Breakup reactions and spectroscopy of neutron drip line nuclei

Takashi Nakamura

Department of Physics,
Tokyo Institute of Technology

ECT Workshop on "Recent advances and challenges in the description of nuclear reactions at the limit of stability", 5-9,March, 2018*

Contents

- <u>Introduction</u>
  --Structure interests: Neutron correlations near/beyond the neutron drip line
  --Reaction Probes: Coulomb Breakup
  Nuclear Breakup
  (Quasi-free Scattering)

- <u>Coulomb/Nuclear Breakup of Halo Nuclei (^{31}Ne,^{6}He,^{22}C)</u>

- <u>Spectroscopy of heavy oxygen isotopes</u> (^{26,27,28}O)

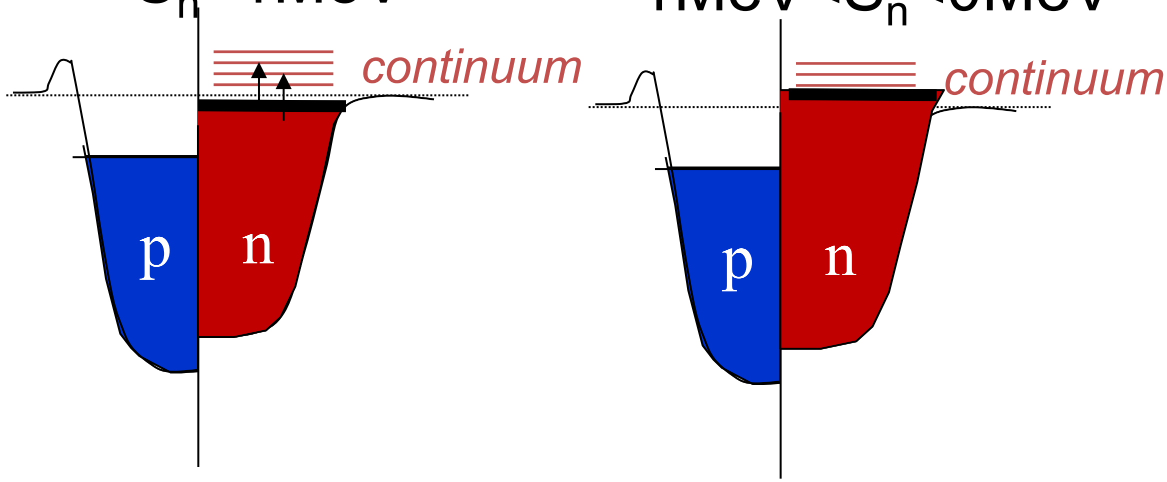
- <u>Summary and Perspectives</u>

Possible strong nn correlation near drip line?

Neutron Drip-line

Beyond

S_n<1MeV   -1MeV< S_n <0MeV



Weakly bound/unbound nuclei --- Threshold → Clustering phenomena

Halo Nuclei (2n-halo)
Weakly Unbound Nuclei

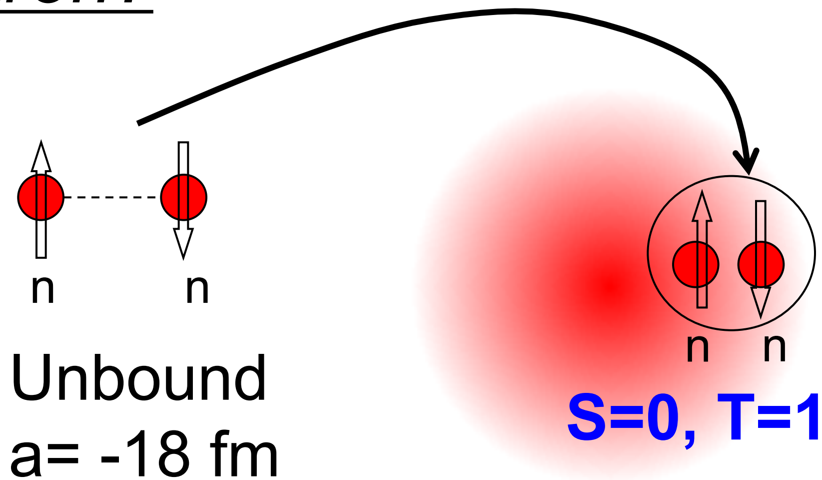
^{4}n: Tetra neutron $E_{4n}=0.83\pm0.65(\mathrm{stat})\pm1.25(\mathrm{syst})$ MeV

K.Kisamori et al., PRL116, 052501 (2016)

^{26}O: ^{24}O+2n $E_{2n}= 0.018\pm0.003(\mathrm{stat})\pm0.004(\mathrm{syst})$ MeV

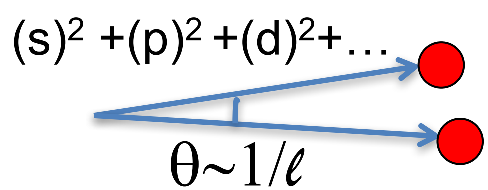
Y.Kondo et al., PRL116,102503(2016).

Dineutron?

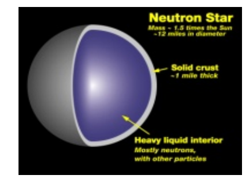


A.B.Migdal
Strongly correlated "dineutron"
on the **surface** of a nucleus
Sov.J.Nucl.Phys.238(1973).

Dineutron:
@ Low-dense neutron skin/halo?
/surface of neutron star?



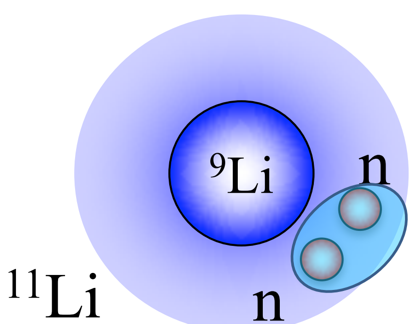
M.Matsuo
PRC73,044309(2006).
A.Gezerlis, J.Carlson,
PRC81,025803(2010)



n-star

Possible dineutron site

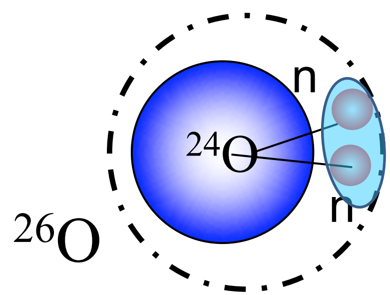
2n Halo Nuclei?

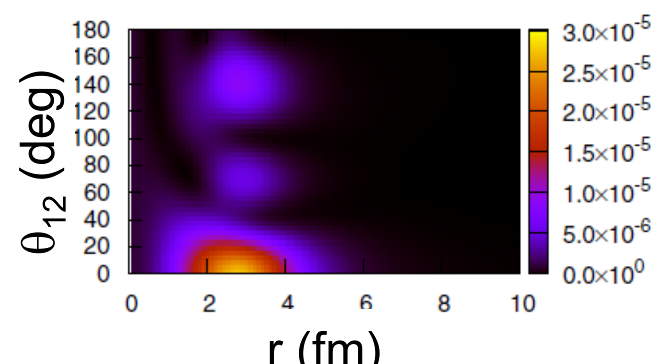


S_{2n}=0.37MeV

T.Nakamura PRL96, 252502 (2006).

2n weakly-unbound nuclei?



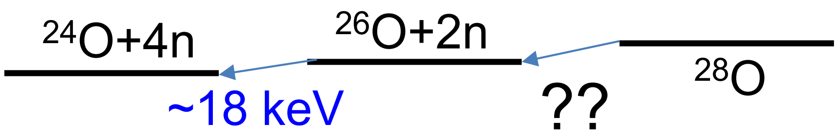


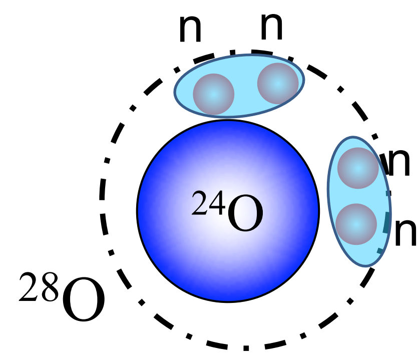
S_{2n}= –0.018(5) MeV

Hagino, Sagawa,
PRC93,034330(2016)

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

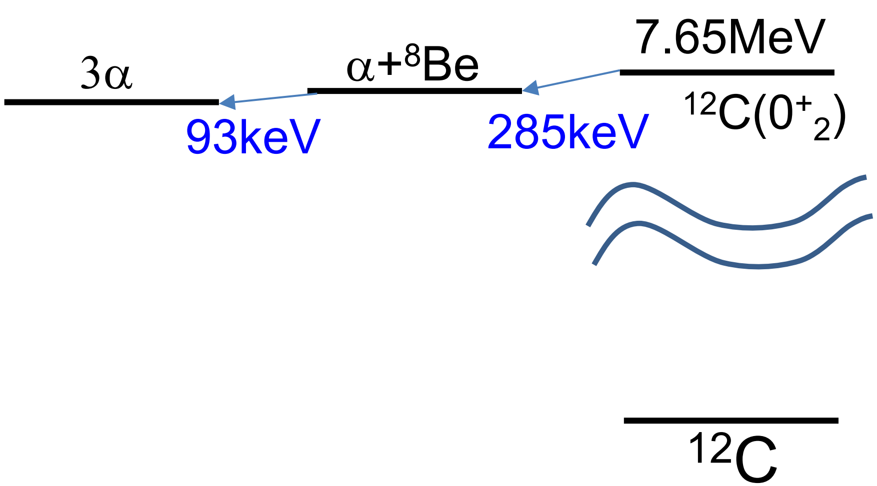
What happens if there are ‘multiple’ dineutrons?



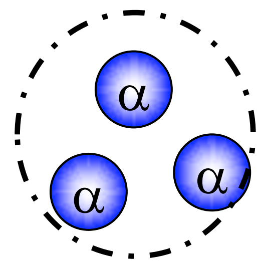


Dineutron-cluster?

Dineutron-condensation?



Hoyle state



alpha-cluster

alpha-condensation

A.Tohsaki, H.Horiuchi, P.Schuck,G.Ropke,
PRL 87, 192501 (2001).

