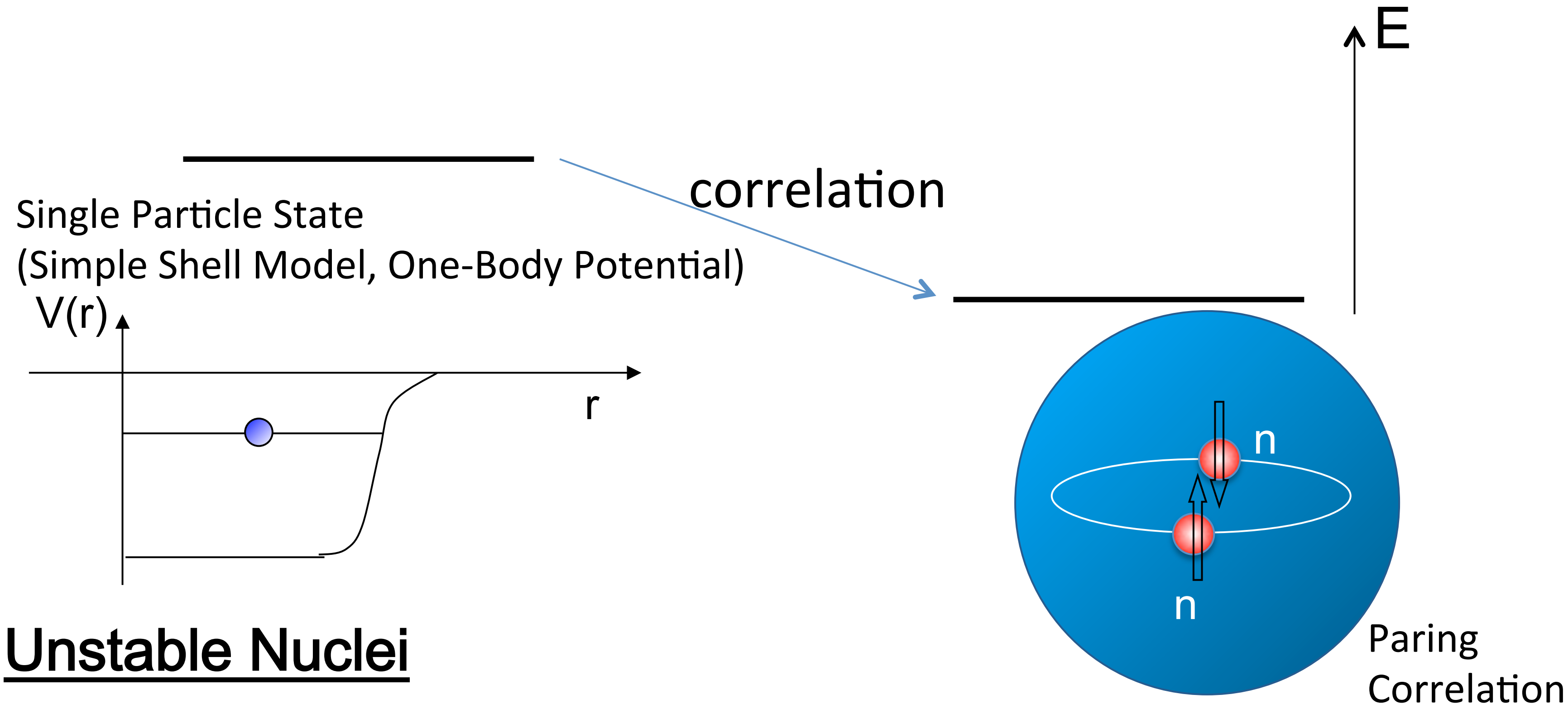
-- Experiment at RIBF, RIKEN

New Magic Number **34**



Correlation

(Large-scale) Shell Model, Deformation, α Cluster, Paring, Super-fluidity, Halo, Skin, Di-neutron, Tensor



Single Particle State
(Simple Shell Model, One-Body Potential)

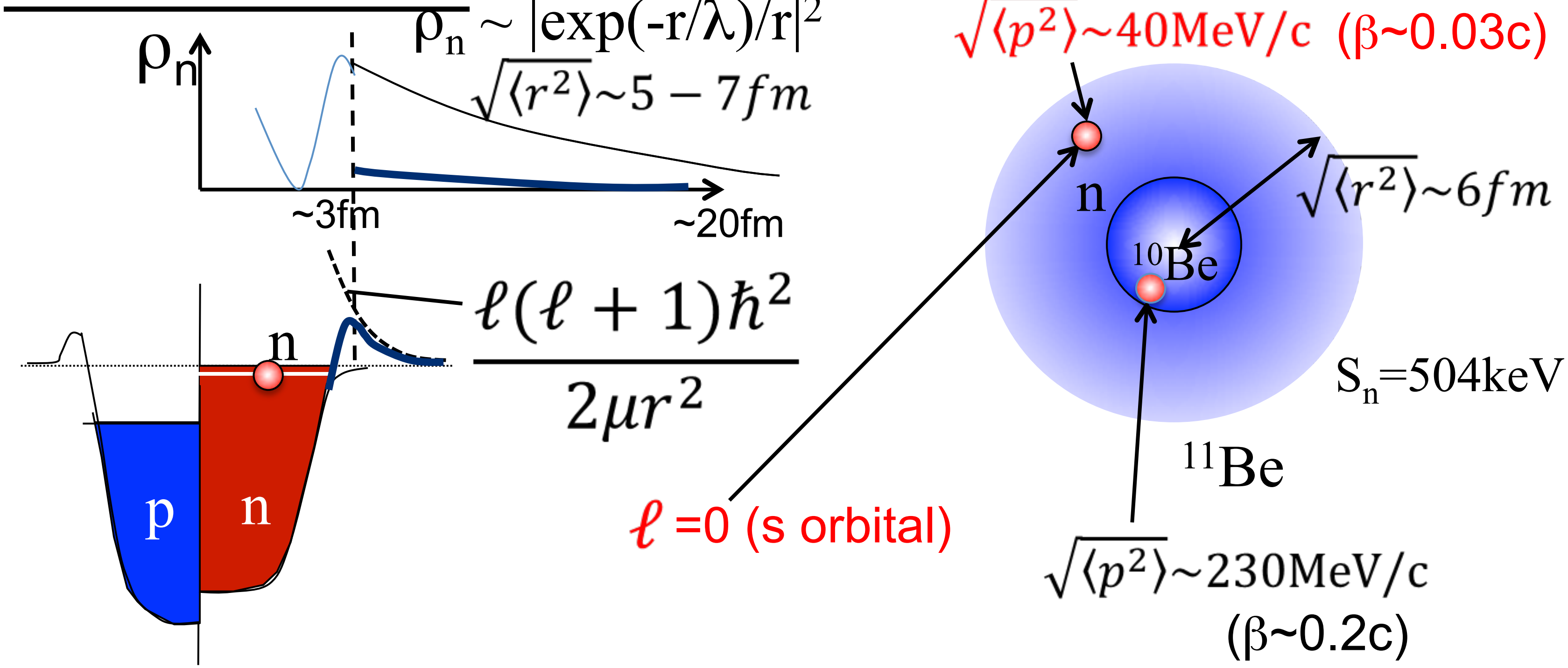
Paring
Correlation

Unstable Nuclei

Importance of **Surface** --- Surface(Halo/Skin), Fermi Surface
proton-neutron asymmetry
Change of **Density**
Importance of **Tensor Force (pn), 3-body Force**

→ Larger Degree of Freedom → Deformation/ Shell Evolution

Neutron Halo 中性子ハロー



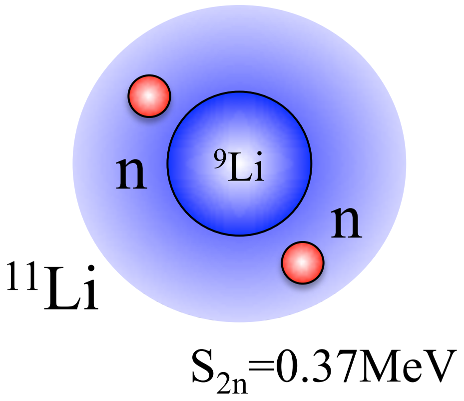
- Small S_n S_n<1MeV<<8MeV
- Extended ρ_n Distribution beyond Range of Nuclear Force

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

- Small Fermi Momentum→ Small Kinetic Energy
- Orbital Angular Momentum $\ell = 0,1$ (Small Centrifugal Barrier)

⇨ Nuclear Stability At the Limit←→ Shell Evolution/Deformation ←→ Halo Structure

Two-neutron Halo



Borromean Ring

^{9}Li + n Barely Unbound

a_s= - (13-23) fm PLB642, 449(2006).

n + n Barely Unbound

a_s= - 18.9(4) fm

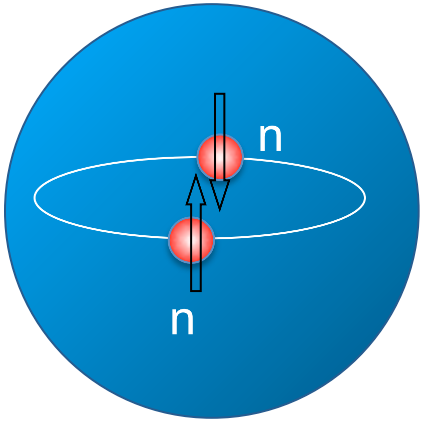
^{9}Li + n+n Bound

S_{2n}=0.37MeV <<8MeV

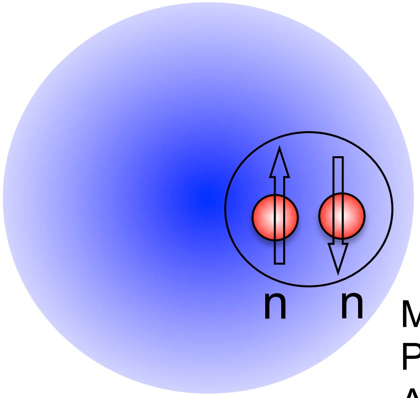
Few-body physics, eg. Efimov?

Dineutron Correlation?

A.B. Migdal Sov.J.Nucl.Phys.238(1973).

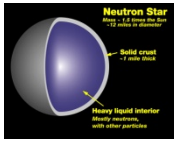


BCS-like
nn correlation
(long range)



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

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

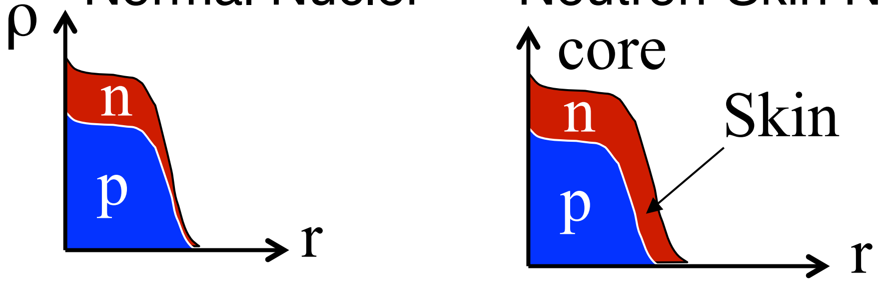


n-star
Superfluidity

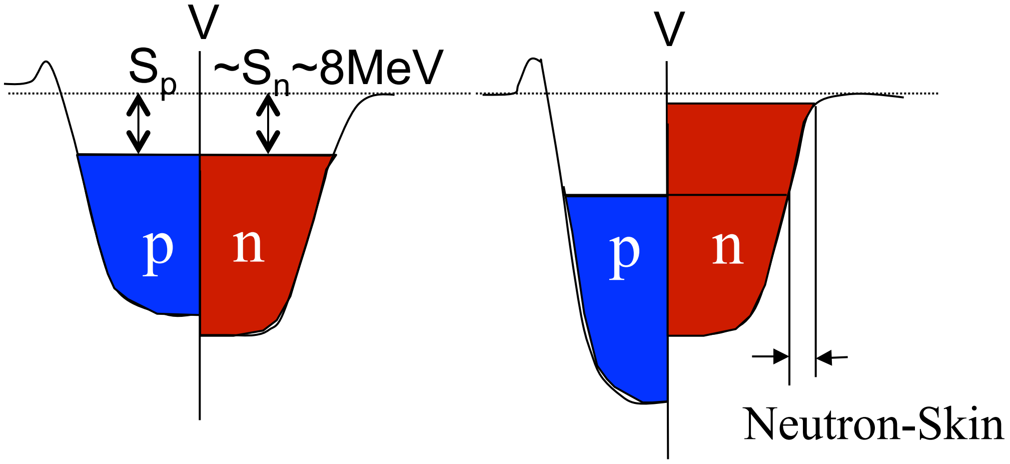
Neutron Skin Nuclei 中性子スキン

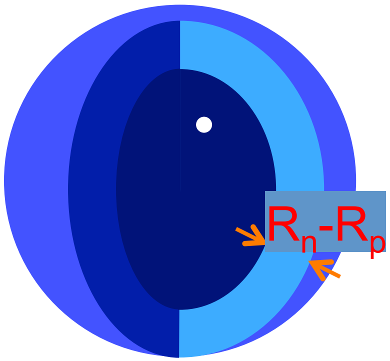
Normal Nuclei

Neutron-Skin Nuclei (Neutron-rich Nuclei)



Larger ρ_n → Larger Pressure → Larger $\langle r_n \rangle$





Neutron-skin
0.2-0.8fm

⇨

Neutron Skin Thickness depends on EOS of neutron matter as in NS radius **Experiments are very difficult! (Tamii's Talk 28th)**

2 Breakup of Drip-Line Nuclei at RIBF

RIBFにおけるドリップライン近傍原子核の分解反応

Evolution Towards/Beyond the Stability Limit

Where is the neutron drip line?

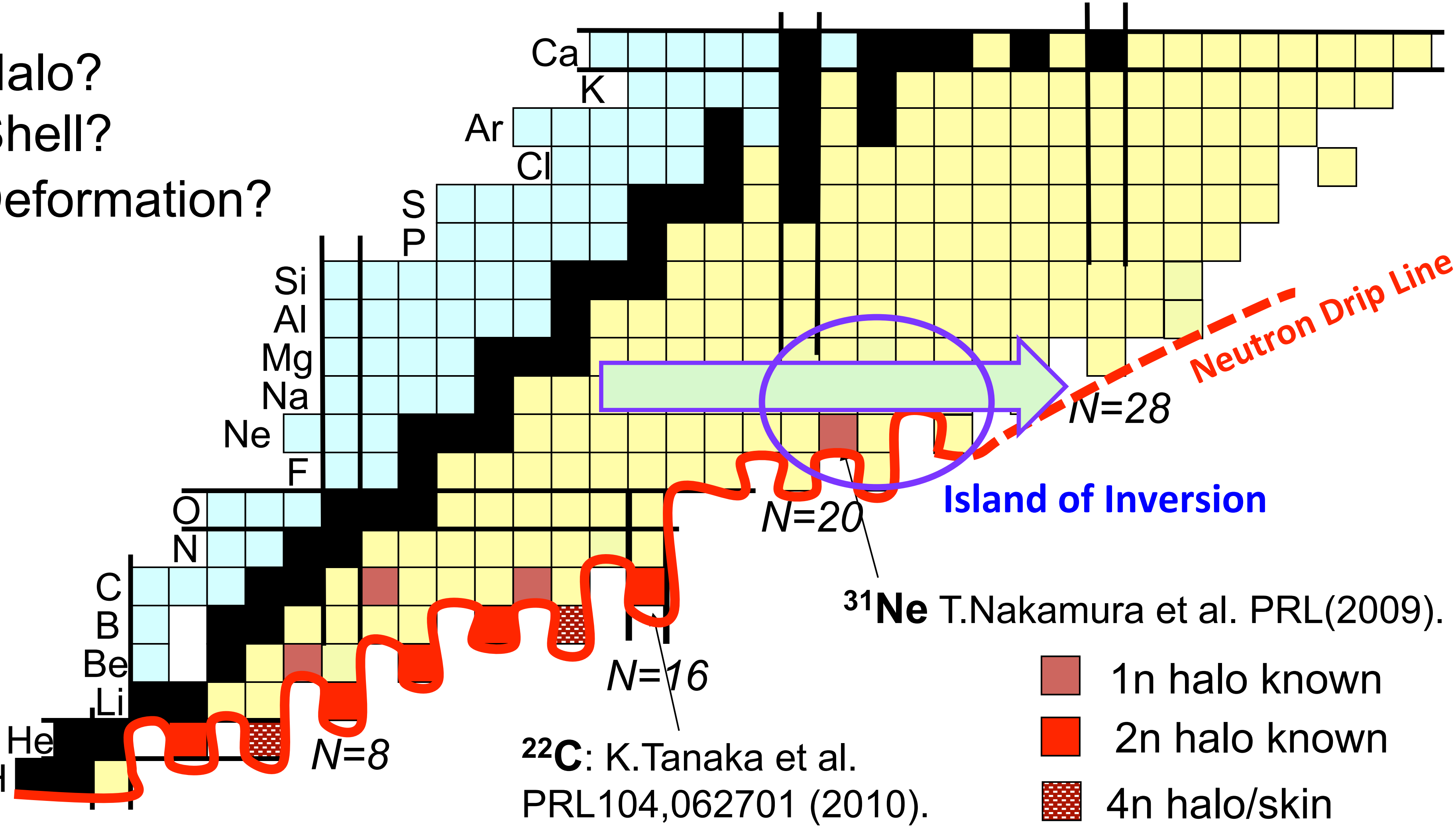
What are characteristic features of drip-line nuclei?

