Weakly bound and unbound nuclei near the Neutron Drip Line

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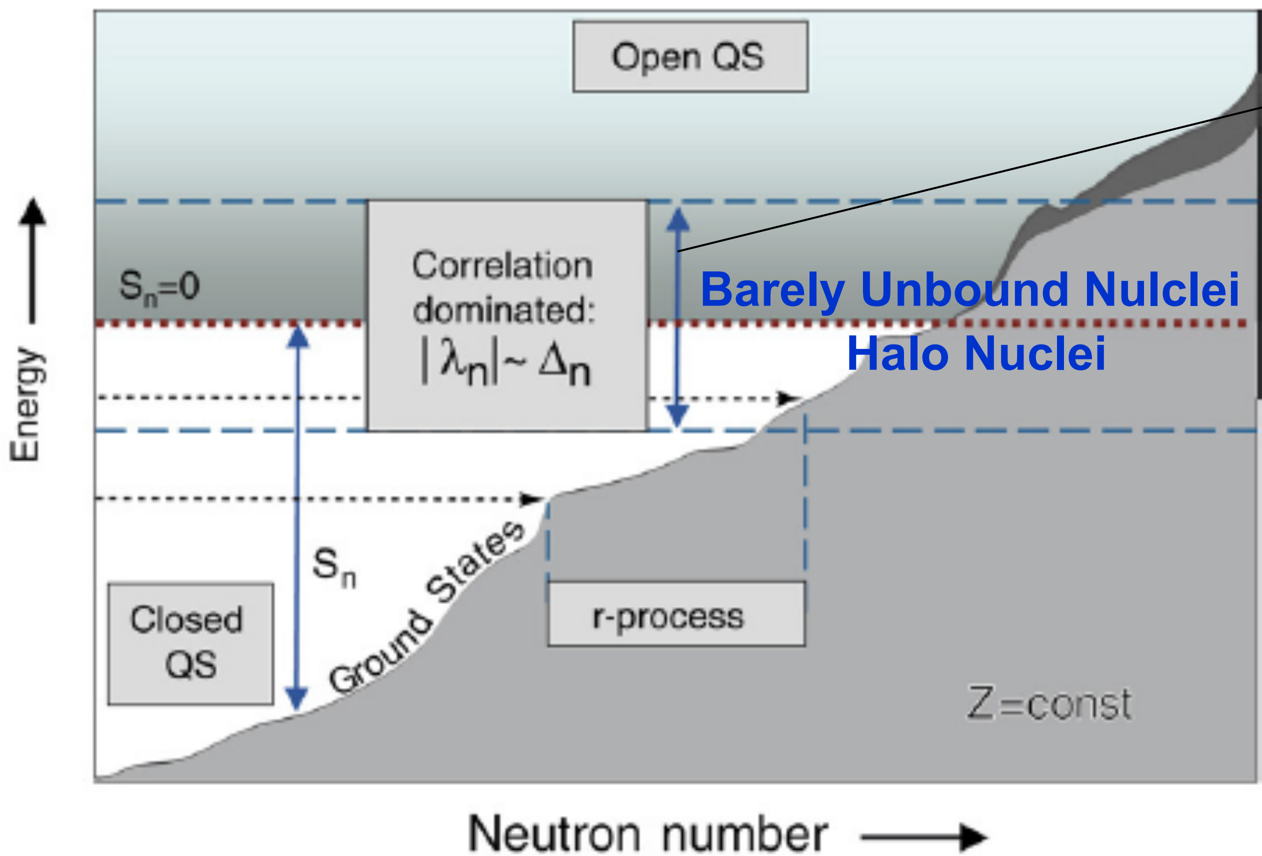
RIKEN NiSHiNA CENTER

International Nuclear Physics Conference, 11-16,Sep.,2016, Adelaide Convention Centre, Australia

Contents

Weakly Bound and Unbound Nuclei

➡ Strong nn Correlations



$$|S_n| << \Delta_n$$

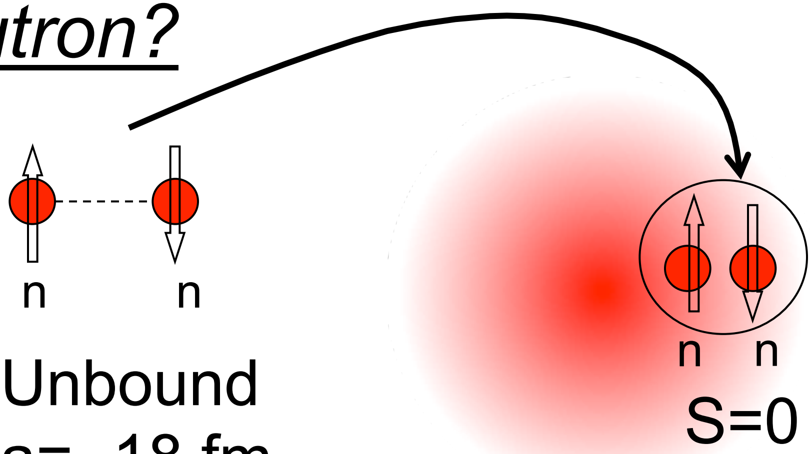
$$S_n \approx -\lambda_n - \Delta_n$$

Fermi Level

paring gap (~2MeV at A=30)

J. Dobaczewski et al., Prog. Part. Nucl. Phys. 59, 432 (2007).

Dineutron?

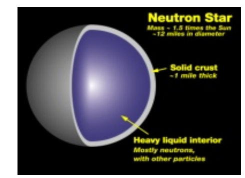


Unbound
a= -18 fm

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

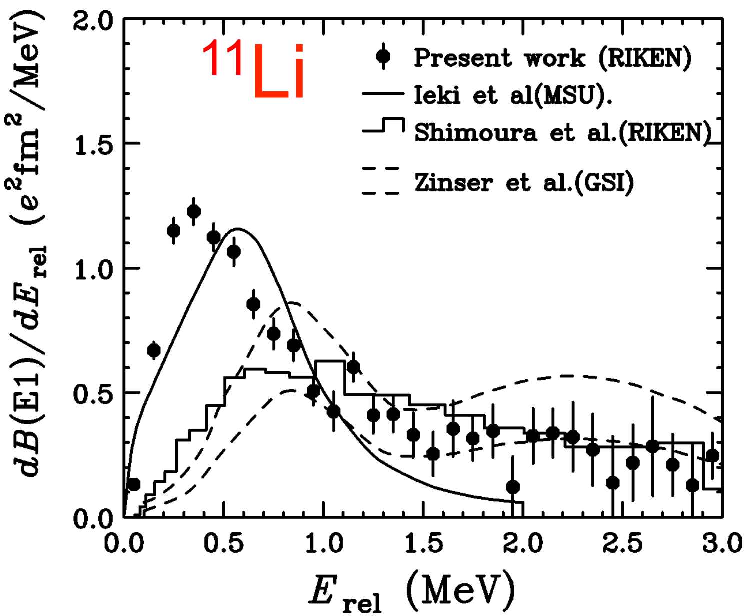
Dineutron:
@ Low-dense neutron skin/halo?
/surface of neutron star?

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

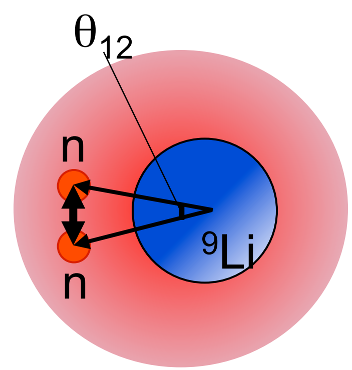


n-star

Electric-Dipole (E1) Response of ^{11}Li



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



Dineutron Correlation
→Strongly Polarized
→ Strong E1 Excitation

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

$$\rightarrow \langle \theta_{12} \rangle = 48^{+14}_{-18}\ \text{deg}.$$

Indirect Hint of Dineutron Correlation

Kubota's talk: ^{11}Li(p,pn)^{10}Li

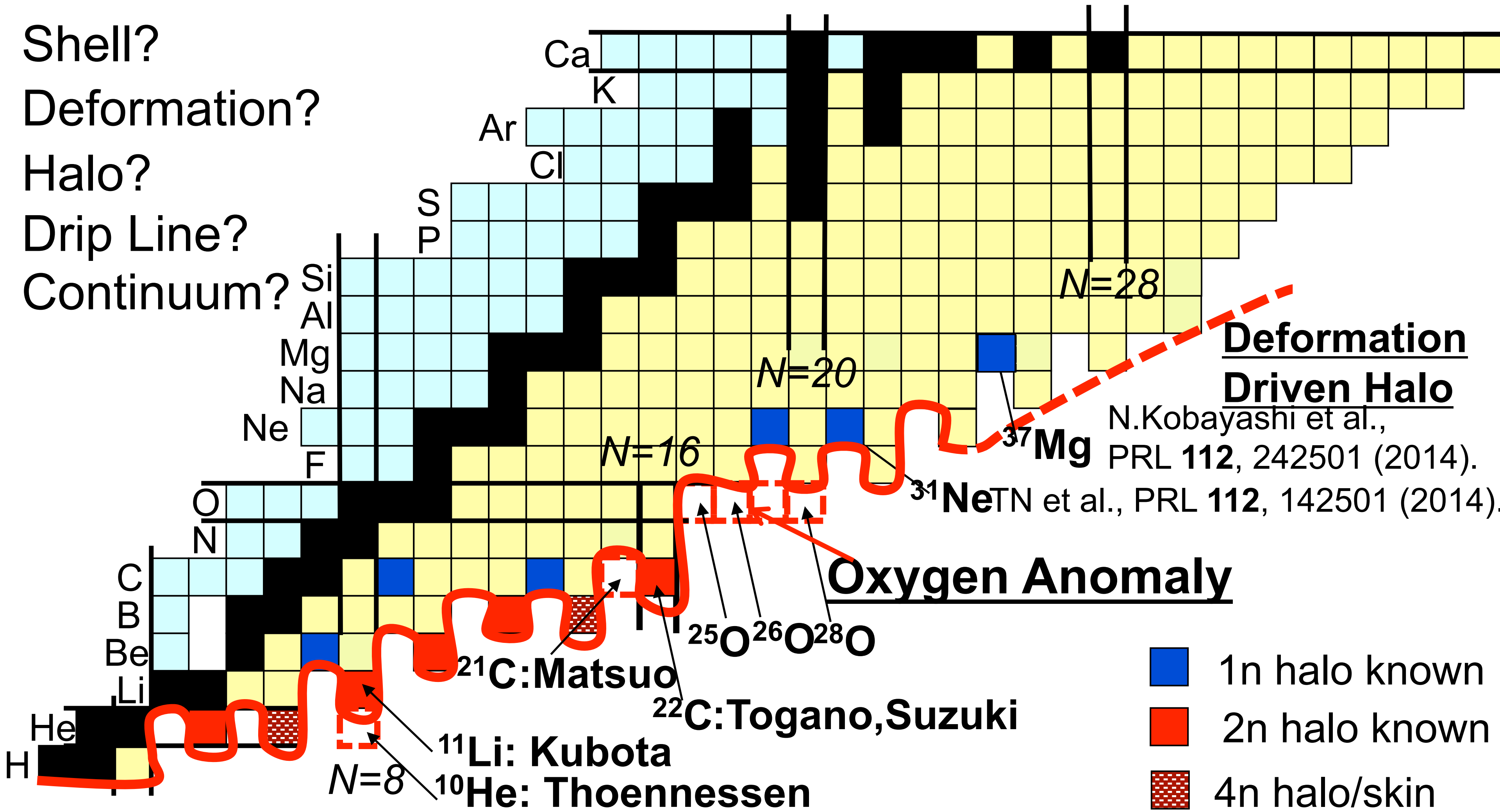
Evolution Towards the Stability Limit

Where is the neutron drip line?

What are characteristic features of drip-line nuclei?

