Shell evolution near and beyond the neutron dripline

Takashi Nakamura

Department of Physics, Institute of Science Tokyo

(←Tokyo Institute of Technology)

Institute of SCIENCE TOKYO

SSNET'2024

Int. Conf. on Shapes and Symmetries in Nuclei:

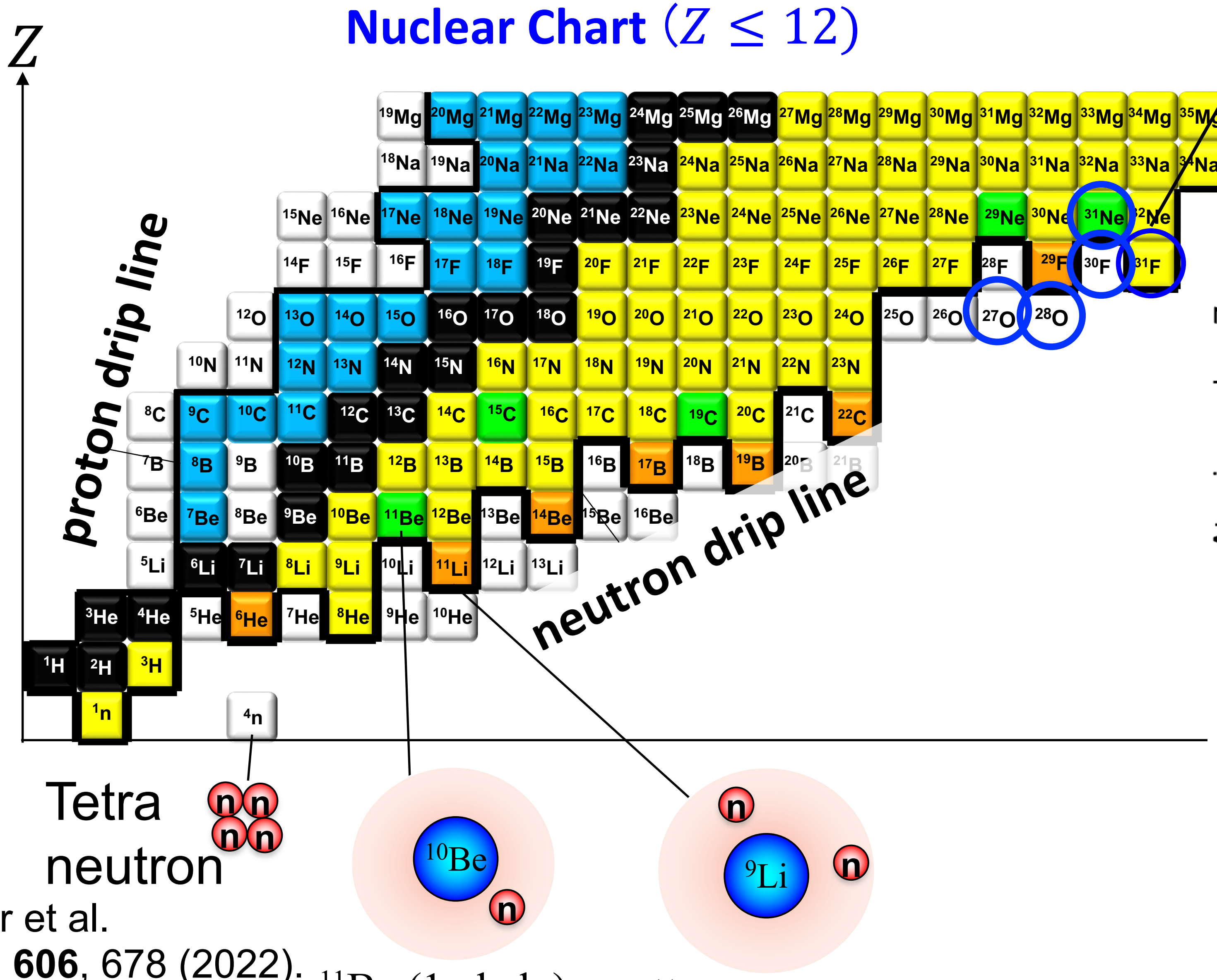
from Experiment to Theory, IJC Lab Orsay, 4-8 Nov 2024

Contents

Nuclear Landscape at the limit

Nuclear Chart $(Z \leq 12)$

Neutron Drip Line
Established up to **Z=10**
D.S. Ahn et al., PRL**123**, 212501 (2019).

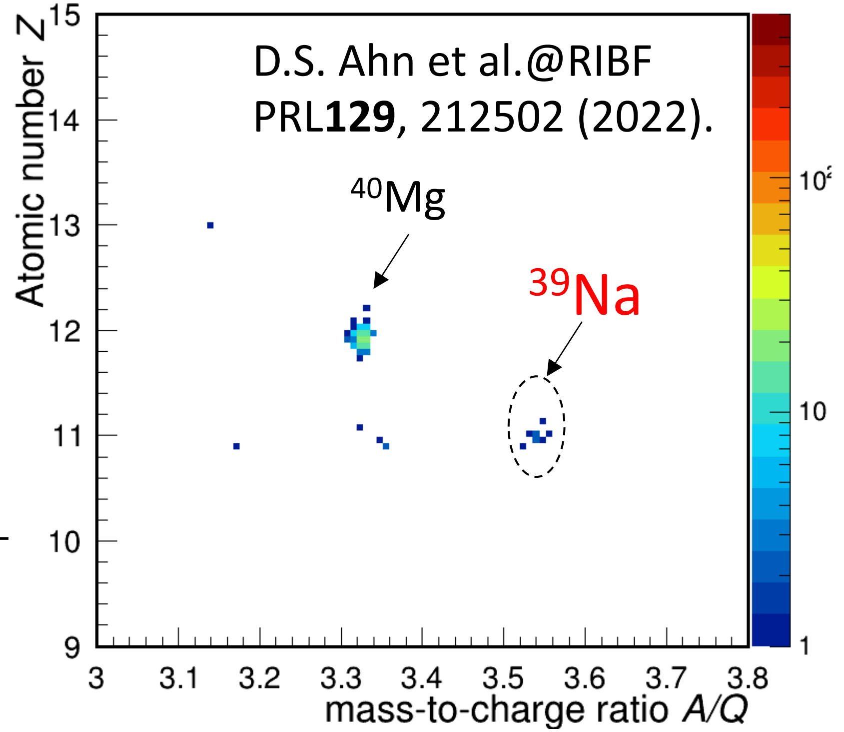


Tetra neutron

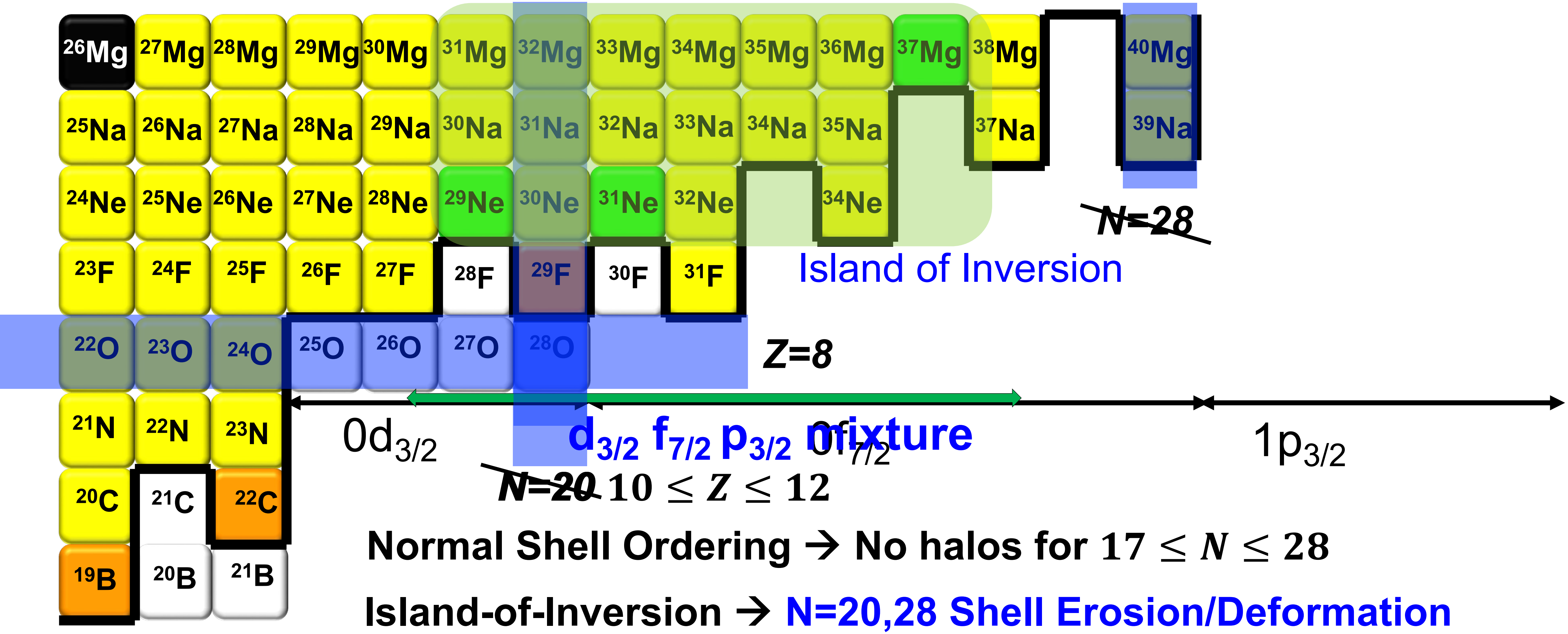
M.Duer et al.
Nature **606**, 678 (2022).
@SAMURAI-RIBF

^{11}Be (1n halo)

^{11}Li (2n halo, Borromean)



Shell Evolution At the Edge of Nuclear Landscape?



Normal Shell Ordering → No halos for $17 \le N \le 28$

Island-of-Inversion → N=20,28 Shell Erosion/Deformation

→p-wave halo in ^{29}F,^{29}Ne,^{31}Ne,^{37}Mg

Bagchi PRL2020, Kobayashi PRC2016,Nakamura PRL2009,PRL2014,Kobayashi PRL2014

→Is ^{28}O doubly magic?

Key Question on the neutron dripline nuclei

- What are the interplay between the Shell evolution, Shape evolution, and the Phenomena due to proximity to the Neutron Drip-line?

