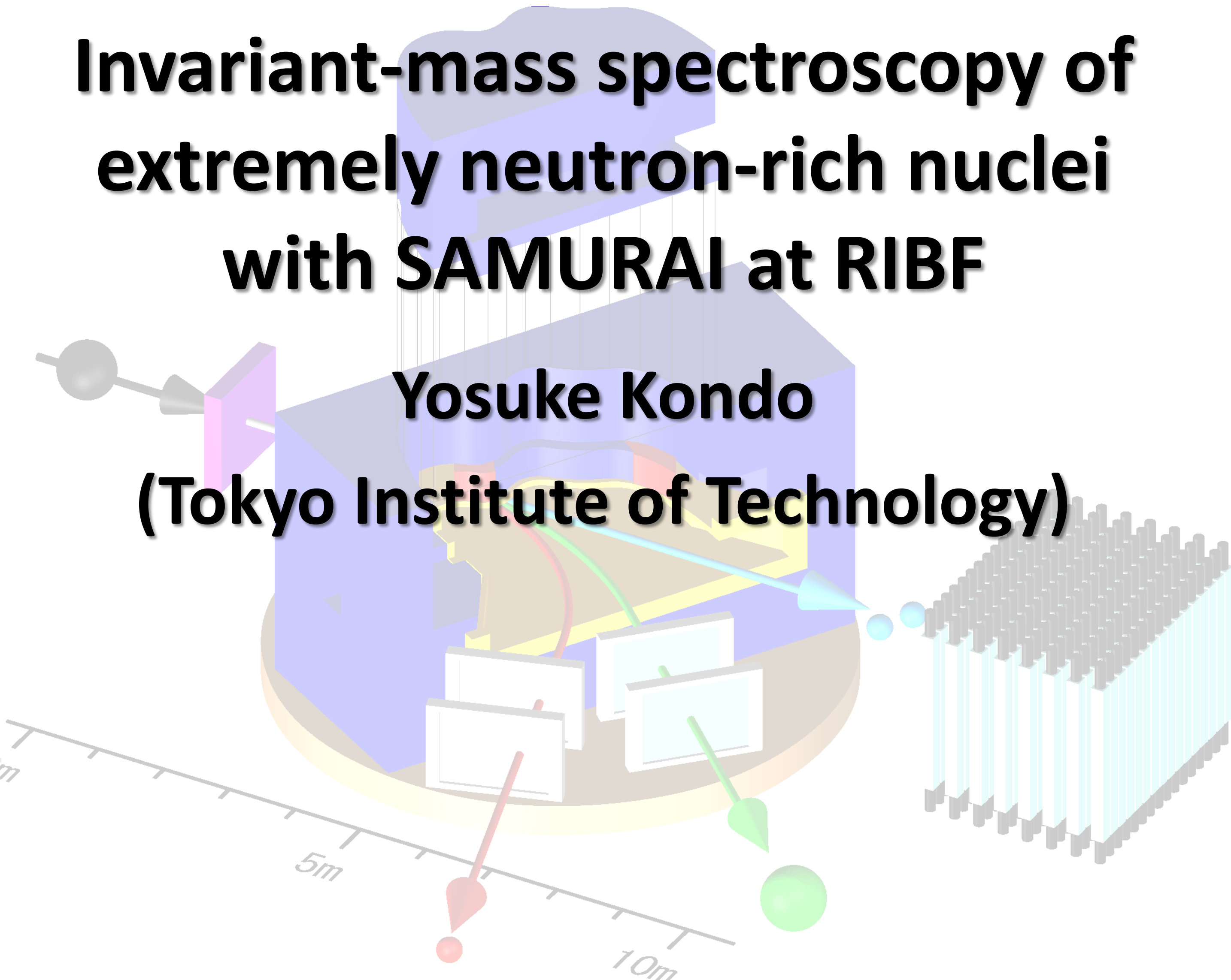
Invariant-mass spectroscopy of extremely neutron-rich nuclei with SAMURAI at RIBF

Yosuke Kondo

(Tokyo Institute of Technology)



ARIS2014, ITO International Research Center (University of Tokyo), June 1-6, 2014

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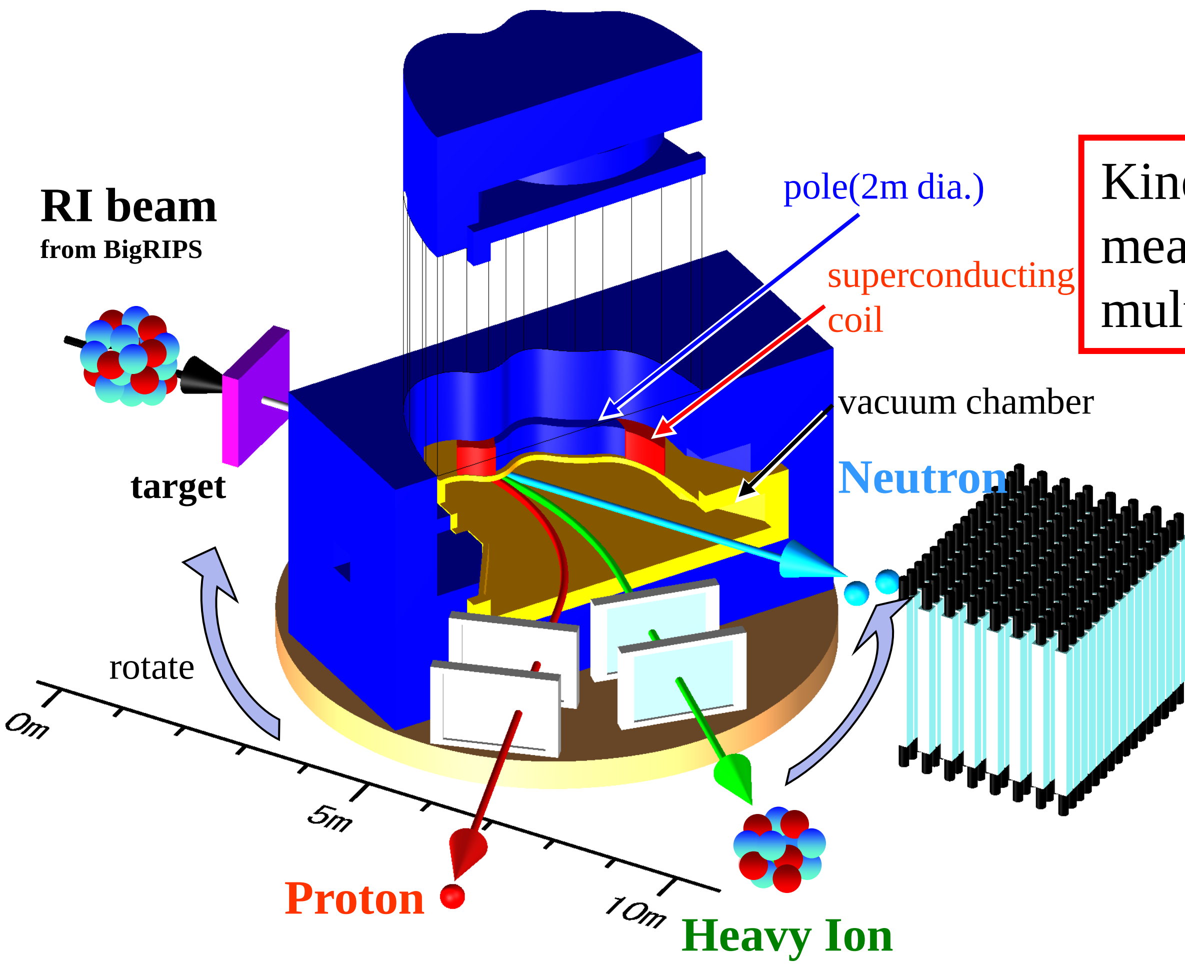
1. Introduction of SAMURAI at RIBF

2. First experimental campaign using SAMURAI for physics programs (Day-One campaign)

SAMURAI

Superconducting **A**nalyzer for **MU**ltiple-particles from **RA**dio**I**sotope Beam



Kinematically complete measurements by detecting multiple particles in coincidence

- Superconducting Magnet
  3T with 2m dia. pole
  (designed resolution 1/700)
  80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors (NEBULA)
- Large Vacuum Chamber
- Rotational Stage

