Exploration of extremes of nuclei at SAMURAI at RIBF

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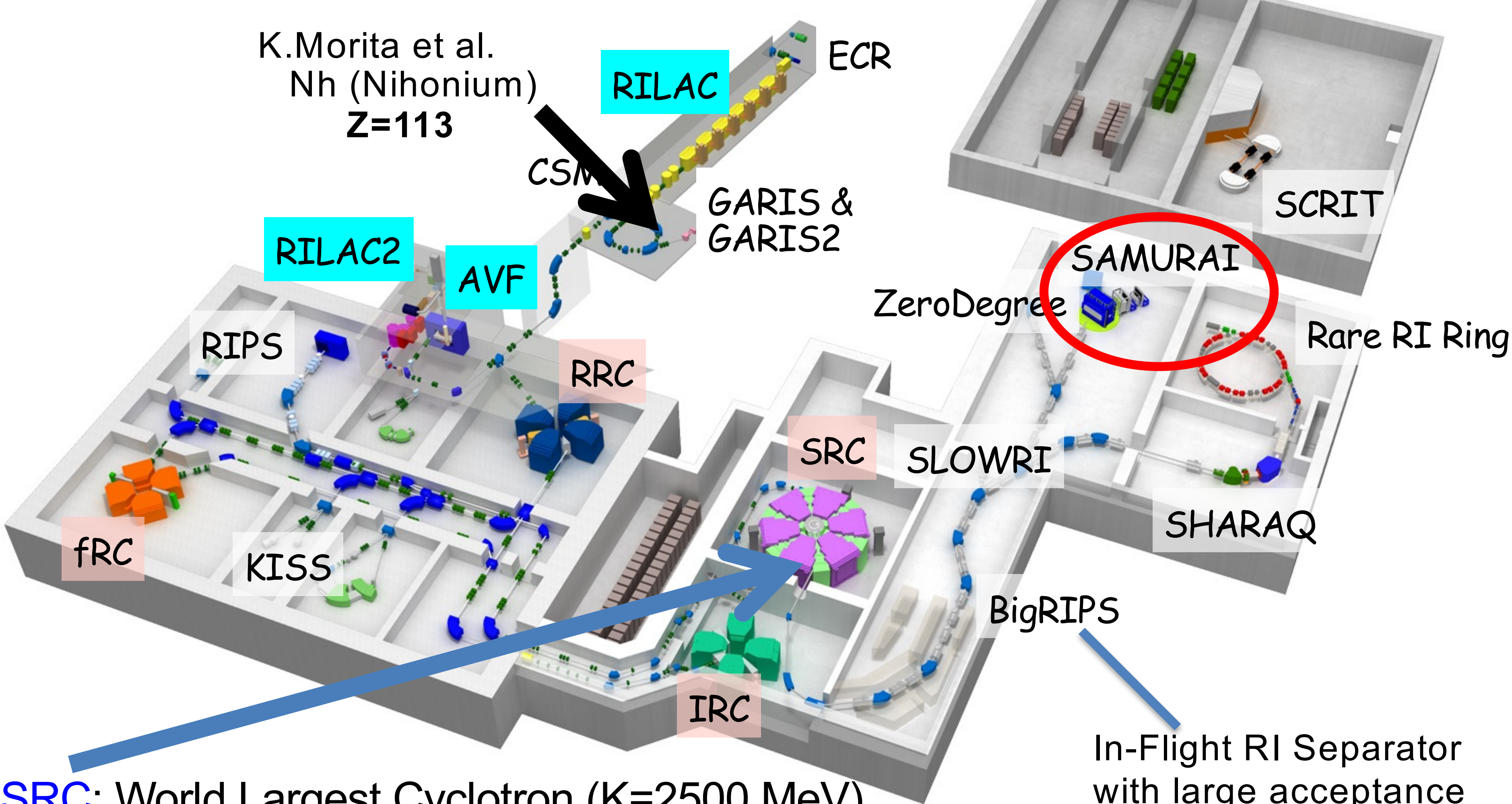
Contents

RI Beam Factory at RIKEN 2007~

The New-generation RI-beam facility in the world



SRC: World Largest Cyclotron (K=2500 MeV)
Heavy Ion Beams up to ^{238}U at 345MeV/u

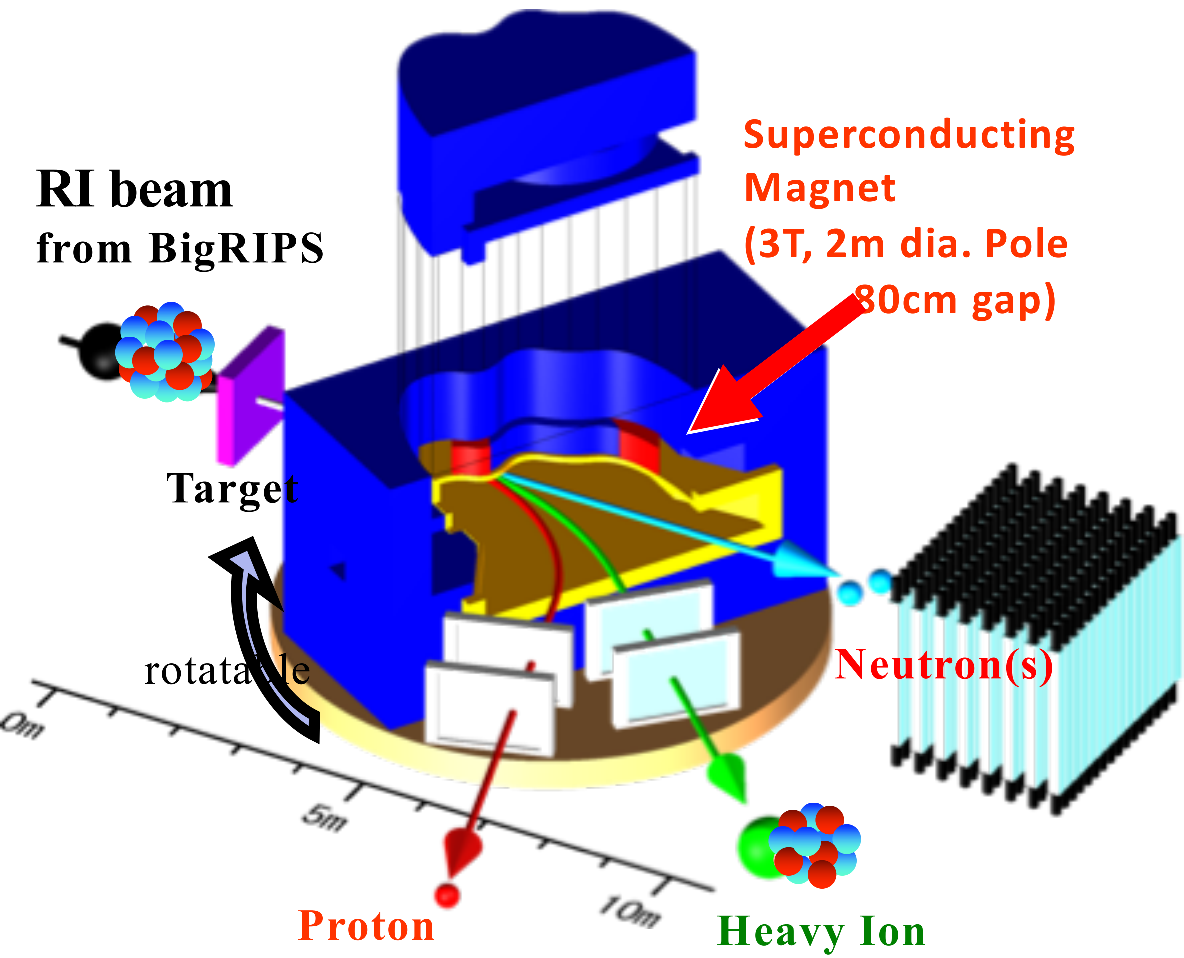
eg. ^{48}Ca: ~700pnA (~4x10^{12}pps) *~10 times compared to 2008*

^{238}U: ~30pnA (~2x10^{11} pps) *~10^{3} times compared to 2007*

SAMURAI at RIBF/RIKEN

Superconducting Analyzer for MUlti-particle from RAdio Isotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence



Large momentum acceptance

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

Good Momentum Resolution

$\Delta p/p \sim 1/1000$

→ $A/\Delta A > 100$ (>5σ)

Large Bending Angle (~60deg)

+4 Tracking Detectors

T.Kobayashi NIMB **317**, 294 (2013)

Large angular acceptance for *n*

+-8.8 deg (H) x +-4.4 deg(V)

(~50% coverage < E_{rel} ~ 5MeV)

TN, Y.Kondo, NIMB **376**, 156 (2016).

Moderate Erel Resolution

ΔE = 200 keV (σ) at E_{rel}=1MeV

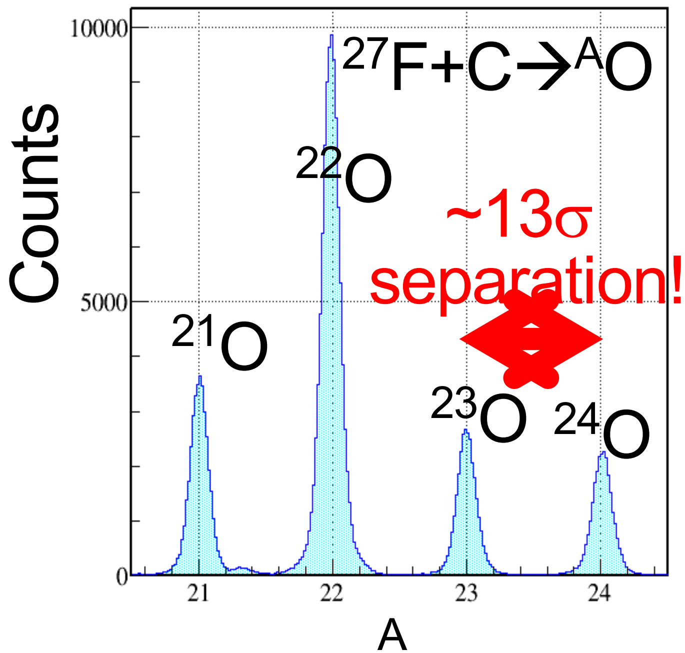
Stage: Rotatable (-5 -- 95 degrees)