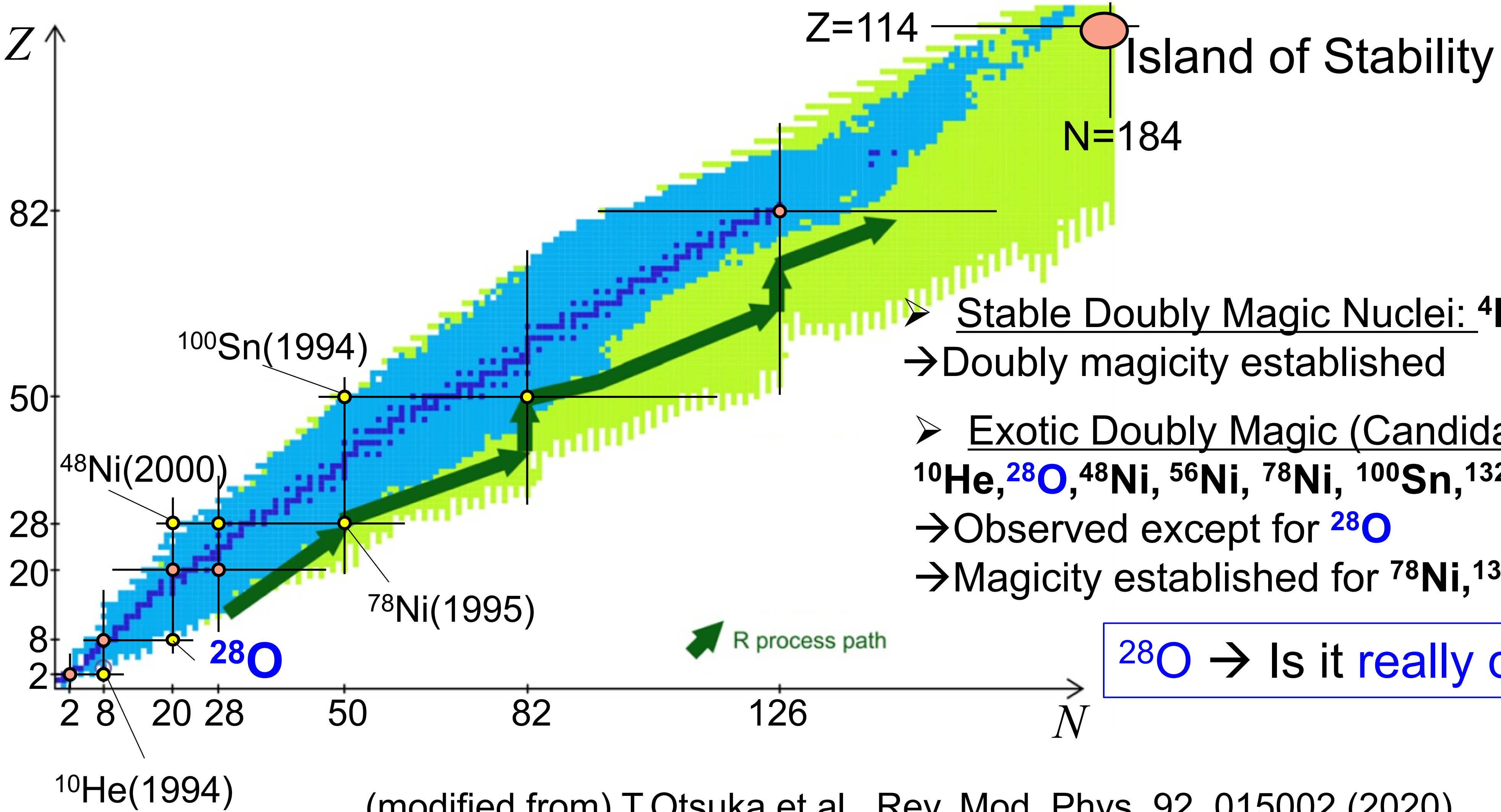
Weakly Bound : Halos
Weakly Unbound: Resonances

Observation of ^{28}O and ^{27}O

Y.Kondo et al., Nature **620**, 965-970 (2023).

Yosuke Kondo

Why ^{28}O? -- Doubly Magic Nuclei by Mayer-Jensens view



(modified from) T.Otsuka et al., Rev. Mod. Phys. 92, 015002 (2020).

- Stable Doubly Magic Nuclei: **^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca, ^{208}Pb**

→Doubly magicity established

- Exotic Doubly Magic (Candidate) Nuclei:

^{10}He, ^{28}O, ^{48}Ni, ^{56}Ni, ^{78}Ni, ^{100}Sn, ^{132}Sn

→Observed except for **^{28}O**

→Magicity established for **^{78}Ni, ^{132}Sn**

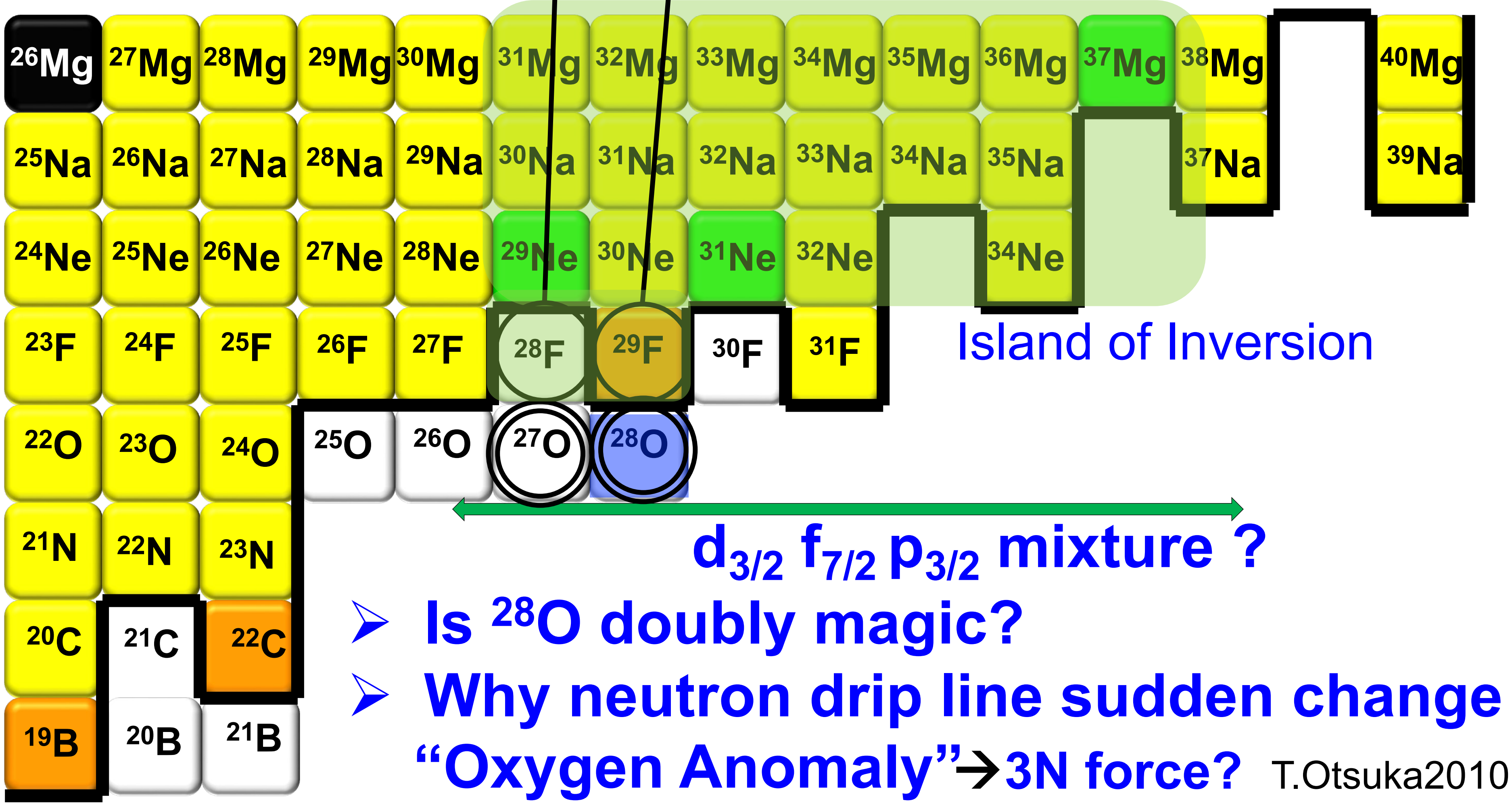
^{28}O → Is it really doubly magic?

Shell Evolution At the Edge of Nuclear Chart?

^{28}**F**:A.Revel,PRL124,152502(2020) p-wave ground state

^{29}**F**: S. Bagchi et al., PRL124, 222504, (2020): p-wave 2n halo

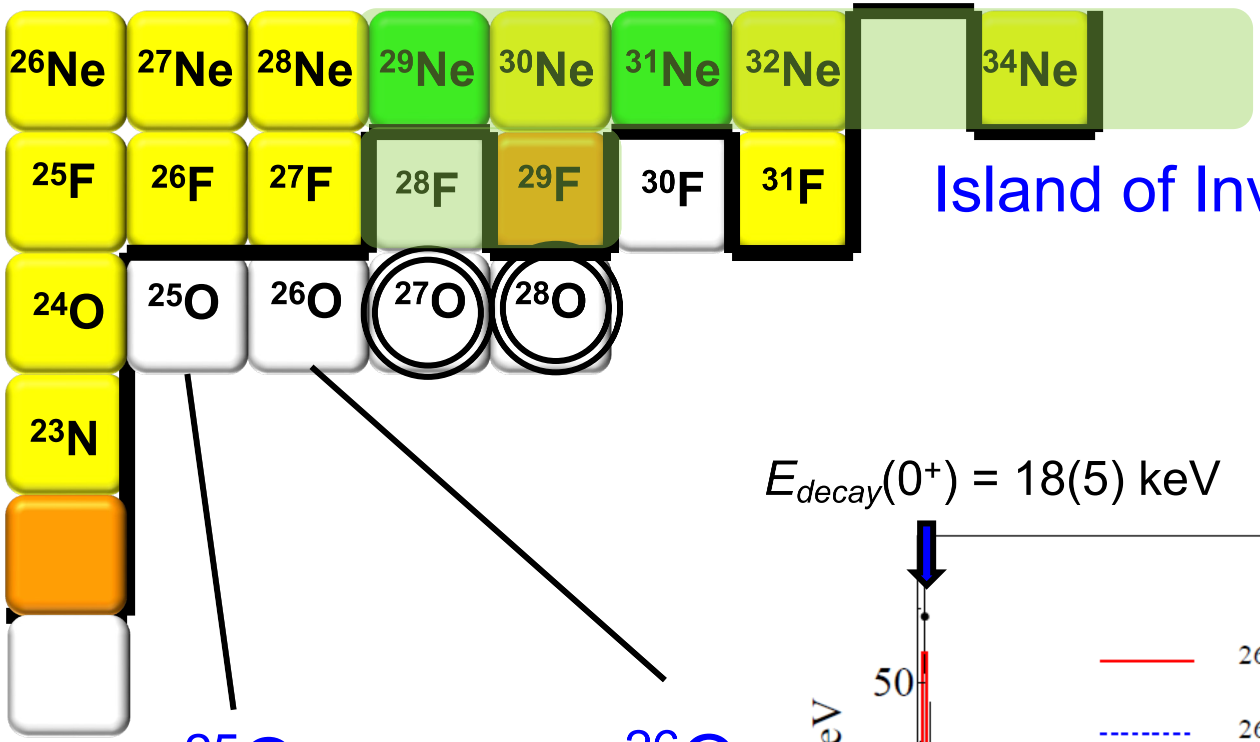
P. Doornenbal, et al., PRC95, 041301(R), (2017): N=20 magicity lost



$d_{3/2}$ $f_{7/2}$ $p_{3/2}$ mixture ?

- **Is ^{28}O doubly magic?**
- **Why neutron drip line sudden change from O to F?**
  “Oxygen Anomaly”→3N force? T.Otsuka2010, G.Hagen 2012, J.Holt 2013
- **“4n” in ^{28}O?**

What is known for oxygen isotopes beyond the dripline?



