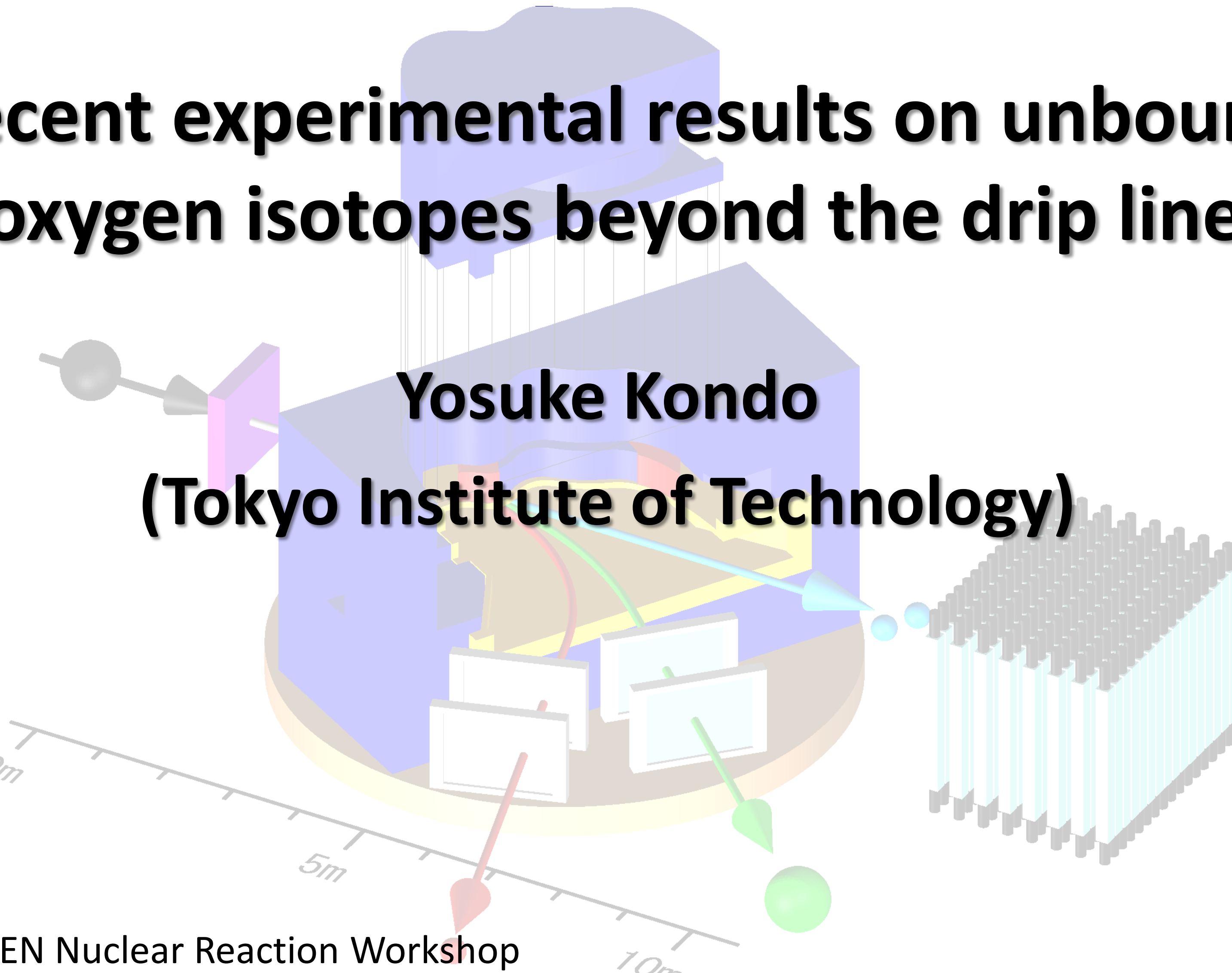
Recent experimental results on unbound oxygen isotopes beyond the drip line



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(Tokyo Institute of Technology)

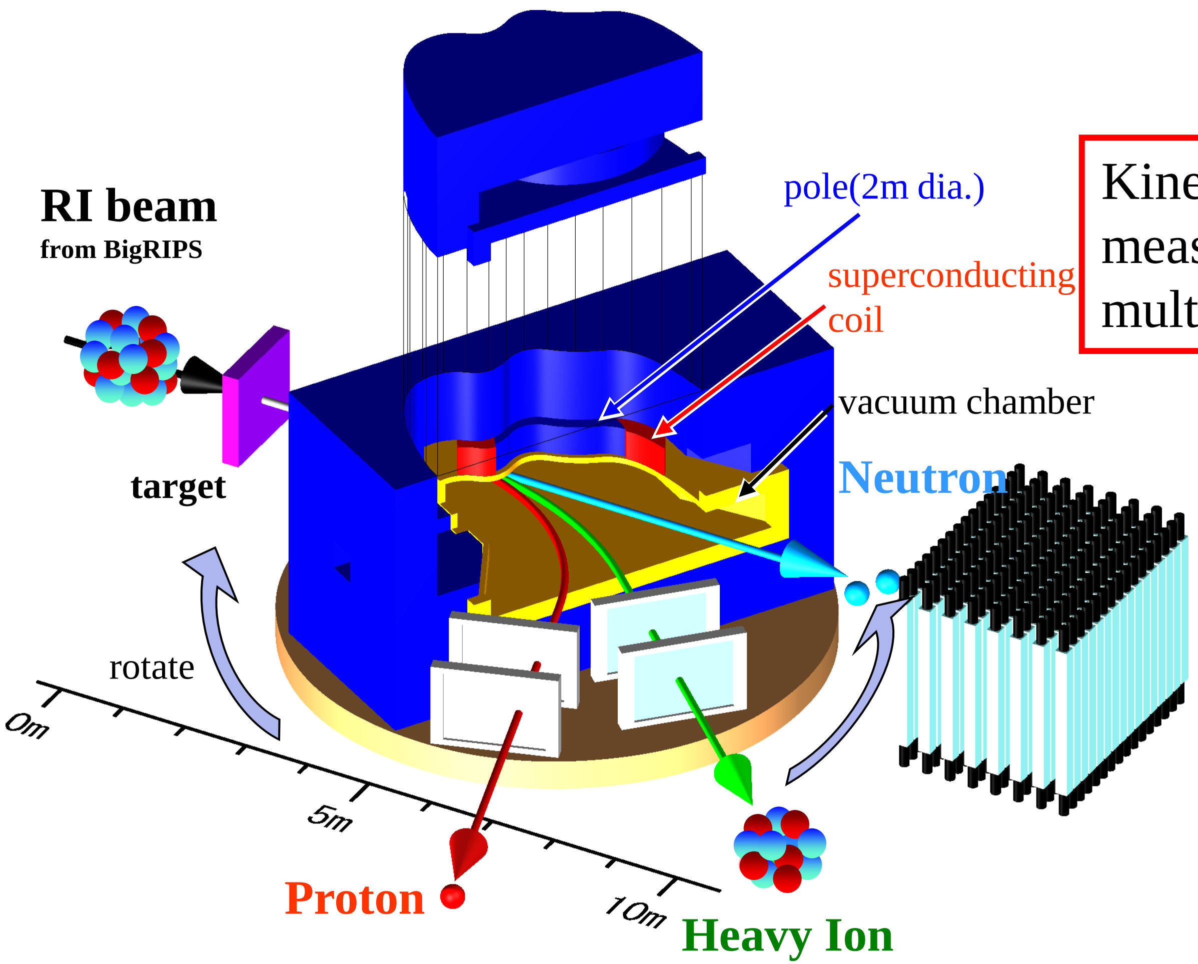
PKU-CUSTIPEN Nuclear Reaction Workshop
Reactions and Spectroscopy of Unstable Nuclei (Peking Univ.), August 10-14, 2014

Contents

1. Introduction of SAMURAI at RIBF

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

Superconducting Analyzer for MUltiple-particles from RAdioIsotope 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