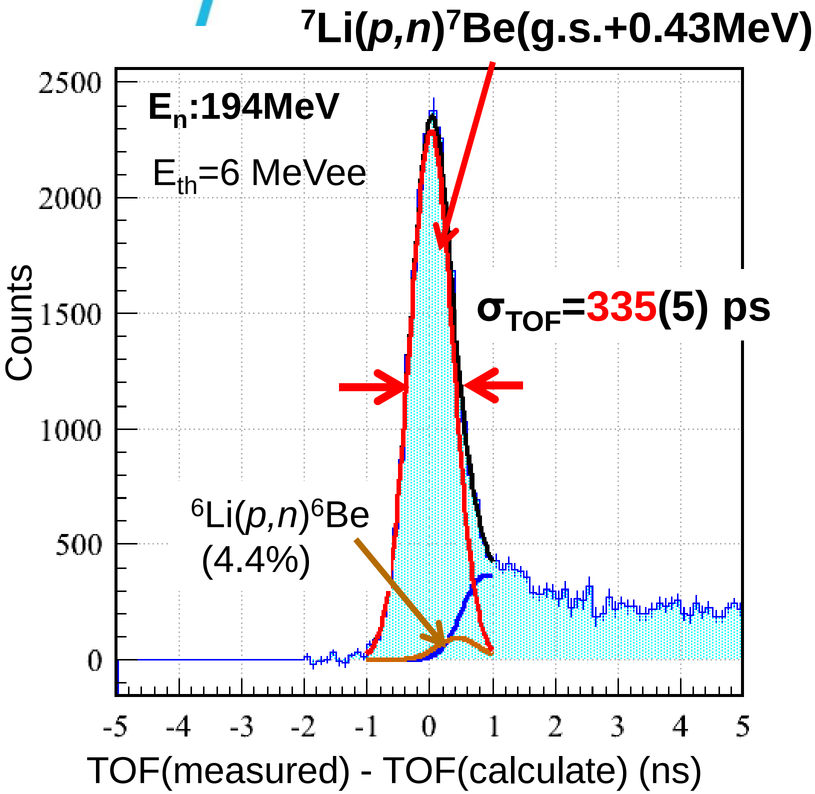
T. Kobayashi et al., NIMB317, 294, (2013)

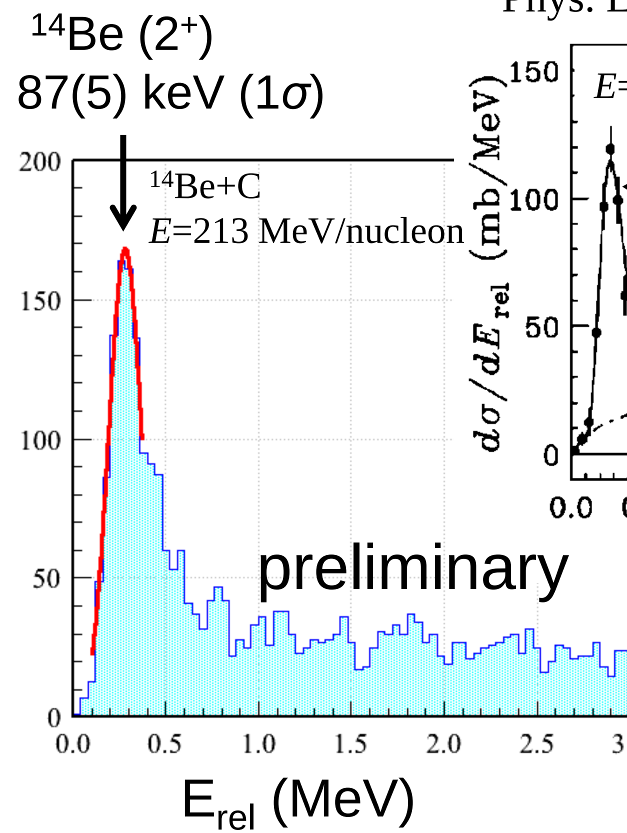
Commissioning in March 2012

Primary Beam: ^{18}**O**: 290 MeV/nucleon: 500 pnA

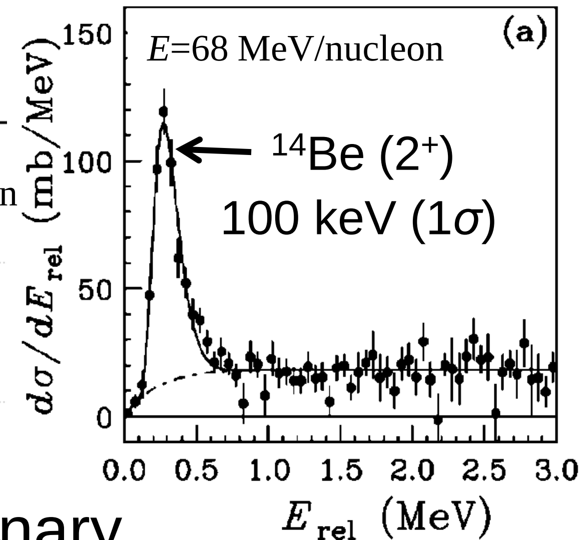
- Kickoff all the detectors, DAQs for **the xn+HI setup**
- Beam transport to SAMURAI
- Heavy ion detectors optimization
- NEBULA calibration
  - Time-zero with high-energy gamma
  - Efficiency measurement (inc. 2n cross talk) with ^{7}Li(p,n) reaction
- Bρ scan for rigidity calibration
- Physics measurements
  - ^{17}C → ^{16}C+n ^{17}C→ ^{15}B+n
  - ^{15}C → ^{14}C+n
  - ^{14}Be→^{12}Be+2n

Everything worked perfectly !!





T. Sugimoto *et al.*,
Phys. Lett. B 654, 160 (2007).



Unfolding the resolutions from other detectors

→ **Intrinsic Resolution: σ_{TOF}=263(6) ps**

cf.) ~300 ps (designed value)

Obtained only in 51min!

^{14}Be: ~2x10^4 pps

Good Resolution as designed !

First experimental campaign using SAMURAI for physics programs (Day-One campaign)