How does nuclear structure evolve towards the drip line?

Halo?

Shell?

Deformation?



^{31}**Ne** T.Nakamura et al. PRL(2009).

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

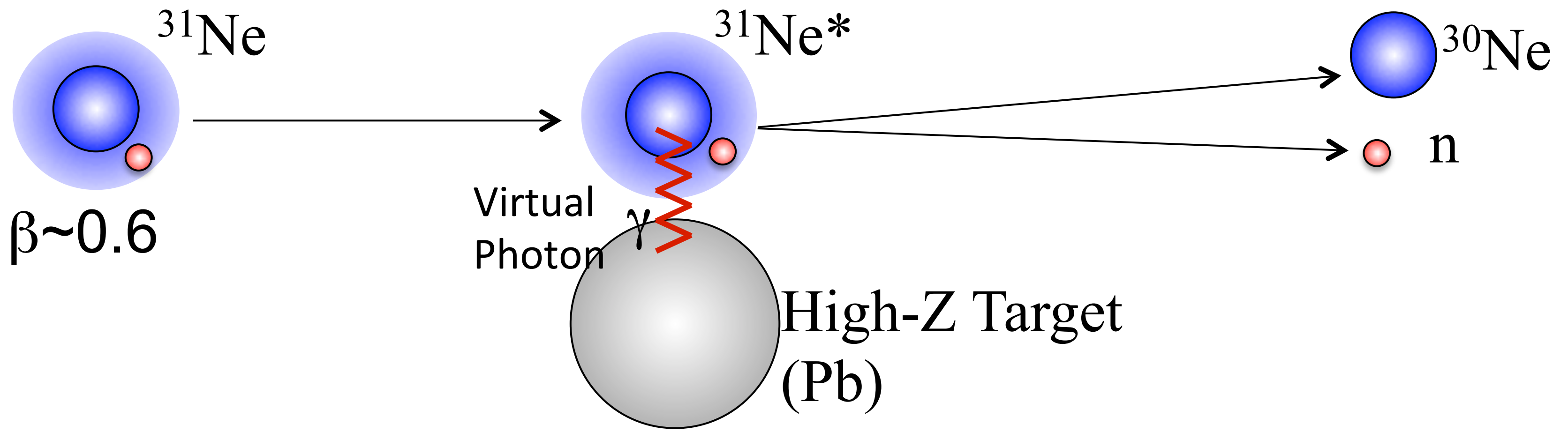
Probe-1: **Coulomb Breakup**

→Photon absorption of a fast projectile

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

Invariant Mass

⇒ E_x, E_{rel}

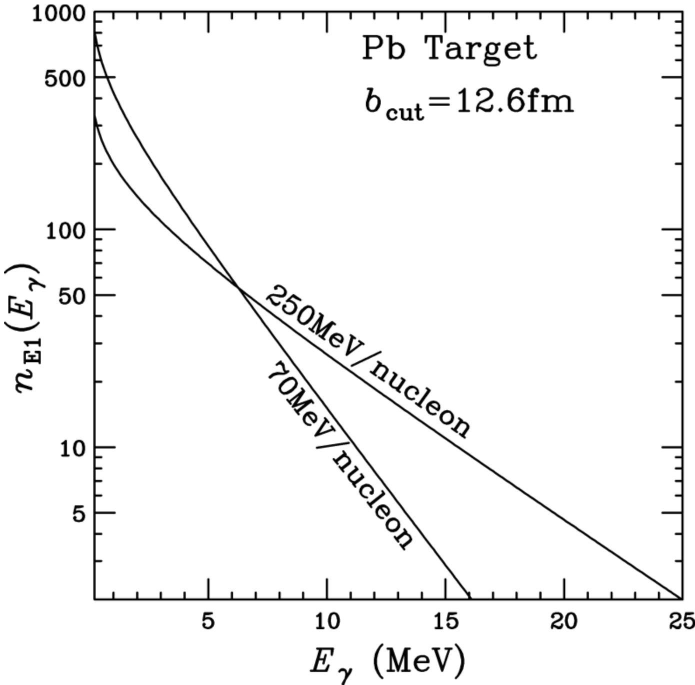


Equivalent Photon Method

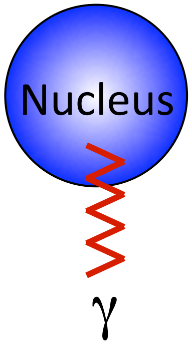
$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x)\frac{dB(E1)}{dE_x}$$

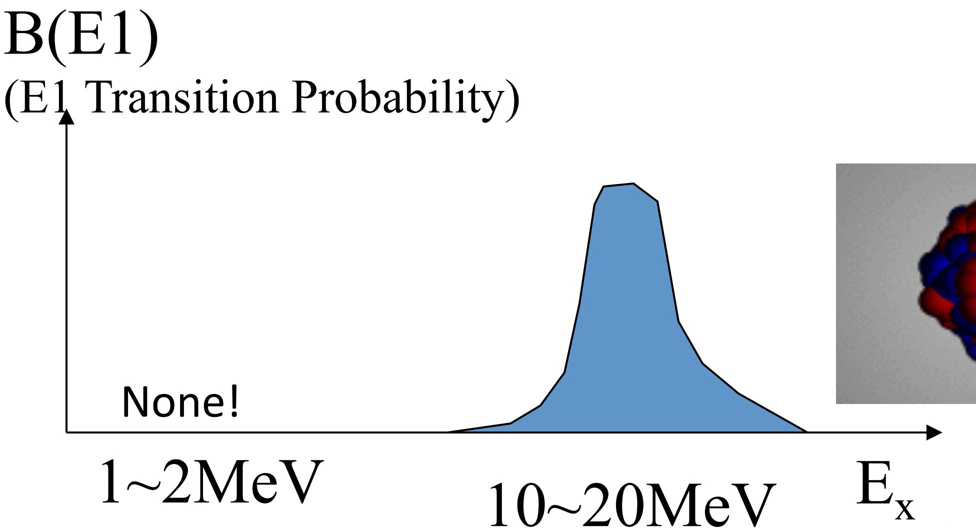
Cross section = (Photon Number)x(Transition Probability)

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



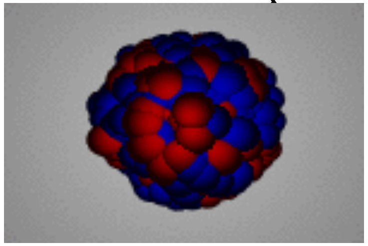
How a nucleus responds, when it absorbs a photon?





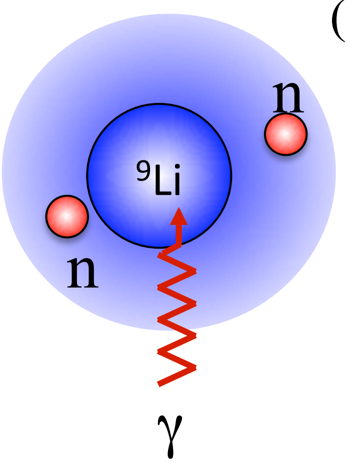
(=Eγ)

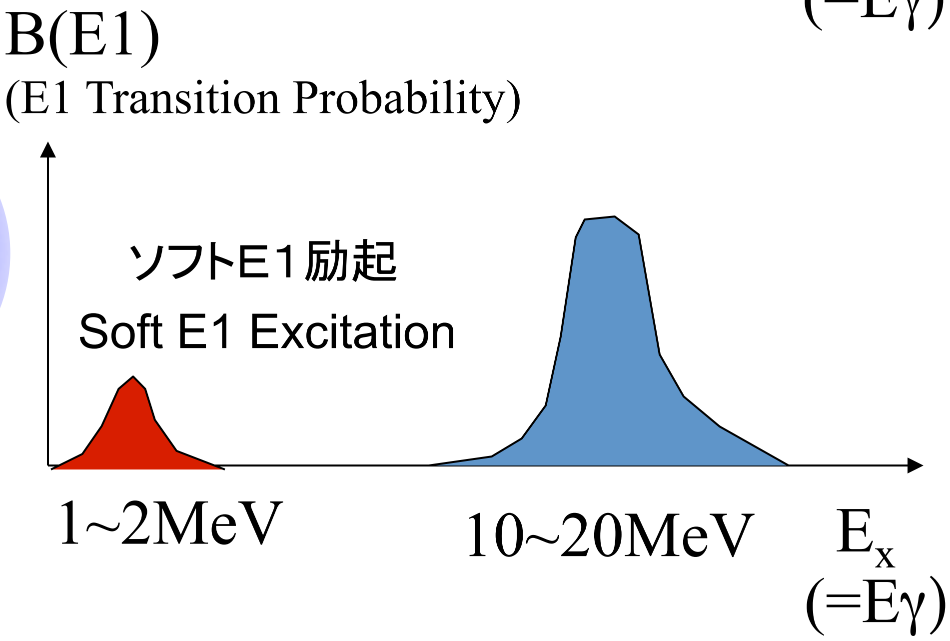
E_x~$80A^{-1/3}$MeV



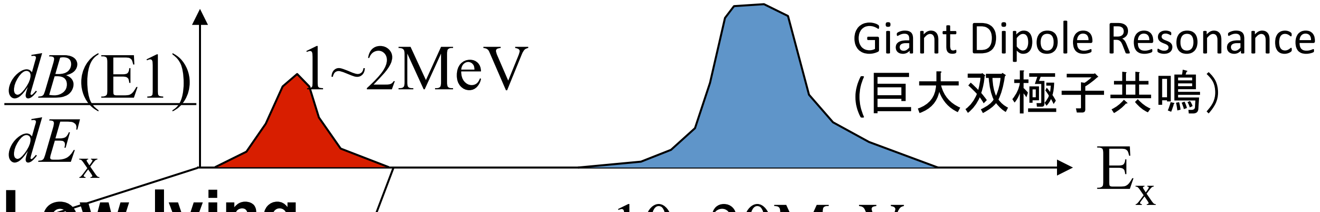
Giant
Dipole
Resonance
(GDR)

巨大双極子共鳴



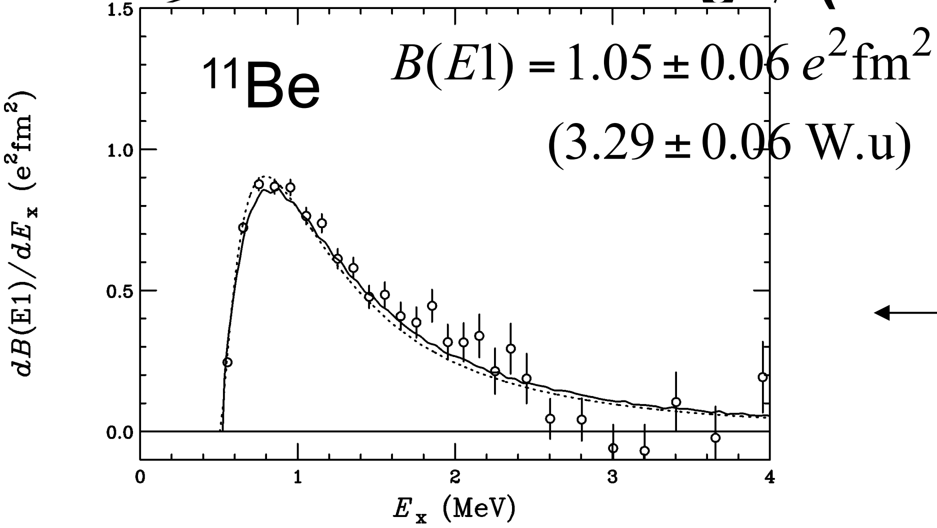


E1 Response of halo nuclei (Coulomb Breakup of 1n halo)



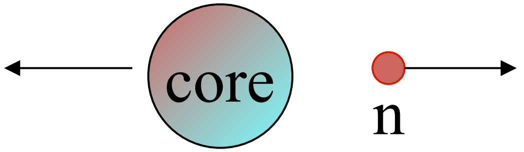
10~20MeV

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



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

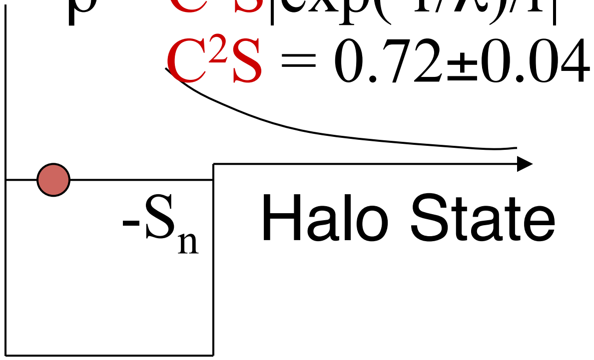
$C^2S = 0.72 \pm 0.04$

E1 Strength

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

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

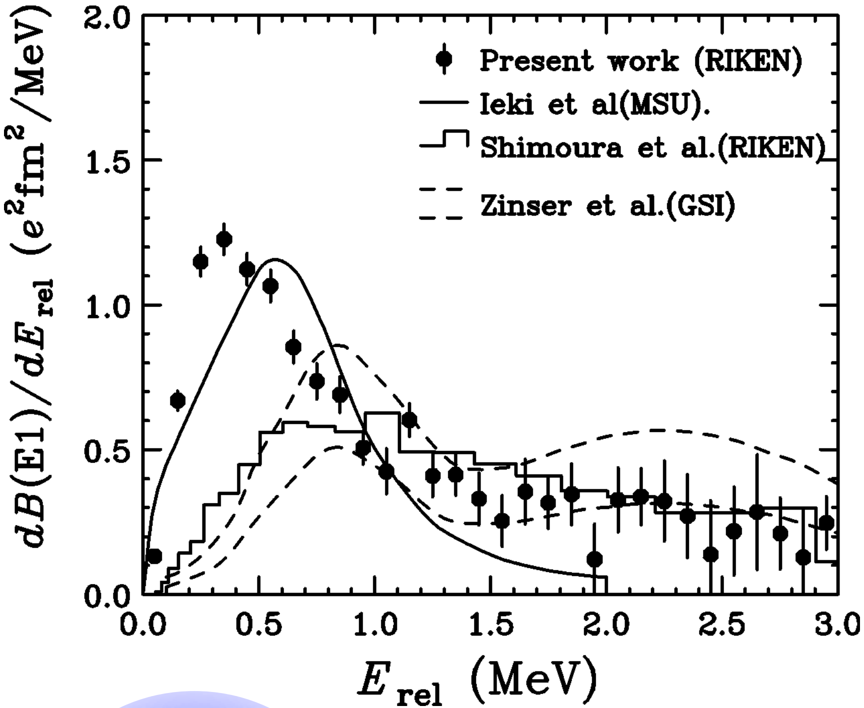
Fourier Transform

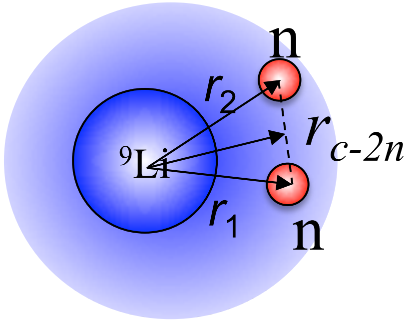


Soft E1 Excitation of 1n halo—Sensitive to S_n, l, C^2S

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

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



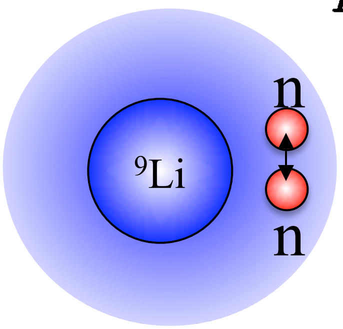


$$B(E1) = \int_{-\infty}^{\infty} \frac{dB(E1)}{dE_x} dE_x$$

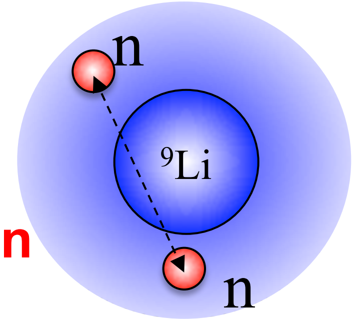
$$= \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\,2} + r_2^{\,2} + 2(\vec{r}_1 \cdot \vec{r}_2)\right\rangle$$