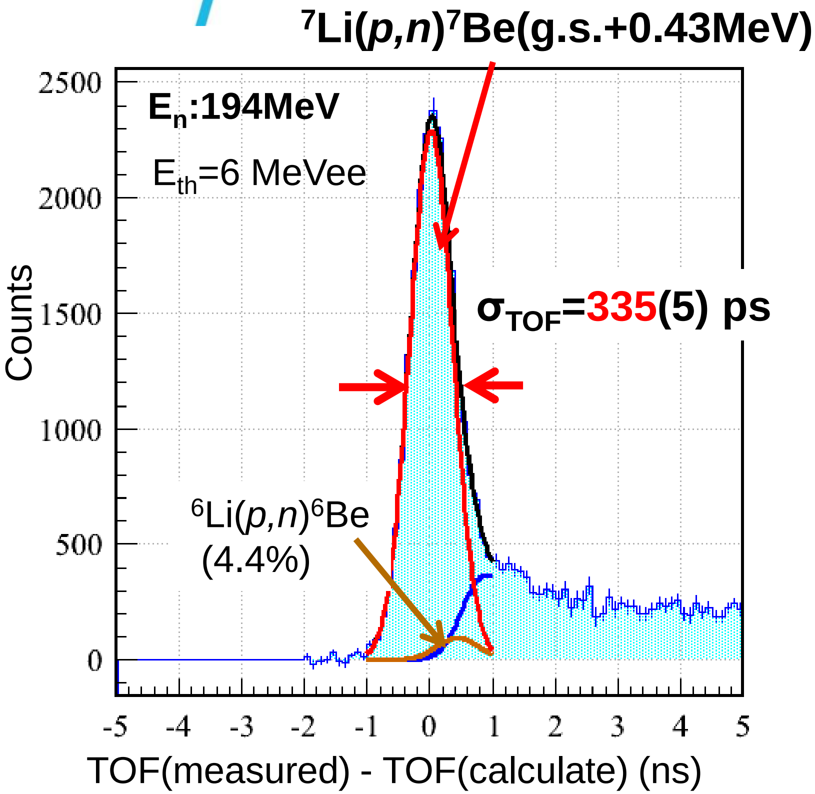
T. Kobayashi et al., NIMB317, 294, (2013)

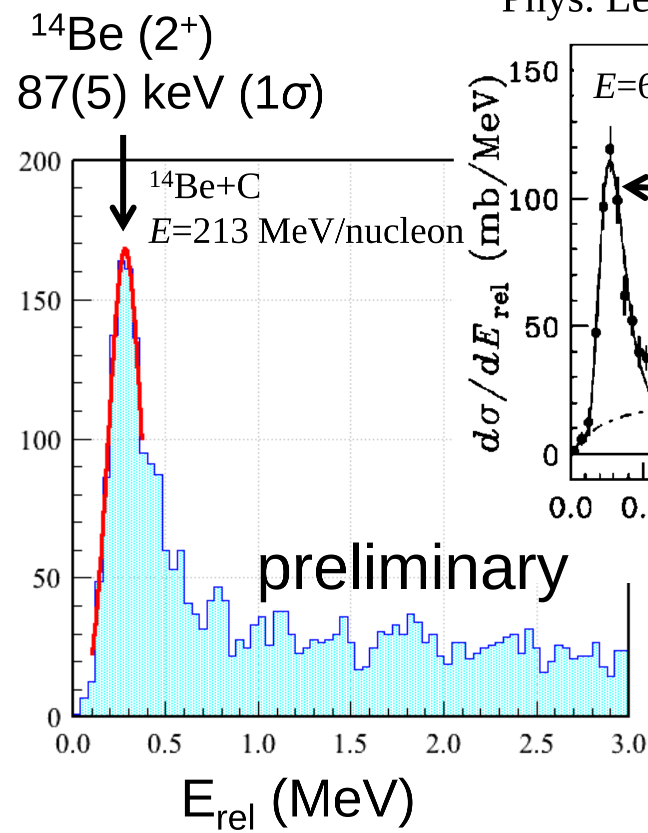
Commissioning in March 2012

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

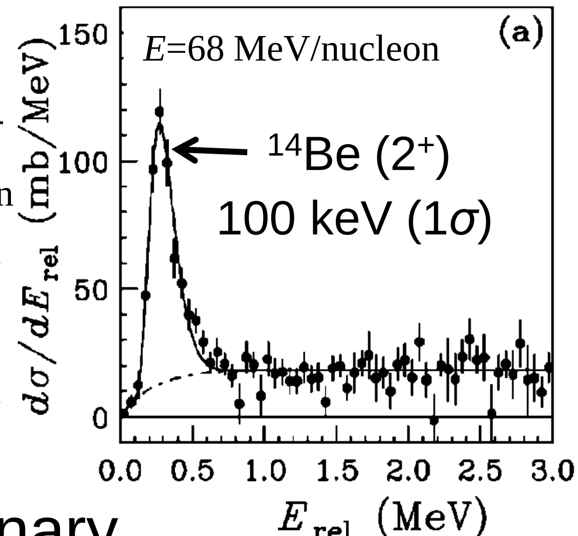
- Kickoff all the detectors, DAQs for **the xn+HI setup**
- Beam transport to SAMURAI
- Heavy ion detectors optimization
- NEBULA calibration
  - Time-zero with high-energy gamma
  - Efficiency measurement (inc. 2n cross talk) with ^{7}Li(p,n) reaction
- Bρ scan for rigidity calibration
- Physics measurements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