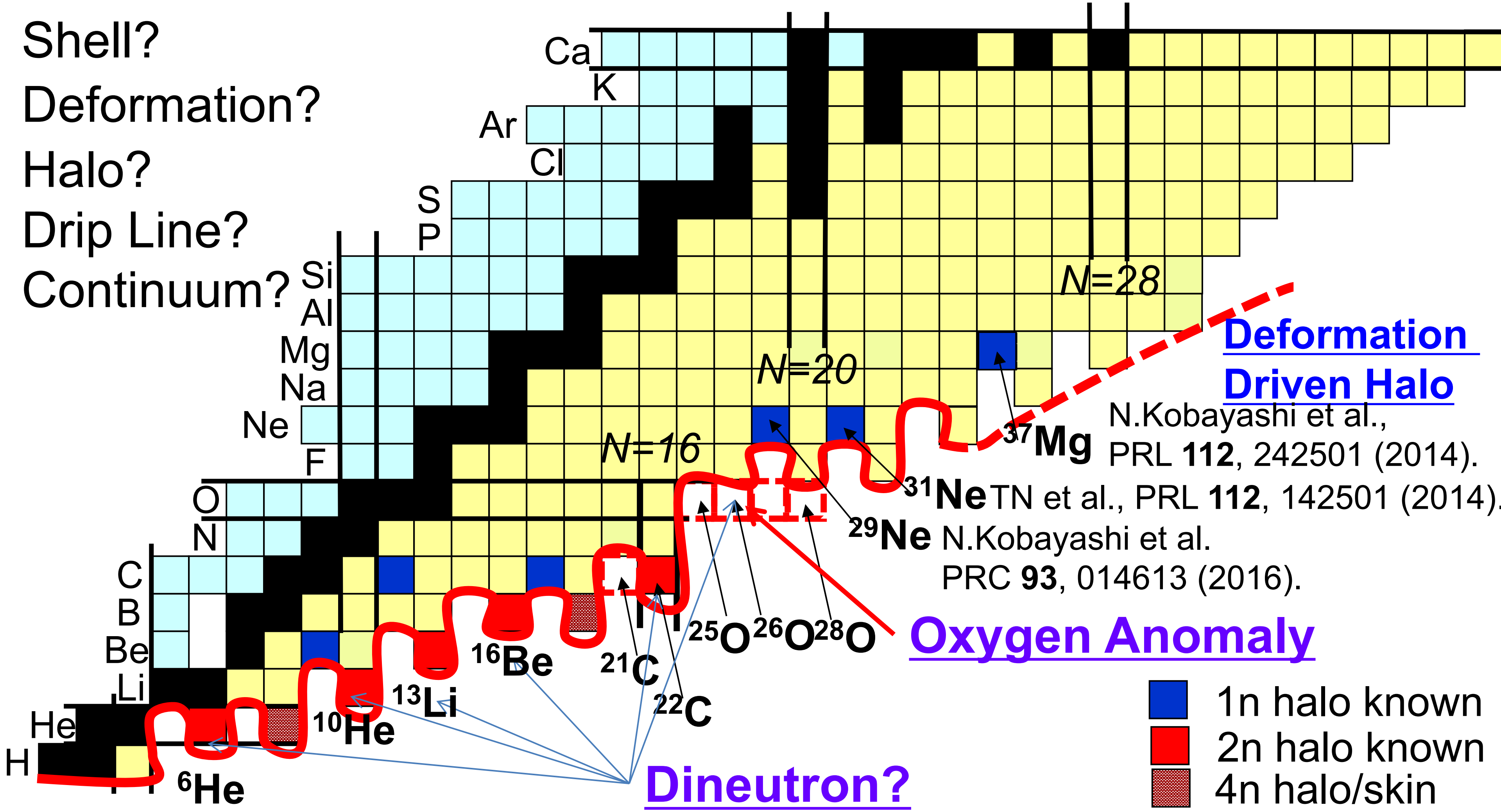
Evolution Towards the Stability Limit

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

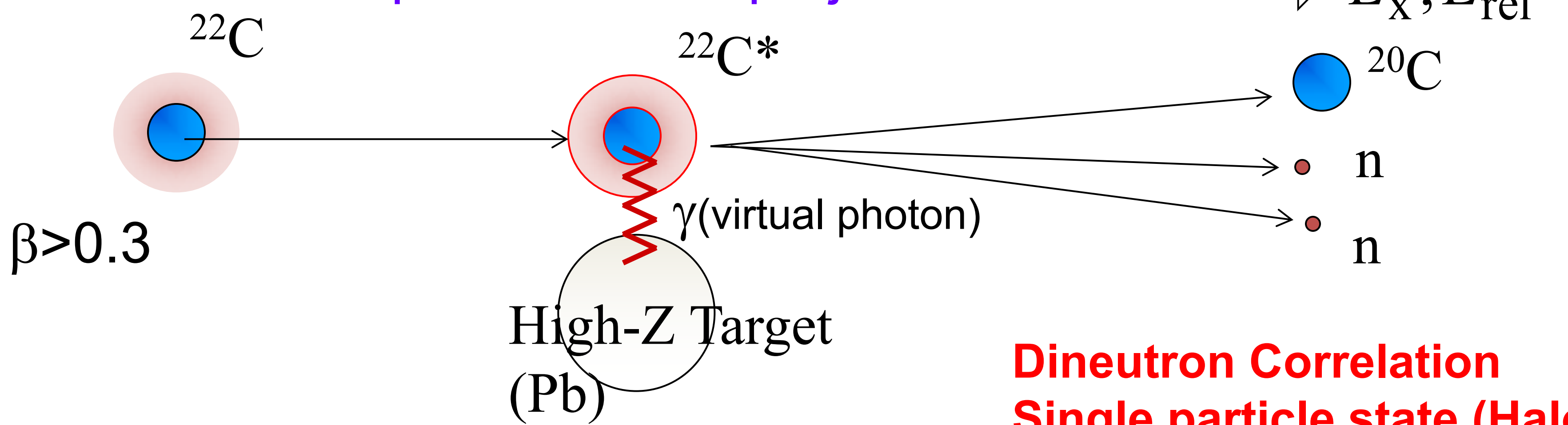
Coulomb Breakup

→Photon absorption of a fast projectile

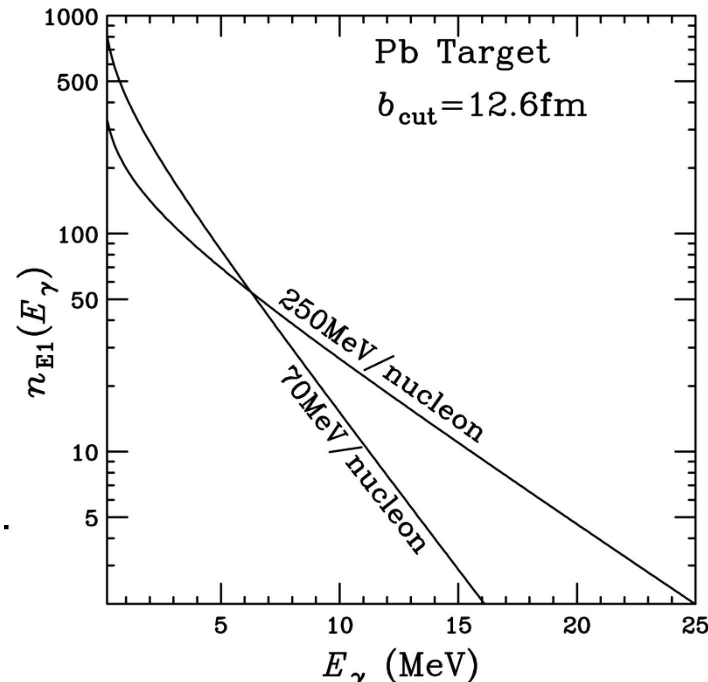
$\vec{P}(n), \vec{P}(n), \vec{P}(^{20}\mathrm{C})$

Invariant Mass

$\Rightarrow E_x, E_{rel}$



Dineutron Correlation
Single particle state (Halo)



Equivalent Photon Method

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

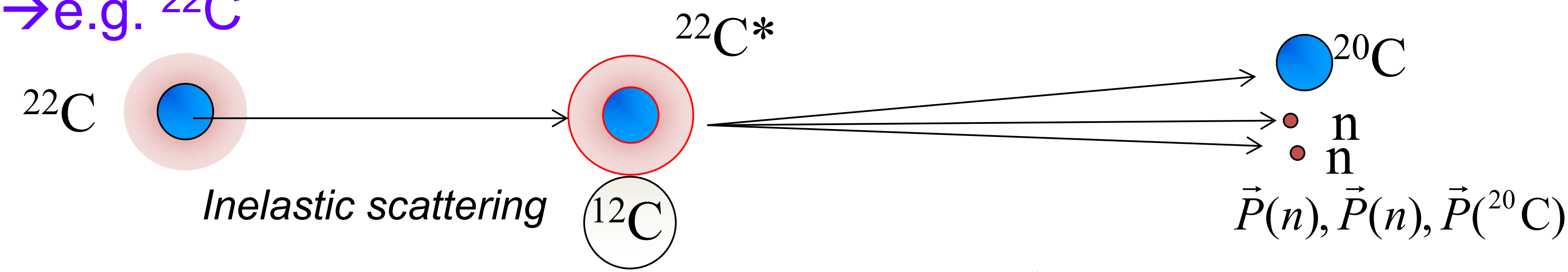
Cross section = (Photon Number)x(Transition Probability)

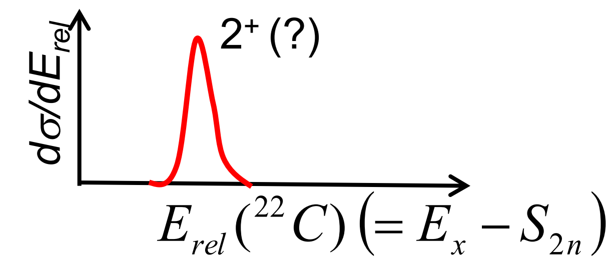
C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).
T. Aumann, T. Nakamura, Phys. Scr. T**152**, 014142(2013).

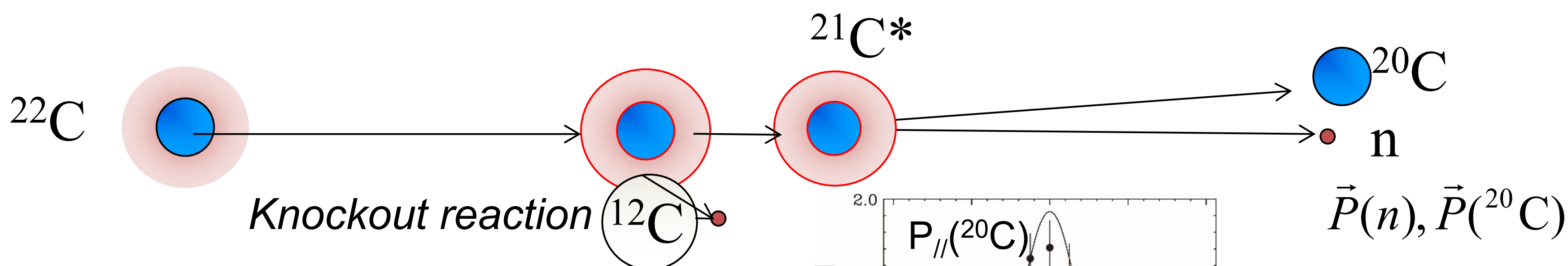
Halo → Soft E1 Excitation
(E1 Concentration at Ex<1MeV)

