Structure of nuclei along and beyond the neutron drip line

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Dynamics of highly unstable exotic light nuclei and few-body systems

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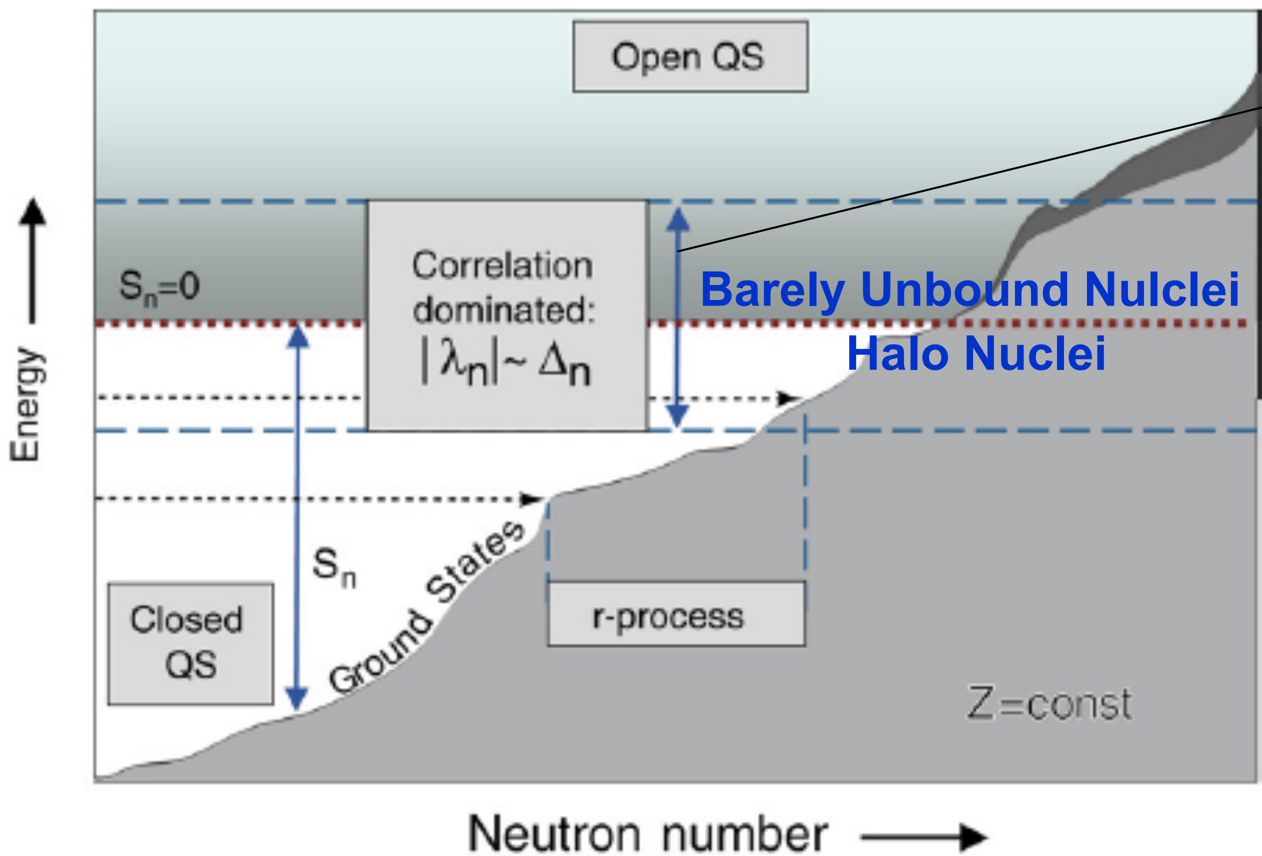
Weakly Bound and Unbound Nuclei

Strong nn Correlations



$$|S_n| << \Delta_n$$

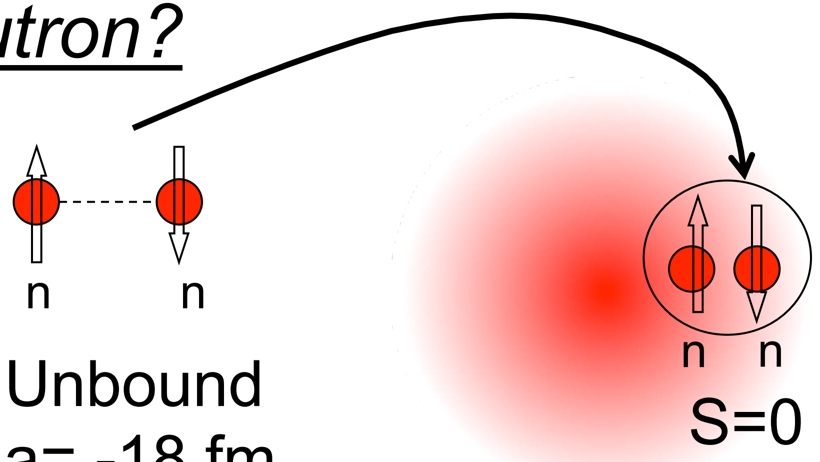
$$S_n \approx -\lambda_n - \Delta_n$$

Fermi Level

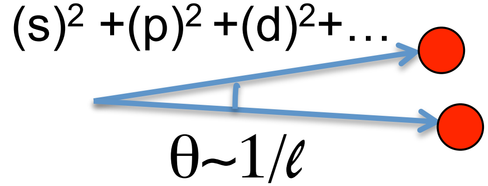
paring gap
(~2MeV at A=30)

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

Dineutron?



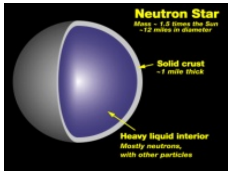
Unbound
a= -18 fm
$(s)^2$



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?

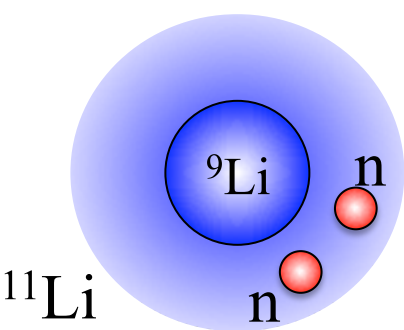
M.Matsuo
PRC73,044309(2006).
A.Gezerlis, J.Carlson,
PRC81,025803(2010)



n-star

Possible dineutron site

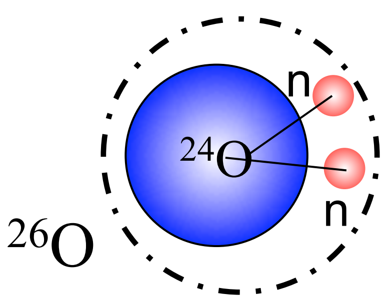
2n Halo Nuclei?



S_{2n}=0.37MeV

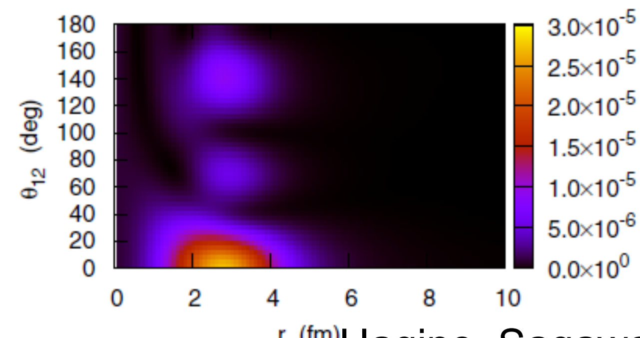
T.Nakamura PRL96, 252502 (2006).

2n weakly-unbound nuclei?



S_{2n}= −0.018(5) MeV

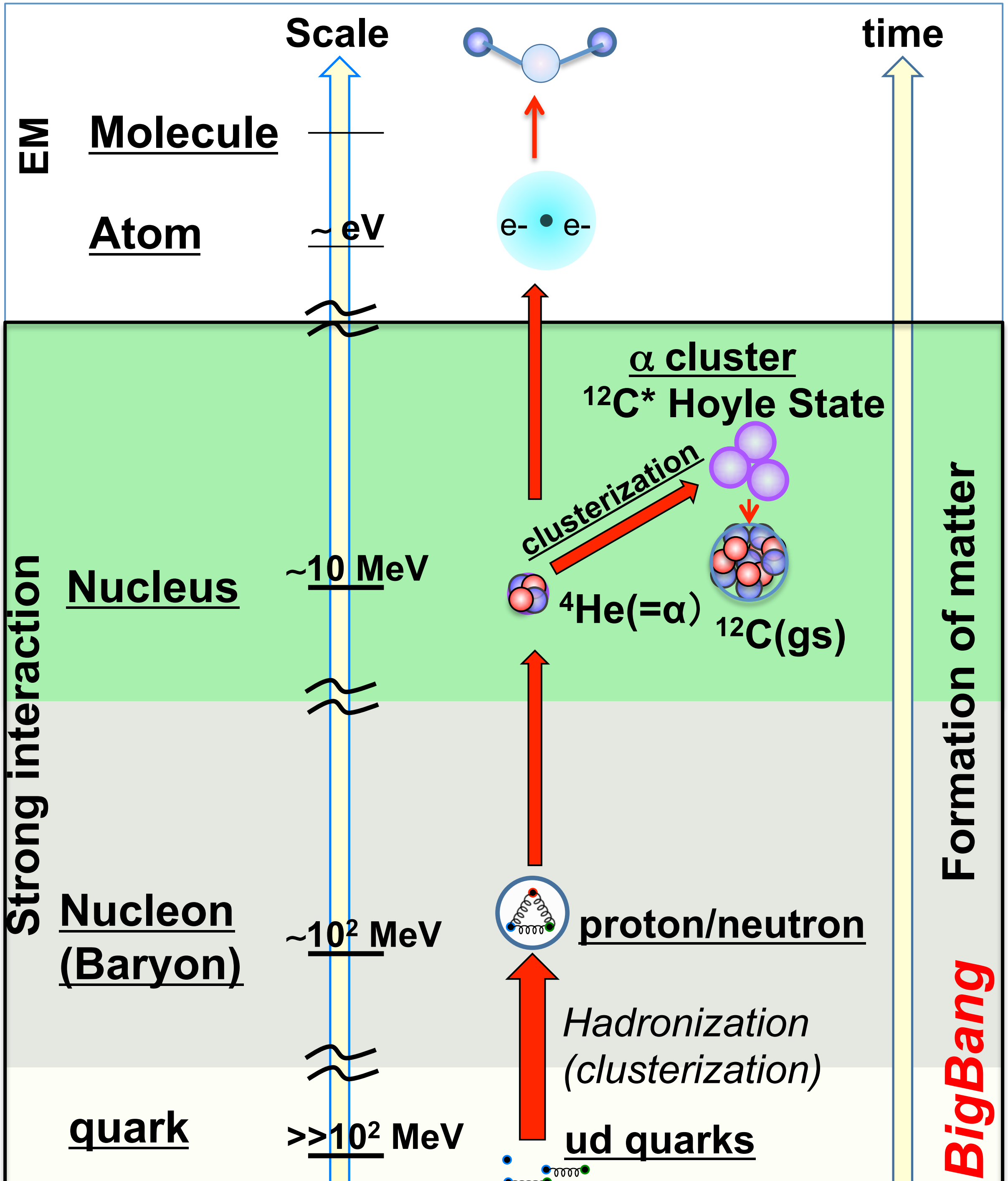
Kondo, TN et al., PRL116,102503(2016).



Hagino, Sagawa,
PRC93,034330(2016)

Mixture of d^2,s^2,p^2

Clustering and Hierarchy of matter



Formation of Atom
→ **Electric charge=0**

Alpha clustering
T=0, S=0

Dineutron clustering?
T=1, S=0

Partially neutralized

Hadronization
→ **Color charge=0**

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?