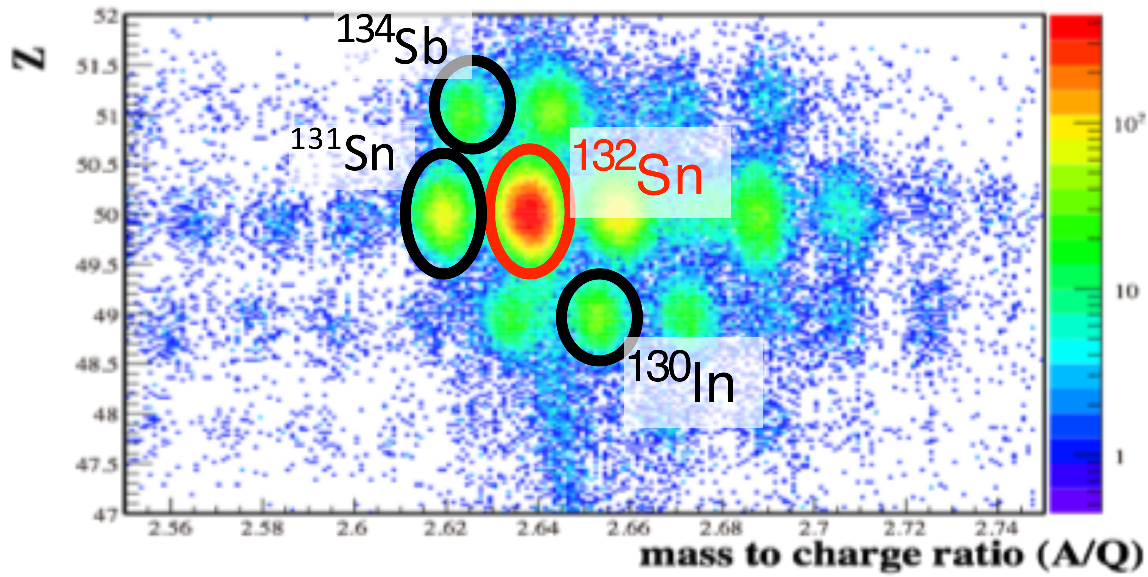
→ Variety of Physics Opportunities

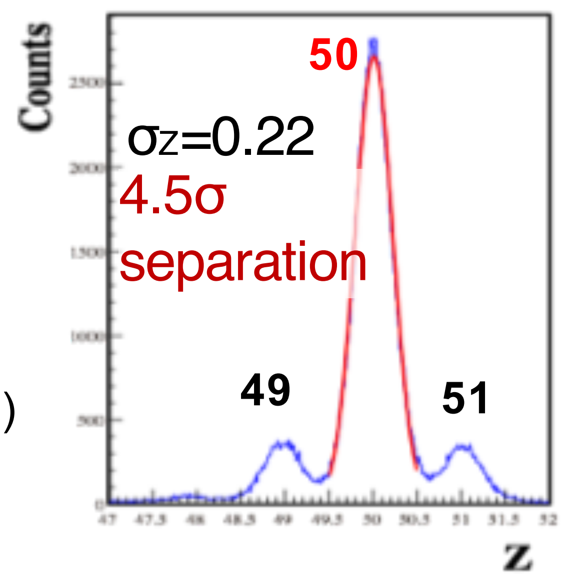
SAMURAI Since 2012

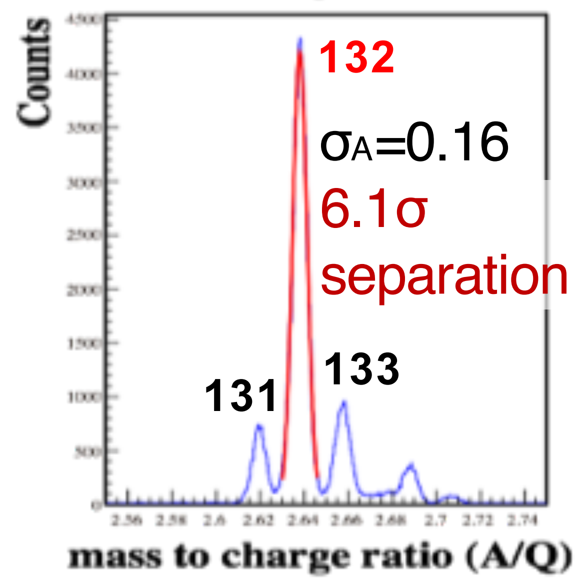
Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

PID at SAMURAI : Mass Resolution









Clear Particle identification

→ High resolving power

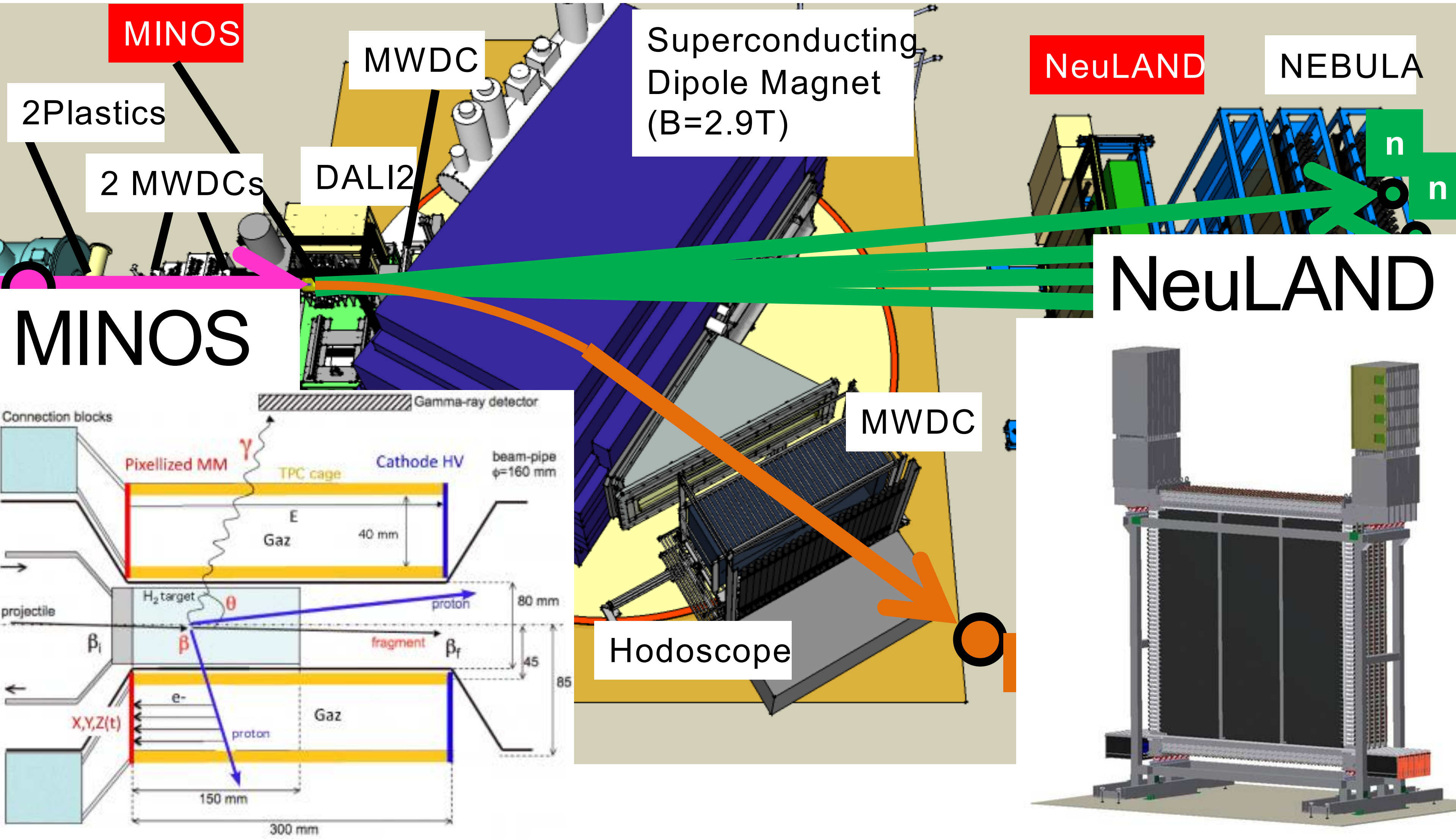
^{24}O: $A/\Delta A$ = 130(FWHM), 62(5σ)

^{132}Sn: $A/\Delta A$ = 340(FWHM), 160(5σ)

$Z/\Delta Z$ = 96(FWHM), 45(5σ)

Great Contributions
from R3B (2015-17, NEULAND)
and CEA Saclay (2014-2017, MINOS)

Slide by Y.Kondo



Experiments with NEULAND (2015-17)

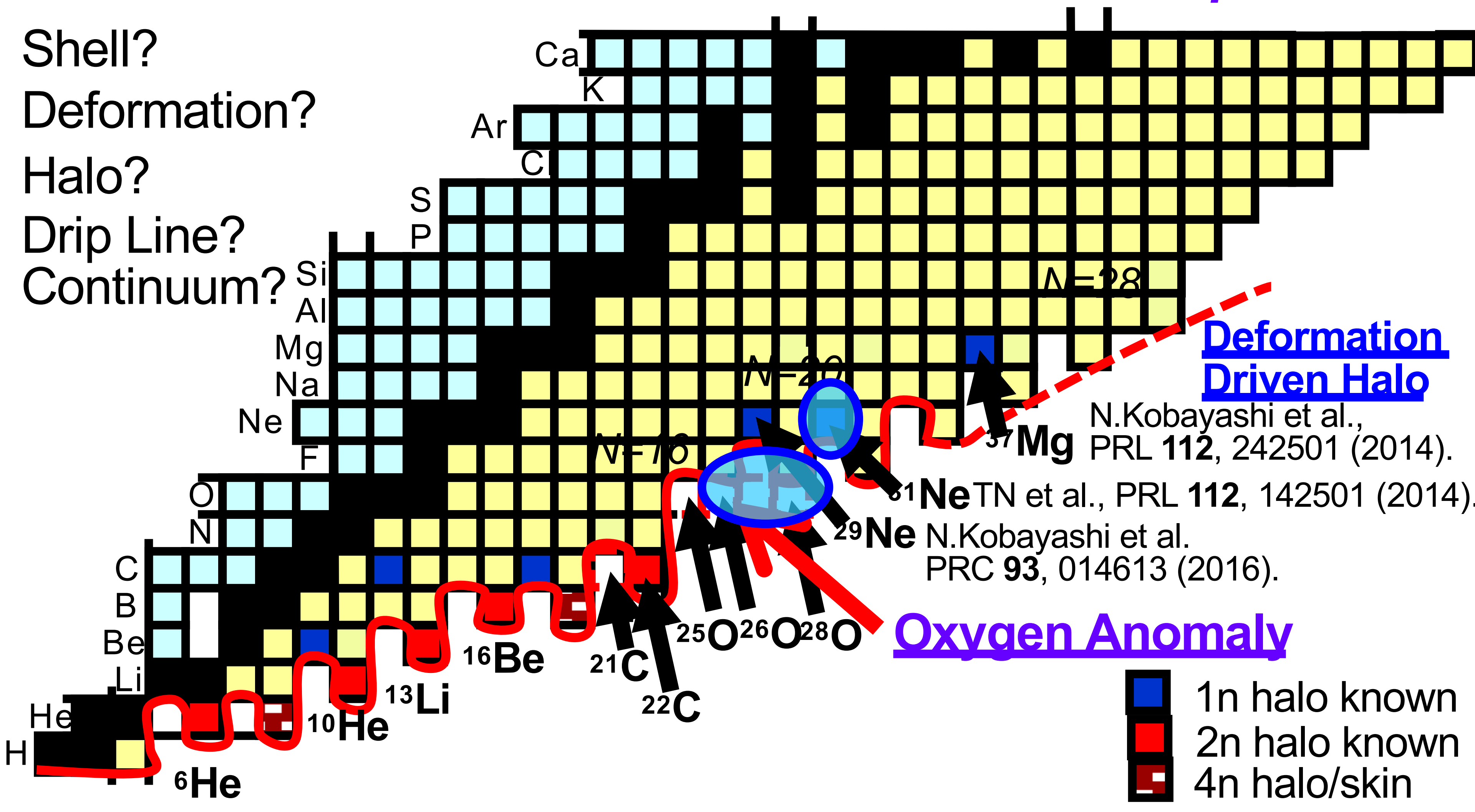
(Partial) List of the experiments using NEULAND+SAMURAI:

- ✓ Spectroscopy of unbound oxygen isotopes II (Y.Kondo) ^{27,28}O
- ✓ Study of density dependence of the symmetry energy with the measurements of charged pion ratio in heavy RI collisions (W.G. Lynch, T. Murakami, T. Isobe, B. Tsang)
- ✓ Search for ^{22}C (2^+), ^{21}B, ^{23}C and ^{25}N: Structure at and beyond the N=16 sub-shell closure (N.A. Orr)
- ✓ Spectroscopy of Odd-A Nuclei in the Island of Inversion (N.Kobayashi) ^{31}Ne etc.
- ✓ Measurement of the neutron-decay lifetime of the ^{26}O ground state at the SAMURAI setup at RIBF (C. Caesar)
- ✓ Electric dipole response of neutron-rich Ca isotopes (T. Kobayashi, Y.Togano)
- ✓ SEASTAR: 3rd Campaign (including "Spectroscopy of neutron-rich Ca isotopes" by J. Lee) (A.Obertelli, P.Dorrnenbal)
- ✓ Many-neutron systems: search for superheavy ^{7}H and its tetraneutron decay (K.Kisamori, M.Miguel)
- ✓ Dipole response of the drip-line nuclei ^{8}He, ^{24}O, and ^{29}F Search for the genuine soft dipole mode (T.Aumann, T.Nakamura)
- ✓ Investigation of the 4n system at SAMURAI by measuring (p,pα) quasi-free scattering at large momentum transfer in complete kinematics(S. Paschalis, D. Rossi)

Evolution Towards the Stability Limit

Where is the neutron drip line?
What are characteristic features of drip-line nuclei?
How does nuclear structure evolve towards the drip line?