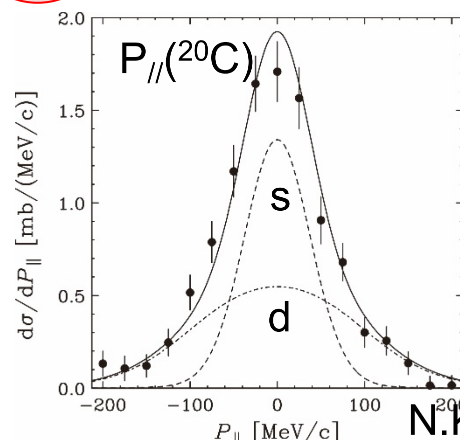
Nuclear Breakup – Case of 2n Halo

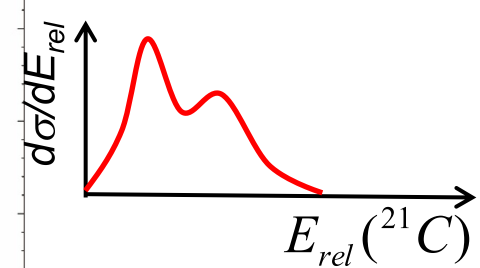
→e.g. ^{22}C





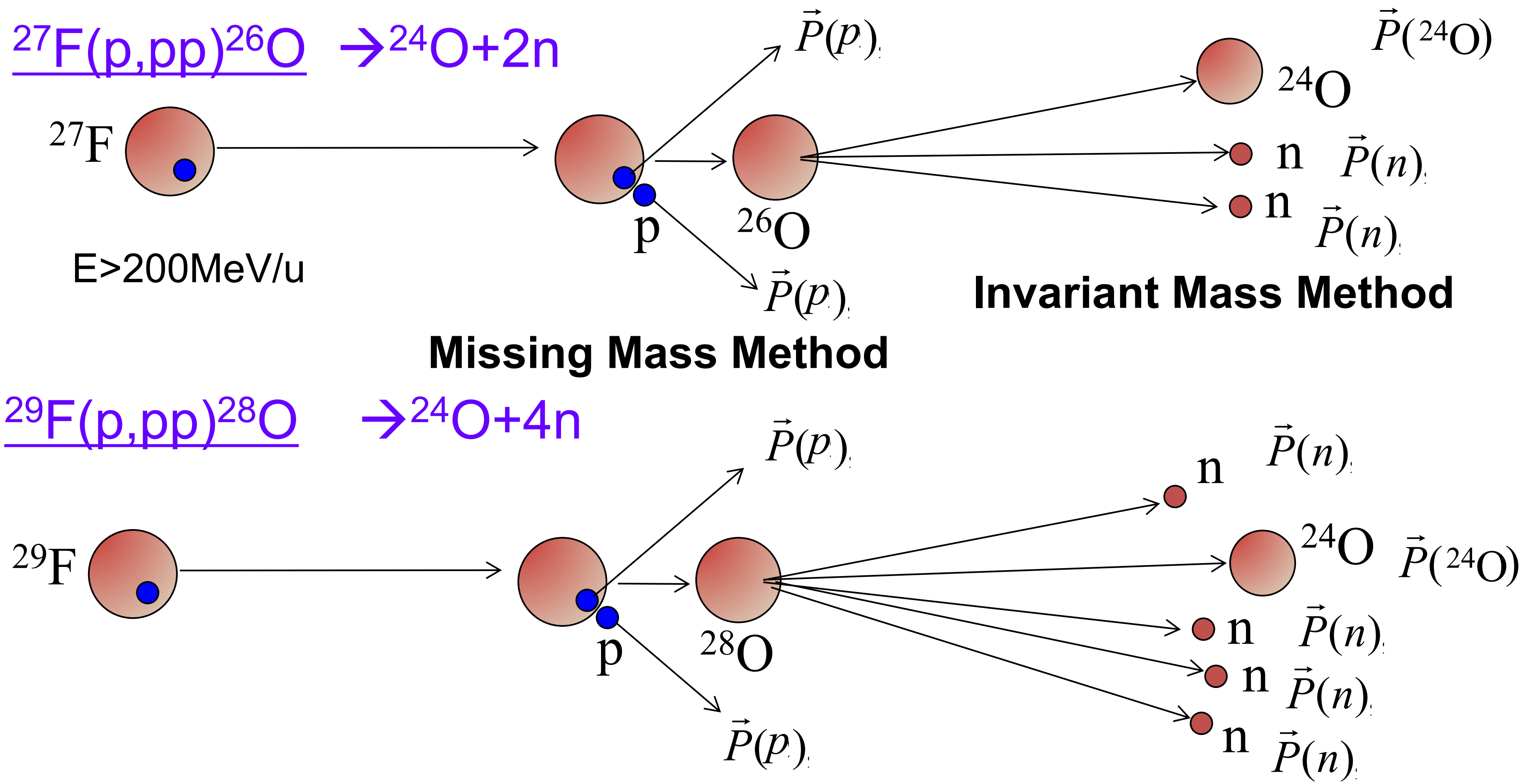






N.Kobayashi,TN,PRC2012

Quasi-free Scattering -with neutron decay



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

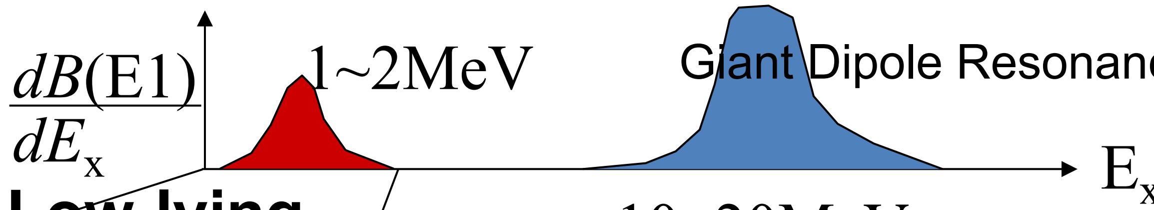
Missing Mass Method: - Low Yield, - Worse Resolution ~ a few MeV
+ Measurement of projectile and recoil protons only

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

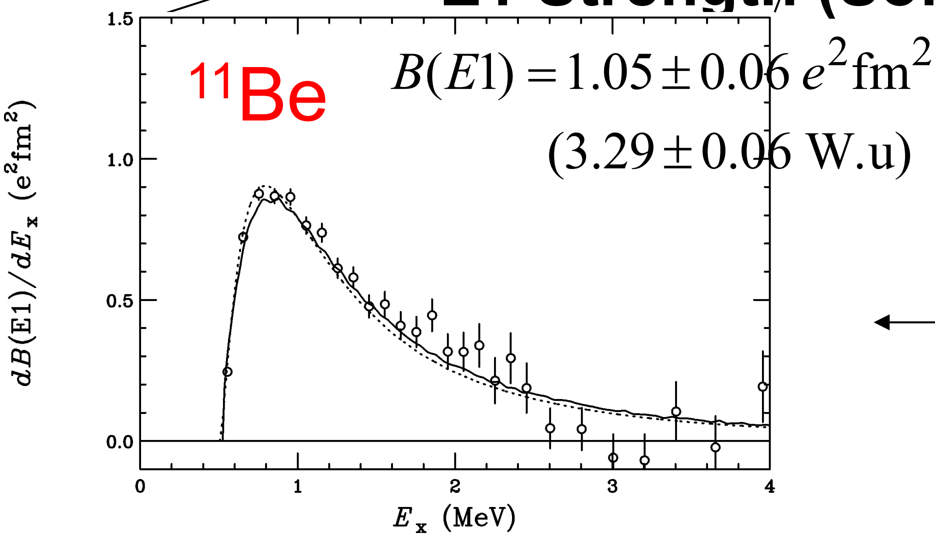
Breakup of 1n Halo Nuclei
in Island of Inversion (^{29}Ne, ^{31}Ne, ^{37}Mg)

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

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

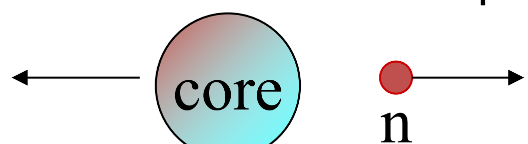


Low-lying E1 Strength (Soft E1 excitation)



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

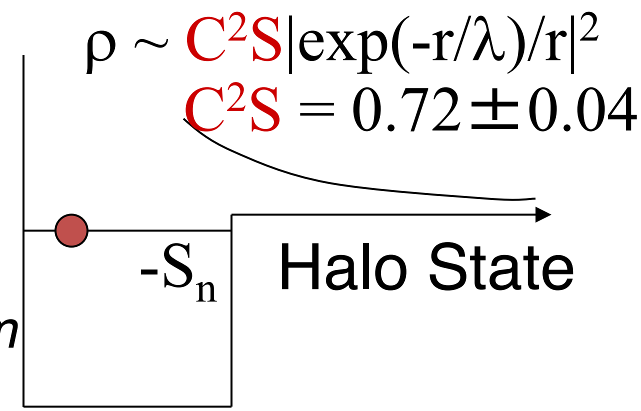
Direct Breakup Mechanism



E1 Strength

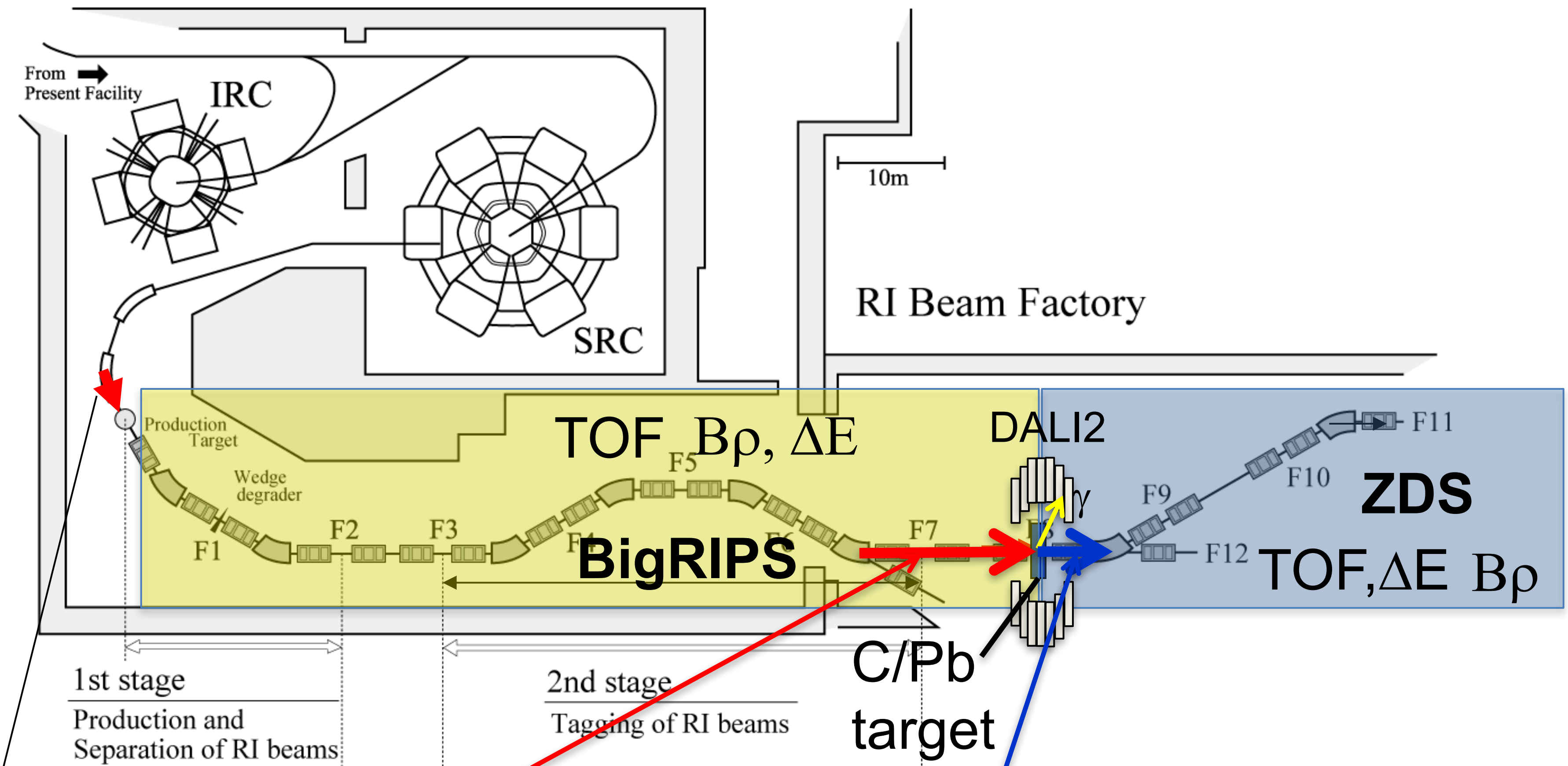
$$\frac{dB(E1)}{dE_x} \propto |\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} r Y^1{}_m|\Phi_{gs}\rangle|^2$$
$$\propto C^2S|\langle \exp(i\boldsymbol{qr})|\frac{Z}{A} r Y^1{}_m|s_{1/2}\rangle|^2$$