Collaborators

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

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

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

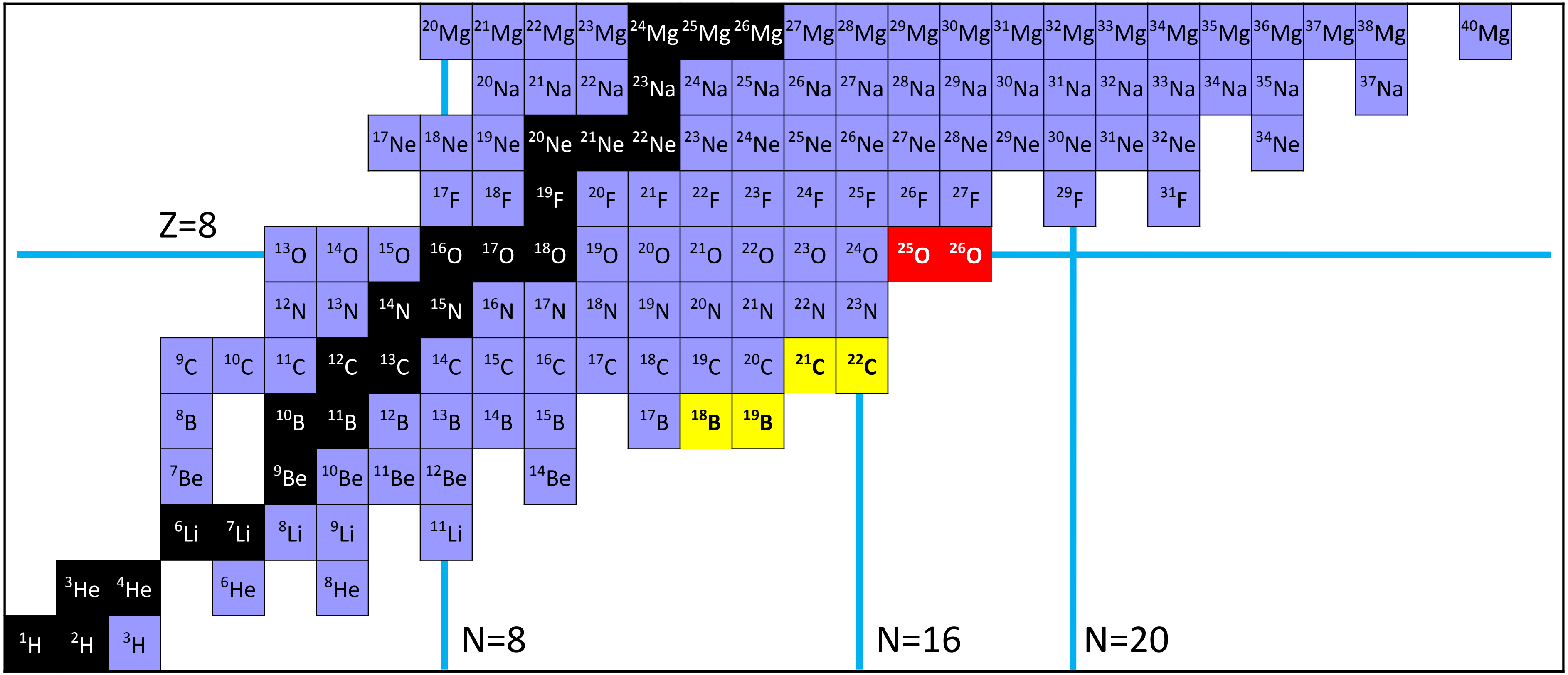
GANIL: A.Navin

Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

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

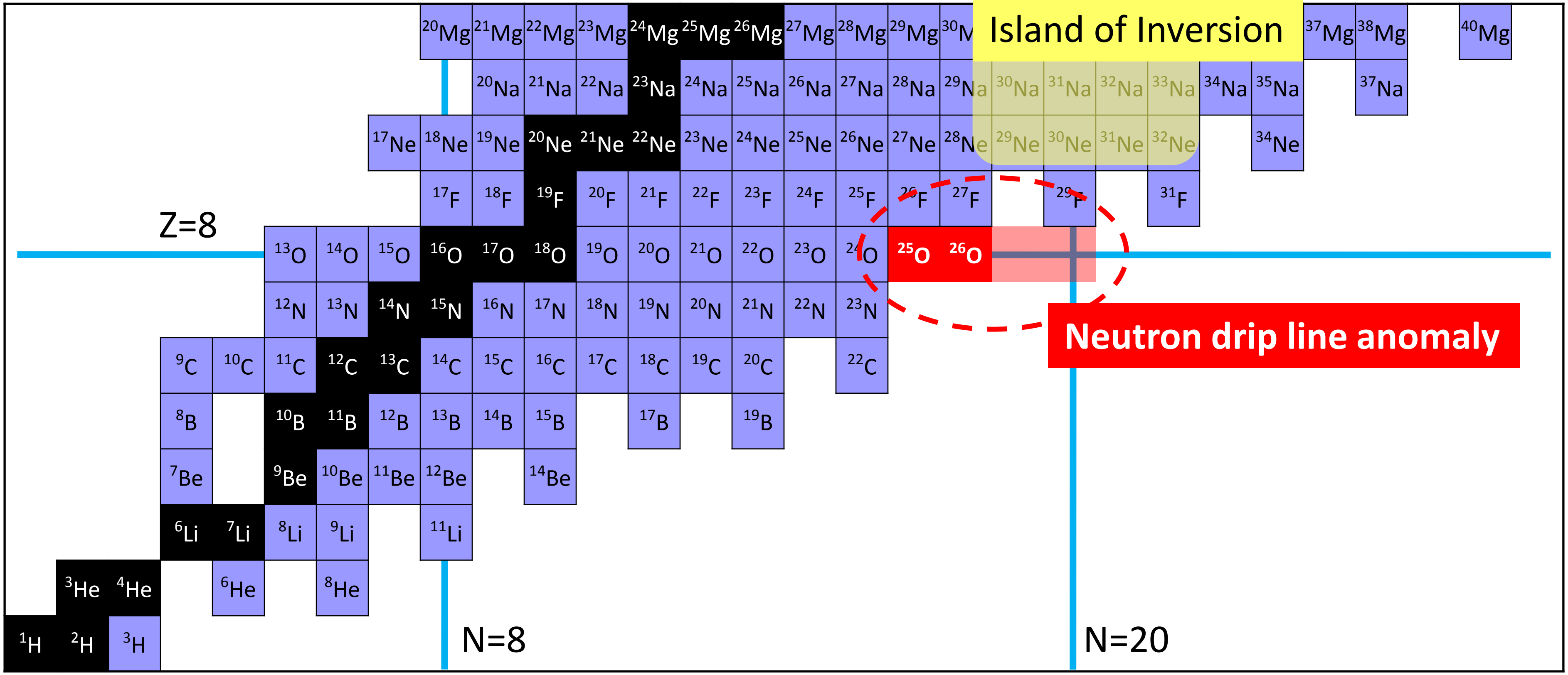
SAMURAI Day-One experiment (May 2012)



First experimental campaign with SAMURAI for physics programs

1. Study of unbound nuclei ^{25}O and ^{26}O (SAMURAI02, Y. Kondo)
2. Coulomb breakup of ^{22}C and ^{19}B (SAMURAI03, T. Nakamura)
3. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B (SAMURAI04, N. A. Orr/J. Gibelin)

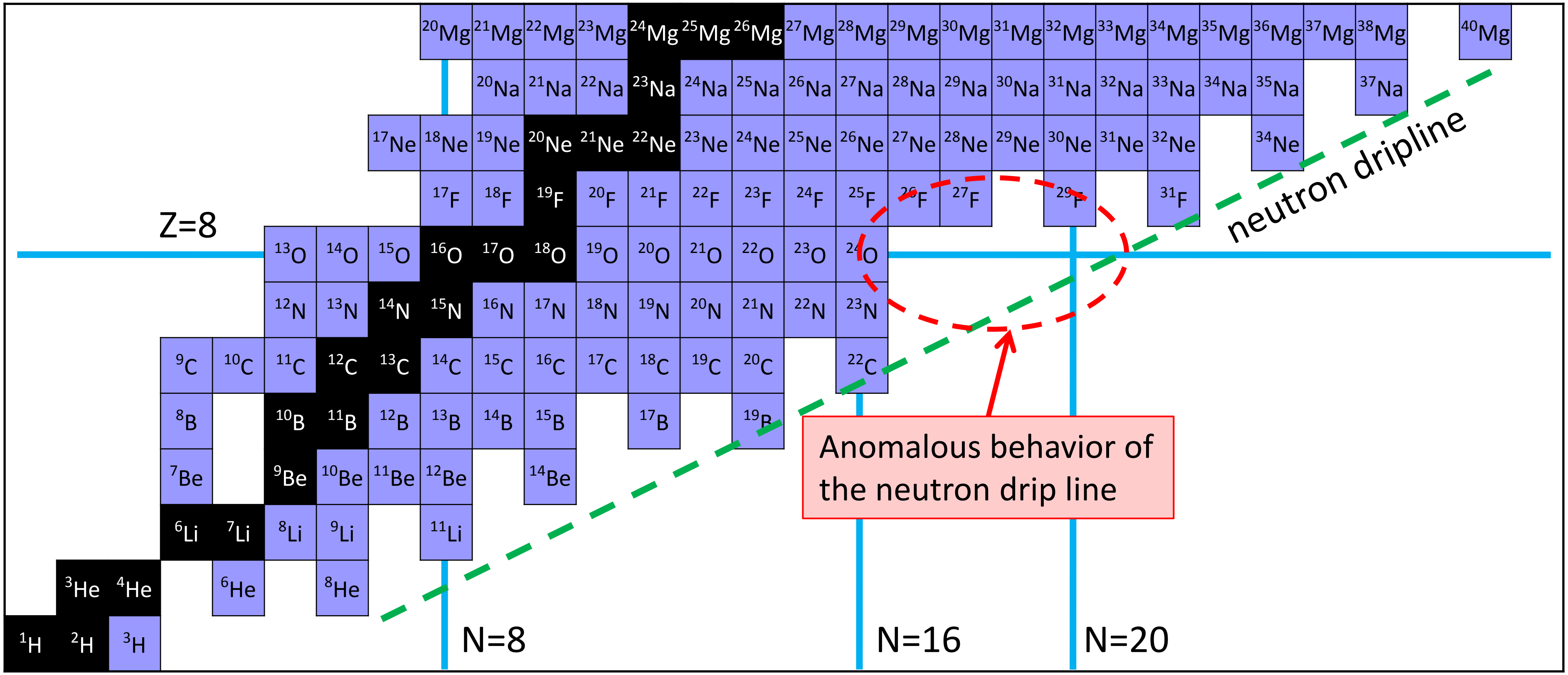
Study of unbound nuclei ^{25}O and ^{26}O



Study of oxygen isotopes beyond the drip line

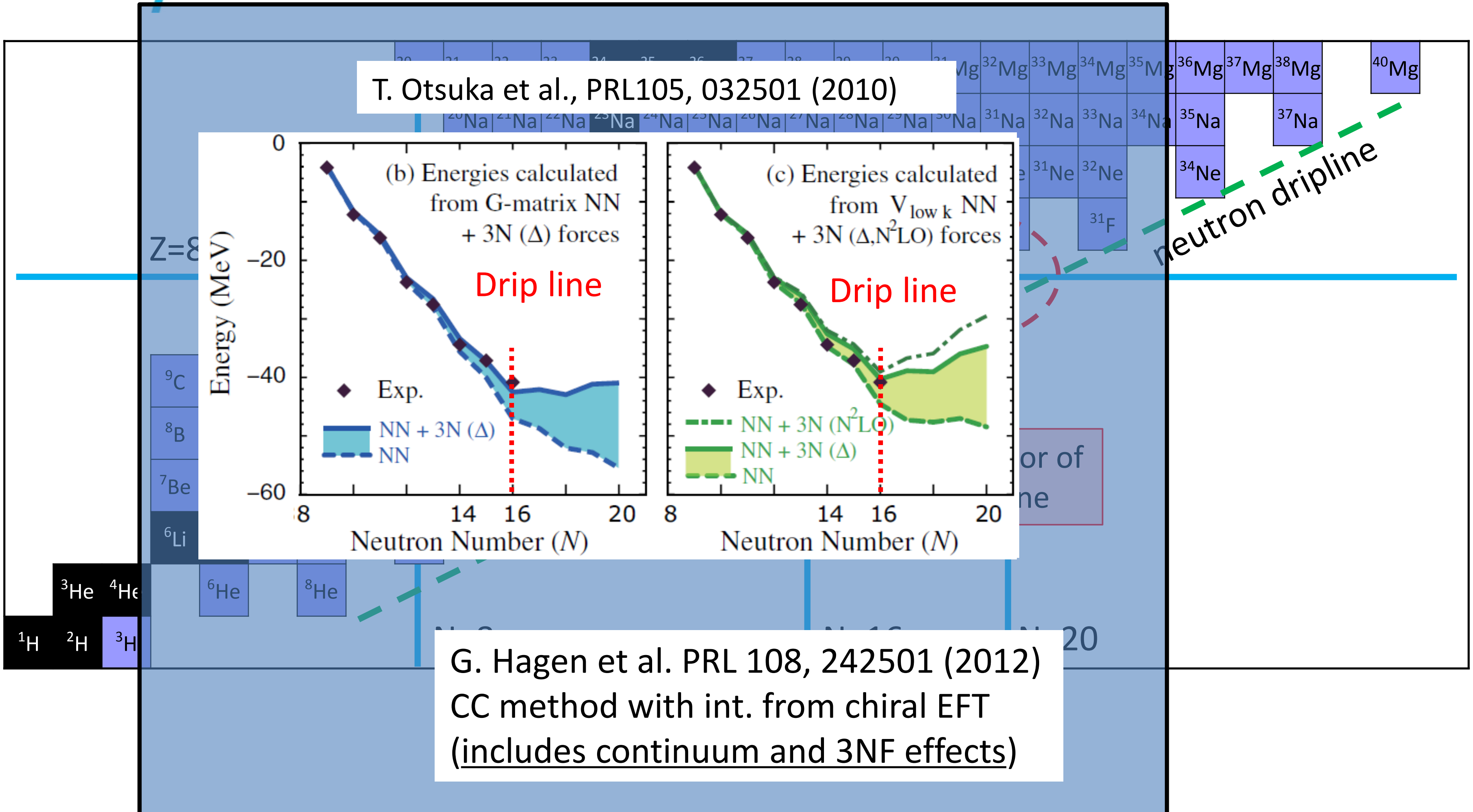
- Drip-line anomaly
- Three nucleon force
- South extreme of the Island of Inversion
- 2n radioactivity of ^{26}O?