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

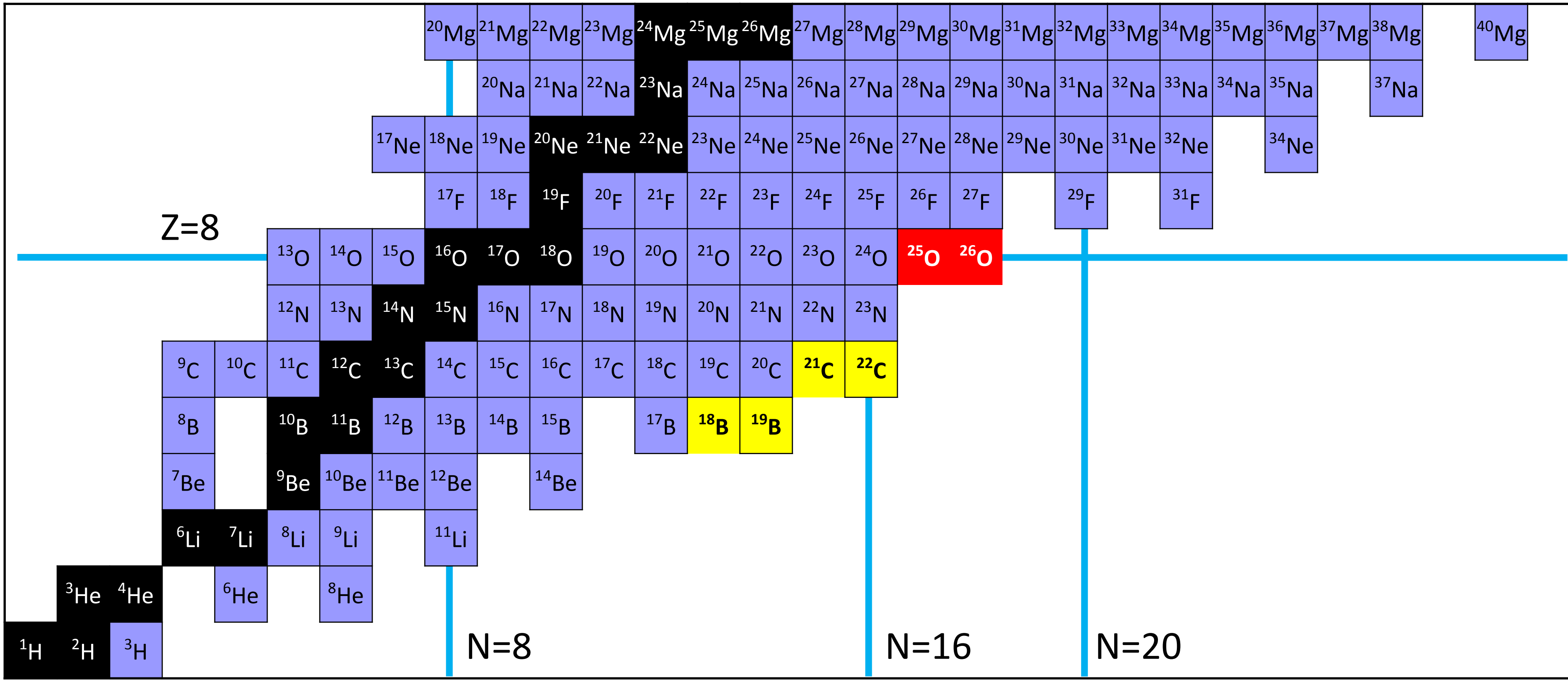
GANIL: A.Navin

Technische Universit¨at Darmstadt: T.Aumann

Rikkyo Univeristy: D.Murai

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

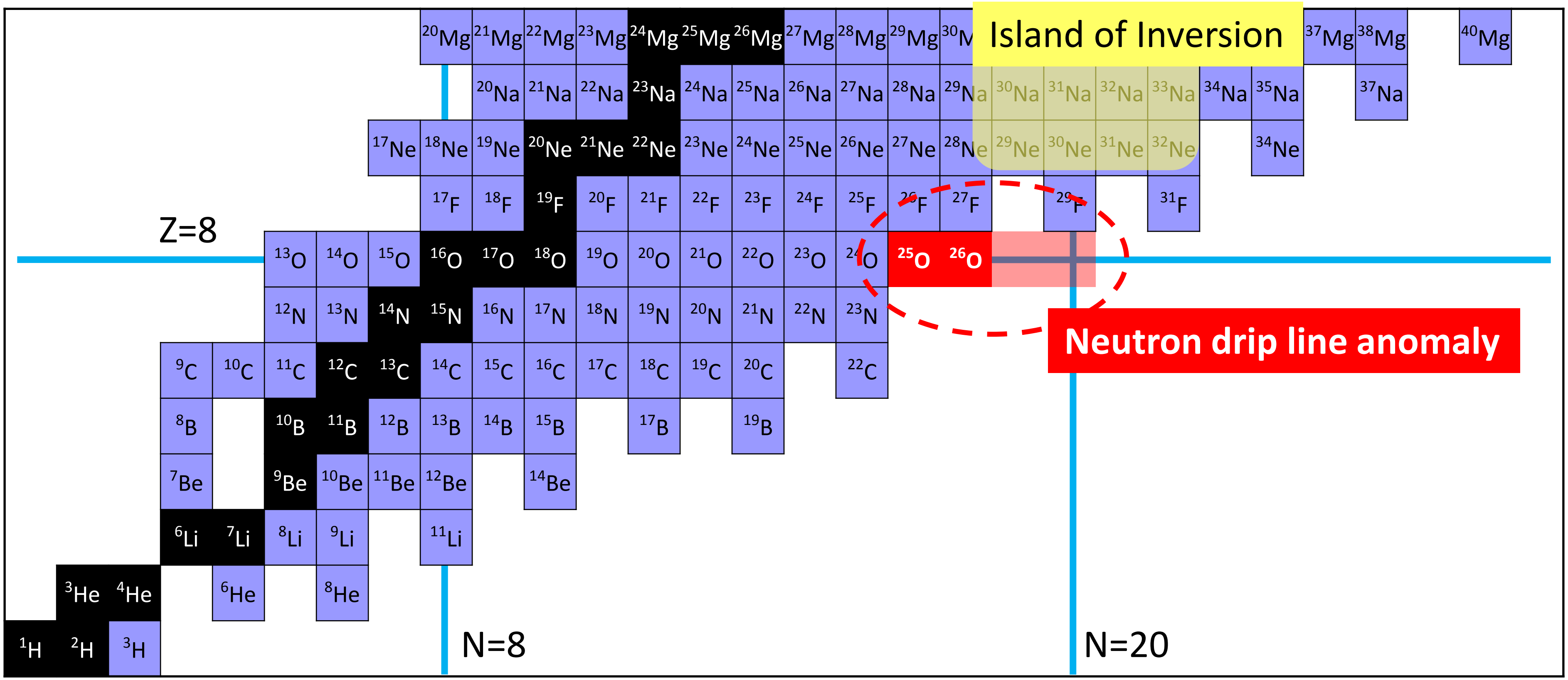
SAMURAI Day-One experiment (May 2012)



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)

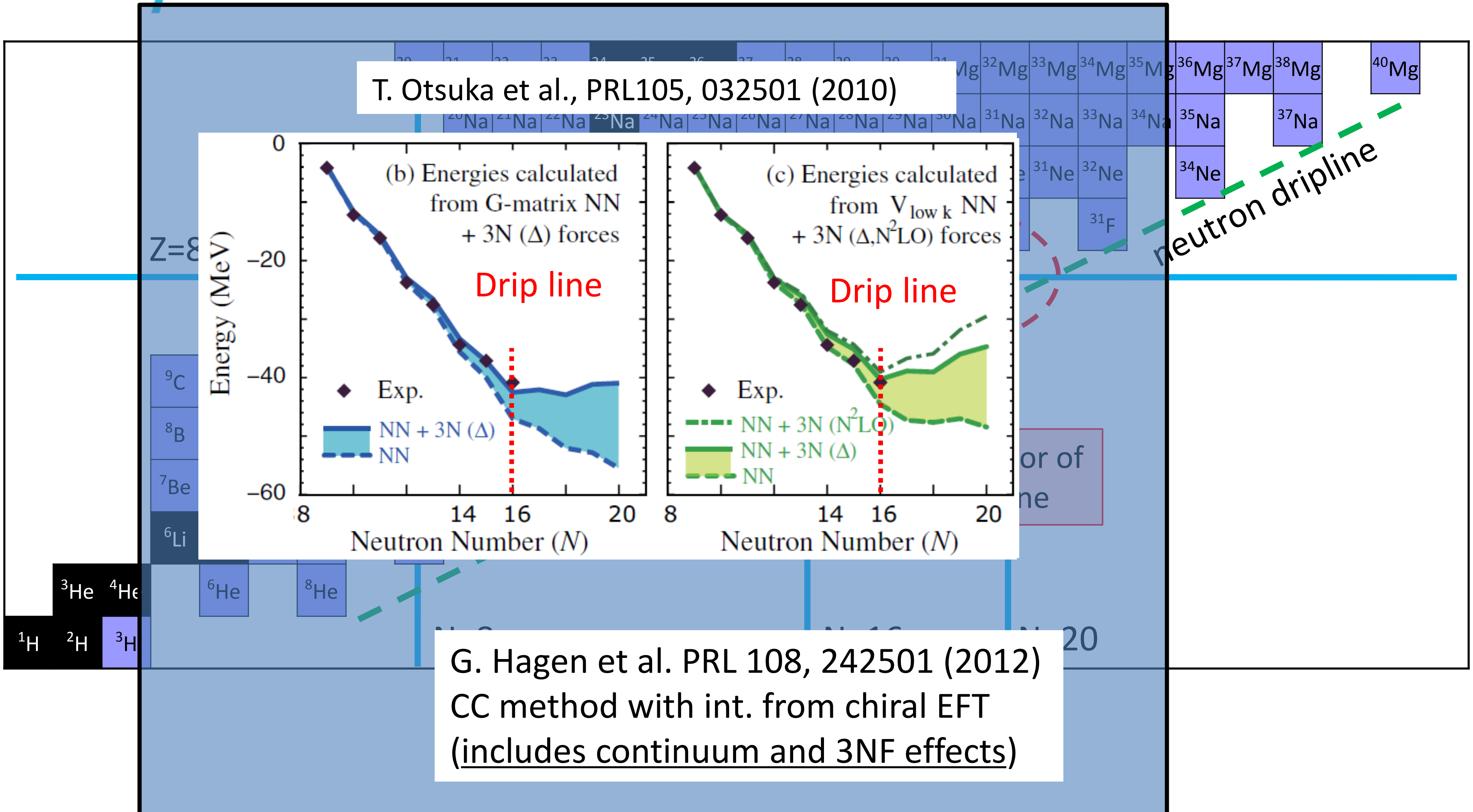
Study of unbound nuclei ^{25}O and ^{26}O



Study of oxygen isotopes beyond the drip line

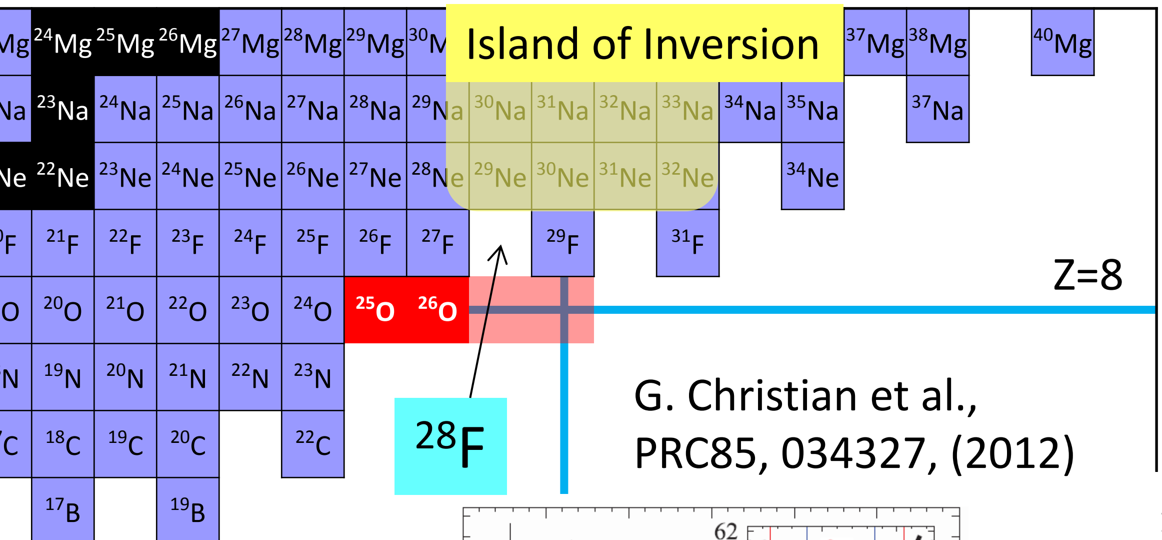
- Drip-line anomaly
- Three nucleon force
- South extreme of the Island of Inversion
- 2n radioactivity of ^{26}O?