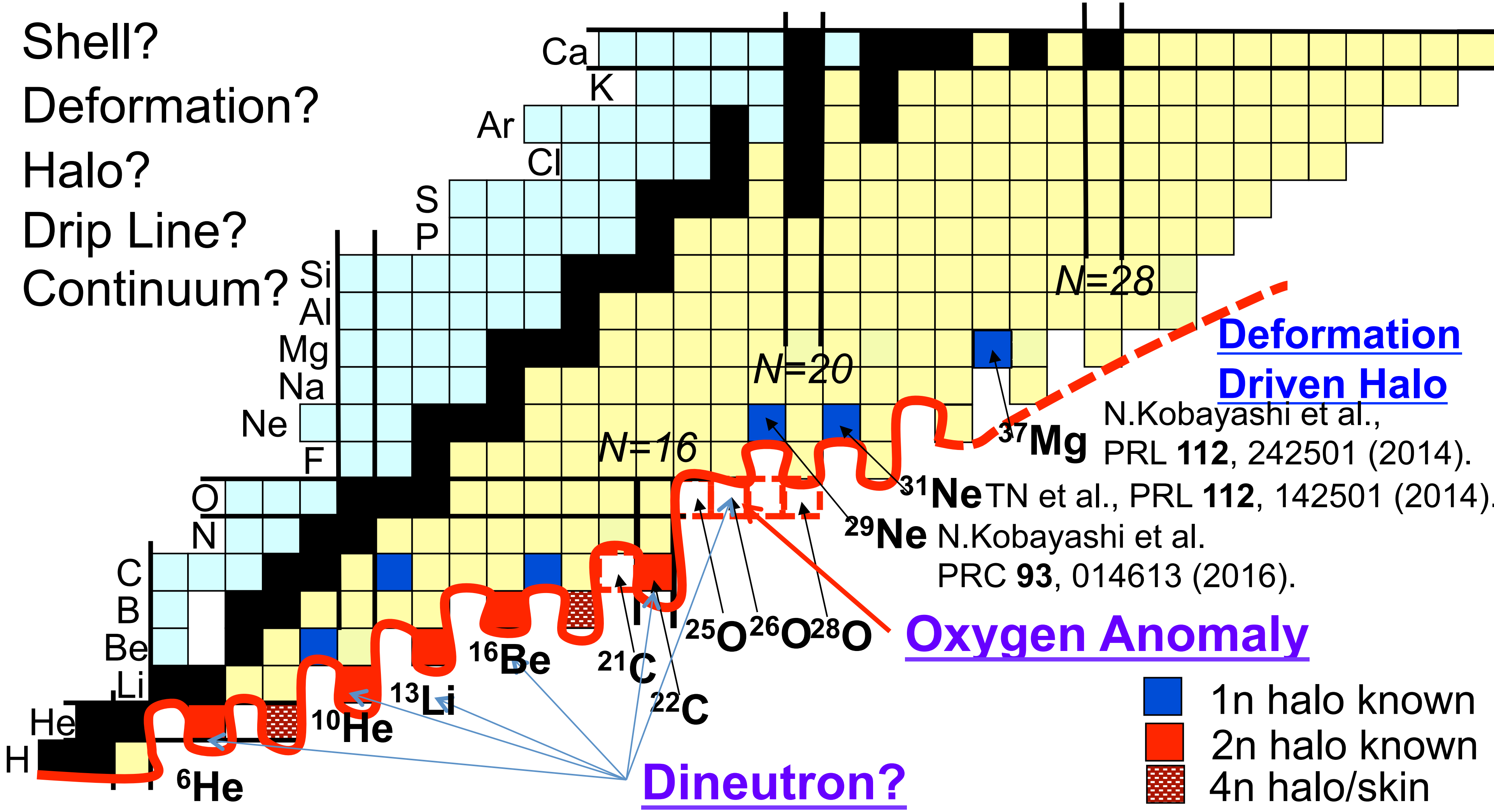
Shell?

Deformation?

Halo?

Drip Line?

Continuum?



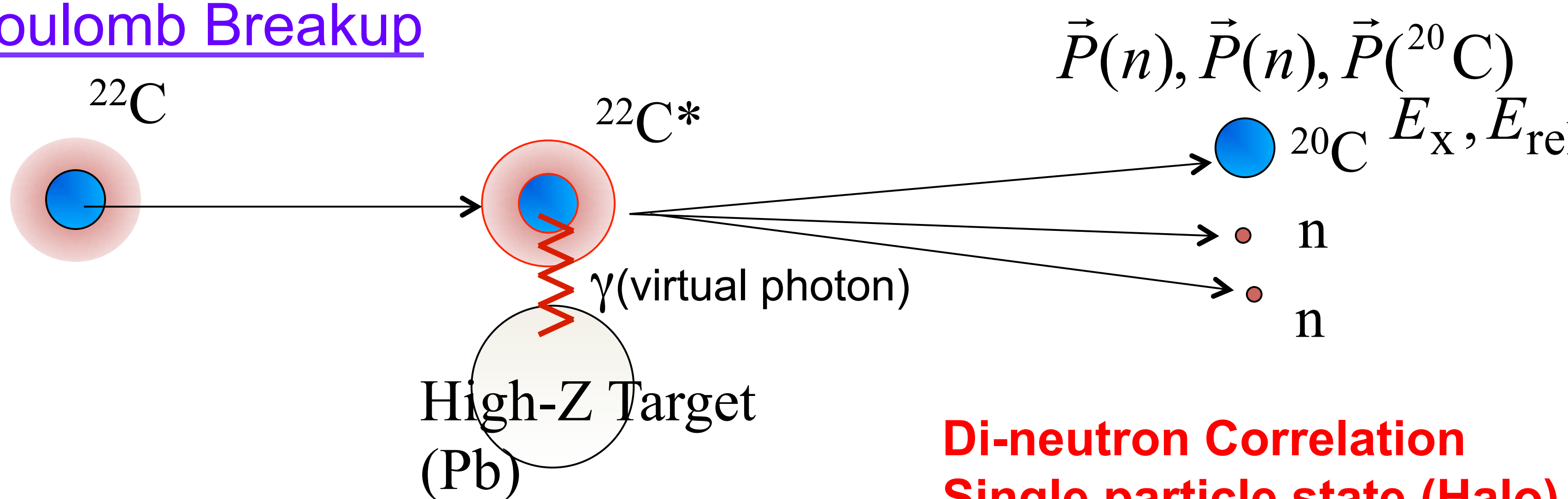
Spectroscopy of 2n Halo Nuclei (^{11}Li, ^{22}C)
---Probed (mainly) by Coulomb Breakup

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

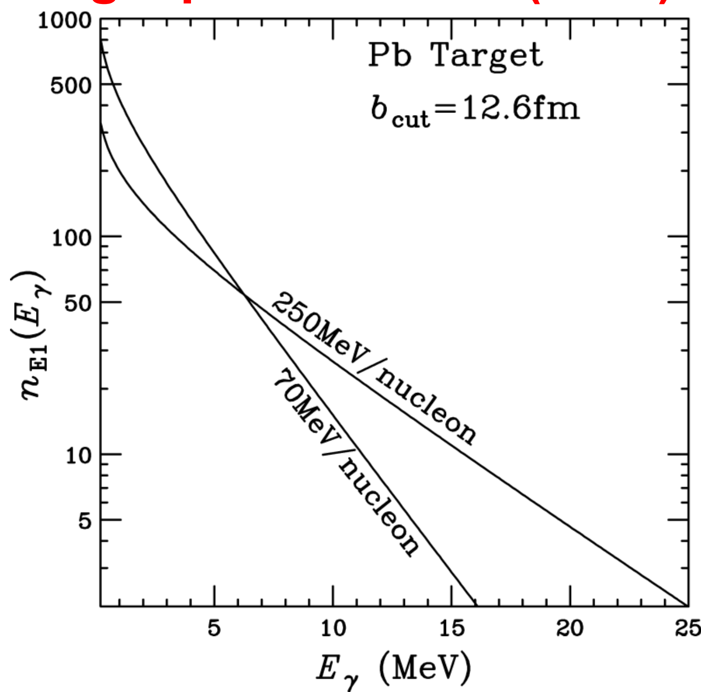
c.f. Talk by Sun Yelei (^{6}He)
Talk by Yuki Kyubota (^{11}Li)

Probe of weakly bound states--*Heavy target*

→Coulomb Breakup



Di-neutron Correlation
Single particle state (Halo)



Equivalent Photon Method

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

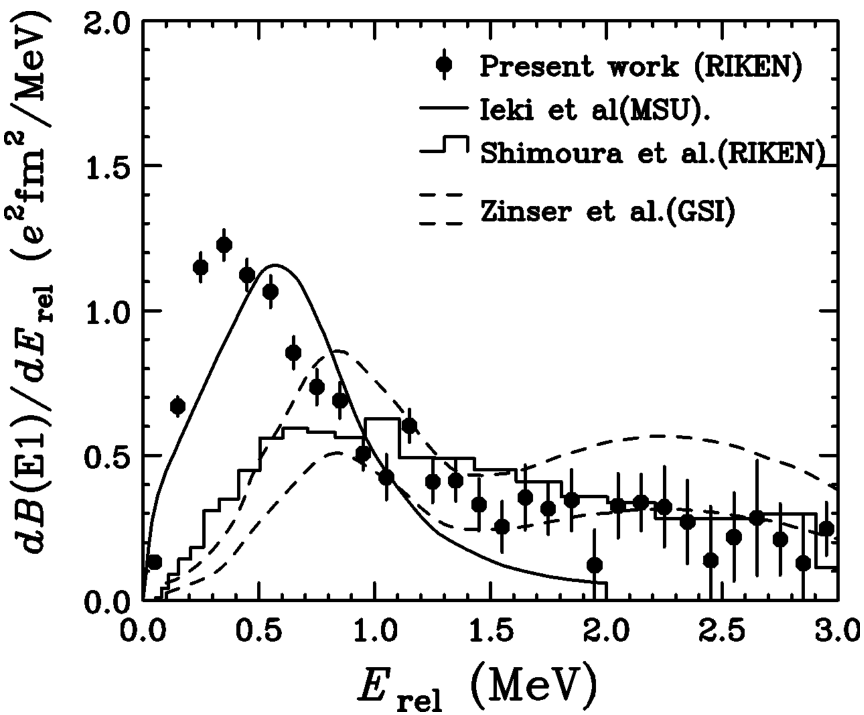
Cross section = (Photon Number)x(Transition Probability)

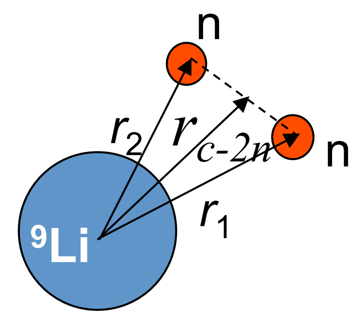
C.A. Bertulani, G. Baur, Phys. Rep. 163,299(1988).

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

Coulomb Breakup of 2n Halo
→ Probe of Dineutron Correlation

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





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

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

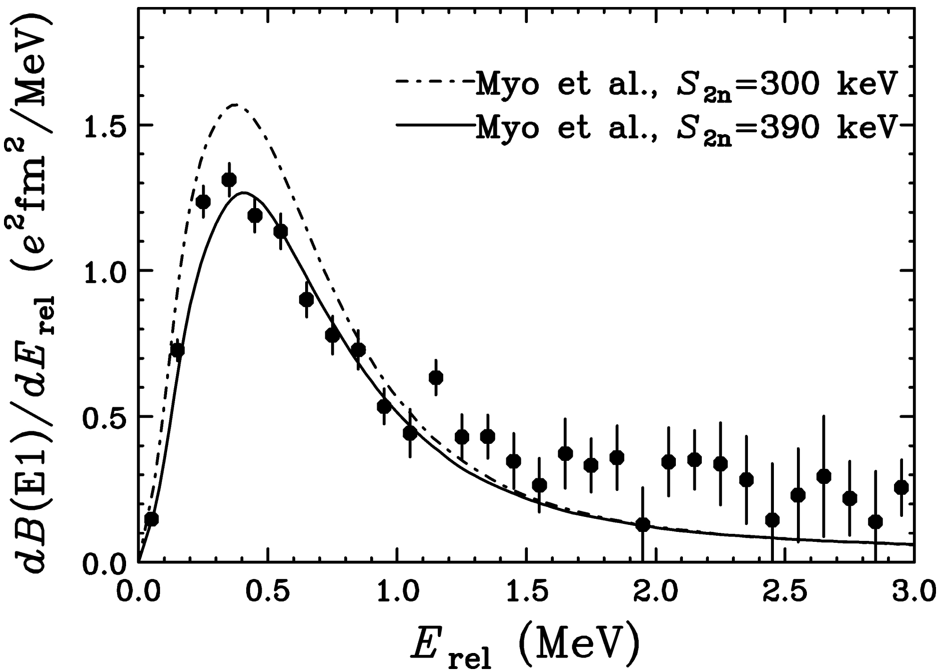
$$B(E1) = 1.42 \pm 0.18\ e^2 fm^2 (E_{\rm rel} \leq 3\mathrm{MeV})$$

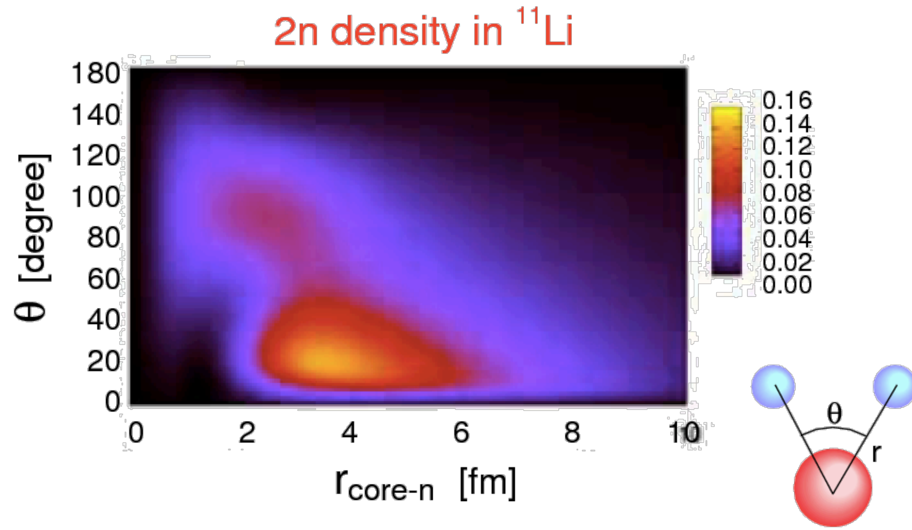
$$\rightarrow 1.78(22)\ e^2 fm^2 \rightarrow \langle \theta_{12} \rangle = 48^{+14}_{-18}\ \mathrm{deg.}$$

Correlation in the Ground State of ^{11}Li

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

Comparison with 3-body theory





Myo et al.,PRC76,024305 (2007).