Fourier Transform



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

Inclusive nuclear/Coulomb Breakup at BigRIPS & ZDS at RIBF



^{48}Ca 345MeV/u

^{31}Ne (230 MeV/u)+C/Pb→^{30}Ne+(γ)+X

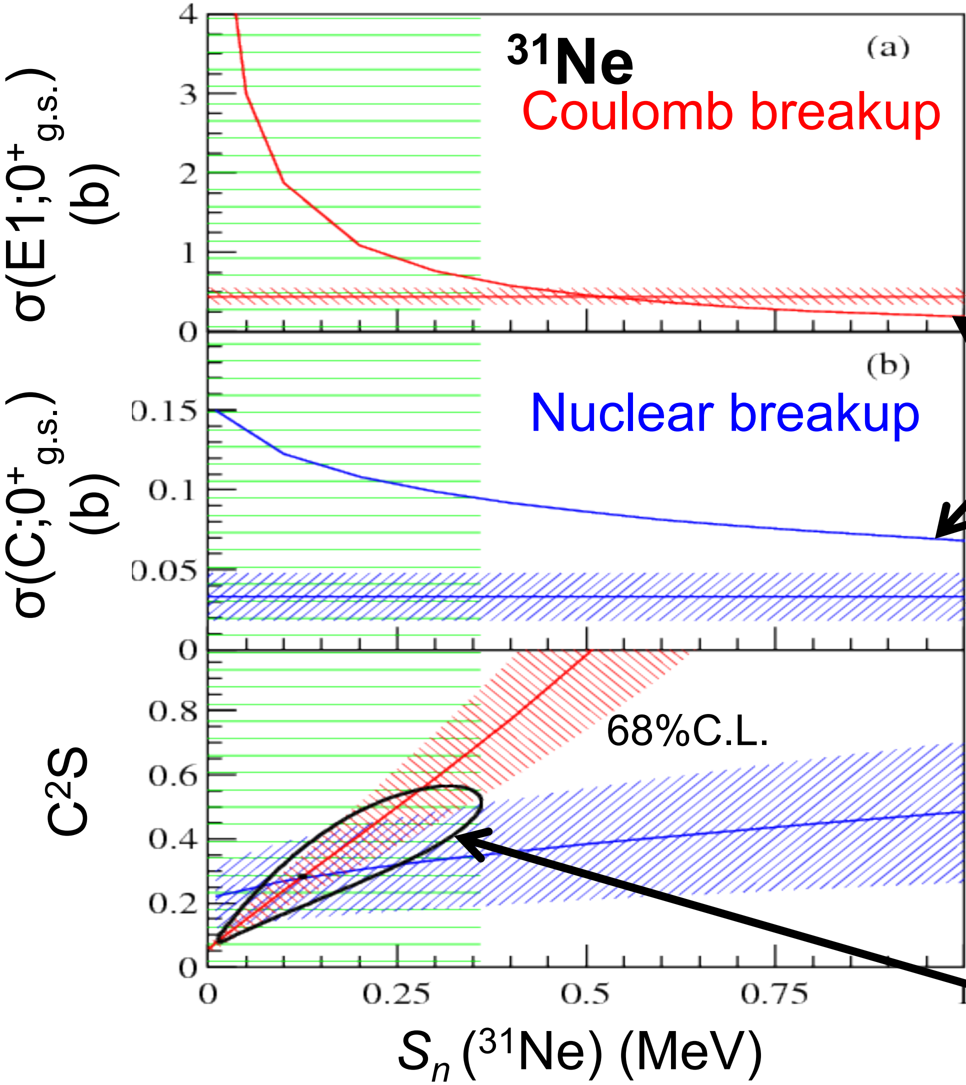
^{37}Mg (240 MeV/u)+C/Pb→^{36}Mg+(γ)+X

^{29}Ne (240 MeV/u)+C/Pb→^{28}Ne+(γ)+X

$\sigma_{-1n}(E1;\ 0_{gs}^{+})$

$\sigma_{-1n}(C;\ 0_{gs}^{+})$

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)

$|^{31}Ne_{g.s.}\rangle$: $3/2^-$
$|^{30}Ne(0^+_{g.s.}) \otimes p_{3/2}\rangle$ component

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

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

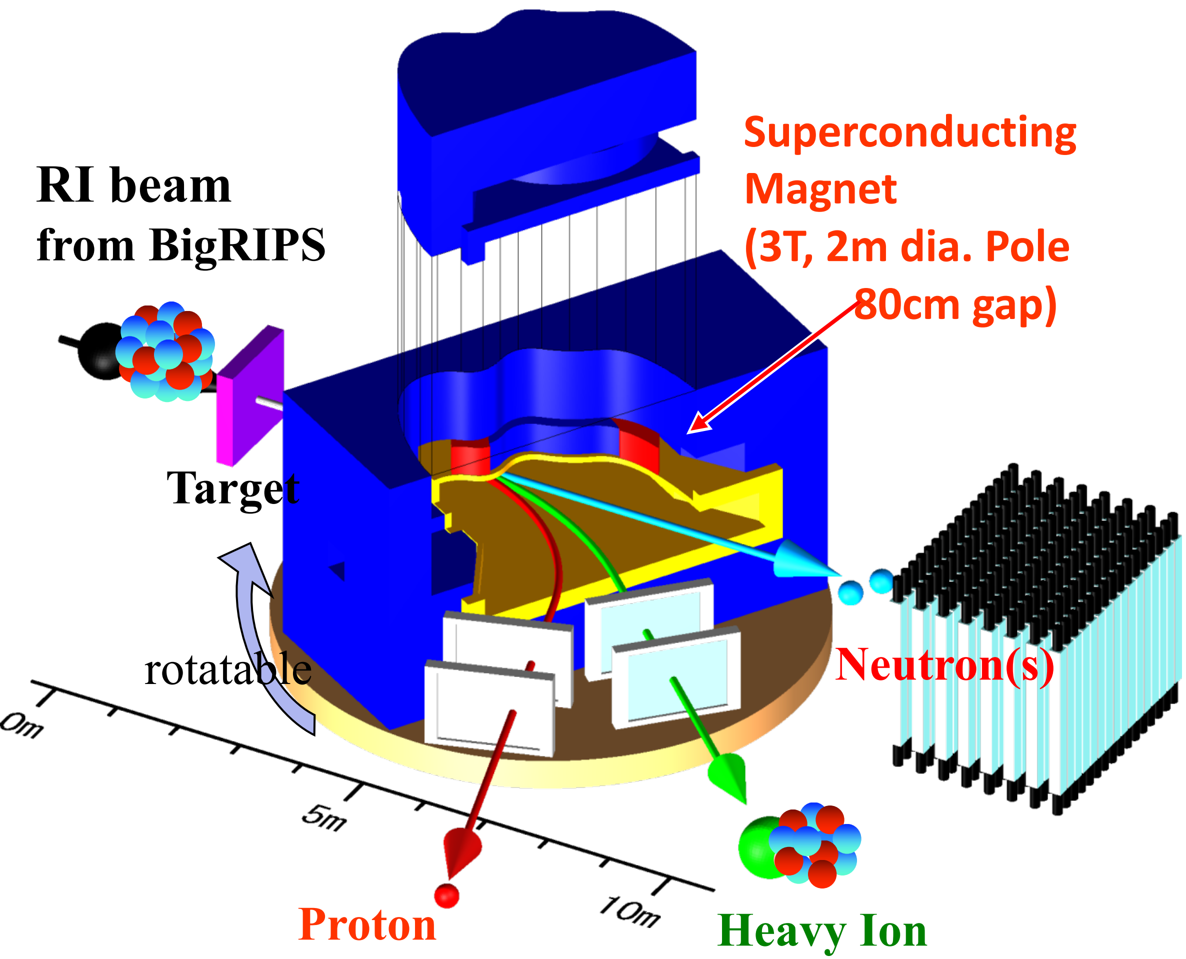
$S_n = 0.15^{+0.16}_{-0.10}$ MeV

^{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

SAMURAI at RIBF/RIKEN

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

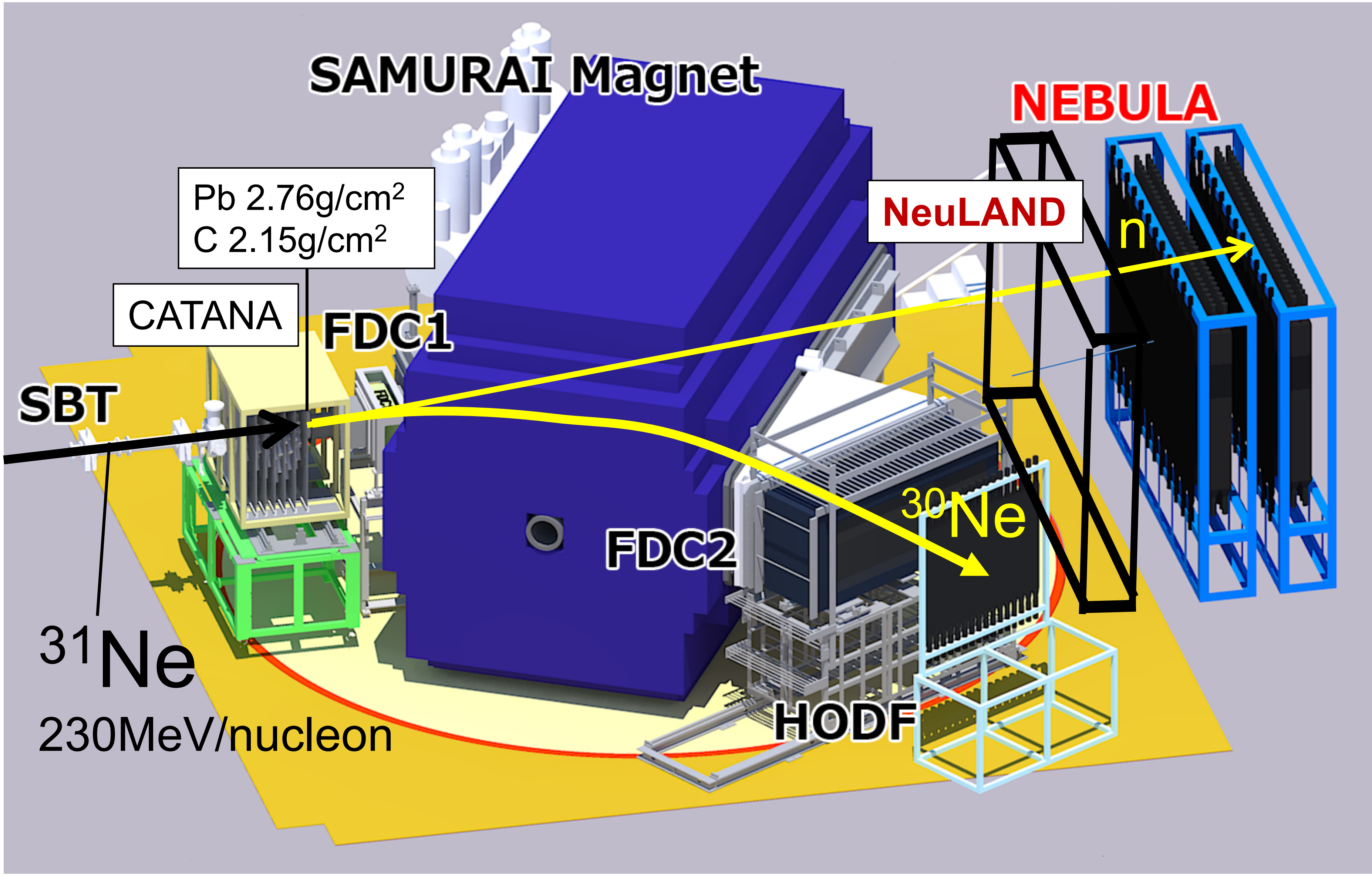
ΔE = 200 keV (σ) at E_{rel}=1MeV

Stage: Rotatable (-5 -- 95 degrees)

→Variety of Physics Opportunities

SAMURAI Experiment

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

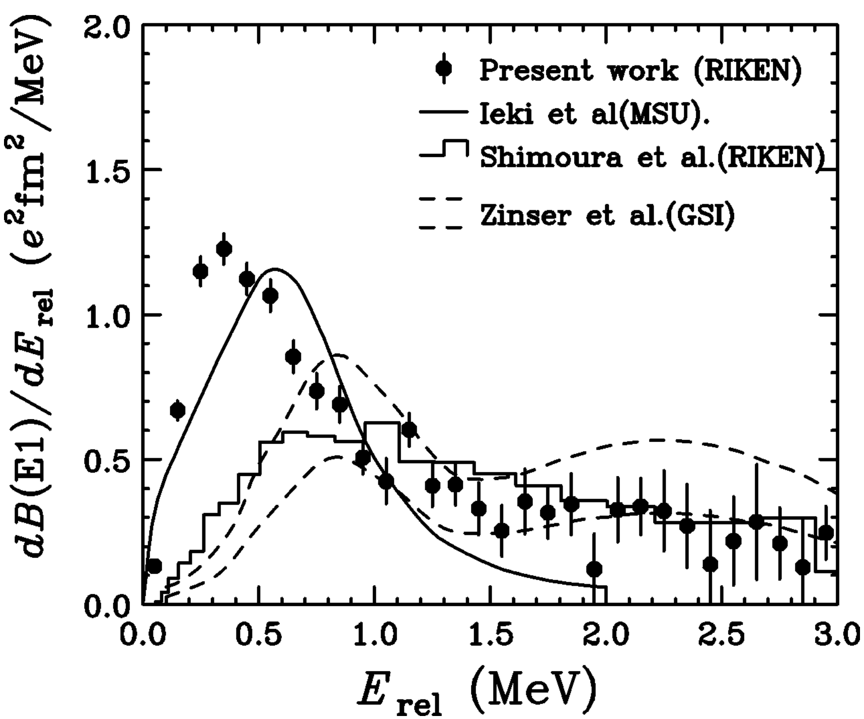


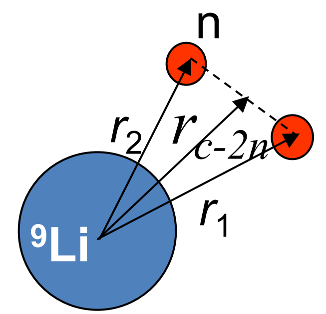
Coulomb Breakup of 2n Halo Nuclei (^{6}He,^{22}C)

Sun Yelei
S. Leblond, J.Gieblin, N.A.Orr
R. Minakata
et al.