Neutron drip line anomaly

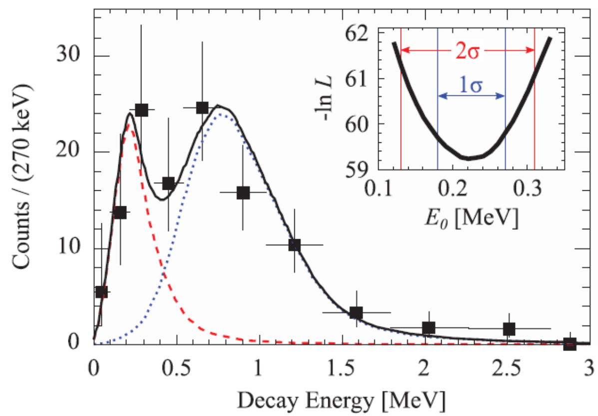


What is the origin of this phenomenon?

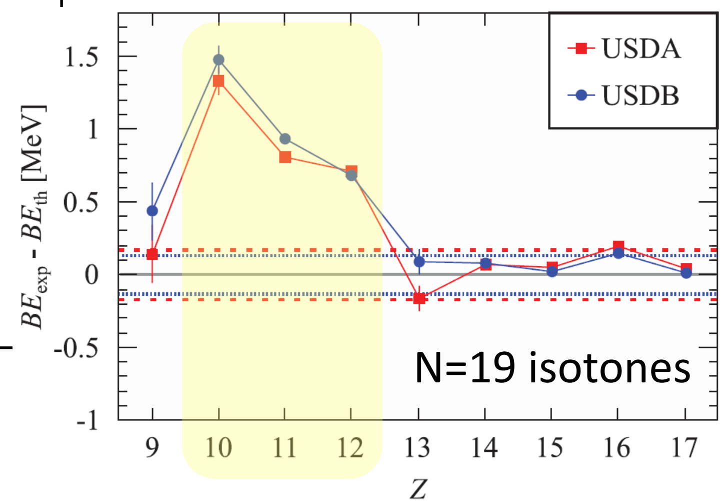
Where is south boundary of Island of Inversion?



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



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

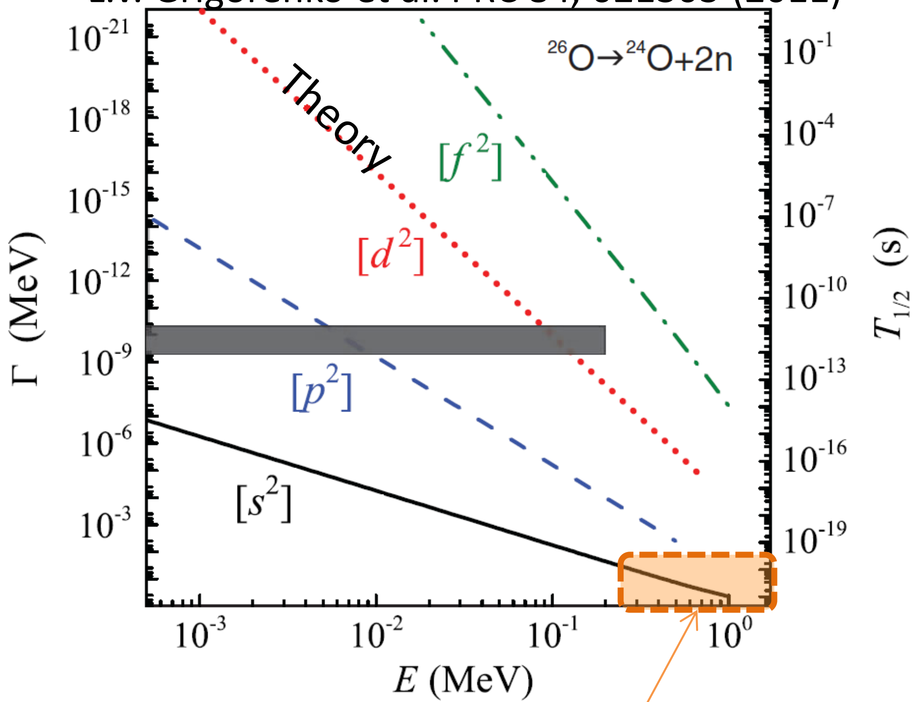


Z=9 is low-Z boundary of Island of Inversion at N=19

→ What about the other isotones?

2n radioactivity of ^{26}O?

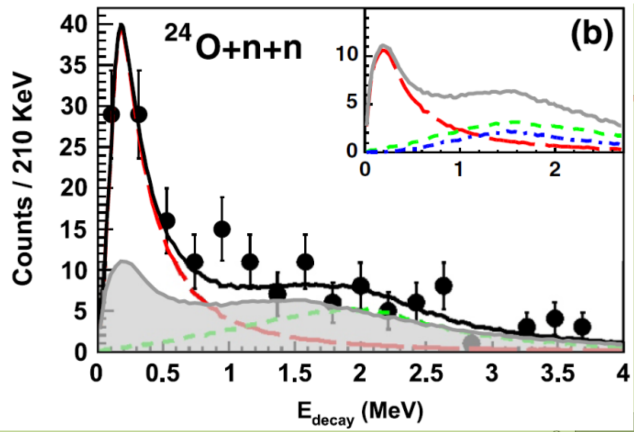
L.V. Grigorenko et al. PRC 84, 021303 (2011)



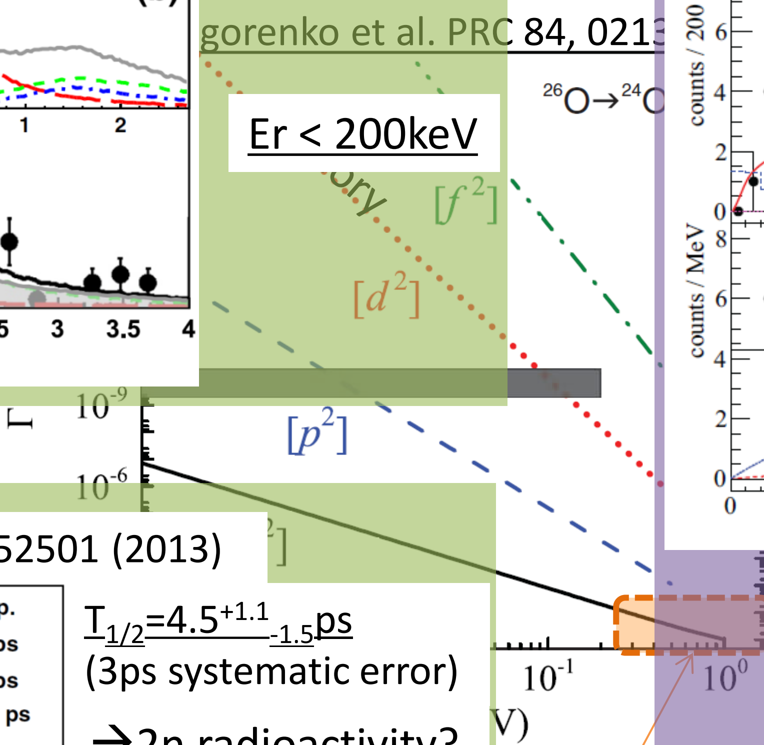
Usual 1n decay
Γ~MeV or keV

2n radioactivity of ^{26}O?