Neutron drip line anomaly



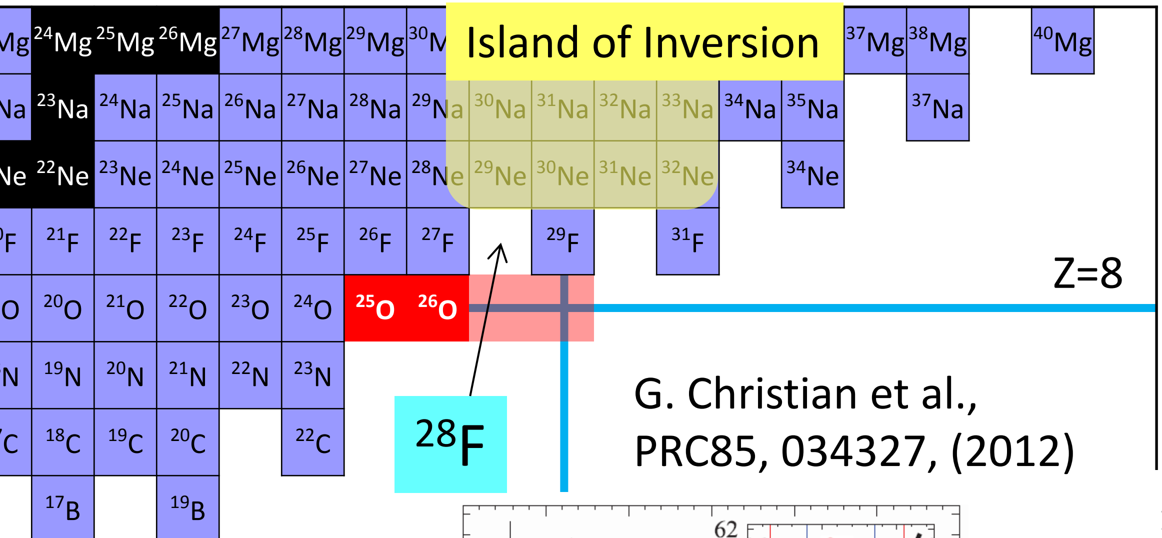
What is the origin of this phenomenon?

Neutron drip line anomaly

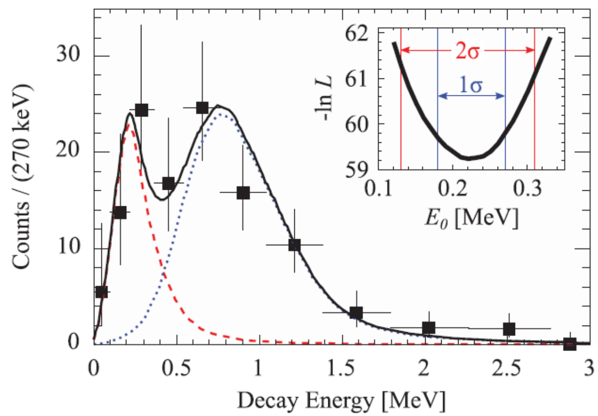


What is the origin of this phenomenon?

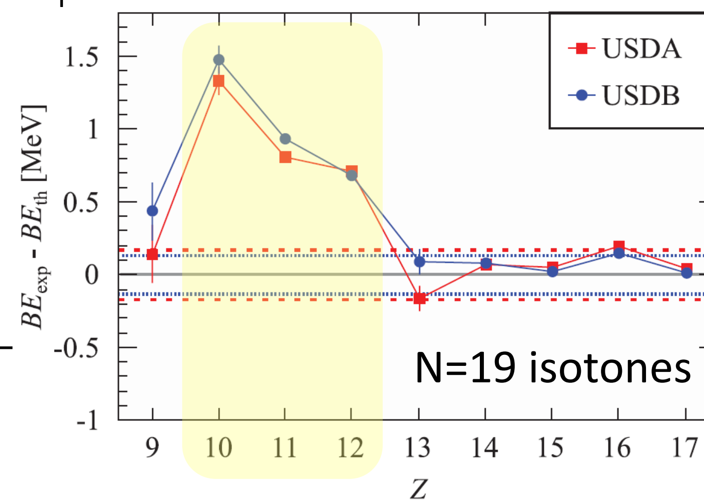
Where is south boundary of Island of Inversion?



G. Christian et al.,
PRC85, 034327, (2012)



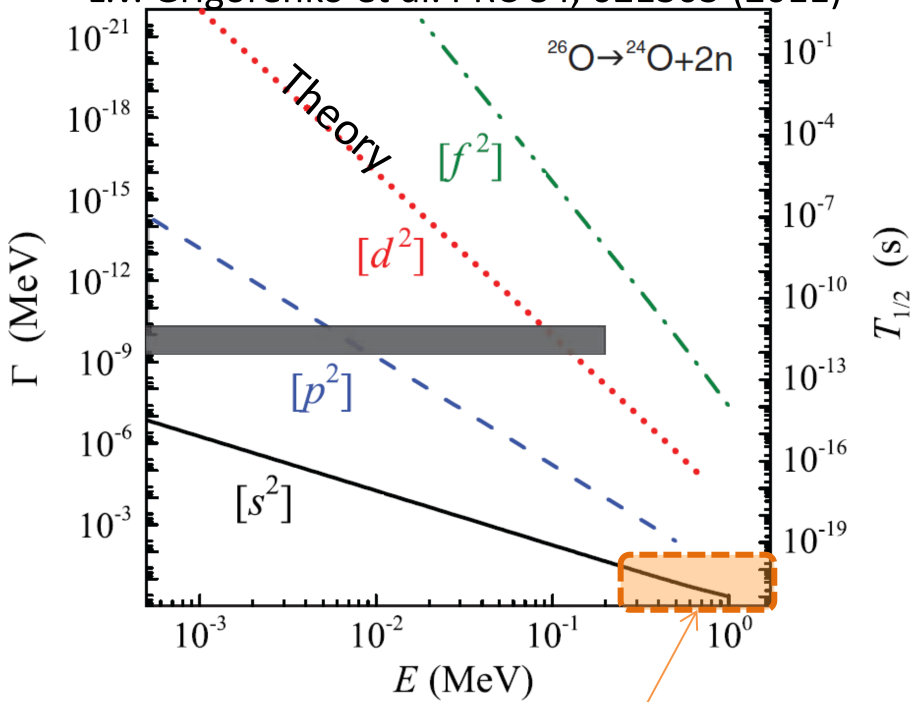
^{28}F Ground state @ 220(50)keV



Z=9 is low-Z boundary of Island of Inversion at N=19
→ What about the other isotones?

2n radioactivity of ^{26}O?