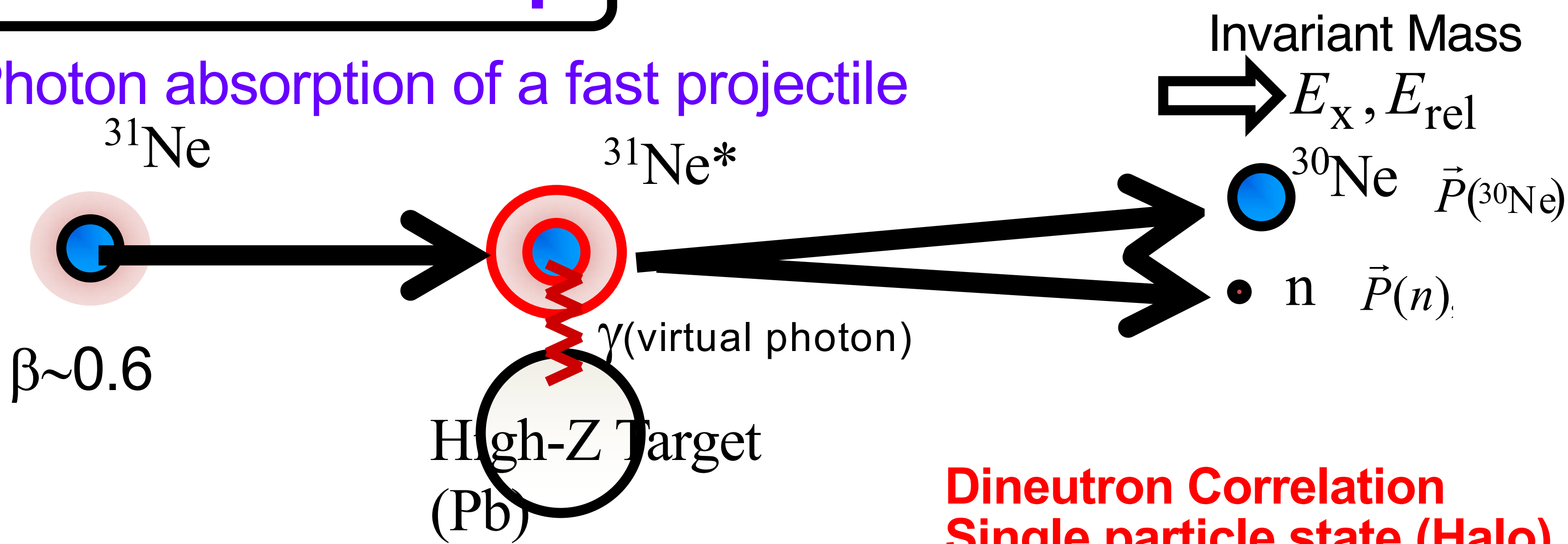
Shell?
Deformation?
Halo?
Drip Line?
Continuum?



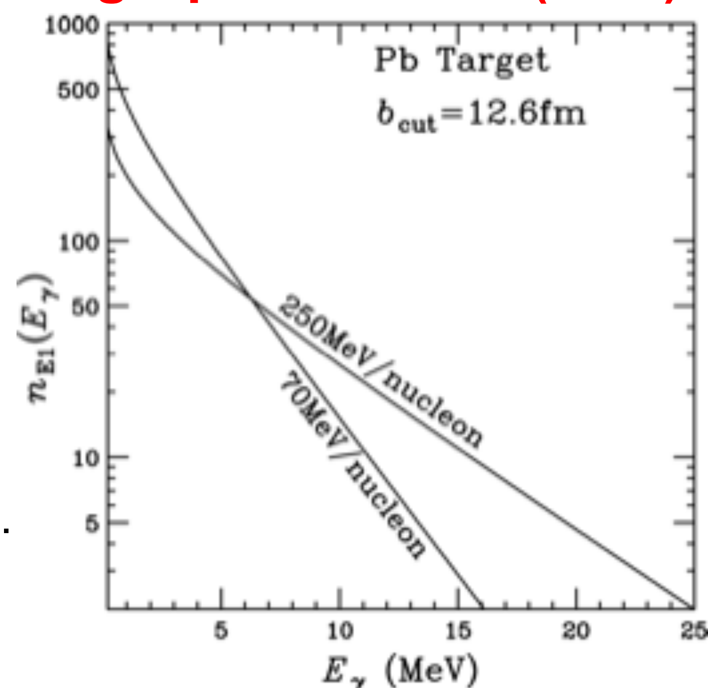
- Reaction Probes

Coulomb Breakup

→Photon absorption of a fast projectile



Dineutron Correlation
Single particle state (Halo)



Equivalent Photon Method

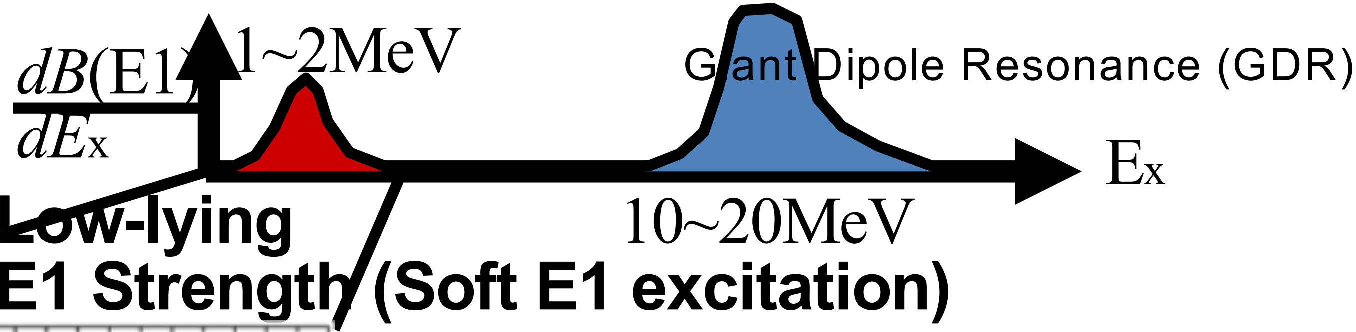
$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x)\frac{dB(E1)}{dE_x}$$

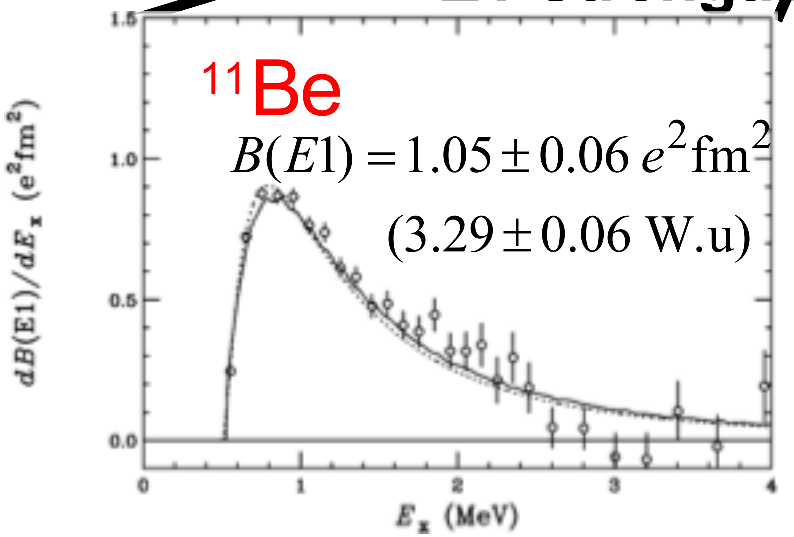
Cross section = (Photon Number)x(Transition Probability)

C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).

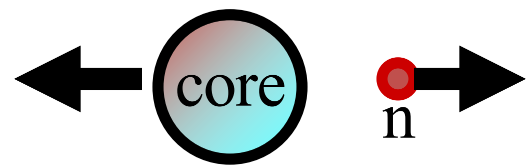
Halo → Soft E1 Excitation
(E1 Concentration at Ex<1MeV)

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





N.Fukuda *et al.*, PRC**70**, 054606 (2004).
T.Nakamura *et al.*,PLB **331**,296(1994).
Palit *et al.,* PRC**68**, 034318(2003).
T.Aumann, T.Nakamura, Phys. Scr. T152 (2013) 014012.



Direct Breakup Mechanism

E1 Strength

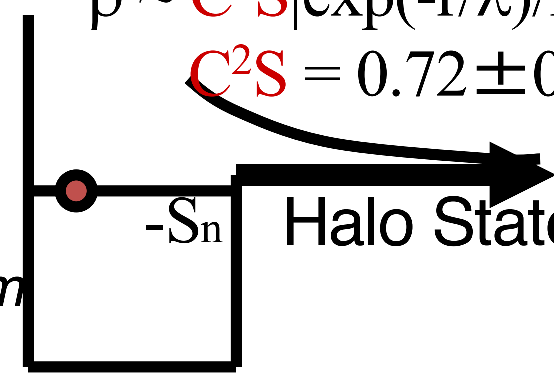
$$\frac{dB(E1)}{dE_x} \propto \left| \langle \exp(i\boldsymbol{qr}) | \frac{Z}{A} rY^1{}_m | \Phi_{gs} \rangle \right|^2$$

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

Fourier Transform

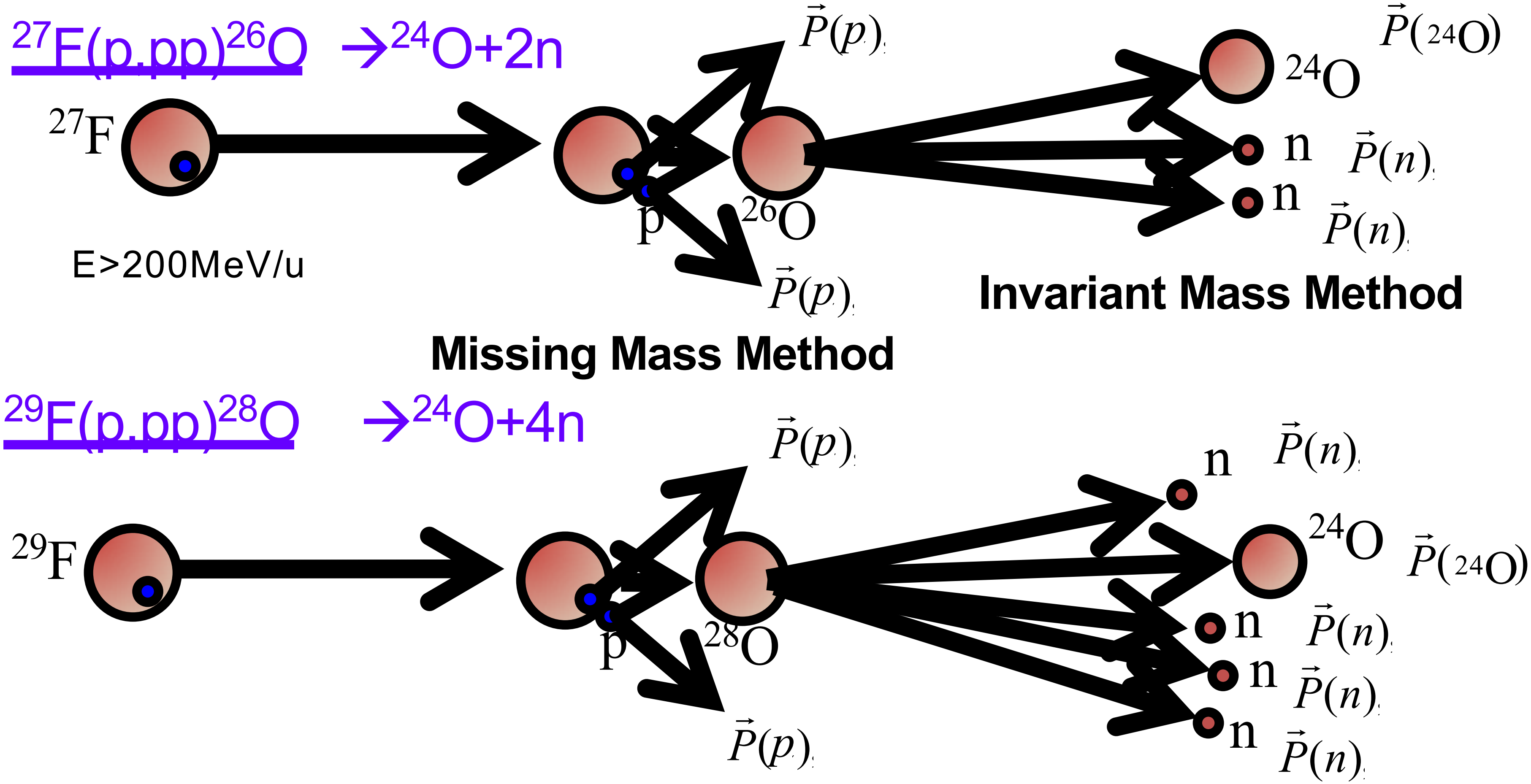
$\rho \sim C^2S|\exp(-r/\lambda)/r|^2$

$C^2S = 0.72 \pm 0.04$



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

Quasi-free Scattering -with neutron decay



Invariant Mass Method: + High Yield, + Good Resolution ~ a few 100 keV
- Require Measurement of All the Decay Particles