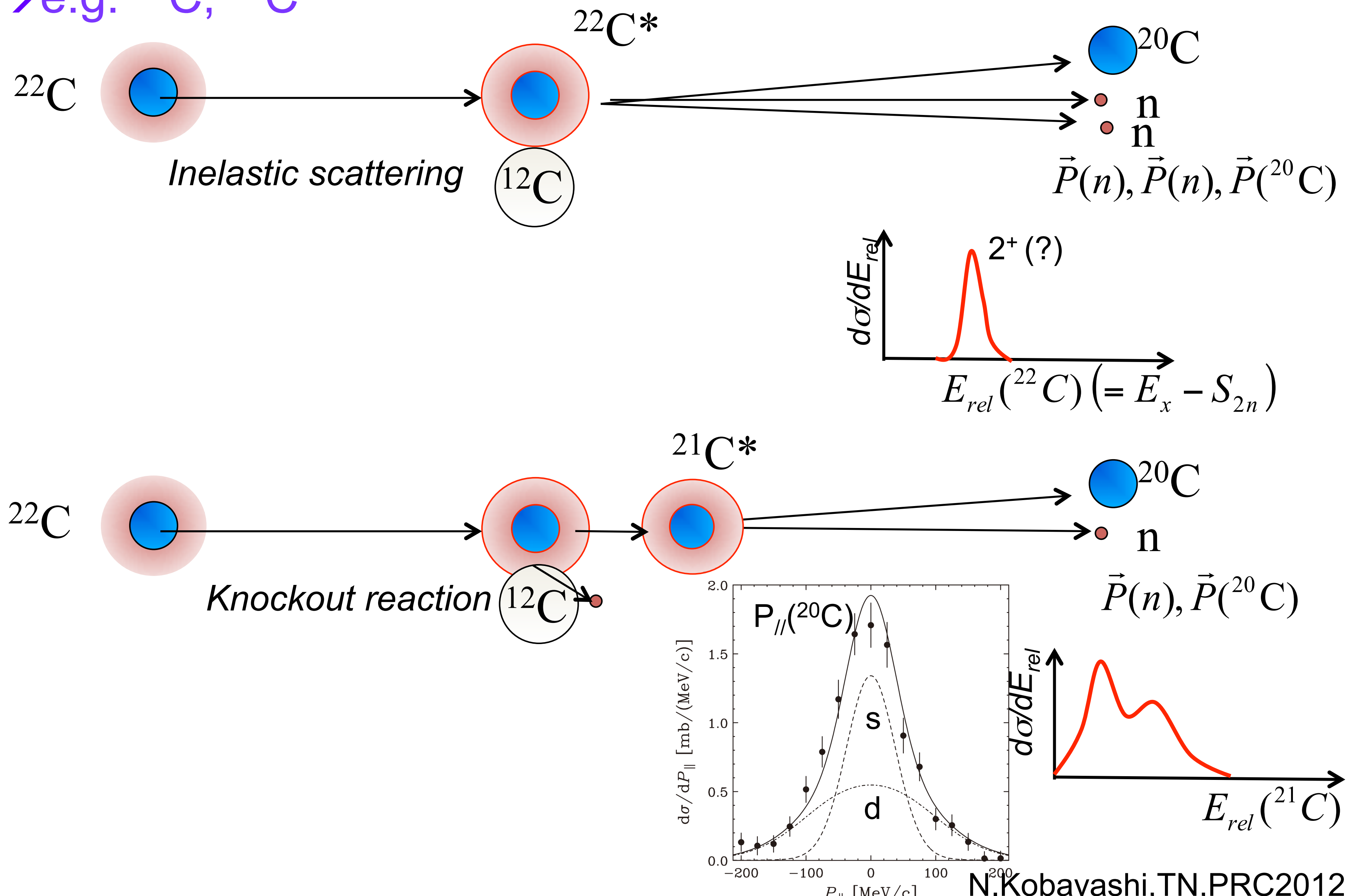
How does nuclear structure evolve towards the drip line?

Shell?
Deformation?
Halo?
Drip Line?
Continuum?



Probe of weakly (un) bound states--*Light target*

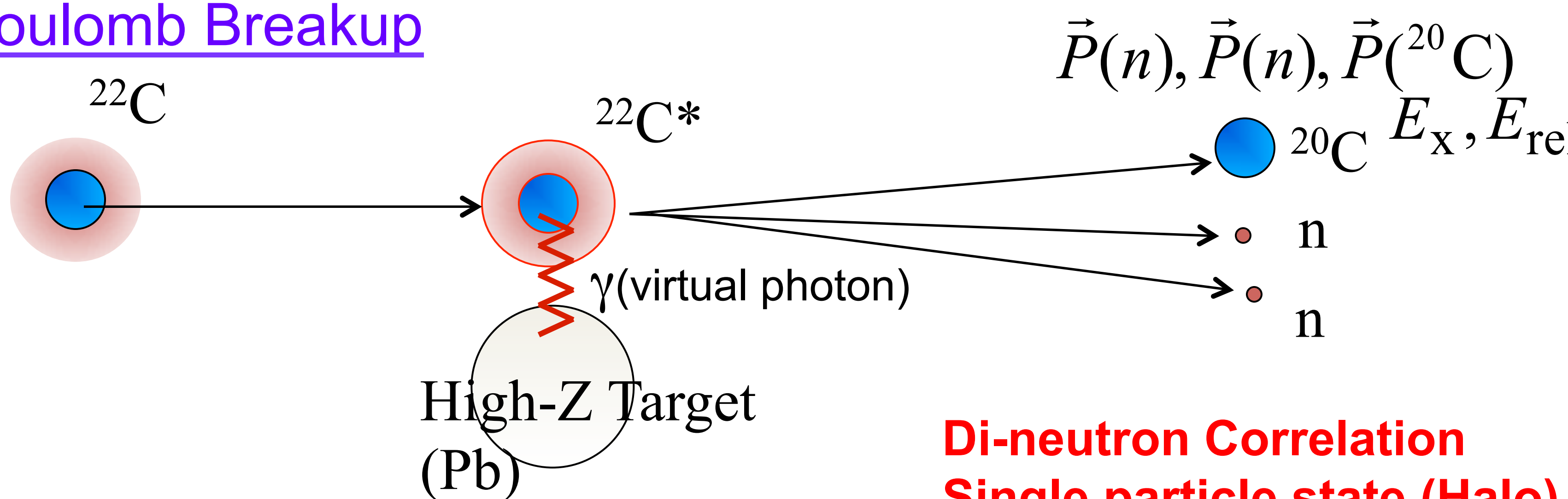
→e.g. ^{22}C, ^{21}C



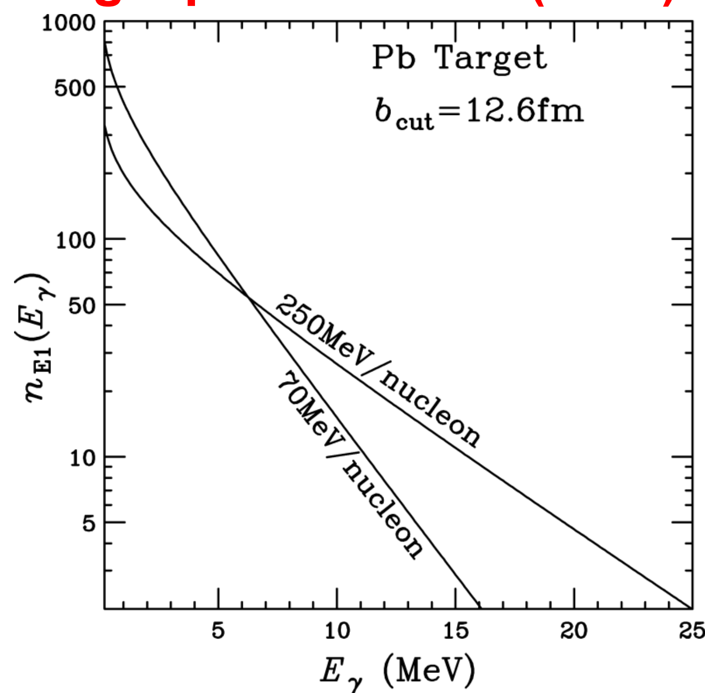
N.Kobayashi,TN,PRC2012

Probe of weakly bound states--*Heavy target*

→Coulomb Breakup



Di-neutron Correlation
Single particle state (Halo)



Equivalent Photon Method

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

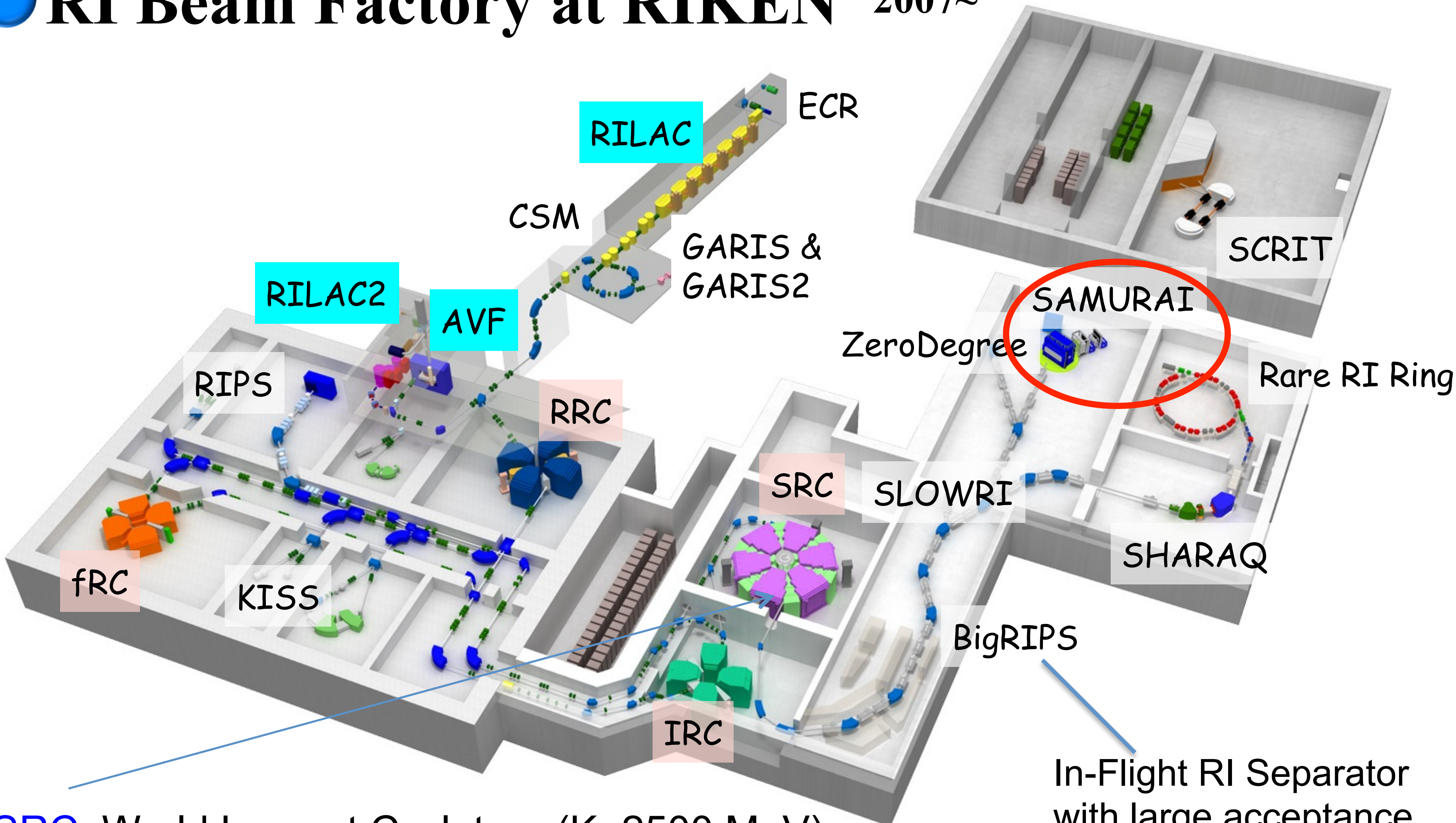
Cross section = (Photon Number)x(Transition Probability)

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

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

SAMURAI Facility at RIBF at RIKEN

RI Beam Factory at RIKEN 2007~



SRC: World Largest Cyclotron (K=2500 MeV)

Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)

