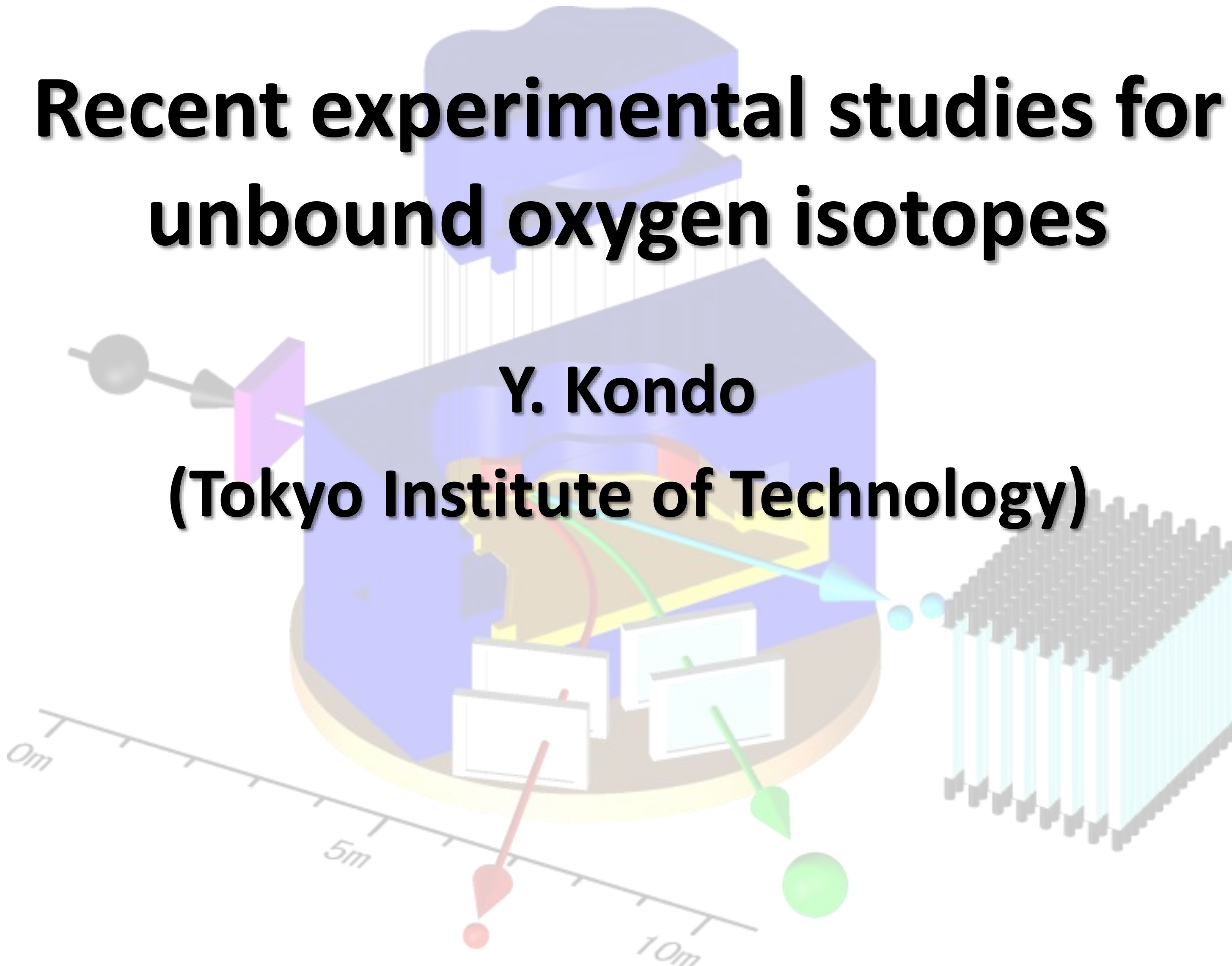
Recent experimental studies for unbound oxygen isotopes

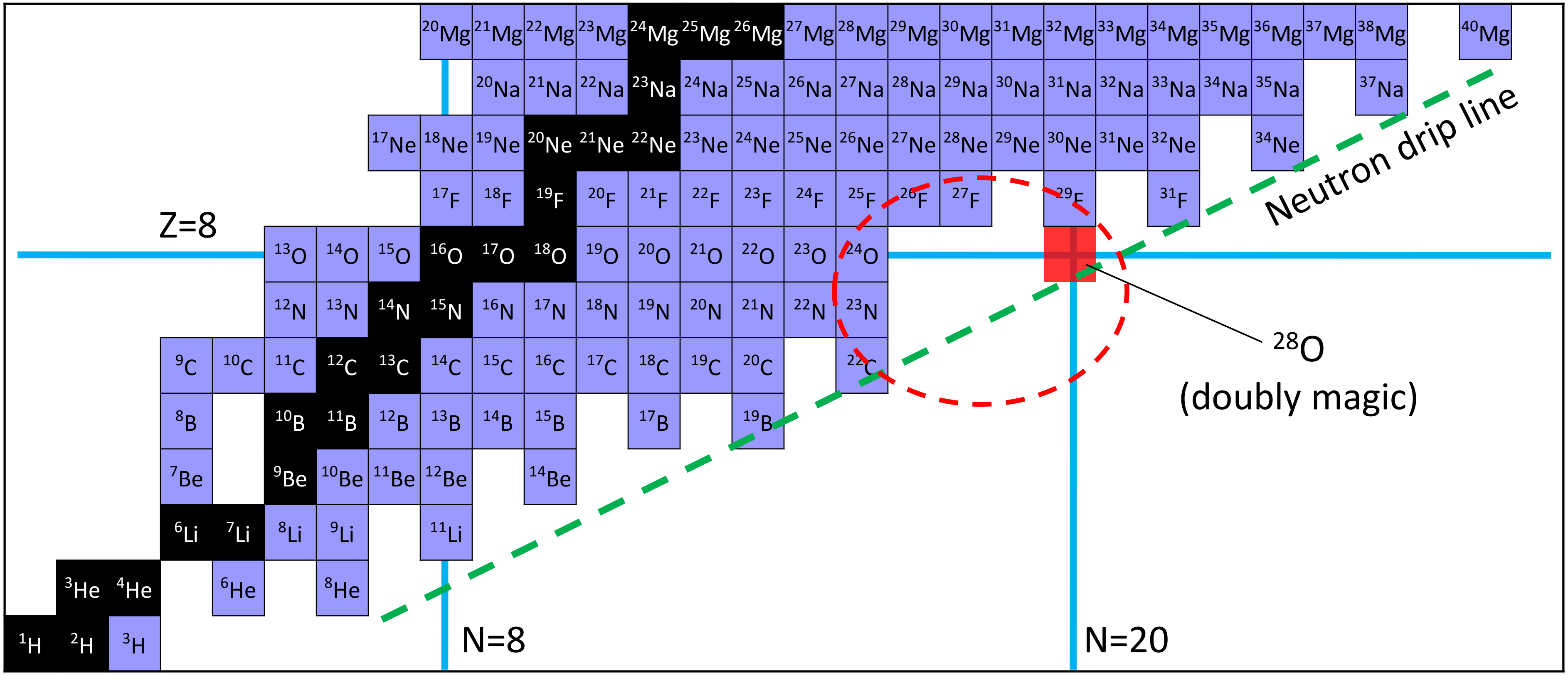
Y. Kondo

(Tokyo Institute of Technology)



RIBF seminar, Apr. 19, RIKEN

Where is neutron drip line?



Neutron drip line : One of the fundamental properties of atomic nuclei

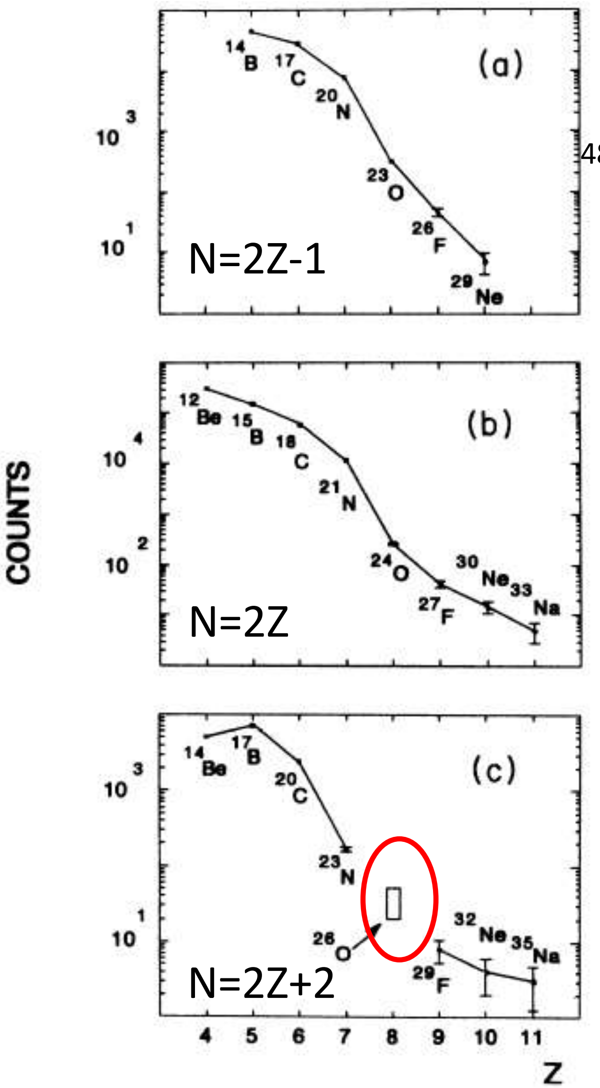
Before 2000: drip line of oxygen was not clear

→Several experiments were performed to search for bound ^{26}O and ^{28}O

Search for bound ^{26}O and ^{28}O

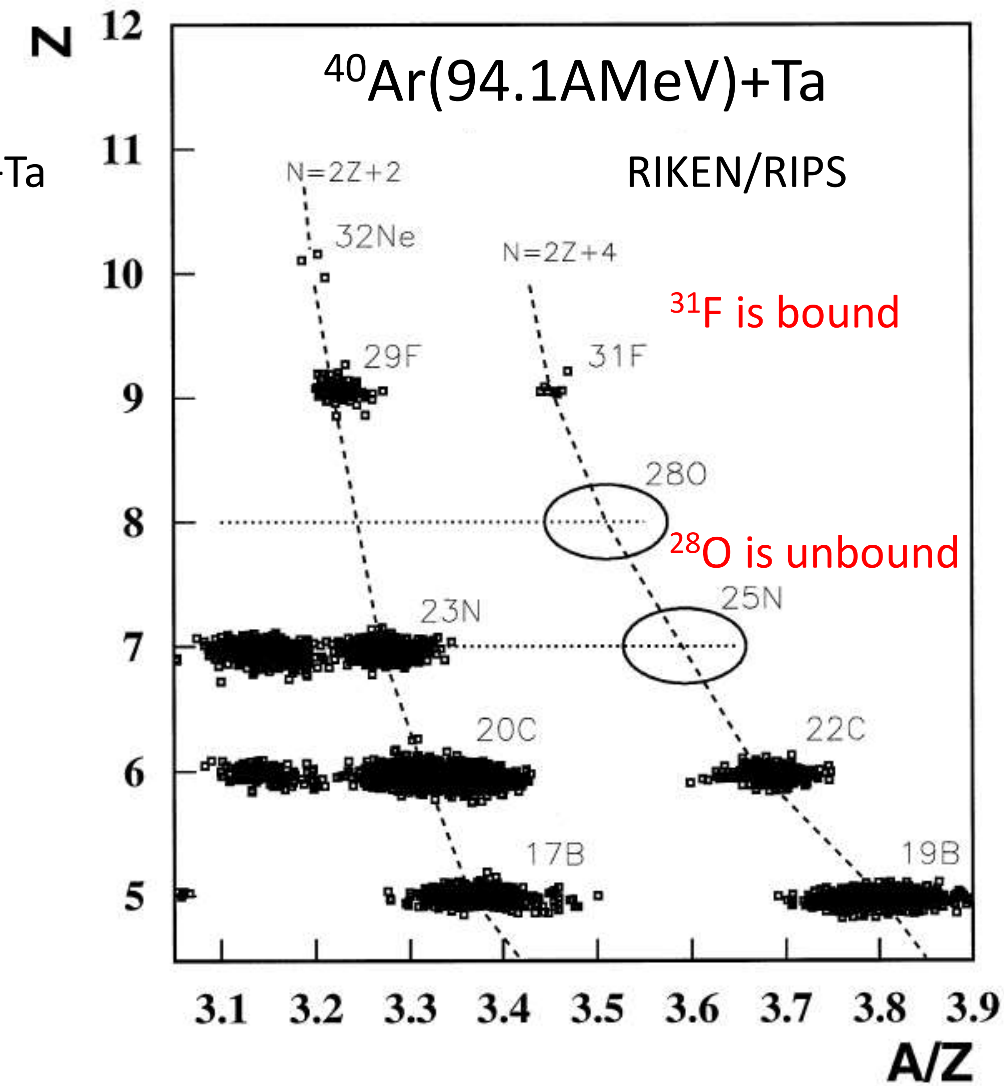
D. Guillemaud-Mueller *et al.* PRC **41,** 937 (1990).