Coulomb Breakup of 2n Halo
→ Probe of Dineutron Correlation

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





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

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

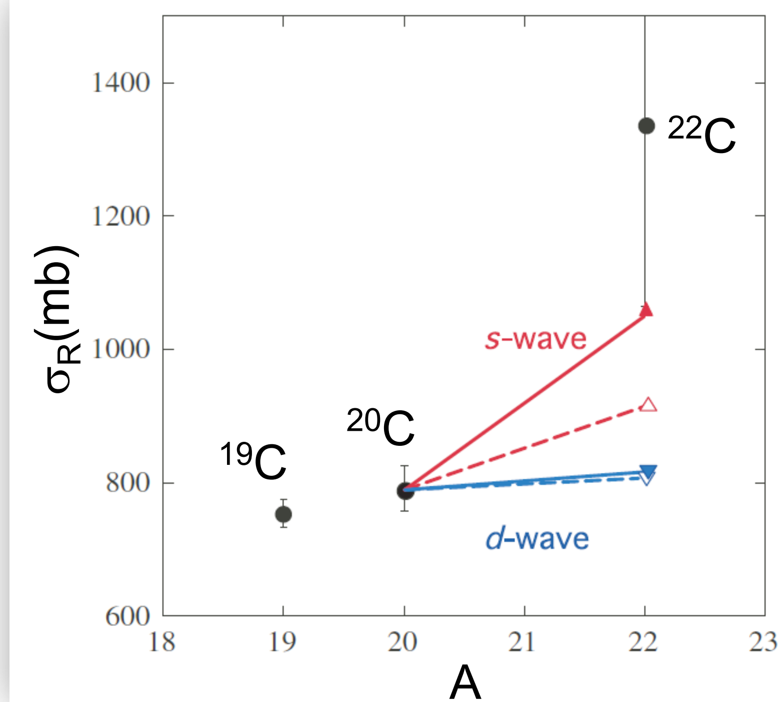
$$B(E1) = 1.42 \pm 0.18\ e^2 fm^2 (E_{\mathrm{rel}} \leq 3\mathrm{MeV})$$

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

Correlation in the Ground State of ^{11}Li

Soft E1 Excitation of 2n-halo
→ dineutron-like correlation

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



☐ Prominent 2n-Halo?

✓ **Huge Reaction Cross Section**

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

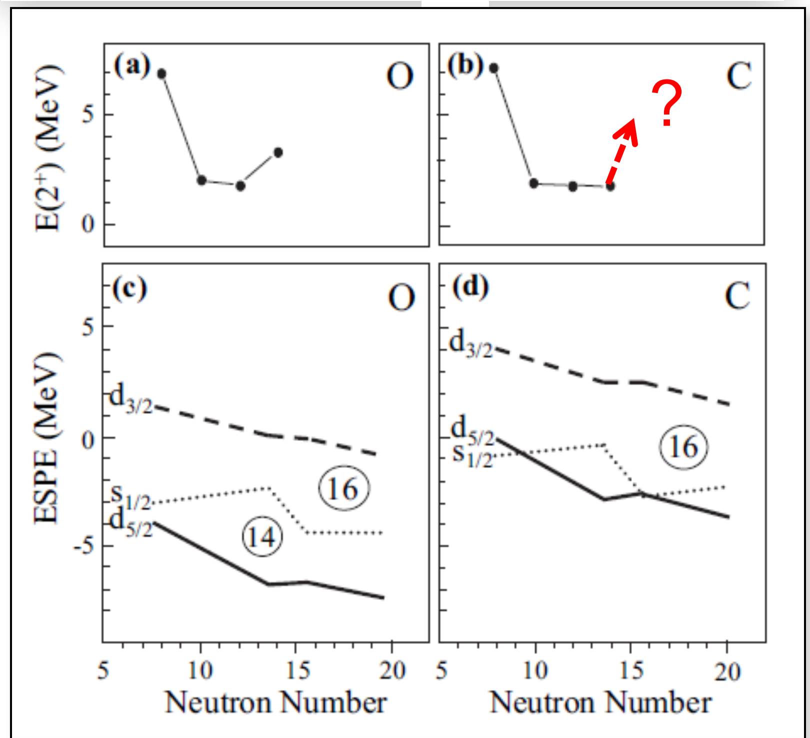
K.Tanaka et al., PRL 104, 062701(2010).

✓ **S_{2n}= –0.14(46) MeV**

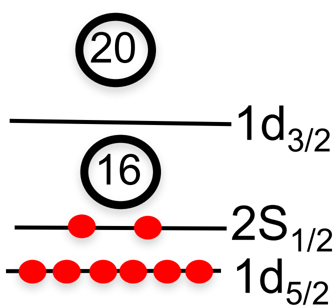
L.Gaudefroy et al. PRL109,202503(2012).

✓ **Narrow Momentum Distribution** ~73MeV/c

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



☐ N=16 Magicity?

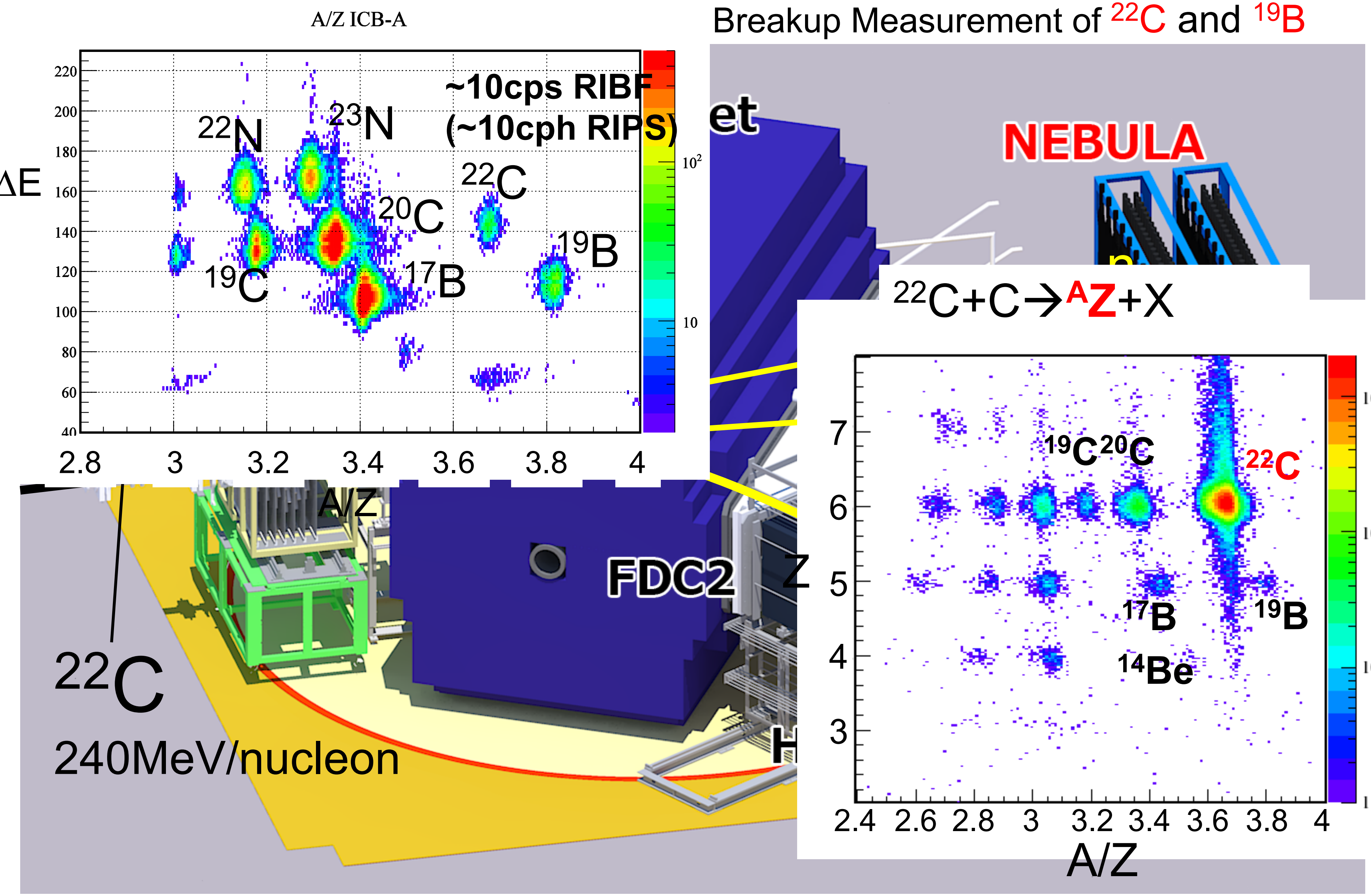


A.Ozawa et al., PRL 84, 5493 (2000).

M.Stanoiu et al., PRC78,034315 (2008).