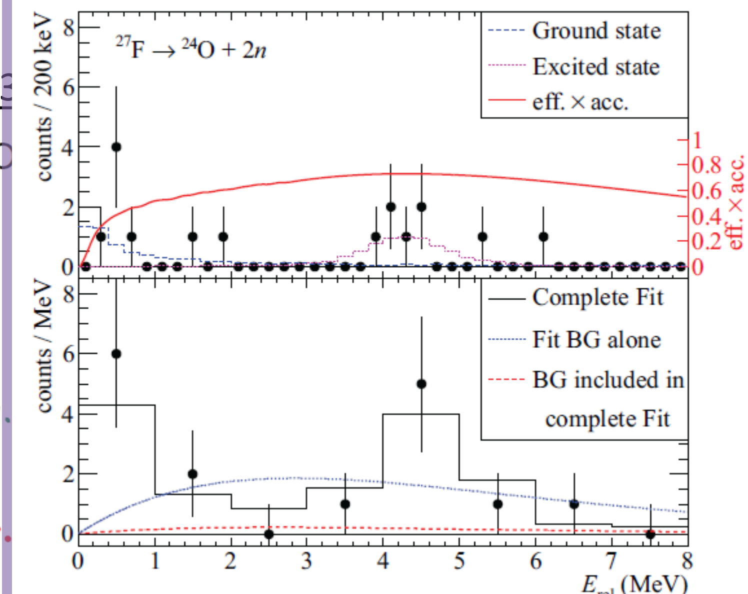
E. Lunderberg et al.PRL108, 142503 (2012)



Er < 200keV



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

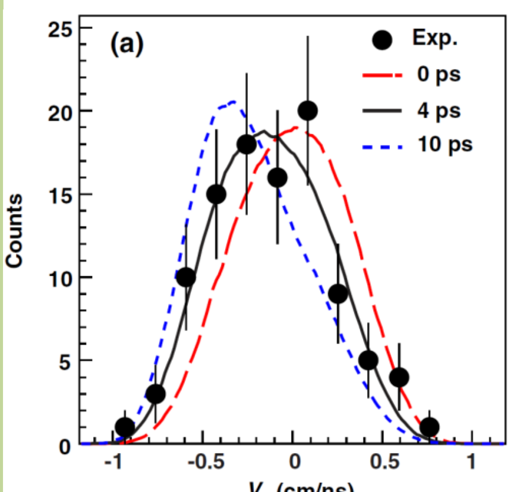


Er < 120keV (95% CL)

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

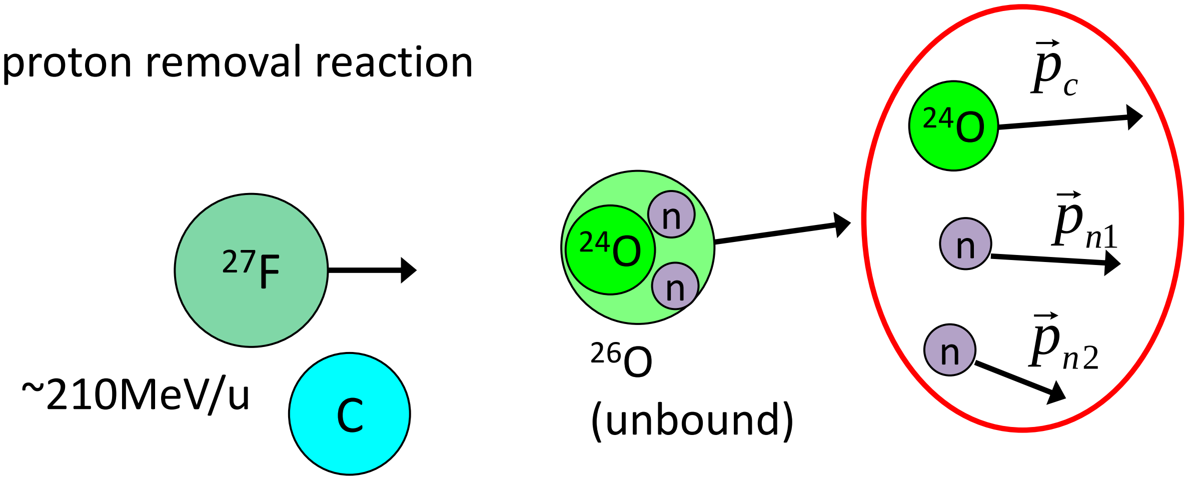
Γ~MeV or keV

Large uncertainty of experimental study

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

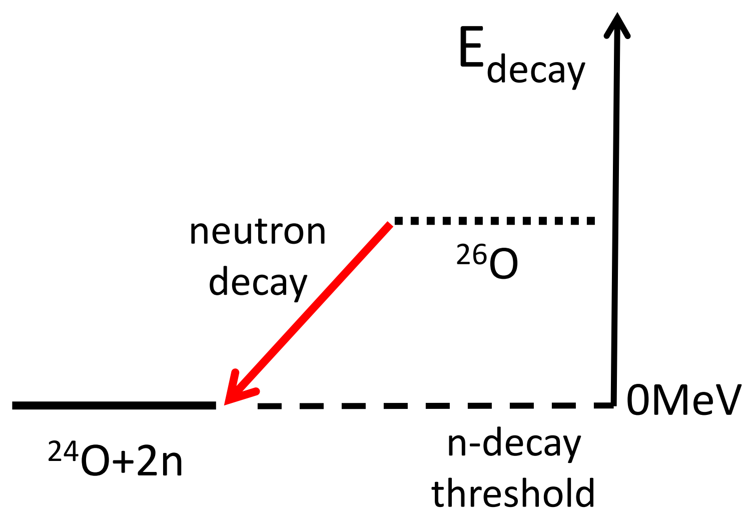
Invariant mass method

one proton removal reaction



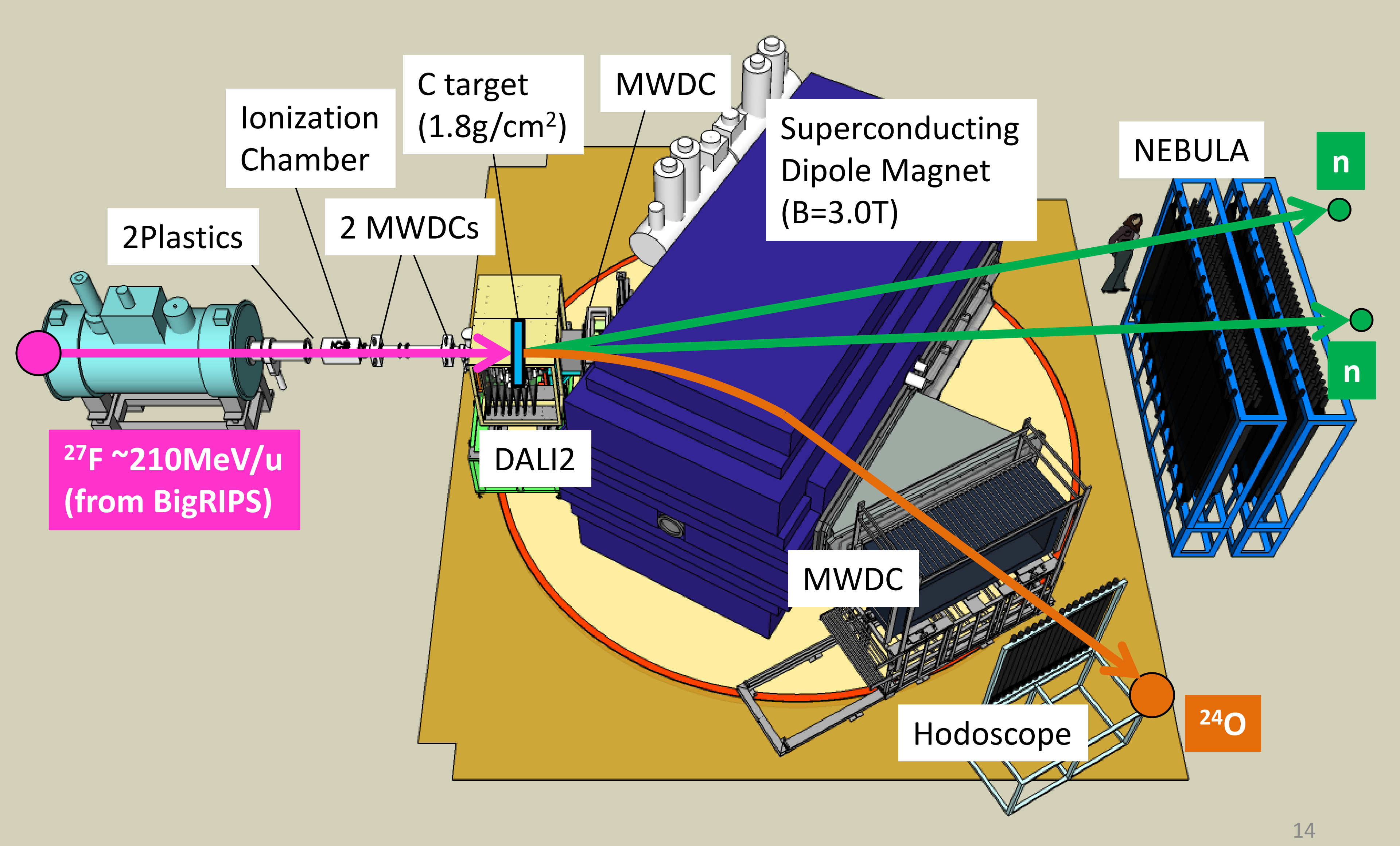
Decay energy (Relative energy)