Core polarization

(Tensor correlation+Pauli Principle)

P(S^2)~ 40% $\sqrt{\langle r_{c-2n} \rangle^2} = 5.38\ \mathrm{fm}$ $\langle \theta_{12} \rangle = 65\,\mathrm{deg}$

Both Charge distribution & B(E1) are reproduced.

^{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

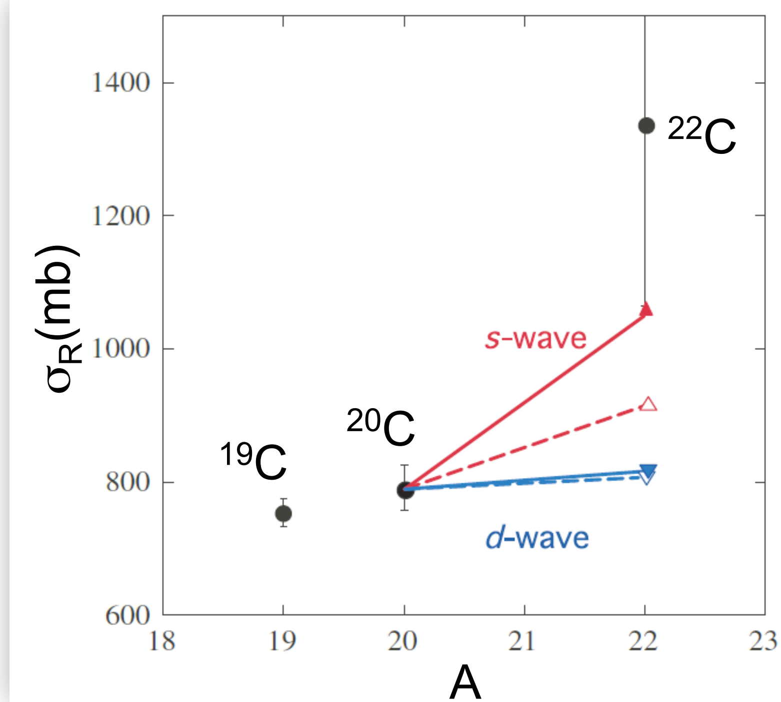
K.Tanaka et al., PRL 104, 062701(2010).

✓ **S_{2n}= −0.14(46) MeV**

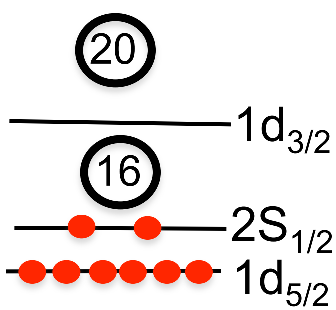
L.Gaudefroy et al. PRL109,202503(2012).

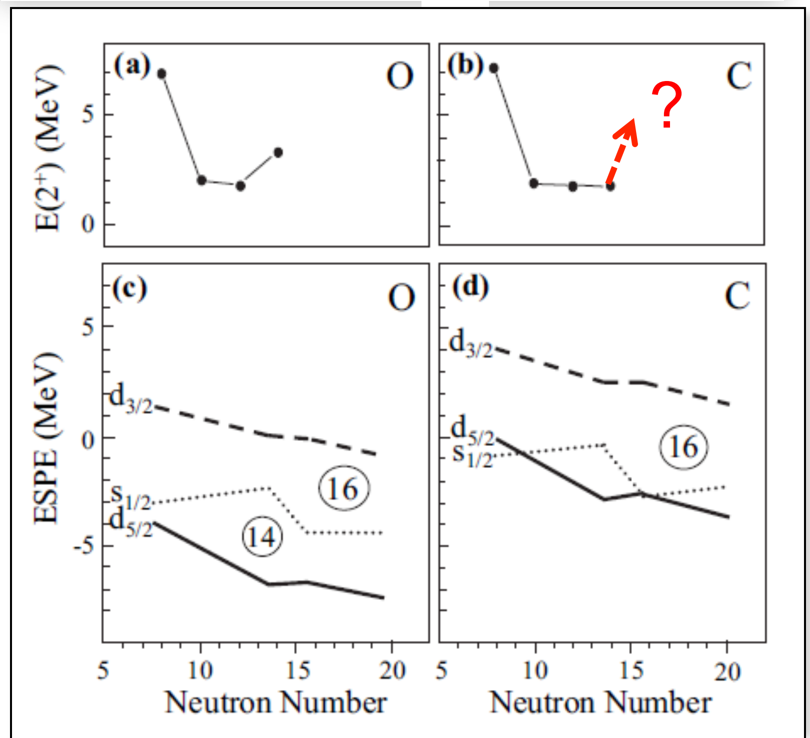
✓ **Narrow Momentum Distribution** ~73MeV/c

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



□ N=16 Magicity?

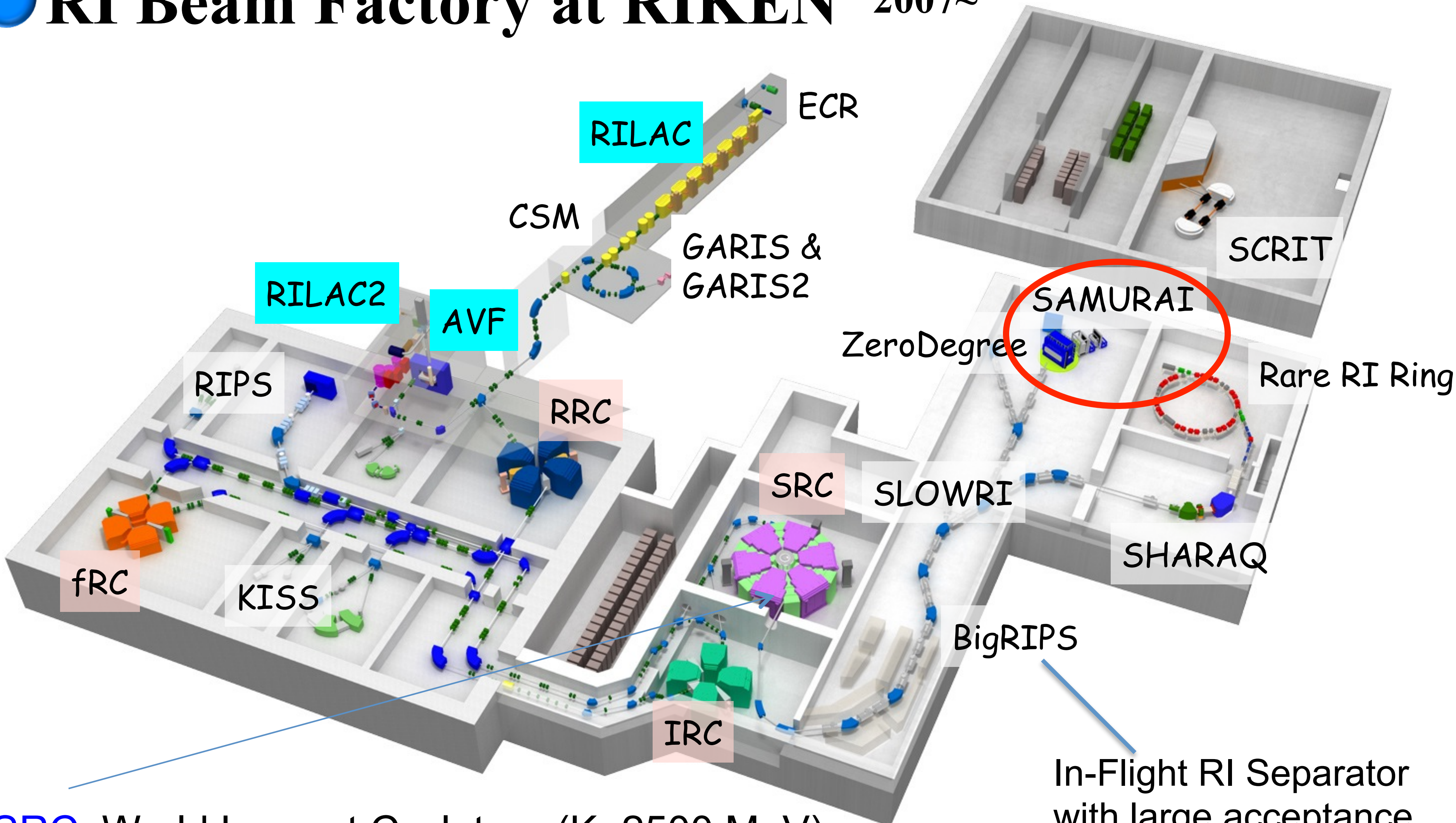




A.Ozawa et al., PRL 84, 5493 (2000).

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

RI Beam Factory at RIKEN 2007~



In-Flight RI Separator with large acceptance

SRC: World Largest Cyclotron (K=2500 MeV)

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

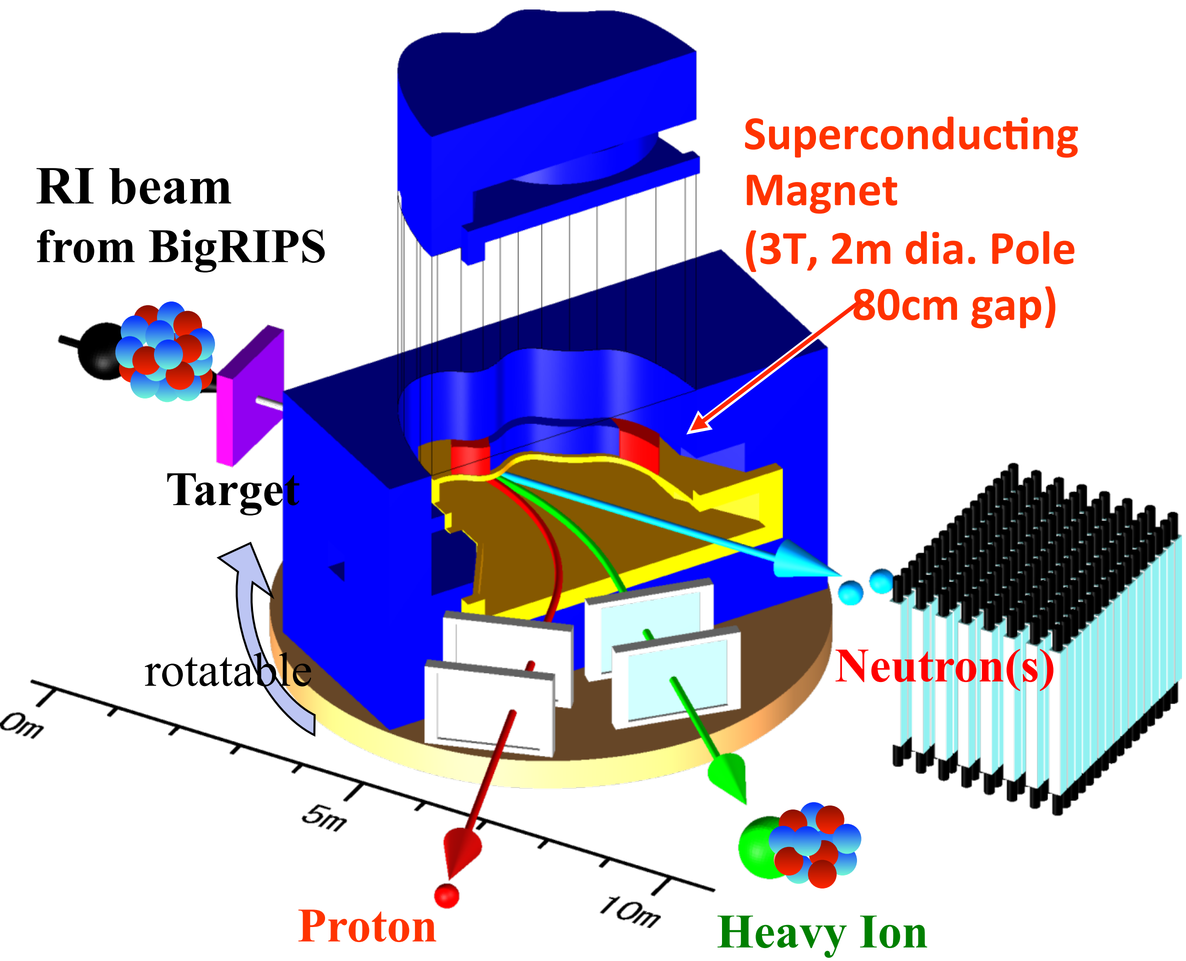
eg. ^{48}Ca: ~500pnA (~3x10^{12}pps) *~10 times compared to 2008*