H. Sakurai *et al.* PLB. **448,** 180 (1999).



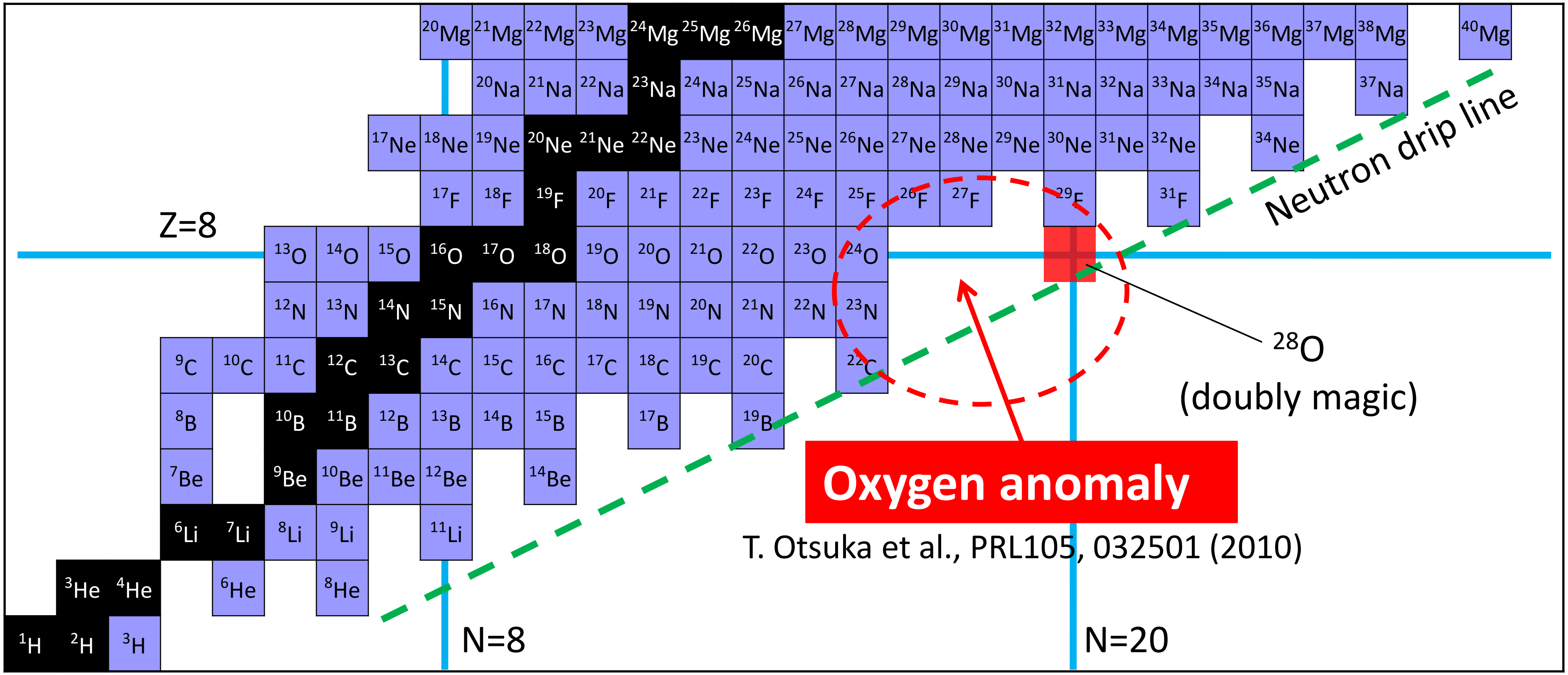
^{48}Ca(44MeV/u)+Ta

GANIL/LISE



^{26}O and ^{28}O are unbound

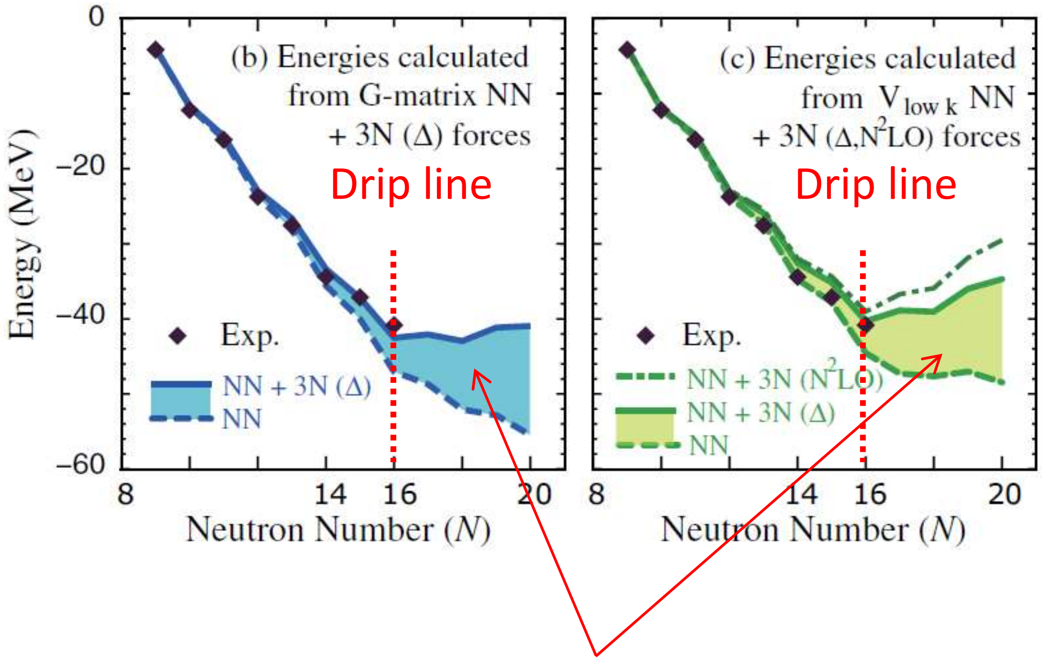
Neutron drip line anomaly (oxygen anomaly)



What is the origin of the “oxygen anomaly”?

Three nucleon force and binding energies of oxygen isotopes

T. Otsuka et al., PRL105, 032501 (2010)



G. Hagen et al. PRL 108, 242501 (2012)

CC method with int. from chiral EFT (includes effects of continuum and 3NF)

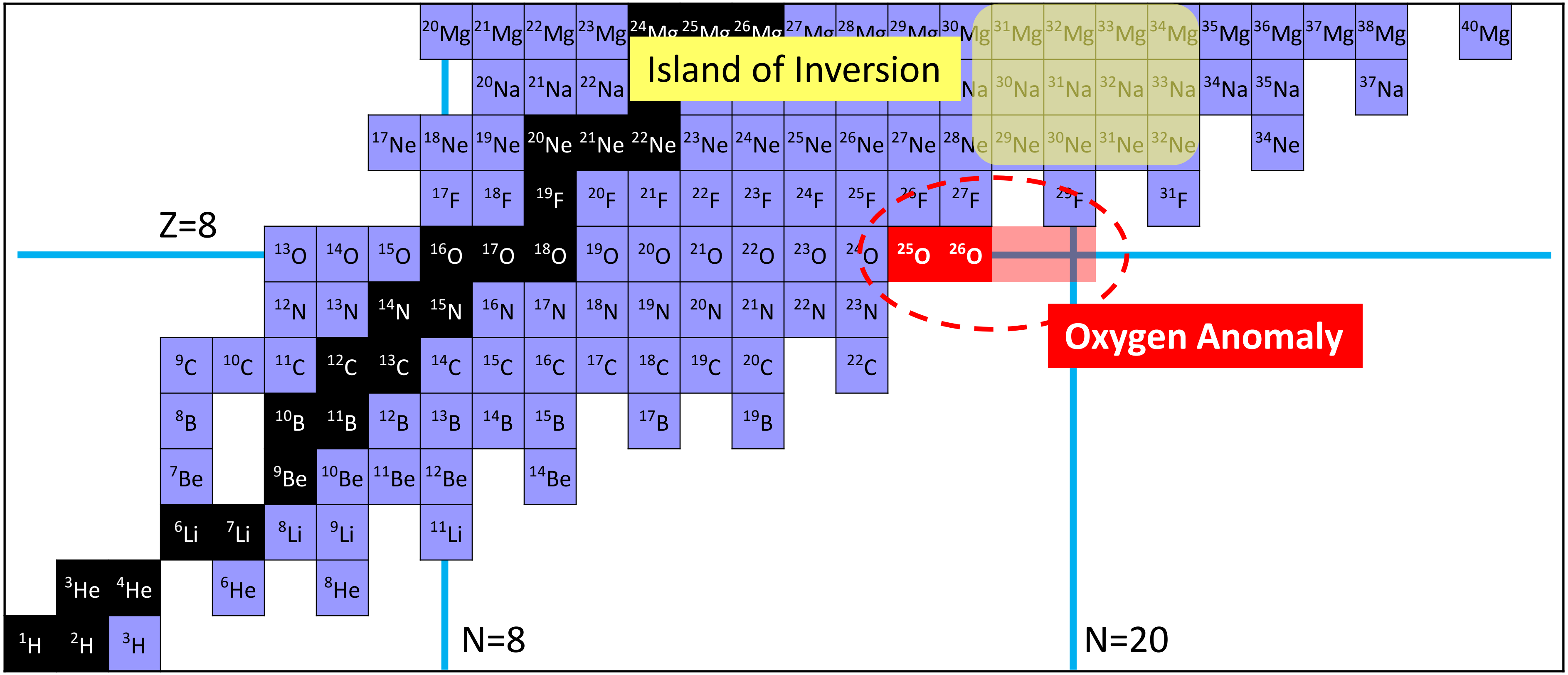
Large effect at N>16

3NF plays an important role in binding

Mass of oxygen isotopes → good test

TOKYO TECH Pursuing Excellence

Unbound oxygen isotopes

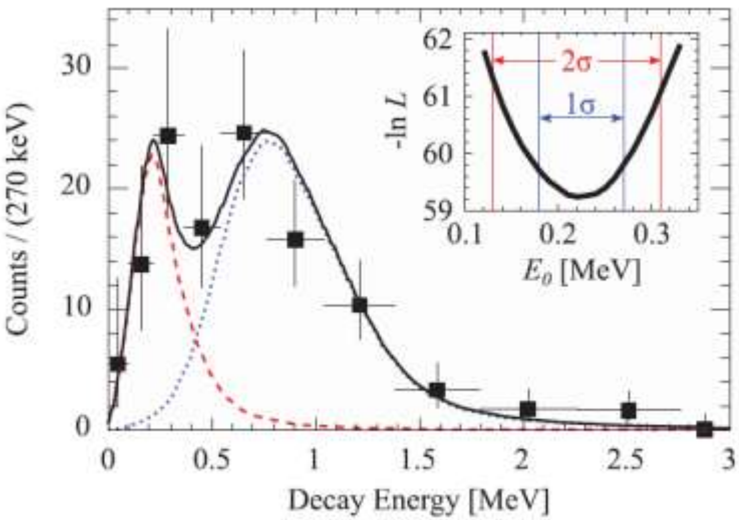


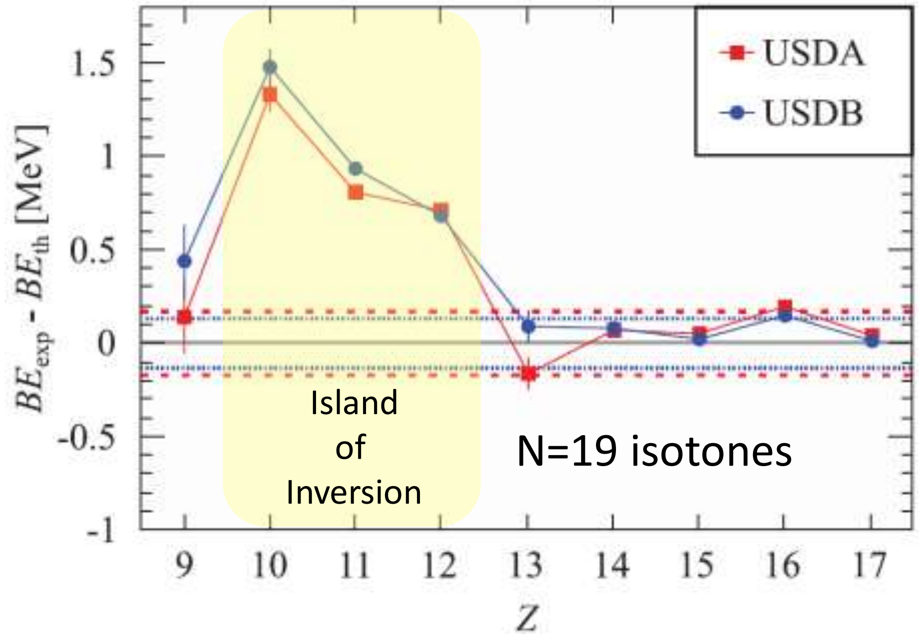
- Unbound oxygen isotopes are related to …
  - Mechanism of drip line anomaly
  - Knowledge of 3NF
  - Shell structure at the south of the Island of Inversion
  - 2n radioactivity in ^{26}O?
  - 2n correlation in ^{26}O?