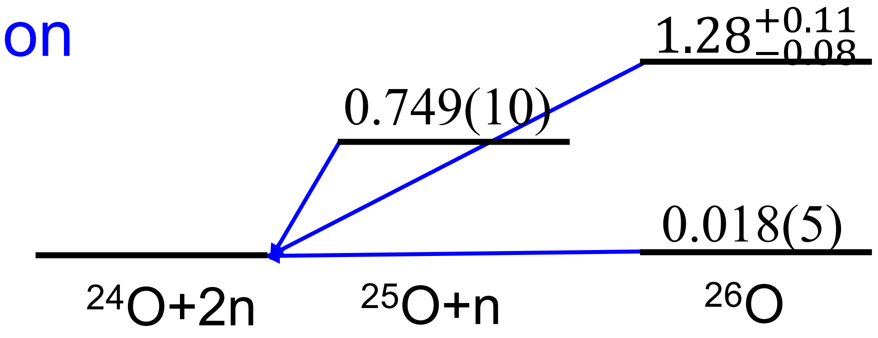
Island of Inversion

^{25}O:

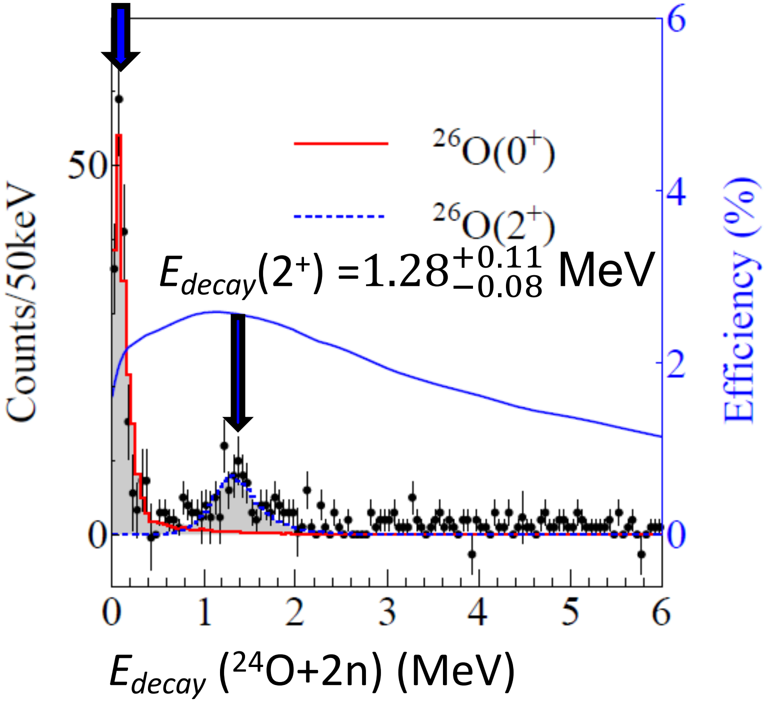
E_{decay}= 749(10) keV
Γ= 88(6) keV

Y. Kondo et al., PRL116, 102503 (2016)
C.R. Hoffman et al., PRL100, 152502 (2008)
C. Caesar et al., PRC88, 034313 (2013)

^{26}O:



$E_{decay}(0^+)$ = 18(5) keV

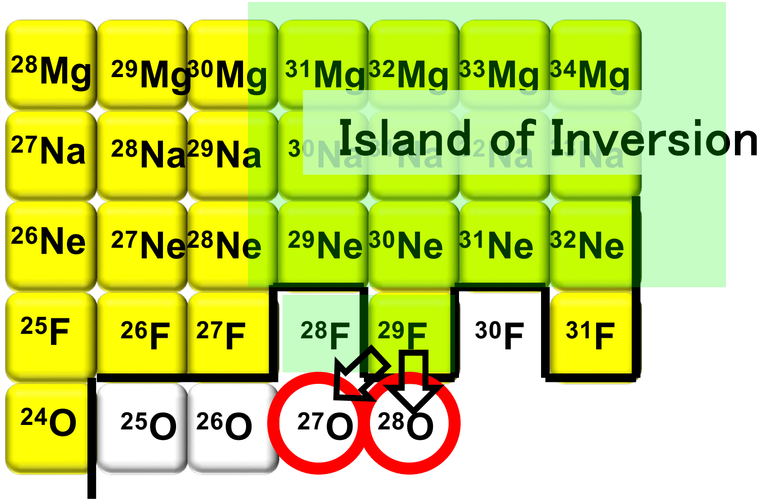


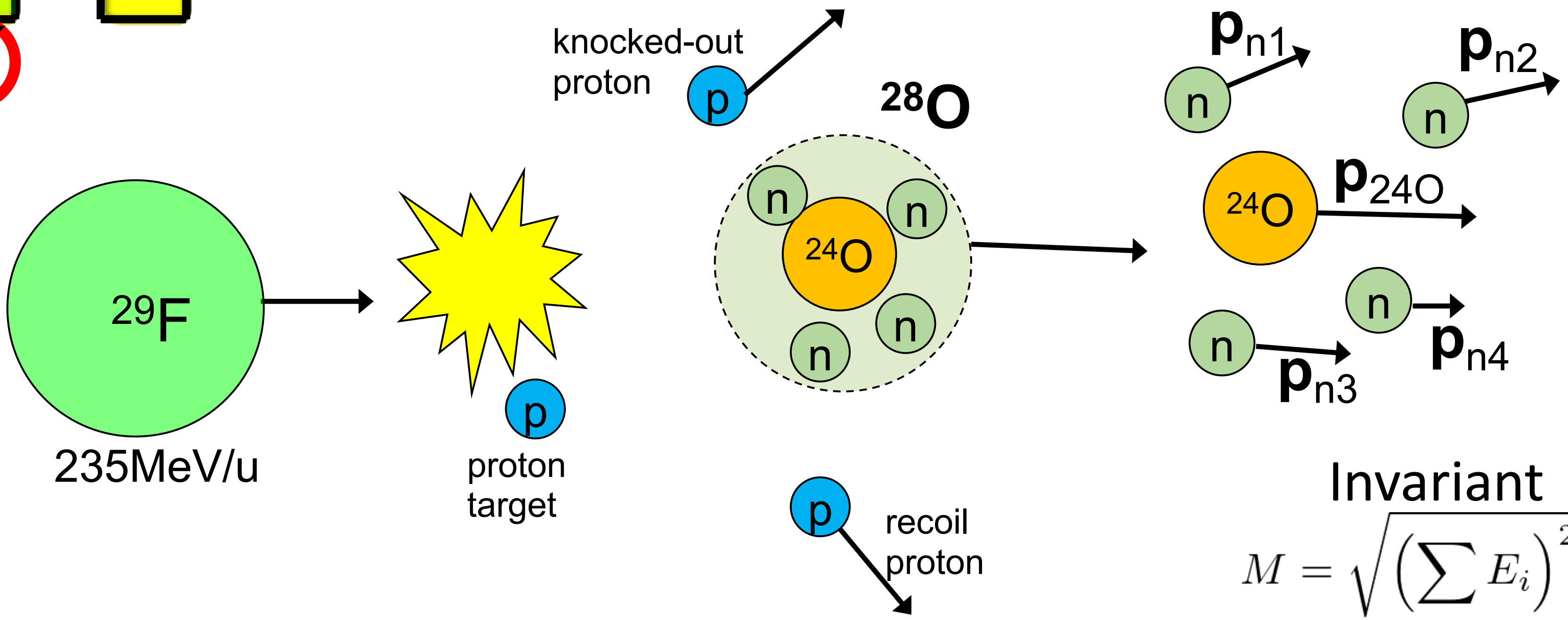
$E_{decay}(2^+) = 1.28^{+0.11}_{-0.08}$ MeV

Y. Kondo et al., PRL116, 102503 (2016)

Method: Invariant mass spectroscopy of ^{27}O and ^{28}O

Y.Kondo et al.
Nature 620, 965 (2023).