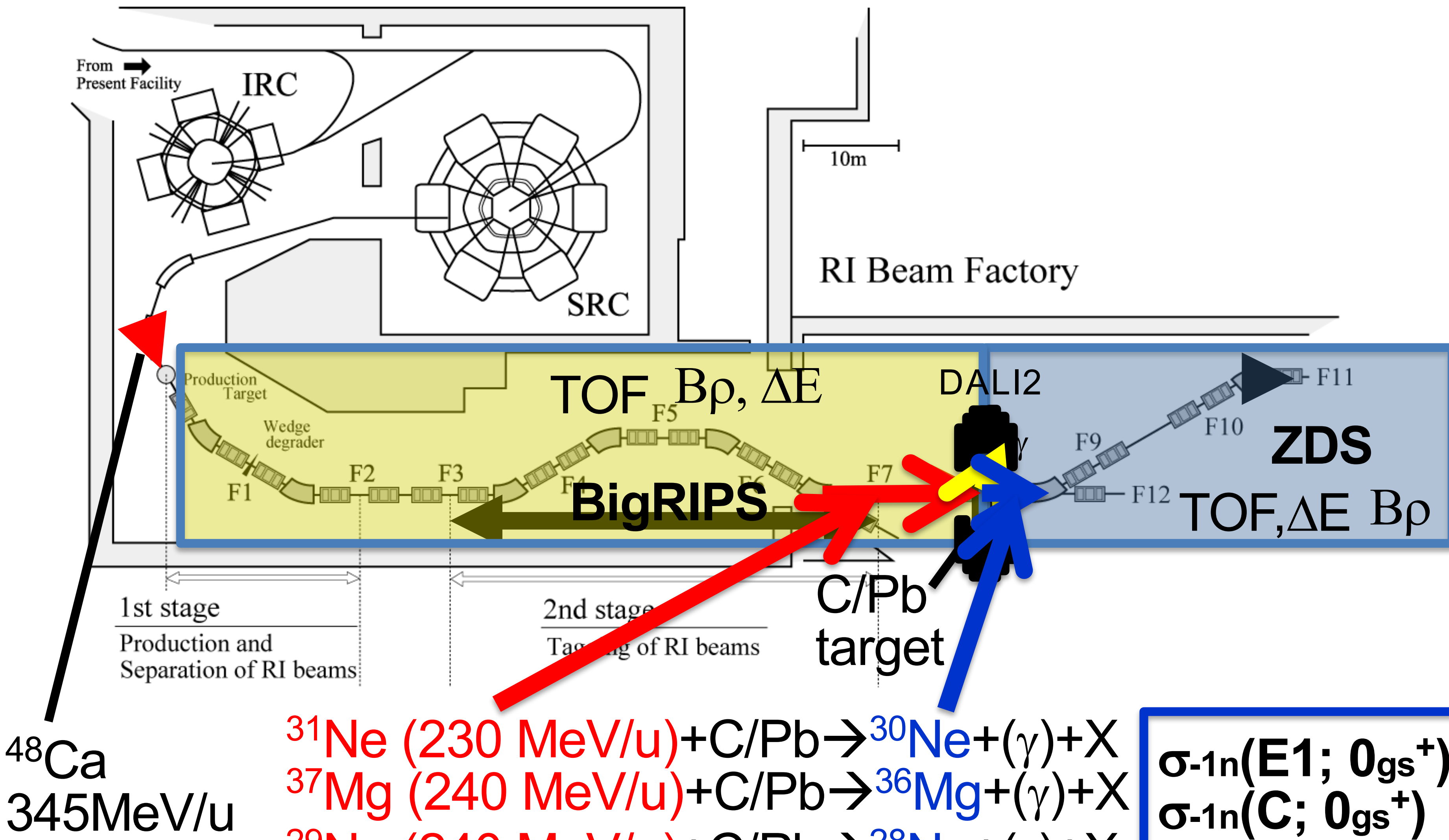
Missing Mass Method: - Low Yield, - Worse Resolution ~ a few MeV
+ Measurement of projectile and recoil protons only

Review: T.Nakamura, H.Sakurai, H.Watanabe, Prog. Part. Nucl. Phys. 97, 53 (2017).

Breakup of 1n Halo Nuclei
in Island of Inversion (^{29}Ne, ^{31}Ne, ^{37}Mg)

N. Kobayashi,
T. Tomai,
Y. Kondo,
TN et al.

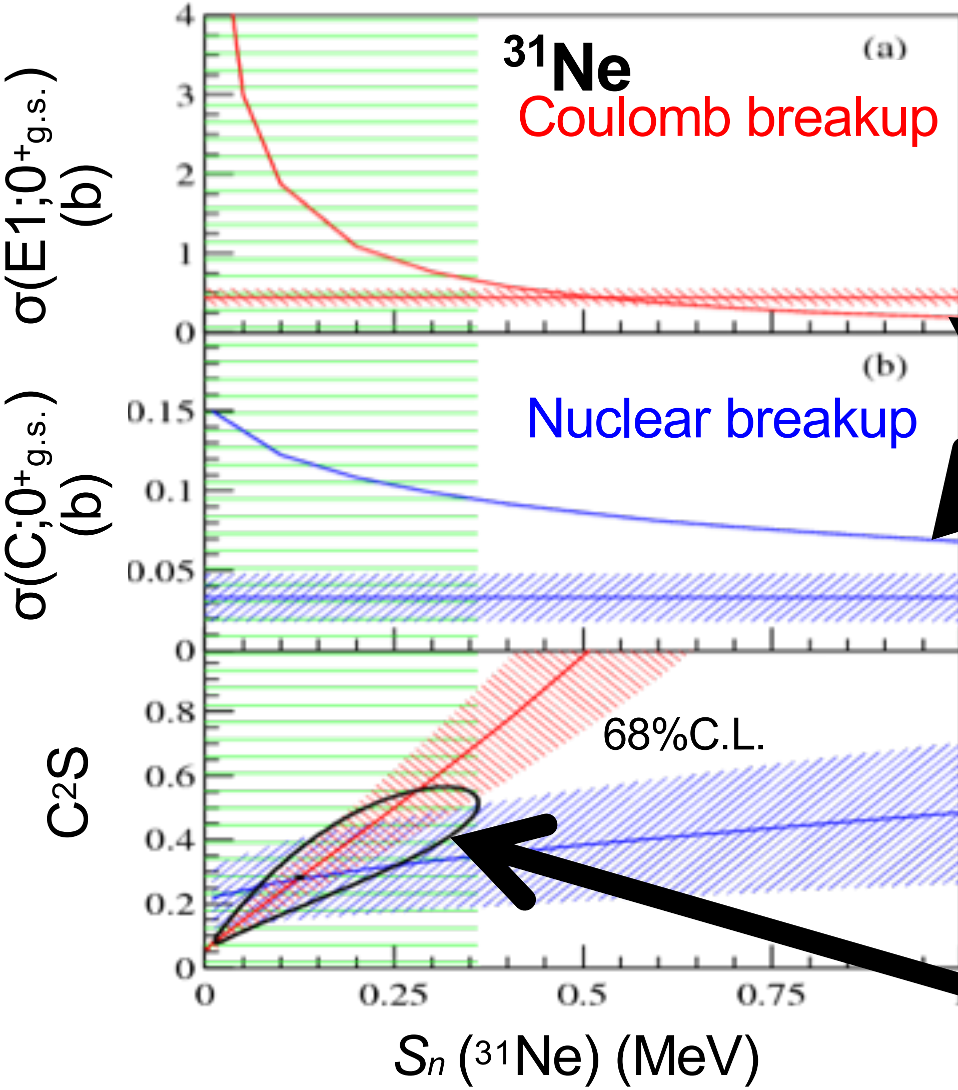
Inclusive nuclear/Coulomb Breakup at BigRIPS & ZDS at RIBF



^{31}Ne (230 MeV/u)+C/Pb→^{30}Ne+(γ)+X
^{37}Mg (240 MeV/u)+C/Pb→^{36}Mg+(γ)+X
^{29}Ne (240 MeV/u)+C/Pb→^{28}Ne+(γ)+X

σ-1n(E1; 0_{gs}^{+})
σ-1n(C; 0_{gs}^{+})