Shell Structure at South of Island of Inversion

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

^{28}F (Z=9, N=19)



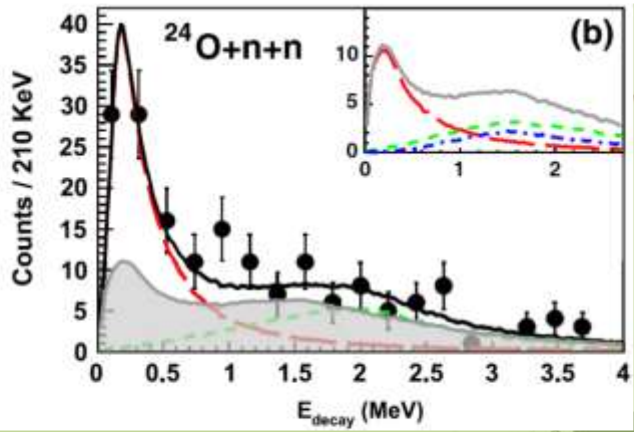


^{28}F Ground state @ 220(50)keV

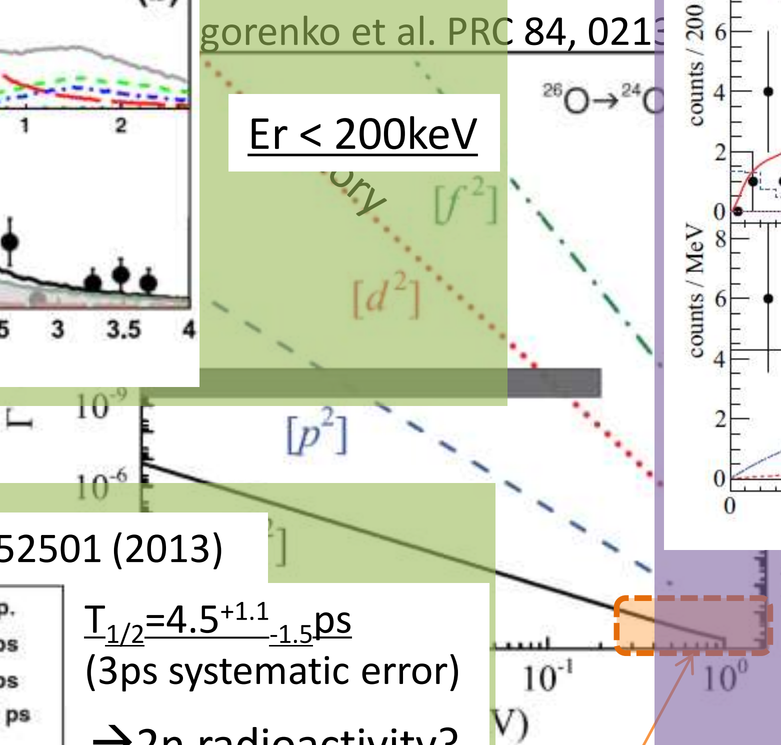
→^{28}F is boundary of Island of Inversion

2n radioactivity of ^{26}O?

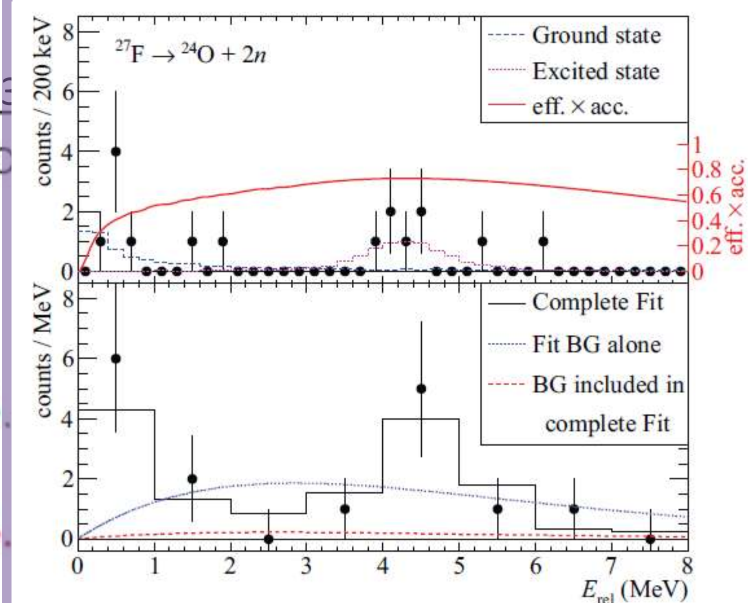
E. Lunderberg et al.PRL108, 142503 (2012)



Er < 200keV



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

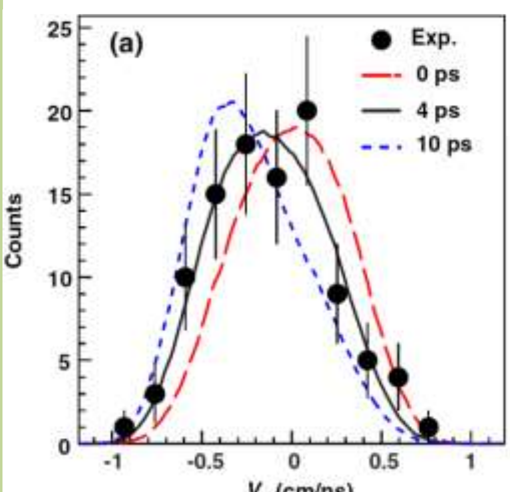


Er < 120keV (95% CL)

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?

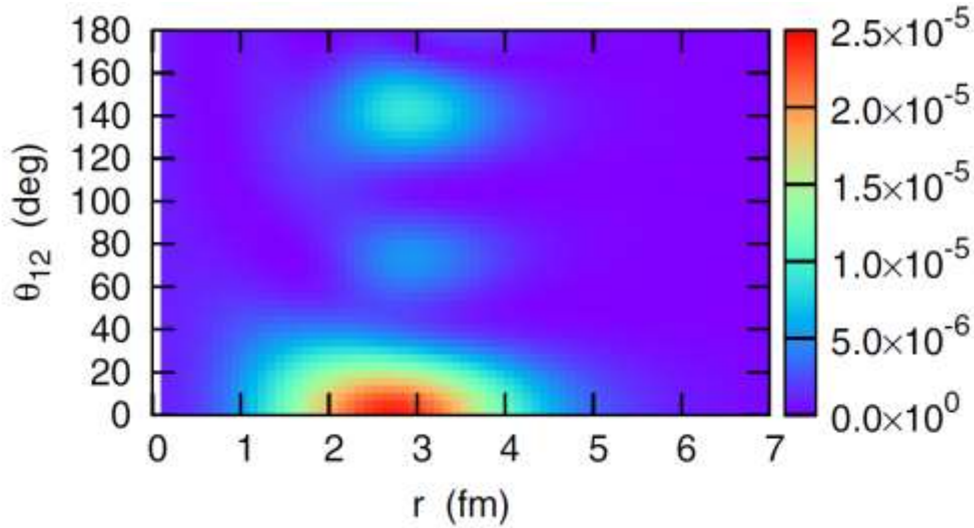
Usual 1n decay

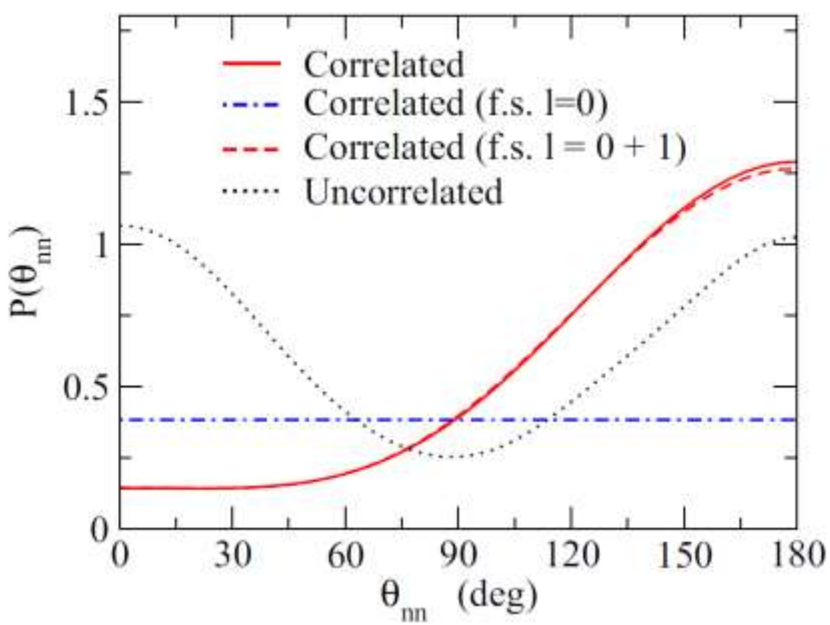
Γ~MeV or keV

Large uncertainty of experimental study

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

2n correlation in ^{26}O?





3-body model calculation

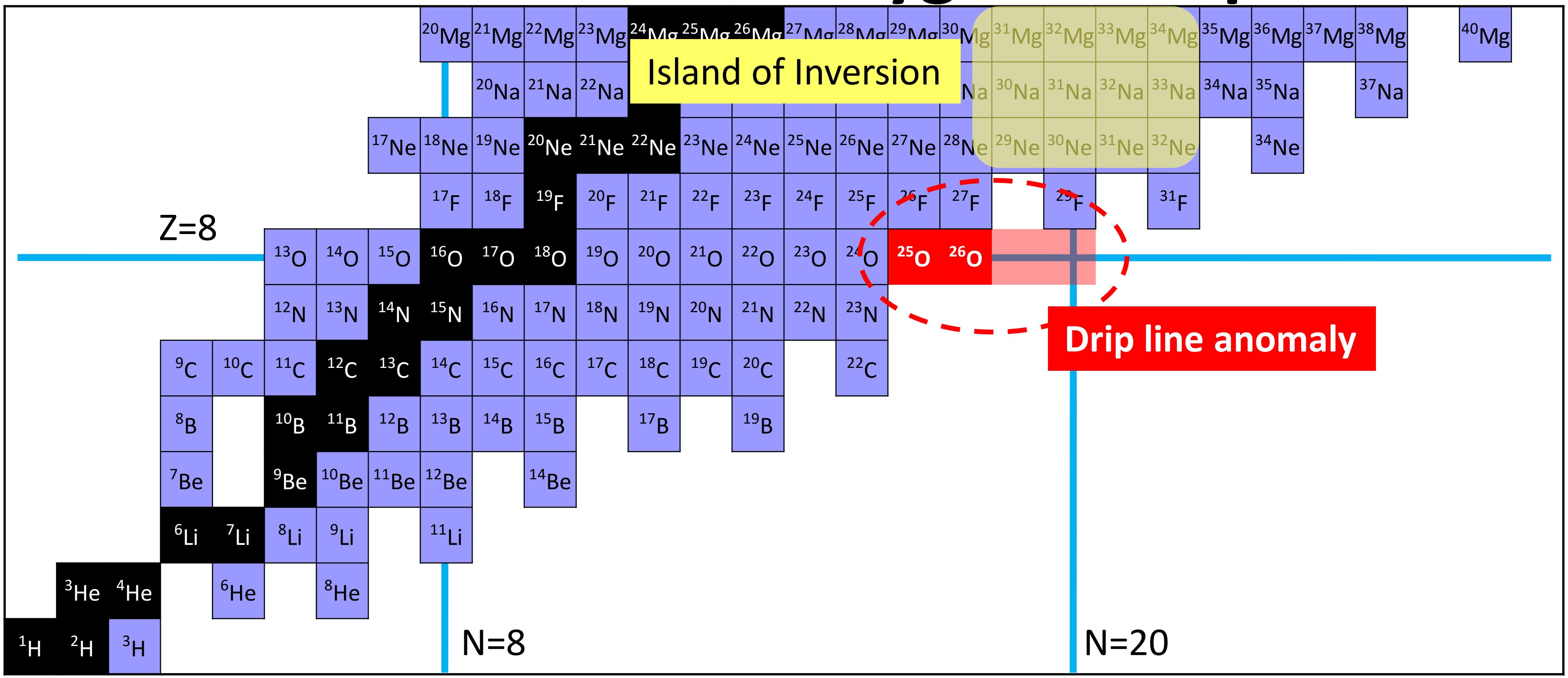
K. Hagino et al., PRC89, 014331 (2014)

K. Hagino et al., PRC93, 034330 (2016)

Spatial 2n correlation in ^{26}O

→ back-to-back 2n emission

Mass measurement of unbound oxygen isotopes

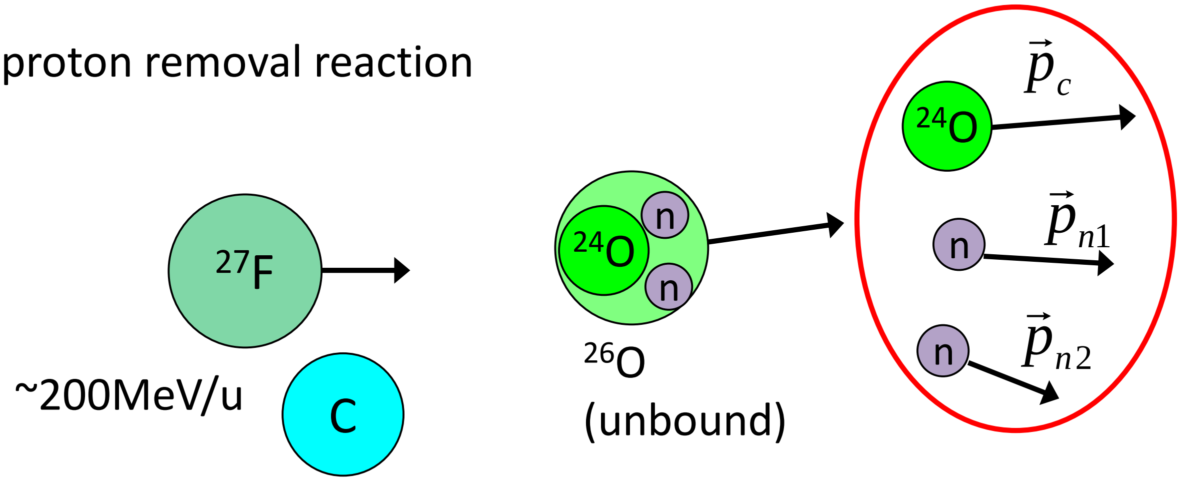


Mass measurements lead to …

- Mechanism of drip line anomaly
- Knowledge of 3NF
- Shell structure at the south of the Island of Inversion
- 2n radioactivity in ^{26}O?
- 2n correlation in ^{26}O?