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

SAMURAI

Superconducting **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

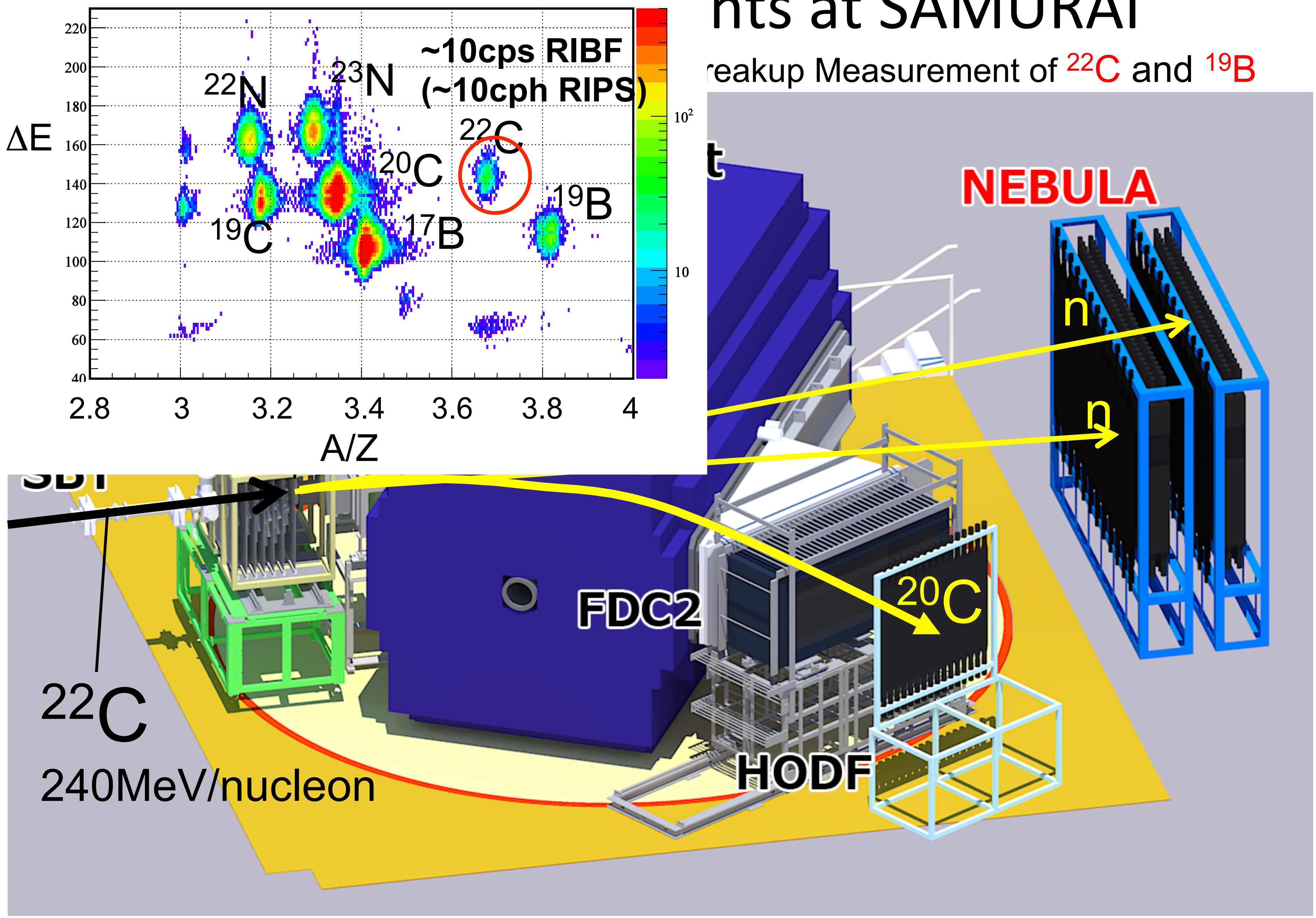
ΔE = 200 keV (σ) at E_{rel}=1MeV

Stage: Rotatable (-5 -- 95 degrees)

→Variety of Physics Opportunities

nts at SAMURAI

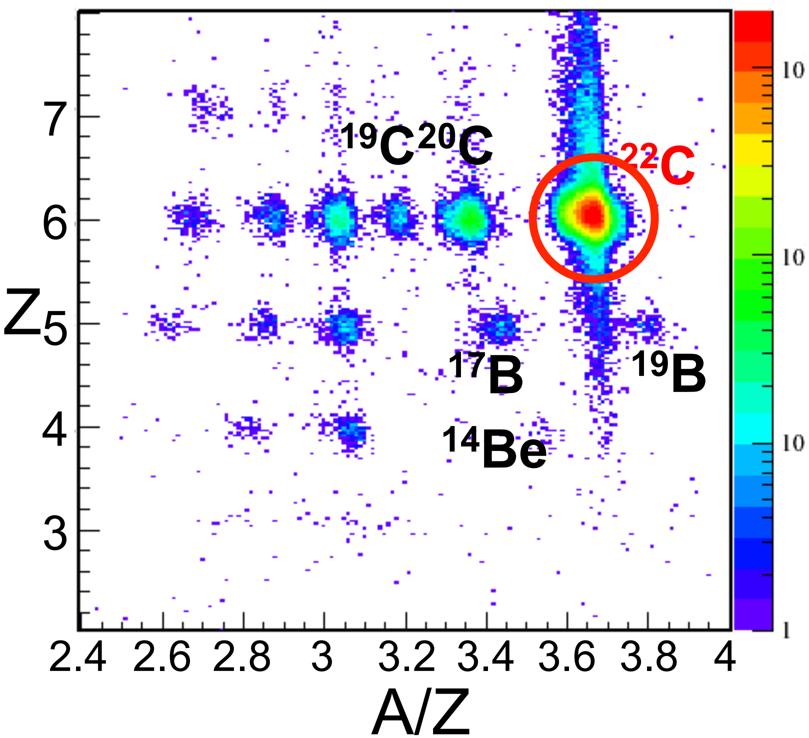
reakup Measurement of ^{22}C and ^{19}B

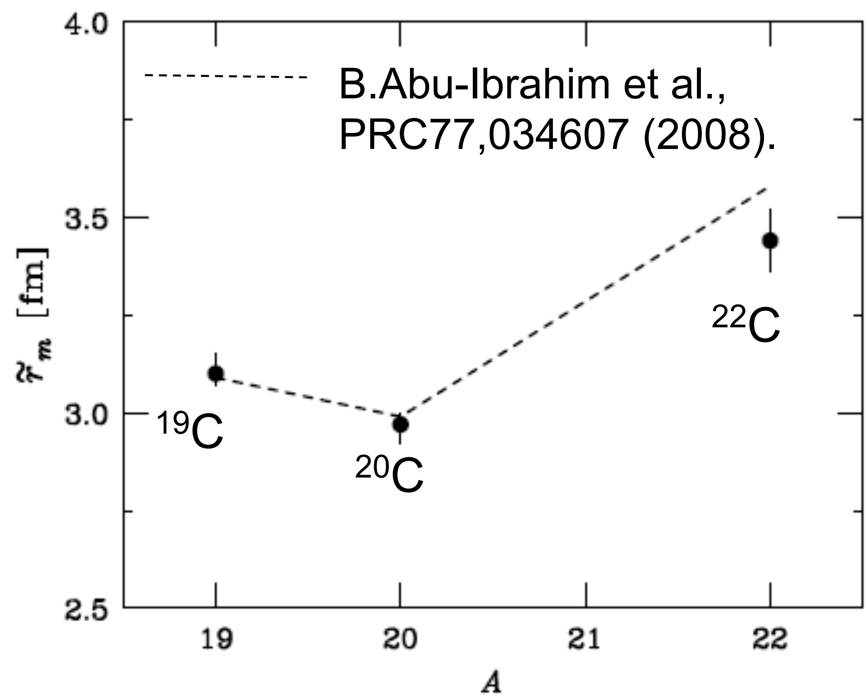


Reaction Cross Section of ^{22}C

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):

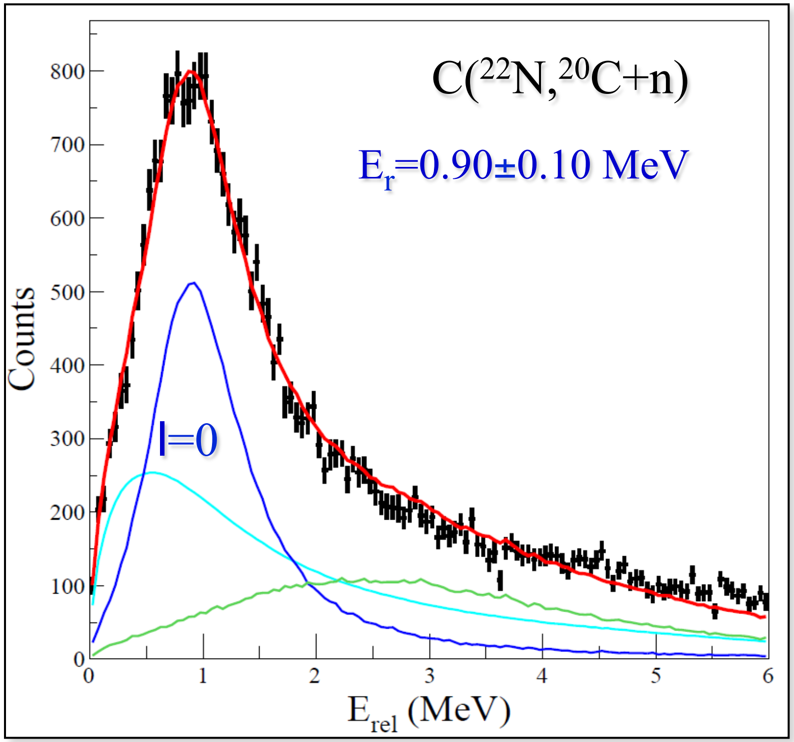
c.f. K.Takaka et al, (p+^{22}C @40 MeV)

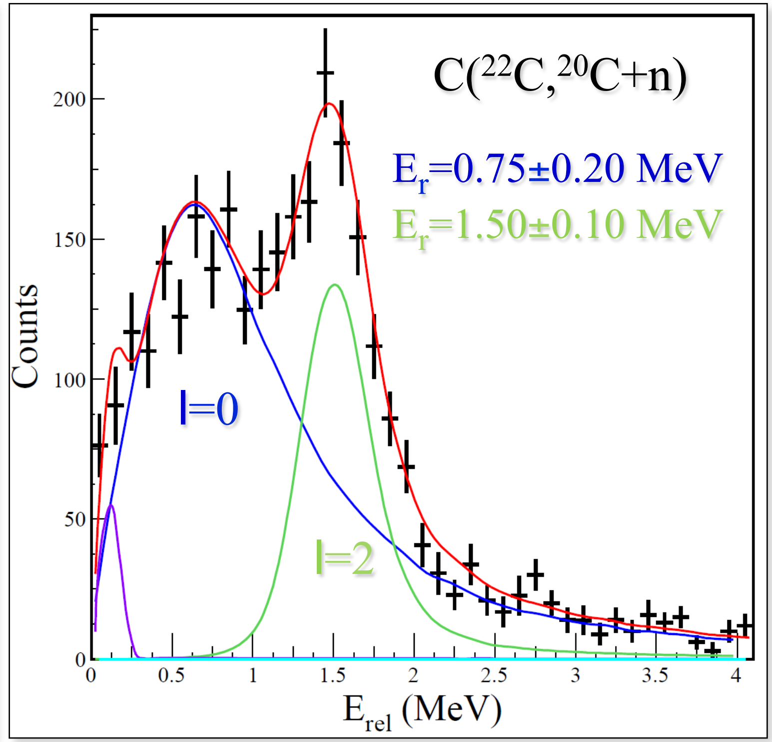
r_{rms}=5.4(9) fm

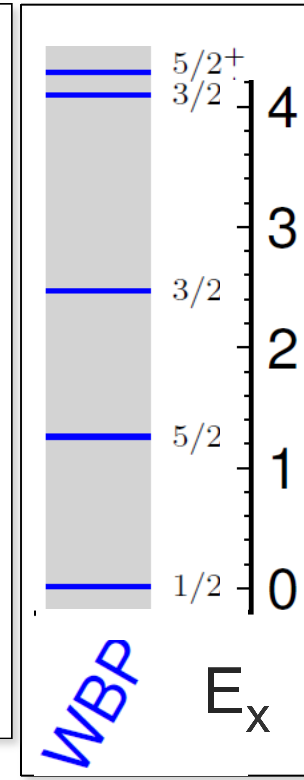
Slide: N.A. Orr, Ph.D thesis of Sylvain Leblond