Deformation Driven p-wave Halo --- ^{31}Ne, ^{37}Mg, ^{29}Ne



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

|^{31}Ne$_{g.s.}$ 〉 : $3/2^-$
|^{30}Ne($0^+_{g.s.}$) ⊗ $p_{3/2}$〉 component

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

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

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

^{31}Ne: **3/2$^-$** **p**-wave
Deformed in spite of **N=21**

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

[321 3/2]
β~0.5

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

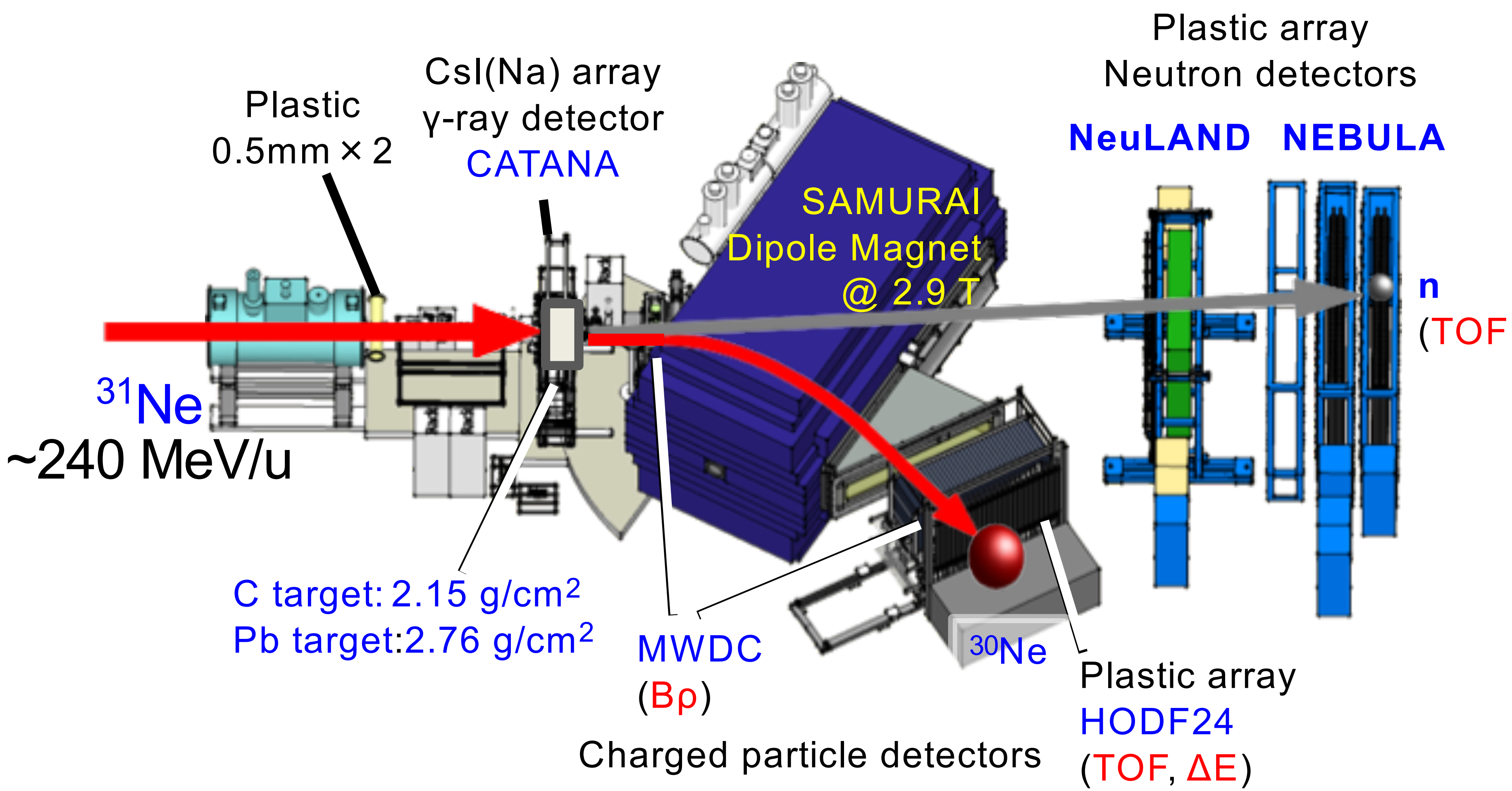
^{31}Ne: TN, N.Kobayashi et al., PRL **112**, 142501 (2014). $3/2^-$ S_n=150(16)keV
^{37}Mg: N.Kobayashi, TN et al., PRL **112**, 242501 (2014). $3/2^-/1/2^-$ S_n=220(12)keV
^{29}Ne: N.Kobayashi, TN et al., PRC **93**, 014613 (2016). $3/2^-$ S_n=960(140) keV

Inclusive at BigRIPS/ZDS
→ Exclusive at SAMURAI

SAMURAI Experiment

Full Exclusive Coulomb Breakup Measurement of **^{31}Ne T.Tomai et al.**

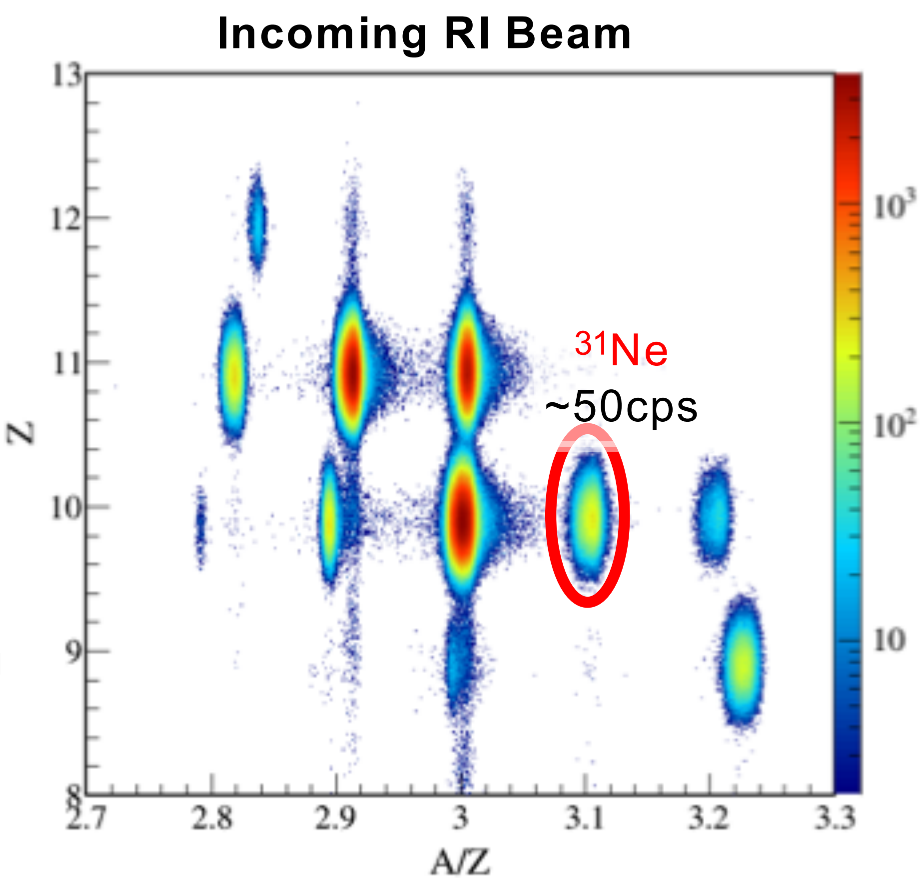
-Autumn,2015

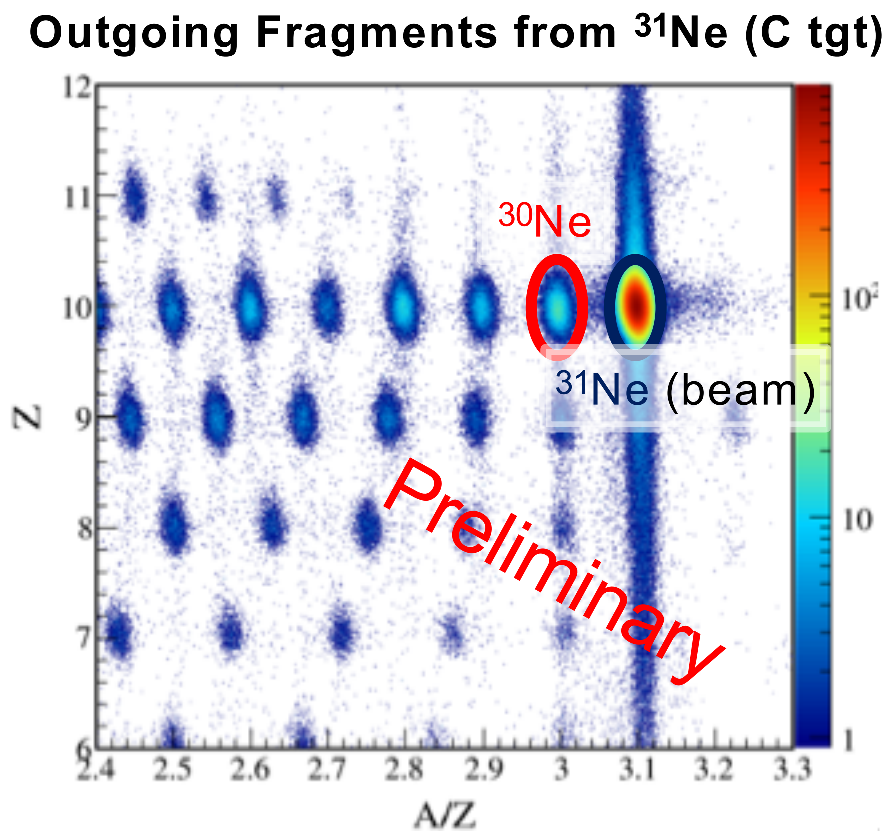


Slide by T.Tomai

PID Spectra

T.Tomai et al.





Intensity: 10 times higher
than previous RIBF experiment in 2008

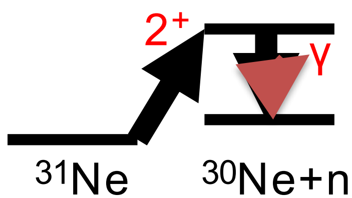
Slide by Tomai

γ-ray spectrum : Excited state component of Coulomb breakup reaction

Preliminary

- How is the excited state component of $^{30}Ne(2^+)$?

$^{31}Ne + Pb \rightarrow {}^{30}Ne + \gamma + n$



$^{30}Ne(2^+)$
792 keV

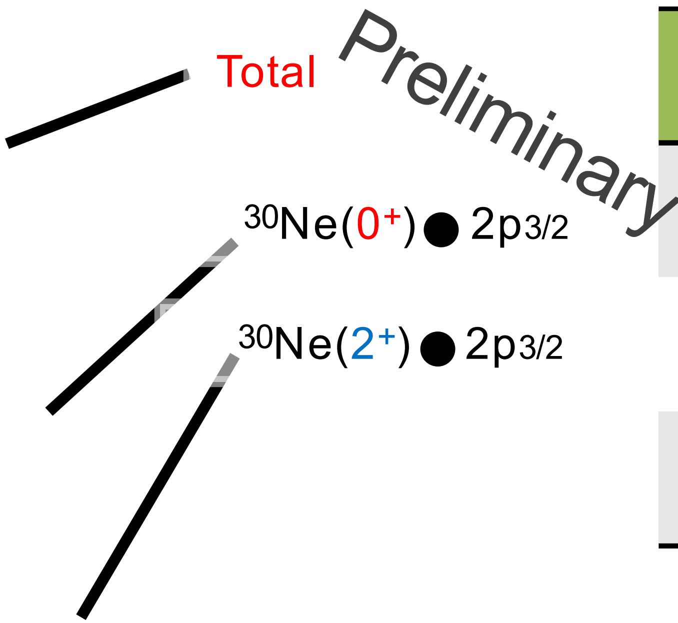
$$|^{31}\mathrm{Ne}(3/2^-)\rangle = \alpha\,|^{30}\mathrm{Ne}(0^+)\otimes 2p_{3/2}\rangle + \beta\,|^{30}\mathrm{Ne}(2^+)\otimes 2p_{3/2}\rangle + \dots$$

Pb target	Exclusive (mb) (require n) Integral Erel=0-5MeV
$^{31}Ne \rightarrow {}^{30}Ne$(total)	479(18)
$^{31}Ne \rightarrow {}^{30}Ne(2^+)$	136(24)
$^{31}Ne \rightarrow {}^{30}Ne(0^+)$	343(30)
Ratio(0^+ : 2^+)	72(6)% : 28(5)%

Slide: T.Tomai

Coulomb breakup of ^{31}Ne: **Energy Spectrum**

Tomai et al.



	S_n (MeV)	C^2S ^{30}Ne(0^+);$3/2^-$	C^2S ^{30}Ne(2^+);$3/2^-$
This work	0.30(1)	0.32(1)	0.41(2)
	(preliminary, statistical error only)		
Prev. work*	$0.15^{+0.16}_{-0.10}$	$0.32^{+0.21}_{-0.17}$	---
SDPF-M		0.21	0.34

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

Consistent with previous work

- Fitted with 2 components

$$\alpha|^{30}\mathrm{Ne}(0^+)\otimes 2p_{3/2}> + \beta|^{30}\mathrm{Ne}(2^+)\otimes 2p_{3/2}>$$

72% Main Halo Component

28% Sub-Halo Component ← γ-ray data

→ **Doubly-component Halo?**

$|^{30}\mathrm{Ne}(0^+)\otimes 2p_{3/2}>$: $|^{30}\mathrm{Ne}(2^+)\otimes 2p_{3/2}>$

→Correspondence with Nilsson/Particle-Rotor Model →Deformation Parameter?

c.f. Y.Urata, K.Hagino, H.Sagawa, PRC83, 041303(R) (2011).