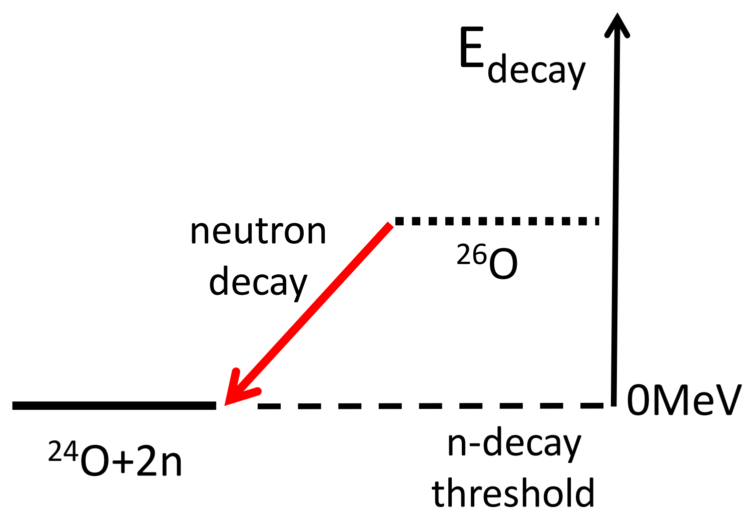
Invariant mass method

One proton removal reaction



Decay energy (Relative energy)

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



One-nucleon removal reaction from neutron-rich nucleus

One-proton removal reaction

- Higher N/Z nucleus is produced
- Ground state is mainly populated

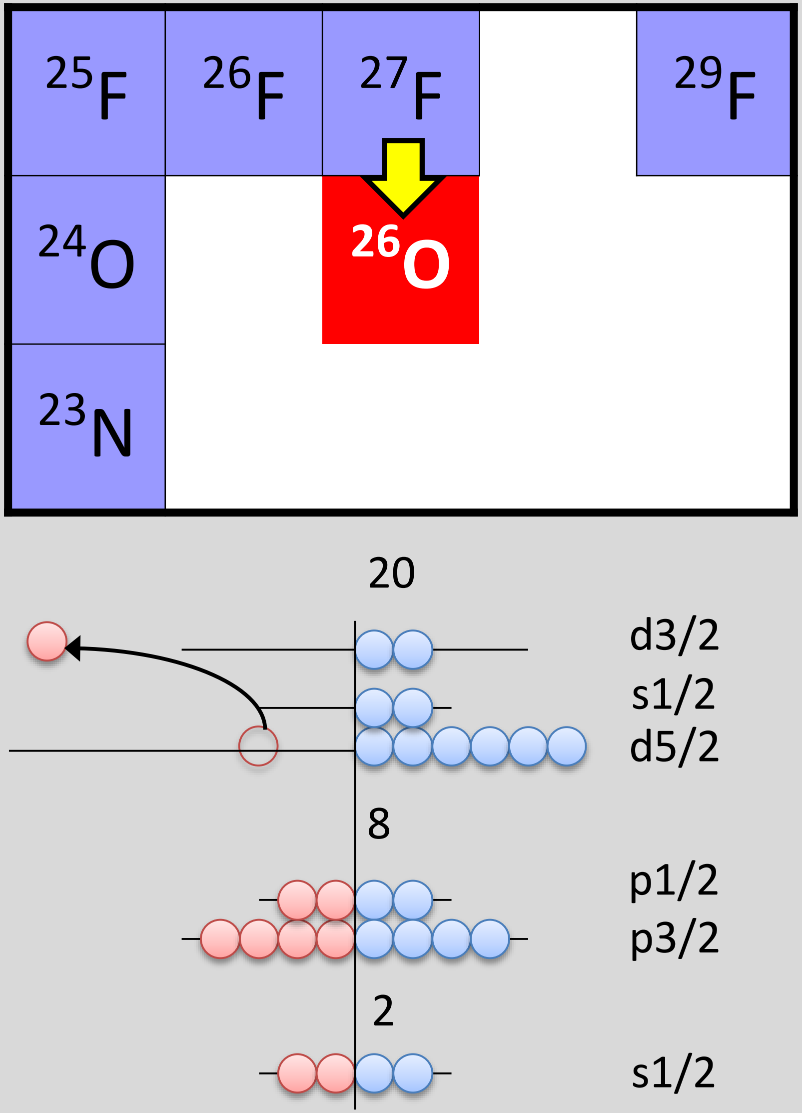
One-neutron removal reaction

- Require neutron-rich beam
- Populate neutron-hole state (ground and excited states)
- Momentum distribution
  - Orbital angular momentum
- Cross section
  - Spectroscopic factor

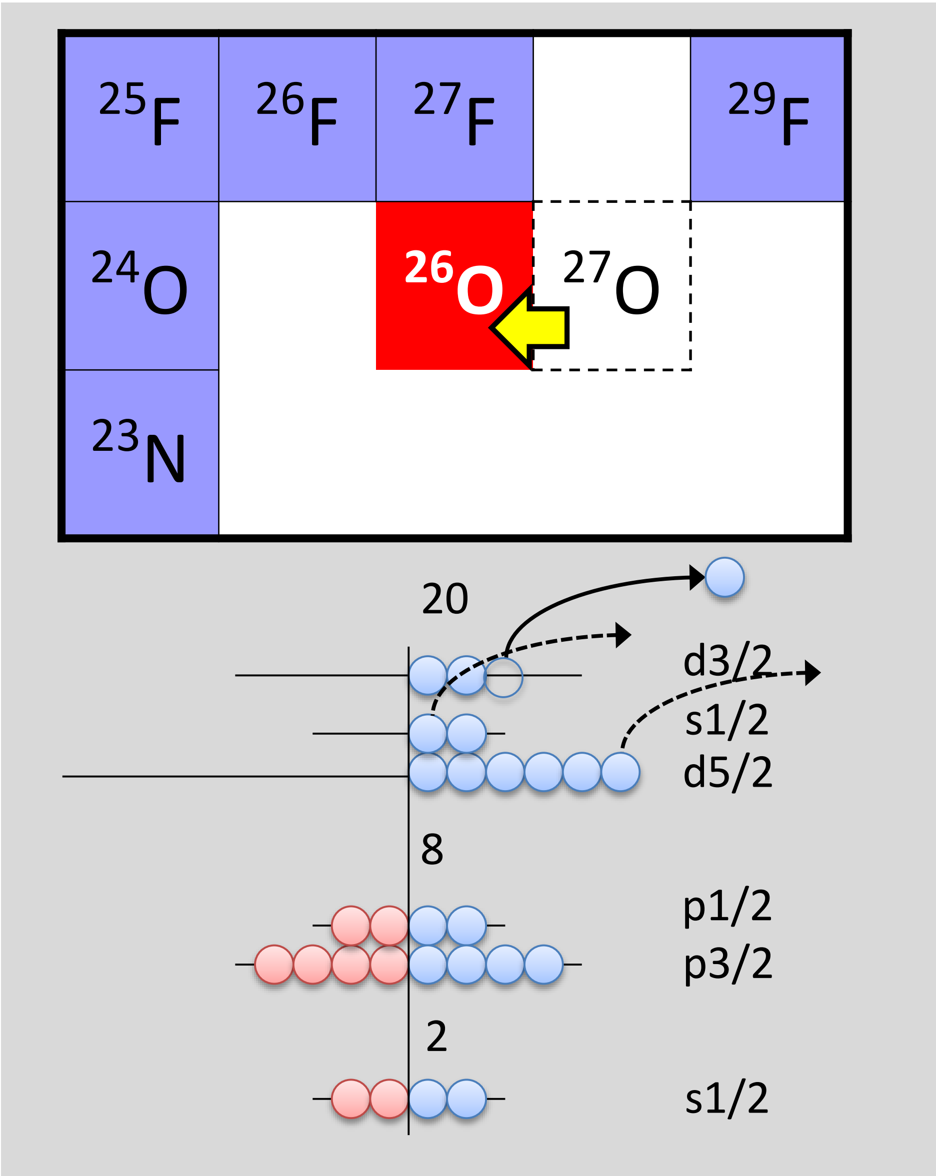
One-nucleon removal reaction from neutron-rich nucleus

One-proton removal reaction

- Higher N/Z nucleus is produced
- Ground state is mainly populated



One-nucleon removal reaction from neutron-rich nucleus



One-neutron removal reaction

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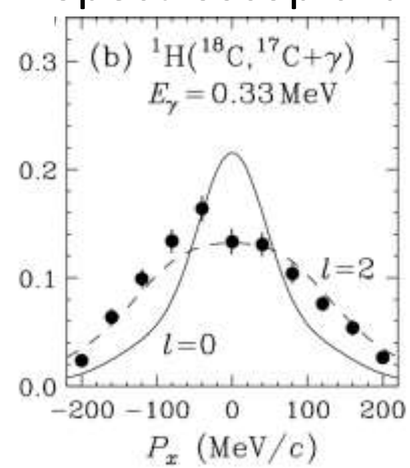
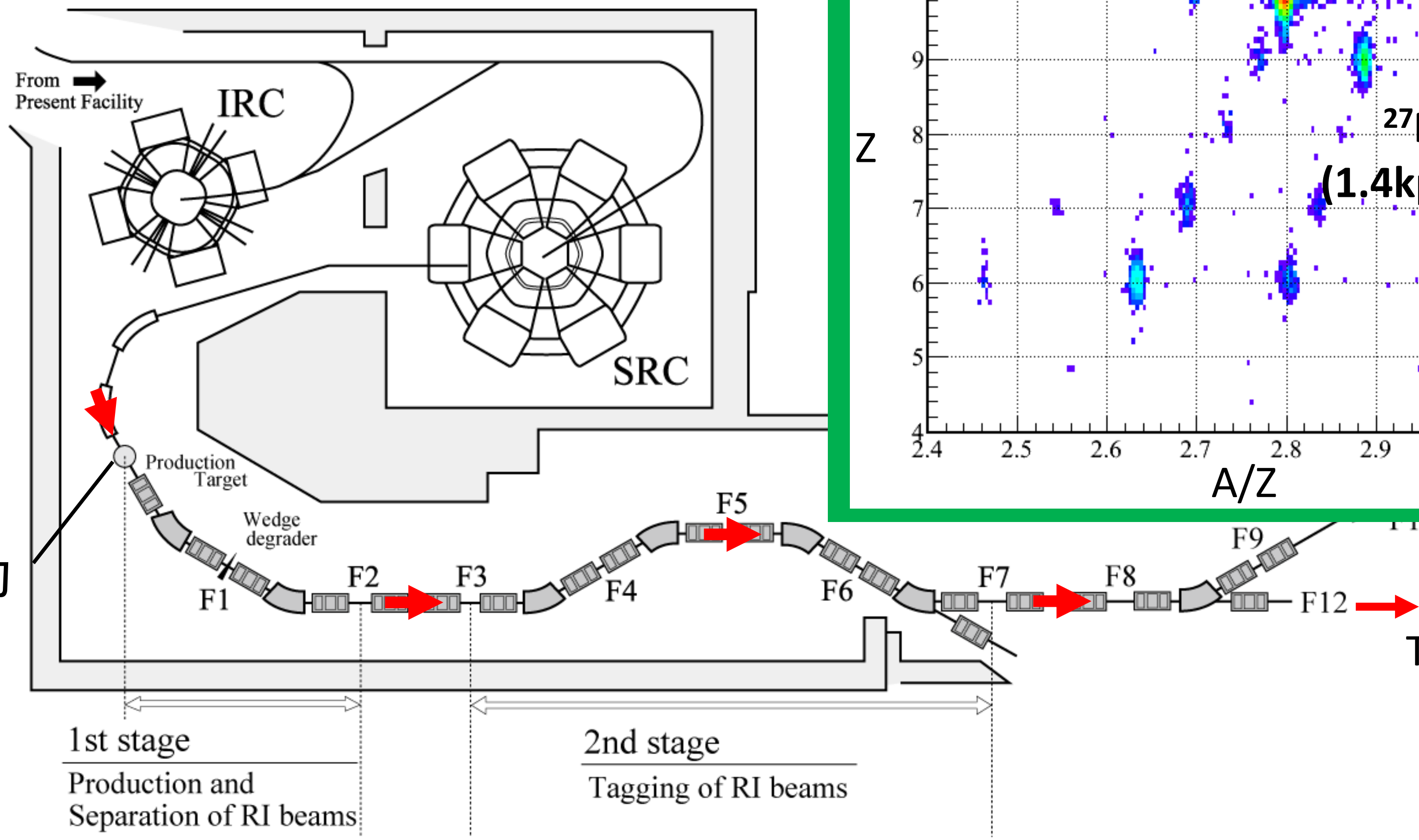
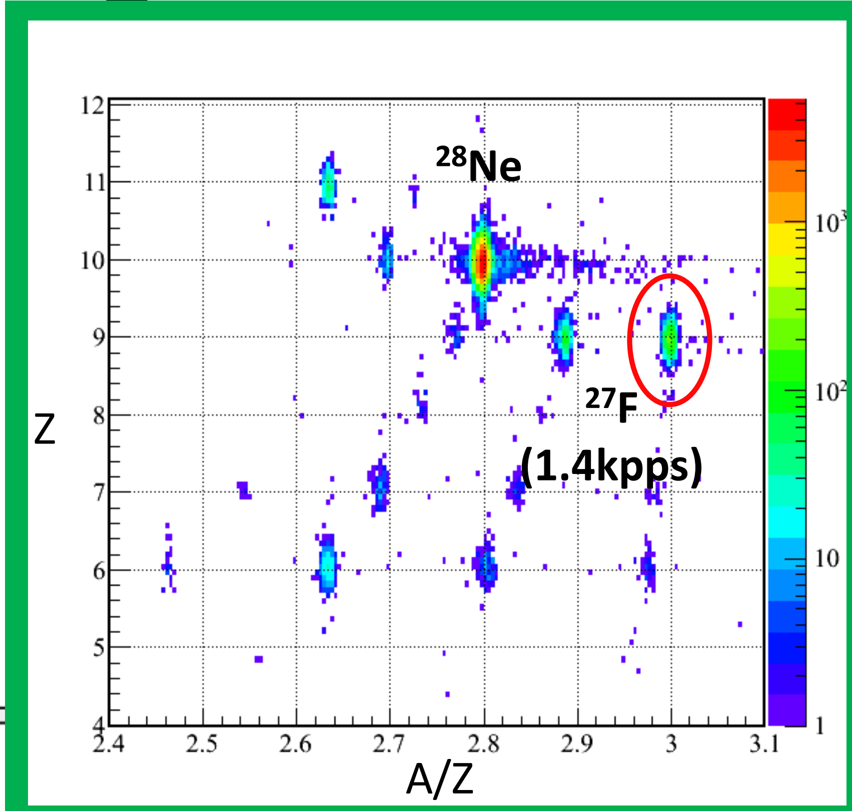