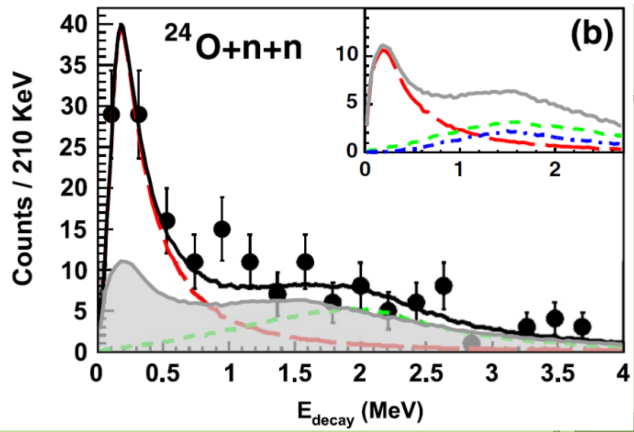
L.V. Grigorenko et al. PRC 84, 021303 (2011)



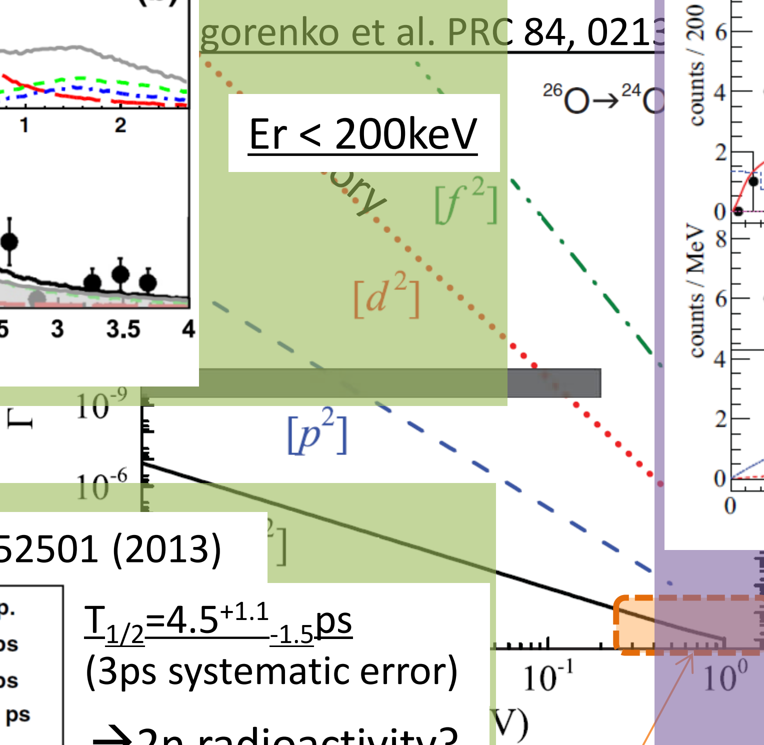
Usual 1n decay
Γ~MeV or keV

2n radioactivity of ^{26}O?

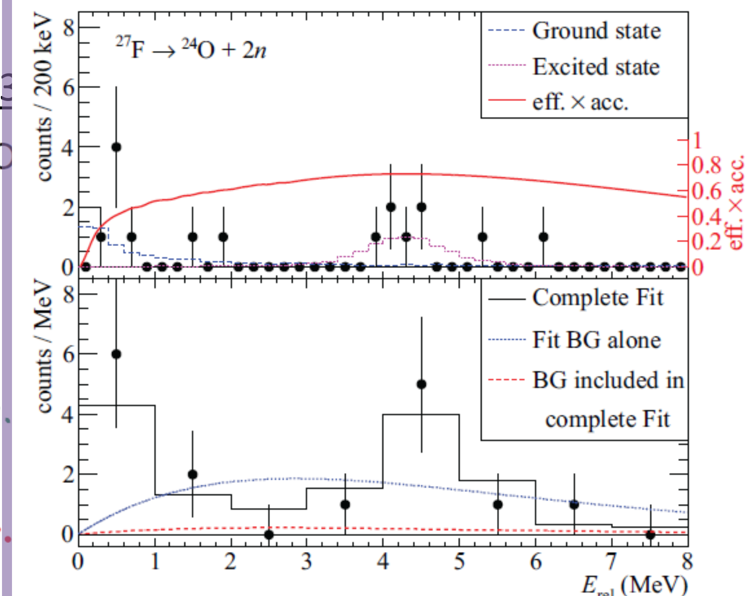
E. Lunderberg et al.PRL108, 142503 (2012)



Er < 200keV



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

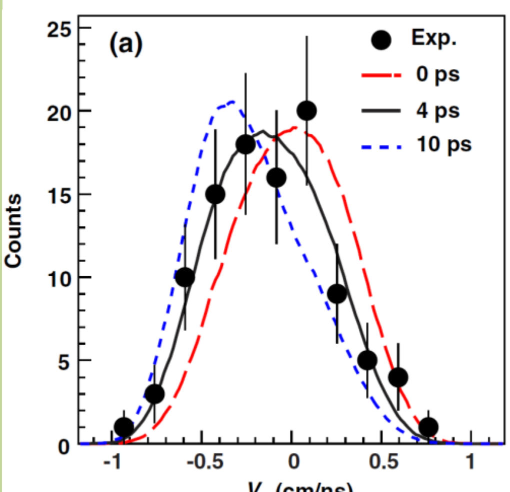


Er < 120keV (95% CL)

τ < 5.7ns

Excite state at 4.2MeV?

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

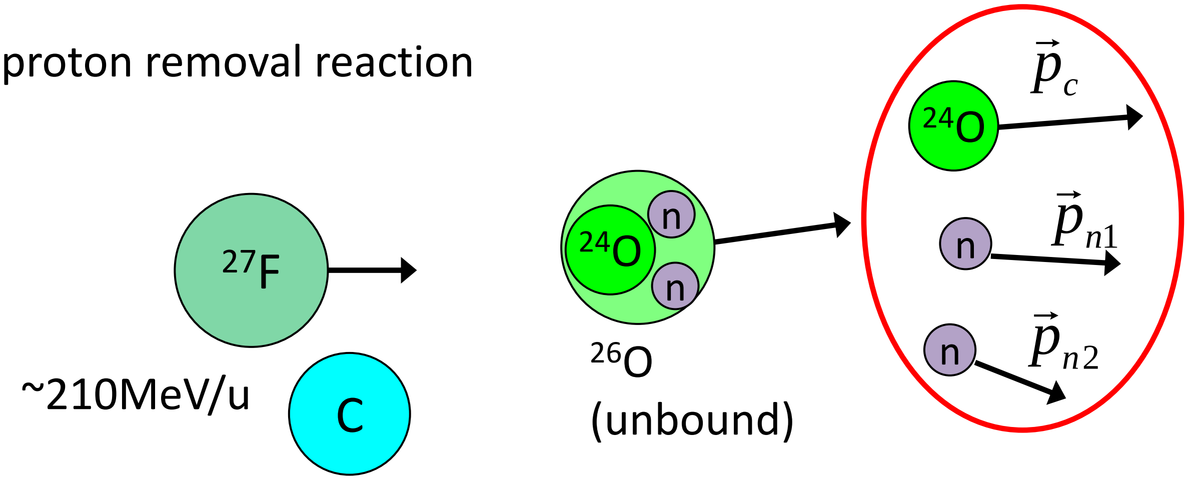
Γ~MeV or keV

Large uncertainty of experimental study

- Only upper limit is given for the ground state energy
- Large systematic error in the lifetime measurement