SAMURAI Experiment May/2012

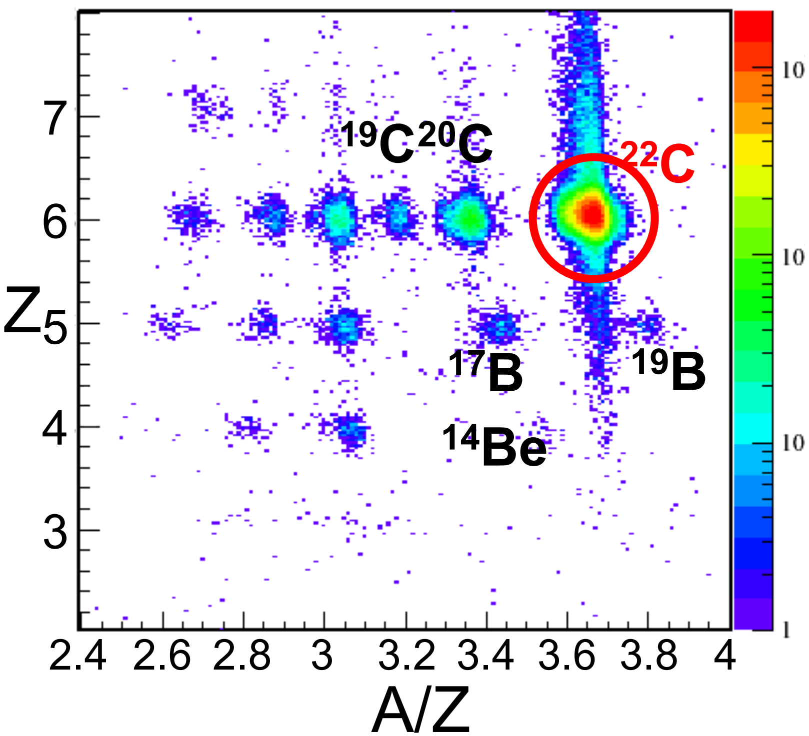
Breakup Measurement of ^{22}C and ^{19}B

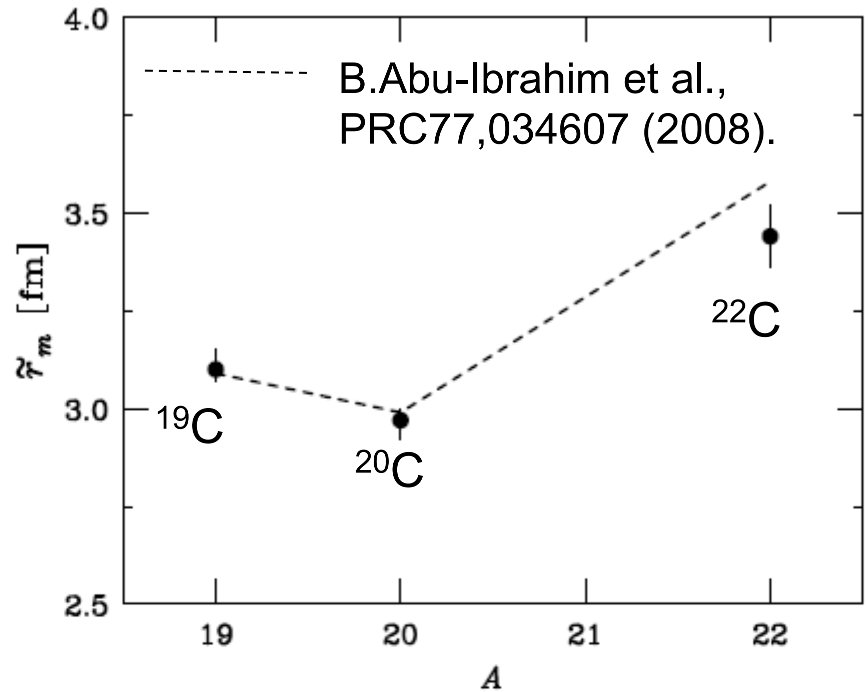


Reaction Cross Section of ^{22}C

Y.Togano, TN, Y.Kondo et al.,
Phys.Lett.B **761**, 412 (2016).

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





σ_R=1.280(23)b : r_{rms}=3.44(8) fm

Smaller than the previous result (~2σ):

c.f. K.Takaka et al, (p+^{22}C @40 MeV)

r_{rms}=5.4(9) fm

Spectroscopy of Barely Unbound 2n emitter ^{26}O (& Other studies on unbound oxygen isotopes)

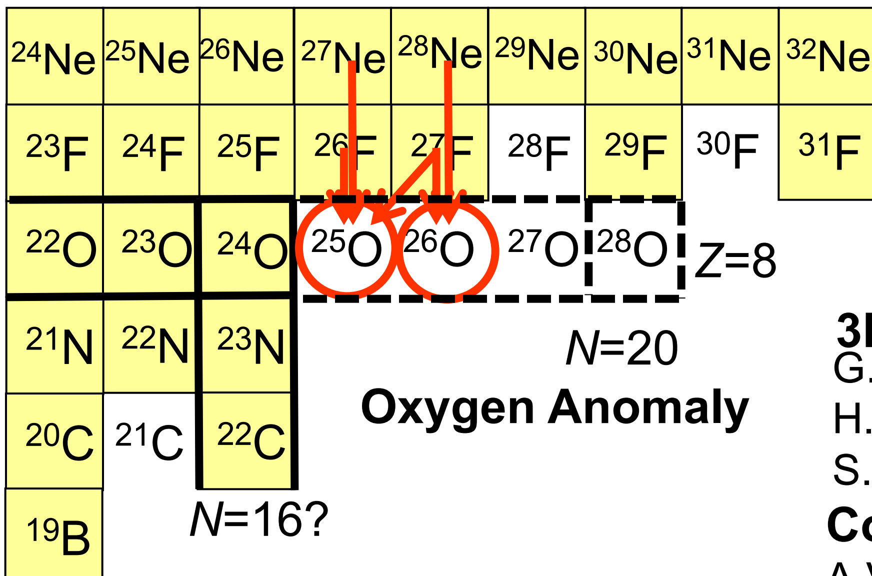
Yosuke Kondo et al.

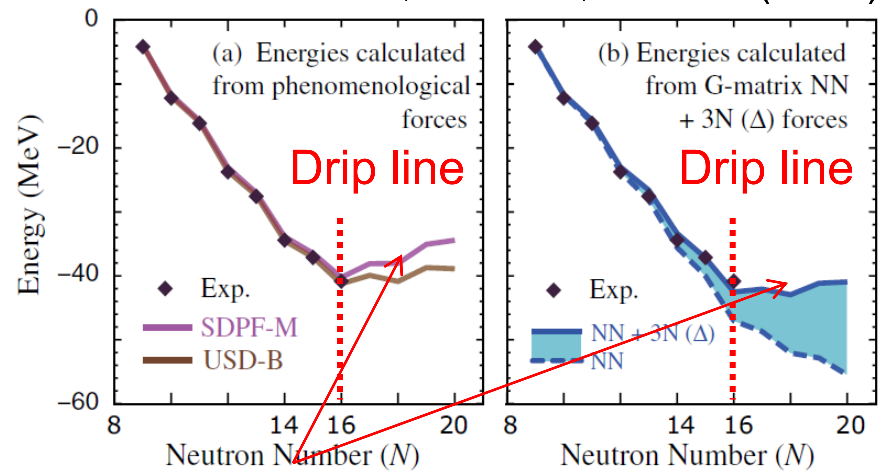
Study of unbound nuclei ^{25}O and ^{26}O at SAMURAI

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).

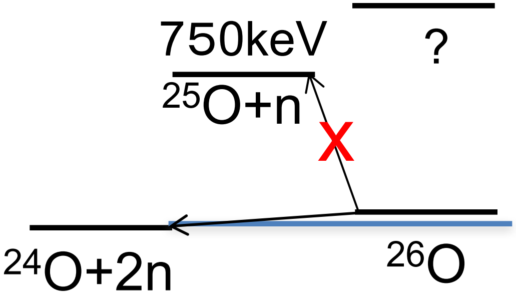
K. Tsukyiyama, T. Otsuka, PTEP2015, 093D01 (2015).

nn correlations:

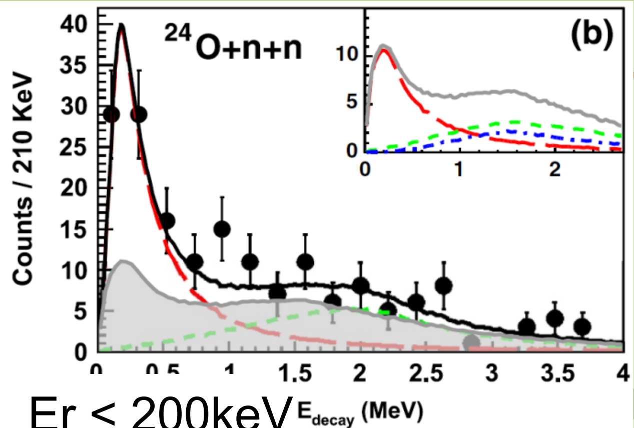
L.V. Grigorenko et al., PRL111,042501(2013).

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

2n radioactivity of ^{26}O?



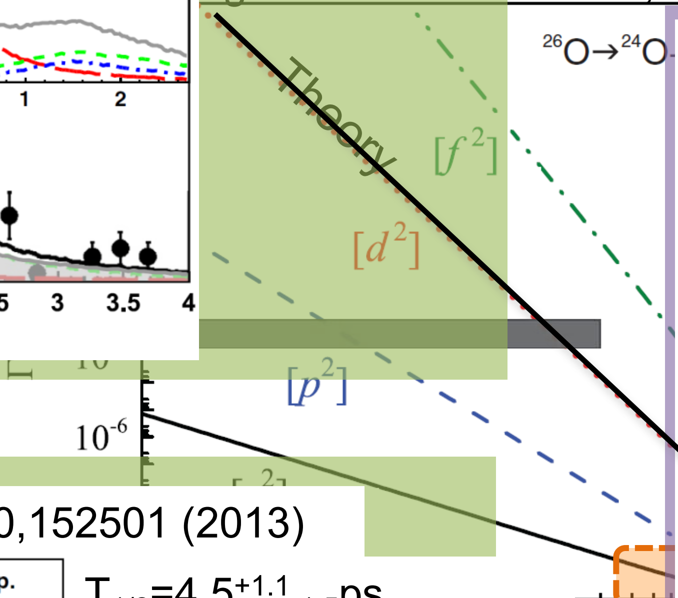
E. Lunderberg et al.
PRL108, 142503 (2012)



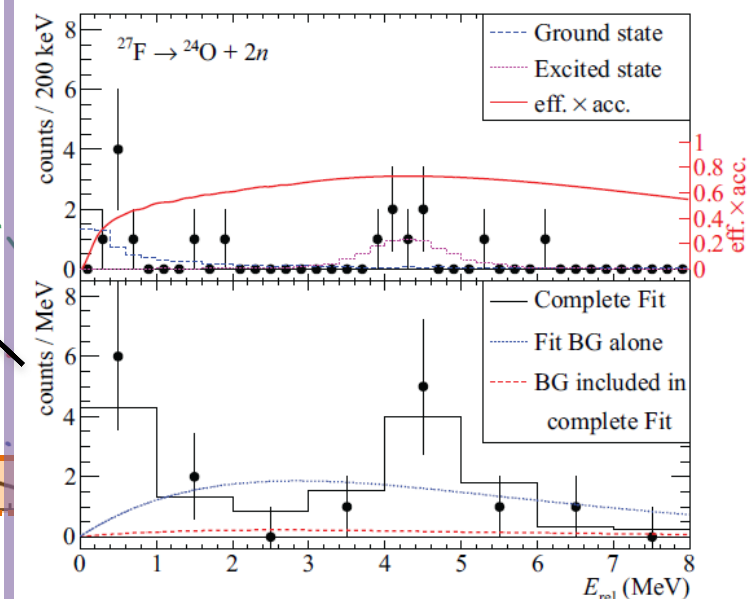
Er < 200keV

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

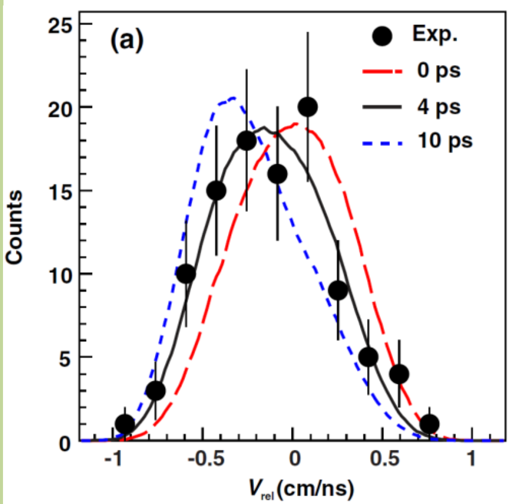
Grigorenko et al. PRC 84, 021303 (2011)



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?