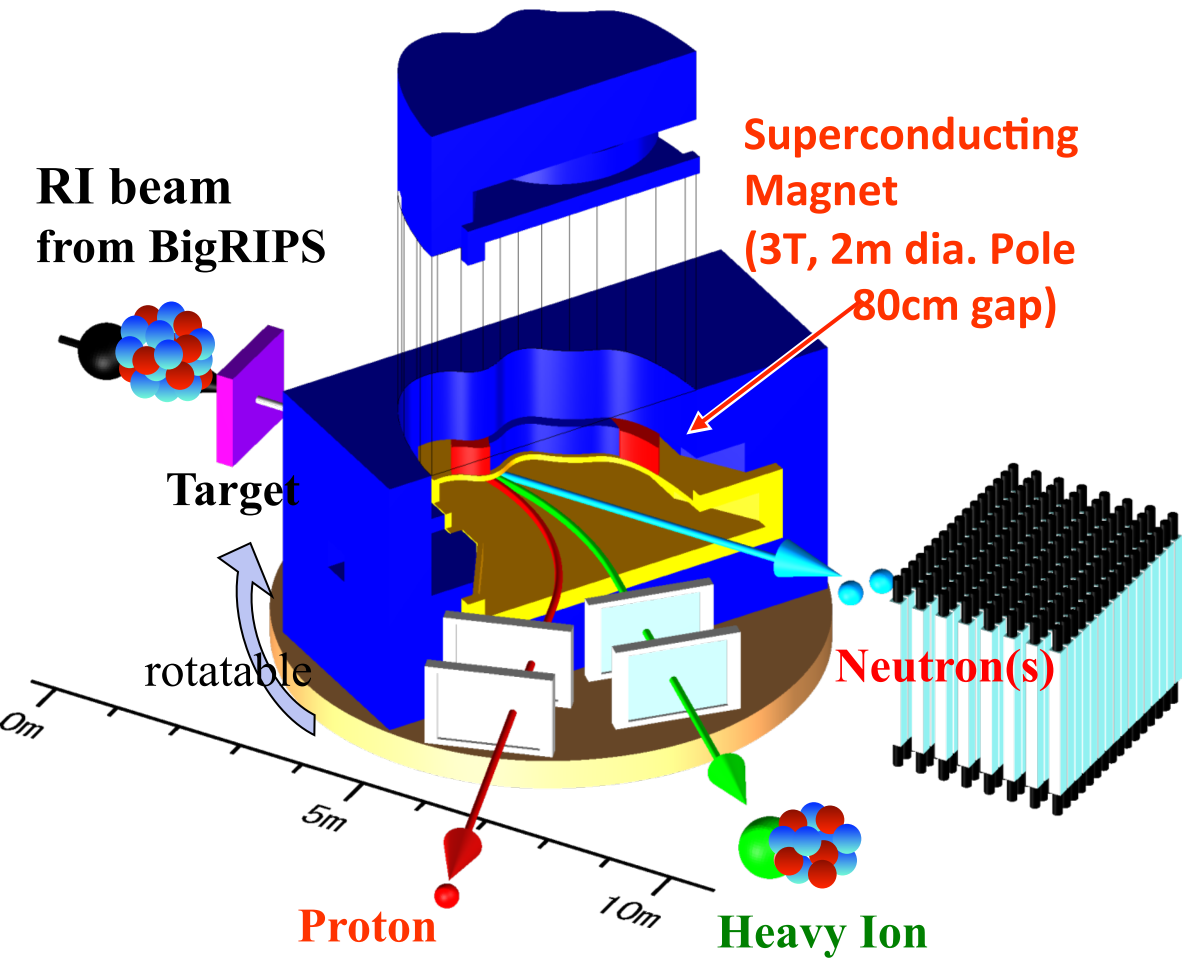
eg. ^{48}Ca: ~500pnA (~3x10^{12}pps) *~10 times compared to 2008*

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

SAMURAI

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

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

→ $A/\Delta A > 100$ ($>5\sigma$)

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

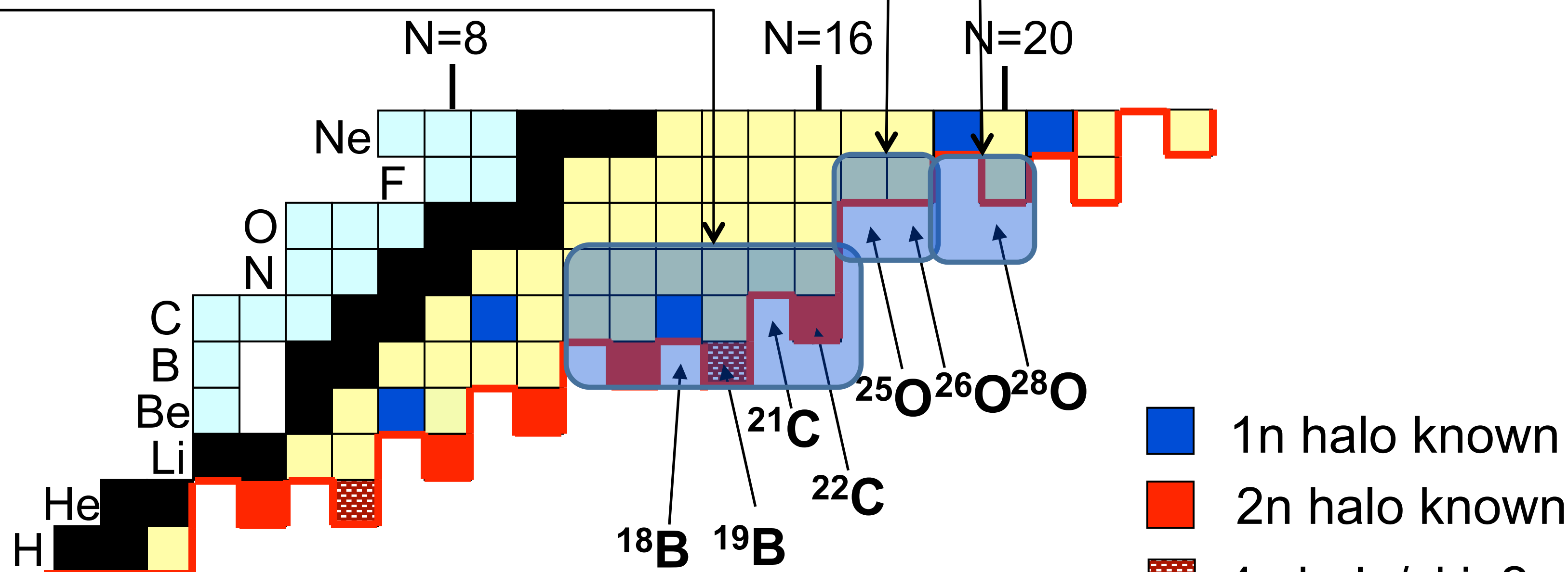
Exploration of Neutron Dripline at SAMURAI

Day-one campaign ^{48}Ca 2012 ~100pnA

Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.
Study of ^{18}B,^{21}C, and excited states of ^{19}B,^{22}C, Orr et al.
Structure of Unbound Oxygen Isotopes ^{25}O,^{26}O, Kondo et al.

Structure of Unbound Oxygen Isotopes II ^{27}O,^{28}O, Kondo et al.

^{48}Ca 2015 400~500 pnA



^{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

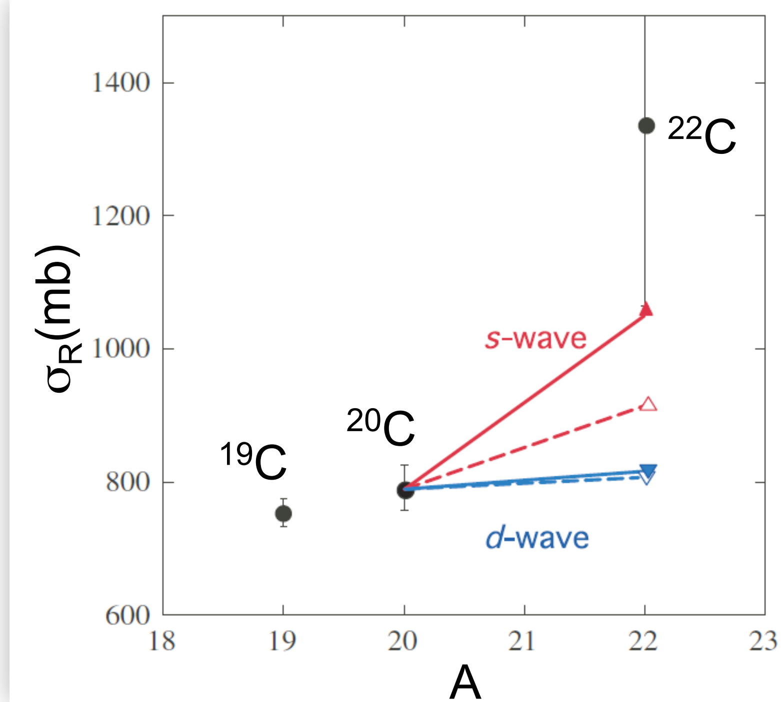
K.Tanaka et al., PRL 104, 062701(2010).

✓ **S_{2n}= −0.14(46) MeV**

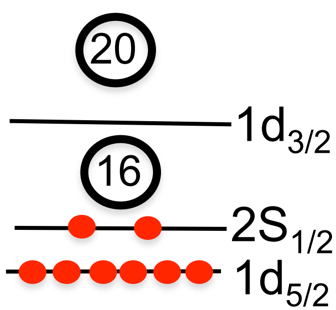
L.Gaudefroy et al. PRL109,202503(2012).

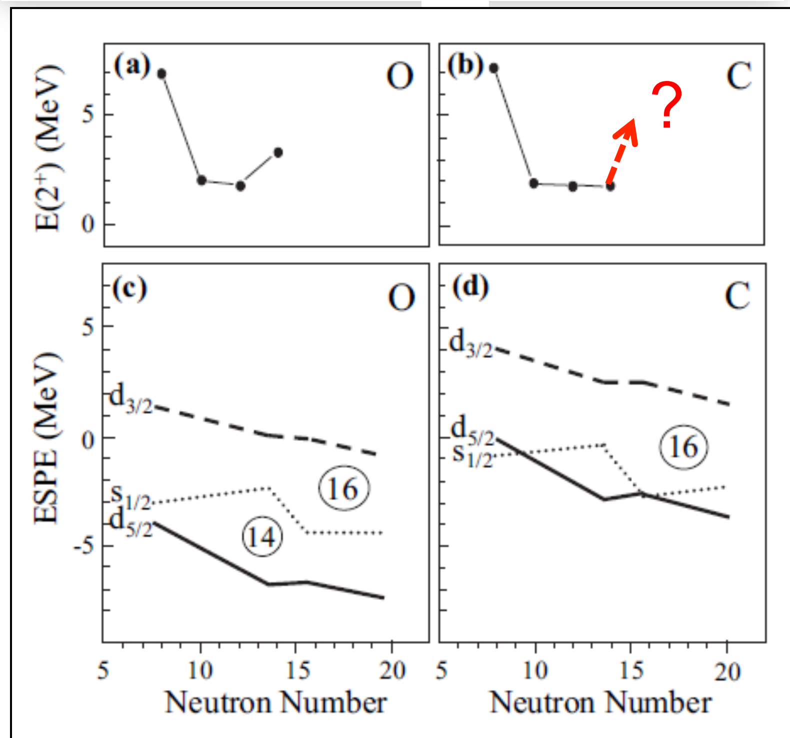
✓ **Narrow Momentum Distribution** ~73MeV/c

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



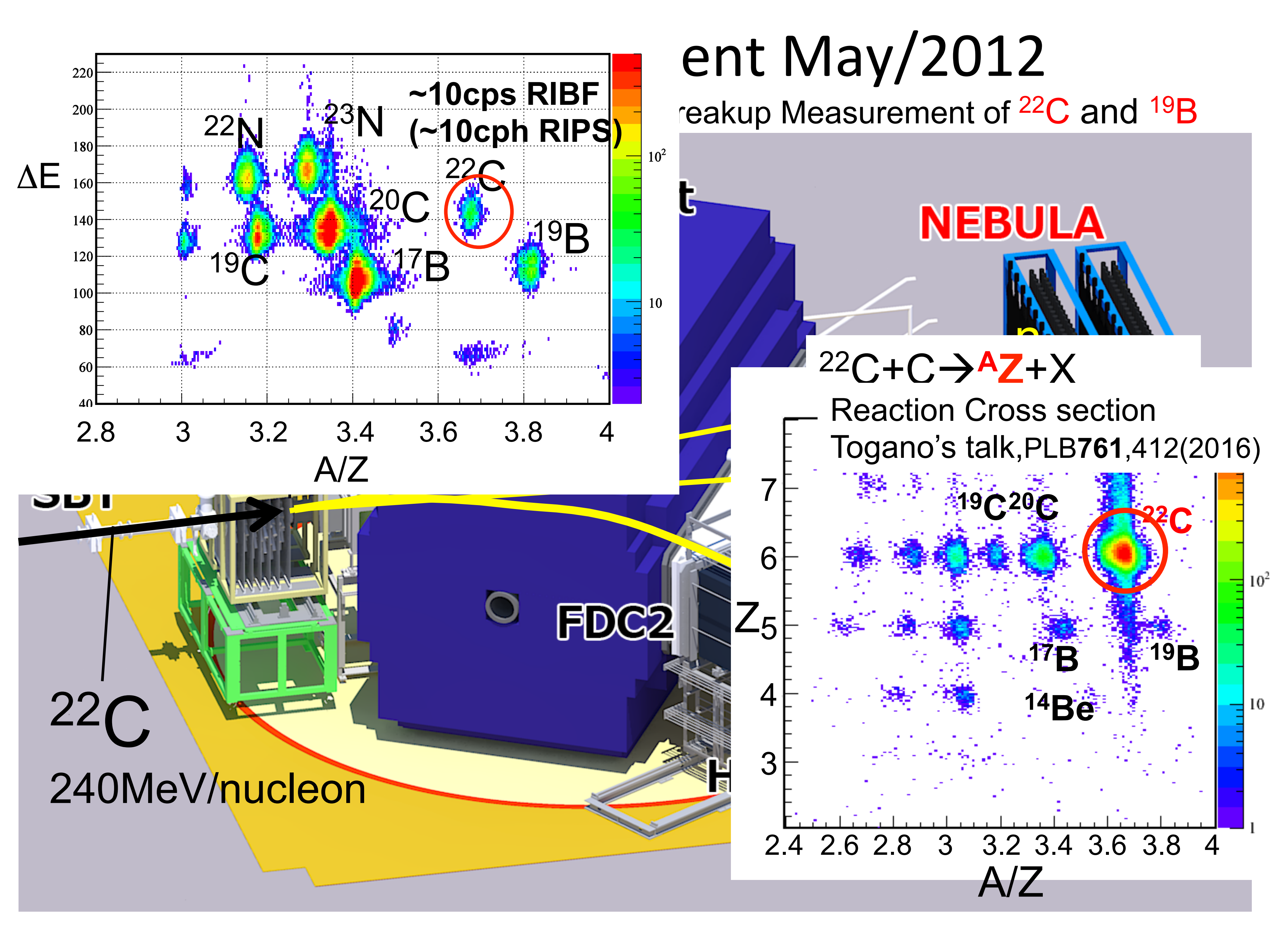
☐ N=16 Magicity?