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

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



Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation



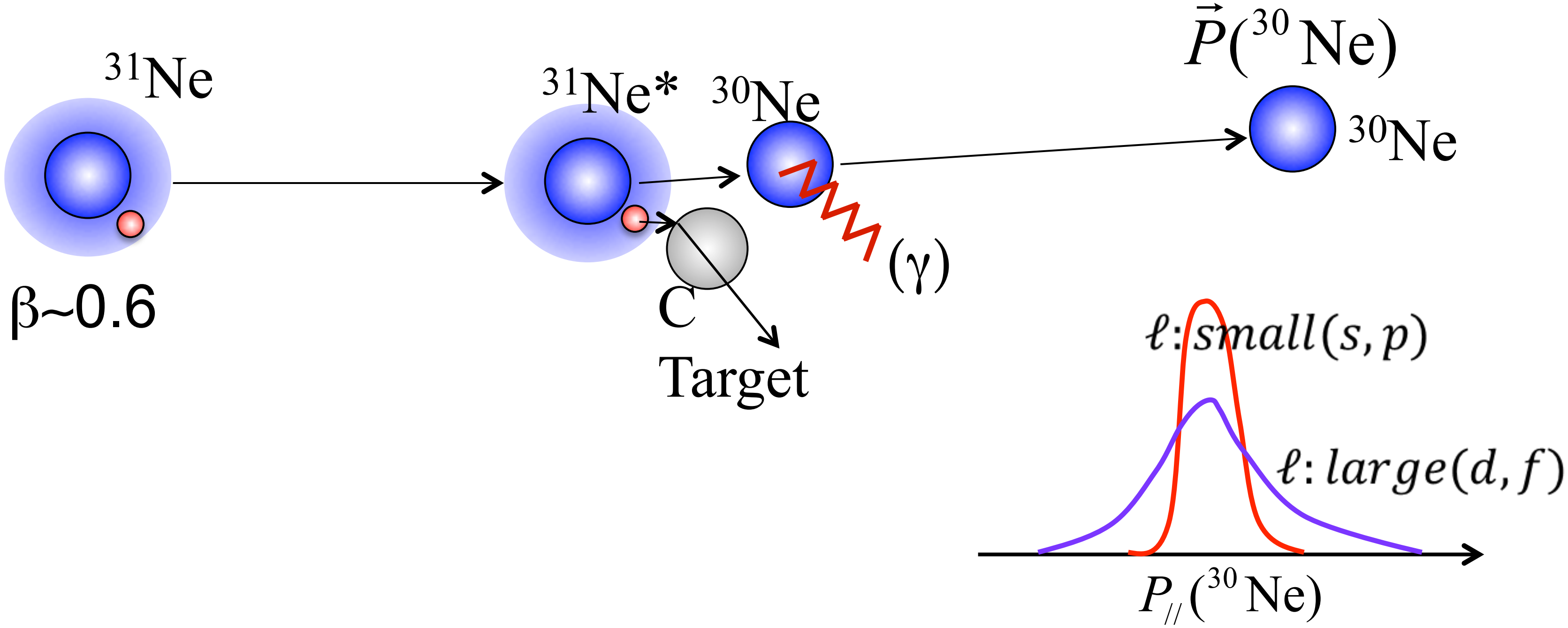
Weak 2n correlation
→Weakly Polarized
→Weak E1 Excitation

^{11}Li S_{2n}=0.37MeV

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

Probe-2: **Nuclear Breakup**

→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

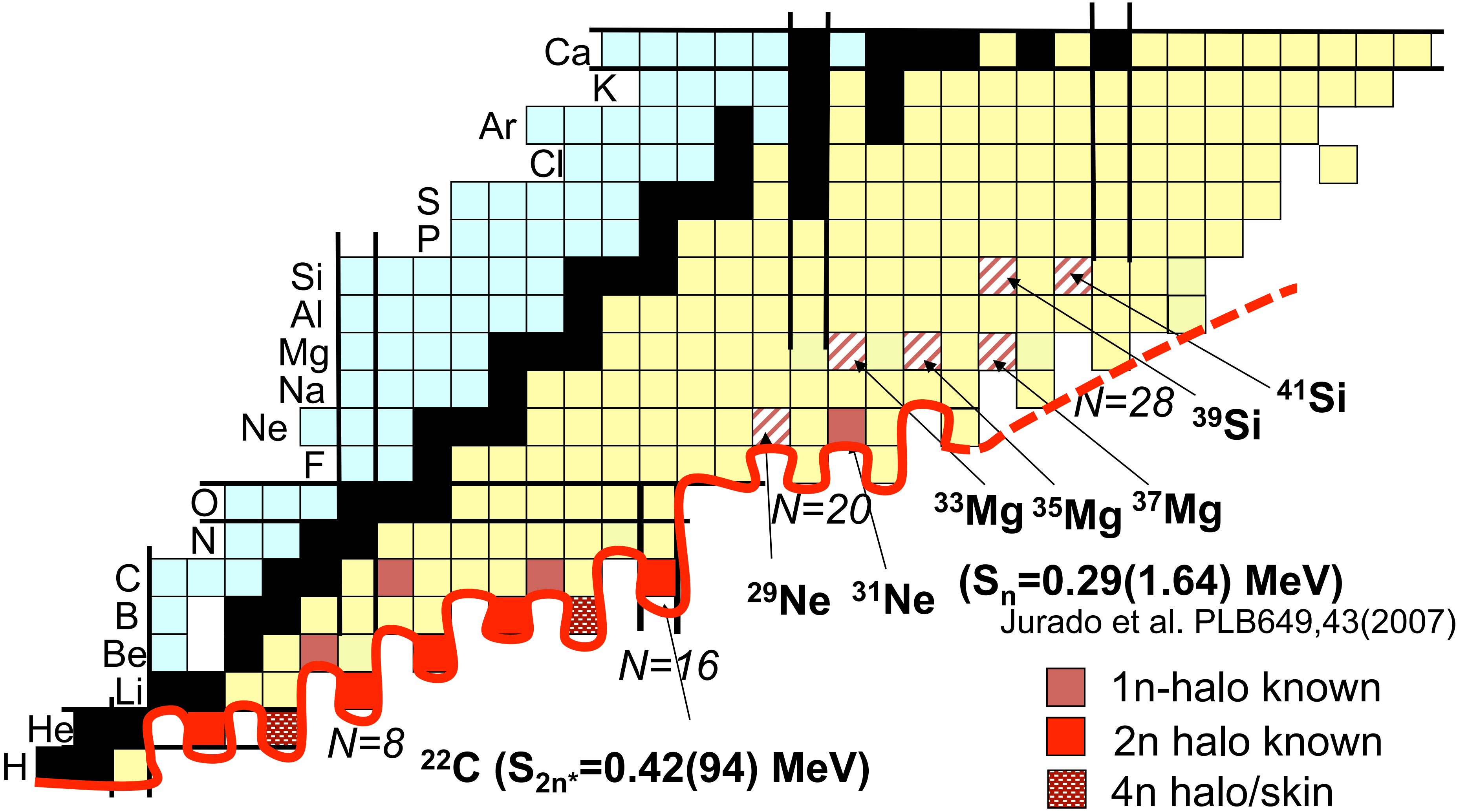
Theory: Eikonal Approximation

Inclusive Coulomb/Nuclear Breakup of Drip-Line Nuclei at RIBF

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

N.Kobayashi, T.N. et al., PRC86, 054604 (2012).

Ph.D Thesis, N.Kobayashi



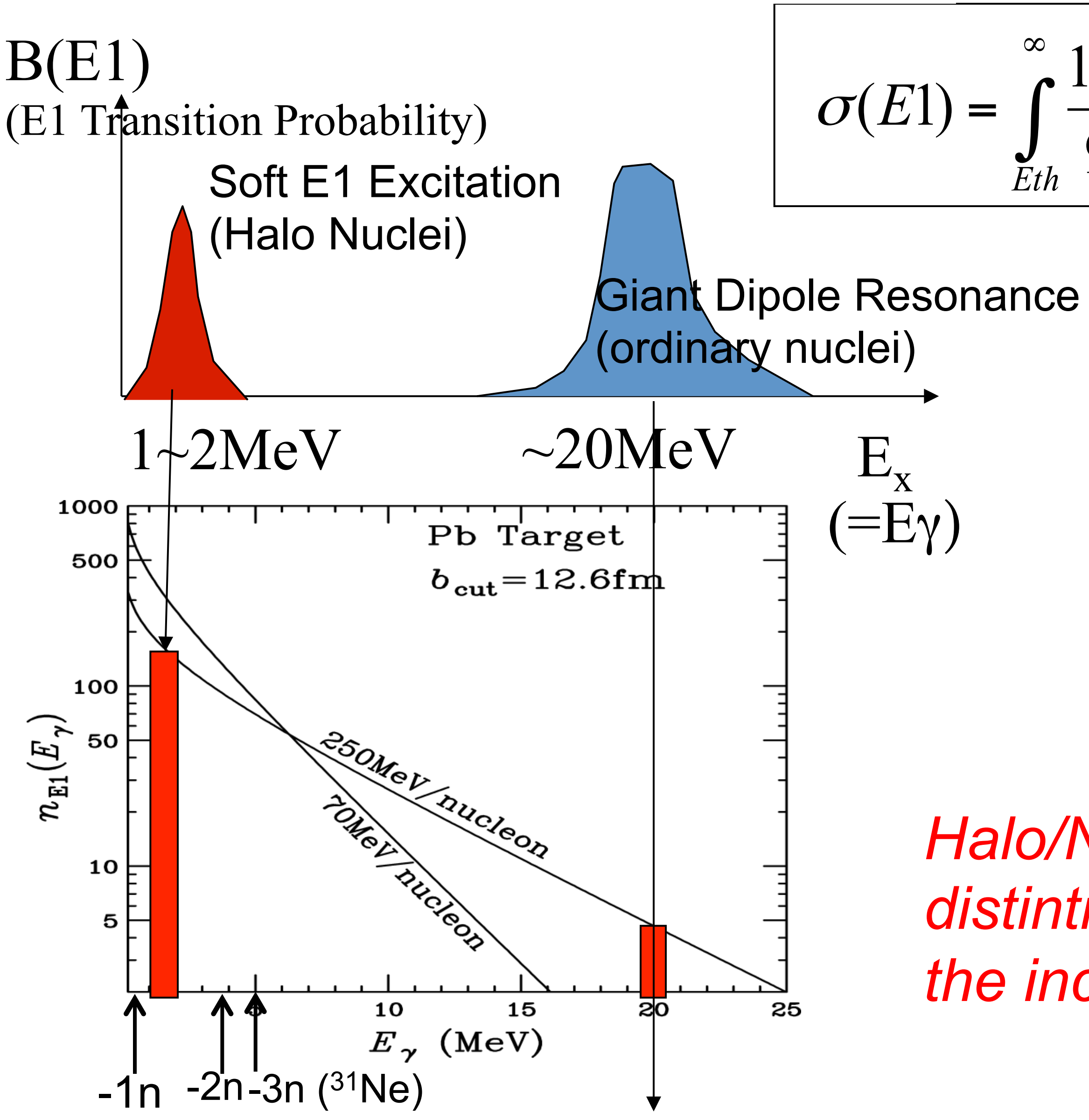
(S_n=0.29(1.64) MeV)

Jurado et al. PLB649,43(2007)

^{22}C (S_{2n*}=0.42(94) MeV)