Invariant mass

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \mathbf{p}_i\right)^2}$$

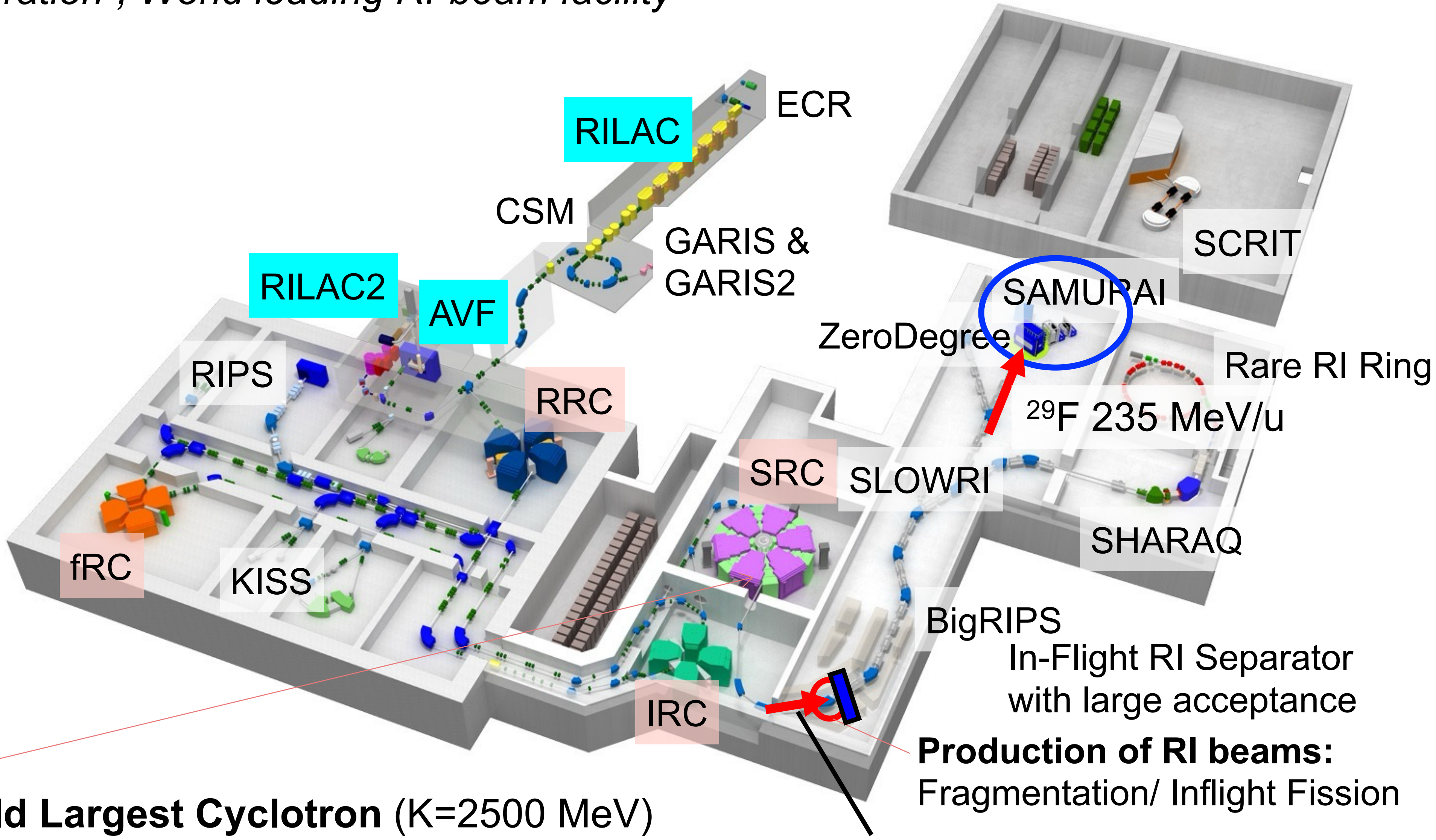
→**4-neutron coincidence**

^{28}O: 1p removal reaction of ^{29}F

^{27}O: 1p1n removal reaction of ^{29}F

RI Beam Factory (RIBF) at RIKEN

The 3rd-generation-, World leading RI-beam facility



^{29}F 235 MeV/u

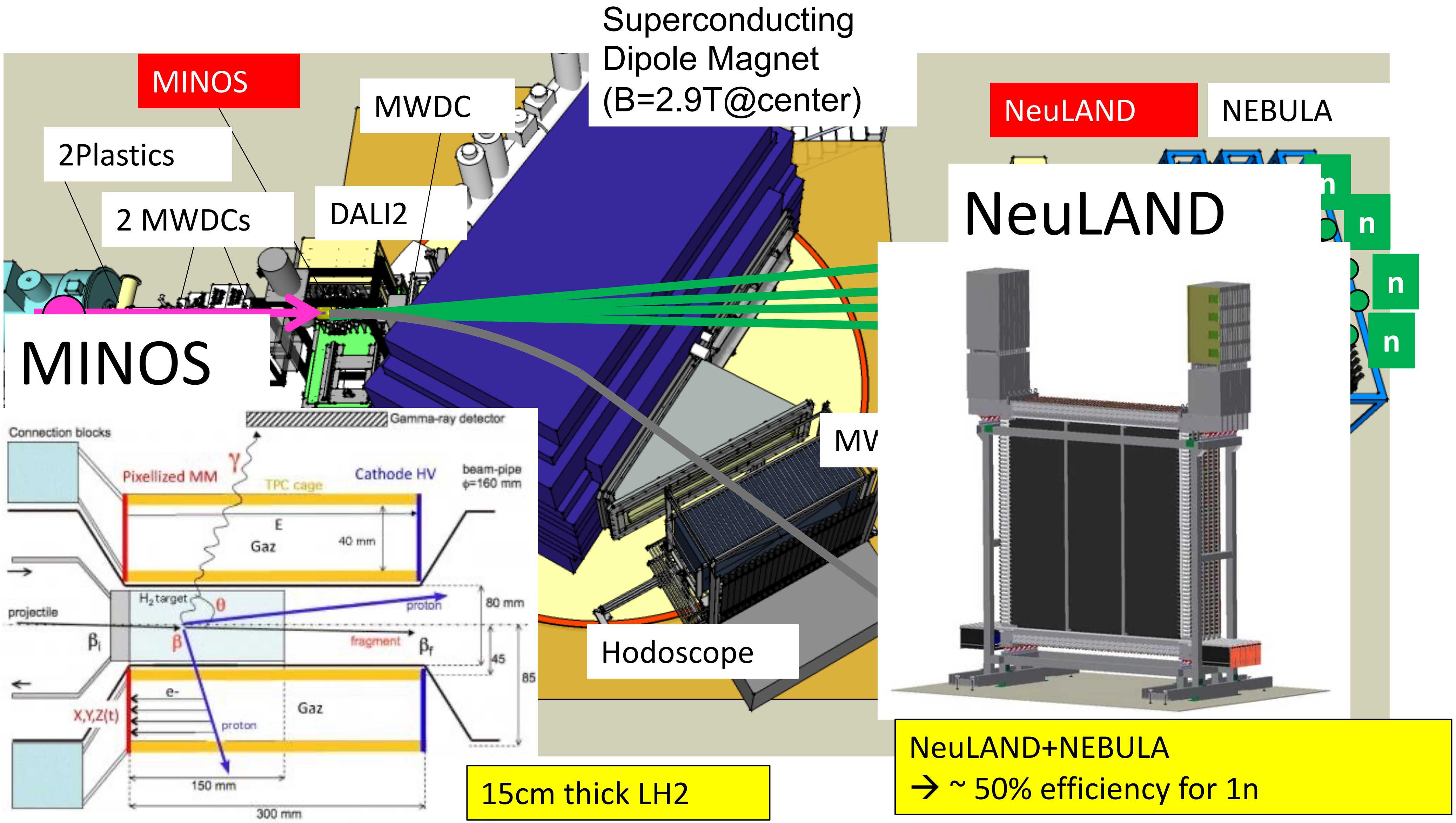
BigRIPS
In-Flight RI Separator
with large acceptance

Production of RI beams:
Fragmentation/ Inflight Fission

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

^{48}Ca 345 MeV/u
~700pnA

^{28}O measurement @ RIBF-SAMURAI



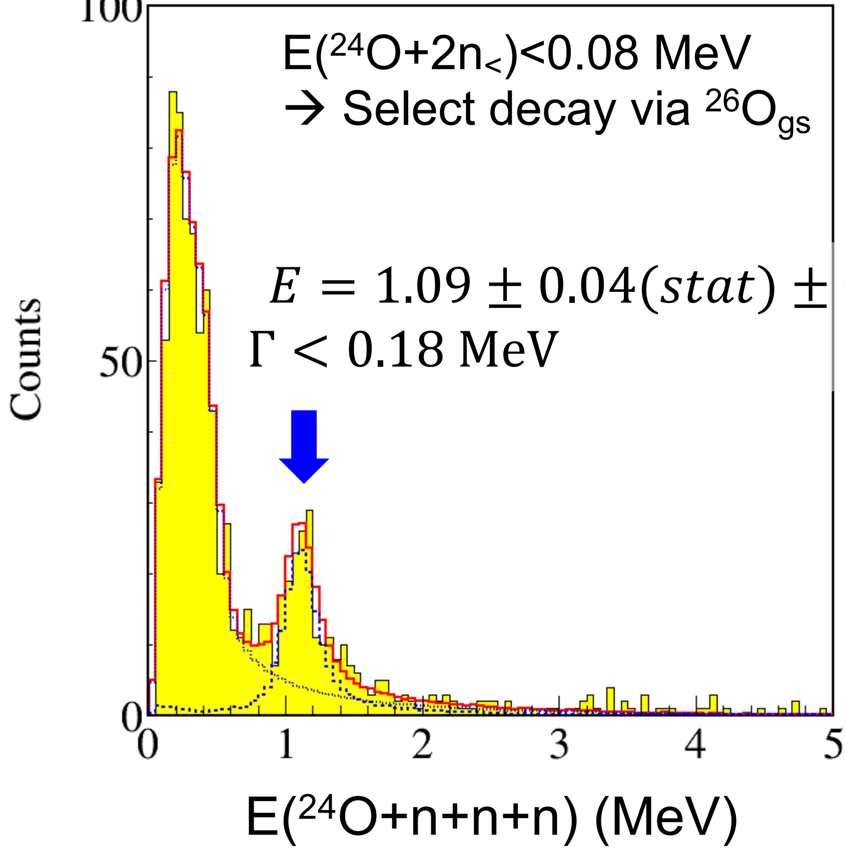
15cm thick LH2

NeuLAND+NEBULA
→ ~ 50% efficiency for 1n

Decay energy spectrum

Y.Kondo et al.
Nature **620**, 965 (2023).

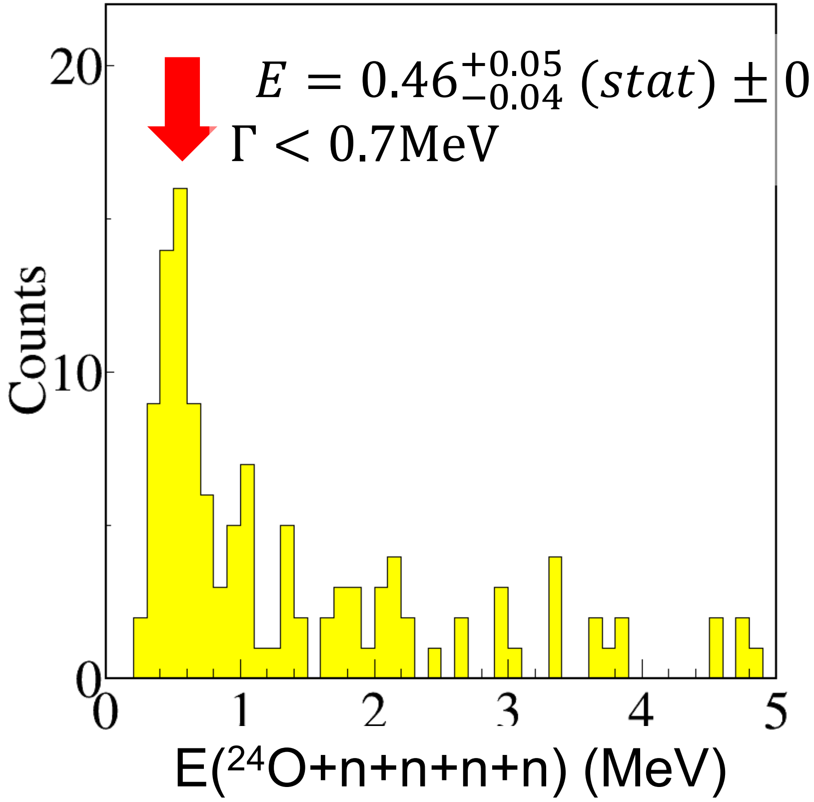
^{27}O $^{29}F+^{1}H \rightarrow ^{24}O+3n$



$E(^{24}O+2n_{<})<0.08$ MeV
→ Select decay via $^{26}O_{gs}$

$E = 1.09 \pm 0.04(stat) \pm 0.02(sys)\mathrm{MeV}$
$\Gamma < 0.18$ MeV

^{28}O $^{29}F+^{1}H \rightarrow ^{24}O+4n$

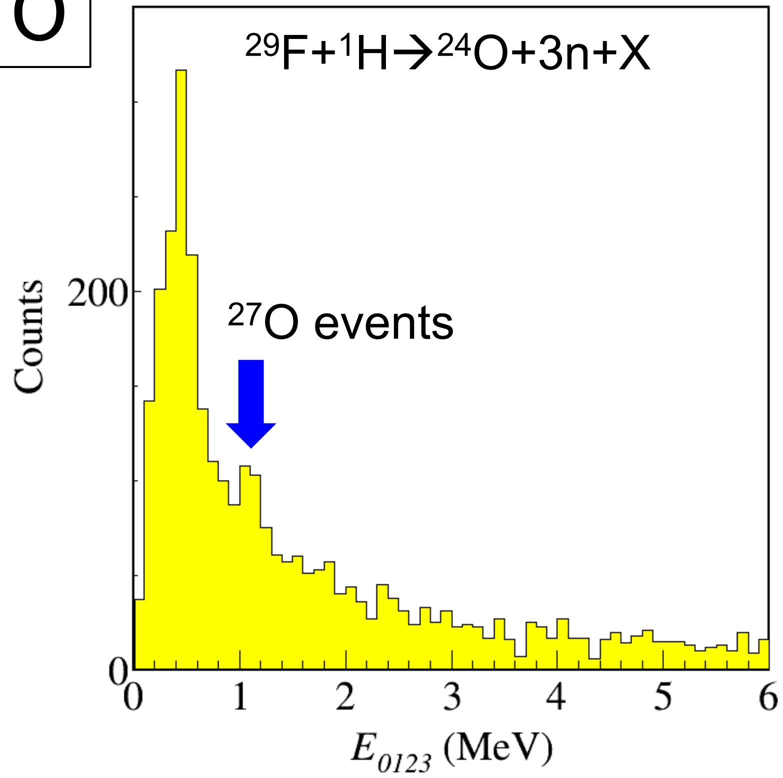


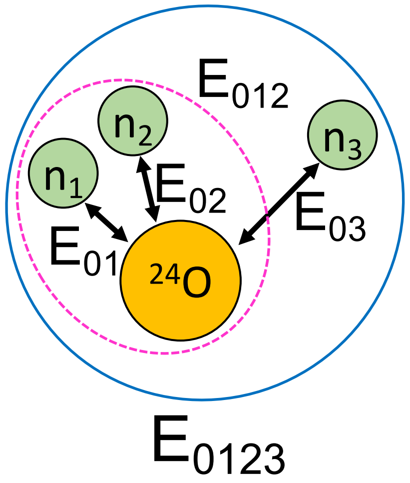
$E = 0.46^{+0.05}_{-0.04}\,(stat) \pm 0.13(sys)\mathrm{MeV}$
$\Gamma < 0.7\mathrm{MeV}$