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

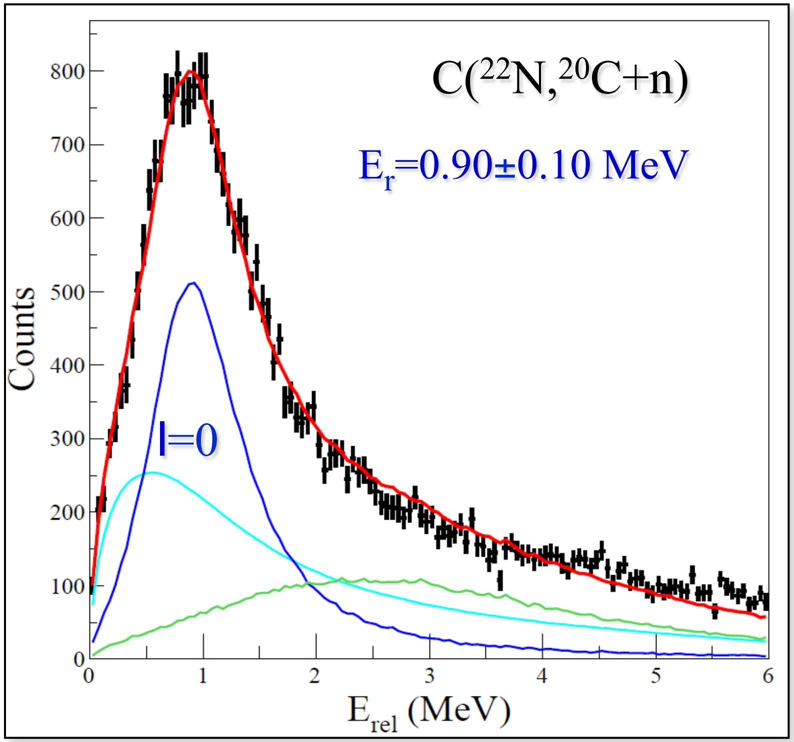
M.Stanoiu et al., PRC78,034315 (2008).

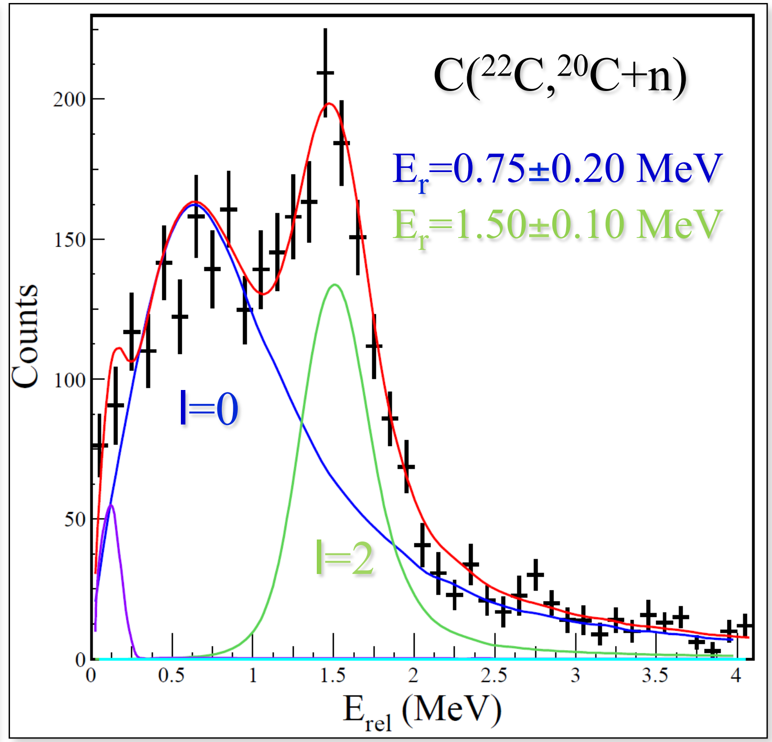

ent May/2012
reakup Measurement of 22C and 19B
~10cps RIBF
(~10cph RIPS)
ΔE
A/Z
22N
23N
22C
20C
19C
17B
19B
NEBULA
FDC2
22C+C→AZ+X
Reaction Cross section
Togano's talk,PLB761,412(2016)
Z
19C
20C
22C
17B
19B
14Be
A/Z
22C
240MeV/nucleon

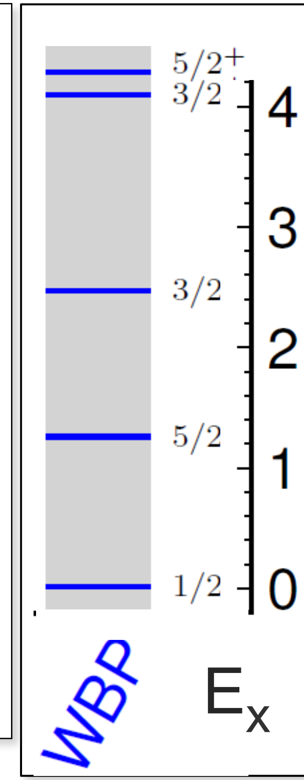
Slide: N.A. Orr, Ph.D thesis of Sylvain Leblond

INVARIANT MASS SPECTROSCOPY OF ^{21}**C**: C(^{22}N / ^{22}C,^{20}C+n) …

… SAMURAI04







	E_x (MeV)	J^π	ℓ	σ_{sp} (mb)	C^2S	$\sigma^{th}_{-1n(e)}$ (mb)
[^{22}C(0^+),^{21}C(J^π)]	0.000	$1/2^+_1$	0	89.35	1.403	137.55
	1.109	$5/2^+_1$	2	29.39	4.212	135.87
	2.191	$3/2^+_1$	2	25.44	0.342	9.55

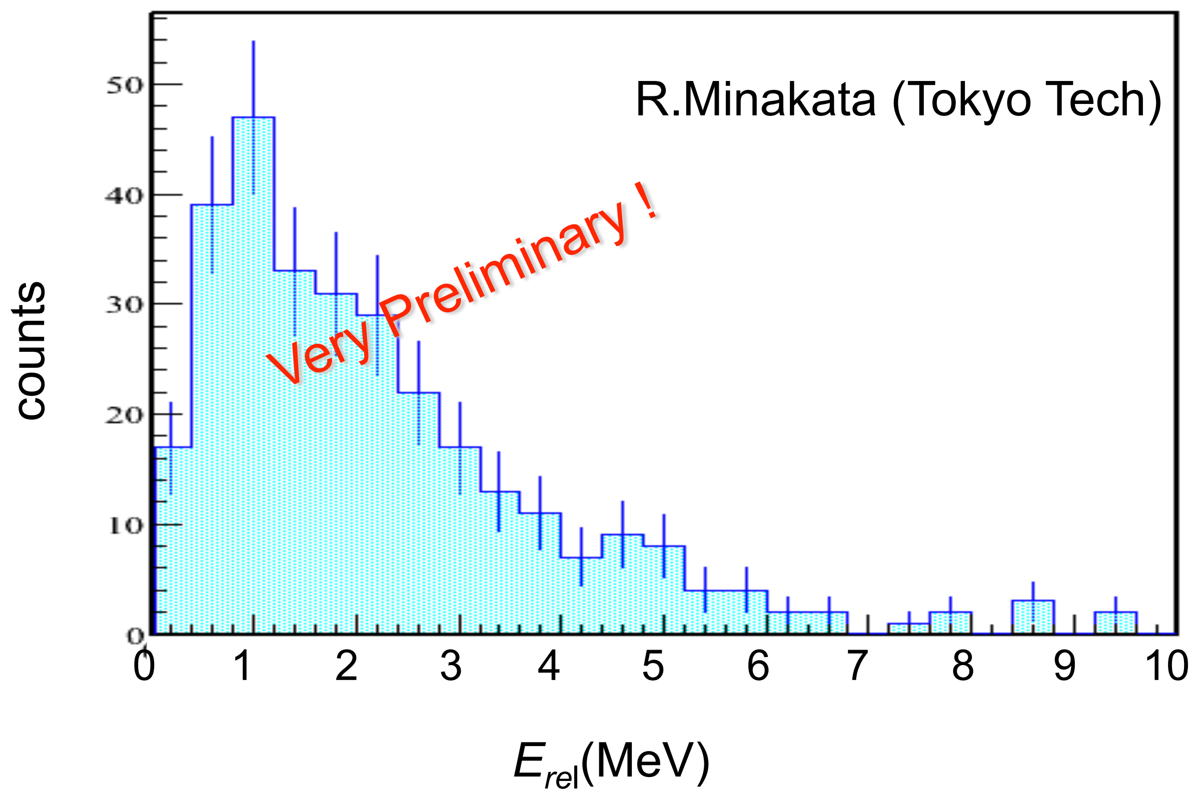
JA Tostevin

S Leblond, PhD Thesis LPC/UCN Dec 2015

Coulomb Breakup of ^{22}C (^{20}C+n+n Spectrum)

Spokesperson: T.Nakamura

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

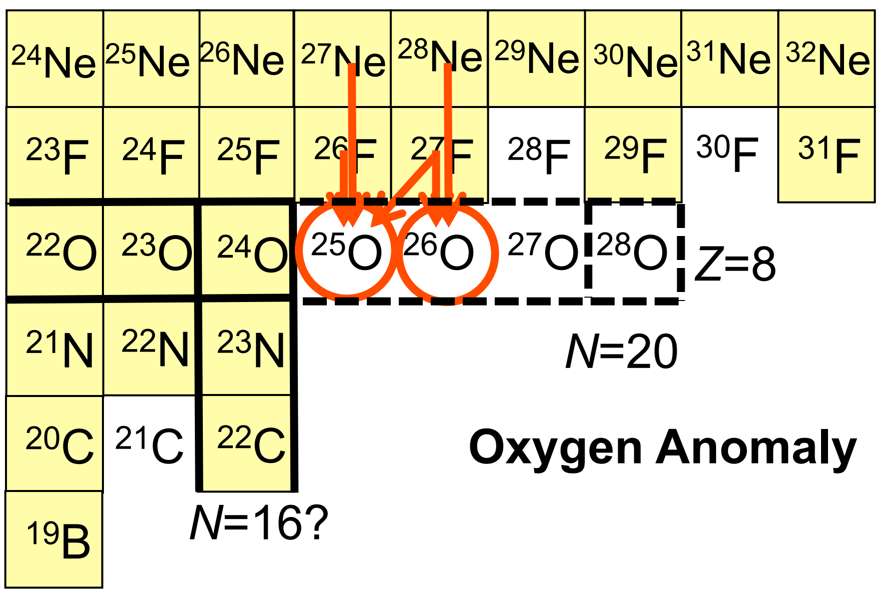


Strong Soft E1 Excitation → Evidence of Halo

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

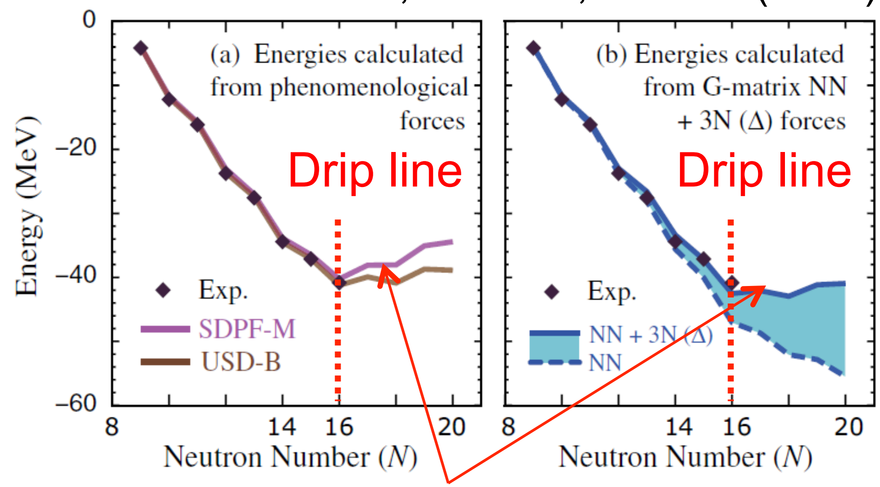
Spokesperson Yosuke Kondo

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



Oxygen Anomaly

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:

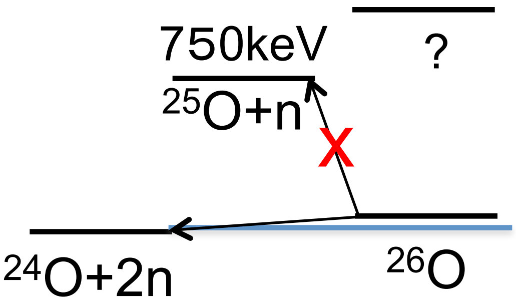
A.Volya, V.Zelevinski, PRL94,052501(2005).

nn correlations:

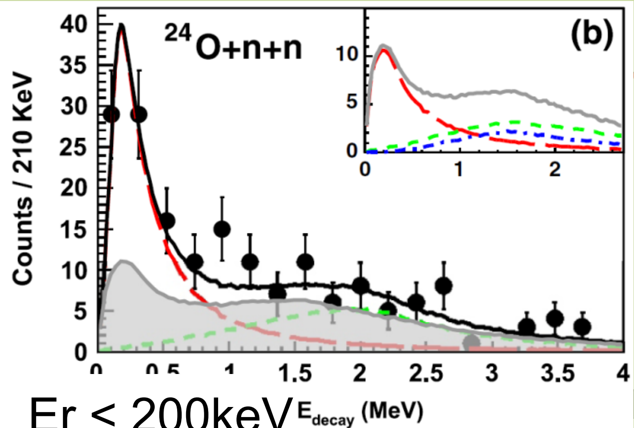
L.V. Grigorenko et al., PRL111,042501(2013)

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

2n radioactivity of ^{26}O?