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

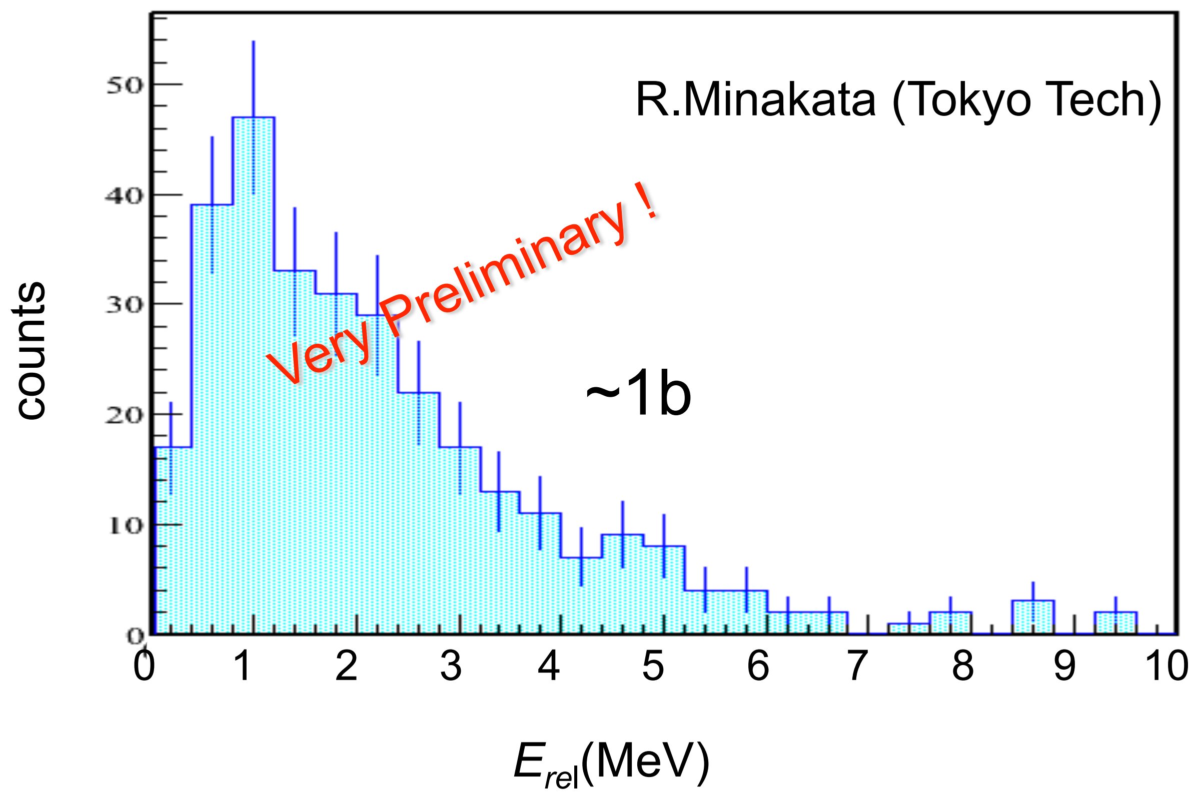
JA Tostevin

S Leblond, PhD Thesis LPC/UCN Dec 2015

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

R. Minakata, T.Nakamura

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



Strong Soft E1 Excitation → Evidence of Halo

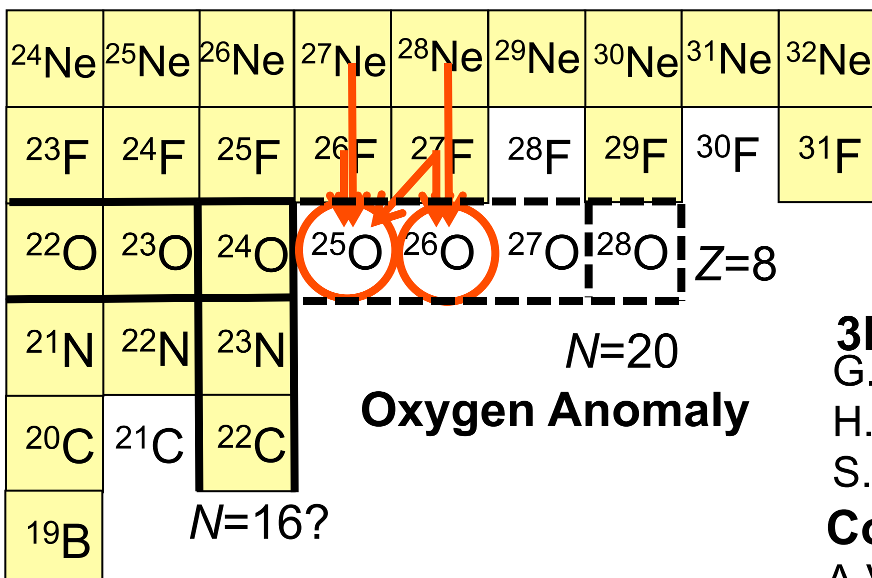
Spectroscopy
of Barely Unbound 2n emitter ^{26}O
(& Other studies on unbound oxygen isotopes)

Yosuke Kondo et al.

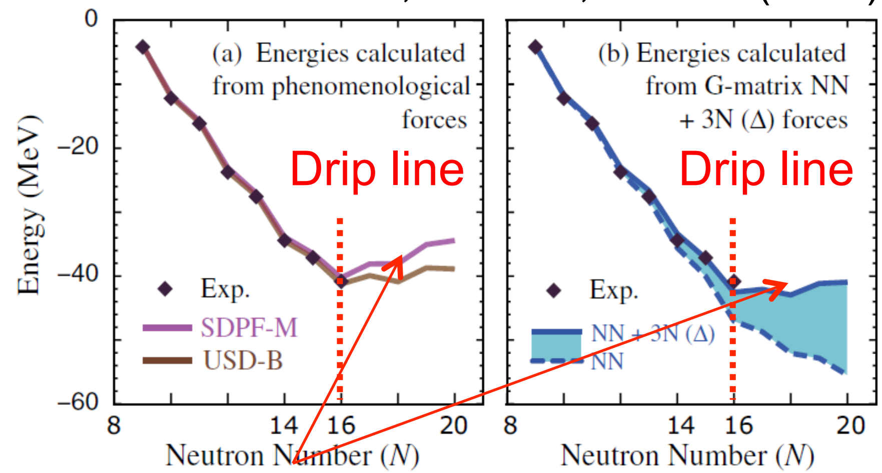
Study of unbound nuclei ^{25}O and ^{26}O at SAMURAI

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).

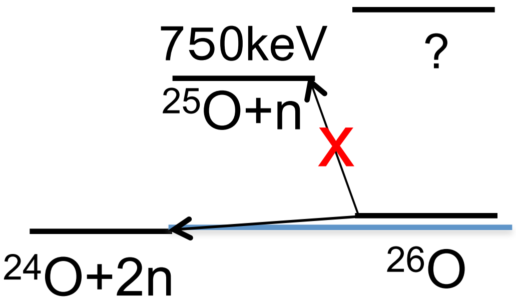
K. Tsukyiyama, T. Otsuka, PTEP2015, 093D01 (2015).

nn correlations:

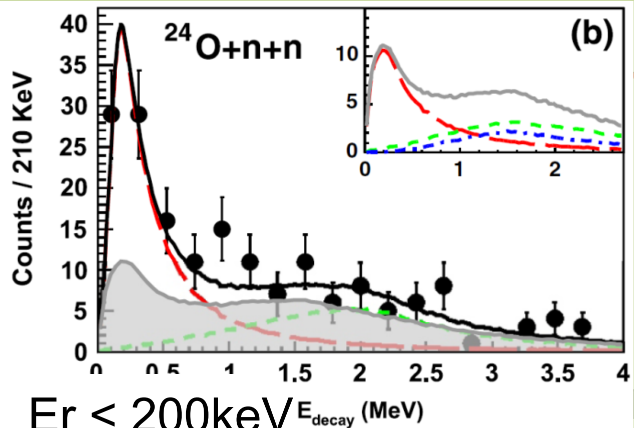
L.V. Grigorenko et al., PRL111,042501(2013).

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

2n radioactivity of ^{26}O?



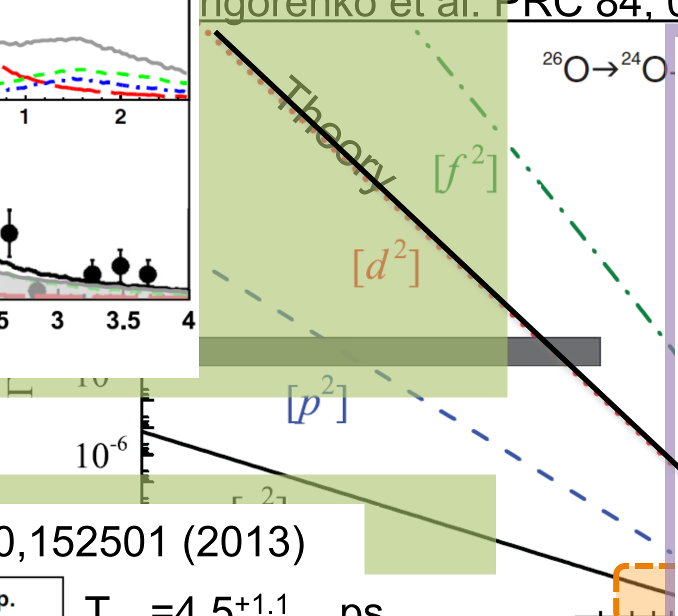
E. Lunderberg et al.
PRL108, 142503 (2012)



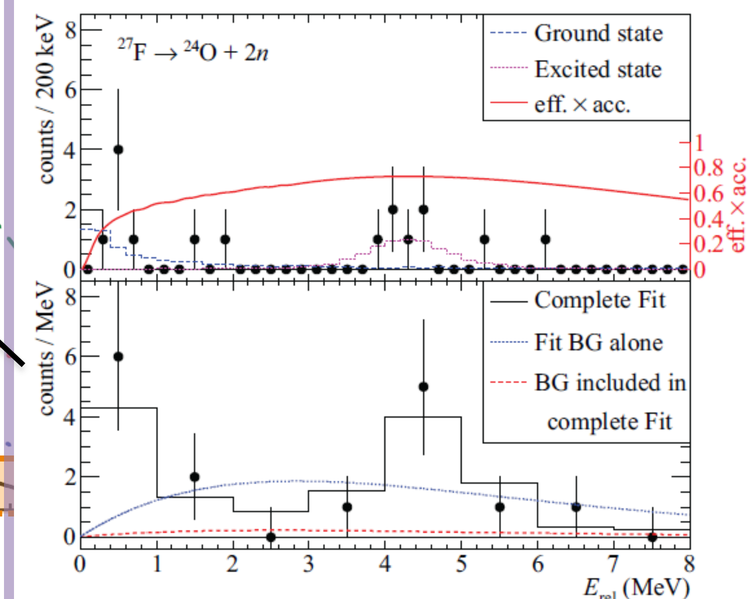
Er < 200keV

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

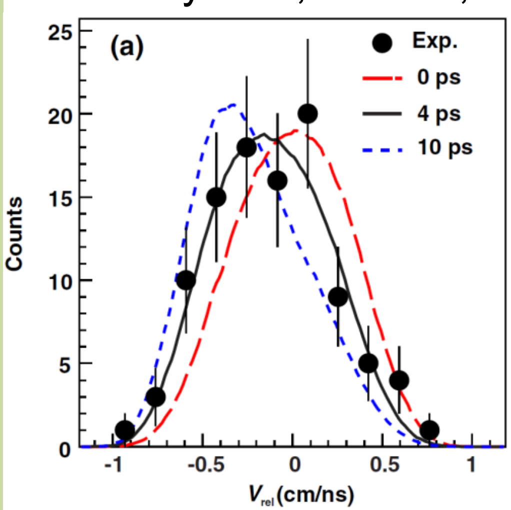
Grigorenko et al. PRC 84, 021303 (2011)



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)

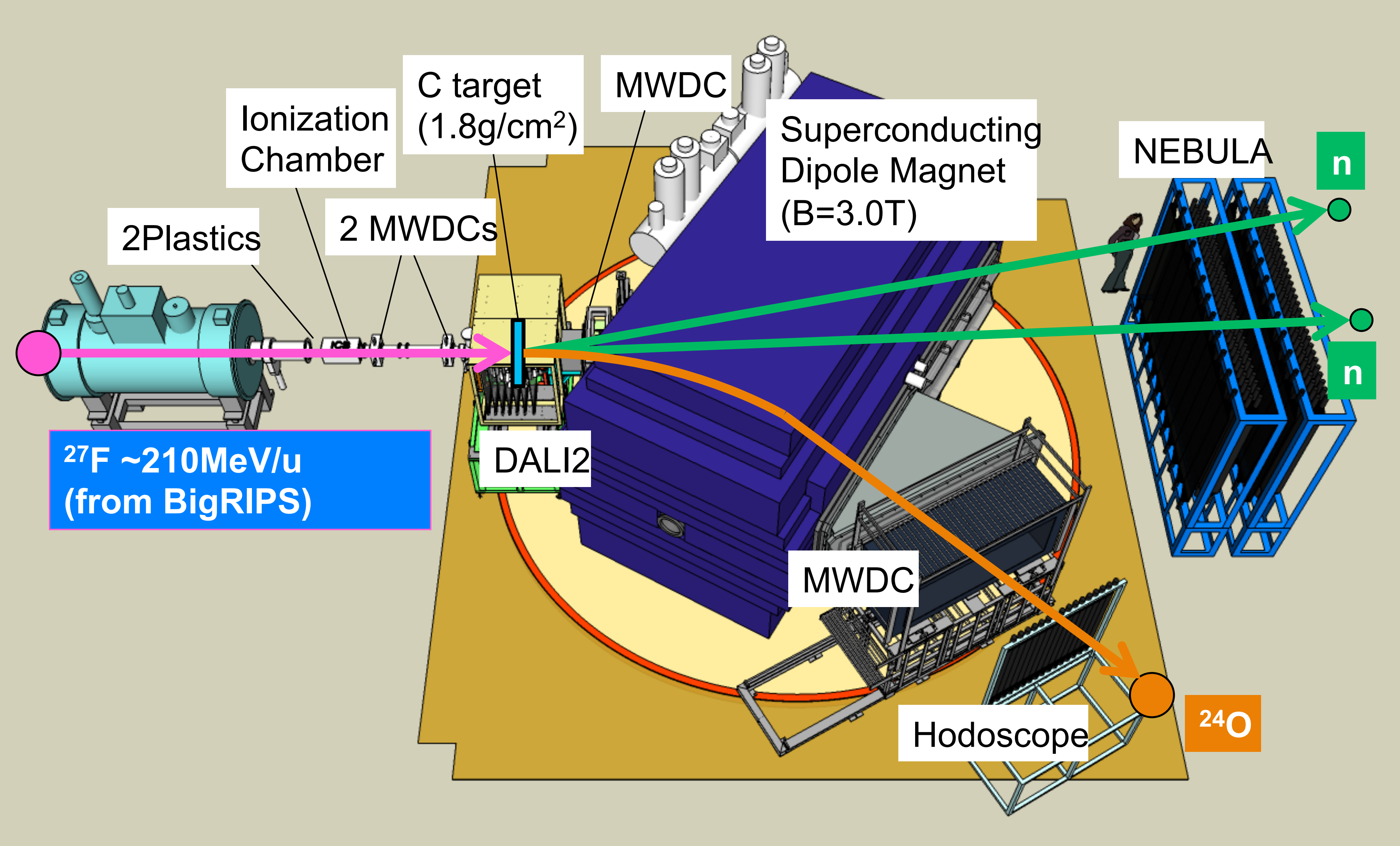
→2n radioactivity?