Y. Kondo et al., PRC79, 014602 (2009)

Experiment @ RIBF

Primary beam
^{48}Ca (345MeV/nucleon)





1次標的
^{9}Be

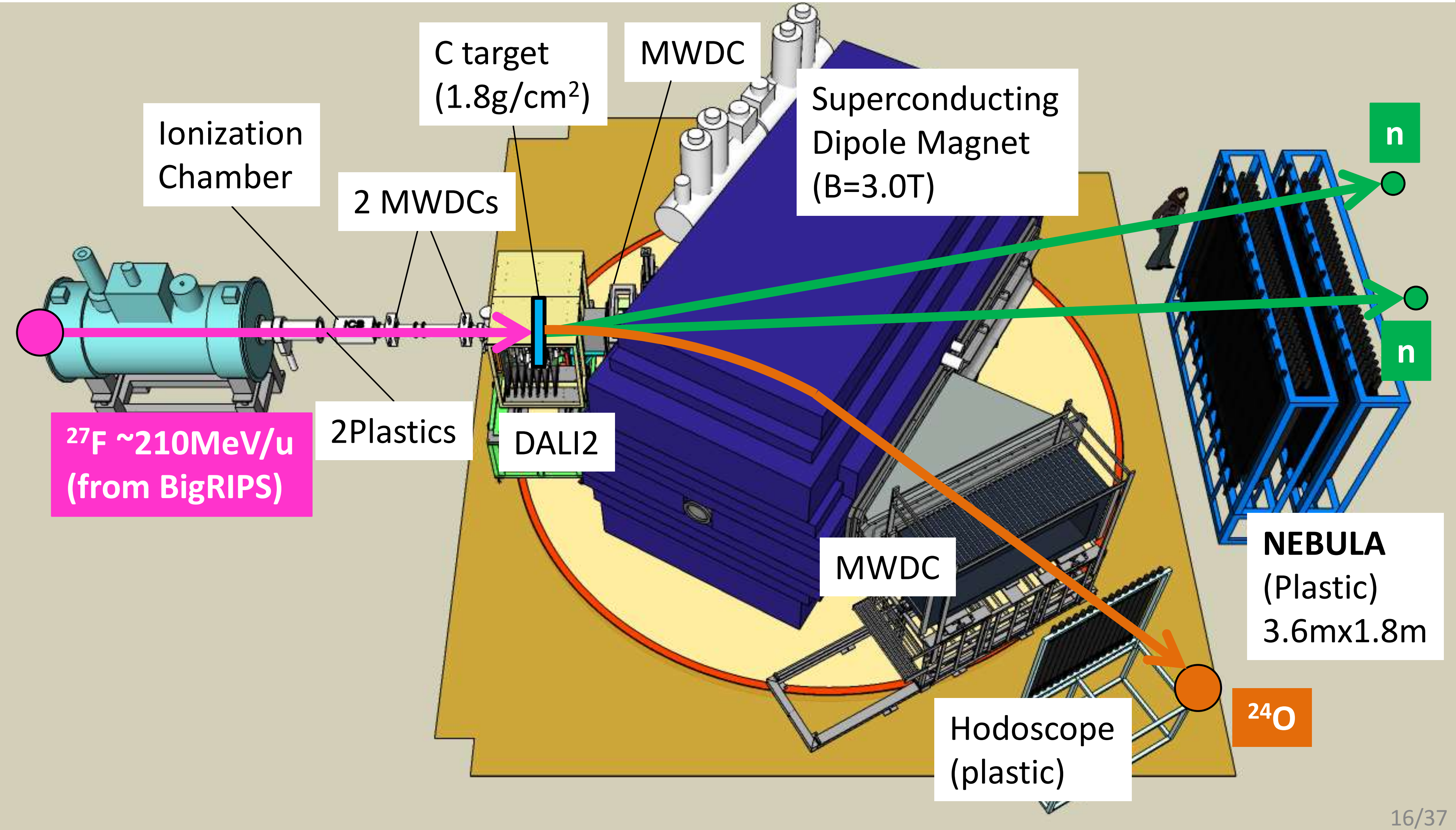
To SAMURAI

BigRIPS Selection/identification of secondary beam

TOKYO TECH Pursuing Excellence

SAMURAI

Superconducting Analyzer for MUlti-particle from RAdioIsotope Beams



SAMURAI Day-one campaign

First experimental campaign with SAMURAI for physics programs

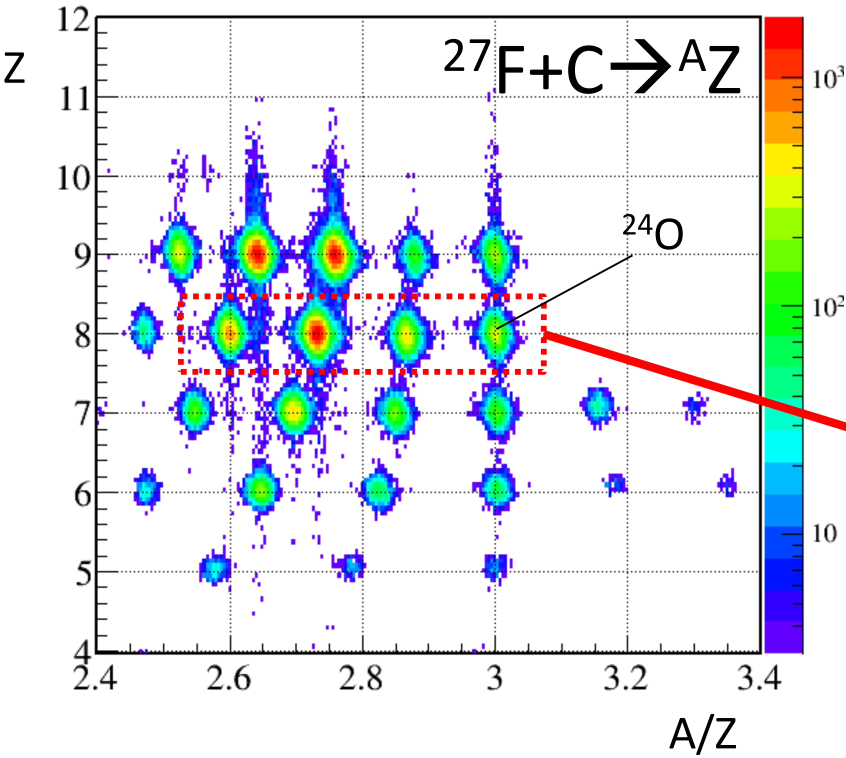
1. Study of unbound nuclei ^{25}O and ^{26}O (SAMURAI02, Y. Kondo)
2. Coulomb breakup of ^{22}C and ^{19}B (SAMURAI03, T. Nakamura)
3. Study of unbound states of ^{22}C, ^{21}C, ^{19}B, ^{18}B (SAMURAI04, N. A. Orr/J. Gibelin)

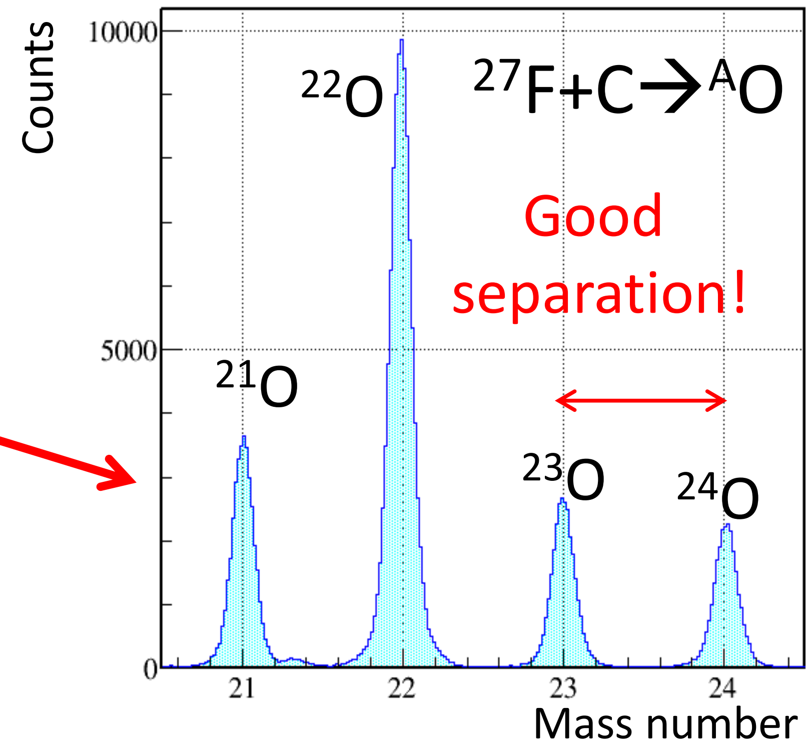
Tokyo Institute of Technology: Y.Kondo, T.Nakamura, N.Kobayashi, R.Tanaka, R.Minakata, S.Ogoshi, S.Nishi, D.Kanno, T.Nakashima, J. Tsubota, A. Saito
LPC CAEN: N.A.Orr, J.Gibelin, F.Delaunay, F.M.Marques, N.L.Achouri, S.Leblond
Tohoku University : T.Koabayshi, K.Takahashi, K.Muto
RIKEN: K.Yoneda, T.Motobayashi ,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

Photo

Construction was completed in 2012

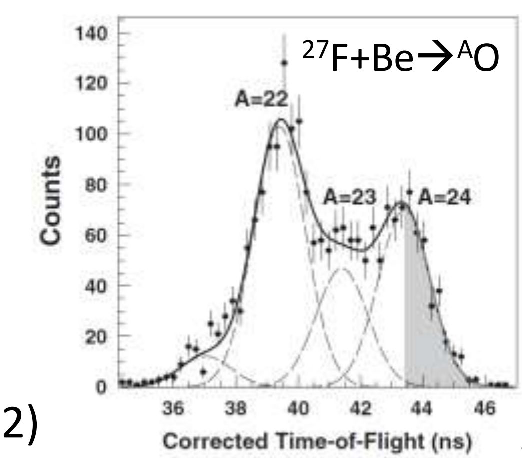
Particle identification @ SAMURAI





Clear Particle identification!

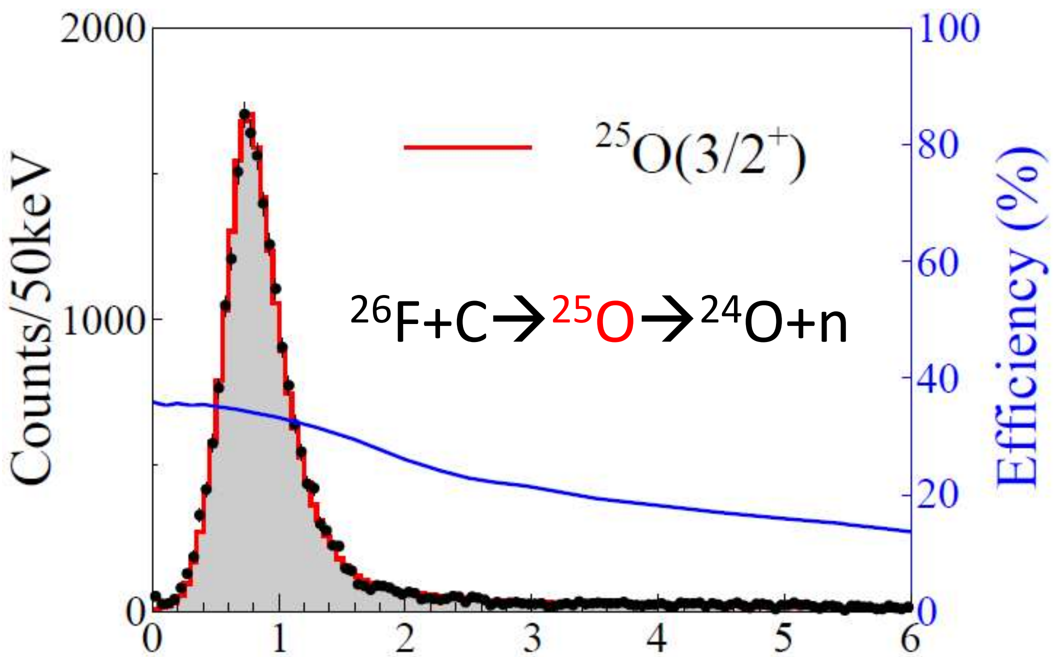
→ High resolving power of the SAMURAI spectrometer