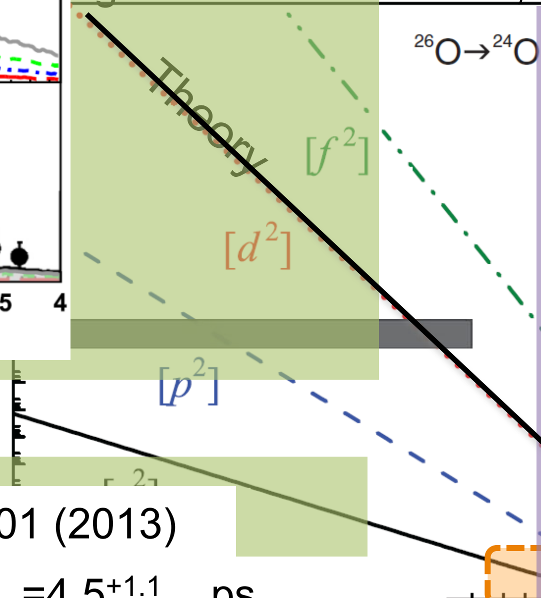
E. Lunderberg et al.
PRL108, 142503 (2012)



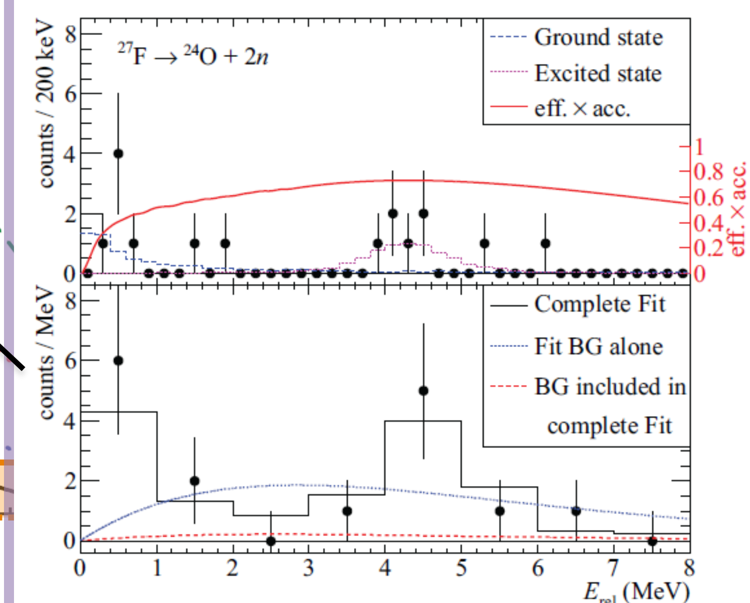
Er < 200keV

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

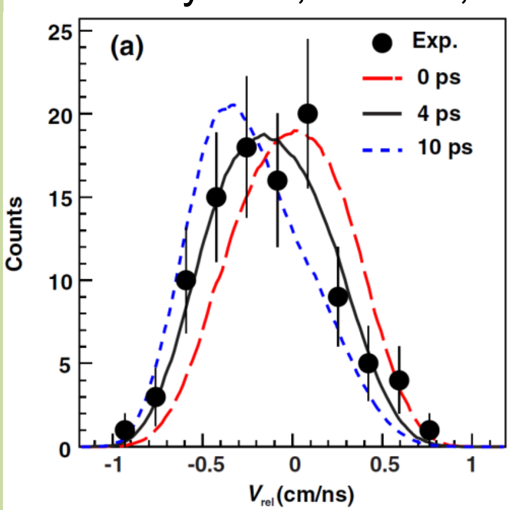
Grigorenko et al. PRC 84, 021303 (2011)



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?