Inclusive Coulomb Breakup

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



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

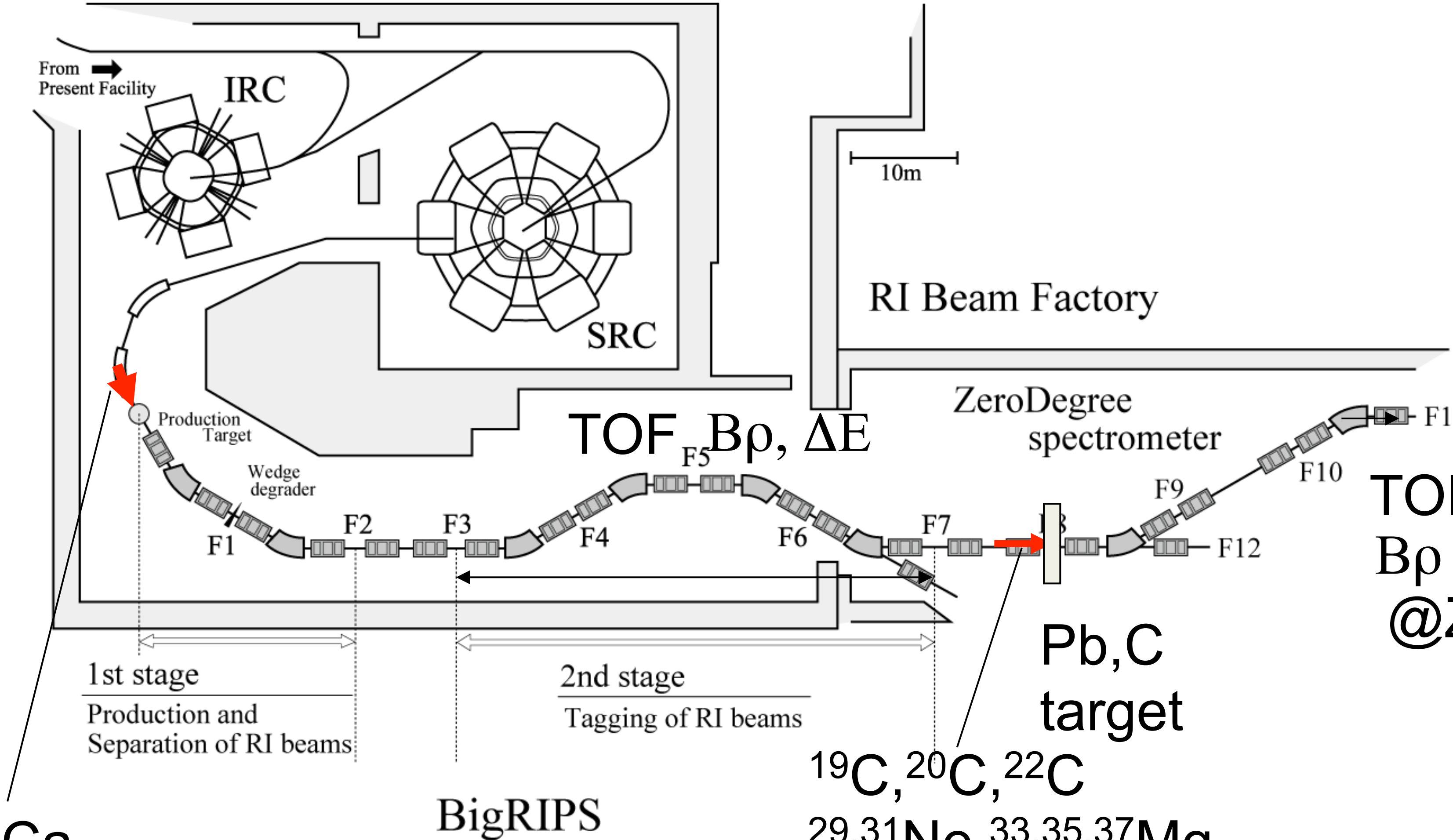
$^{22}C+Pb \rightarrow ^{20}C+X$

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

<~0.1b

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

Experiment at BigRIPS & ZDS at RIBF



TOF,Bρ, ΔE

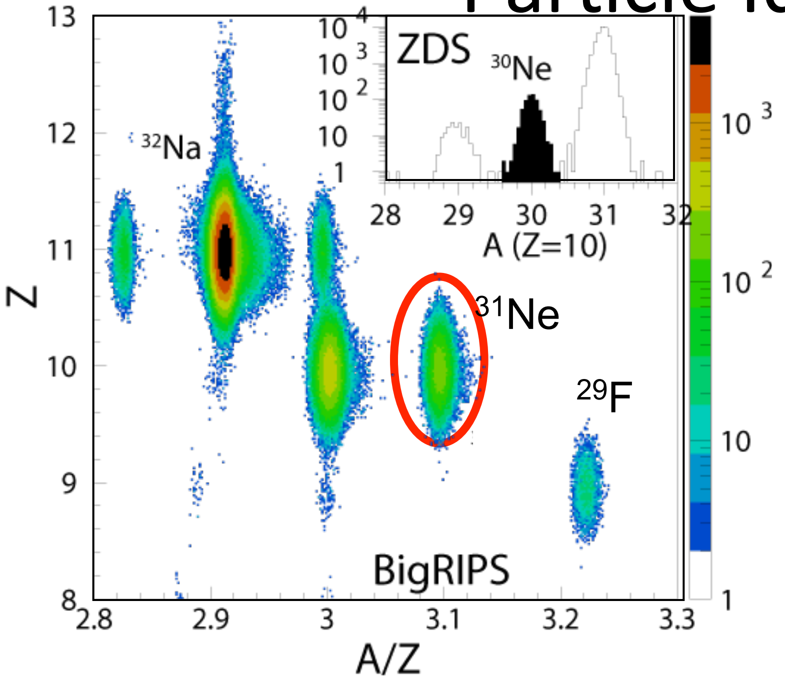
TOF,ΔE
Bρ
@ZDS

Pb,C
target

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

^{19}C,^{20}C,^{22}C
^{29,31}Ne,^{33,35,37}Mg
^{39,41}Si
230~240MeV/nucleon

Particle Identification



RI beam Intensity @RIBF

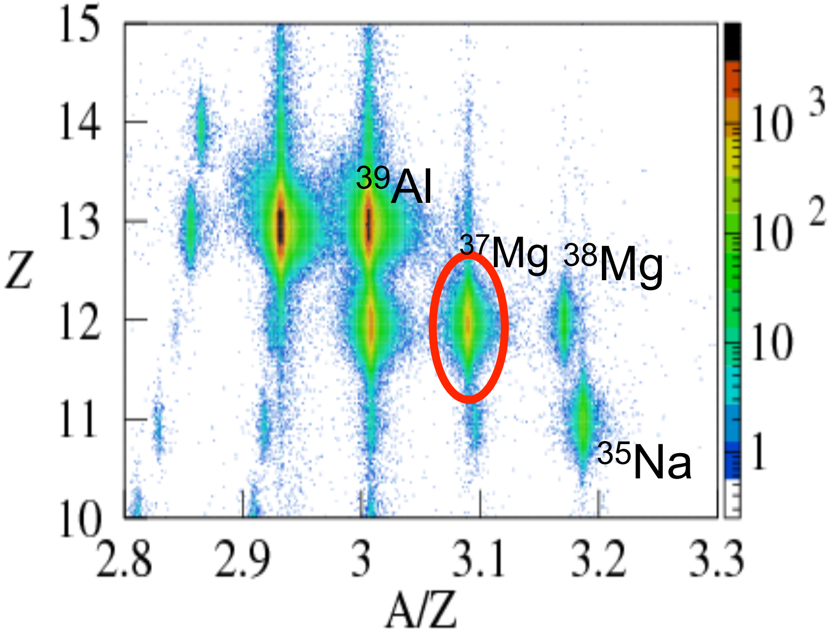
~10^3-10^4 times/RIPS

^{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



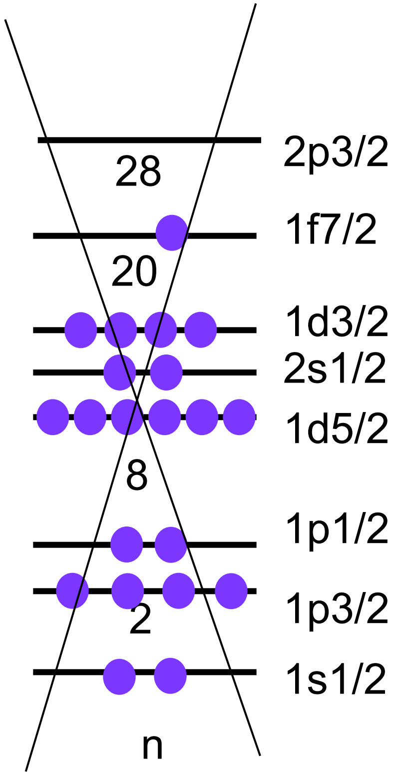
^{48}Ca@100pnA 2010
(→200pnA in 2012)

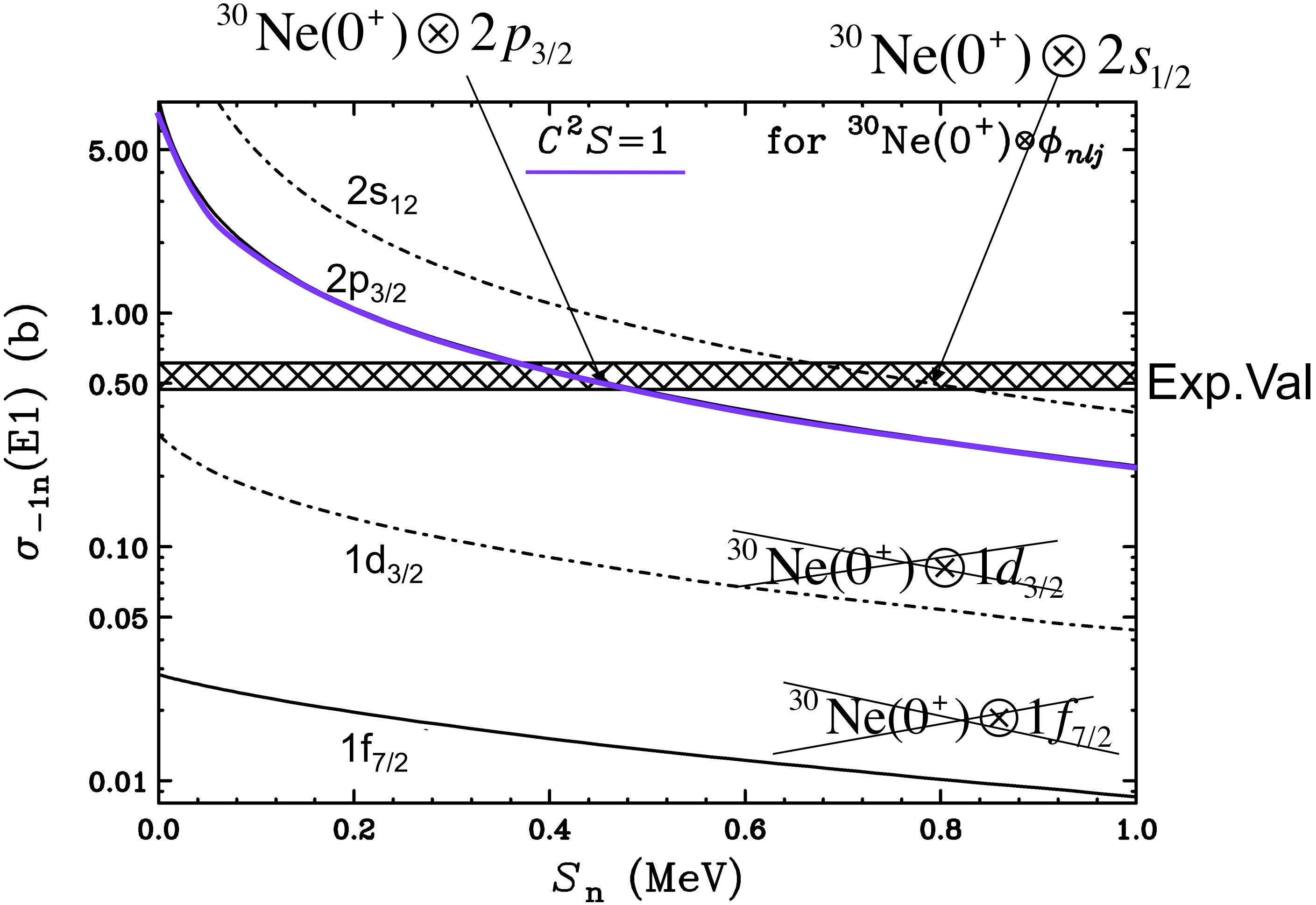
^{37}Mg: 244MeV/nucleon

~6 counts/s

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

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





2p$_{3/2}$ or 2s$_{1/2}$ Low-L orbits → Large E1→1n-halo structure of ^{31}Ne

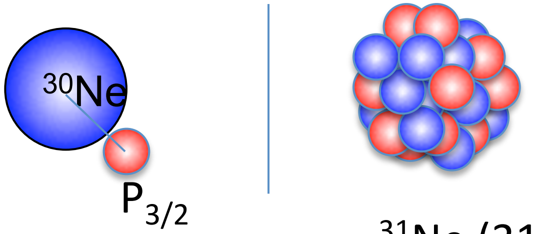
^{30}Ne(0$^+$)X1f$_{7/2}$ Excluded →Shell gaps(20,28) vanish at ^{31}Ne

Sn/C^{2}S→ Nuclear Breakup (^{31}Ne+C, γ coincidence, Kinematically complete measurement of Coulomb Breakup)

Spectroscopic Factor

例：^{31}Ne:　31体系の波動関数と、1粒子軌道[core x n]のOverlap

$$\boxed{C^2S(0^+;p_{3/2}) = \left\langle {}^{30}\mathrm{Ne}(0^+)\otimes p_{3/2} \middle| {}^{31}\mathrm{Ne}_{\mathrm{gs}}(3/2^-)\right\rangle}$$



^{31}Ne (31体系,J^π=3/2$^-$)

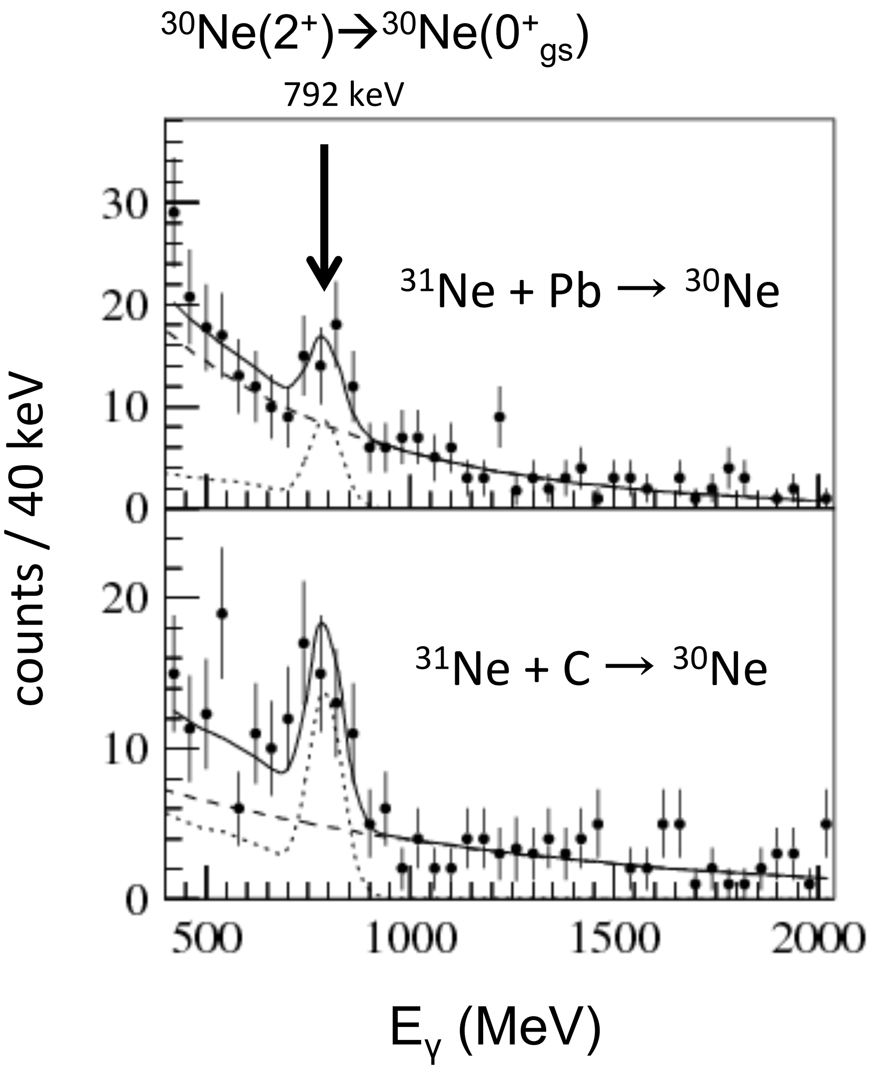
実験：ストリッピング反応(d,p),1粒子分離反応
断面積∝C^2S

理論：殻模型で行列要素計算が可能　→

$$A+1 \leftrightarrow B$$

$$\boxed{C^2S(J_A{}^{\pi};nlj) = \frac{\left\langle J_B \| a_j{}^{+} \| J_A \right\rangle}{\sqrt{2J_B+1}}}$$

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



$^{30}\mathrm{Ne}(2^+) \rightarrow {}^{30}\mathrm{Ne}(0^+_{\mathrm{gs}})$

792 keV

Fitted with a response function (GEANT4)
+ exponential background

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

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

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

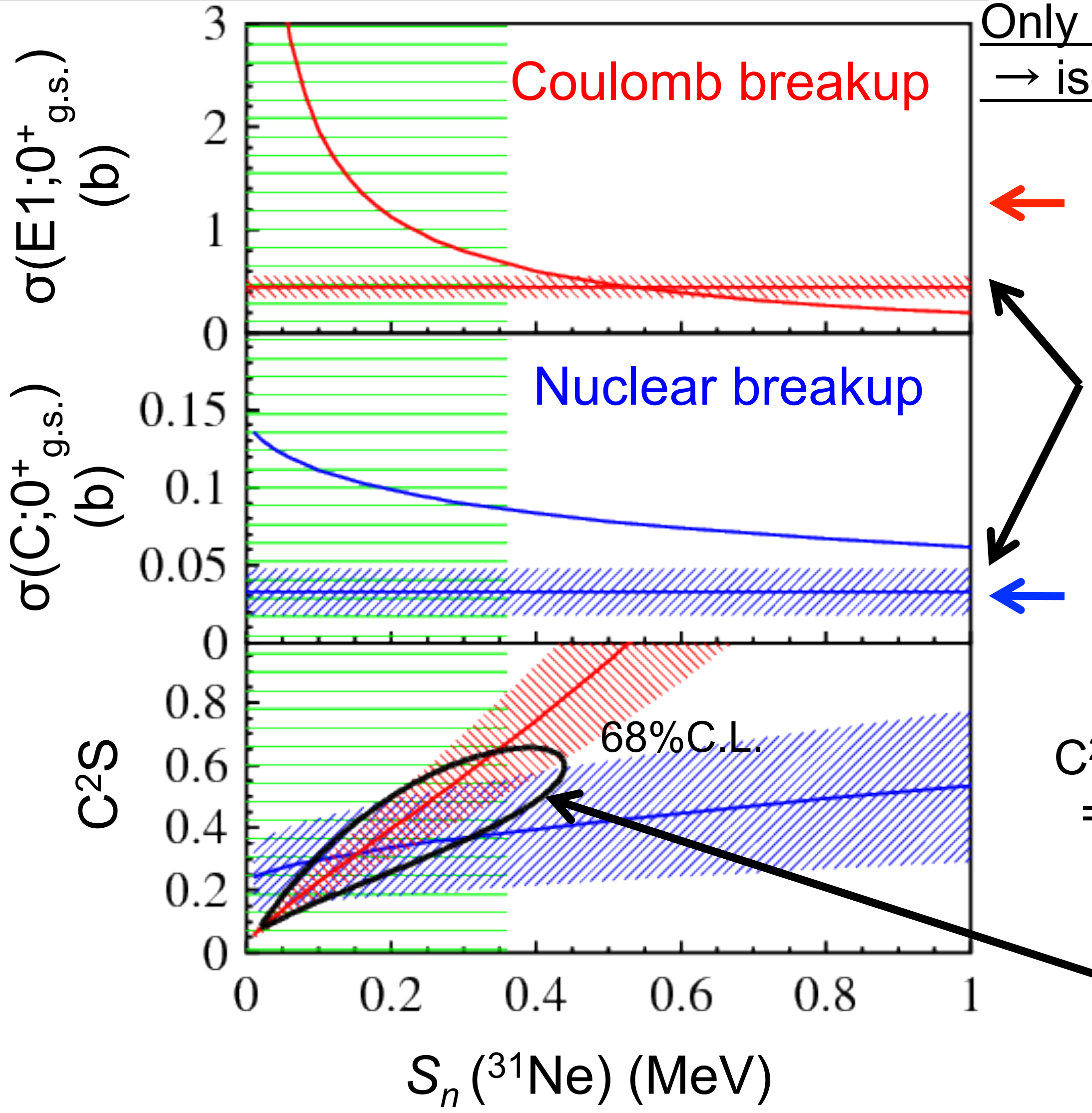
Inclusive $\sigma_{-1n}(C) = 90(7)$ mb
$\sigma_{-1n}(C; 2^+, 4^+, \text{etc.}) = 57(13)$ mb
$\rightarrow \sigma_{-1n}(C; 0^+_{\mathrm{g.s.}}) = 33(15)$ mb