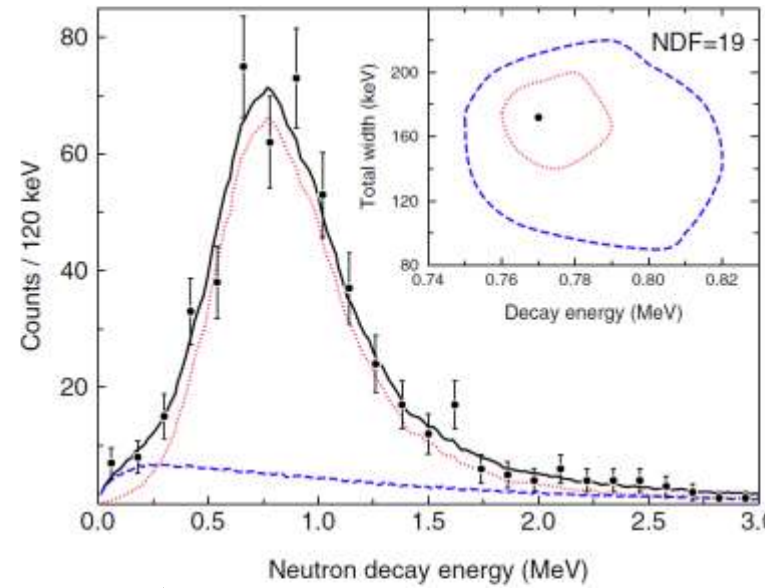


E. Lunderberg et al.
PRL108, 142503 (2012)

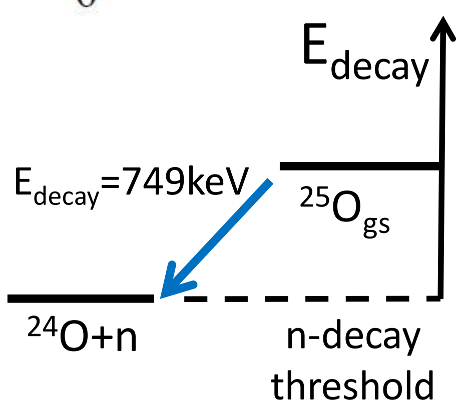
Result of ^{25}O

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





Decay energy (MeV)



Fit by d-wave Breit-Wigner shape

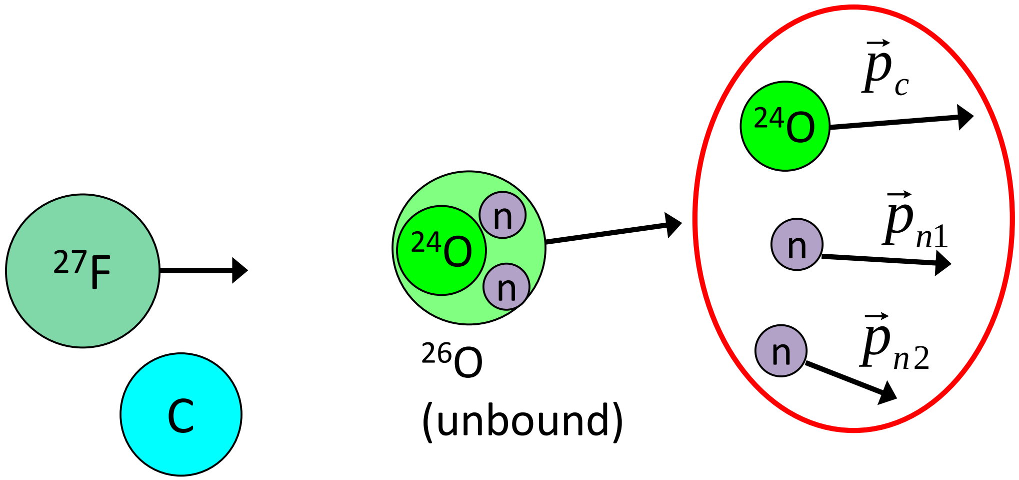
E= 749(10) keV

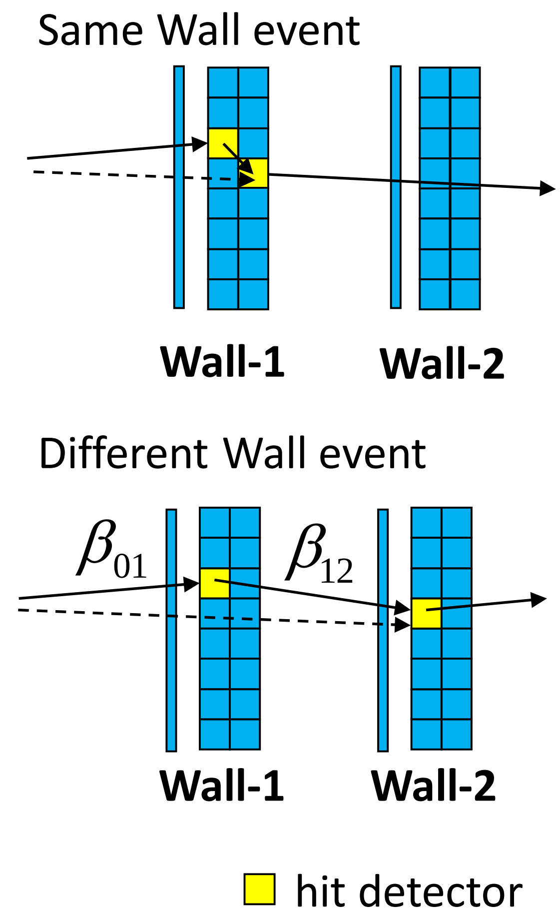
Γ= 88(6) keV

50 times higher statistics!

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

Neutron crosstalk

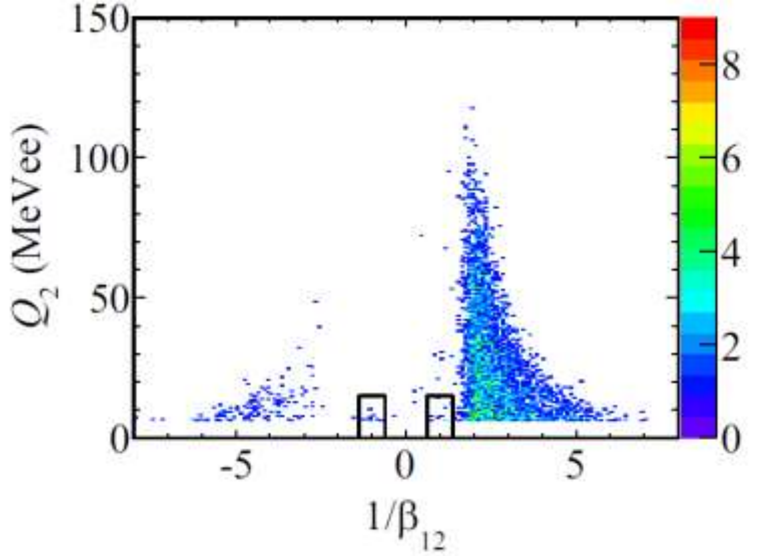


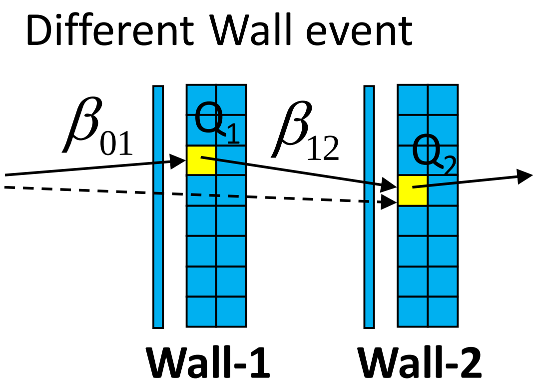


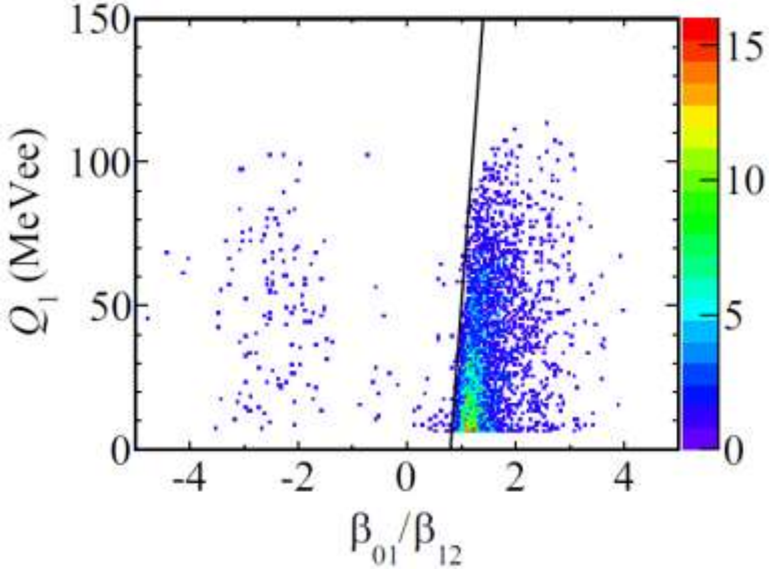
- Crosstalk … multiple hits caused by 1n
  - should be eliminated
  - Same wall event → position & timing information
    - 2 hits are regarded as 1n if positions & timing are close
    - lose efficiency for small E_{rel}
  - Different wall event → velocity information
    - event is regarded as crosstalk if $\beta_{01} > \beta_{12}$
      - because crosstalk neutron must be slow
    - can measure up to E_{rel}~0

Crosstalk analysis (example)

$^7Li(p,n)^7Be$(g.s.+0.43MeV) @ 200MeV



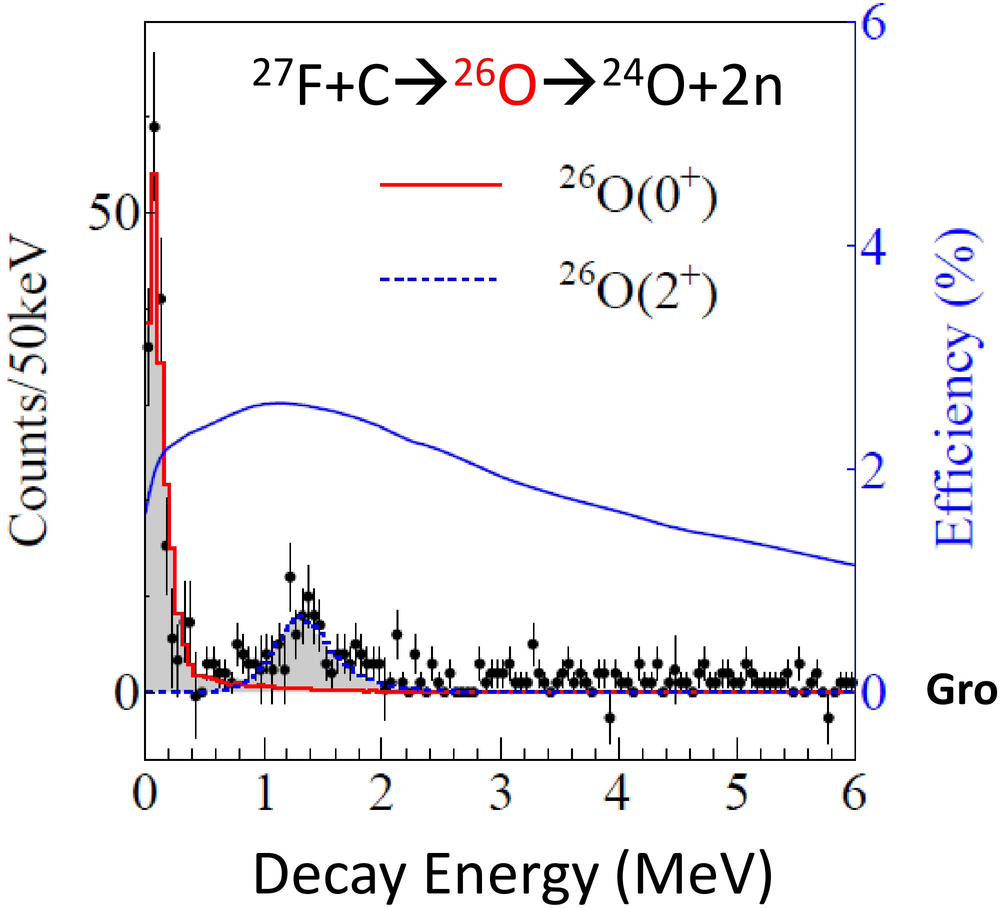


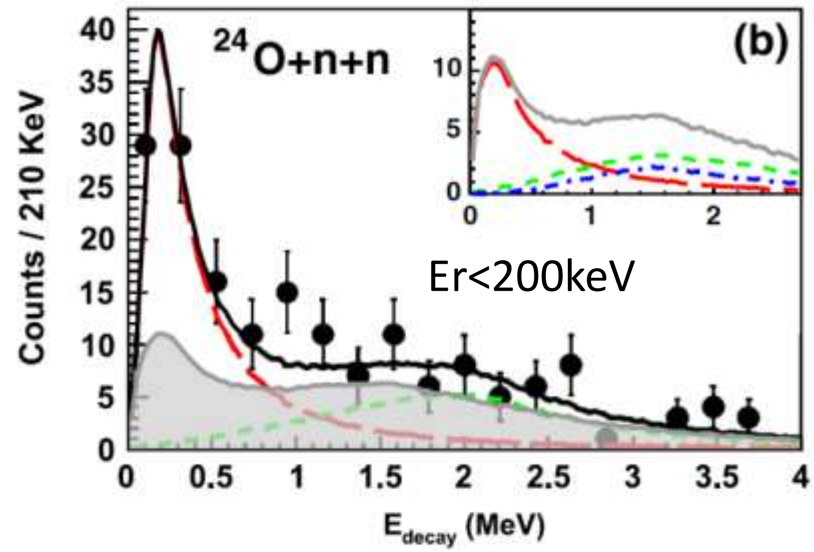


- T. Nakamura, Y. Kondo, NIMB in press, arXiv:1512.08380

Result of ^{26}O

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





Ground state

5 times higher statistics than previous study

18±3(stat)±4(syst)keV

(from fit of E_{fn} spectrum)