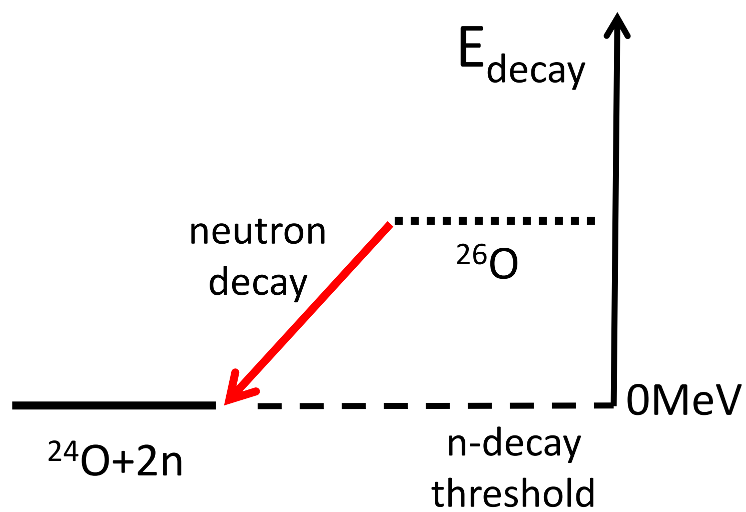
Invariant mass method

one proton removal reaction



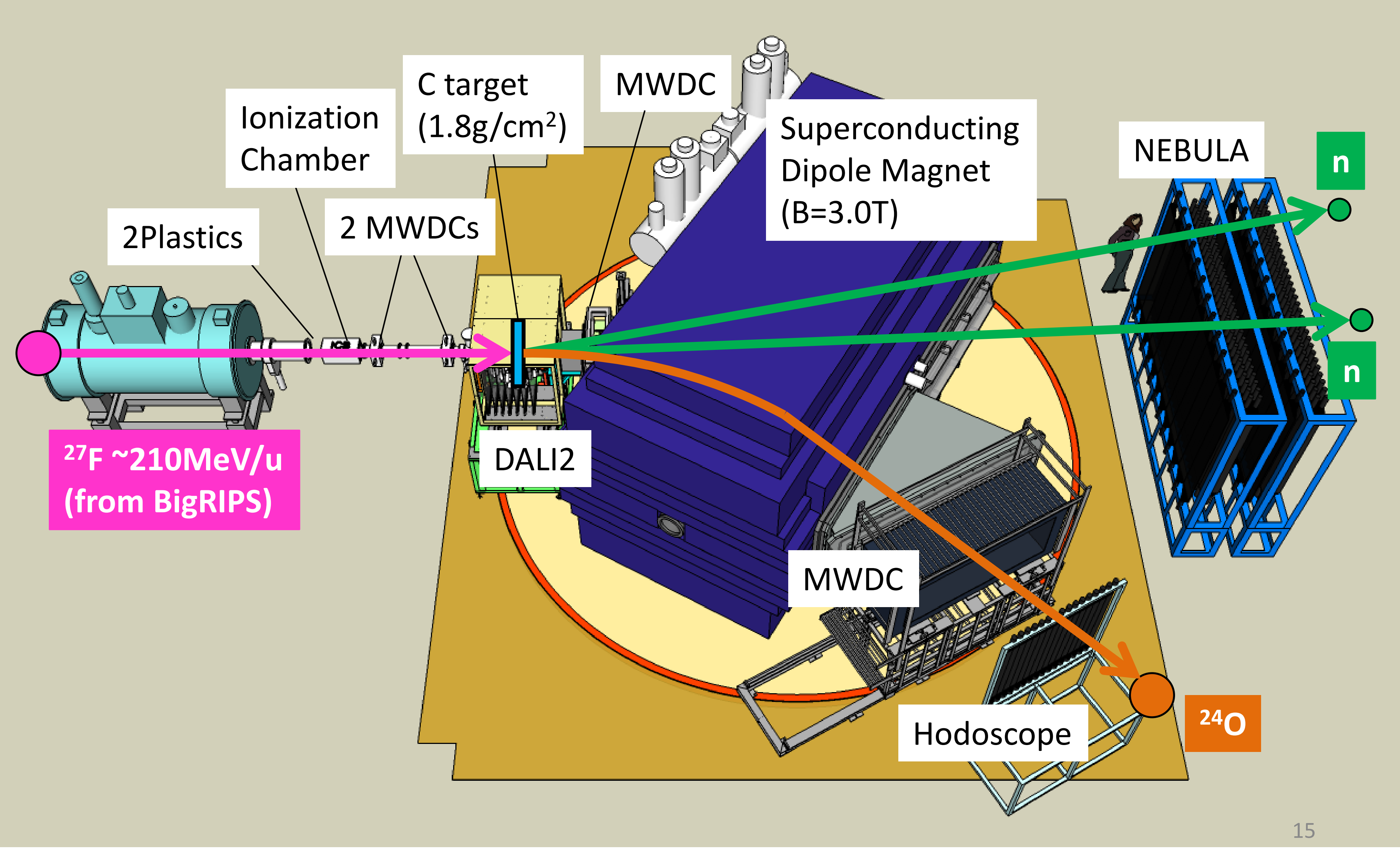
Decay energy (Relative energy)

$$E_{decay} = \underbrace{\sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}}_{\text{Invariant mass}} - \sum M_i$$



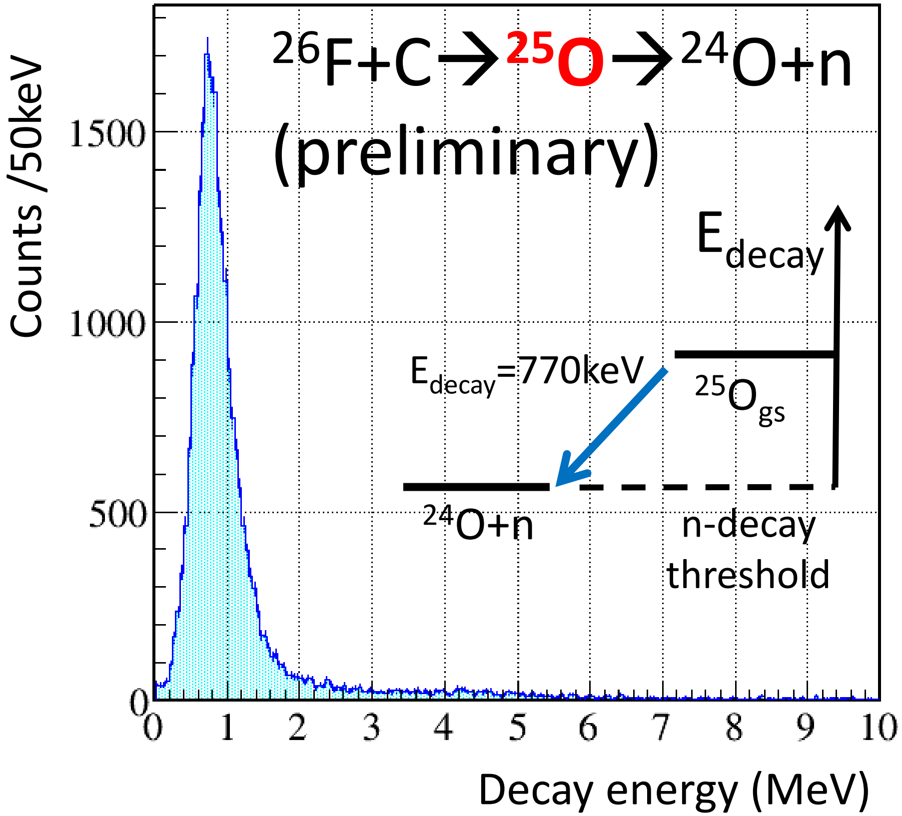
<u>Necessary to detect all the decay particles</u>

Experimental setup

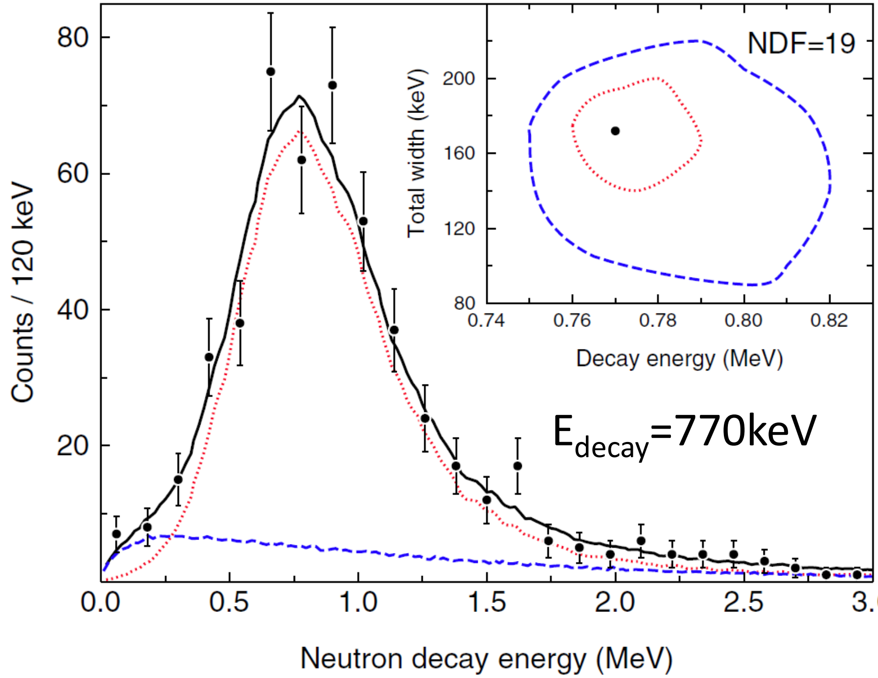


Experimental Results

Decay energy spectrum ($^{26}F+C \rightarrow ^{25}O \rightarrow ^{24}O+n$)



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



50 times higher statistics!

Another decay channel ($^{25}O \rightarrow ^{23}O+2n$) can be studied

Decay energy spectrum (^{27}F+C→^{26}O→^{24}O+2n)

Ground state

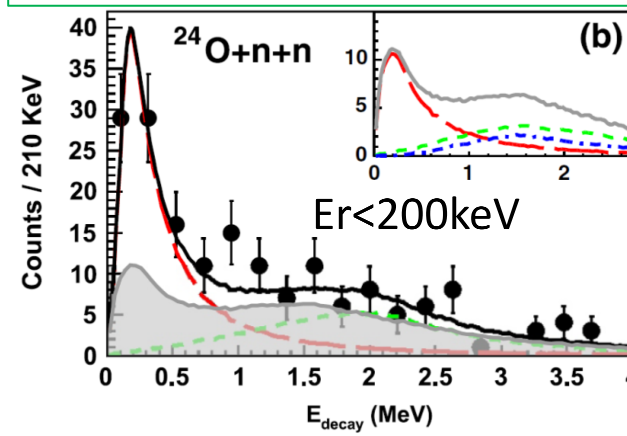
^{27}F+C→^{26}O→^{24}O+2n
(preliminary)