Usual 1n decay
Γ~MeV or keV

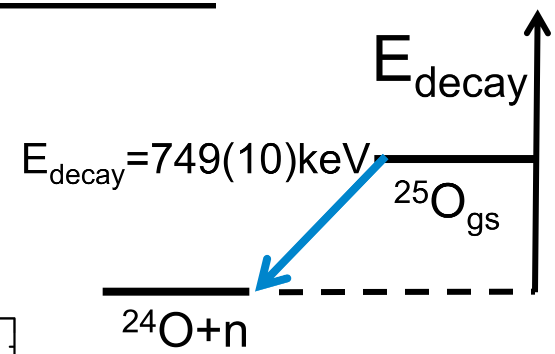
Er < 120keV (95% CL)
τ < 5.7ns

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?

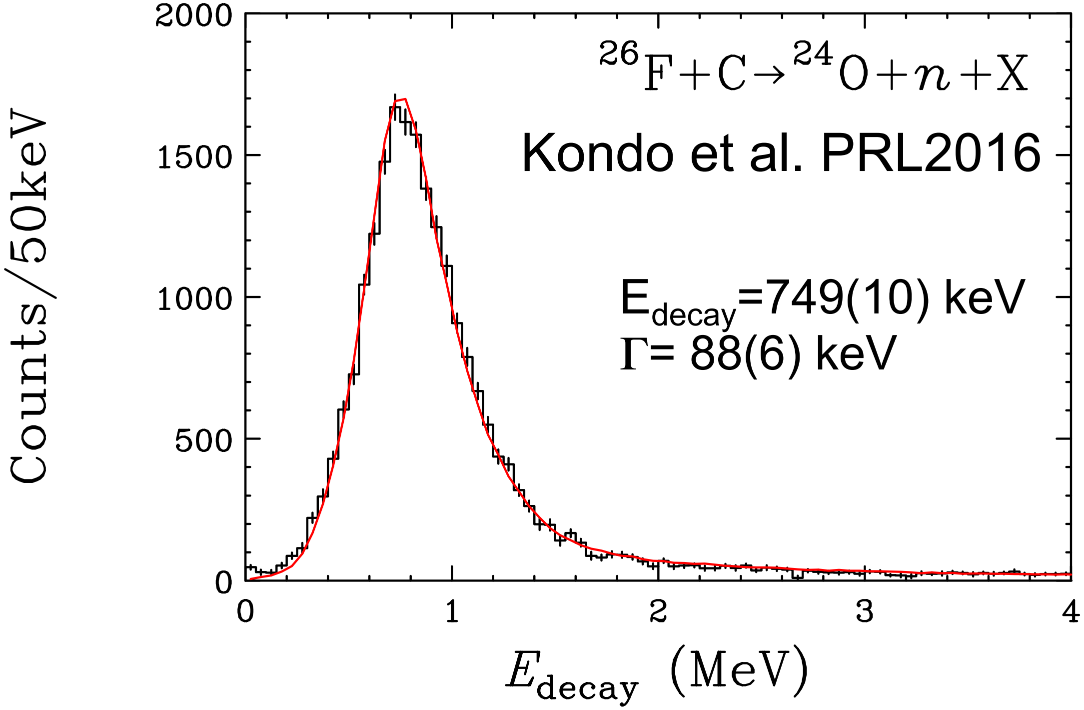
Experimental Setup at SAMURAI at RIBF

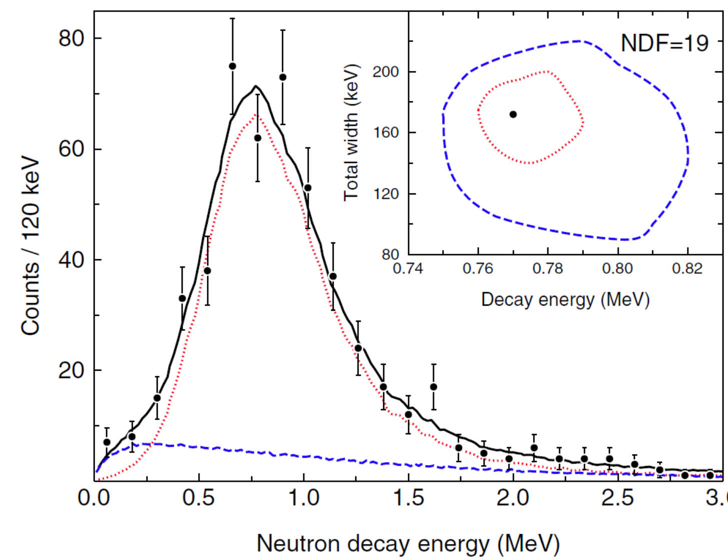


Decay energy spectrum of ^{25}O



^{26}F+C→ ^{25}O*→^{24}O+n



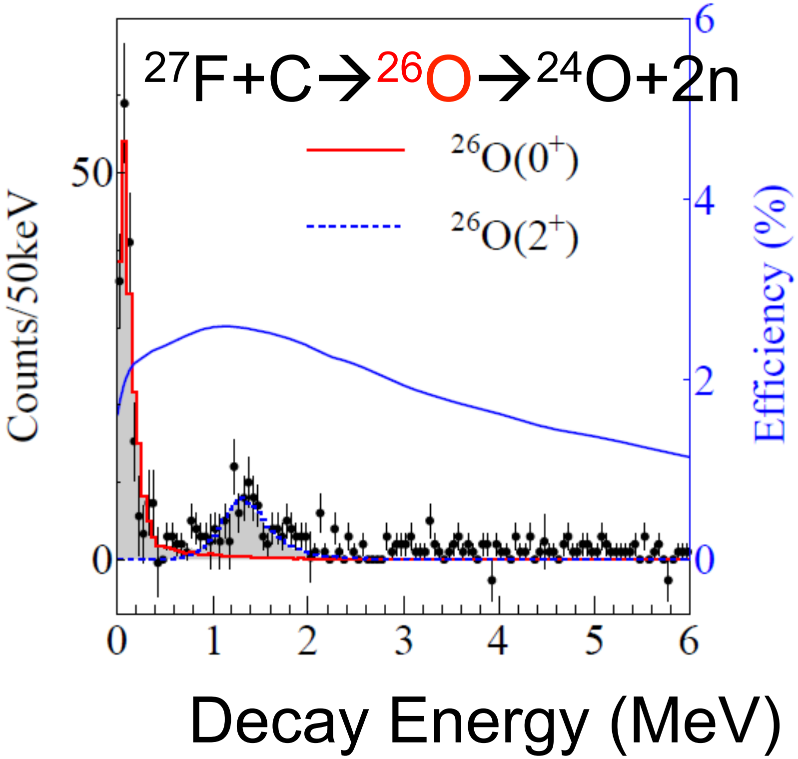


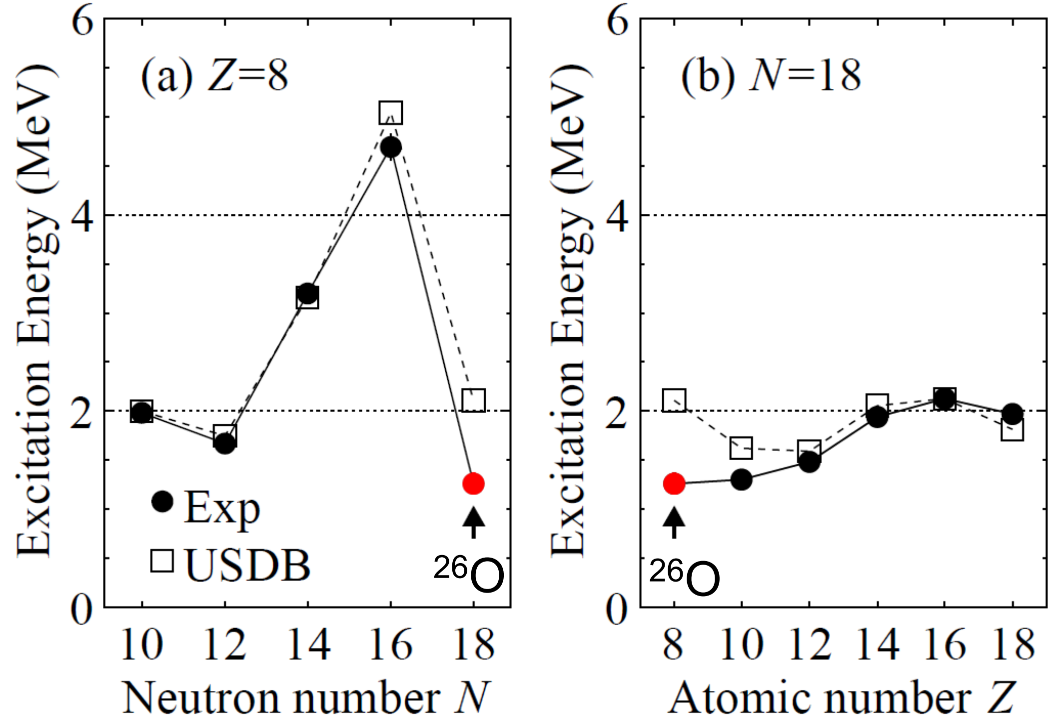
C.R.Hoffman et al.,(MSU) PRL100, 152502 (2008)

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

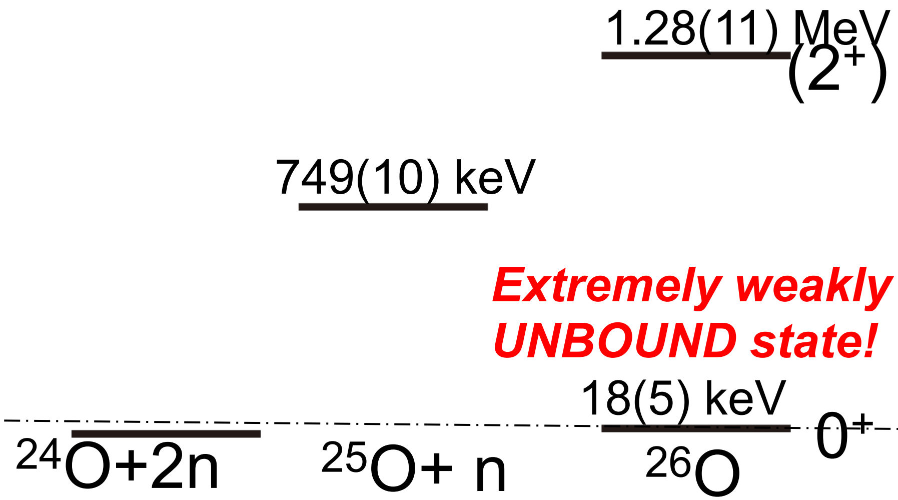
→effects of

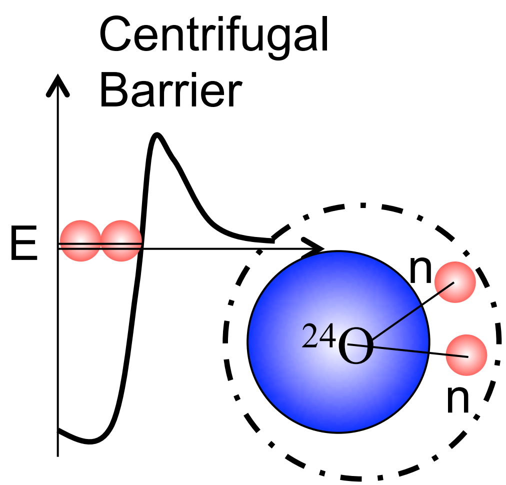
pf shell?, **continuum**?