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

Combined analysis
-- 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^+) $\otimes 1p_{3/2}$



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

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

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

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

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

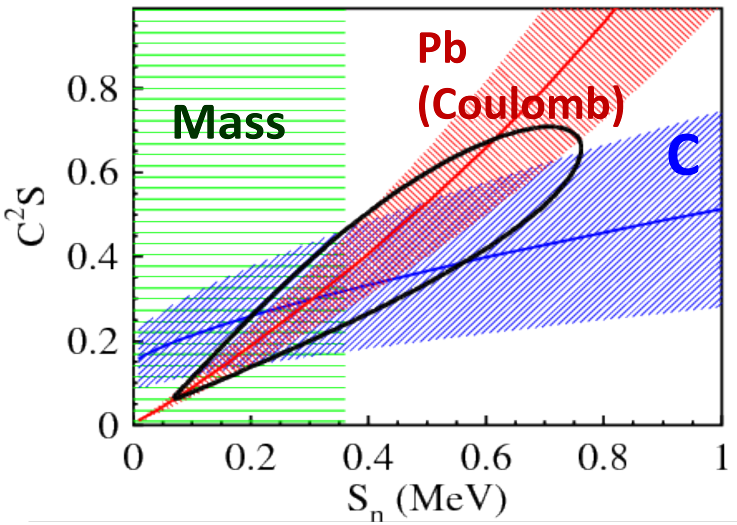
$$C^2S = 0.32^{+0.21}_{-0.17}$$

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

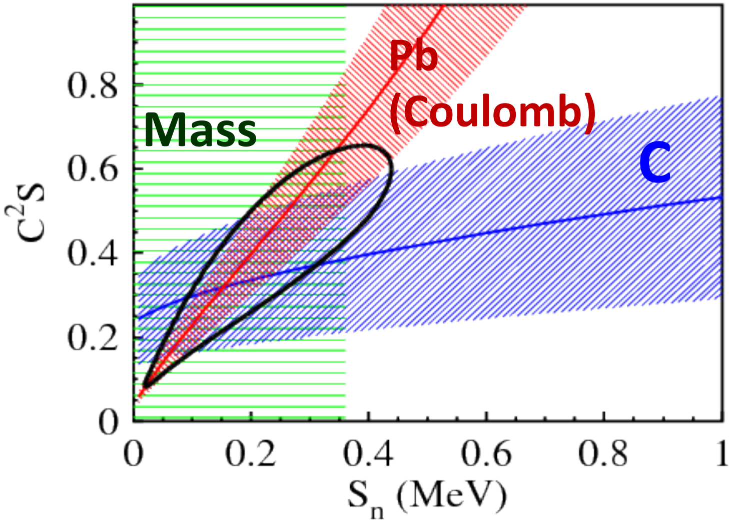
Possible configurations

--Overlap: Breakup by Pb(Coulomb) and C

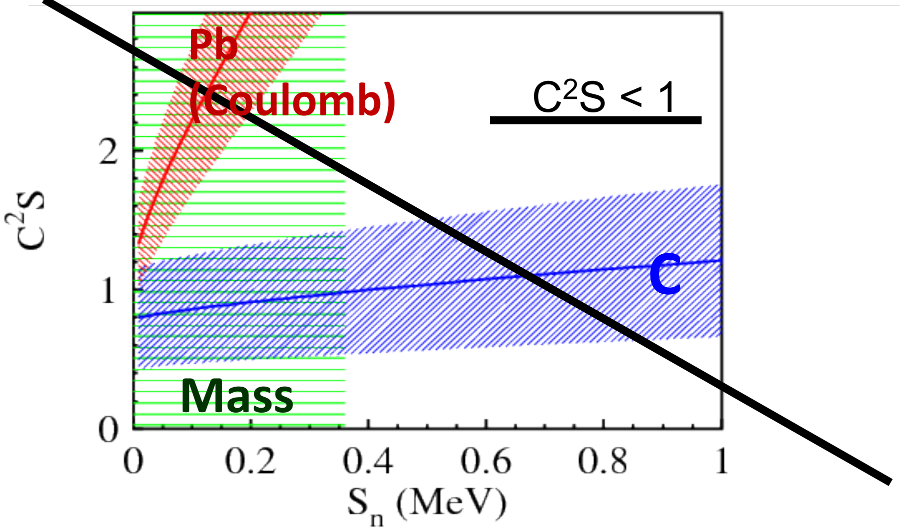
$^{31}\mathrm{Ne}(\mathbf{1/2^{+}}) : {}^{30}\mathrm{Ne}(0^{+}) \otimes 1s_{1/2}$



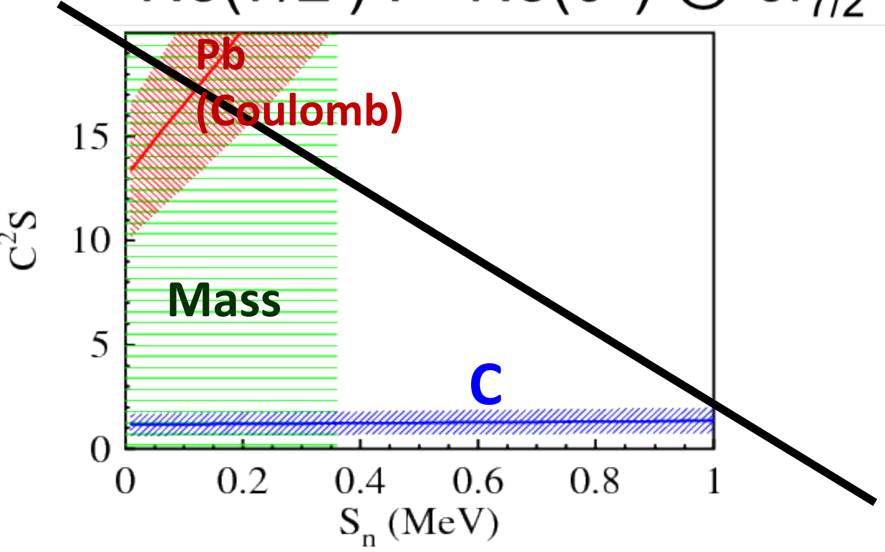
$^{31}\mathrm{Ne}(\mathbf{3/2^{-}}) : {}^{30}\mathrm{Ne}(0^{+}) \otimes 1p_{3/2}$



$^{31}\mathrm{Ne}(3/2^{+}) : {}^{30}\mathrm{Ne}(0^{+}) \otimes 0d_{3/2}$

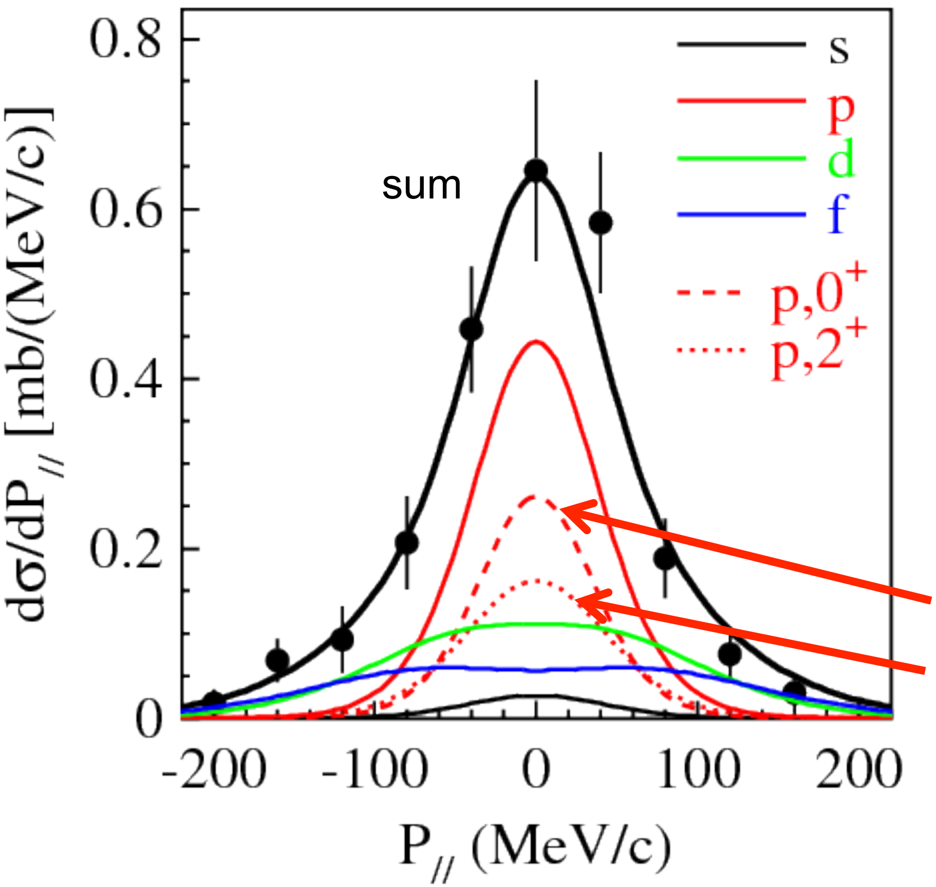


$^{31}\mathrm{Ne}(7/2^{-}) : {}^{30}\mathrm{Ne}(0^{+}) \otimes 0f_{7/2}$



Inclusive momentum distribution of ^{30}Ne fragment (C target) Case of *p*-neutron removal (^{31}Ne(3/2$^-$))

Lines were calculated based on eikonal model.



State	C^{2}S	σ(mb)
$\lvert {}^{30}\mathrm{Ne}\otimes s\rangle$	0.09	3.0
$\lvert {}^{30}\mathrm{Ne}\otimes p\rangle$	0.55	45.7
$\lvert {}^{30}\mathrm{Ne}\otimes d\rangle$	1.33	27.8
$\lvert {}^{30}\mathrm{Ne}\otimes f\rangle$	0.80	18.8
	total	93 mb
	Exp.	90(7) mb

State	C^{2}S
$\lvert {}^{30}\mathrm{Ne}(0^+_{g.s.})\otimes 1p_{3/2}\rangle$	0.26
$\lvert {}^{30}\mathrm{Ne}(2^+_1)\otimes 1p_{3/2}\rangle$	0.265

Combined analysis (SM: 0.21)

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

P-wave Neutron Halo surrounding the deformed Core.

Picture of ^{31}Ne extracted from Breakup Reactions

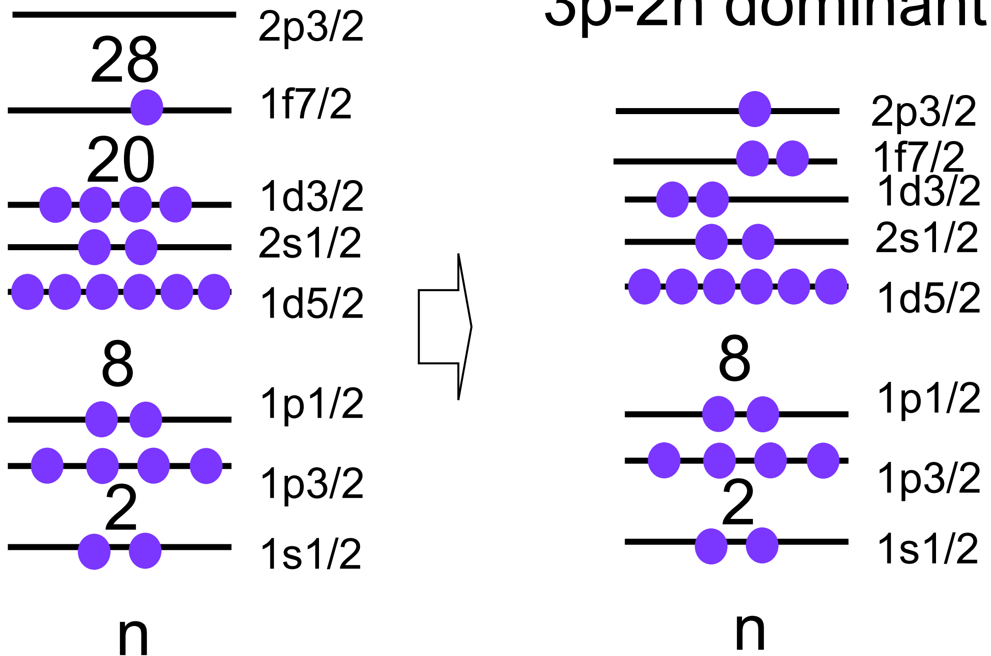
Extremely Small Separation Energy
Large Configuration Mixing

$$J^{\pi} = 3/2^{-},\ C^2S(0^{+}; p_{3/2}) = 0.32^{+0.21}_{-0.17}$$
$$S_n = 0.15^{+0.16}_{-0.10}\ \mathrm{MeV}$$

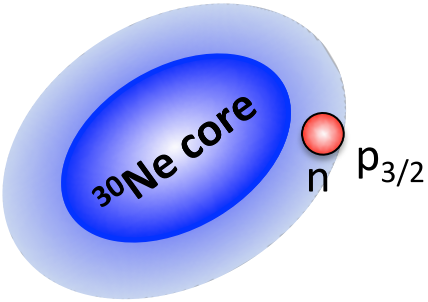
Excellent Agreement with Large Scale Shell Model !

(SPDF-M Interactions Utsuno, Otsuka)

3p-2h dominant



1n Halo, Deformed, Nucleus



N=20,28 gap
→Disappeared

Large Q-moment, E2 transition

→Q_0~60fm^2

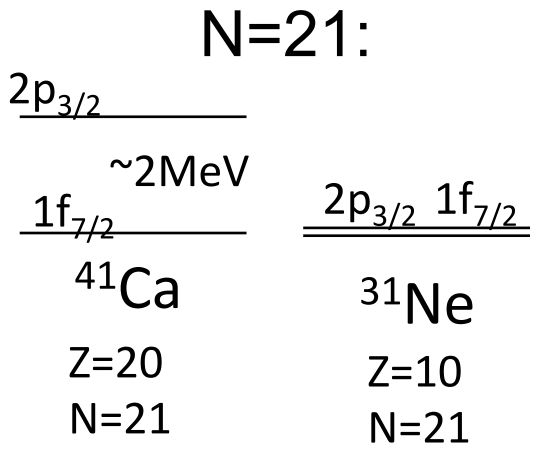
β~0.5 (長径/短径~2)

$$R(\theta,\varphi) = R_0\left[1 + \beta Y_{20}(\theta,\varphi)\right]$$

大規模シェルモデル計算ー不安定核の”形”も調べられるようになった!