Excited state（new）

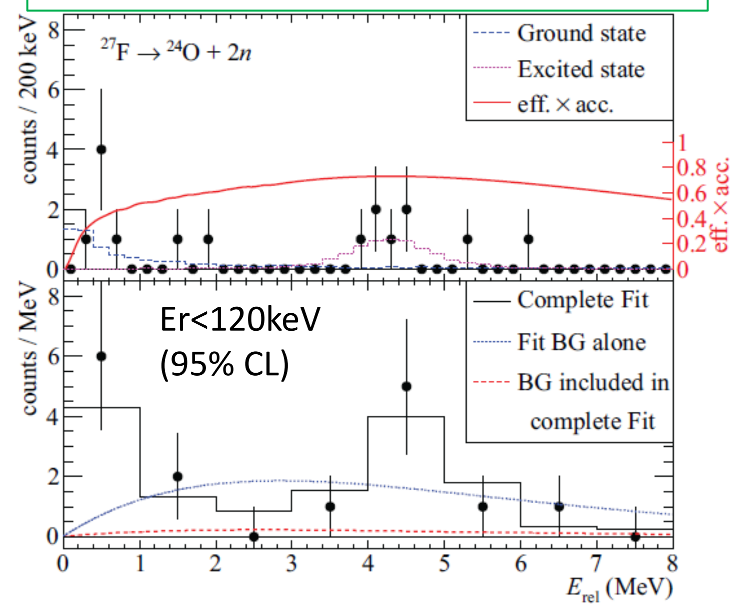
Counts /100keV

Decay energy (MeV)

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



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



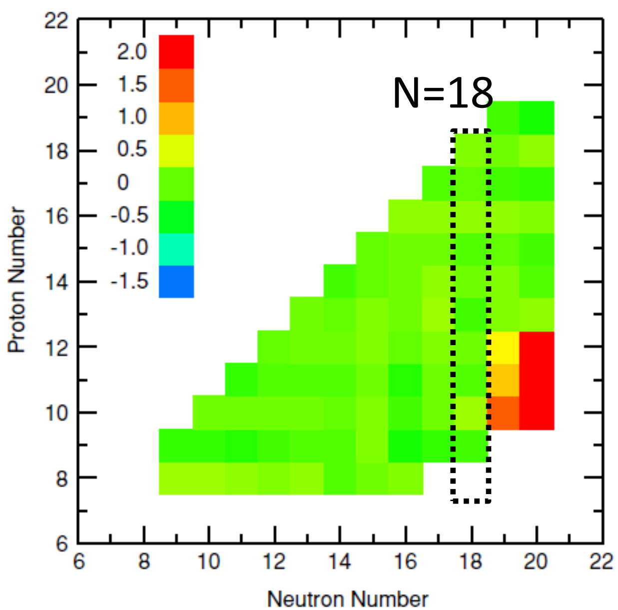
Ground state
- 5 times higher statistics
- →better determination of energy

Excited state at ~1.3MeV
- First observation
- Most probably 2^+

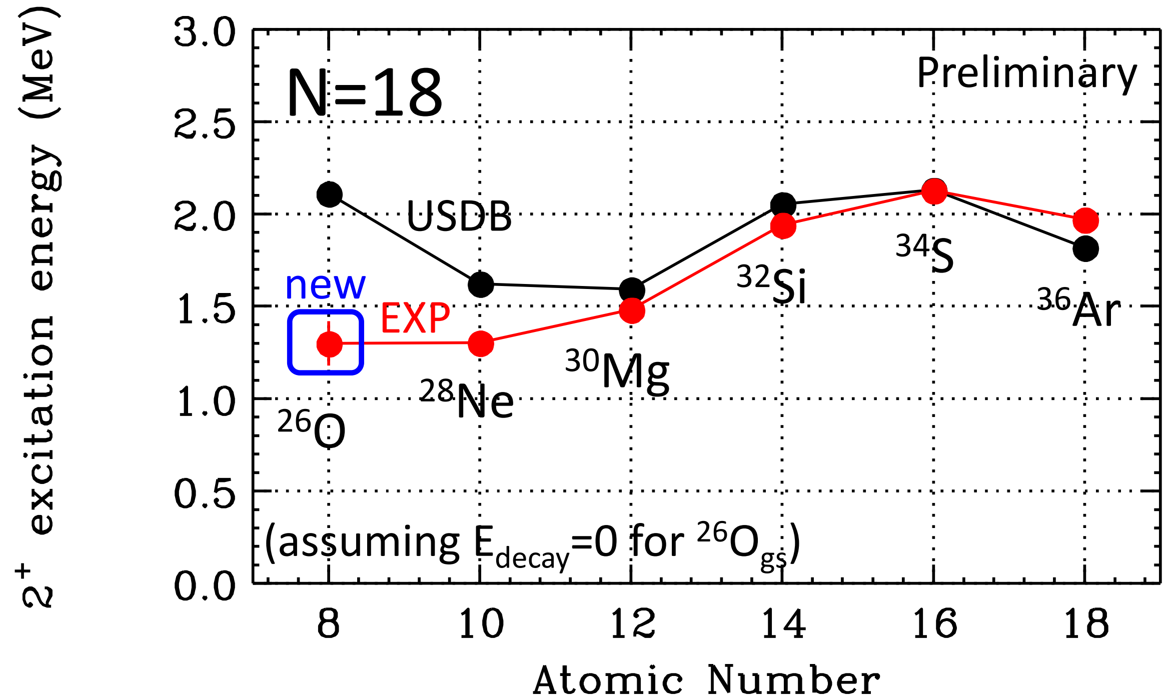
No peak at ~4.2MeV

Comparison with USDB calculation

B.A. Brown, W.A. Richter
PRC74, 034315 (2006)



Difference between ground state energies of EXP and USDB calculation



Ground state

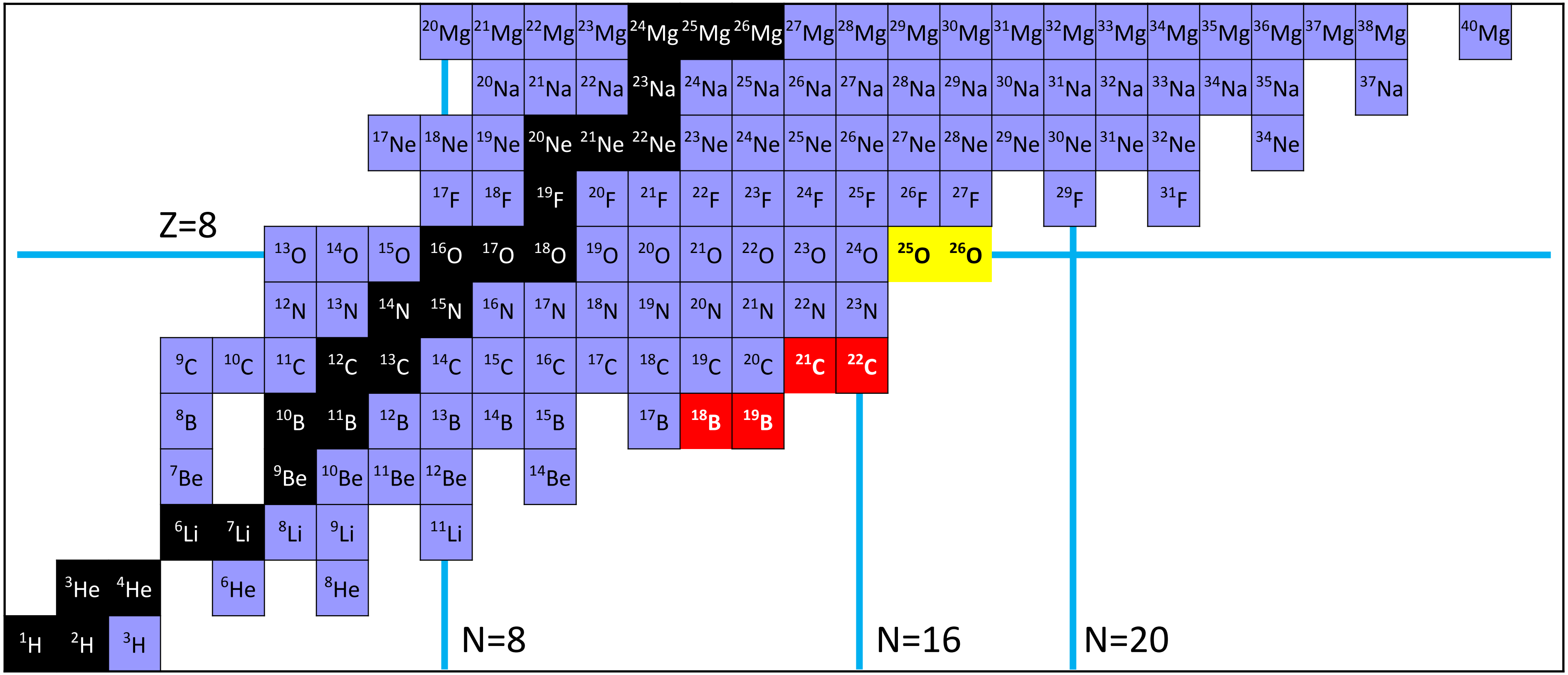
- USDB predicts S_{2n}= - 0.35MeV for ^{26}O ground state
  (Almost consistent with experiment)

2+ state

- Calculation overestimates at low Z
  →effect of pf-shell? or continuum effect?