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

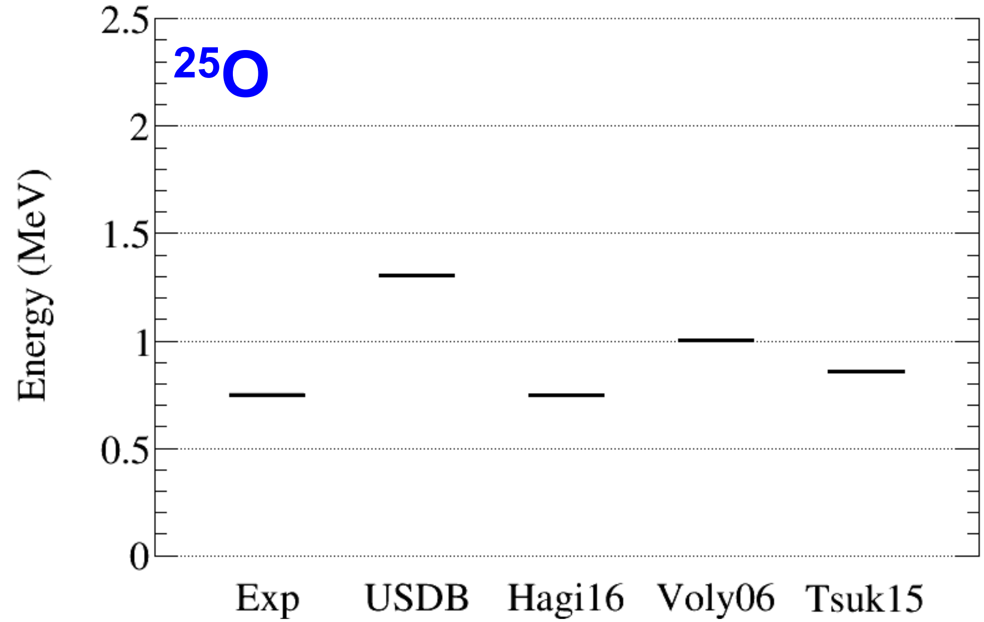
Y. Kondo et al., Phys. Rev. Lett. 116, 102503, (2016)

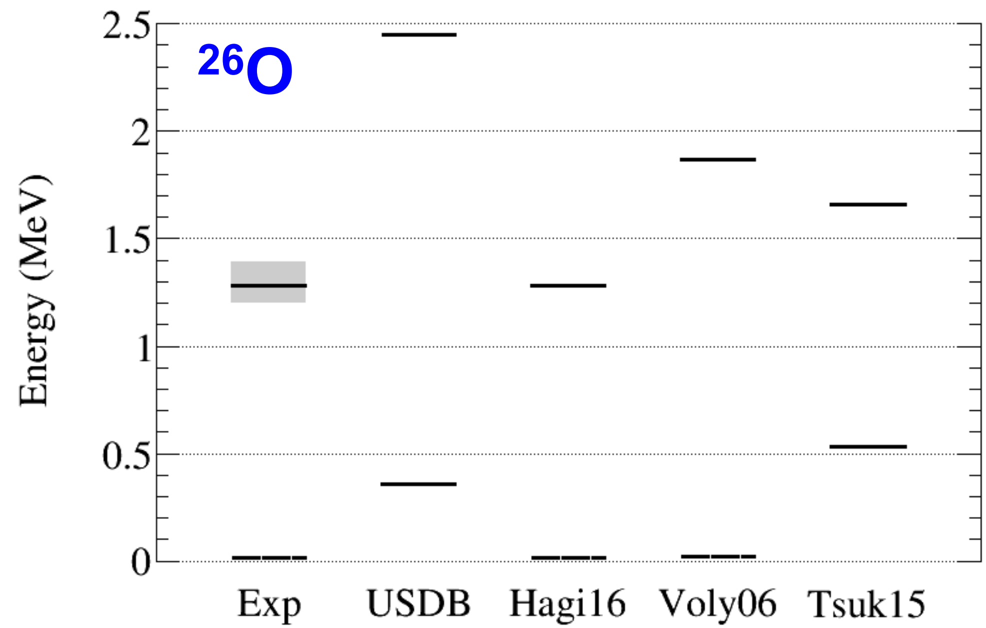
Spectra of ^{25}O and ^{26}O





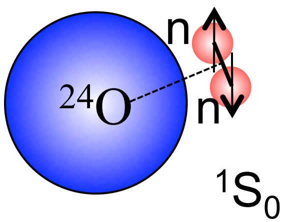
Strong 2n correlation?





Hagi16: K.Hagino,H.Sagawa,PRC93,034330(2016).
Voly06: A.Volya,V.Zelevinsky,PRC74,064314(2006).
Tsuk15: K. Tsukyiyama, T. Otsuka, PTEP2015, 093D01 (2015).

Can we observe directly the dineutron correlation?

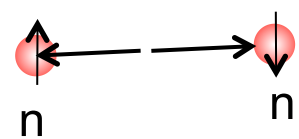


<u>**Summary of "possible" dineutron (eg. ^{26}O)**</u>

1. Mixture of different L (parities) → Dineutron formation

$(0d_{3/2})^2 + (s)^2 + (p)^2 + \ldots$

2. Spatially compact → Large width in Momentum



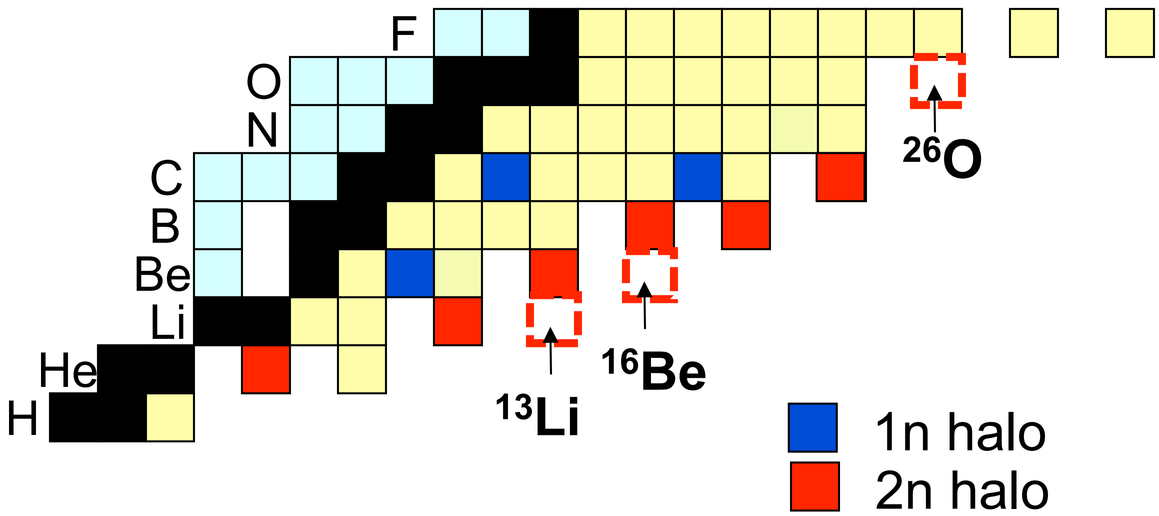
$P_1 \sim -P_2$

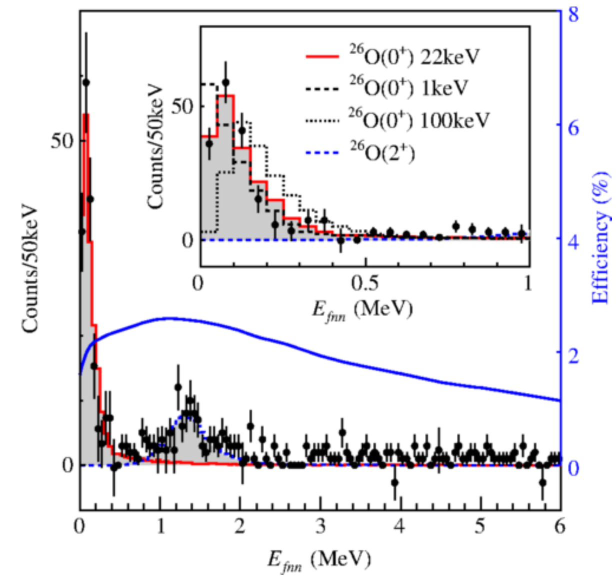
Can we see the dineutron correlation by 2n decay?

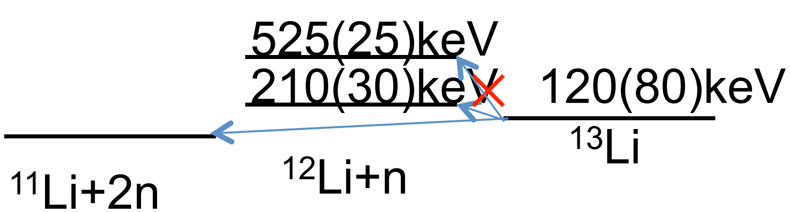
3. Effect of Final State Interactions (inc. Tunneling Effect)

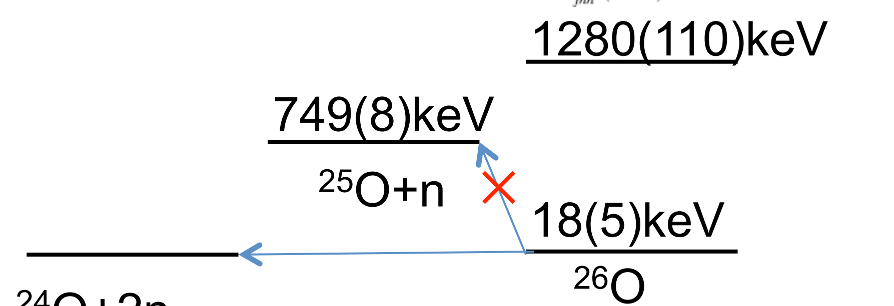
Barely Unbound State (Resonance) with respect to **2n**, but **not to 1n**

→ Suitable for nn correlation studies since it naturally decays by 2n









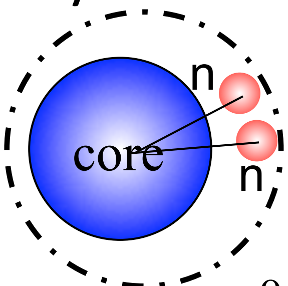
Free from ^{24}O-n FSI!

Z. Kohley et al.,
Phys.Rev.C 87, 011304(R) (2013).

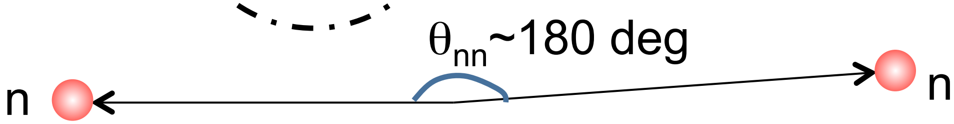
Y.Kondo, T.Nakamura et al.,
Phys. Rev. Lett. 116, 102503 (2016).

Angular Correlation for deneutron?

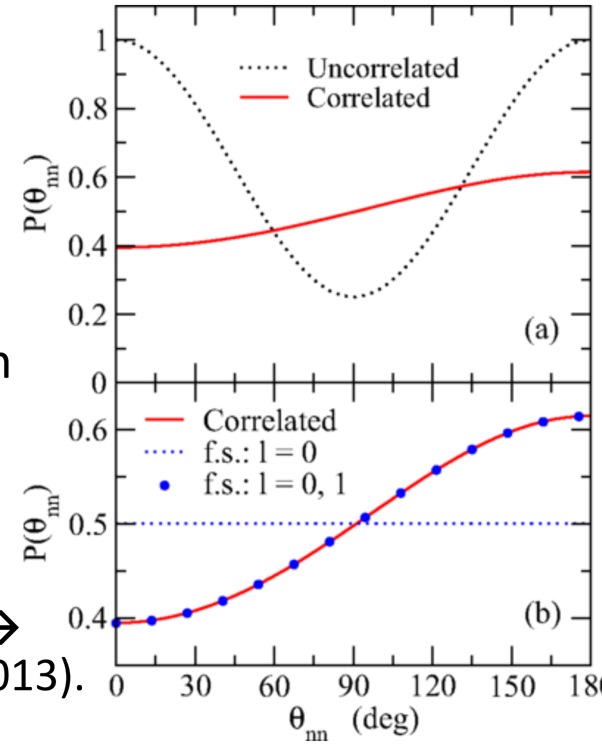
- nn decay from "Dineutron correlation"



Spatially compact nn (dineutron)
→ larger relative momentum

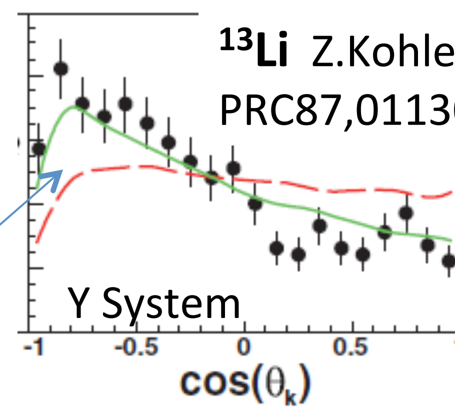


Predicted for ^{26}O by Hagino,Sagawa, PRC93,034330(2016).→
Similar distribution shown in Grigorenko PRL111,042501 (2013).



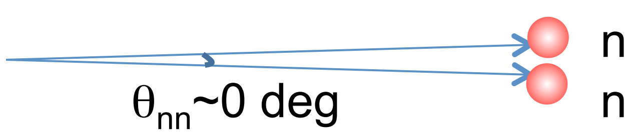
- nn decay from "nn virtual state"

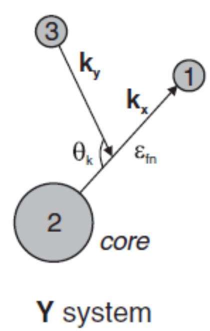
→ "nn virtual state (FSI) coupled in the exit channel" for E_{nn} >100 keV (Alexander Volya, Private comm.)