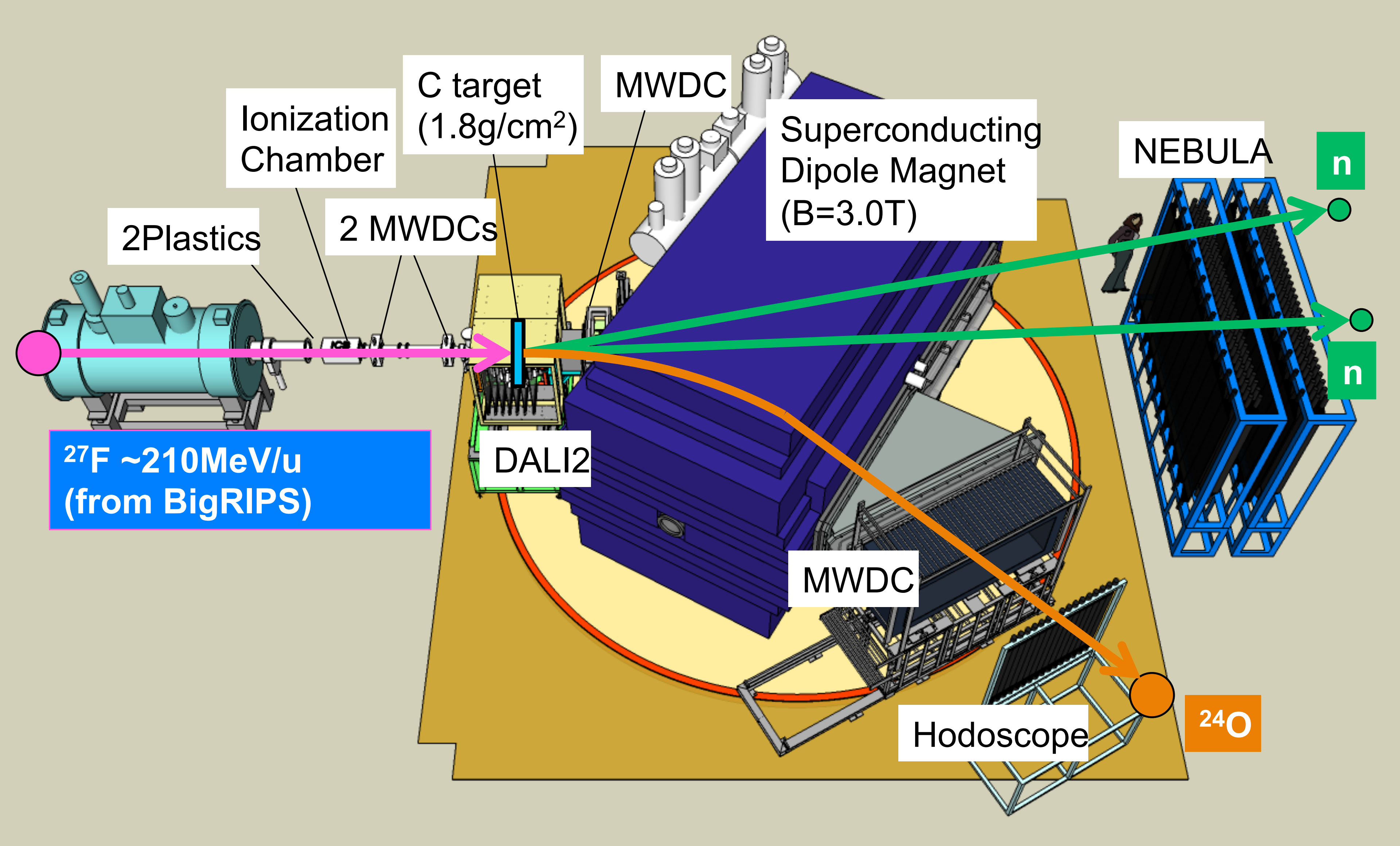
Usual 1n decay
Γ~MeV or keV

Er < 120keV (95% CL)
τ < 5.7ns

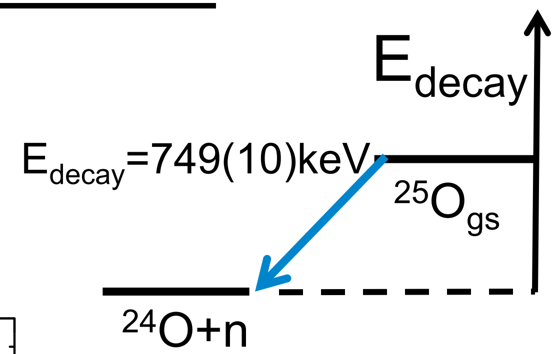
Large uncertainty of experimental study

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

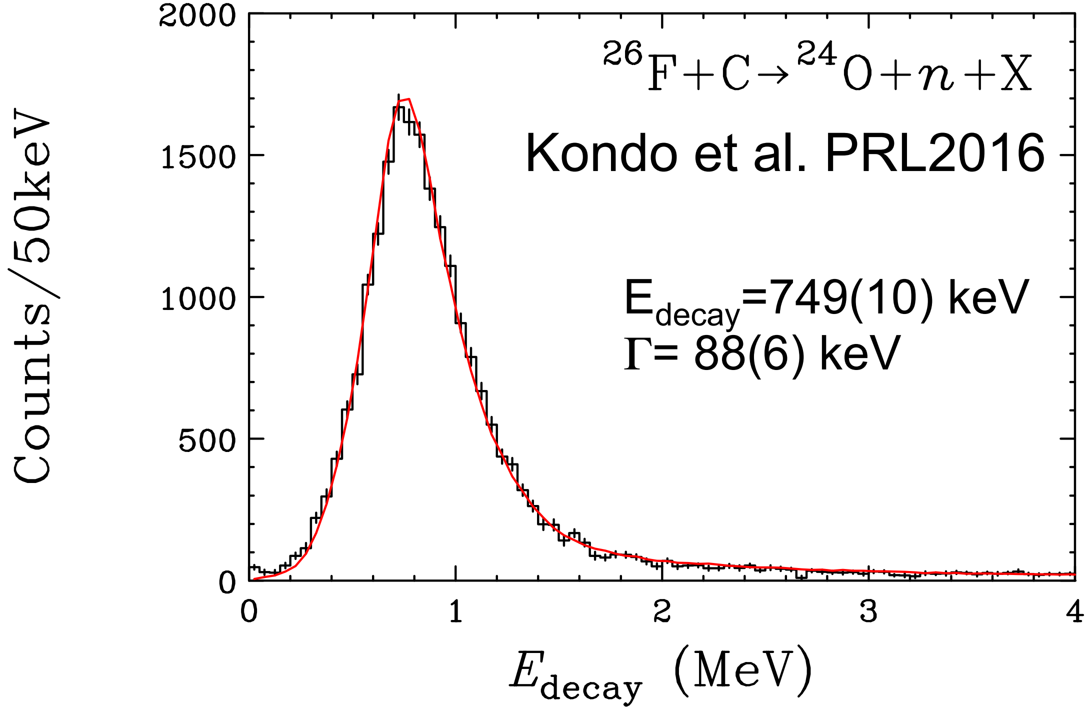
Experimental Setup at SAMURAI at RIBF

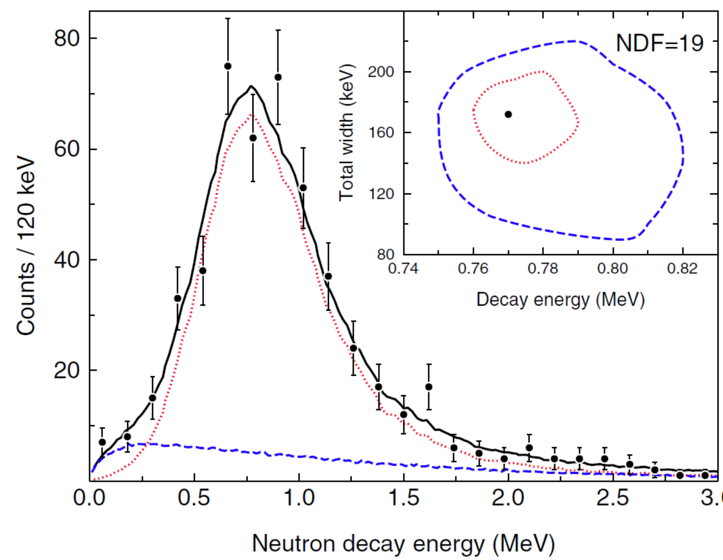


Decay energy spectrum of ^{25}O



$^{26}F+C \rightarrow$ $^{25}O^*$ $\rightarrow ^{24}O+n$



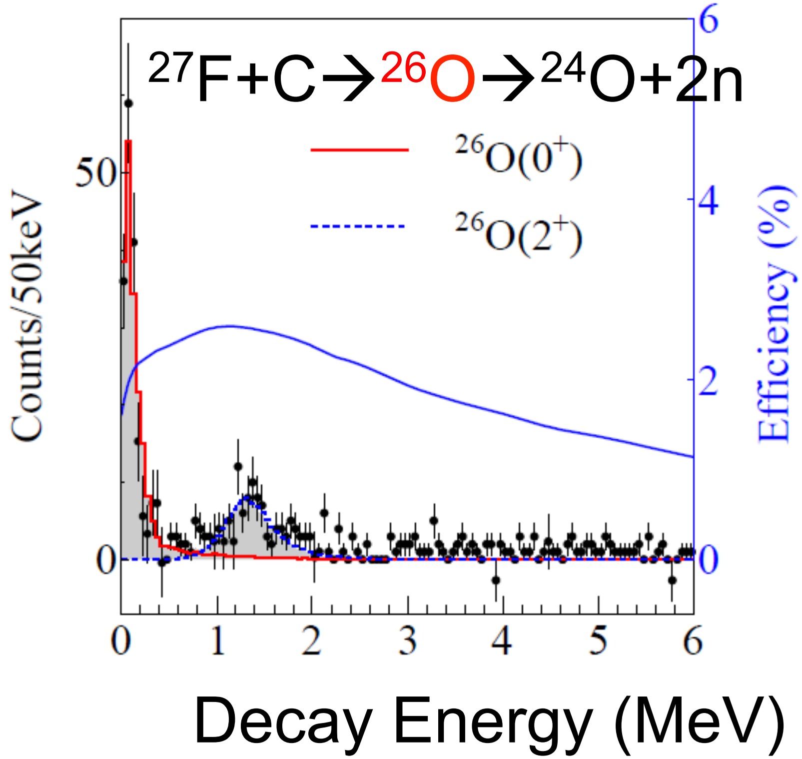


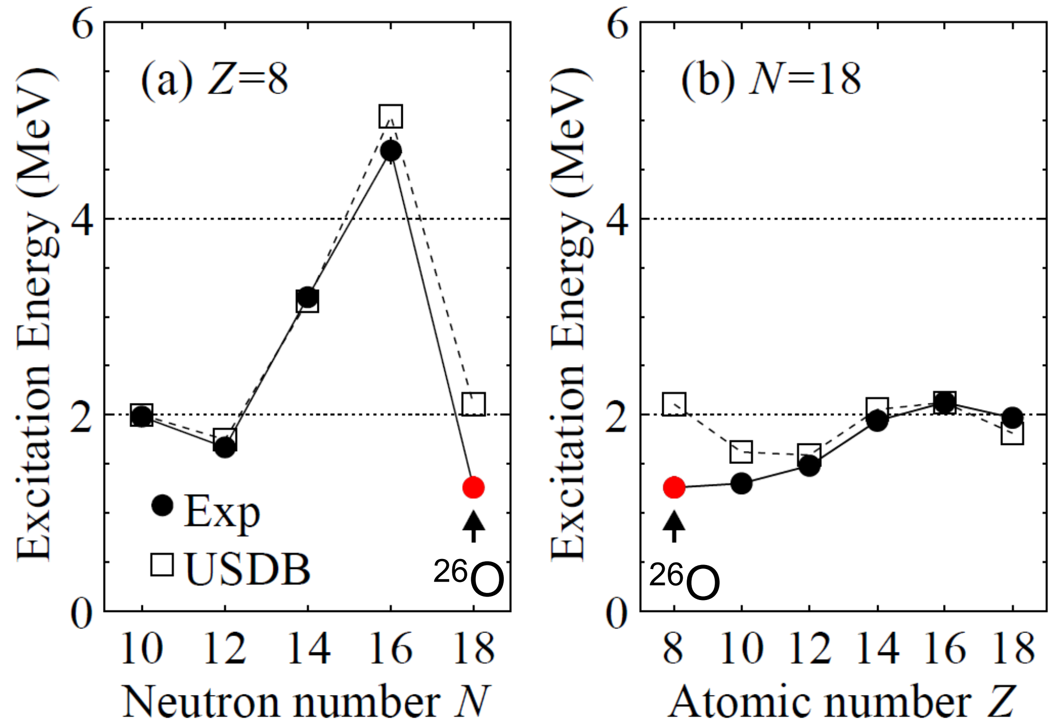
C.R.Hoffman et al.,(MSU) PRL100, 152502 (2008)

Previous Works

	E_r	Γ	τ	Ref.
^{25}O(g.s.)	725^{+54}_{-29}	20^{+60}_{-20}	$\geqslant 8.2 \times 10^{-12}$	(GSI) C.Caesar, PRC 2013
	770^{+20}_{-10}	172^{+30}_{-30}	–	(MSU) Hoffman, PRL 2008

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

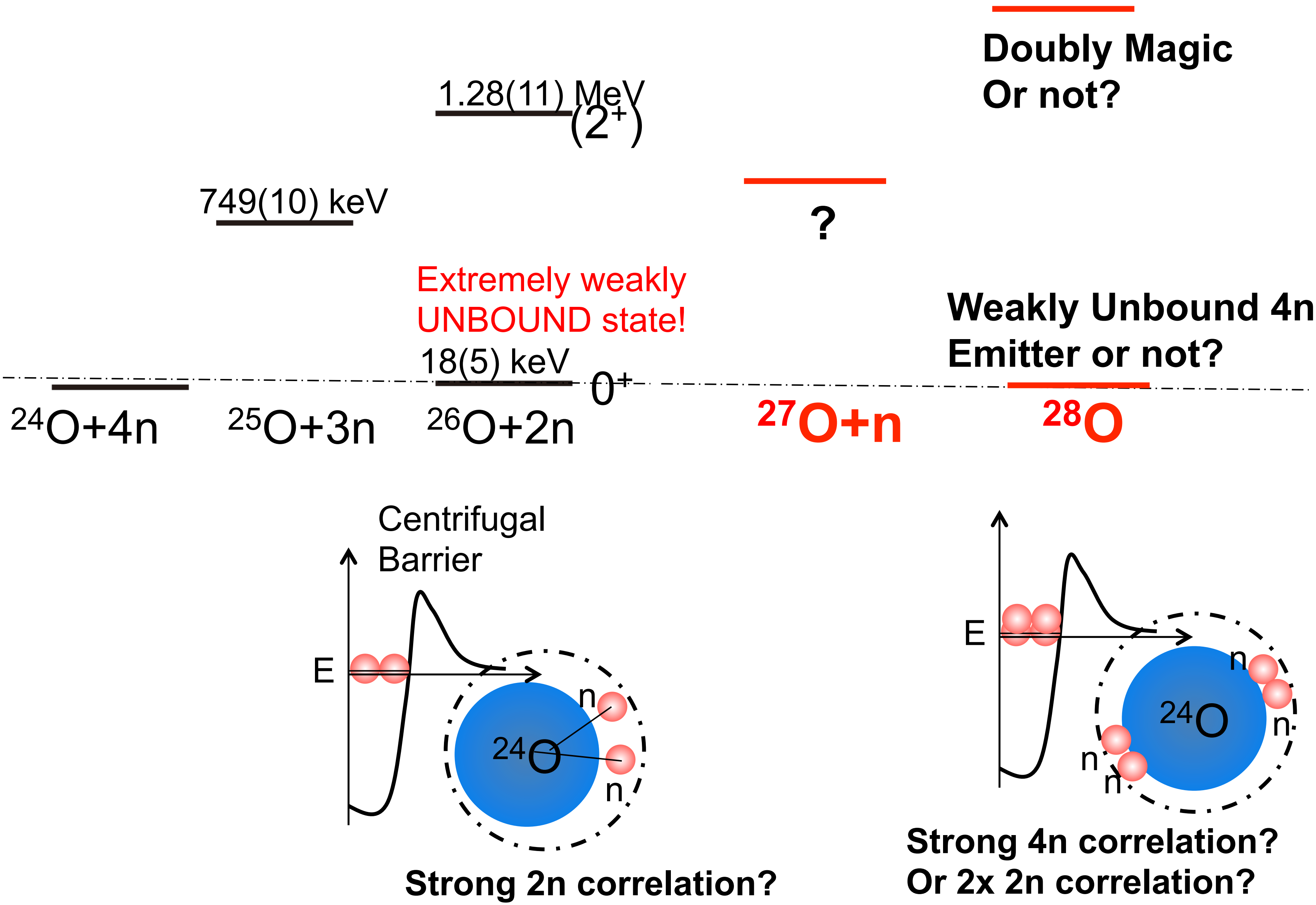
→effects of

pf shell?, **continuum**?

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

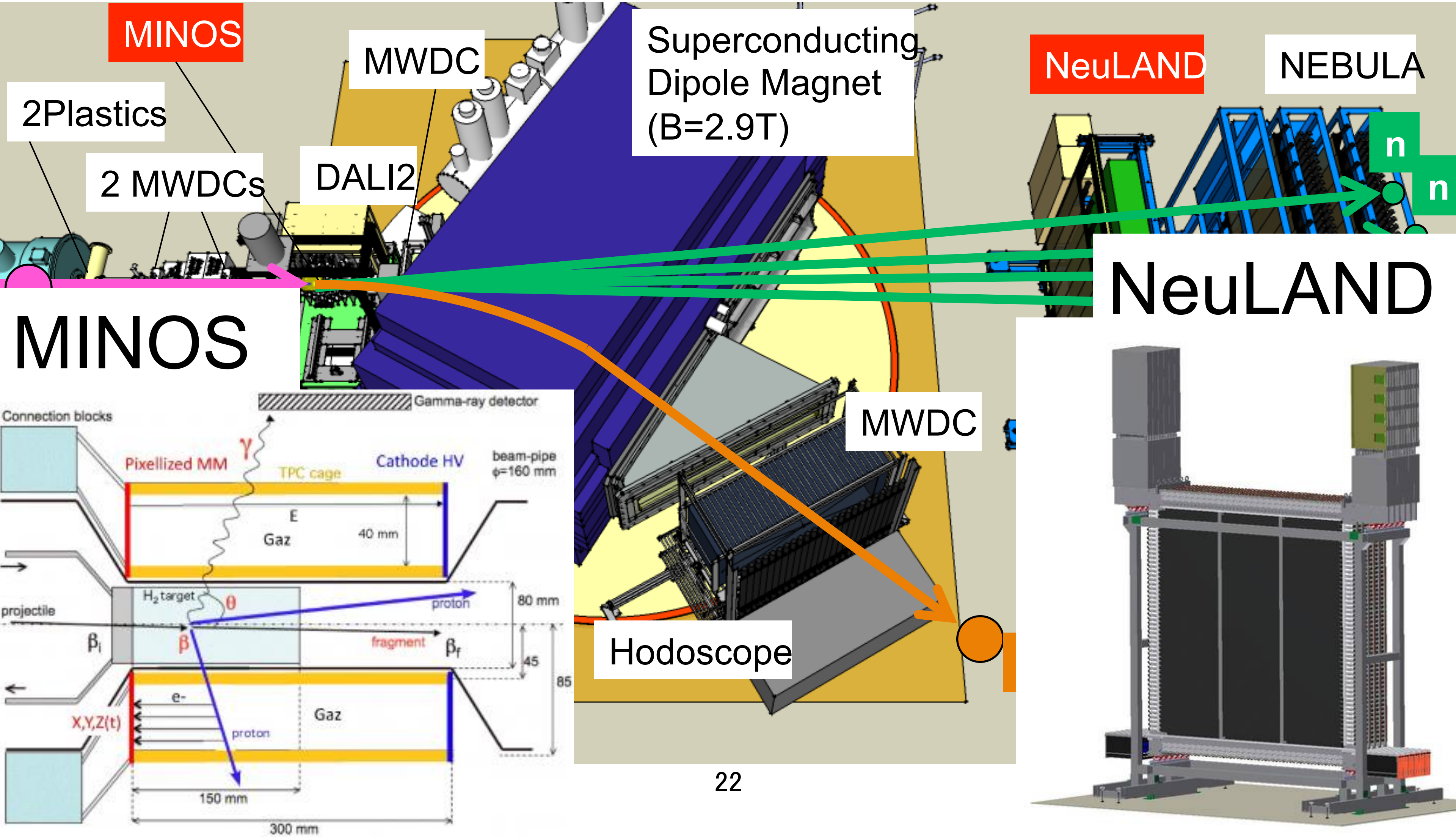
Y. Kondo et al., Phys. Rev. Lett. 116, 102503, (2016)