- E.g. Continuum shell model predicts 1.8MeV
  A. Volya, V. Zelevinsky, PRC74, 064314 (2006)

SAMURAI Day-One experiment



First experimental campaign with SAMURAI (May 2012)

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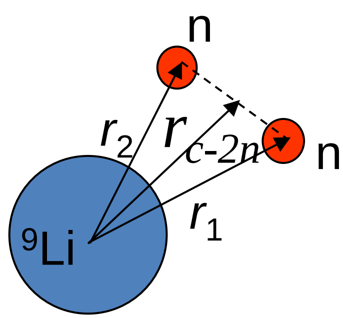
Coulomb breakup of ^{22}C and ^{19}B ~Probe of di-neutron correlation~



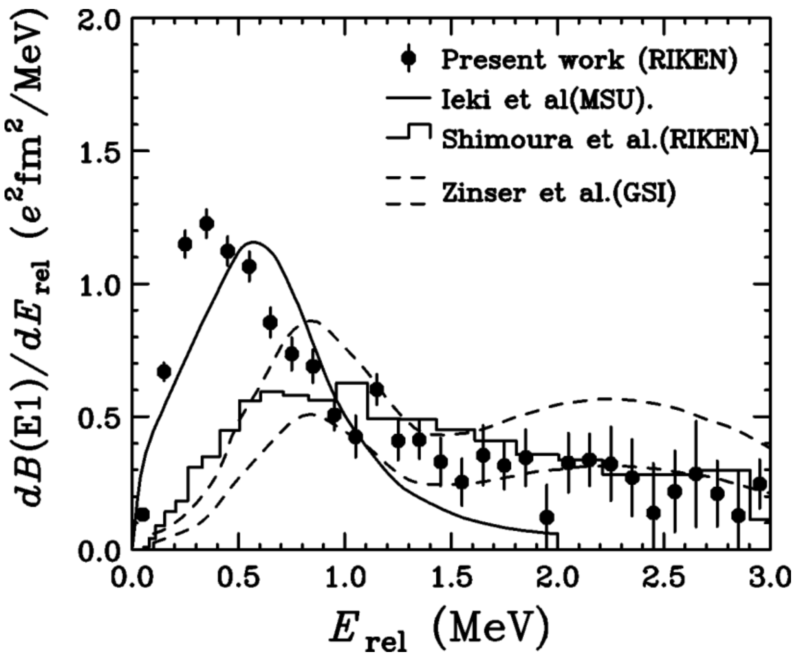
$$B(E1)=\int_{-\infty}^{\infty}\frac{dB(E1)}{dE_x}dE_x$$

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

Low energy E1 excitation of 2n-halo
→ dineutron-like correlation

e.g. ^{11}Li

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

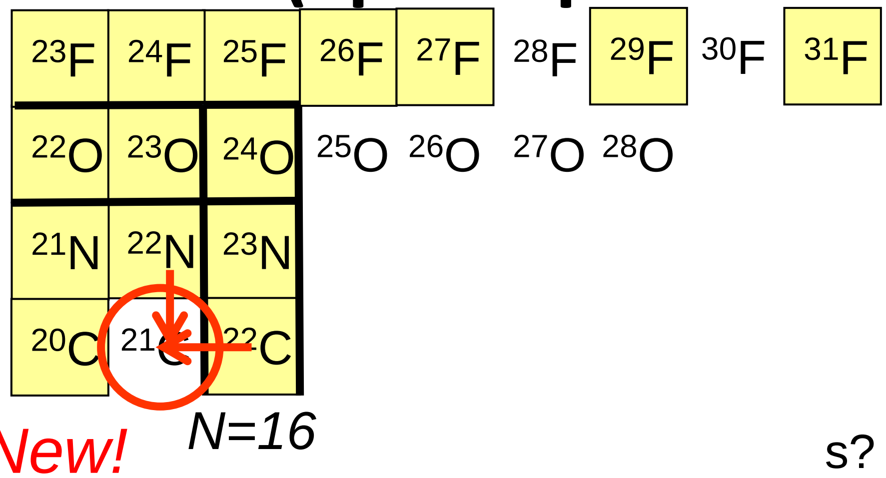


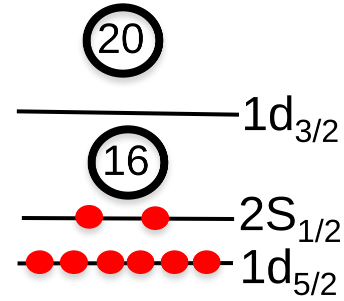
$$B(E1)=1.42\pm0.18\,e^2\,fm^2(E_{\rm rel}\le 3{\rm MeV})$$

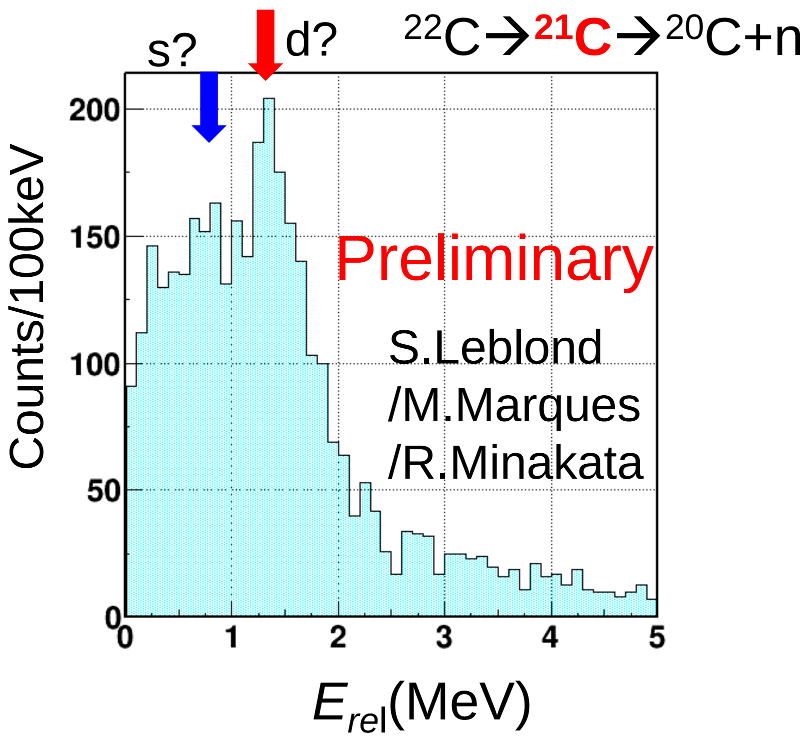
$$\rightarrow 1.78(22)\,e^2\,fm^2\rightarrow\langle\theta_{12}\rangle=48^{+14}_{-18}\,{\rm deg}.$$

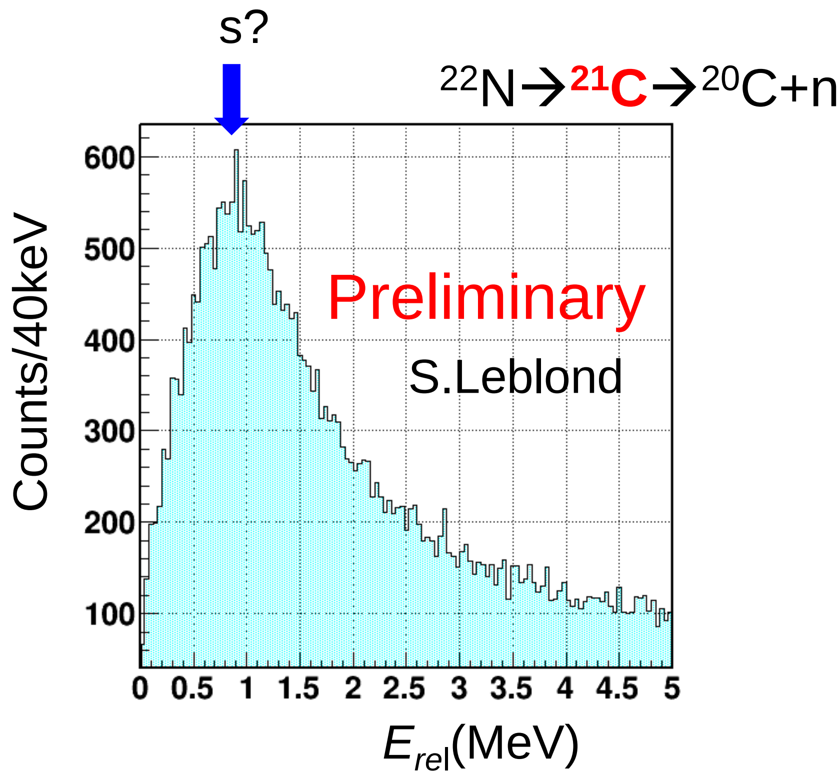
What about heavier Borromean nuclei ^{22}C and ^{19}B?

Study of the unbound nucleus ^{21}C (Spokesperson: N.A. Orr/J. Gibelin)









Summary

- **SAMURAI is now available**
  - SAMURAI collaboration page

    http://ribf.riken.jp/SAMURAI/Collaboration/

- **SAMRUAI Day-One Experimental campaign on 2012**
  1. Study of unbound nuclei ^{25}O and ^{26}O
     - Higher statistics for $^{26}O(0^+)$
     - New observation of $^{26}O(2^+)$
  2. Coulomb breakup of ^{22}C and ^{19}B
  3. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B
     - Preliminary decay energy spectra have been obtained