^{13}**Li** Z.Kohley PRC87,011304(2013)

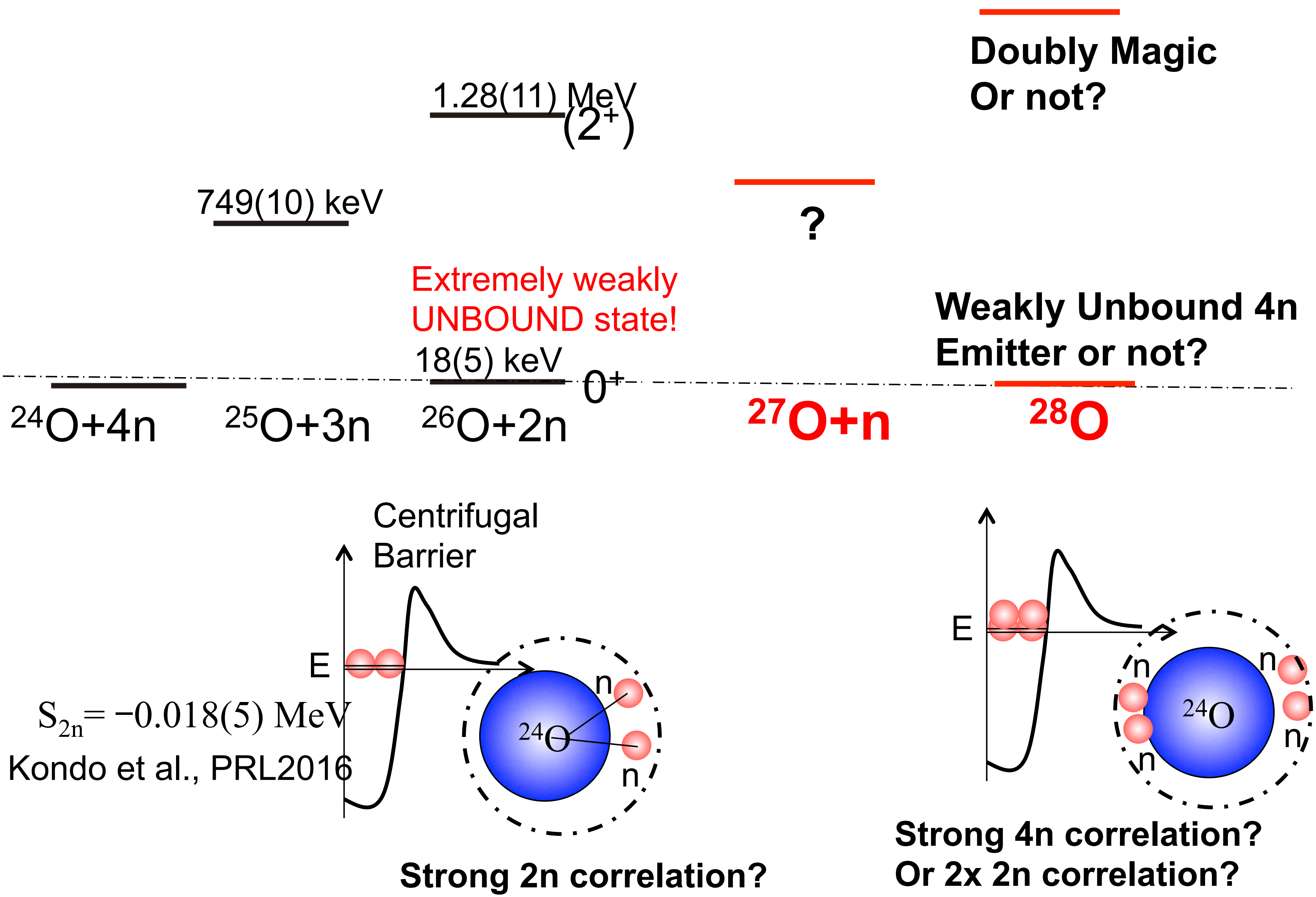
nn: Same direction





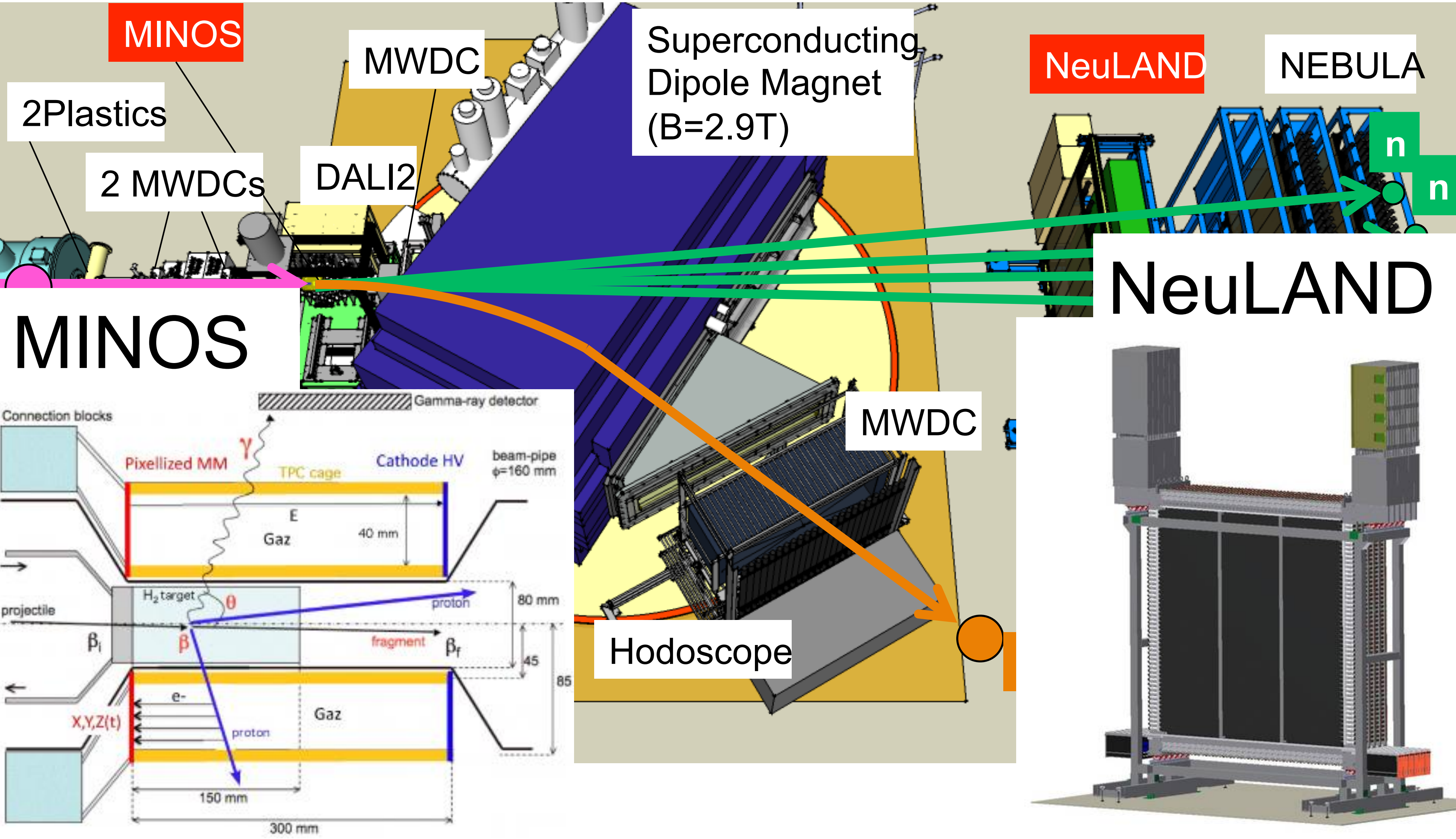
nn decay in the same direction:
Observed also for ^{16}Be:
A. Spyrou et al.,
PRL 108, 102501 (2012).

Towards the possible doubly magic nucleus ^{28}O

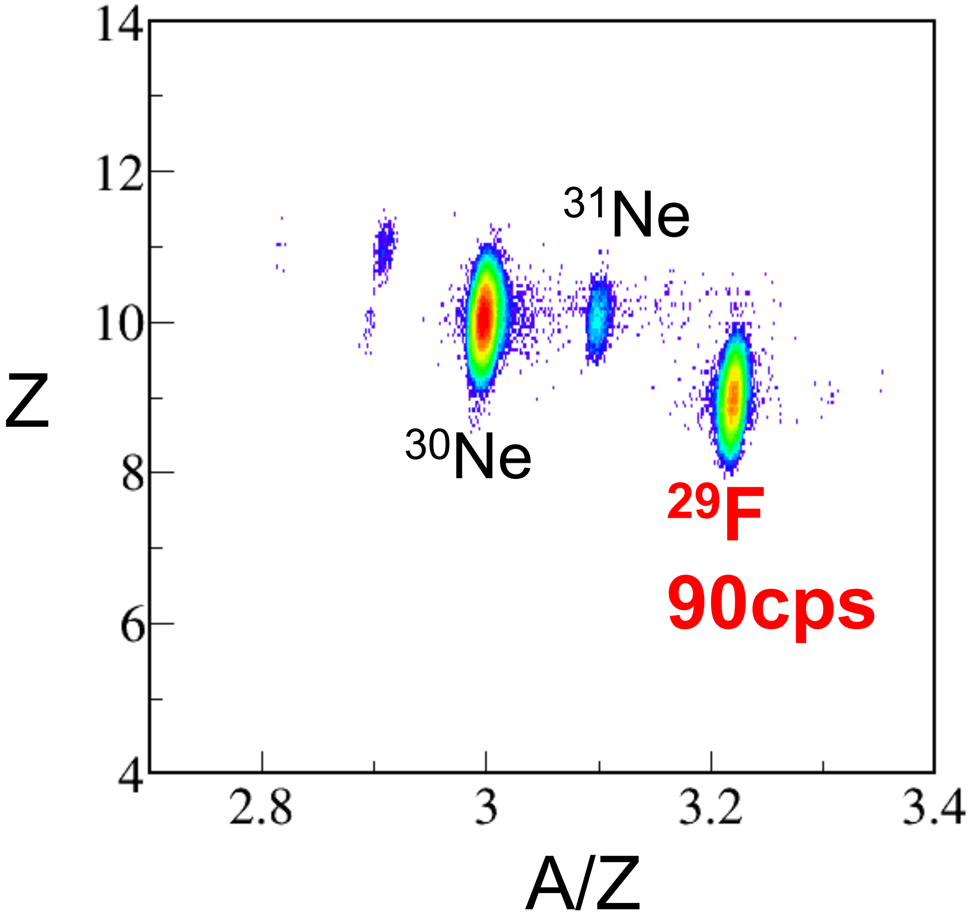


^{27,28}O measurements in 2015 (SAMURAI21)

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

- ✓ **Dineutron Correlation in 2n Halo nuclei**

  ^{11}Li, ^{22}C

  SAMURAI: Useful Facility for Drip Line Nuclei

  - ✓ **Reaction Cross Section of ^{22}C**

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

  - ✓ **Spectroscopy of ^{21}C**

    S.Leblond, J.Gebelin, M.Marques, N.Orr,
    → ^{21}C spectrum → pin down s and d 1hole state of ^{22}C

- ✓ **Barely unbound 2n emitter ^{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 along n-drip line

Day-one Collaboration

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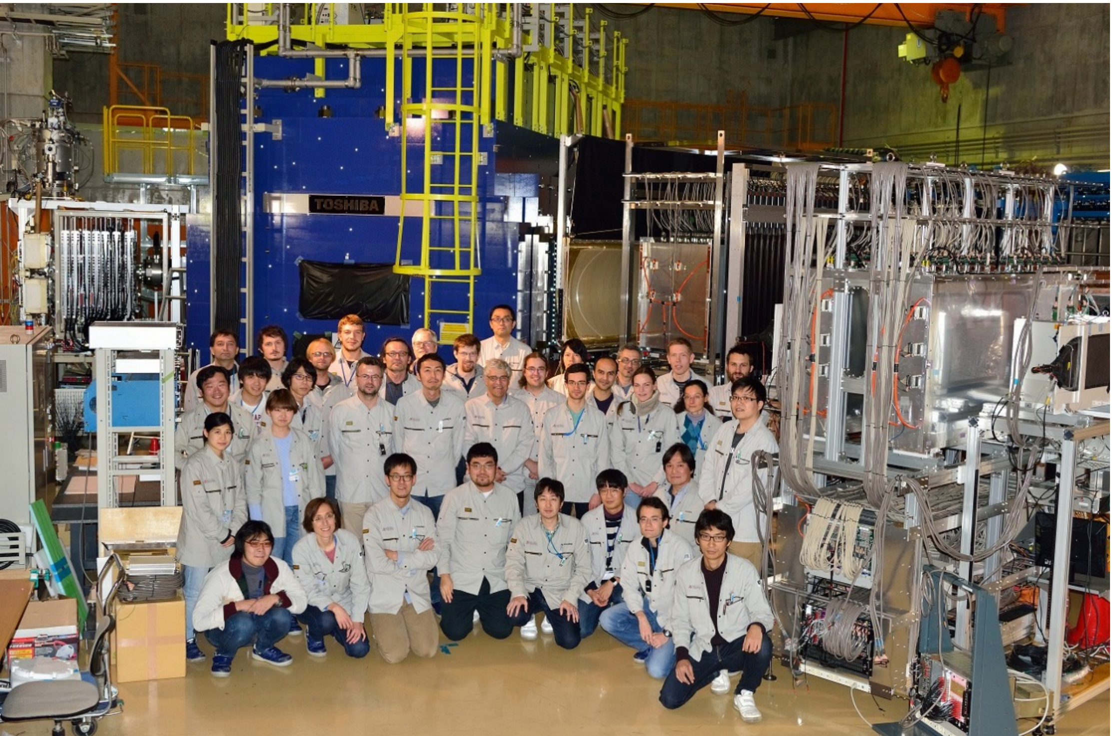
SAMURAI21 collaboration—^{27,28}O



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