Theoretical consideration (^{31}Ne)

どうして変形したのか？



N=21:

$2p_{3/2}$

~2MeV

$1f_{7/2}$

^{41}Ca

Z=20

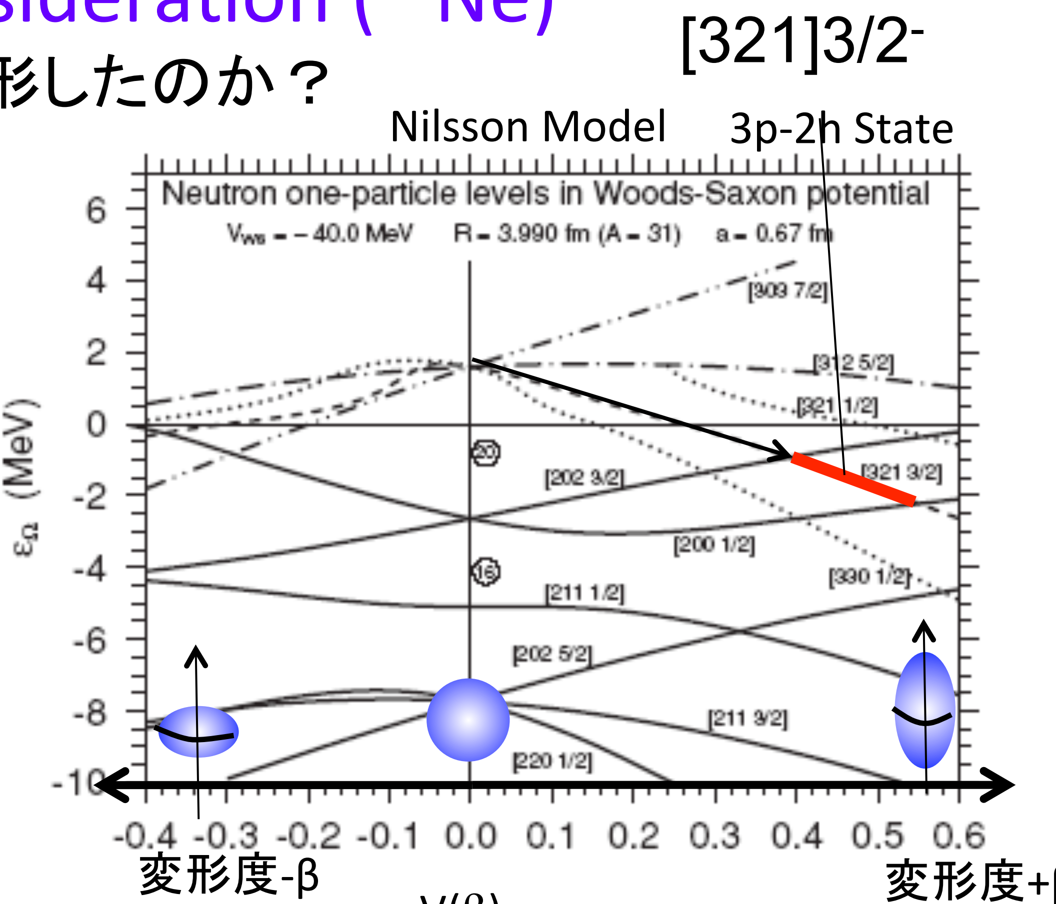
N=21

$2p_{3/2}$ $1f_{7/2}$

^{31}Ne

Z=10

N=21



fp Degeneracy

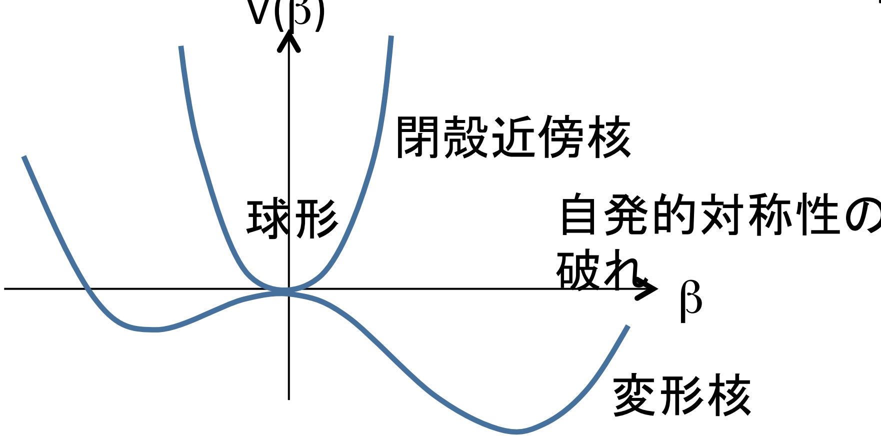
→Quadrupole Deformation

(Nuclear Jahn-Teller Effect)

fp Degeneracy の原因：

Fermi面近傍,Weakly Bound

テンソル力(pn 相互作用）



Y.Utsuno et al.PRC60,054315(1999).

I.Hamamoto, PRC76,054319(2007).

I.Hamamoto, PRC85,064329(2012).

In 2012

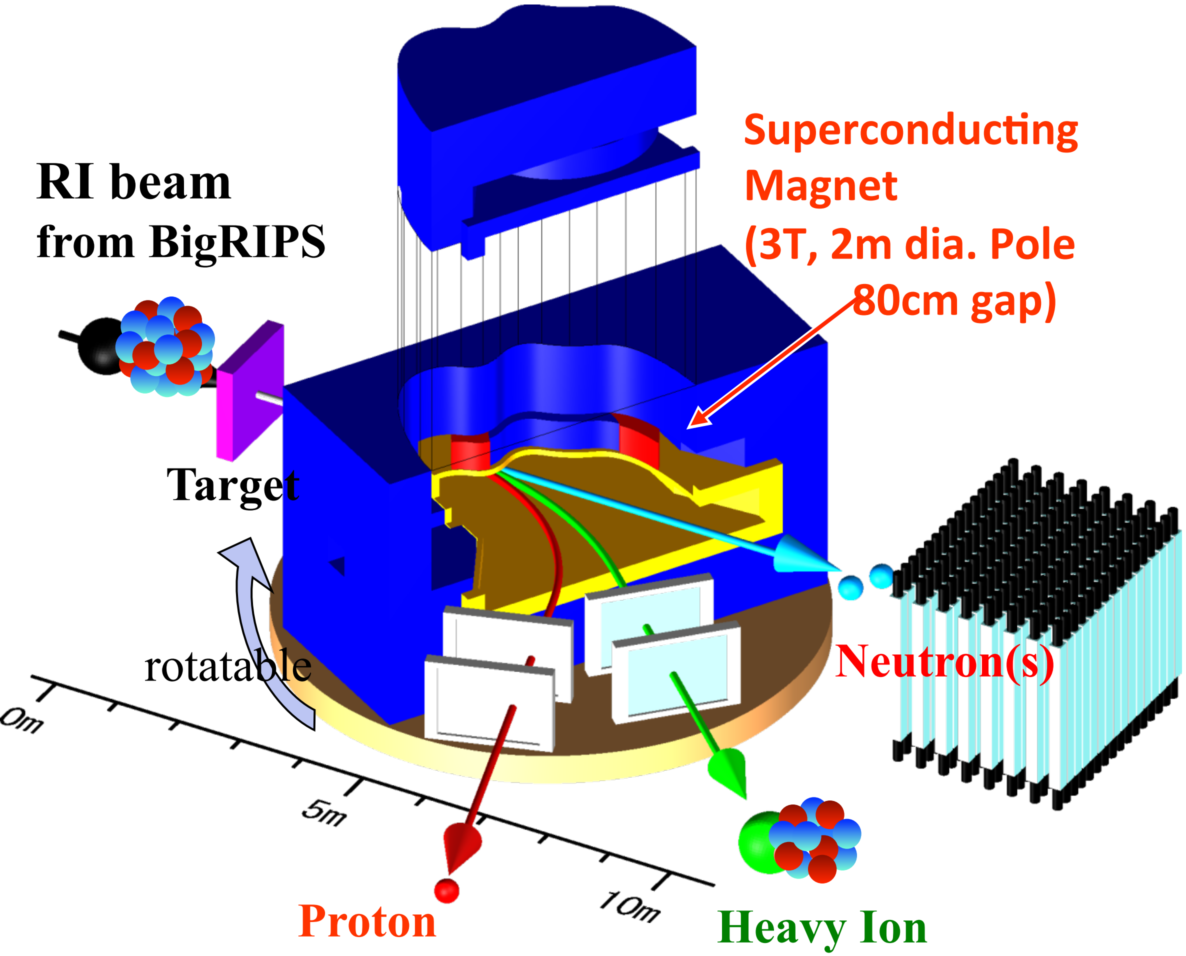
Inclusive → Exclusive

ZDS → SAMURAI

SAMURAI （多種粒子測定装置）

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence 不安定核反応の完全運動学測定のためのスペクトロメータ（世界最高性能）



Large momentum acceptance

$B\rho_{max} / B\rho_{min} \sim 2 - 3$

Good Momentum Resolution

$\Delta p/p \sim 1/700$ (designed value)

(5σ separation for A=100)

Large angular acceptance for *n*

20 deg (H) x 10 deg(V)

(~100% coverage < E_{rel} ~ 2MeV,

~ 30% coverage at E_{rel} ~ 10 MeV)

Stage: Rotatable (-5 -- 95 degrees)

Versatile Usage

Invariant mass for n+HI

Invariant mass for p+HI

(p,n),(p,p'),(p,pn)(p,pp) etc.

Heavy Ion Collision

polarized deuteron, etc.

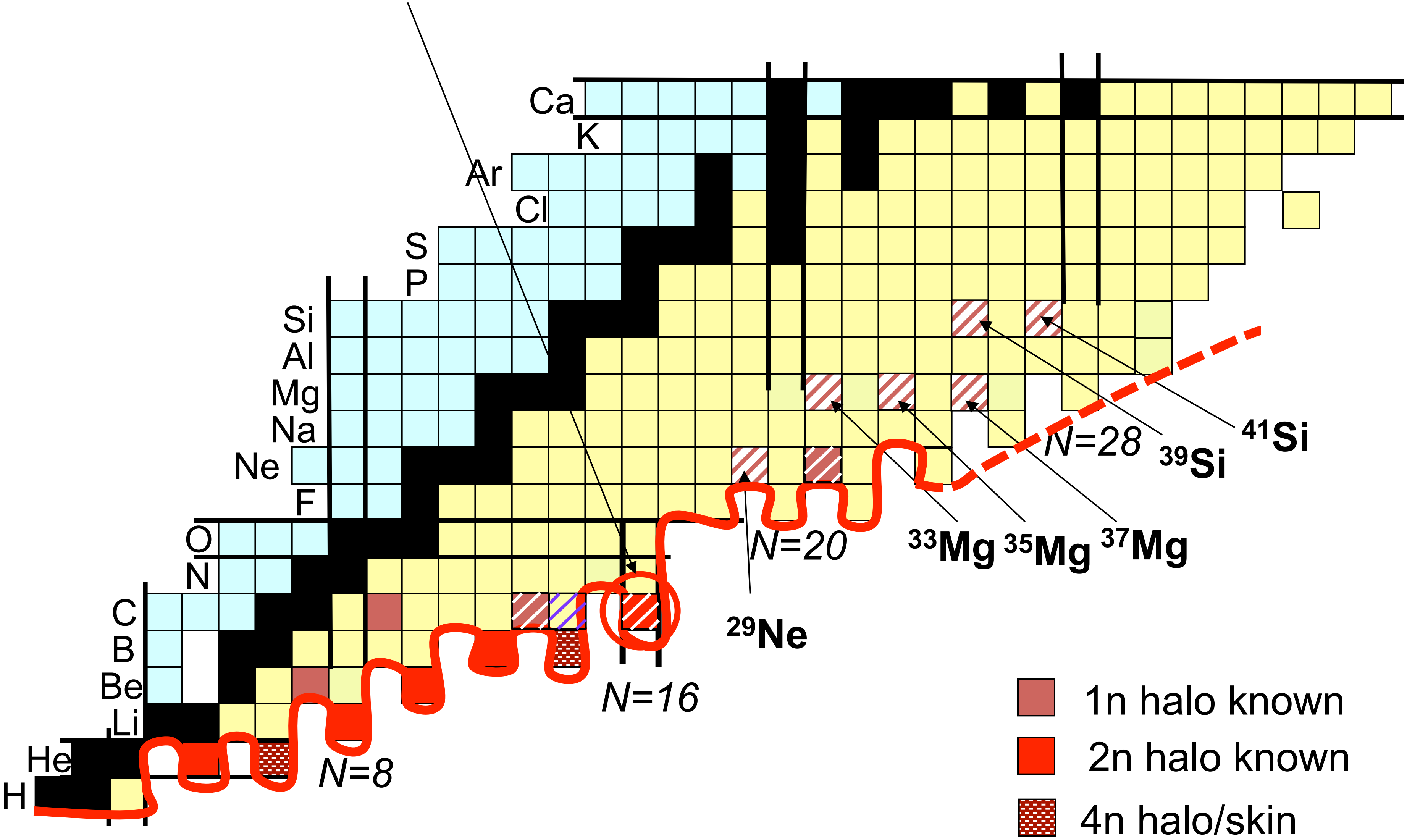
SAMURAI

-- New Spectrometer in RIBF --

Commissioning Experiment March 2012

Slide: K. Yoneda

^{22}C N=16


Ca
K
Ar
Cl
S
P
Si
Al
Mg
Na
Ne
F
O
N
C
B
Be
Li
He
H
N=8
N=16
N=20
N=28
^{29}Ne
^{33}Mg
^{35}Mg
^{37}Mg
^{39}Si
^{41}Si
1n halo known
2n halo known
4n halo/skin

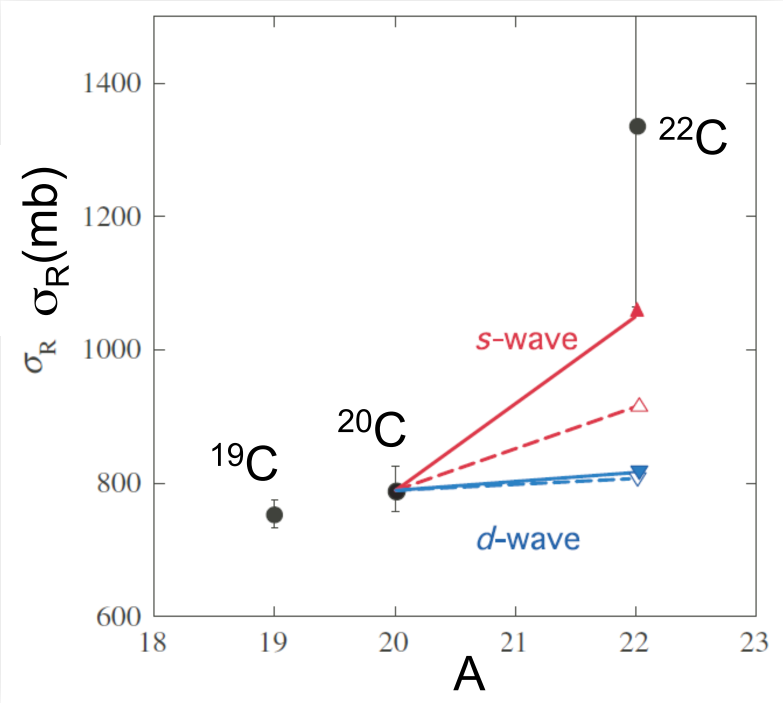
^{22}C

☐ Prominent 2n-Halo?

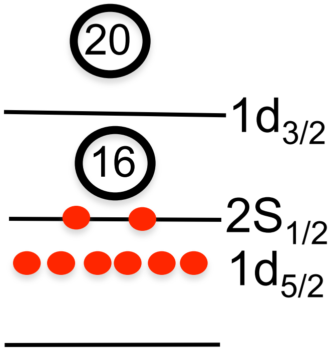
Reaction cross section measurements

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

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



☐ N=16 Magicity?



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

☐ Heaviest s-wave dominant 2n Halo within reach?

c.f. $3s_{1/2}$ Halo: Far away for the current and near-future RIB facilities

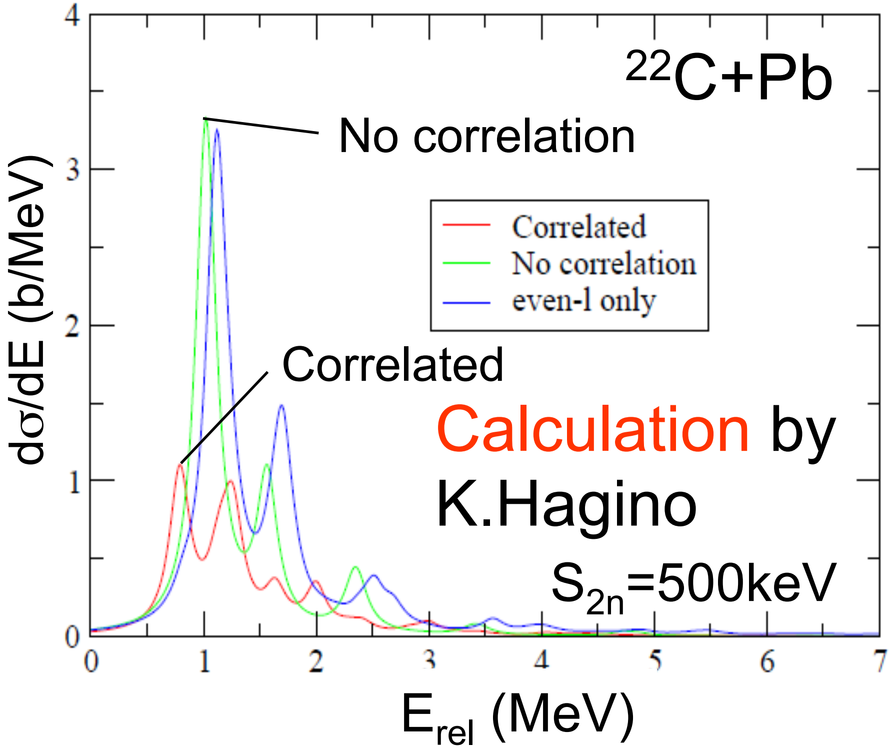
N~60-70

Kinematically Complete Measurement of Coulomb/Nuclear Breakup of ^{22}C

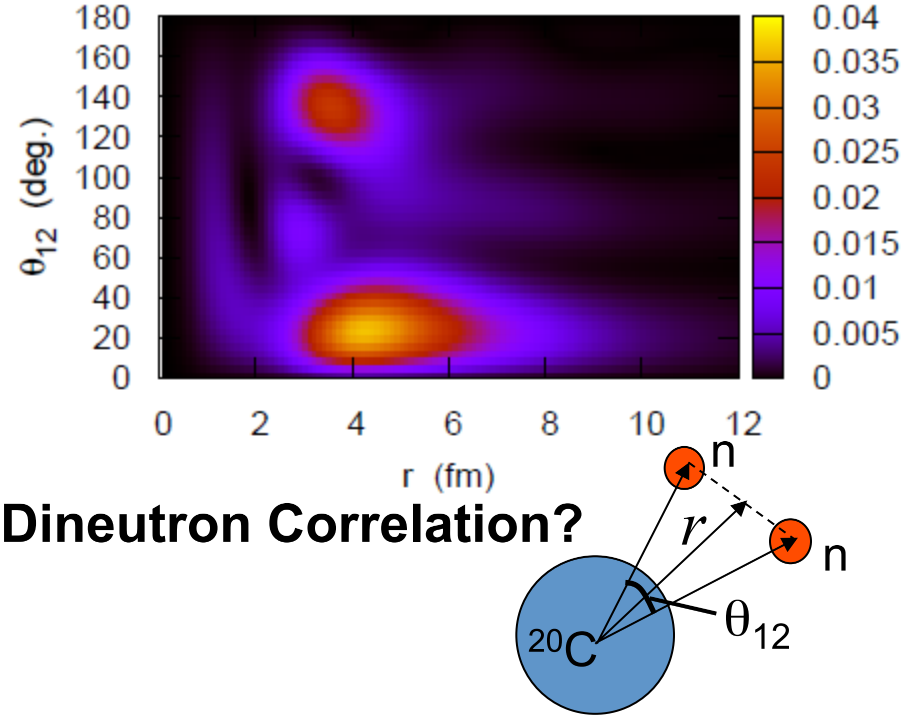
Coulomb Breakup of ^{22}C

Soft E1 Excitation---Good Probe for 2n correlation

e.g. **^{11}Li** T.Nakamura et al. PRL96,252502(2006).