Finite value is determined for the first time

2^+ excited state

Observed for the first time

$1.28^{+0.11}_{-0.08}$ MeV

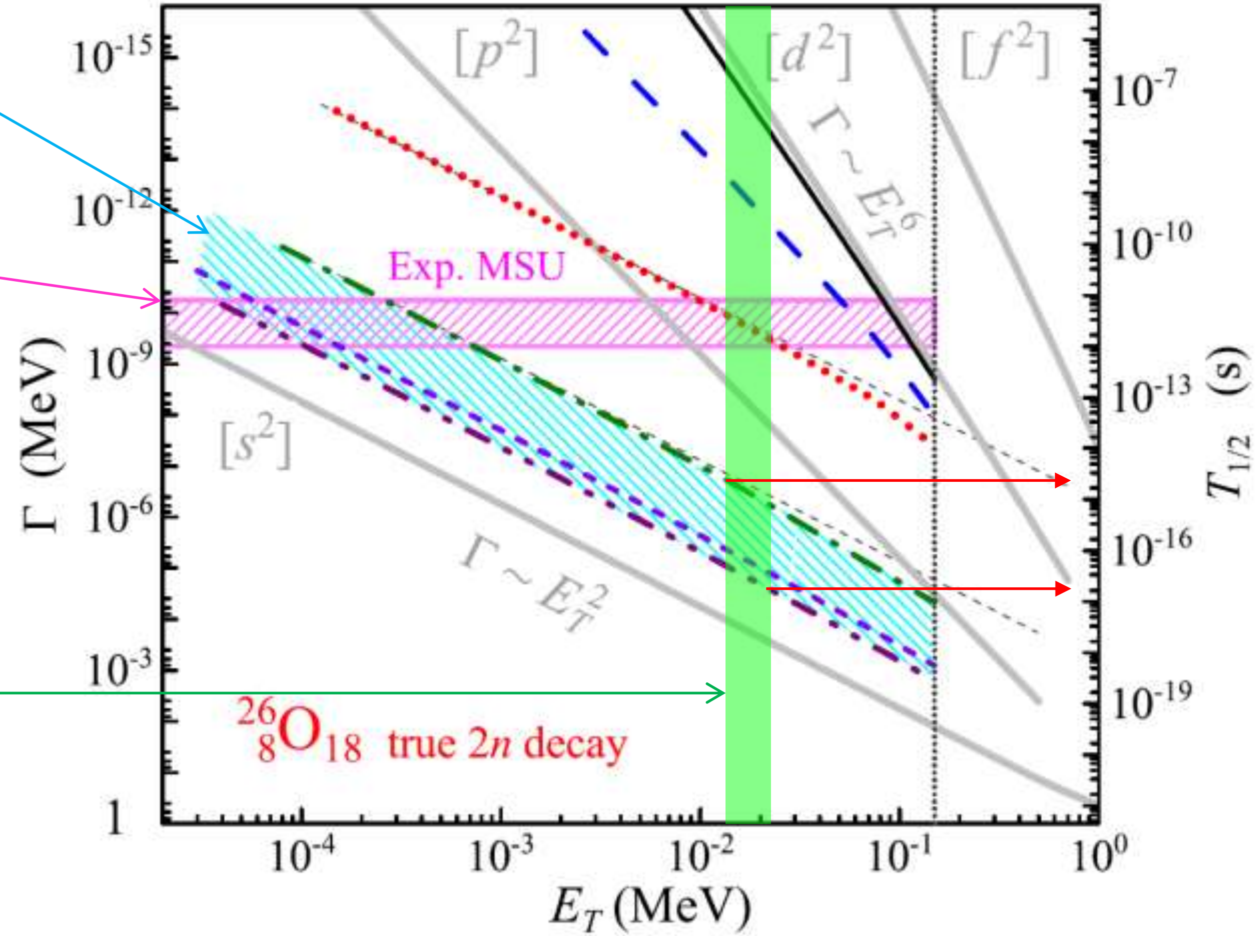
Decay energy resolution
FWHM=110keV @ 20keV
FWHM=540keV @ 1.3MeV

^{26}O 2n radioactivity?

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

Z. Kohley et al,
PRL110,152501 (2013)

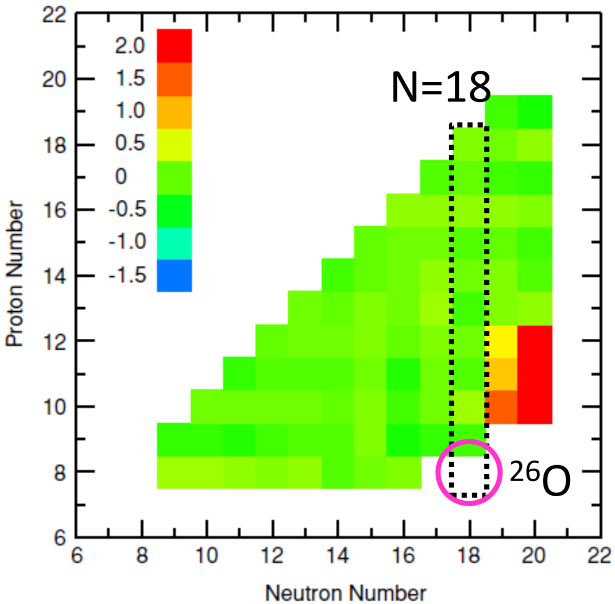
This work



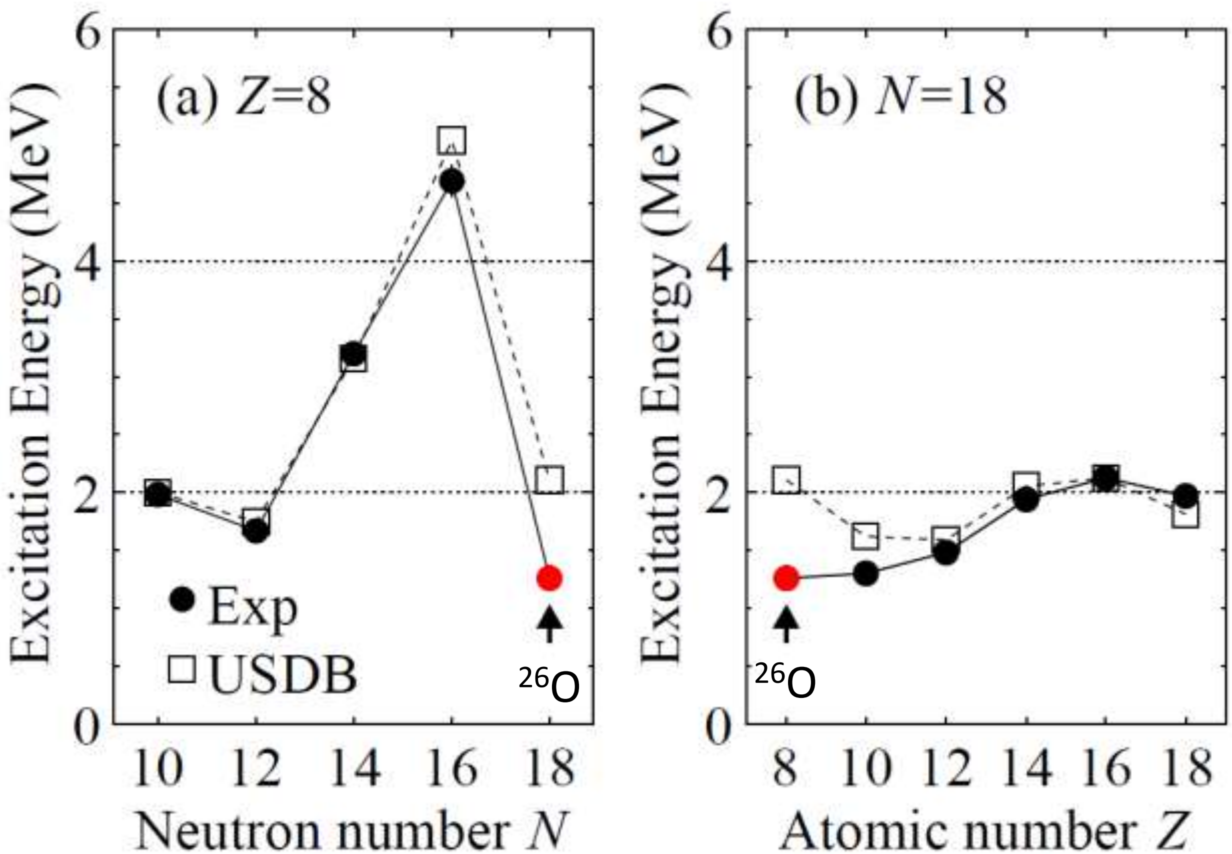
- Not consistent with lifetime meas. and 3body model
  - E_T=18keV (present work)
    - → $T_{1/2}=10^{-15}\sim10^{-17}$sec? (based on 3 body model)

Systematics of 2^+ energy

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

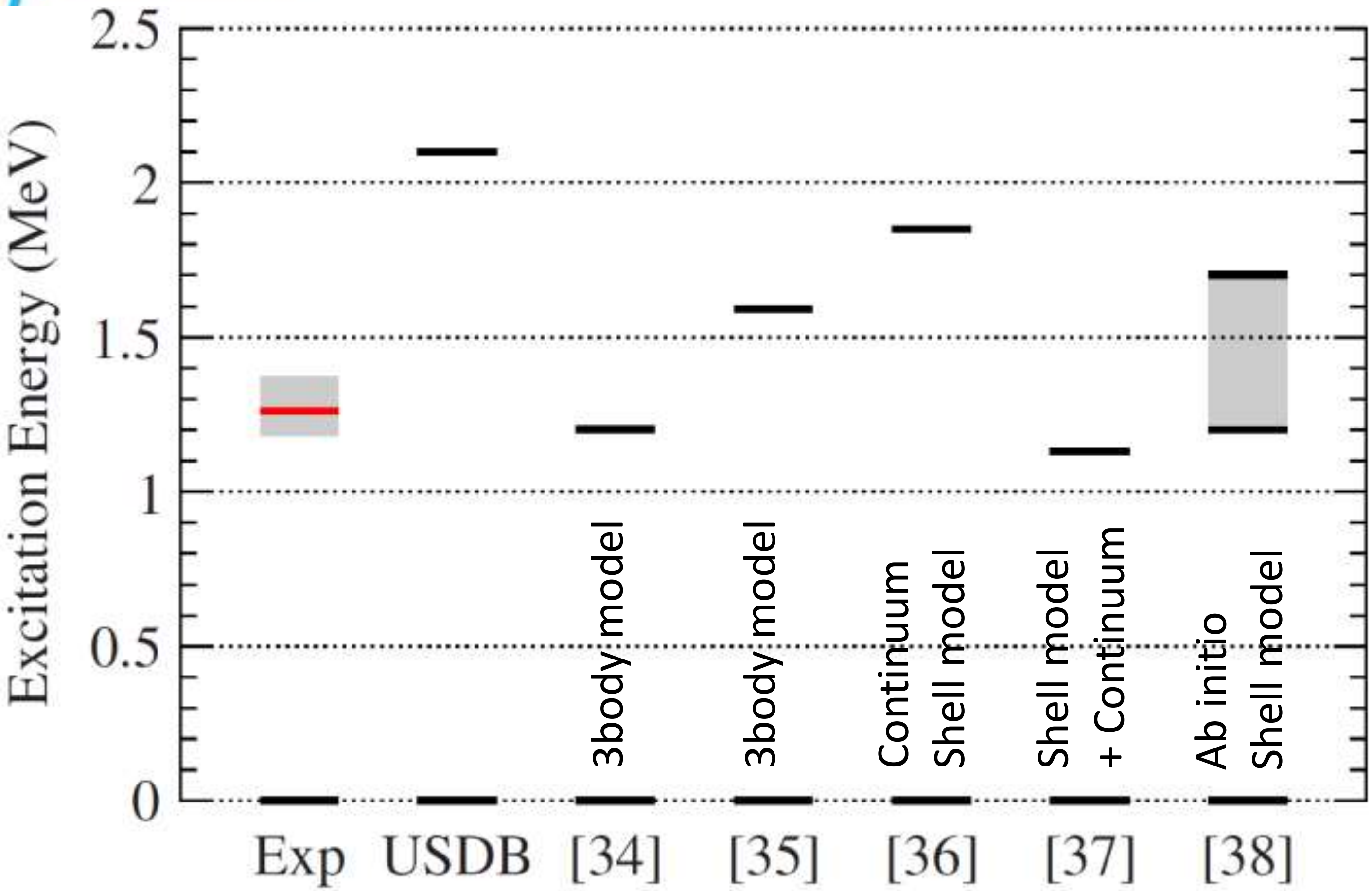


Difference of ground state energies between Exp and USDB calculation



- N=16 shell closure is confirmed
- USDB cannot describe 2^+ energy at ^{26}O
  →effect of pf shell? and/or continiuum?