Decay energy spectrum (^{24}O+3n coincidence)

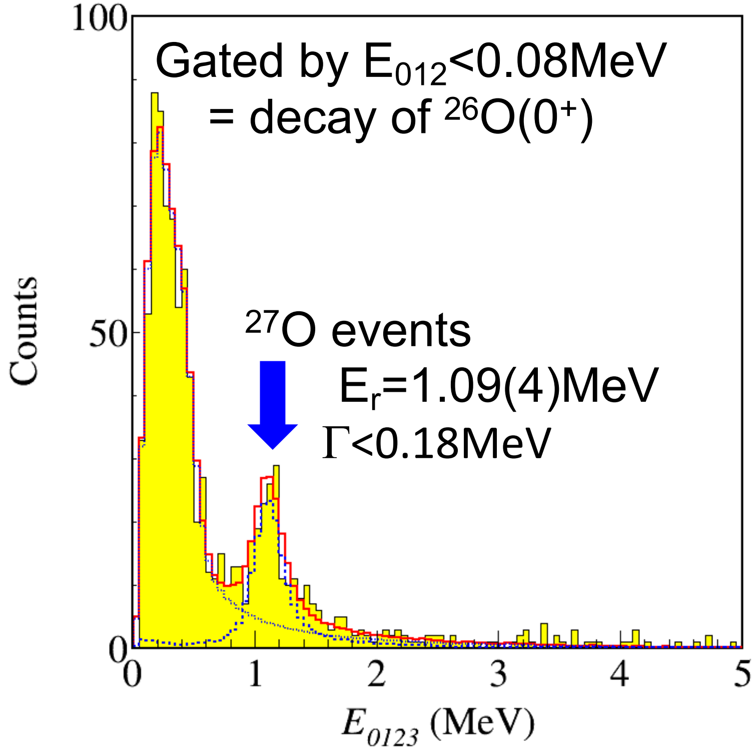
Y.Kondo et al.
Nature **620**, 965 (2023).

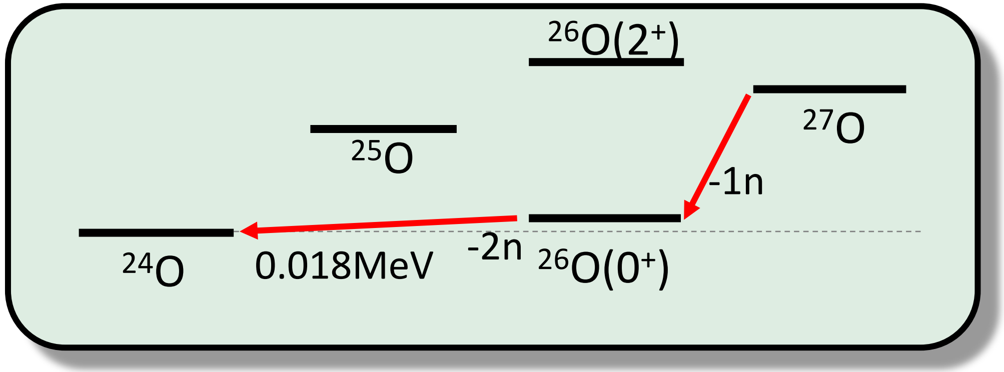
^{27}O





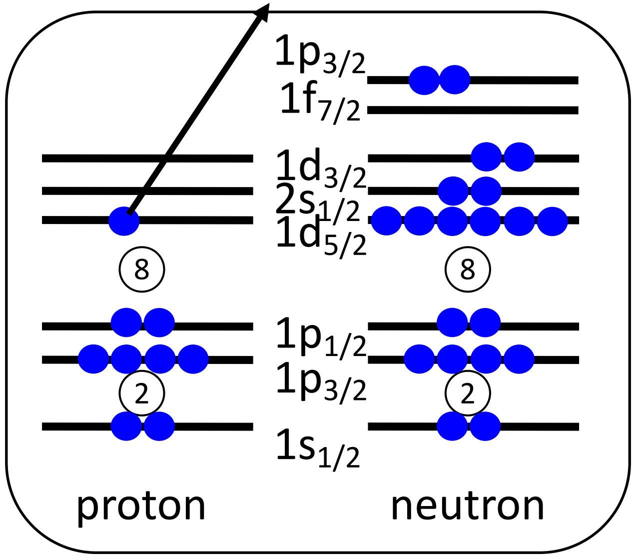
$E_{01}<E_{02}<E_{03}$





Is ^{28}O doubly magic?

^{29}F



2p2h $(2\hbar\omega)$ config.

$C^2S(\pi 1d_{5/2})$ ~0 → ^{28}O can be doubly magic
(neutron configurations between ^{29}F and ^{28}O: different)

$C^2S(\pi 1d_{5/2})$ ~1 → neutron config. of ^{28}O ~ ^{29}F

Current result

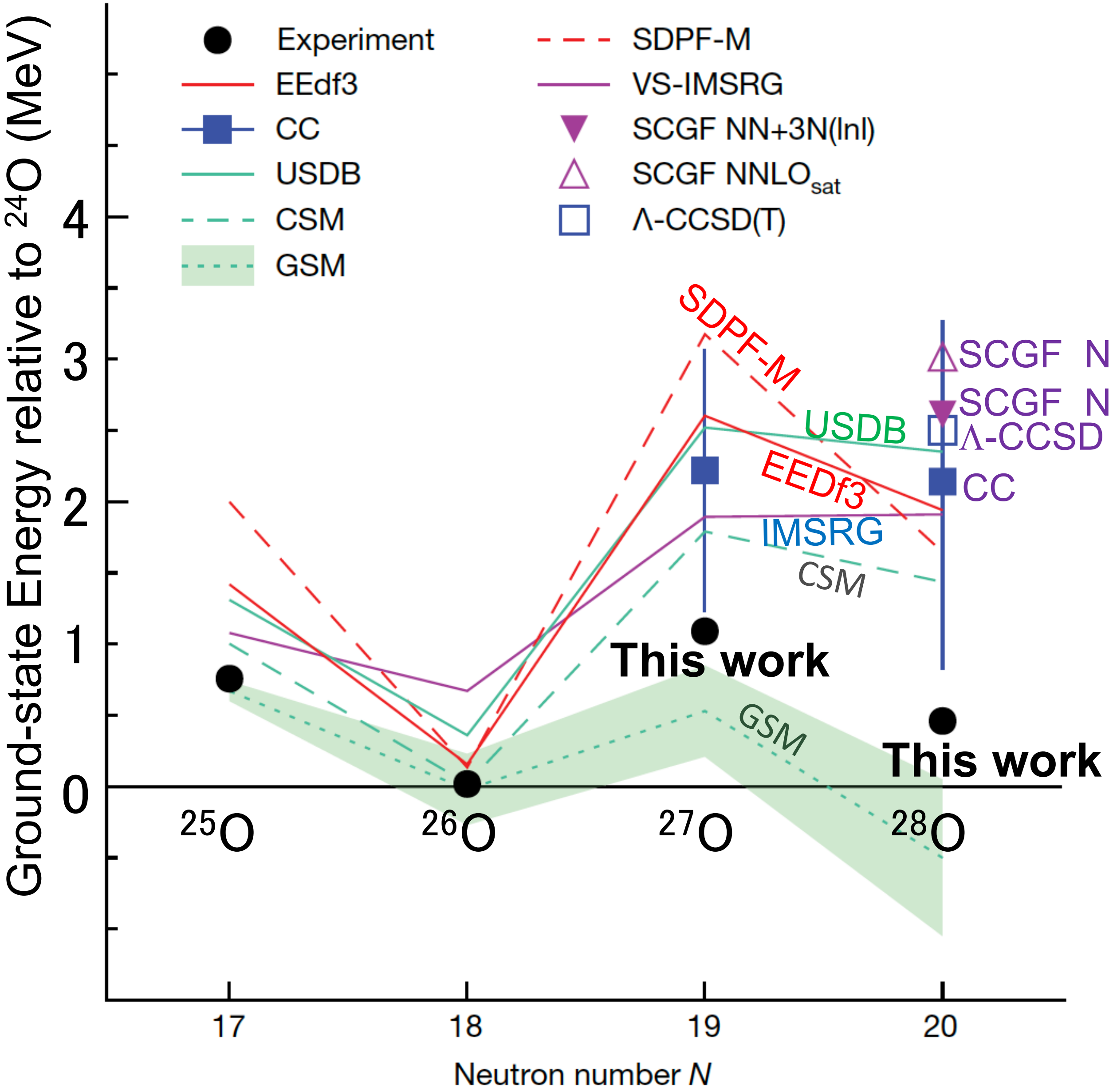
$$\sigma_{-1p} = 1.36^{+0.16}_{-0.14}\ \mathrm{mb}$$ (syst. error 0.13 mb)

$$\Rightarrow C^2S(\pi 1d_{5/2}) = 0.48^{+0.05}_{-0.06}(stat) \pm 0.05(syst)$$

Shell model calculation (EEdf3, mod ver. of EEdf1) → $C^2S=0.68$
consistent with exp. (~30% reduction factor considered)
If ^{28}O is 100% closed-shell config → $C^2S=0.13$

***N=20* neutron magicity disappears in ^{28}O**

Comparison with theories $^{25-28}O$



Conventional SM

USDB: B. A. Brown, W.A. Richter, PRC**74**, 034315 (2006).

Large-scale SM

SDPF-M: Y.Utsuno et al.,PRC**60**, 054315 (1999).

EEDf3: N.Tsunoda et al., PRC**95**, 021304(R) (2017).; N.Tsunoda et al.,Nature **587**, 66(2020).

Ab-initio Calculations

SCGF: V. Somà et al., PRC**101**, 014318 (2020).

L-CCSD: G. Hagen et al., Phys. Scr. **91**, 063006 (2016).

CC (Coupled-Cluster method with statistical approach): This work (Nature 2023)

IMSRG: S.R. Stroberg et al.,, PRL**126**, 022501 (2021).