Calculation by K.Hagino



Dineutron Correlation?

Correlated: $\alpha|(2s_{1/2})^2\rangle + \beta|(1d_{3/2})^2\rangle + \gamma|(2p_{3/2})^2\rangle + \gamma|(1f_{7/2})^2\rangle$ ….

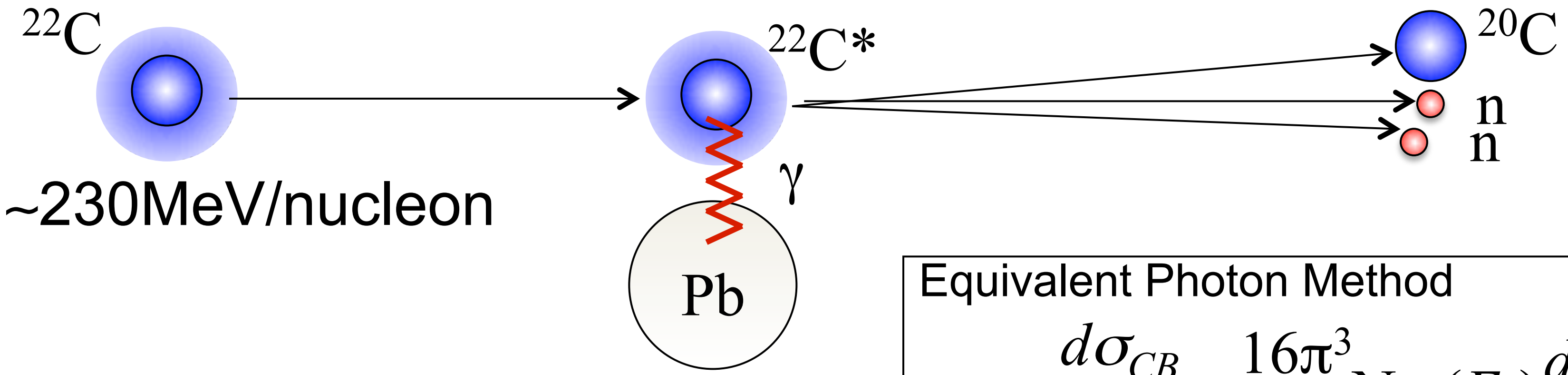
1.05b	62.5%	24.2%	4.7%	3.8%

Non-Correlated: $|(2s_{1/2})^2\rangle$

(s only) 1.66b 100%

→Kinematically Complete Measurement of Coulomb Breakup

Coulomb Breakup

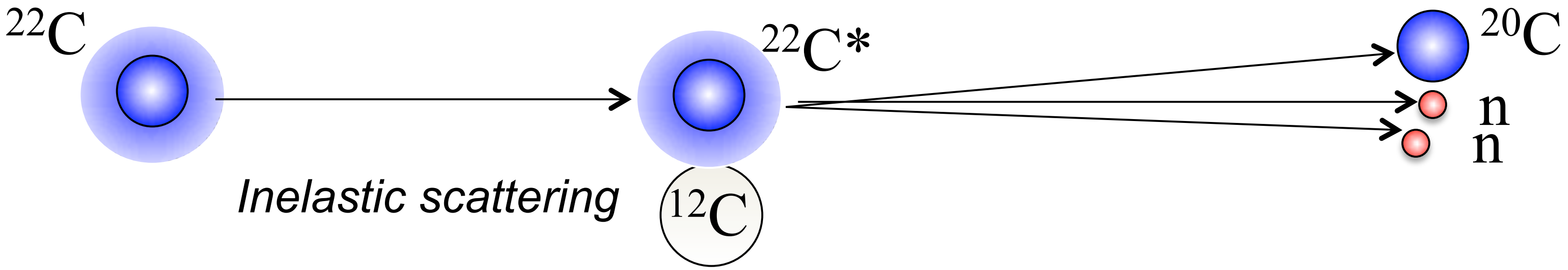


~230MeV/nucleon

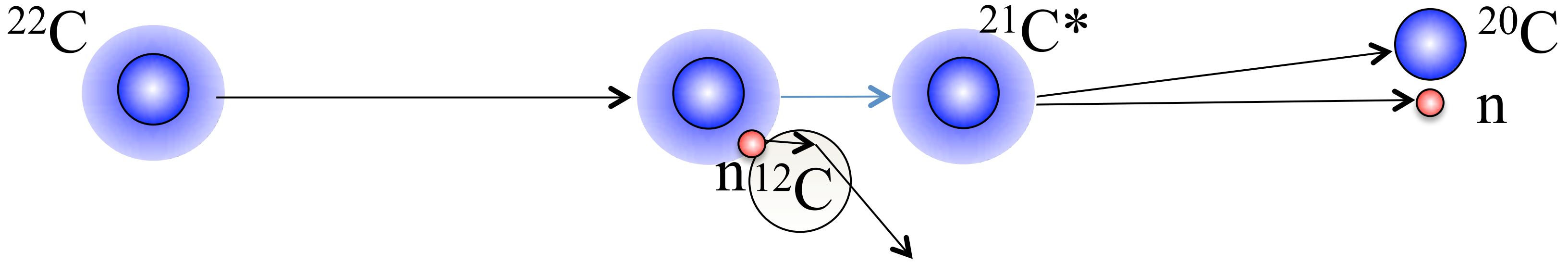
Equivalent Photon Method

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

Nuclear Breakup



Inelastic scattering



Invariant Mass Spectroscopy of ^{21}C and ^{22}C

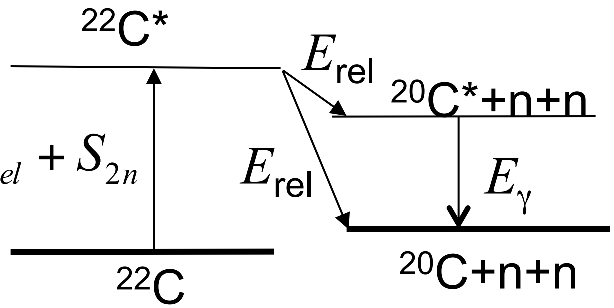
Pb(^{22}C,^{20}C+*n*+*n*)

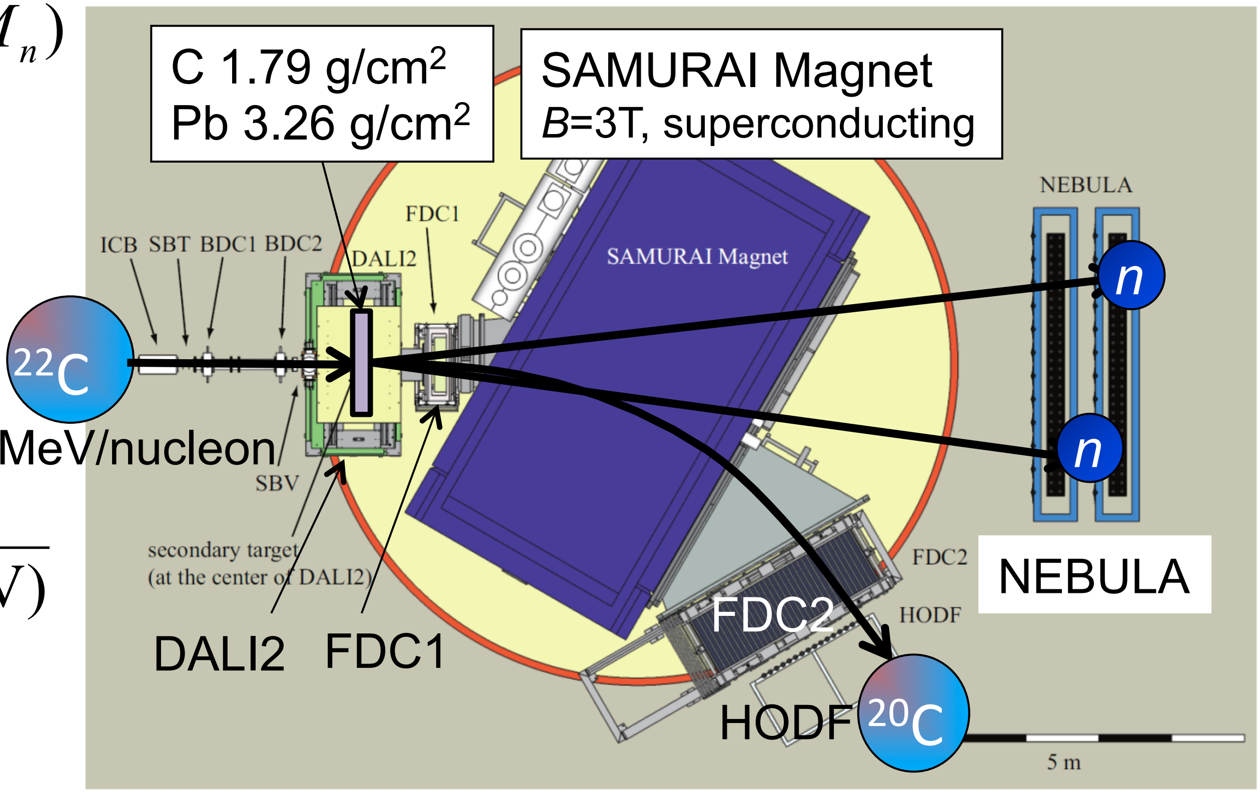
C(^{22}C,^{20}C+*n*+*n*)

$$M^* = \sqrt{(E_{20} + E_n + E_n)^2 - (\vec{P}_{20} + \vec{P}_n + \vec{P}_n)^2}$$

$$E_{\mathrm{rel}} = M^* - (M_{20} + M_n + M_n)$$

$$E_x = E_{rel} + S_{2n}$$




C 1.79 g/cm^2
Pb 3.26 g/cm^2

SAMURAI Magnet
B=3T, superconducting

~230 MeV/nucleon

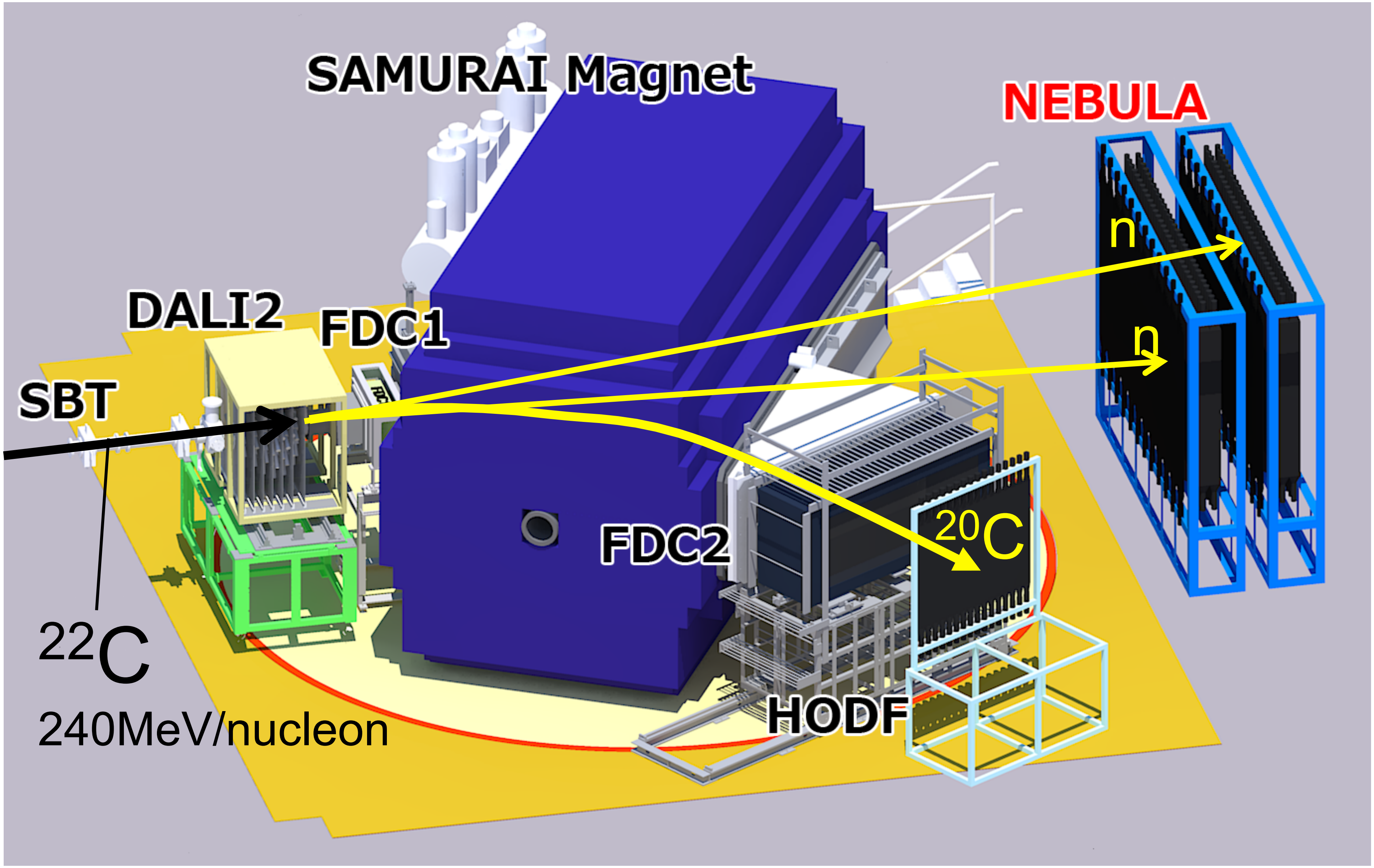
Good Energy Resolution

$$\Delta E_{\mathrm{rel}}(\mathrm{MeV}) = a\sqrt{E_{\mathrm{rel}}(\mathrm{MeV})}$$

$$a \approx 0.2\ \mathrm{MeV}\ (1\sigma)$$

SAMURAI Experiment May/2012

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



RI Beam Spectra @ SAMURAI May/2012

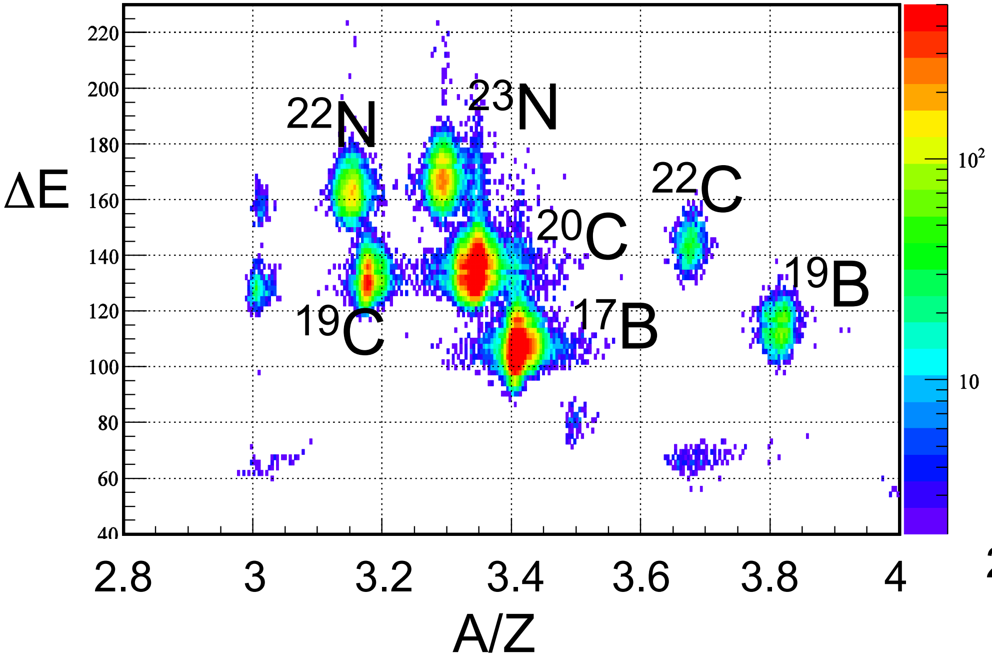
^{48}Ca 150~200pnA (Max 250pnA)