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



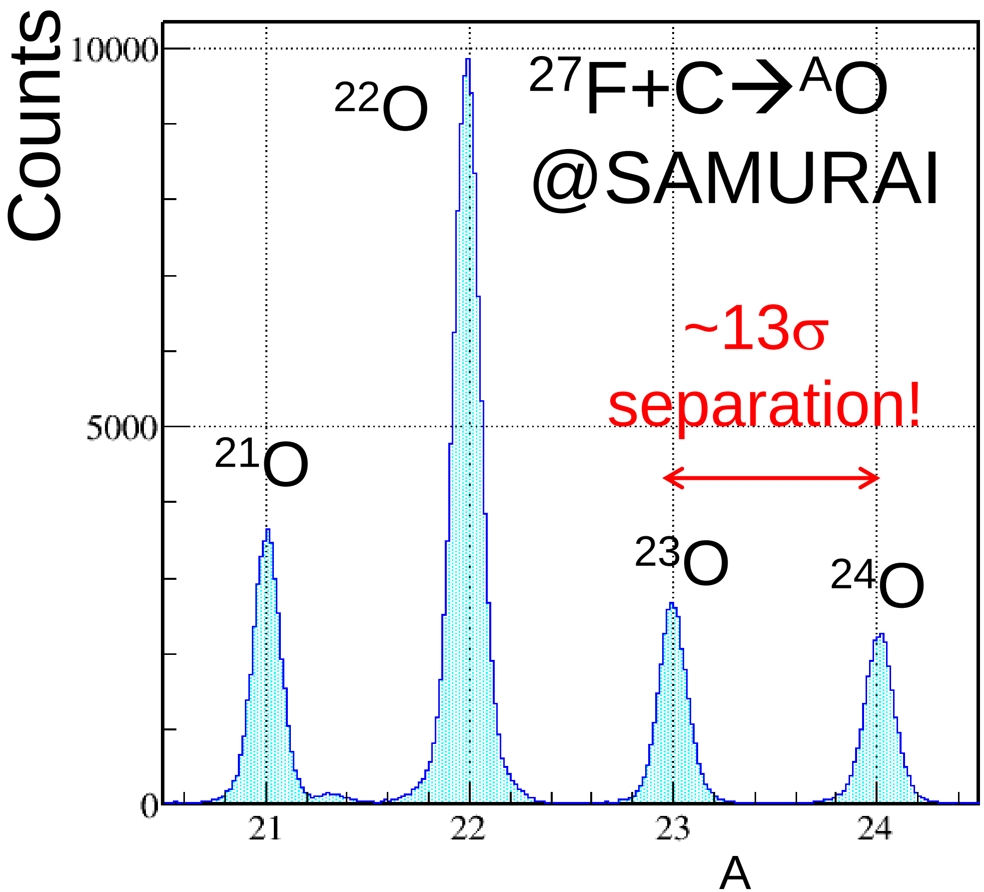
<u>Necessary to detect all the decay particles</u>

Experimental setup

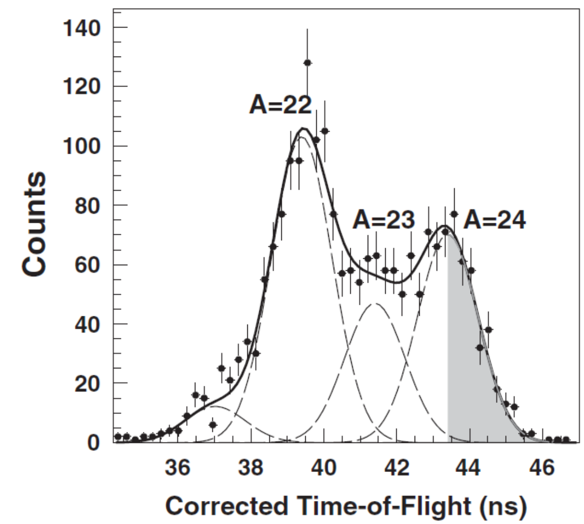


Experimental Results

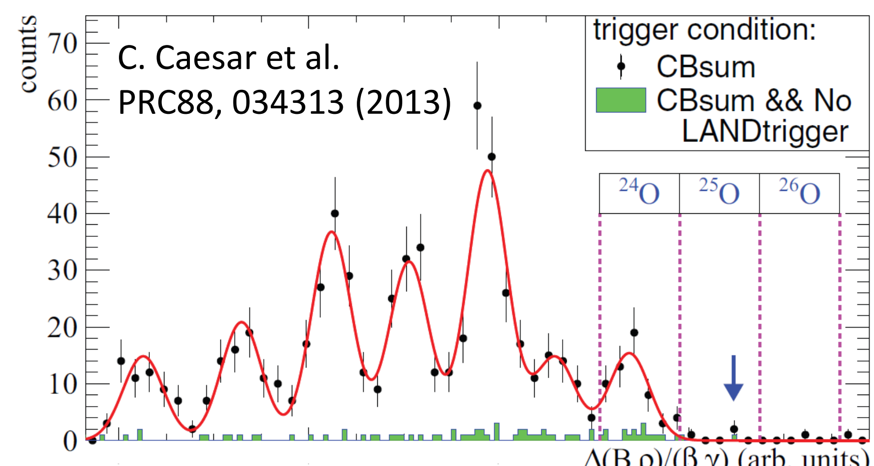
Mass identification @ SAMURAI



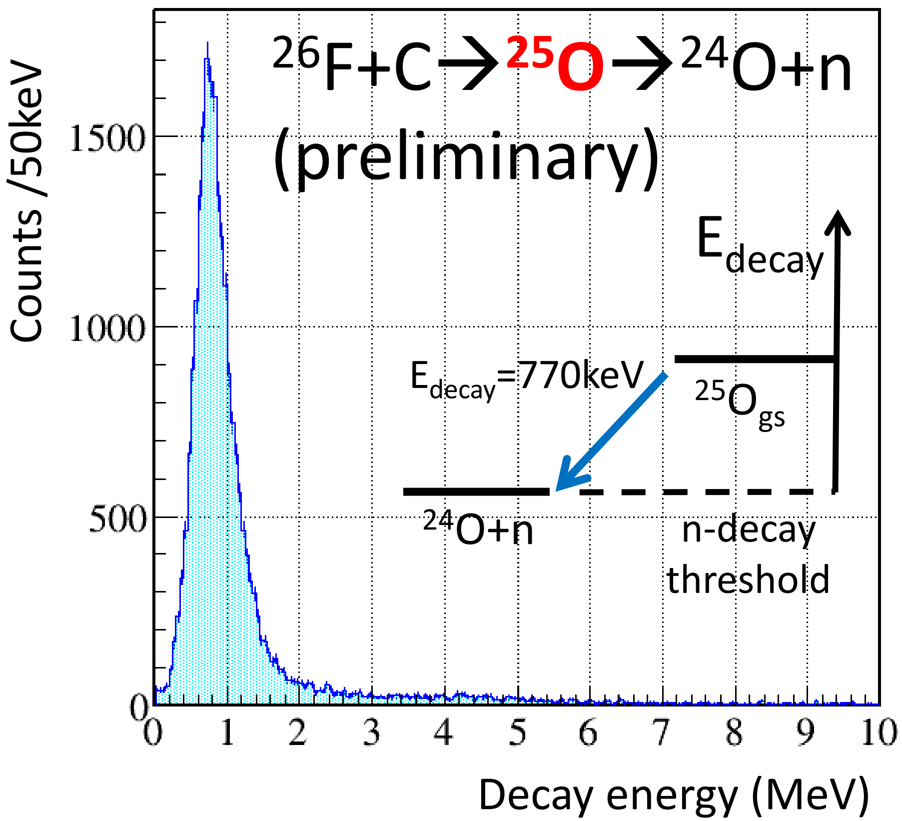
E. Lunderberg et al.
PRL108, 142503 (2012)