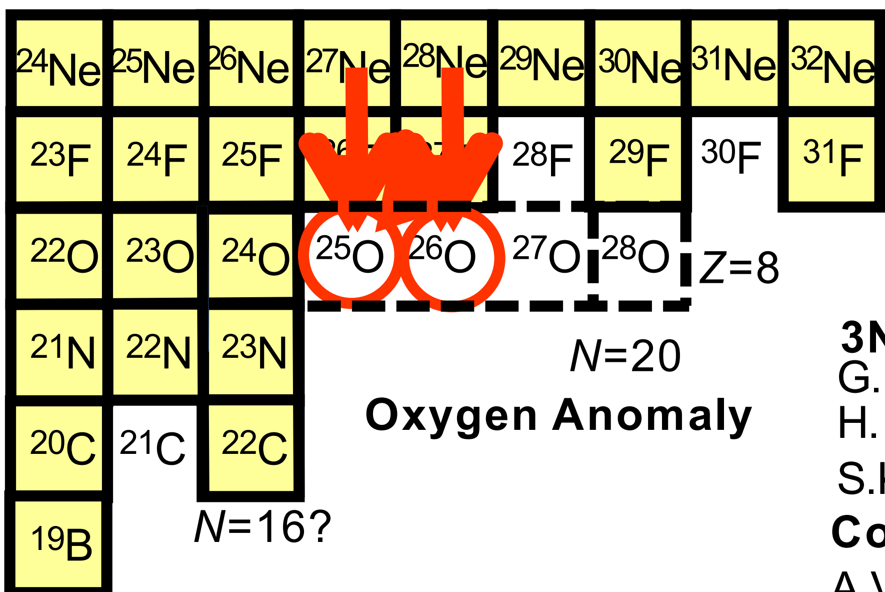
Spectroscopy of Barely Unbound $^{26,27,28}O$ (& Other studies on unbound oxygen isotopes)

Yosuke Kondo et al.

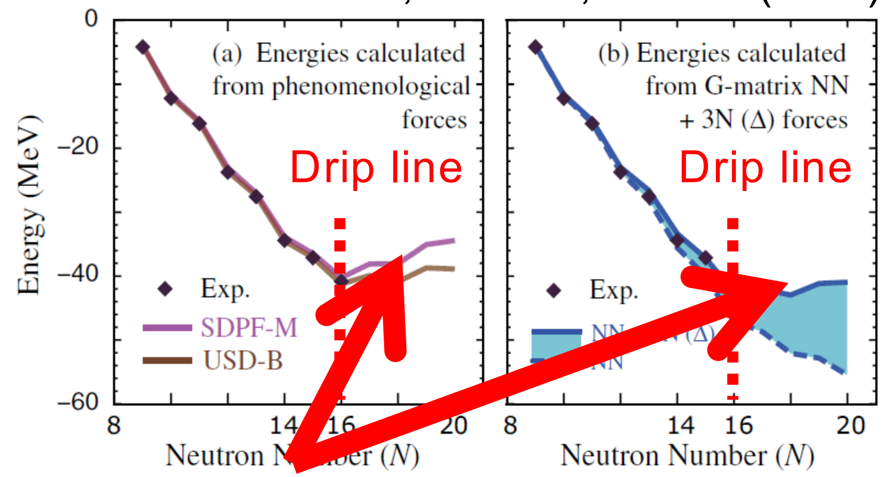
Study of unbound nuclei ^{25}O and ^{26}O at SAMURAI

Spokesperson Yosuke Kondo

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



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



3N force: significant at N>16

G. Hagen et al., PRL108, 242501(2012).

H. Hergert et al., PRL110, 242501(2013).

S.K.Bogner et al., PRL113, 142501(2014).

Continuum Effect:

A.Volya, V.Zelevinski, PRL94,052501(2005).

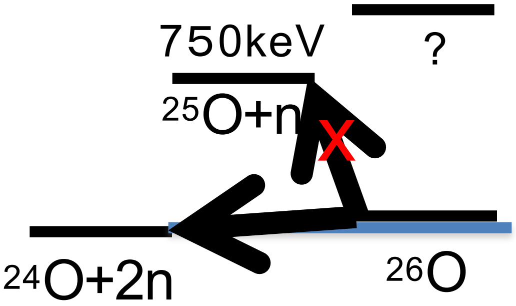
K. Tsukyiyama, T. Otsuka, PTEP2015, 093D01 (2015).

nn correlations:

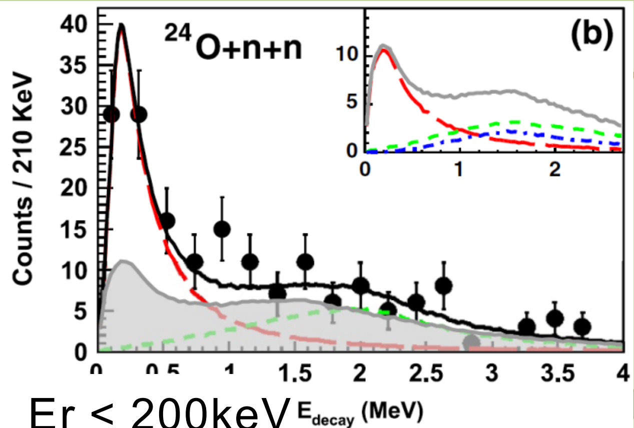
L.V. Grigorenko et al., PRL111,042501(2013).

K. Hagino, H. Sagawa PRC89,014331(2014).

2n radioactivity of ^{26}O?



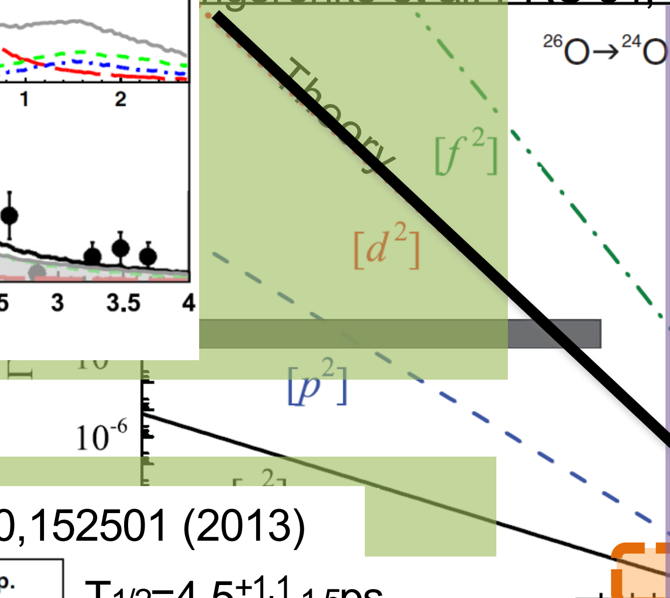
E. Lunderberg et al.
PRL108, 142503 (2012)



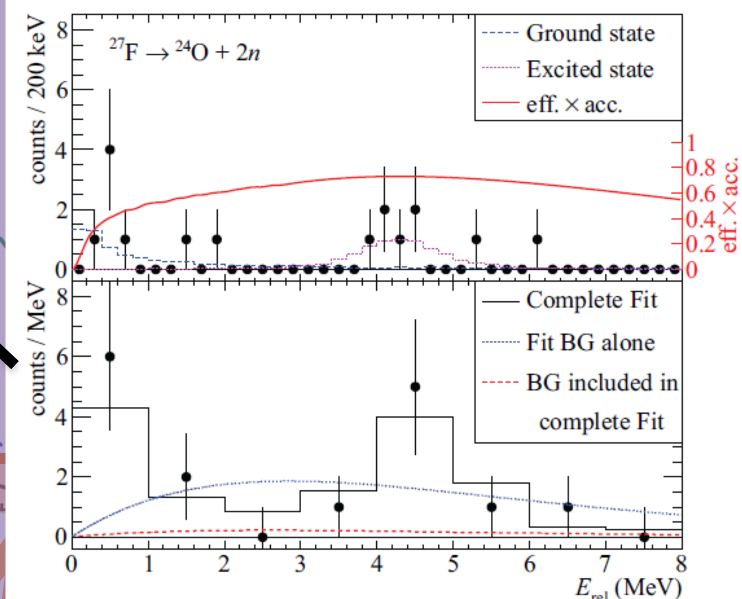
Er < 200keV

^{26}O: $^{24}O(0^+) \otimes (\nu d_{3/2})^2$

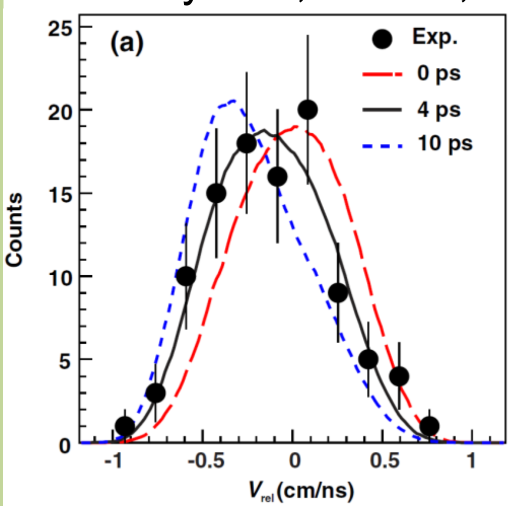
rigorenko et al. PRC 84, 021303 (2011)



C. Caesar et al.PRC88, 034313 (2013)



Z. Kohley et al,PRL110,152501 (2013)



$T_{1/2}=4.5^{+1.1}_{-1.5}$ps
(3ps systematic error)

→2n radioactivity?