SM with continuum effects

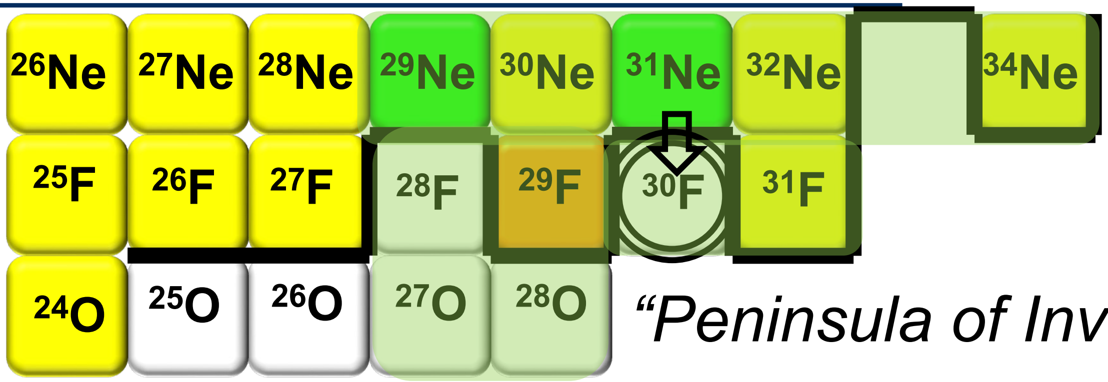
CSM: A. Volya et al., PRC74, 064314, (2006).

GSM: K. Fossez et al., *PRC 96, 024308 (2017).*

J.G. Li et al., PRC 103, 034305 (2021).

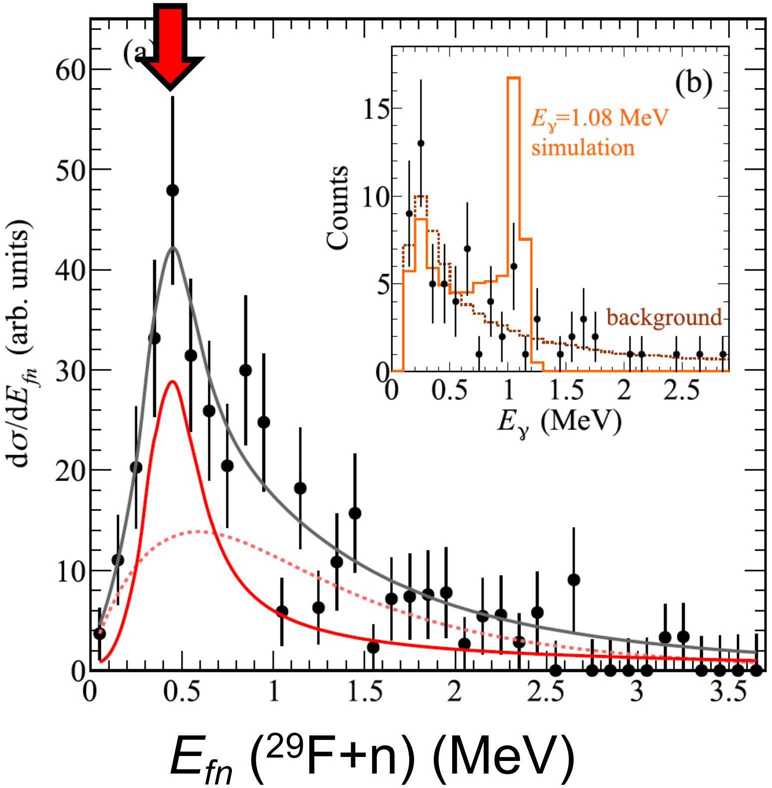
Observation of ^{30}F

J.Kahlbow, T.Aumann, O.Sorlin, Y.Kondo, TN et al.,
PRL 133, 082501 (2024). @SAMURAI at RIBF

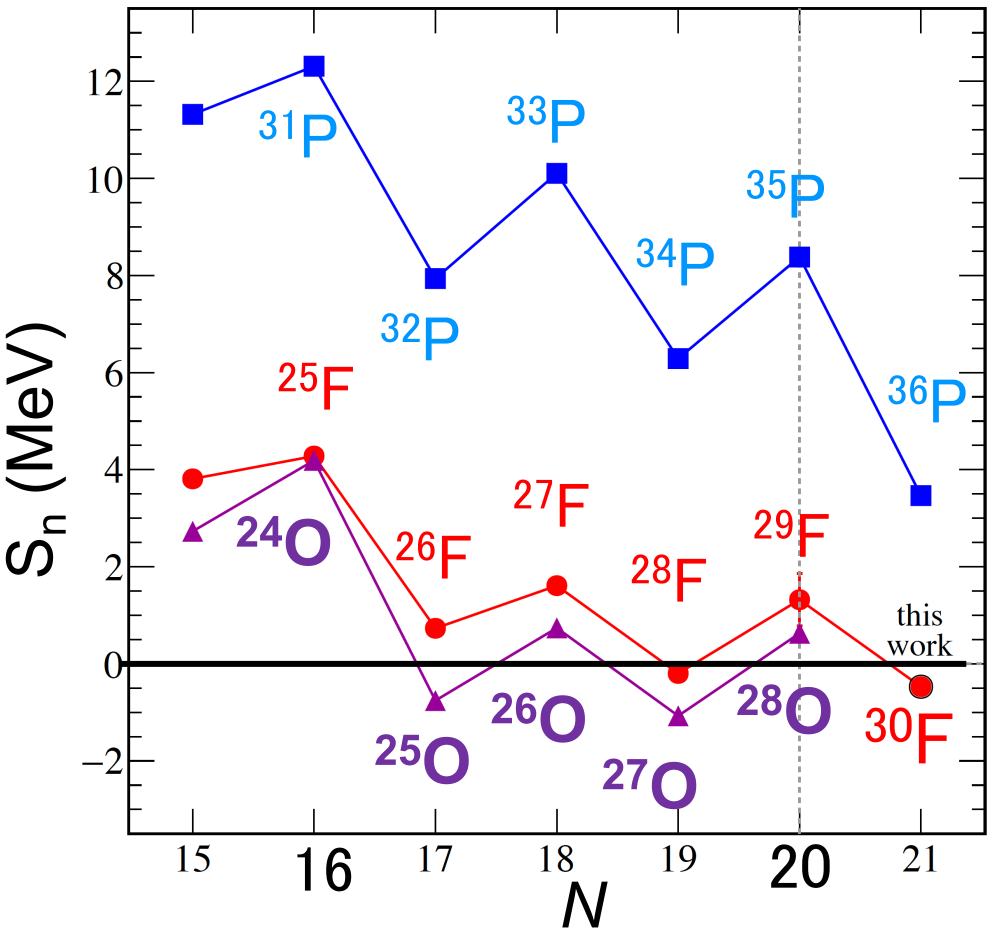


"Peninsula of Inversion"

E_{fn} (^{29}F+n)= $472 \pm 58(stat) \pm 33(sys)$ keV



Heaviest resonance
so far observed
beyond
neutron dripline



S_n for O and F with $N > 16$: **Similar, Nearly-Flat Trend**

→**N=20 magicity Lost** also at **^{30}F** →**^{31}F : p-wave halo**

→**Superfluidity due to d-f-p mixture for n with Z=8 closure**

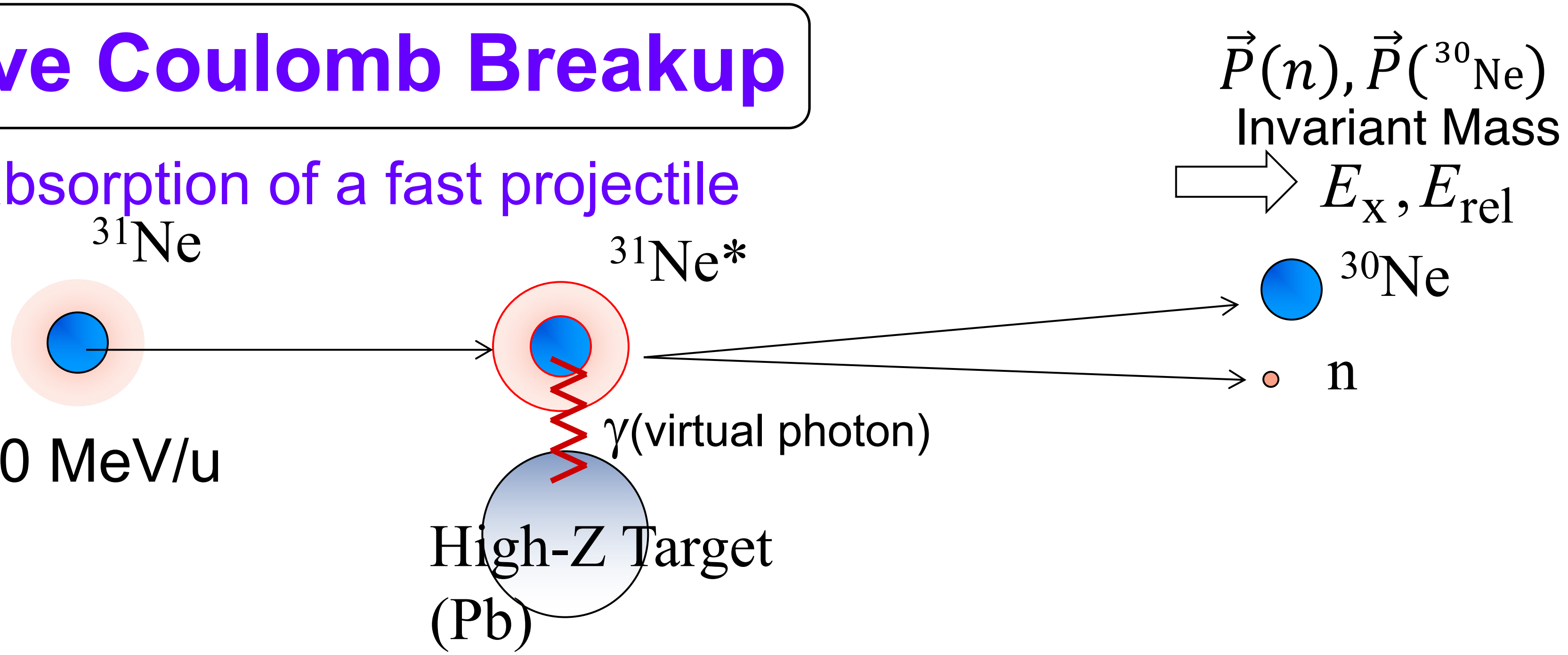
Slight Deviation with SM (SDPF-U-MIX20) →Continuum Effects ?