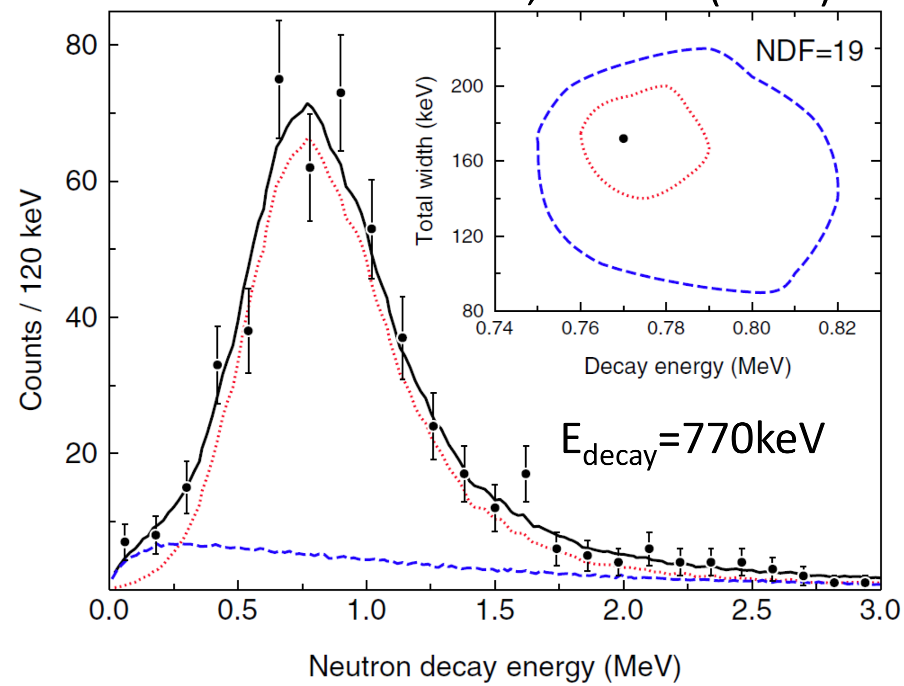
Clear Particle identification!
→ High resolving power of SAMURAI



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 ($^{27}F+C \rightarrow {}^{26}O \rightarrow {}^{24}O+2n$)

Counts /100keV

Ground state

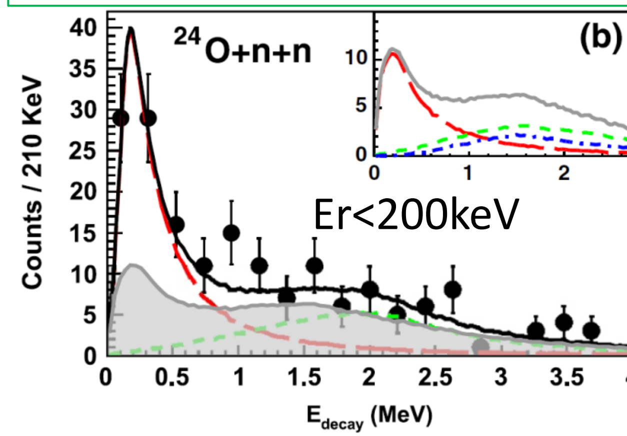
$^{27}F+C \rightarrow {}^{26}O \rightarrow {}^{24}O+2n$

(preliminary)

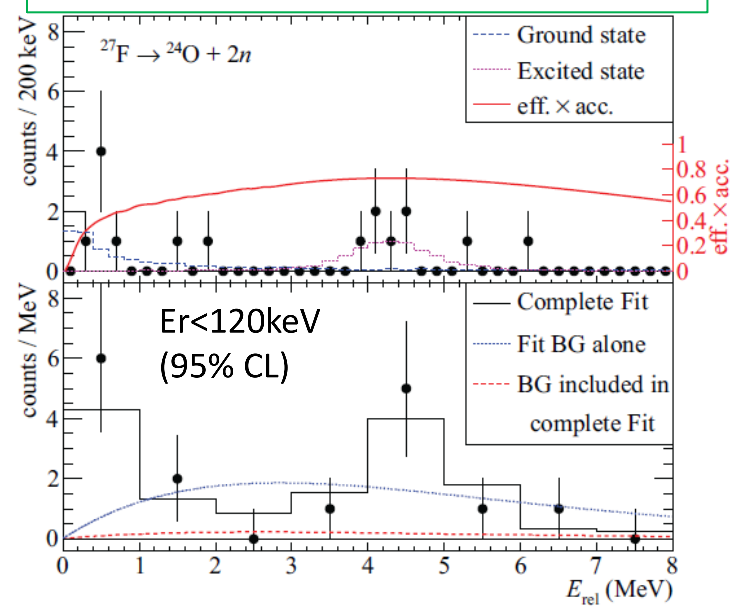
Excited state（new）

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

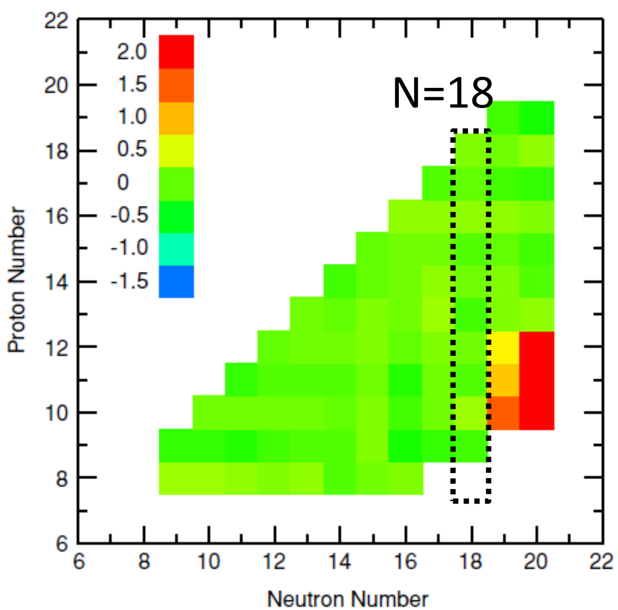
Excited state at ~1.3MeV

- First observation
- Most probably 2^+

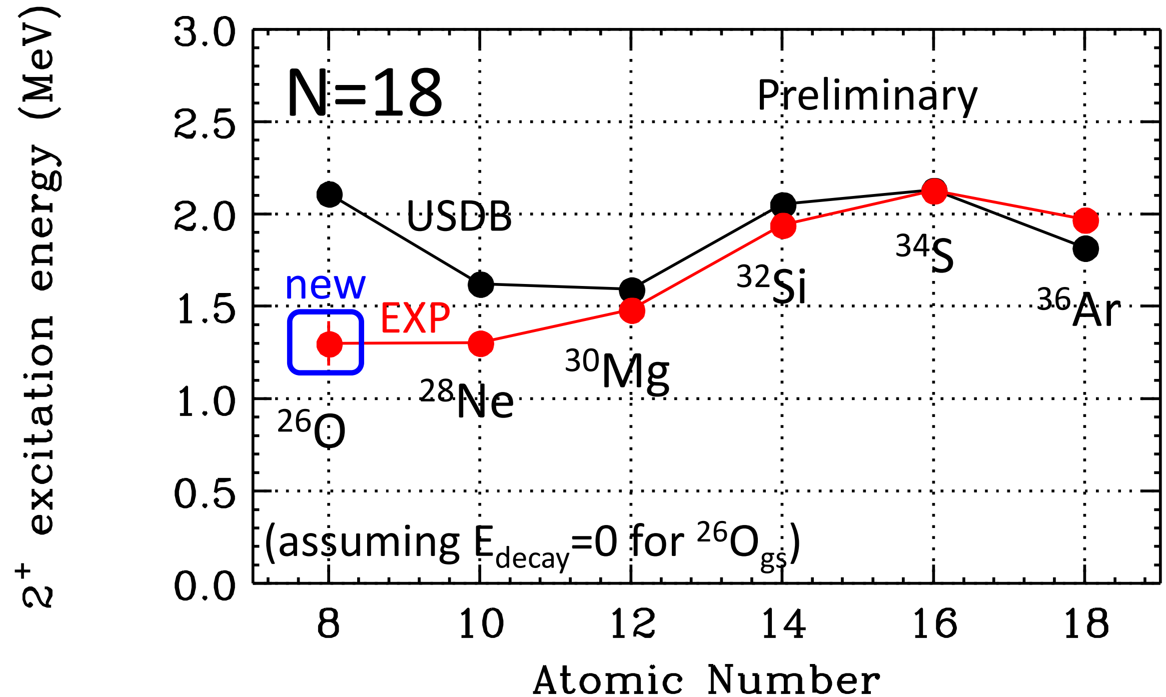
No peak at ~4.2MeV

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

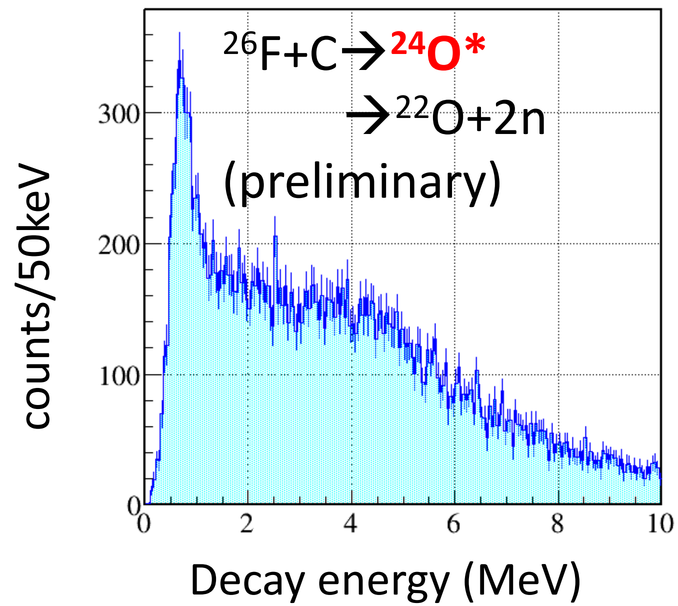
- USDB predicts S_{2n}= - 0.35MeV for ^{26}O ground state (Almost consistent with experiment)