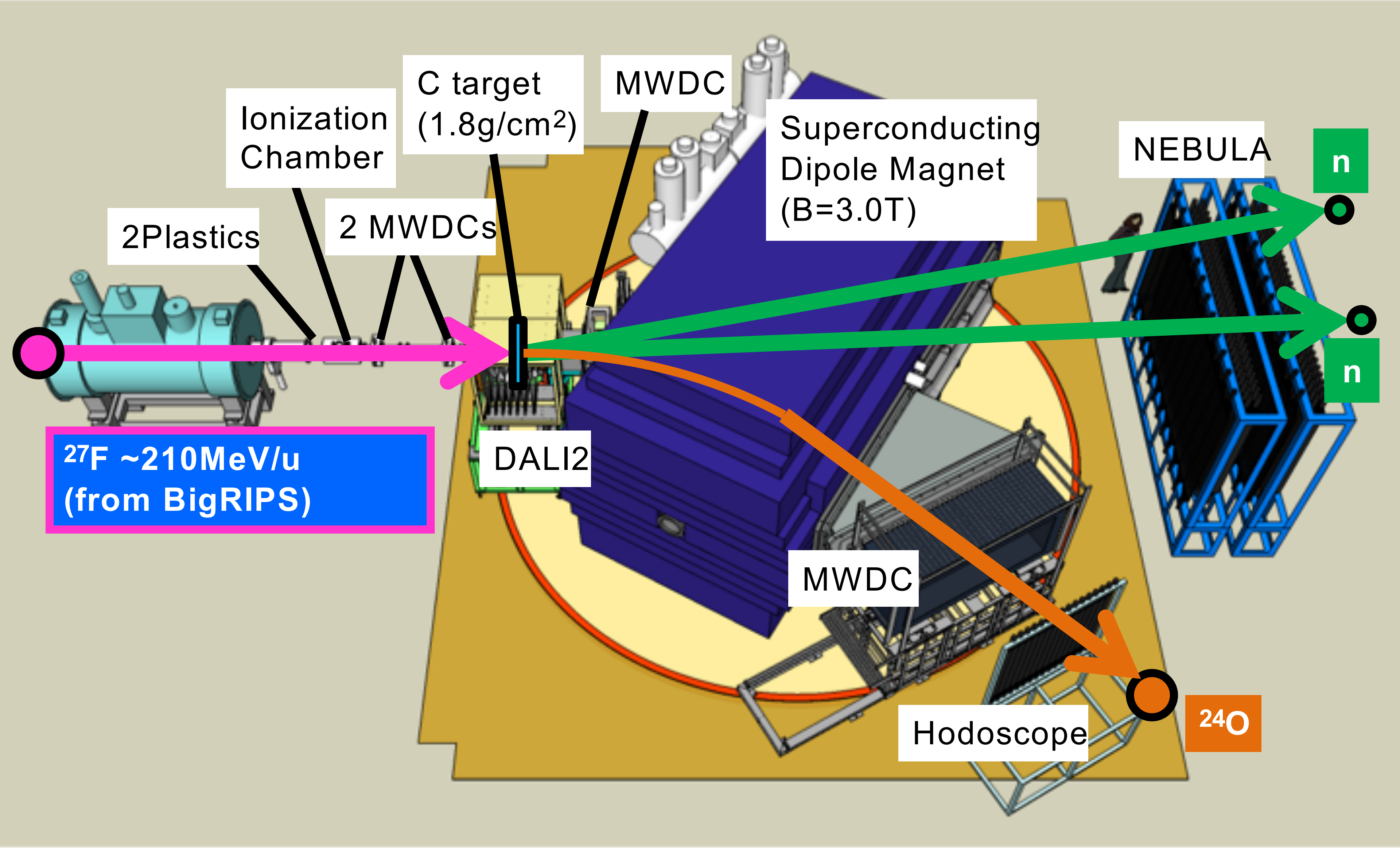
Usual 1n decay
Γ~MeV or keV

Er < 120keV (95% CL)
τ < 5.7ns

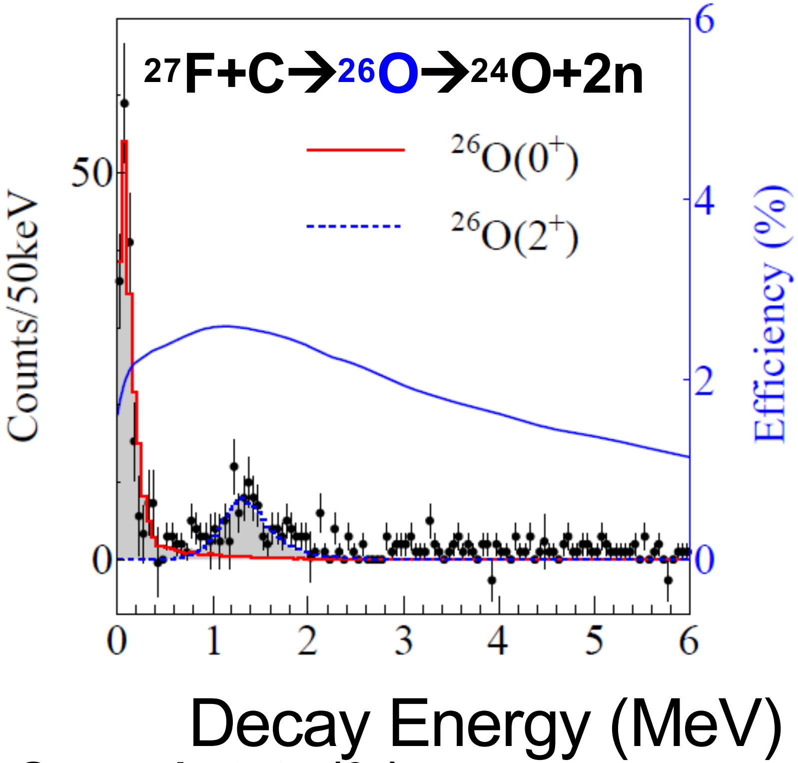
Excite state at 4.2MeV?

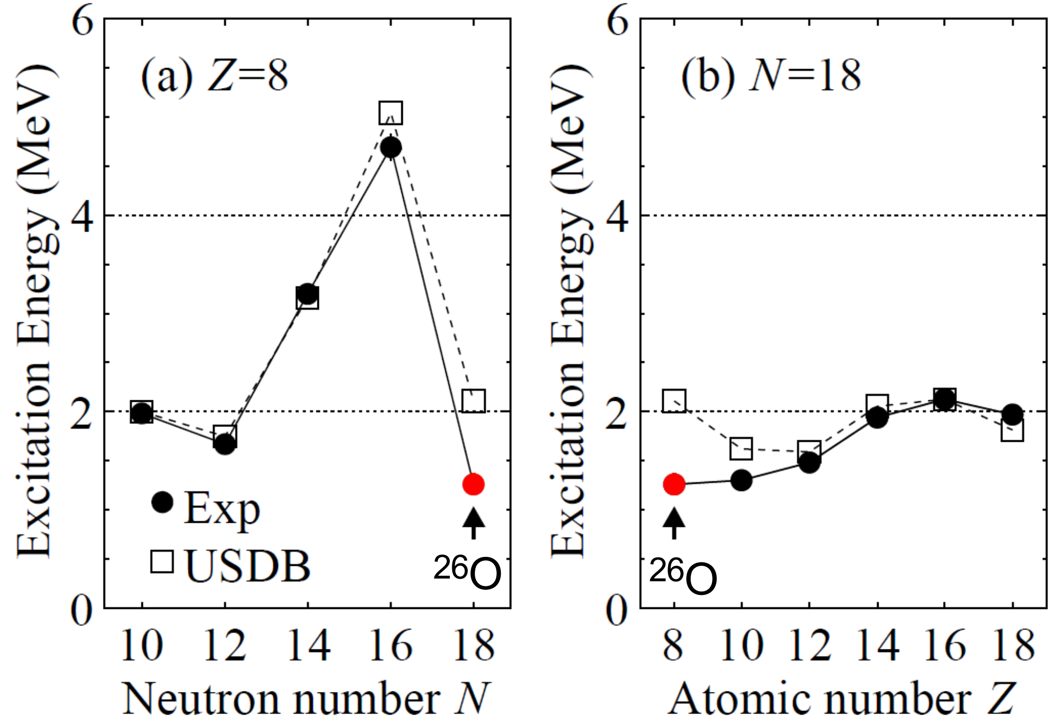
Large uncertainty of experimental study
- Only upper limit is given for the ground state energy
- Large systematic error in the lifetime measurement
- Excited State of ^{26}O?

Experimental Setup at SAMURAI at RIBF



Study of ^{26}O (SAMURAI02)





Ground state (0⁺)

5 times higher statistics than previous study

18±3(stat)±4(syst)keV

Finite value is determined for the first time

1st excited state (2⁺)

Observed for the first time

$1.28^{+0.11}_{-0.08}$MeV

N=16 shell closure is confirmed

USDB cannot describe 2⁺ energy at ^{26}O

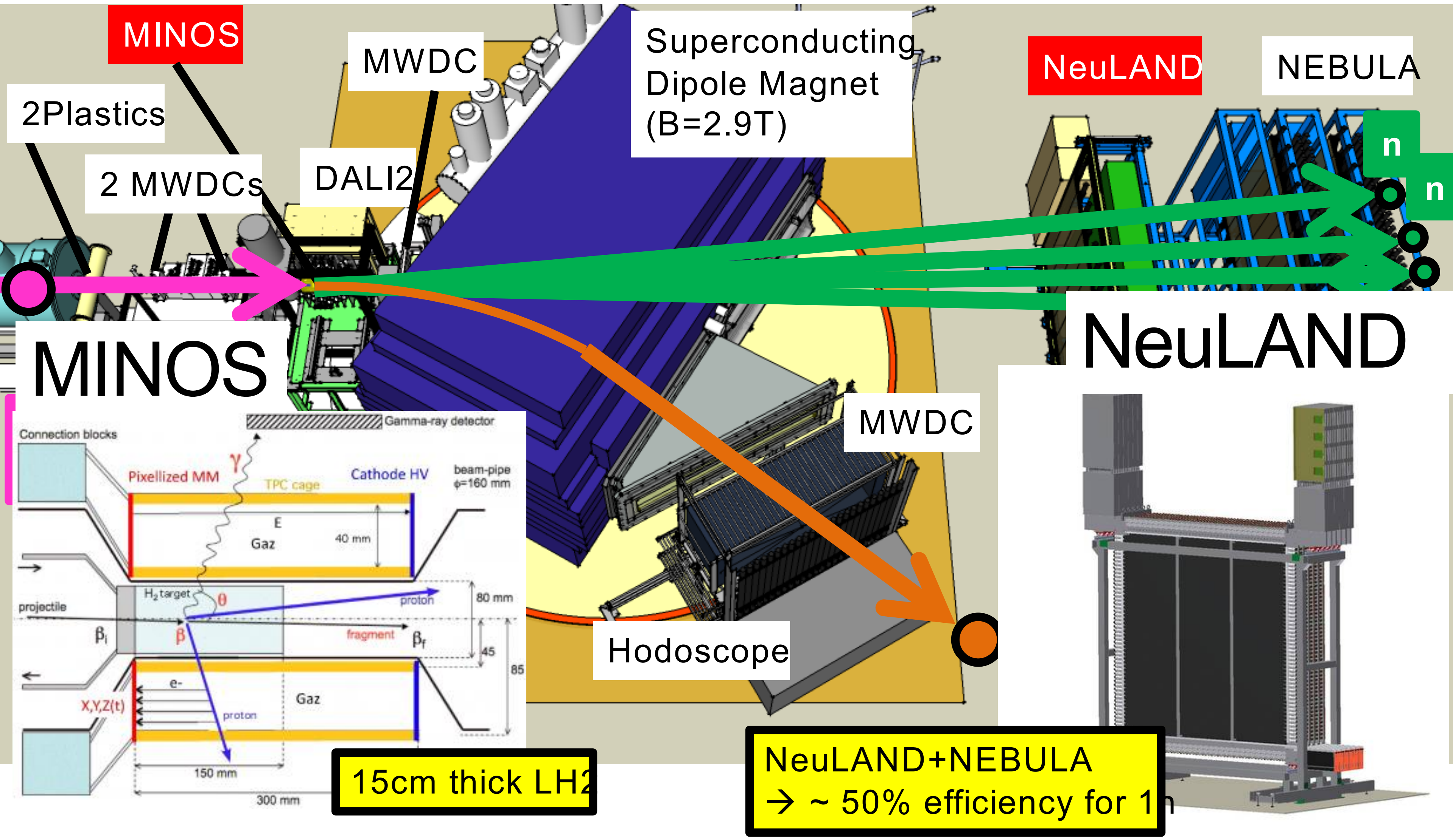
→effects of

pf shell?, **continuum**?

2n Correlations?, **3N force?**

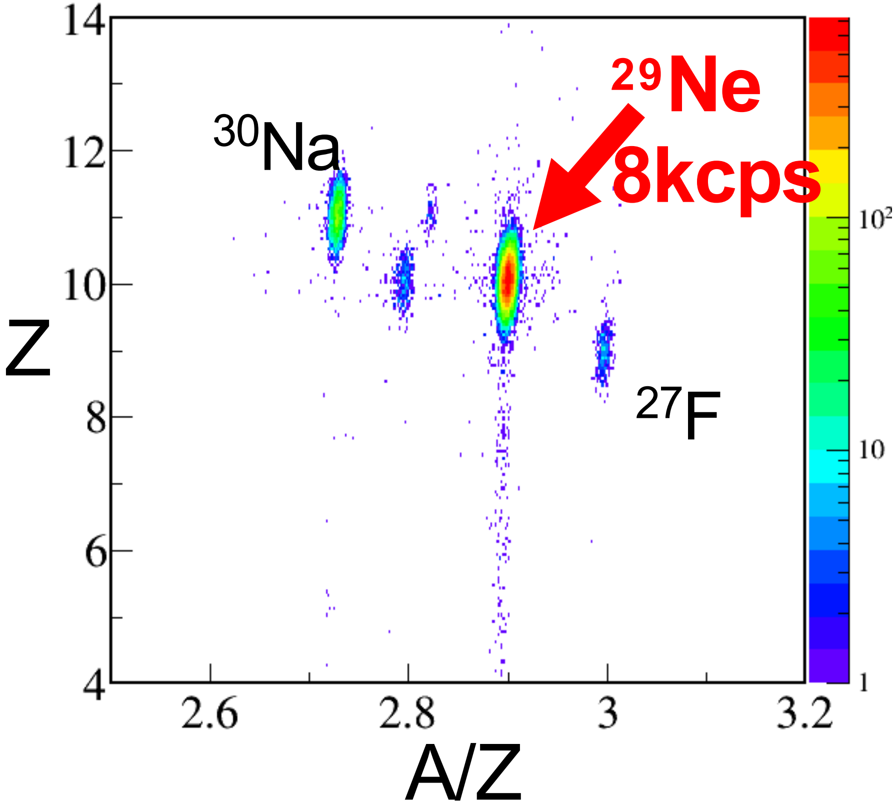
Y. Kondo et al., Phys. Rev. Lett. 116, 102503, (2016)