Tuned for **^{22}C**

(^{22}C+Pb/C→^{20}C+n+n)

^{22}C ~10 /s (@150pnA)

^{23}N ~80 /s

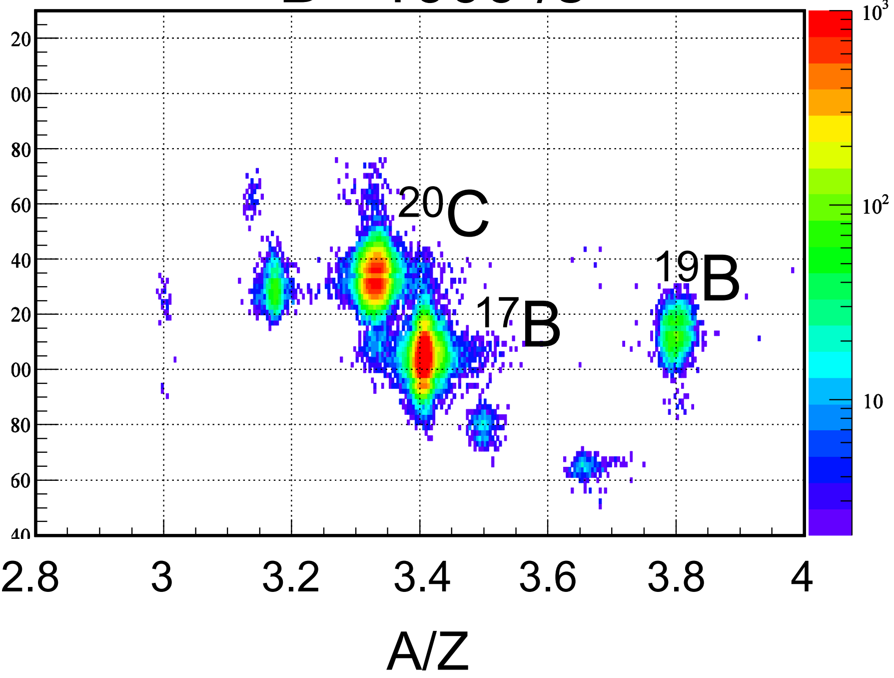


Tuned for **^{19}B**

(^{19}B+Pb/C→^{17}B+n+n)

^{19}B ~50 /s (@200pnA)

^{17}B ~1000 /s



High intense RIBF Beam

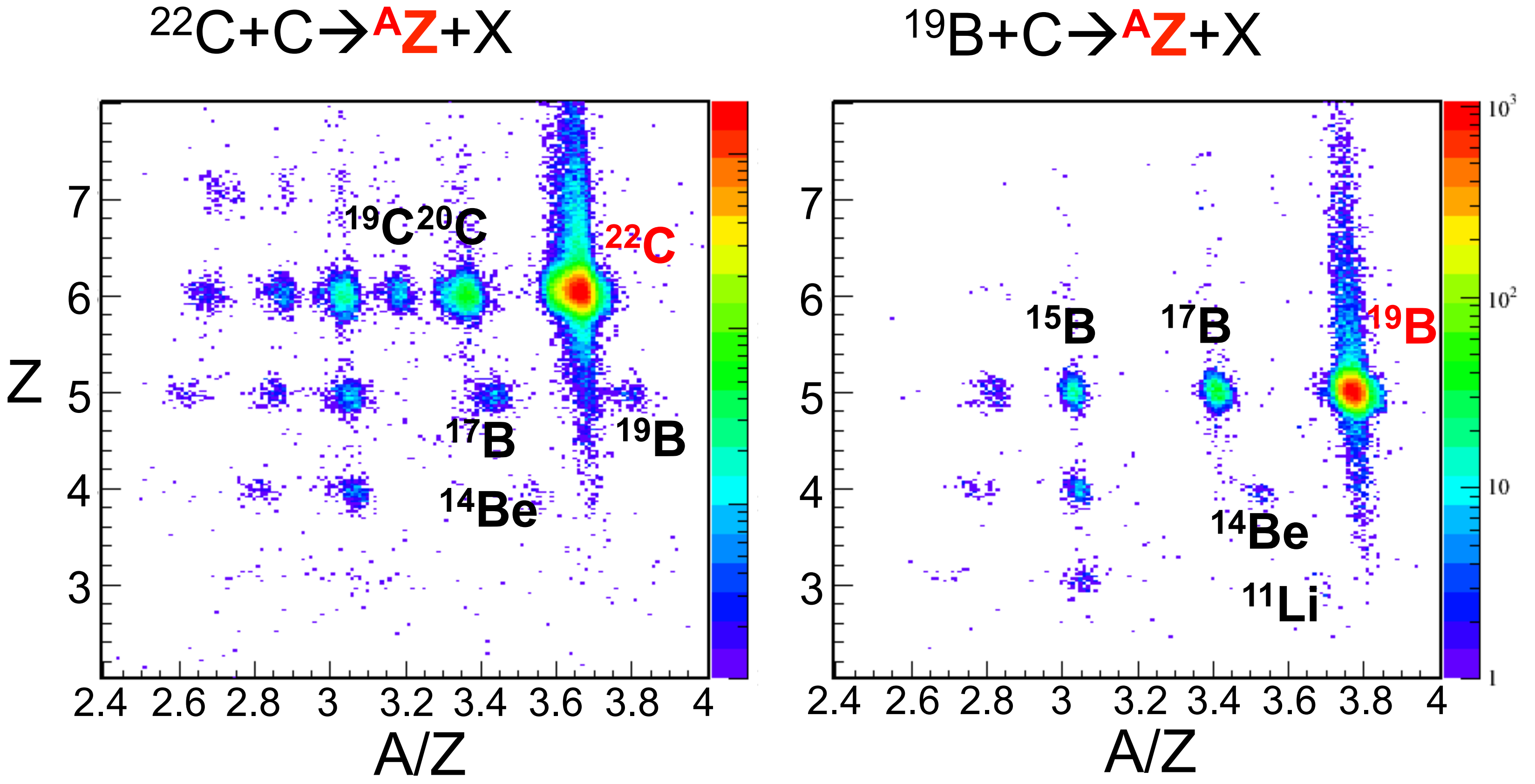
^{22}C: **~10/s** (*c.f. 10/hour K.Tanaka,PRL2010, RIPS@RIKEN*)

Gain of ~3600!

Results on Inclusive Data

PID of Downstream Detectors at SAMURAI

By S.Ogoshi
Beam Trigger

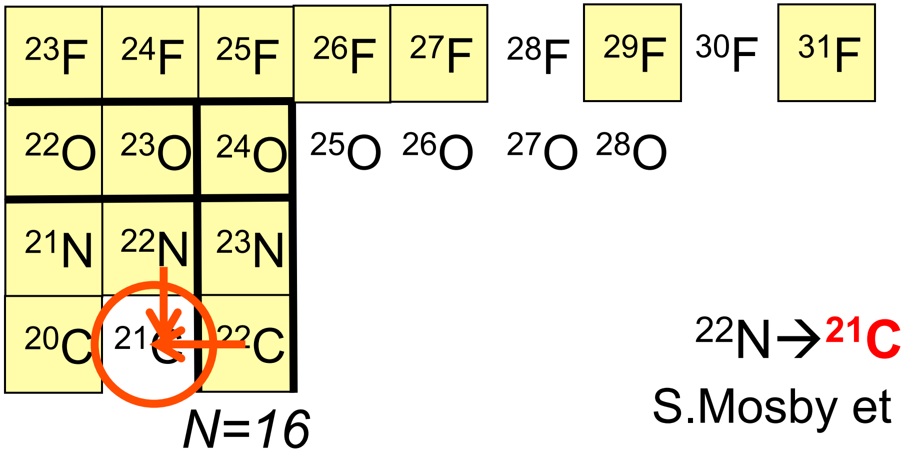


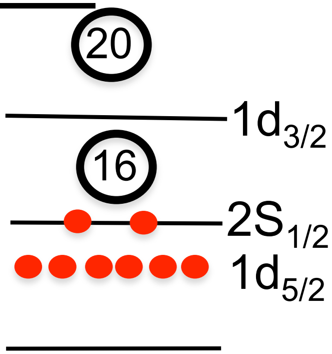
$^{22}C+C \rightarrow {}^{A}Z+X$

$^{19}B+C \rightarrow {}^{A}Z+X$

Clear Separation of Mass and Charge
Reaction Cross Sections → Matter Radii of Halo Nuclei ^{22}C and ^{19}B
Inclusive –xn cross sections → Reaction Theory, Shell Structure

Heavy Ion + 1 neutron : $^{22}C+C \rightarrow {}^{21}C^* \rightarrow {}^{20}C+n$





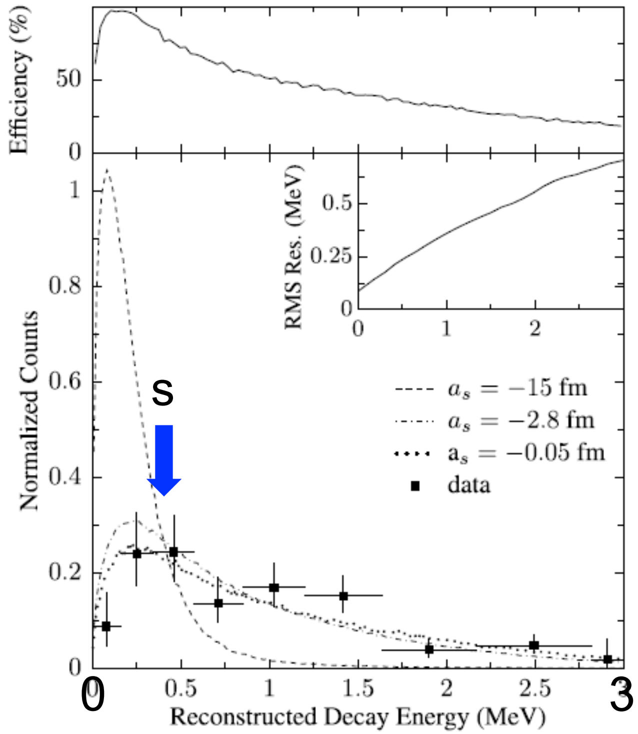
$^{22}N \rightarrow {}^{21}C^* \rightarrow {}^{20}C+n$

S.Mosby et al.(MSU) NPA909,69(2013)

Counts/100keV

d?

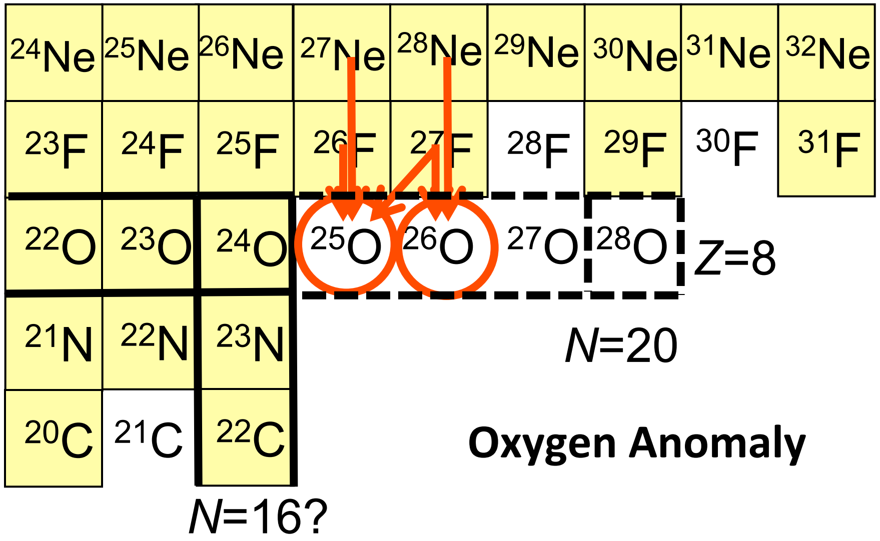
S?



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

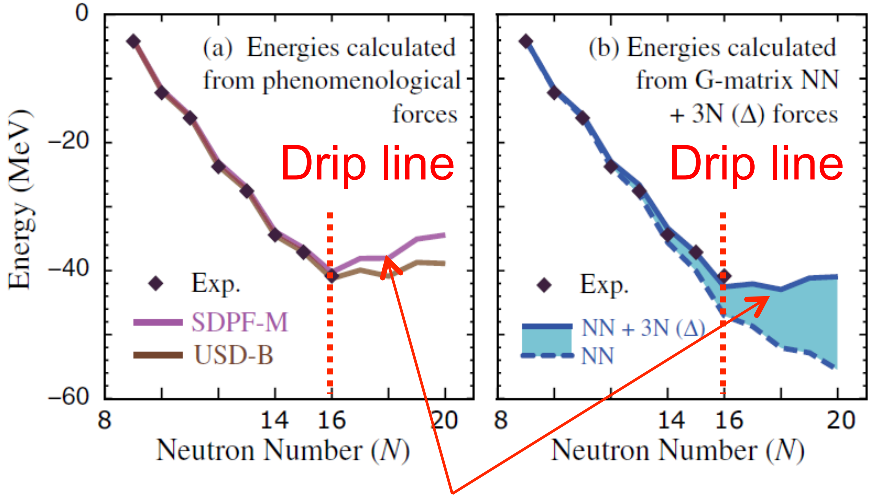
Spokesperson Yosuke Kondo

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



Oxygen Anomaly

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



- ^{25}O and ^{26}O measurement as a 1st step
- ^{26}O 2n radioactivity

($t_{1/2}$~4.5(3) ps? Kohley PRL 2013)

The effect is large at N>16

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

→Talk by Kondo on 28th!

Summary and Outlook

- 不安定核の研究：急速に進展
- さまざまな反応を駆使して、不安定核のミクロな構造の解明ができる　（アイディア次第で新たなプローブに）
- ^{31}Ne, ^{22}C　→Halo, Deformation, Dineutron : New Correlation 新物理への展開
- RIBFは世界の不安定核の拠点
- 不安定核：元素合成や、高密度天体の構造・生成メカニズムの解明に重要
- 核理論の最近の進展：めざましい。(Ab-Initio計算、大規模殻模型計算＠京）

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

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)

Collaborators

Tokyo Institute of Technology: **Y.Kondo, T.Nakamura**, N.Kobayashi, R.Tanaka, R.Minakata, S.Ogoshi, S.Nishi, D.Kanno, T.Nakashima

LPC CAEN: **N.A.Orr**, J.Gibelin, F.Delaunay, F.M.Marques, N.L.Achouri, S.Leblond

Tohoku University : T.Koabayshi, K.Takahashi, K.Muto

RIKEN: K.Yoneda, T.Motobayashi ,H.Otsu, T.Isobe, H.Baba,H.Sato, Y.Shimizu, J.Lee, P.Doornenbal, S.Takeuchi, N.Inabe, N.Fukuda, D.Kameda, H.Suzuki, H.Takeda, T.Kubo

Seoul National University: Y.Satou, S.Kim, J.W.Hwang

Kyoto University : T.Murakami, N.Nakatsuka

GSI : Y.Togano

Univ. of York: A.G.Tuff

GANIL: A.Navin

Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

Universit´e Paris-Sud, IN2P3-CNRS: M.Vandebrouck