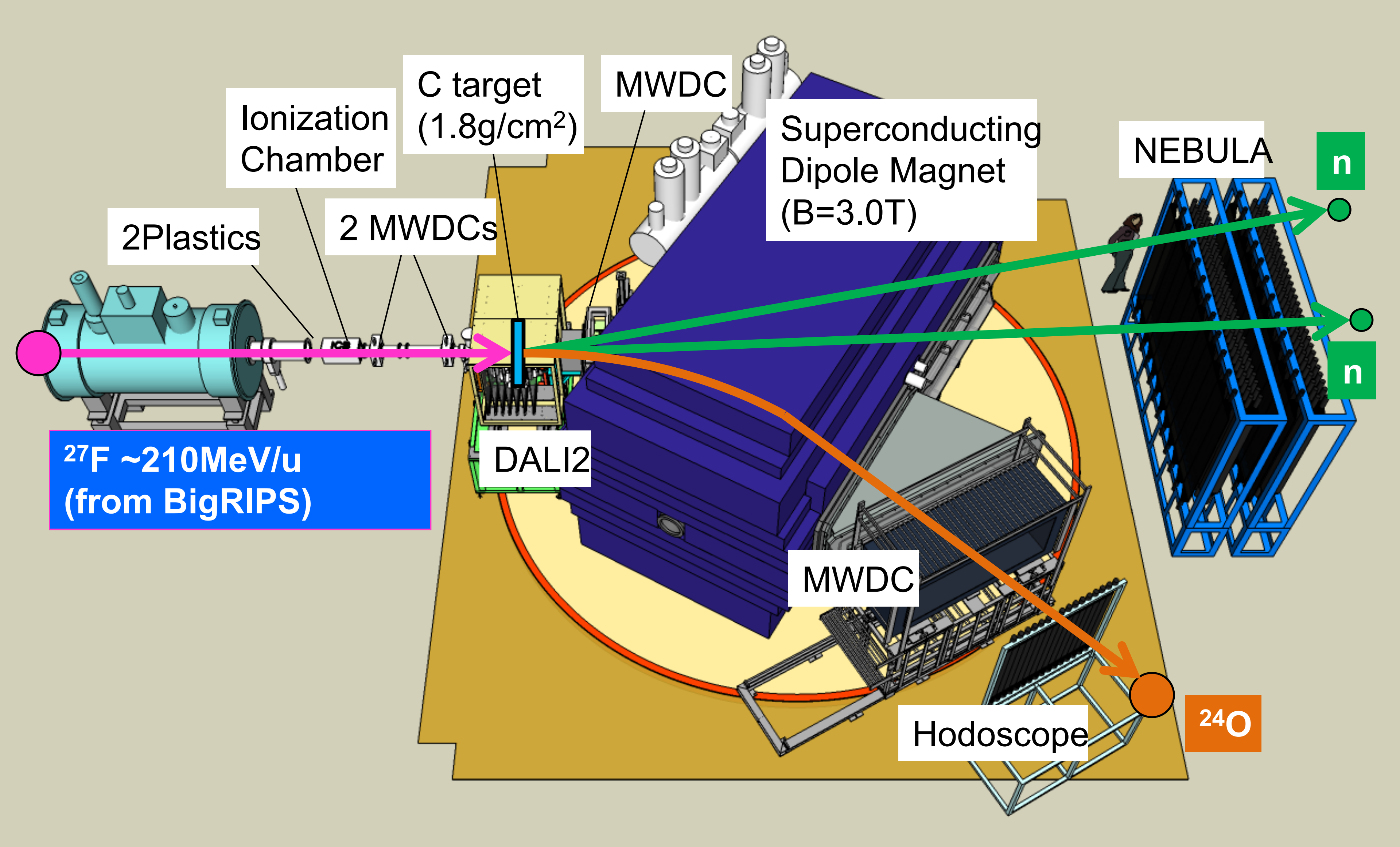
Usual 1n decay
Γ~MeV or keV

Er < 120keV (95% CL)
τ < 5.7ns

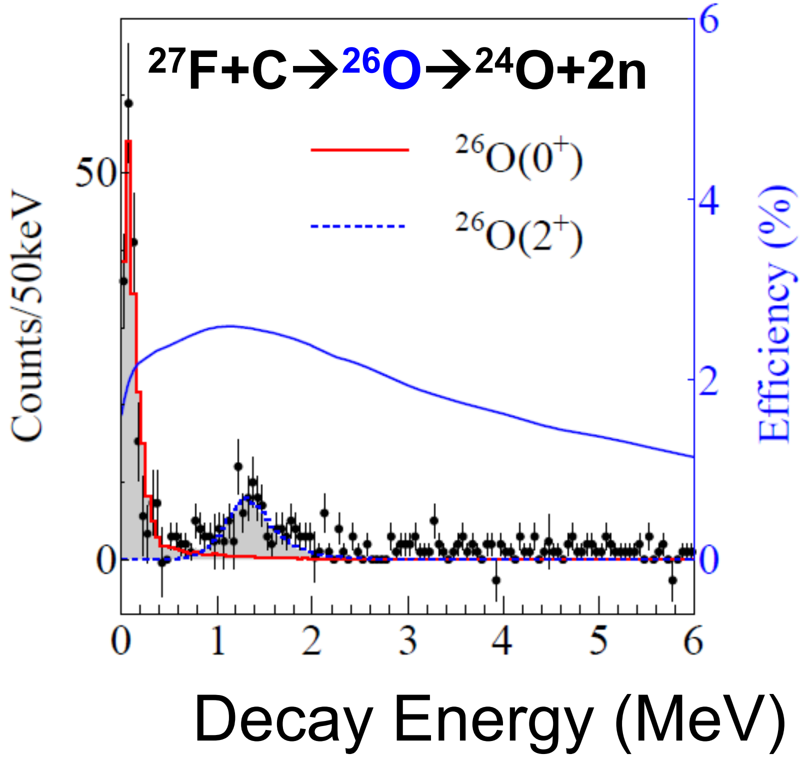
Excite state at 4.2MeV?

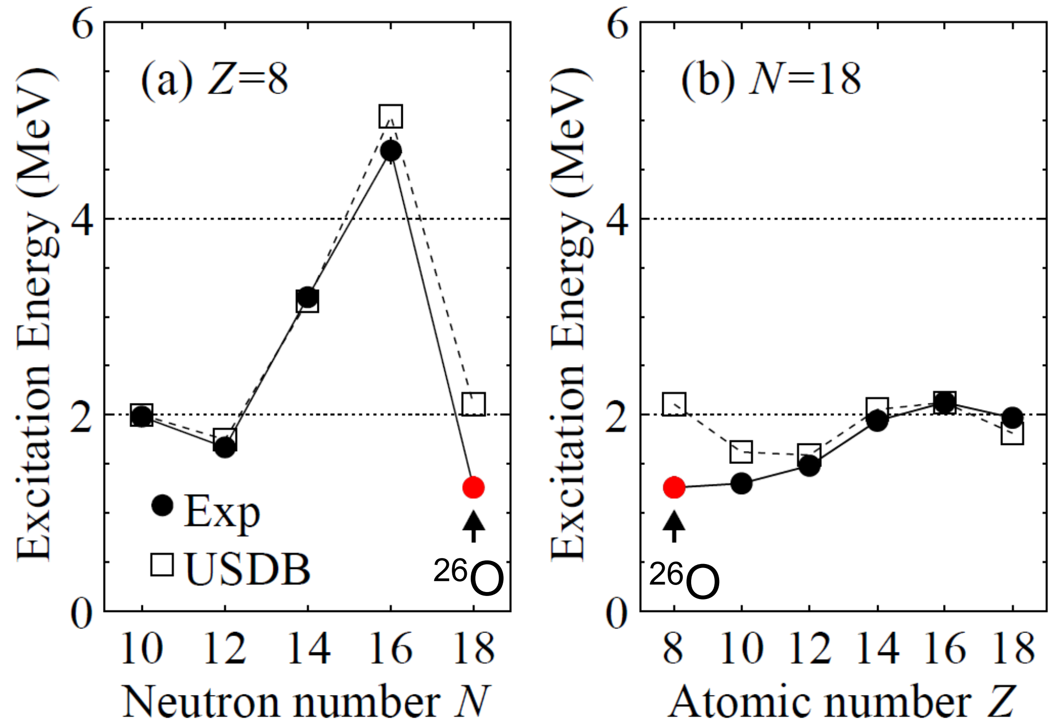
Large uncertainty of experimental study
- Only upper limit is given for the ground state energy
- Large systematic error in the lifetime measurement
- Excited State of ^{26}O?

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**?