Masses of Oxygen Isotopes Beyond the dripline

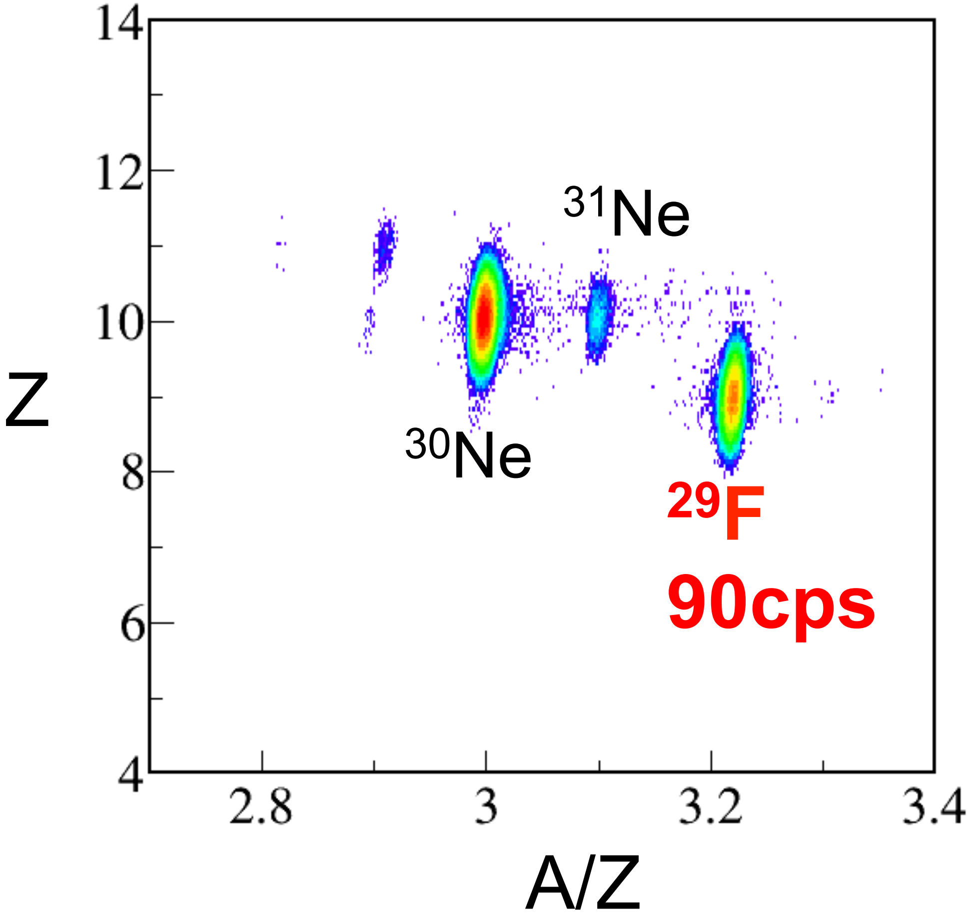


^{27,28}O measurements in 2015 (SAMURAI21)

Slides: Y.Kondo



High intense beam of ^{29}F



High intense ^{29}F beam
(^{48}Ca intensity > 500pnA)

+ thick LH_2 target (15cm)

→highest luminosity for ^{28}O

Analysis: Under Progress

Summary and Outlook

- ✓ **Barely bound and unbound nuclei**

  Strong neutron-neutron correlation (dineutron correlation) expected

- ✓ **Drip-line region near N=14--28**

  Currently Most Exotic Region where one can (nearly) reach the n-drip line

- ✓ **Coulomb and Nuclear Breakup**

  →Useful tool to probe weakly (un)bound states

- ✓ **SAMURAI Facility at RIBF (since 2012)**

  Powerful equipment for various experiments using RI beams

- ✓ **Coulomb/Nuclear Breakup of ^{22}C at SAMURAI**

  S.Leblond, J.Gebelin, M.Marques, N.Orr, R.Minakata, S.Ogoshi et al.
  →^{21}C spectrum → pin down s and d 1hole state of ^{22}C
  Large Coulomb breakup cross sections

- ✓ **Spectroscopy of ^{25,26,27,28}O at SAMURAI** **Y.Kondo** et al.

  →^{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?**
  Y. Kondo et al., PRL 116, 102503, (2016) .

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

Near Future: Variety of spectroscopies along n-drip line

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

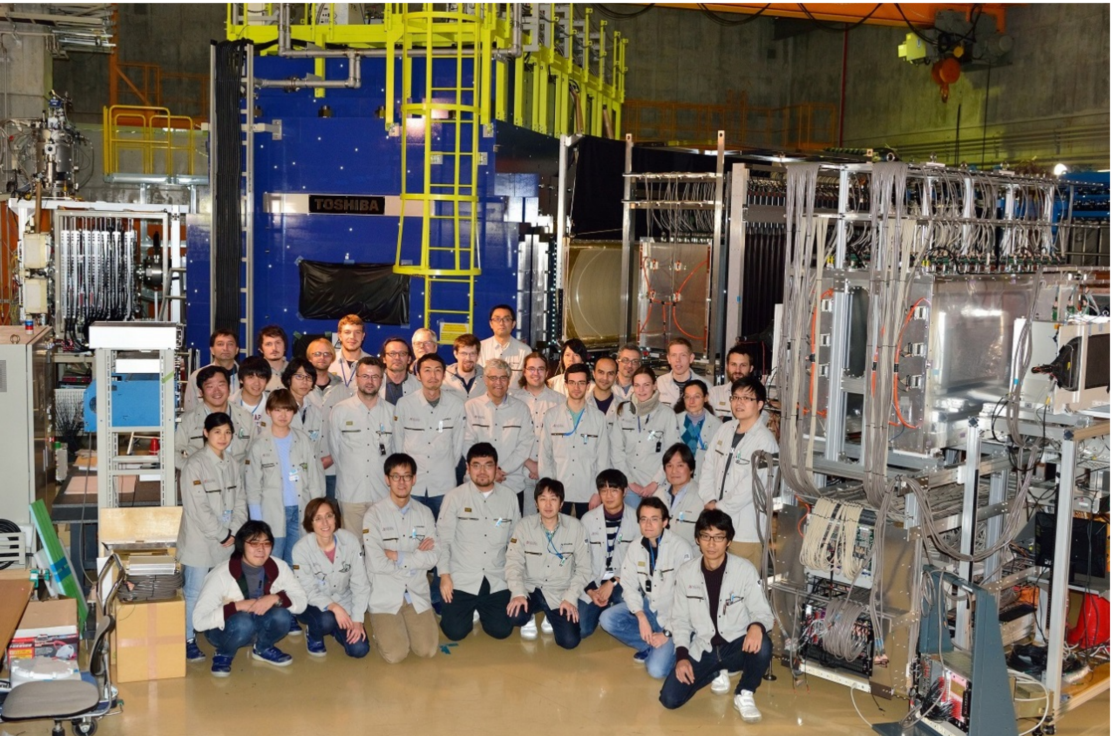
GANIL: A.Navin

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

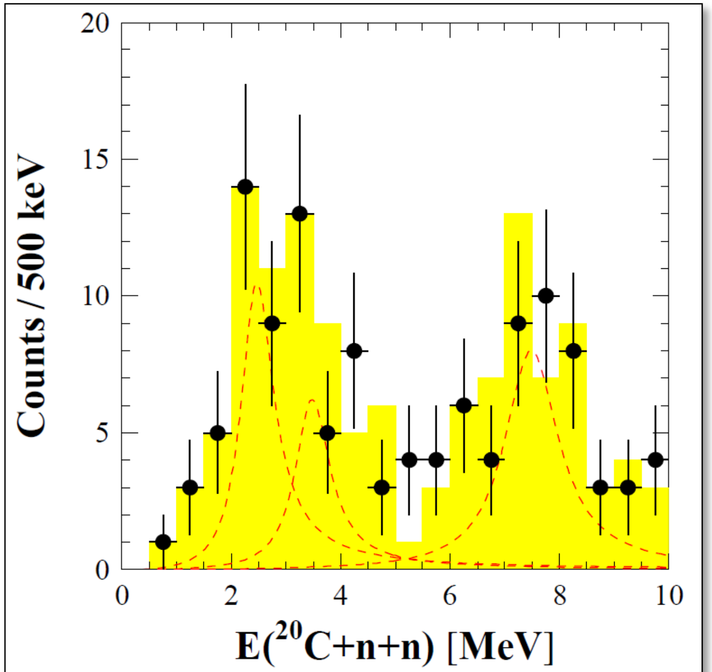
88 Participants
25 Institutes

Backup

N=16 $^{22}C(2^+)$ *SAMURAI04 – DAYONE: C(^{23}N,^{20}C+n+n) …*

J.Gibelin, N.A.Orr

… SAMURAI + NEBULA



BEAMTIME = 1.4 DAYS

< ^{23}N > ≈ 45 pps

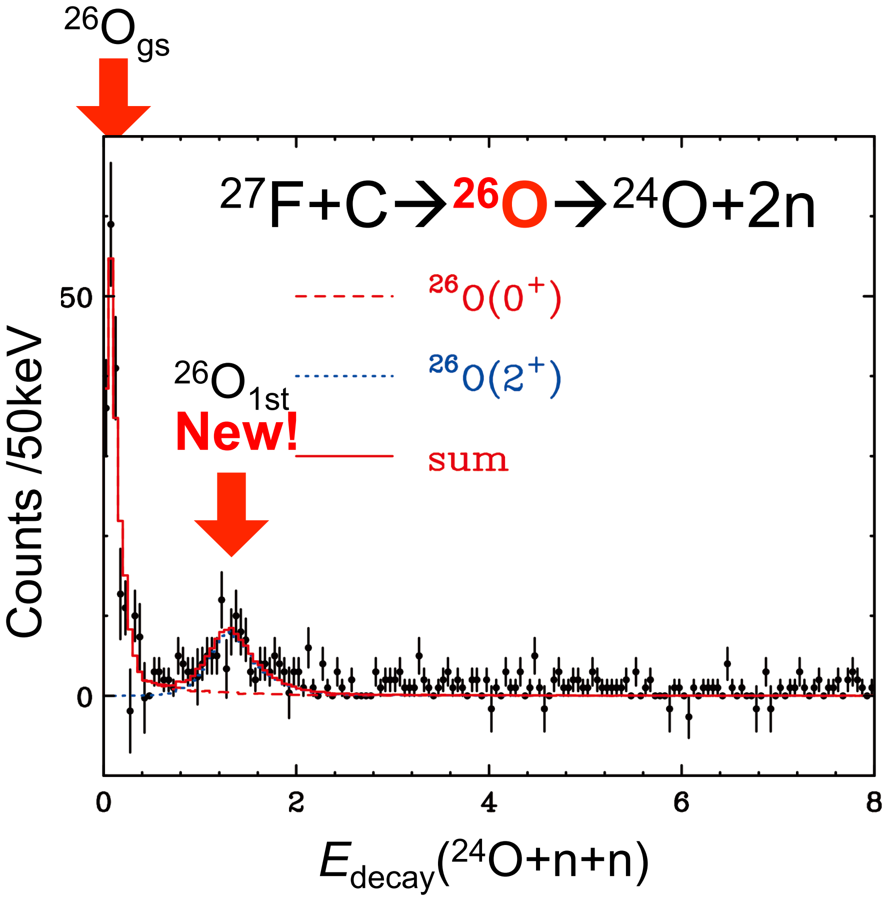
C TARGET = 2 g/cm^2

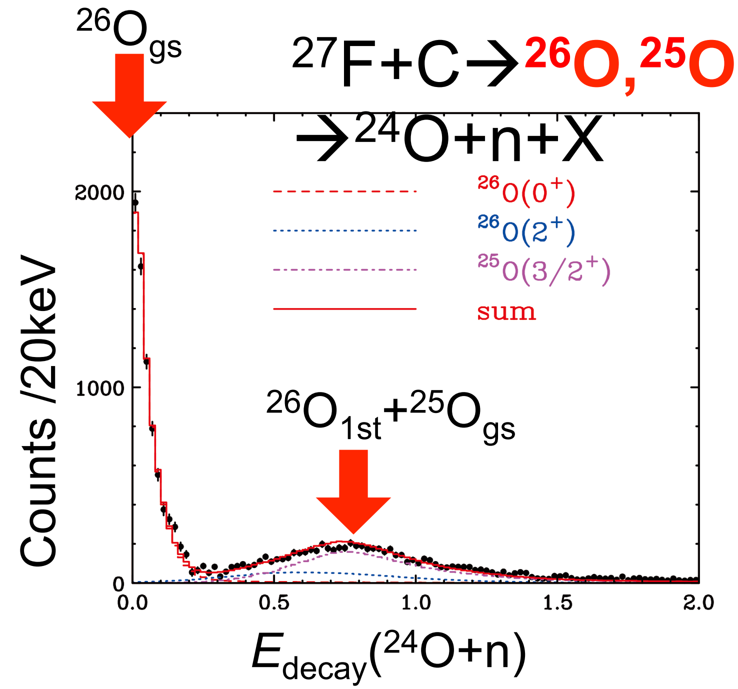
<^{23}N|^{22}C>

SHELL MODEL- WBP

E_X [MeV]	J^π	C^2S
0.0	0^+	0.86
3.9	2^+	0.22
4.6	2^+	0.51
8.0	2^+	1.4
9.6	1^+	0.85