^{28}O measurement @ RIBF-SAMURAI

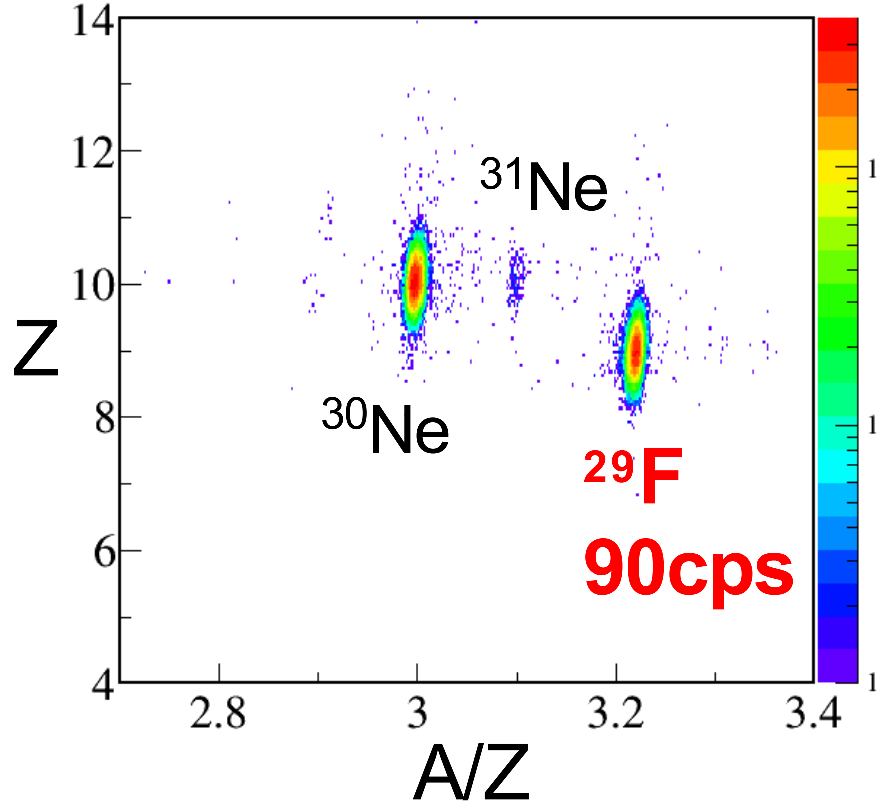


Secondary beam

^{29}Ne beam setting
(^{27}O measurement)

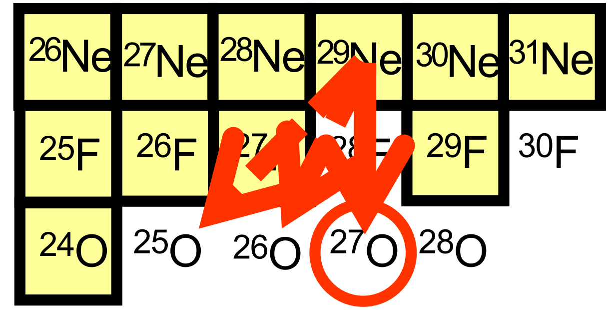


^{29}F beam setting
(^{28}O measurement)



Preliminary decay energy spectra

(subsystems, 1n/2n coincidence)



Includes

$^{27}O \rightarrow {}^{24}O + n (+2n)$

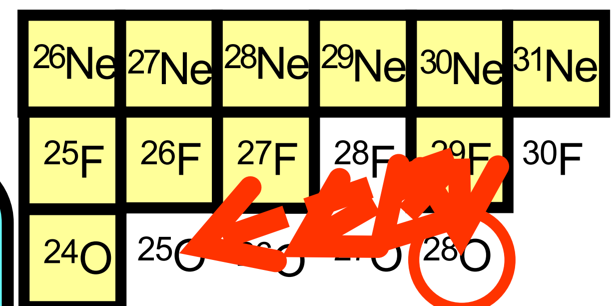
$^{26}O \rightarrow {}^{24}O + n (+n)$

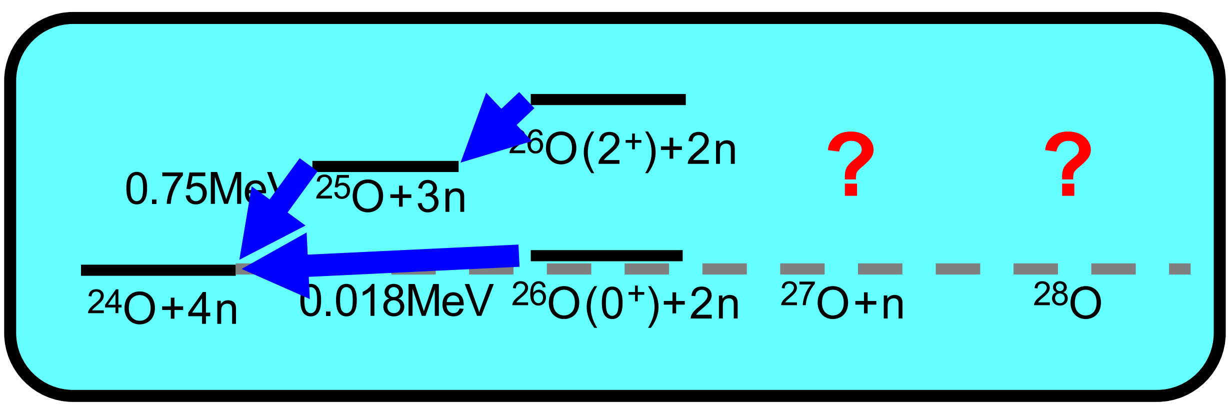
$^{25}O \rightarrow {}^{24}O + n$

Includes

$^{27}O \rightarrow {}^{24}O + 2n (+n)$

$^{26}O \rightarrow {}^{24}O + 2n$

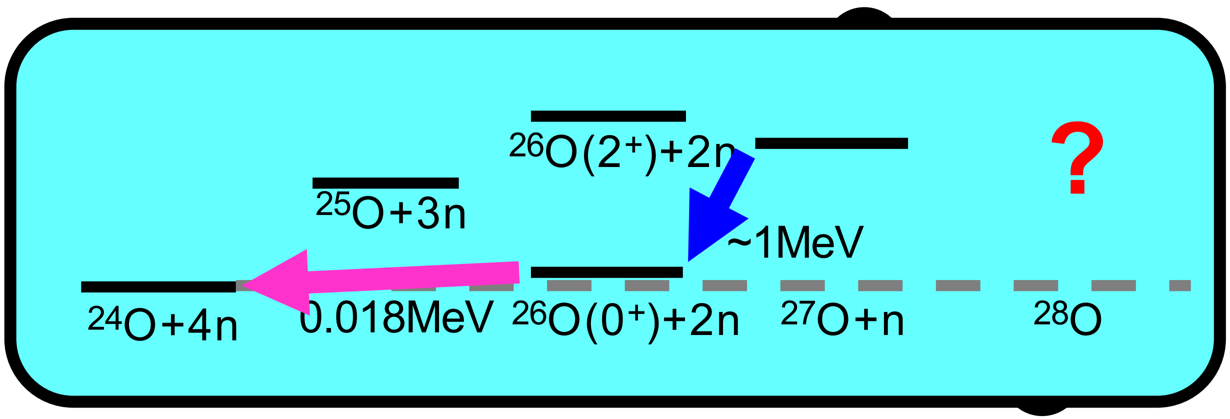




Slide by Y.Kondo

Analysis of 2n coincidence events

$^{29}Ne+^{1}H \rightarrow ^{24}O+2n+X$
(^{27}O measurement)



$^{29}F+^{1}H \rightarrow ^{24}O+2n+X$
(^{28}O measurement)

Will be checked from analysis of 3n/4n coincidence events

Slide by Y.Kondo

Summary and Outlook

- **SAMURAI at RIBF since 2012**
  - ✓ Large Acceptance, Multi-Purpose Spectrometer with Neutron/Heavy ion/proton detectors
  - ✓ **NeuLAND(2015-2017)** and MINOS(2014-2017)
    →Great Contributions to explore the extreme of nuclei
  - ✓ A Variety of Opportunities for RI-Beam Science
- **Probes for extremes: Breakup, Quasi-free Scattering**
- **Coulomb Breakup of Island-of-inversion nucleus: ^{31}Ne**
- **Spectroscopy of $^{26-28}$O: Exploration beyond the drip line**

^{26}O: *Y. Kondo et al., PRL 116, 102503, (2016) .*

Combination of the State-of-the-art-detectors
with Advanced Facilities
→Essential for Exploring the Extremes of Nuclei
Near Future:→ More Extremes are to be Explored !

Review: T.Nakamura, H.Sakurai, H.Watanabe, Prog. Part. Nucl. Phys. 97, 53 (2017).

Day-one Collaboration

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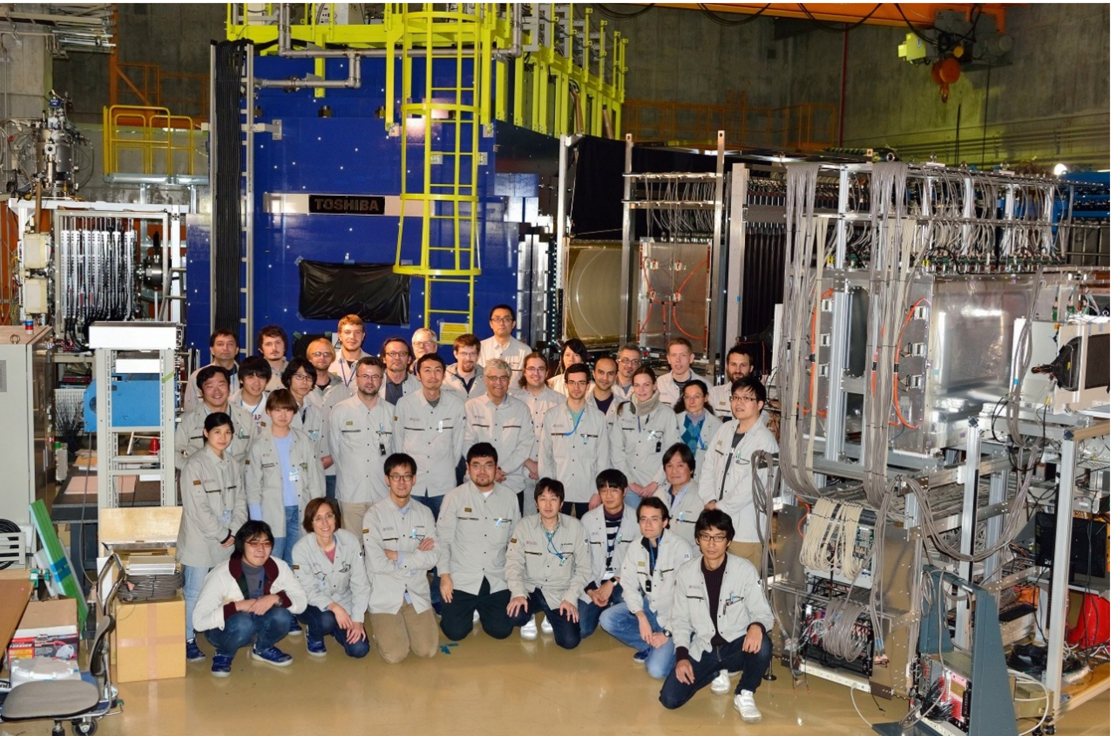
SAMURAI21 collaboration—^{27,28}O



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