Halo-Shell Interplay—^{31}Ne (Z=10, N=21)

Takato Tomai, PhD Thesis

Exclusive Coulomb Breakup

→Photon absorption of a fast projectile



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

Invariant Mass

$\Rightarrow E_x, E_{rel}$

$^{31}\mathrm{Ne}$

$^{31}\mathrm{Ne}^*$

$^{30}\mathrm{Ne}$

n

240 MeV/u

γ(virtual photon)

High-Z Target (Pb)

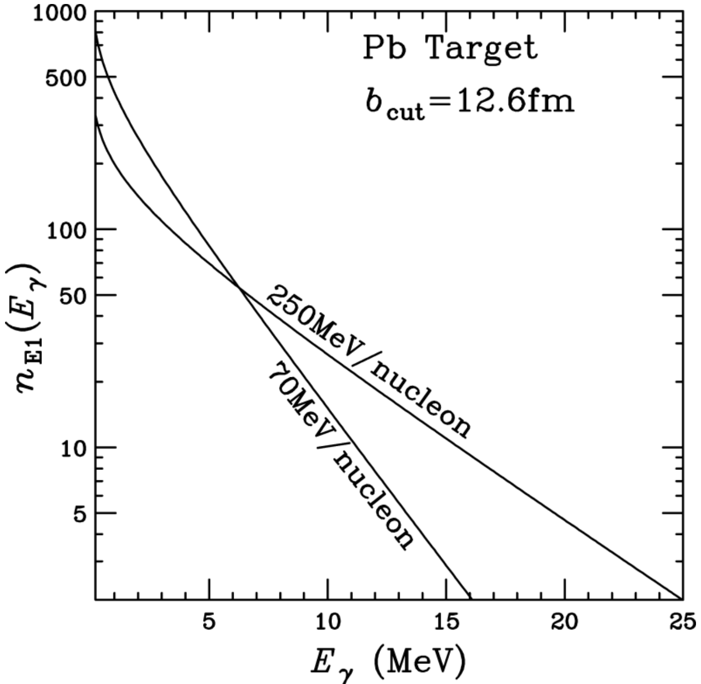
Equivalent Photon Method

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

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

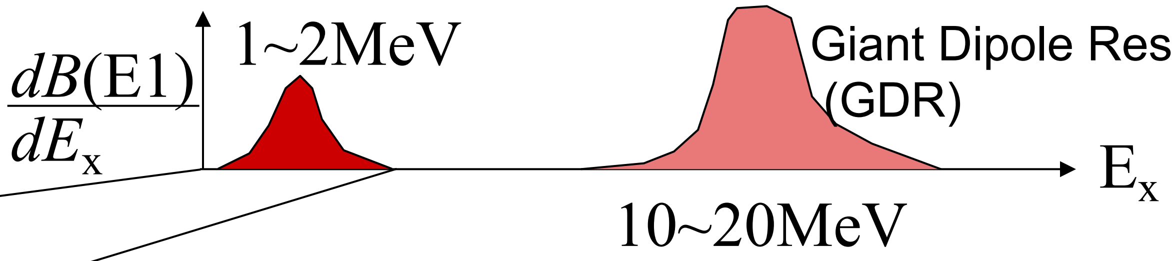
C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).

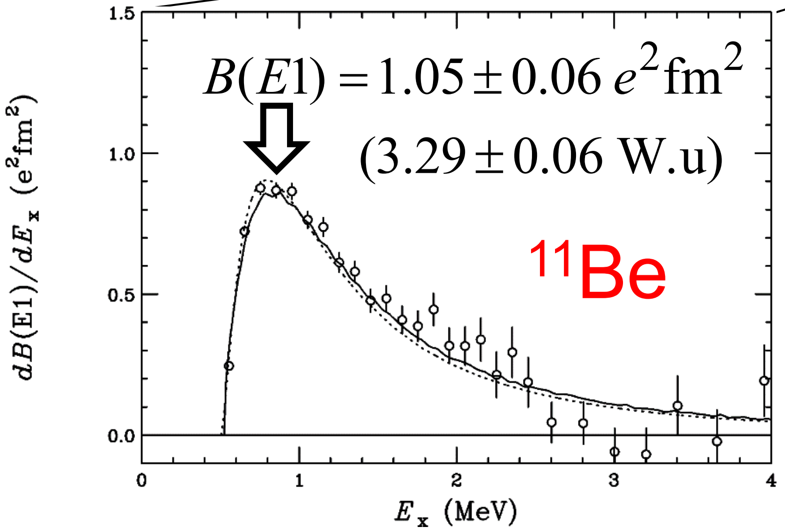
Halo → Soft E1 Excitation
(E1 Concentration at Ex<1MeV)



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

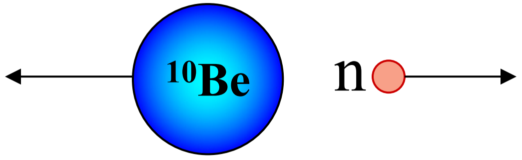
Low-lying
E1 Strength
(Soft E1 excitation)





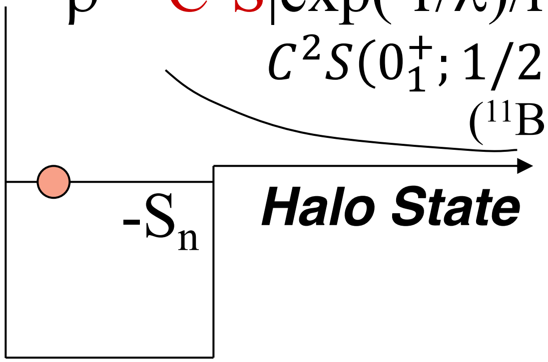
N.Fukuda, TN et al., PRC70, 054606 (2004)
TN *et al.*,PLB 331,296(1994)
Palit et al., PRC68, 034318(2003)

Direct Breakup Mechanism



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

$C^2S(0_1^+;1/2^+) = 0.72 \pm 0.04$
(^{11}Be Fukuda2004)



Halo State

E1 Strength

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

⇔ ***Fourier Transform***

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

e.g. Peak Energy

s-wave halo: $E_{rel}^{(peak)} \cong \frac{3}{5}S_n$ p-wave halo (p→s): $E_{rel}^{(peak)} \cong 0.18S_n$

γ-ray spectrum : Excited ^{30}Ne-core component

^{31}Ne+C→^{30}Ne*+X ↳ γ

new

new

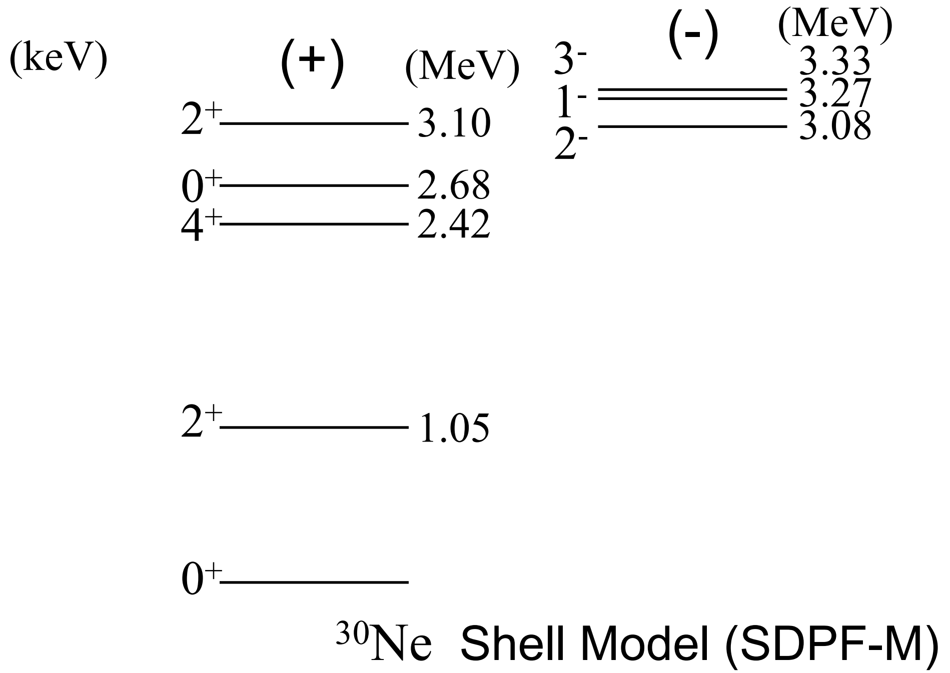
new

(2⁻,3⁻)

(1⁻)

(0⁺,2⁺,2⁻,3⁻)

(4⁺)



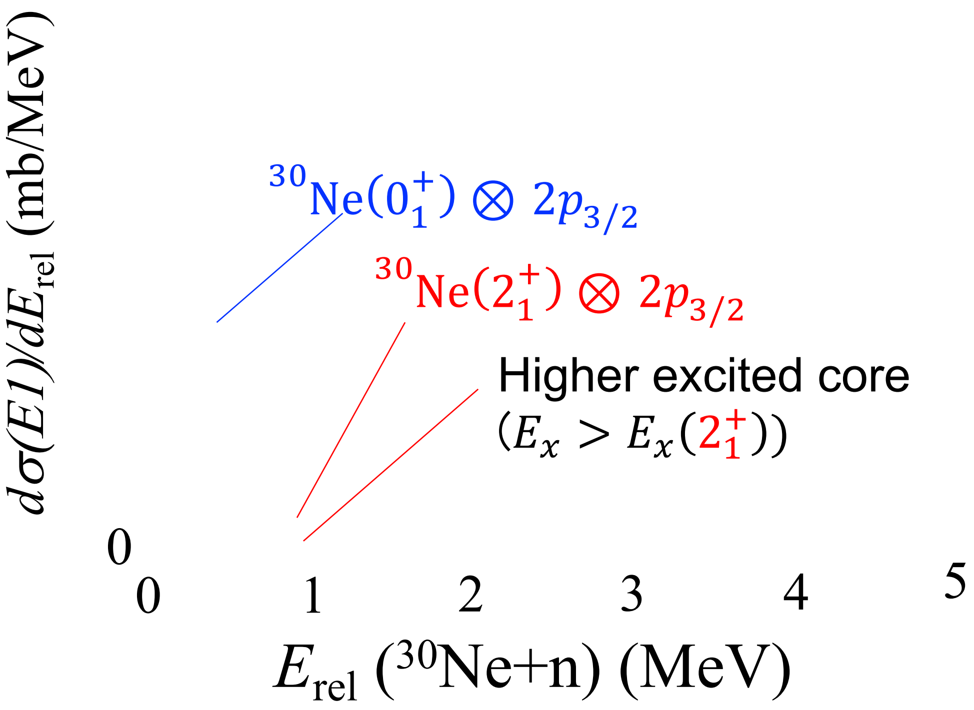
^{30}Ne Shell Model (SDPF-M)

^{31}Ne+Pb

$$\left|{}^{31}\mathrm{Ne}(3/2^-)\right> = \alpha\left|{}^{30}\mathrm{Ne}(0_1^+)\otimes 2p_{3/2}\right> + \beta\left|{}^{30}\mathrm{Ne}(2_1^+)\otimes 2p_{3/2}\right> \cdots$$

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

^{31}Ne+Pb→^{30}Ne+n+X
(Coulomb)



$$|^{31}\mathrm{Ne}(3/2^-)> = \alpha\left|^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}\right> + \beta\left|^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}\right> + \cdots$$

$$\alpha^2 = C^2S(0_1^+; 3/2^-) \qquad \beta^2 = C^2S(2_1^+; 3/2^-)$$

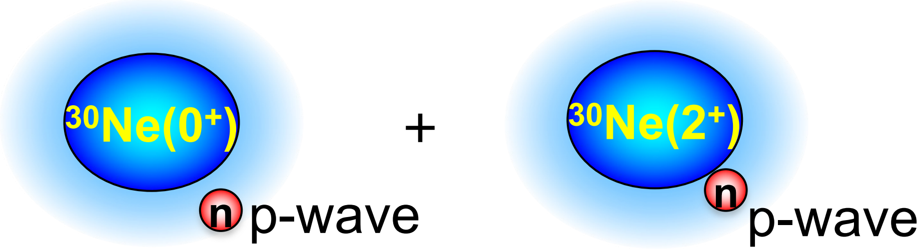
$^{30}\mathrm{Ne}(0_1^+) \otimes 2p_{3/2}$ $^{30}\mathrm{Ne}(2_1^+) \otimes 2p_{3/2}$

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

Double-Component Halo: Unique to p-wave halo

$$\left|{}^{31}\mathrm{Ne}(3/2^-)\right> = \alpha\left|{}^{30}\mathrm{Ne}(0_1^+)\otimes 2p_{3/2}\right> + \beta\left|{}^{30}\mathrm{Ne}(2_1^+)\otimes 2p_{3/2}\right>$$

$$S^{(\mathrm{eff})}{}_n = S_n + E_x(2_1^+) \sim 1.0\mathrm{MeV}$$



Double-Component Halo:

- ✓ Unique feature of **p-wave halo**

Preliminary

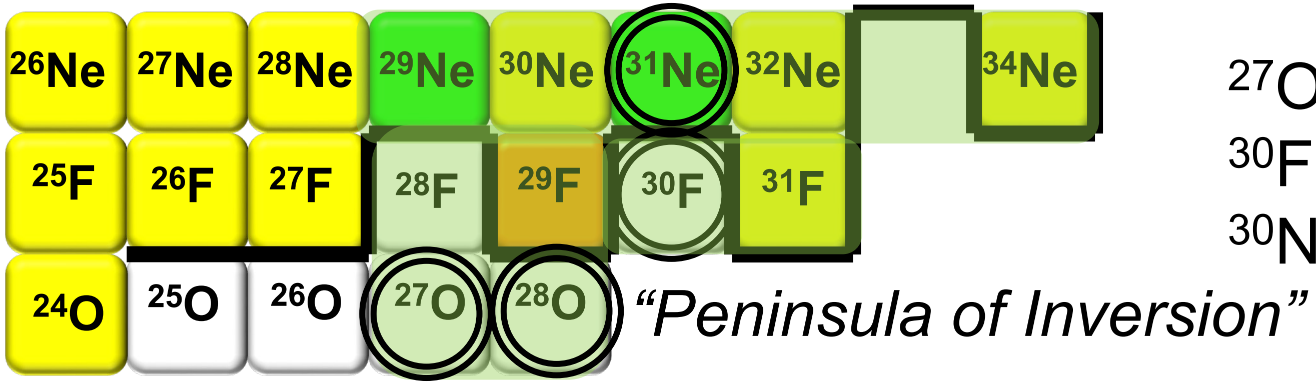
c.f. **Single**-component for **s-wave halo**

$$\left|{}^{11}\mathrm{Be}(1/2^+)\right> = \alpha\left|{}^{10}\mathrm{Be}(0_1^+)\otimes 2s_{1/2}\right> + \beta\left|{}^{10}\mathrm{Be}(2_1^+)\otimes 1d_{5/2}\right>$$

s-wave halo

non-halo

Summary



^{27}O,^{28}O: Y.Kondo Nature **620**, 965 (2023).
^{30}F: J.Kahlbow, PRL **133,** 082501 (2024).
^{30}Ne: T.Tomai, *In prepartation*

- ✓ Neutron dripline→Boundary of Open/Closed Quantum Systems→Universal features
- ✓ ^{29}F(p,2p)^{28}O, ^{29}F(p,2pn)^{27}O, ^{31}Ne(p,2p)^{30}F at SAMURAI at RIBF
  - ✓ World-first invariant mass spectroscopy with 4n+fragment in coincidence
  - ✓ **^{28}O:** unbound by 4n emission with $E = 0.46^{+0.05}_{-0.04}\,(stat) \pm 0.13(sys)$MeV
  - ✓ **^{27}O:** unbound by 3n emission with $E = 1.09 \pm 0.04(stat) \pm 0.02(sys)$MeV
  - ✓ **^{28}O:** N=20 magicity is lost: Not a doubly magic nucleus
  - ✓ **^{30}F**: $E = 0.472 \pm 0.058(stat) \pm 0.033(sys)$MeV
  - ✓ **^{30}F:** N=20 magicity lost: →^{31}F p-wave halo, Superfluidity for O/F with N>16
- ✓ Halo-Shell Interplay: ^{31}Ne :
  - ➢ Exclusive **Coulomb Breakup** of ^{31}Ne
    - ✓ Soft-E1 Excitation→**Double halo components: Unique feature of p-wave halo**

Perspectives

- More exotic weakly bound and unbound nuclei along the neutron drip line

  ^{6}n, ^{28}O(2_1^+), ^{29}O …

→Understand Microscopically Shell-Halo Interplay

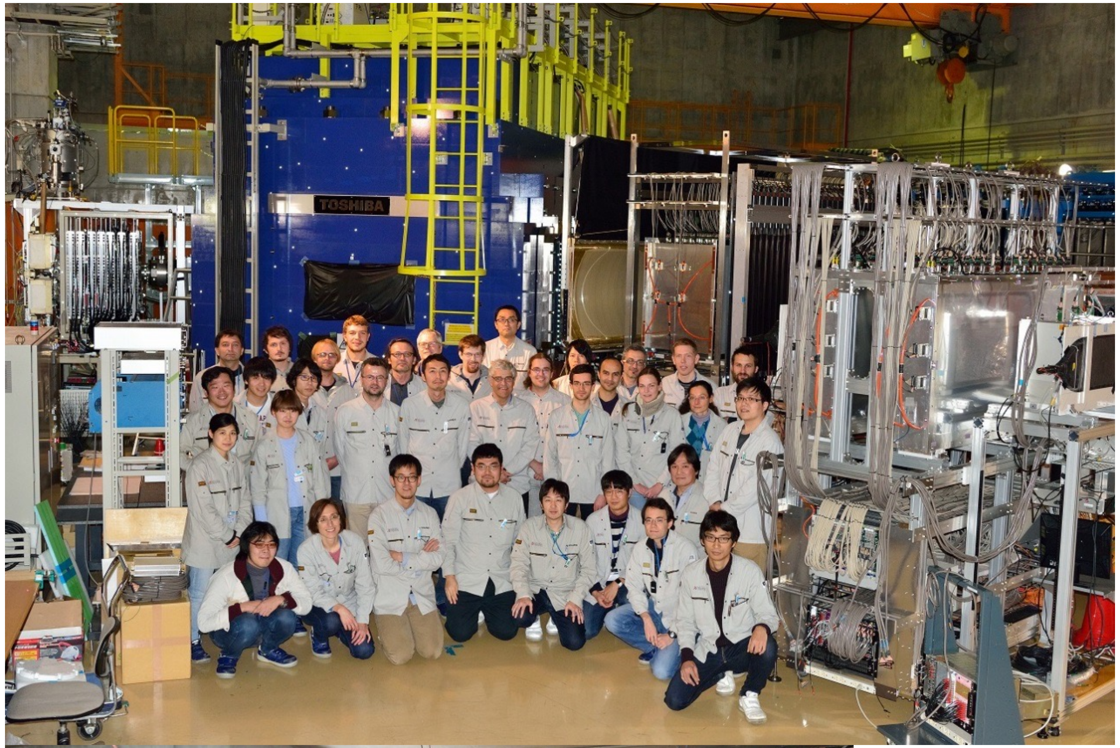
→Many-body effects at the boundary open-closed quantum systems

→Universal Features with Exotic hadrons and Ultra-cold atoms

- Multi-neutron detections

→Key to understanding physics near and beyond the neutron drip line

SAMURAI21 collaboration—^{27,28}O, ^{28}F, ^{30}F



Y.Kondo, **T.Nakamura**, N.L.Achouri, H.Al Falou,
L.Atar, T.Aumann, H.Baba, K.Boretzky, C.Caesar, D.Calvet,
H.Chae, N.Chiga, A.Corsi, H.L.Crawford, F.Delaunay,
A.Delbart, Q.Deshayes, Zs.Dombrádi, C.Douma, Z.Elekes,
P.Fallon, I.Gašparić, J.-M.Gheller, J.Gibelin, A.Gillibert,
M.N.Harakeh, A.Hirayama, C.R.Hoffman, M.Holl, A.Horvat,
Á.Horváth, J.W.Hwang, T.Isobe, **J.Kahlbow**,
N.Kalantar-Nayestanaki, S.Kawase, S.Kim, K.Kisamori,
T.Kobayashi, D.Körper, S.Koyama, I.Kuti, V.Lapoux,
S.Lindberg, F.M.Marqués, S.Masuoka, J.Mayer, K.Miki,
T.Murakami, M.A.Najafi, K.Nakano, N.Nakatsuka,
T.Nilsson, A.Obertelli, F.de Oliveira Santos, N.A.Orr,
H.Otsu, T.Ozaki, V.Panin, S.Paschalis, **A.Revel**,
D.Rossi, A.T.Saito, T.Saito, M.Sasano, H.Sato, Y.Satou,
H.Scheit, F.Schindler, P.Schrock, M.Shikata, Y.Shimizu,
H.Simon, D.Sohler, O.Sorlin, L.Stuhl, S.Takeuchi,
M.Tanaka, M.Thoennessen, H.Törnqvist, Y.Togano,
T.Tomai, J.Tscheuschner, J.Tsubota, T.Uesaka, H.Wang,
M.Yasuda, Z.Yang, K.Yoneda

Tokyo Tech, Argonne, ATOMKI, CEA Saclay, Chalmers,
CNS, Cologne, Eotvos, GANIL, GSI, IBS, KVI-CART,
Kyoto Univ., Kyushu Univ., LBNL, Lebanese-French
University of Technology and Applied Science, LPC-CAEN,
MSU, Osaka Univ., RIKEN, Ruđer Bošković Institute, SNU,
Tohoku Univ., TU Darmstadt, Univ. of Tokyo

88 Participants (+analysis) 25 Institutes

Y.Kondo et al., Nature **620**, 965-970 (2023).
A. Revel et al., PRL124,152502(2020). (^{28}F)
J. Kahlbow et al., PRL in Press (^{30}F)

Exclusive Coulomb/nuclear breakup of ^{31}Ne

- Collaborators
  - **T. Tomai**,[A] N. Kobayashi,[B] T. Nakamura,[A] Y. Togano,[Q] Y. Kondo,[A] S. Takeuchi,[A] A. T. Saito,[A] T. Ozaki,[A] A. Hirayama,[A] M. Yasuda,[A] H. Yamada,[A] T. Kobayashi,[D] S. Koyama,[E] S. J. Kim,[F] J. W. Hwang,[F] H. Otsu,[C] Y. Shimizu,[C] N. A. Orr,[G] J. D. Gibelin,[G] T. Aumann,[H] H. Sato,[C] P. C. Doornenbal,[C] H. Baba,[C] T. Isobe,[C] N. L. Achouri,[G] M. Marques,[G] F. L. Delaunay,[G] Q. Deshayes,[G] A. Revel,[I] O. Sorlin,[I] V. Panin,[C] I. Gašparić,[J] H. T. Toernqvist,[H] S. Y. Park,[K] I. K. Hahn,[K] Y. Kubota,[C] M. Sasano,[C] L. Stuhl,[E] D. H. Kim,[K] M. Matsumoto,[A] M. Parlog,[G] D. M. Rossi,[H] L. Atar,[H] S. Lindberg,[L] J. Kahlbow,[H] S. Paschalis,[M] S. Sakaguchi,[N] R. Reifarth,[O] L. Mullay,[C] F. Browne,[P] M. L. Cortes Sua,[C] S. D. Chen,[C] J. Steinhauser[A]
    Theories: J.A. Tostevin[R], A. Poves[S], Y. Utsuno[T], K.Hagino[U]

- Institution
  - TokyoTech[A], Osaka U. RCNP[B], RIKEN Nishina center[C], Tohoku U.[D], U. Tokyo CNS[E], Seoul N. U.[F], LPC-ENSICAEN[G], GSI[H,], GANIL[I], IRB[J], Ewha W. U.[K], Chalmers U. T.[L], U. York[M], Kyushu U.[N], U. Frankfurt[O], U. Brighton[P], U. Rikkyo[Q], U. Surrey[R], U. Autonoma-Madrid[S], JAEA[T],Kyoto U[U]

T. Tomai,
PhD thesis
Paper in Preparation