Decay energy spectrum of ^{26}O (^{24}O+2n, ^{24}O+n)



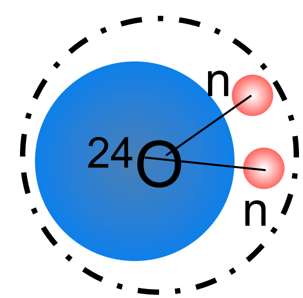


$E_{decay}(^{24}O+n+n)$
$= E_{decay}(^{24}O+n) + E_{decay}(^{25}O+n)$

Finite Value!

$$E_{decay}(^{26}O_{gs}) = 18 \pm 3(stat) \pm 4(syst)\,\mathrm{keV}$$

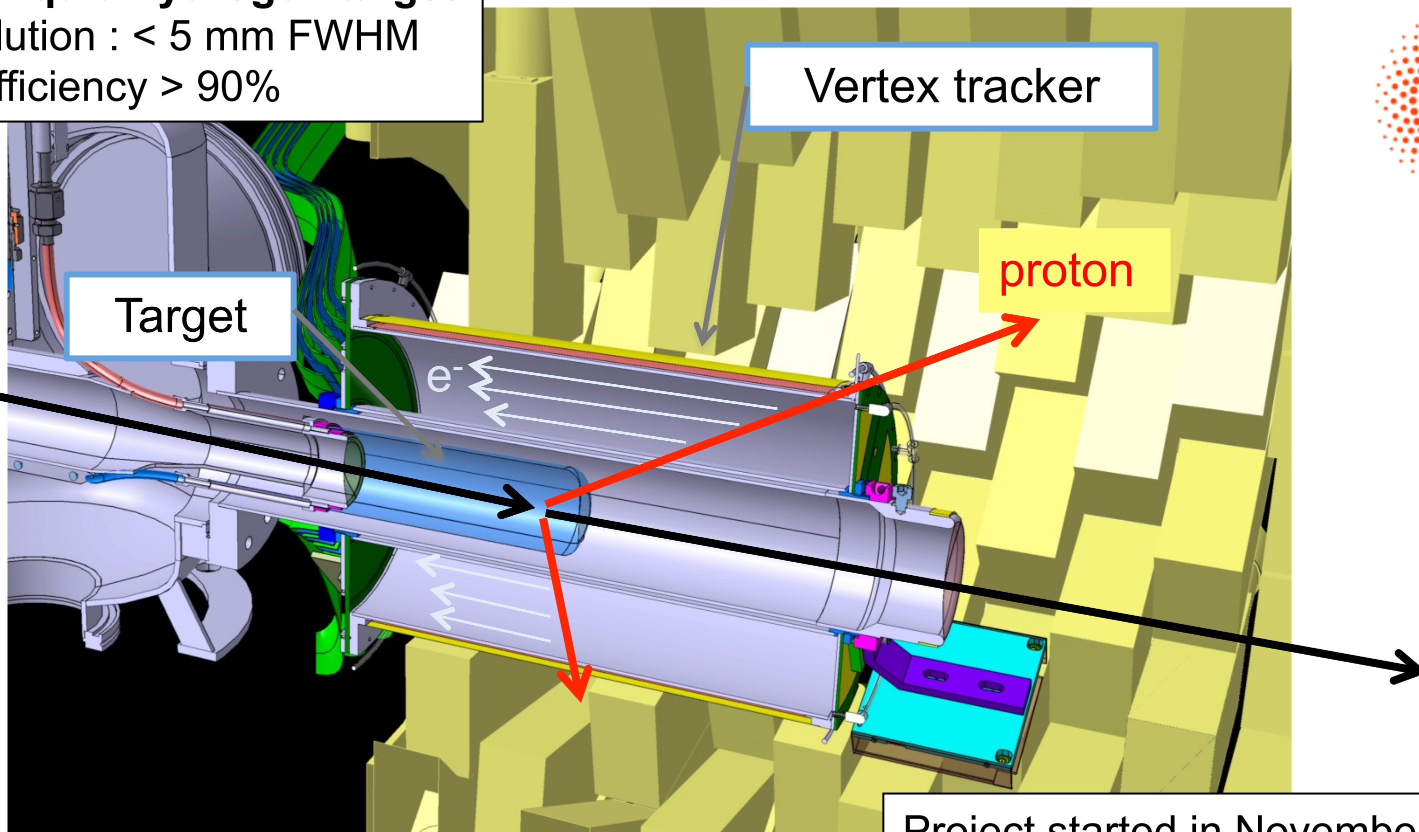
$$E_{decay}(^{26}O_{1st}) = 1.28^{+0.11}_{-0.08}\,\mathrm{MeV}$$ Most likely 2^+



No peak at ~4.2MeV

Slide by Obertelli,
CEA SACLAY, Obertelli et al.

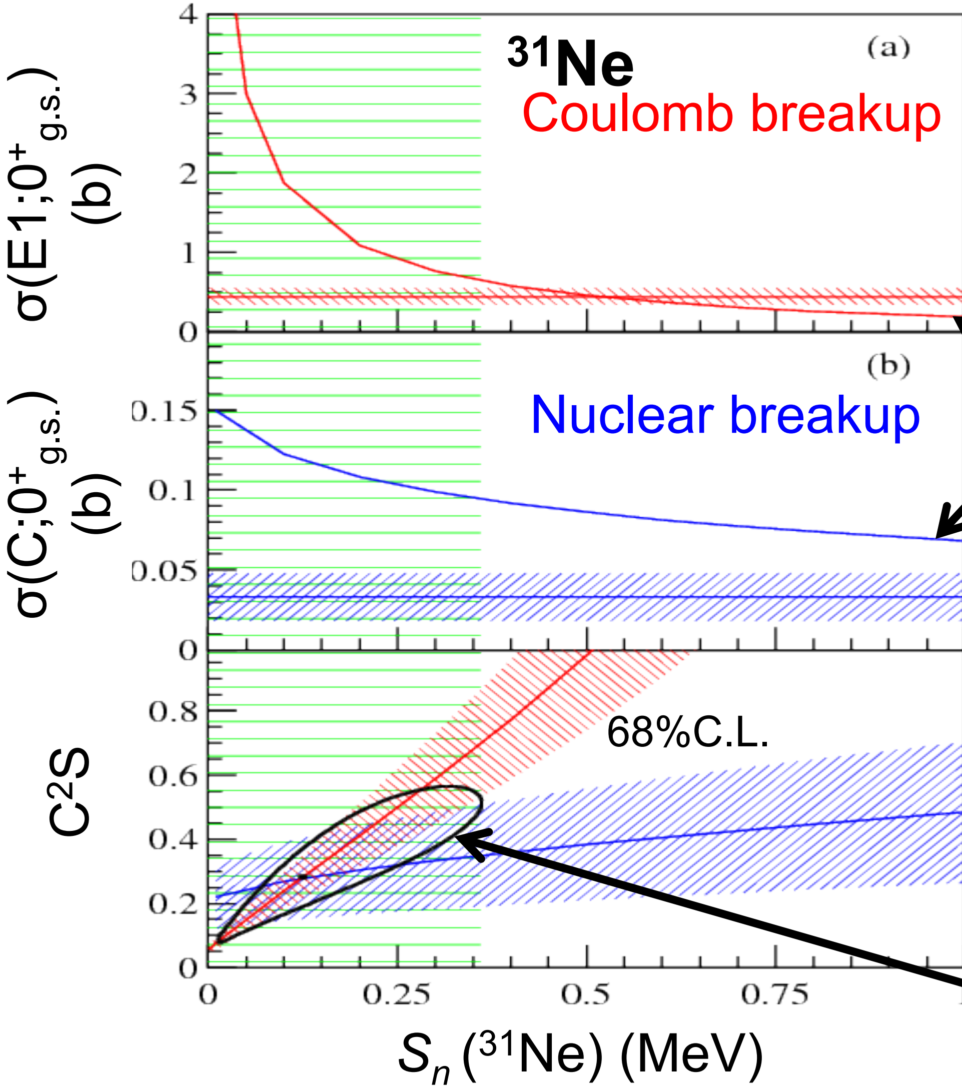
60-200 mm **liquid hydrogen target**
Vertex resolution : < 5 mm FWHM
Detection efficiency > 90%



Project started in November 2010
In use at the RIBF since 2014

DALI2: S. Takeuchi et al., Nucl. Instr. Meth. A **763**, 596 (2014)
MINOS: A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

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)

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

Exp. $\sigma_{-1n}(E1;0^+_{g.s.})$ = 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. $\sigma_{-1n}(C;0^+_{g.s.})$ = 33(15) mb

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

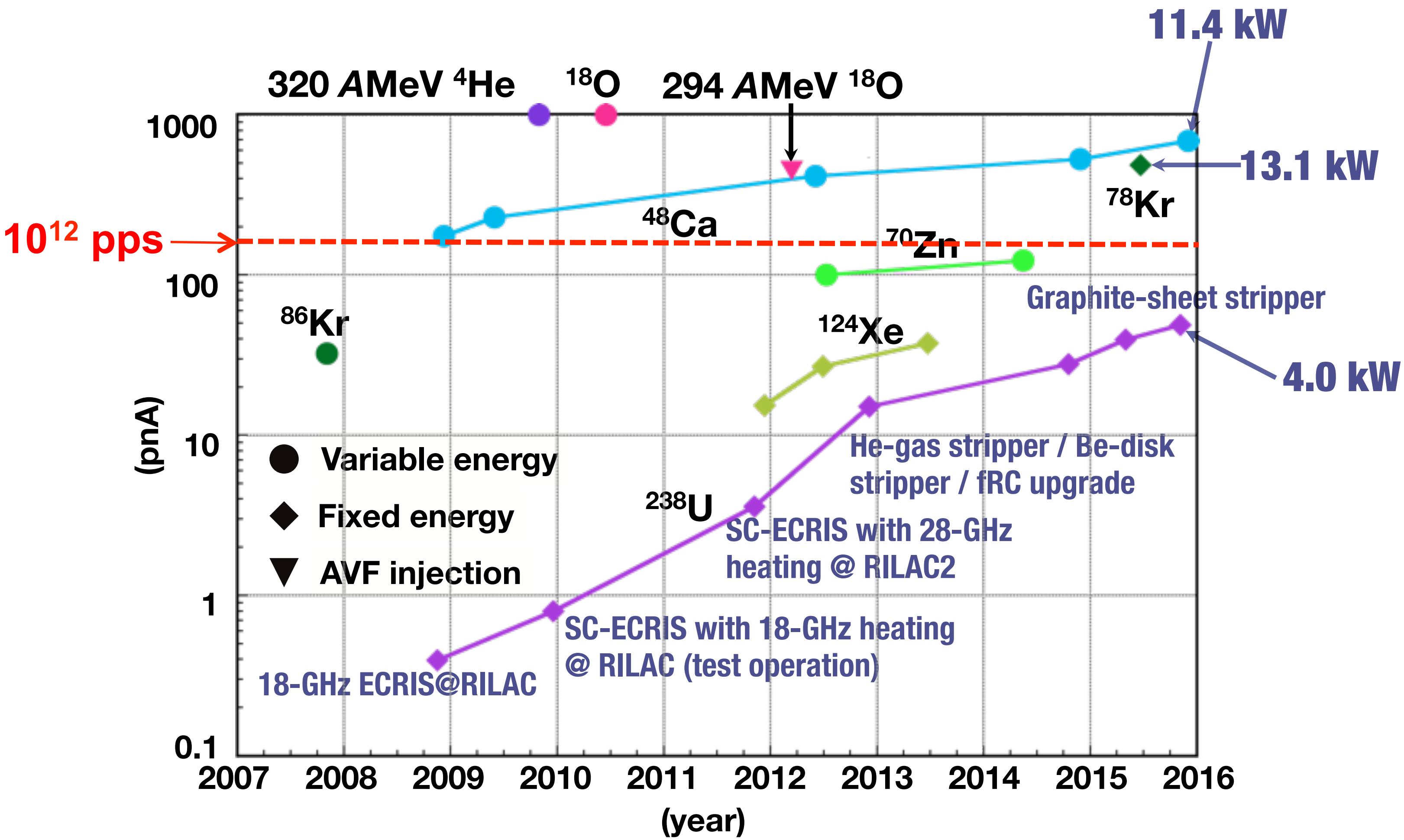
$$C^2S = 0.32^{+0.21}_{-0.17}$$

[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

RIBF Performance Summary



Beam energies of the beams without explicitly indicated are 345 AMeV.

Courtesy of N. Fukunishi