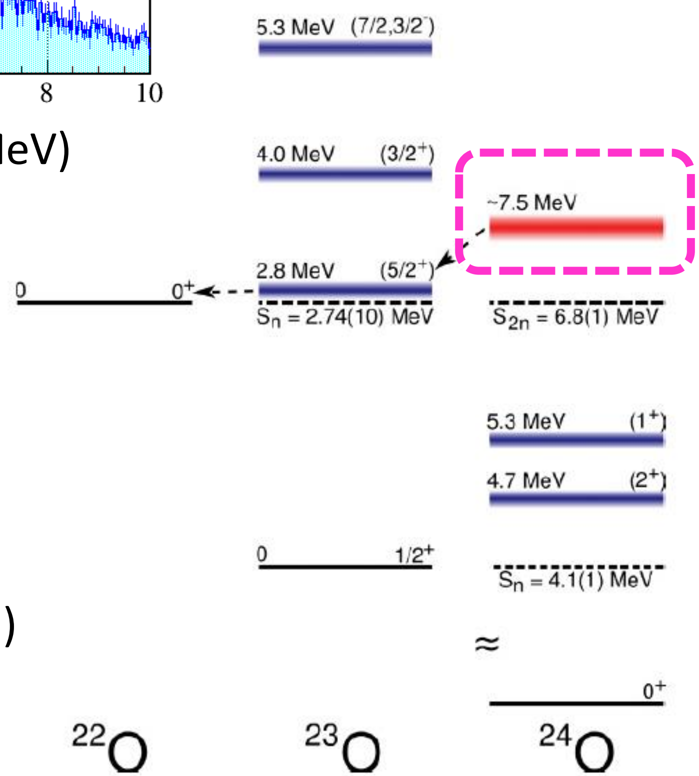
2+ state

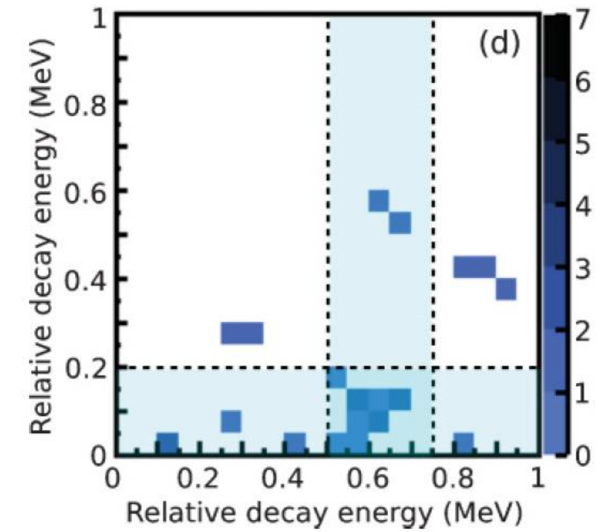
- Calculation overestimates at low Z
  →effect of pf-shell? or continuum effect?

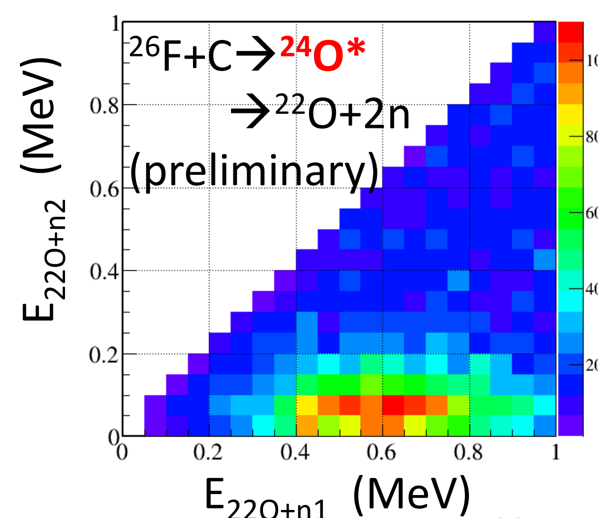
- E.g. Continuum shell model predicts 1.8MeV
  A. Volya, V. Zelevinsky, PRC74, 064314 (2006)

^{24}O excited state







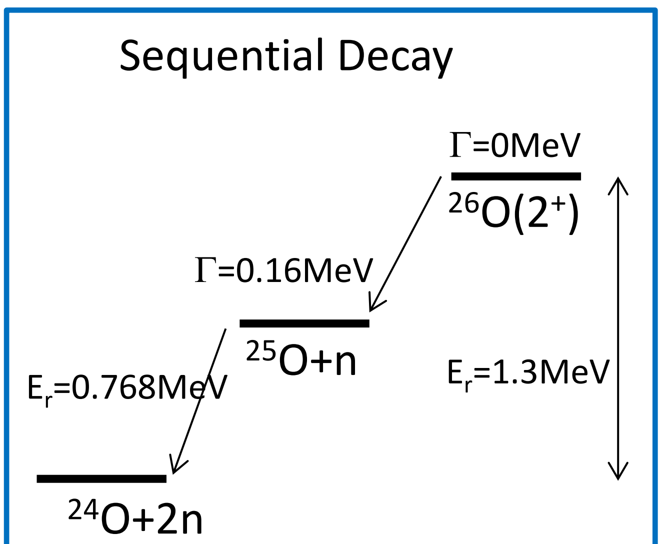


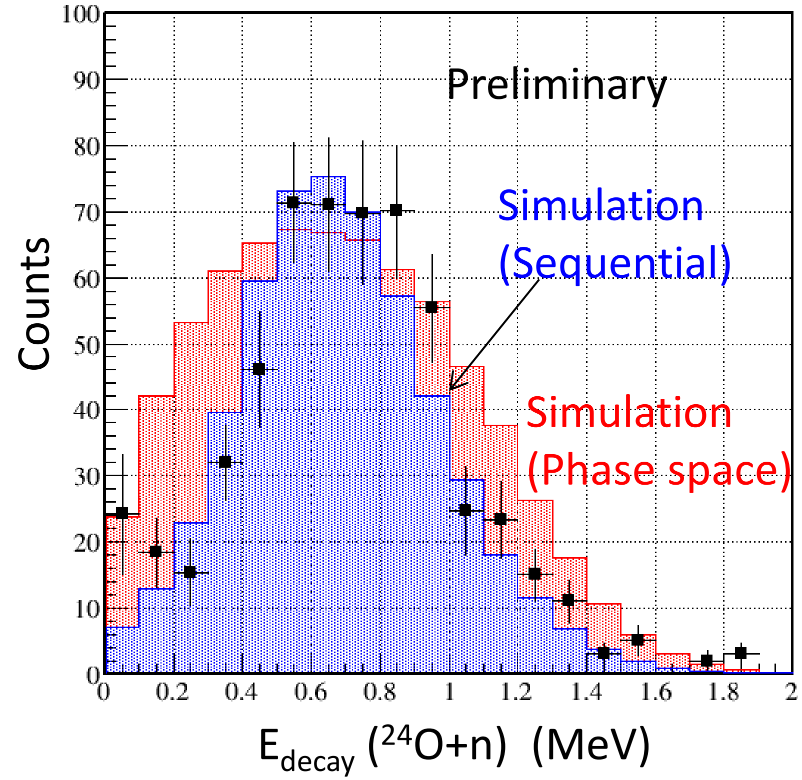
C.R. Hoffman et al,
PRC83, 031303 (2011)

Sequential decay of $^{26}O(2^+)$

Gated by 3-body decay energy
0.8MeV<E_{decay}(^{24}O+n+n)<2MeV

E_{decay} (^{24}O+n+n) (MeV)





<u>2^+ state decays sequentially</u>

Summary

- **SAMURAI is now available**
  - SAMURAI collaboration page
    http://ribf.riken.jp/SAMURAI/Collaboration/

- **SAMRUAI Day-One Experimental campaign on 2012**
  - Study of unbound nuclei ^{25}O and ^{26}O
    - Higher statistics for $^{26}O(0^+)$
    - New observation of $^{26}O(2^+)$
      - Sequential decay through $^{25}O_{gs}$
    - Confirmation of excited state of ^{24}O