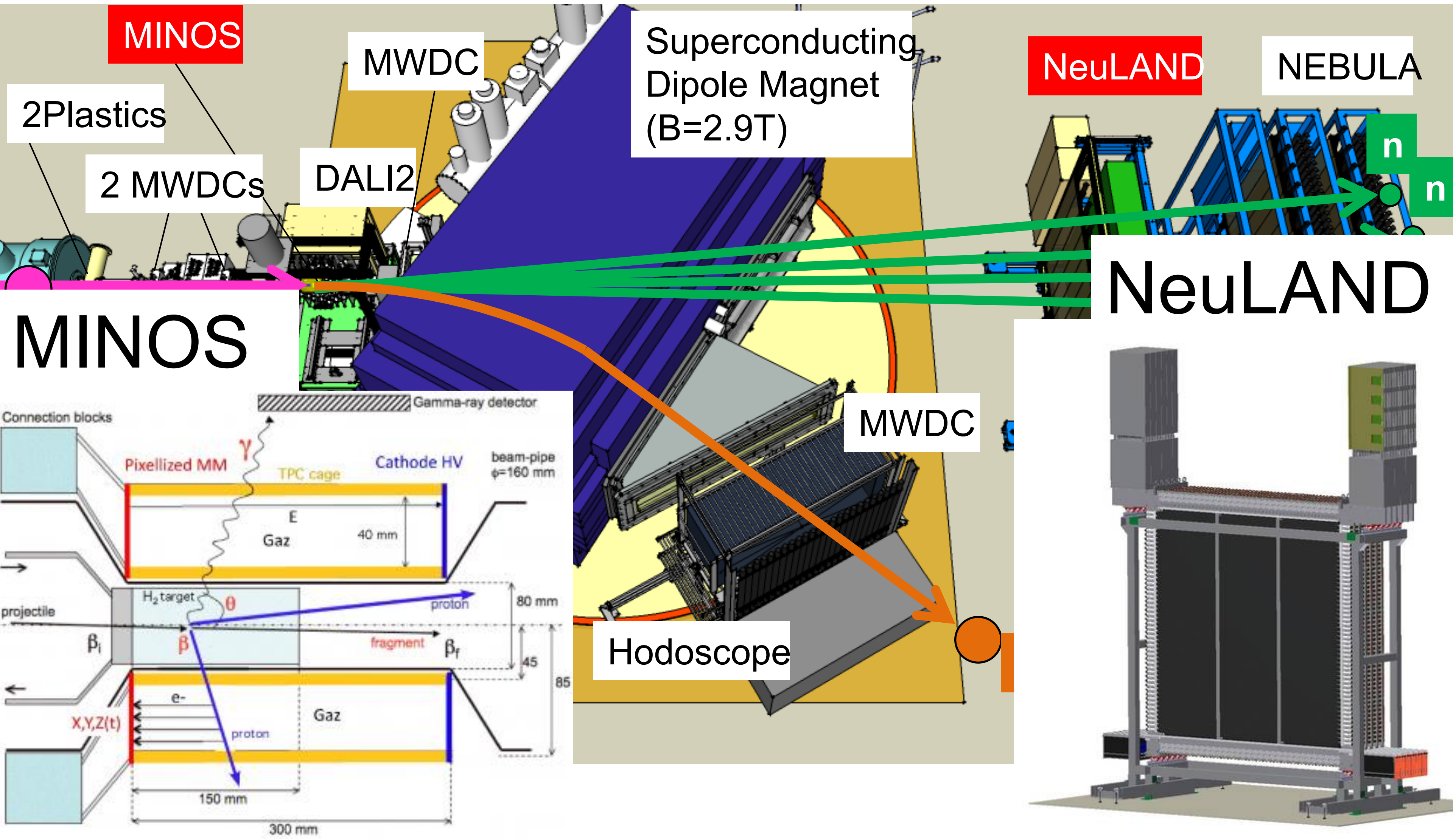
2n Correlations?, **3N force?**

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

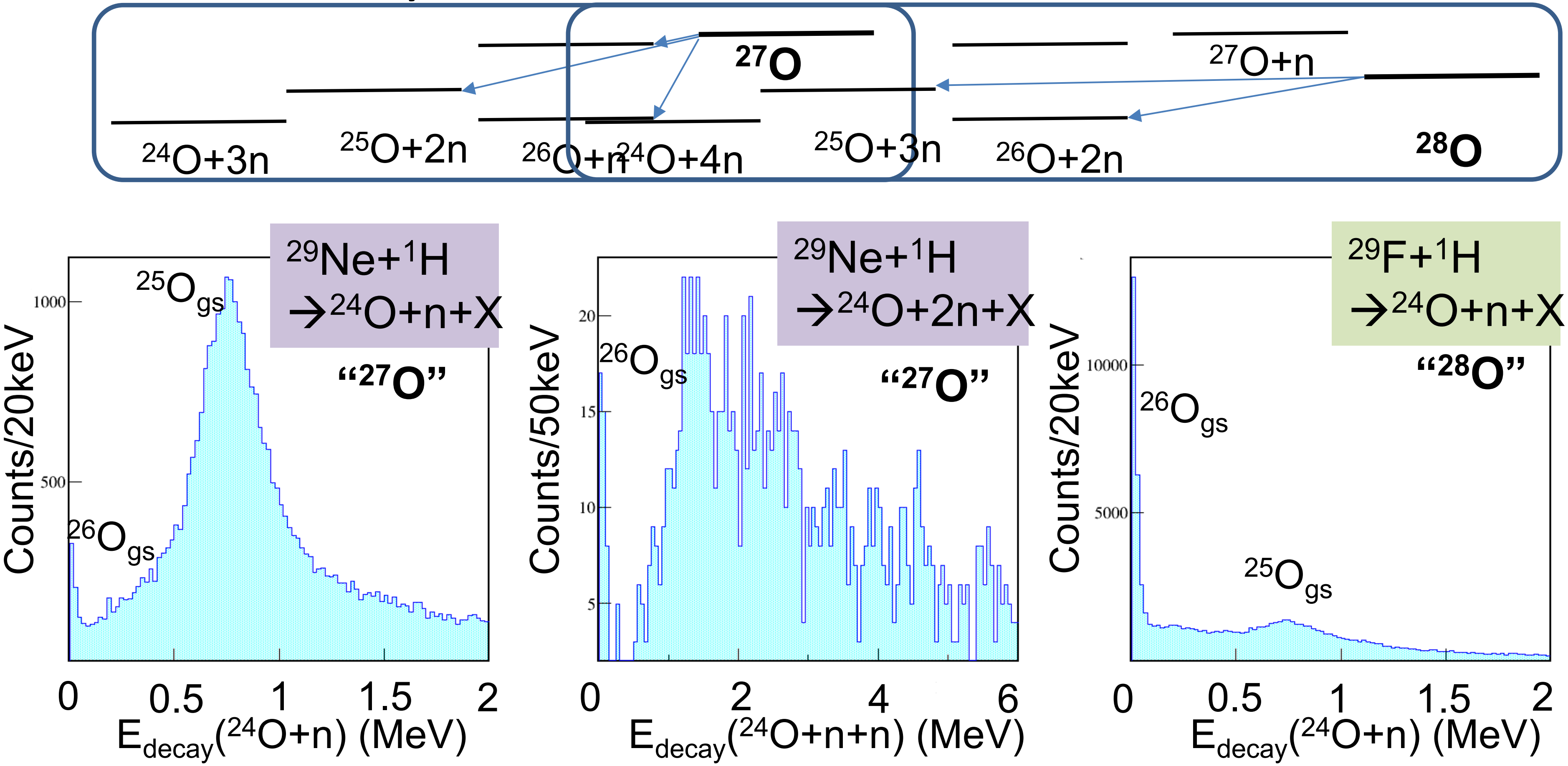
Towards ^{28}O (doubly magic nucleus?)

$^{27,28}O$ measurements in 2015 (SAMURAI21)

Slides: Y.Kondo



Preliminary results: $^{27,28}O \rightarrow {}^{24}O+n+X, {}^{24}O+2n+X$

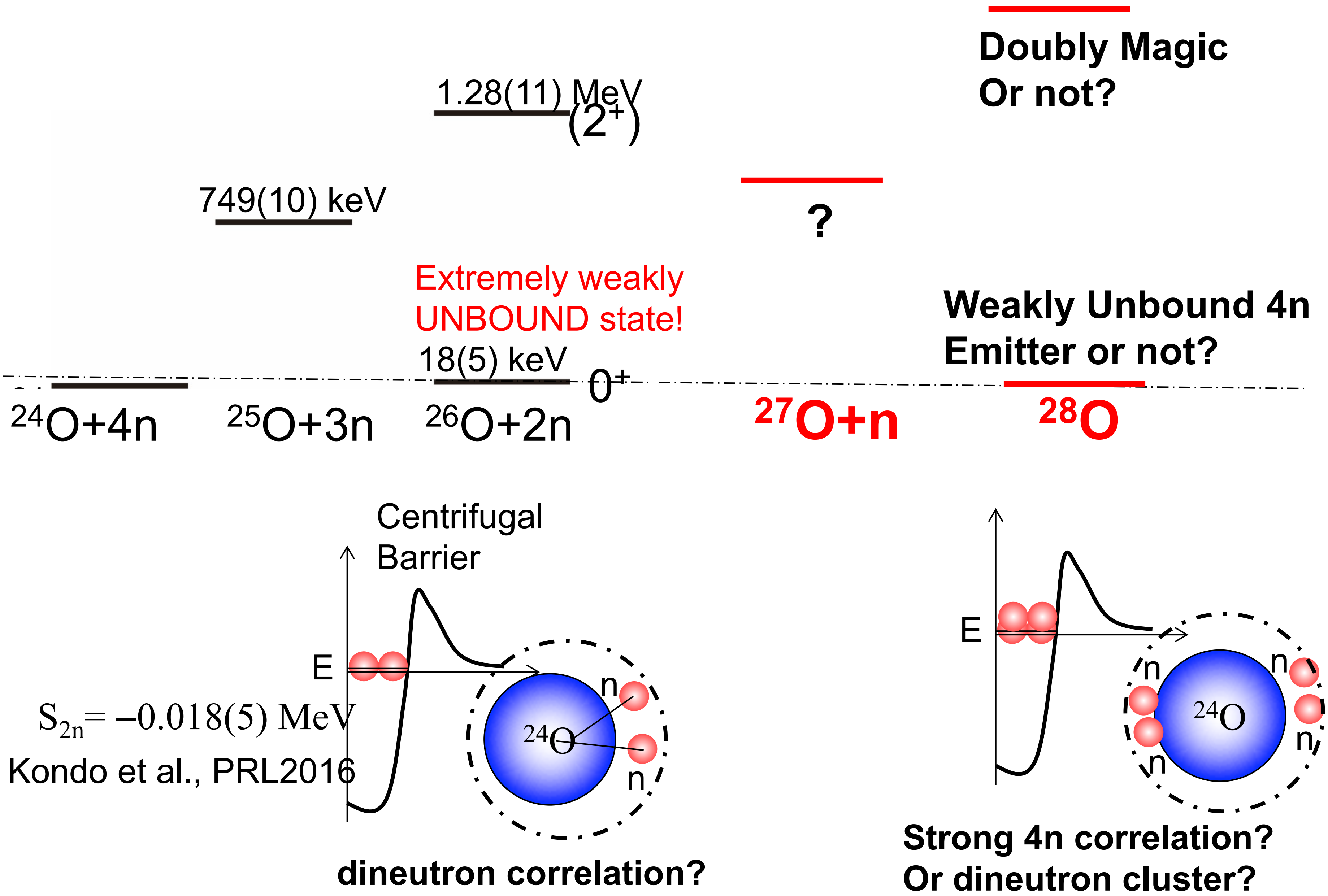


- ✓ Known ^{25}O, ^{26}O states have been observed (Direct production or sequential decay from ^{27}O or ^{28}O)
- ✓ Hints of intermediate (continuum) states from the decays of ^{27}O, ^{28}O states

  $^{27}O^* \rightarrow {}^{25}O+2n \rightarrow {}^{24}O+3n$

→Further analysis is on going for ^{24}O+3n, ^{24}O+4n spectra

Dineutron Cluster?



Summary and Outlook

- ✓ **Structure Interests: Barely bound and unbound nuclei**

  → Clustering at drip line? → **Dineutron?** **S=0,T=1 (c.f. S=T=0 for α)**

- ✓ **Probes: Coulomb/nuclear breakup, Quasi-free Scattering**
- ✓ **Breakup of Iol nuclei: ^{31}Ne**
- ✓ **Coulomb breakup of 2n Halo nuclei** ^{11}Li, ^{6}He, ^{22}C
  - ✓ **Reaction Cross Section of ^{22}C**

    Y.Togano, TN, Y.Kondo et al., PLB **761**, 412 (2016).

- ✓ **Spectroscopy of unbound nuclei by quasi-free scattering**

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

  →**^{26}O(0^+_{gs}): Very weakly unbound 2n states → Correlation? Continuum?**

  ^{26}O(2^+): Found for the first time at E_{rel}=1.28(11) MeV → Shell Evolution?

  → **^{27,28}O : Experiment Successfully Done, Nov-Dec, 2015.**

Near Future: Variety of spectroscopies with Coulomb/nuclear breakup reactions, Quasi-free scattering Along n-drip line

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

Day-one Collaboration

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

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

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

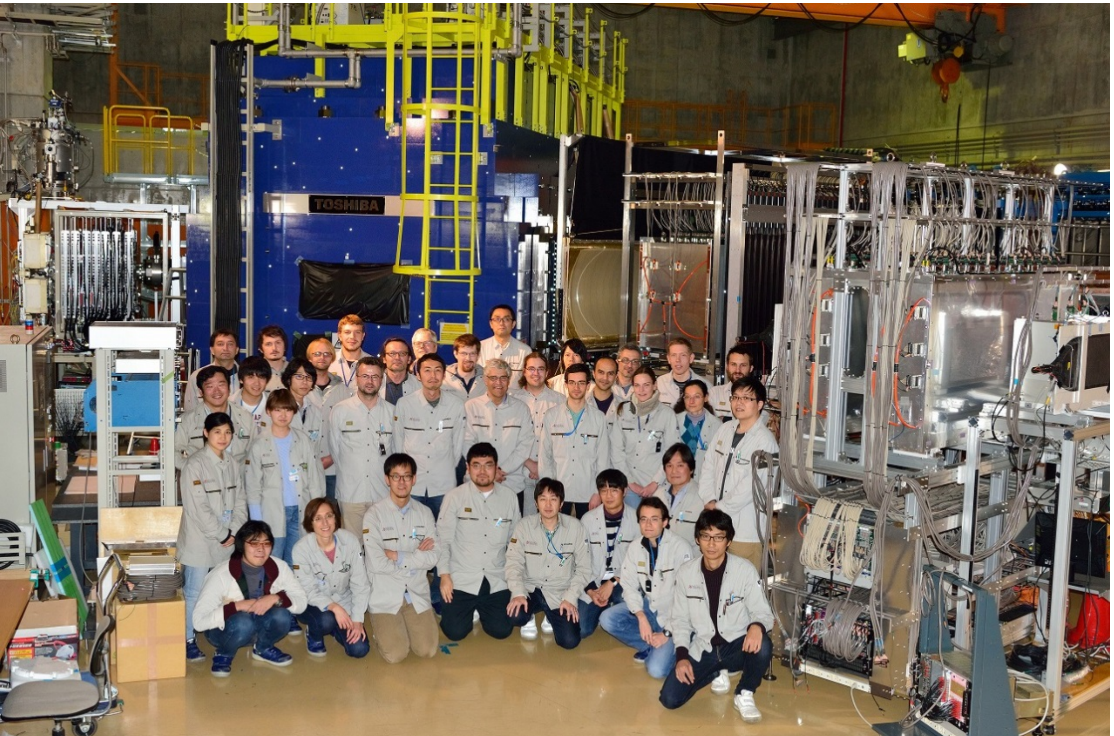
GANIL: A.Navin

Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

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

SAMURAI21 collaboration—^{27,28}O



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, 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
25 Institutes