Other Recent Theories



[34] K. Hagino et al., PRC90, 027303, (2014)

[35] L.V. Grigorenko et al., PRC91, 064617, (2015)

[36] A. Volya et al., PRC74, 064314, (2006)

[37] K. Tsukiyama et al., PTEP2015, 093D01 (2015)

[38] S.K. Bogner et al., PRL113, 142501, (2014)

3NF, pf shell, 2n correlation, continuum are important key words

Short Summary

- Invariant mass spectroscopy of ^{25}O and ^{26}O
  - ^{25}O
    - Improved statistics → possibility of 2n decay channel
  - ^{26}O
    - First determination of the finite g.s. energy (not upper limit)
      - Much shorter lifetime than measured? (model dependent)
    - First observation of 2+ state
      - pf-shell, continuum, 2n correlation, 3NF are key effects

PRL 116, 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

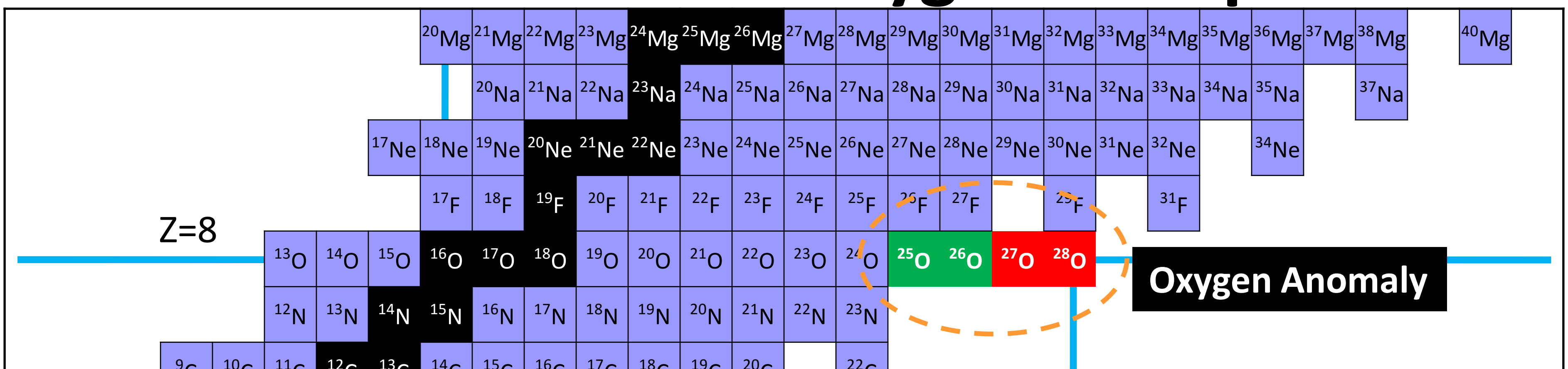
Y. Kondo,[1] T. Nakamura,[1] R. Tanaka,[1] R. Minakata,[1] S. Ogoshi,[1] N. A. Orr,[2] N. L. Achouri,[2] T. Aumann,[3,4] H. Baba,[5] F. Delaunay,[2] P. Doornenbal,[5] N. Fukuda,[5] J. Gibelin,[2] J. W. Hwang,[6] N. Inabe,[5] T. Isobe,[5] D. Kameda,[5] D. Kanno,[1] S. Kim,[6] N. Kobayashi,[1] T. Kobayashi,[7] T. Kubo,[5] S. Leblond,[2] J. Lee,[5] F. M. Marqués,[2] T. Motobayashi,[5] D. Murai,[8] T. Murakami,[9] K. Muto,[7] T. Nakashima,[1] N. Nakatsuka,[9] A. Navin,[10] S. Nishi,[1] H. Otsu,[5] H. Sato,[5] Y. Satou,[6] Y. Shimizu,[5] H. Suzuki,[5] K. Takahashi,[7] H. Takeda,[5] S. Takeuchi,[5] Y. Togano,[4,1] A. G. Tuff,[11] M. Vandebrouck,[12] and K. Yoneda[5]

[1]*Department of Physics, Tokyo Institute of Technology, 2-12-1 O-Okayama, Meguro, Tokyo 152-8551, Japan*
[2]*LPC Caen, ENSICAEN, Université de Caen, CNRS/IN2P3, F-14050 Caen, France*
[3]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[4]*ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[5]*RIKEN Nishina Center, Hirosawa 2-1, Wako, Saitama 351-0198, Japan*
[6]*Department of Physics and Astronomy, Seoul National University, 599 Gwanak, Seoul 151-742, Republic of Korea*
[7]*Department of Physics, Tohoku University, Miyagi 980-8578, Japan*
[8]*Departiment of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan*
[9]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[10]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France*
[11]*Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom*
[12]*Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, Université de Paris Sud, F-91406 Orsay, France*

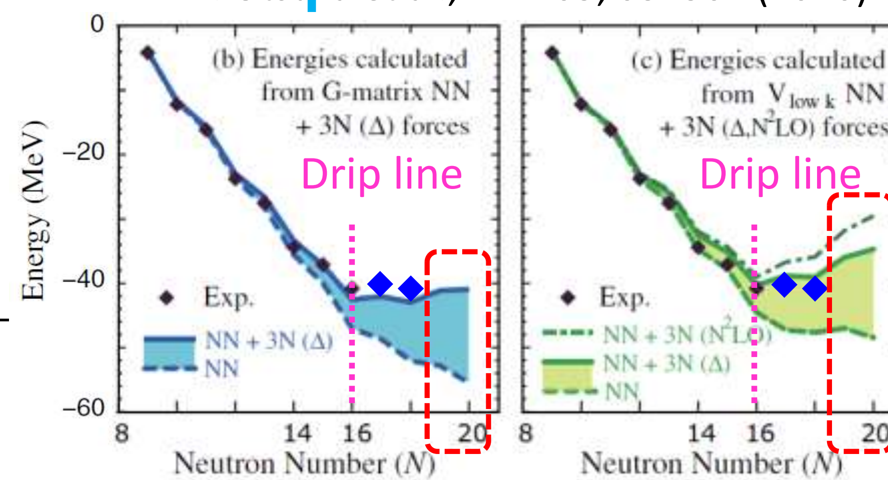
(Received 27 August 2015; published 9 March 2016)

The unbound nucleus ^{26}O has been investigated using invariant-mass spectroscopy following one-proton removal reaction from a ^{27}F beam at 201 MeV/nucleon. The decay products, ^{24}O and two neutrons, were detected in coincidence using the newly commissioned SAMURAI spectrometer at the RIKEN Radioactive Isotope Beam Factory. The ^{26}O ground-state resonance was found to lie only $18 \pm 3(\text{stat}) \pm 4(\text{syst})$ keV above threshold. In addition, a higher lying level, which is most likely the first 2^+ state, was observed for the first time at $1.28^{+0.11}_{-0.08}$ MeV above threshold. Comparison with theoretical predictions suggests that three-nucleon forces, *pf* shell intruder configurations, and the continuum are key elements to under-

Mass measurement of unbound oxygen isotopes



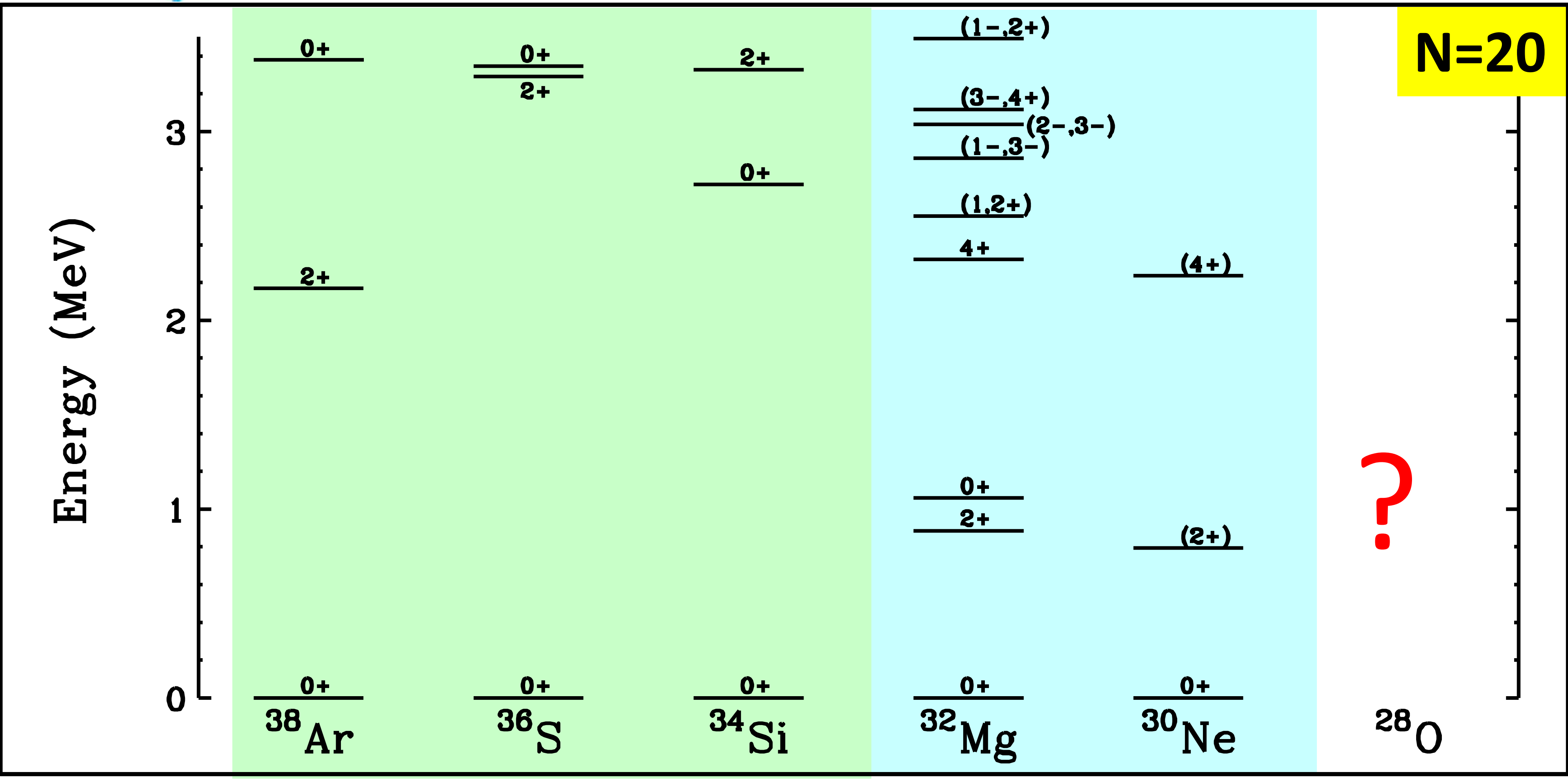
T. Otsuka et al., PRL105, 032501 (2010)



☑ First step : ^{25}O, ^{26}O → Completed

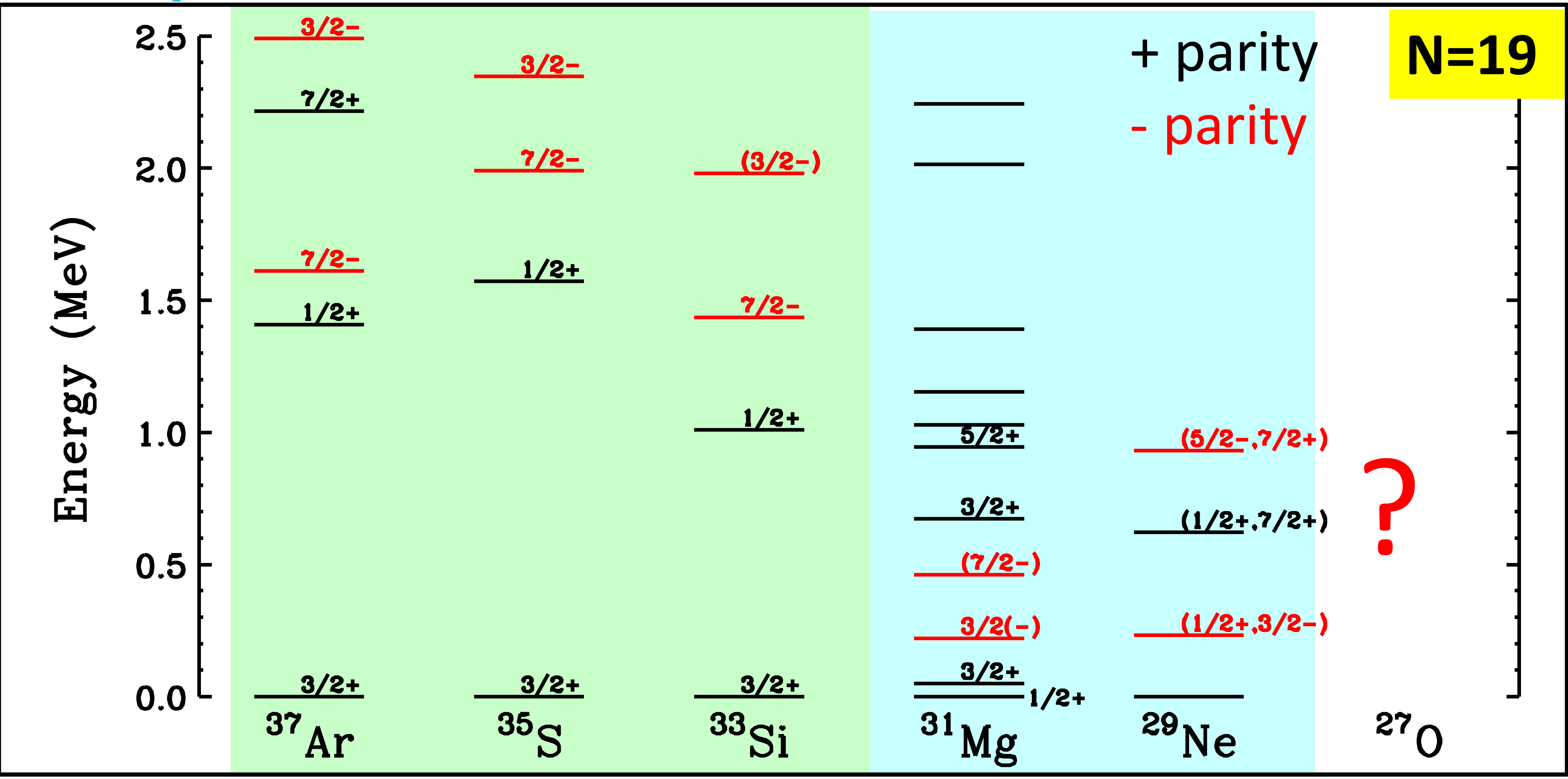
☐ Second step: ^{27}O, ^{28}O → Experiment in Nov-Dec, 2015

Excited states of N=20 nuclei



- Is ^{28}O doubly magic?

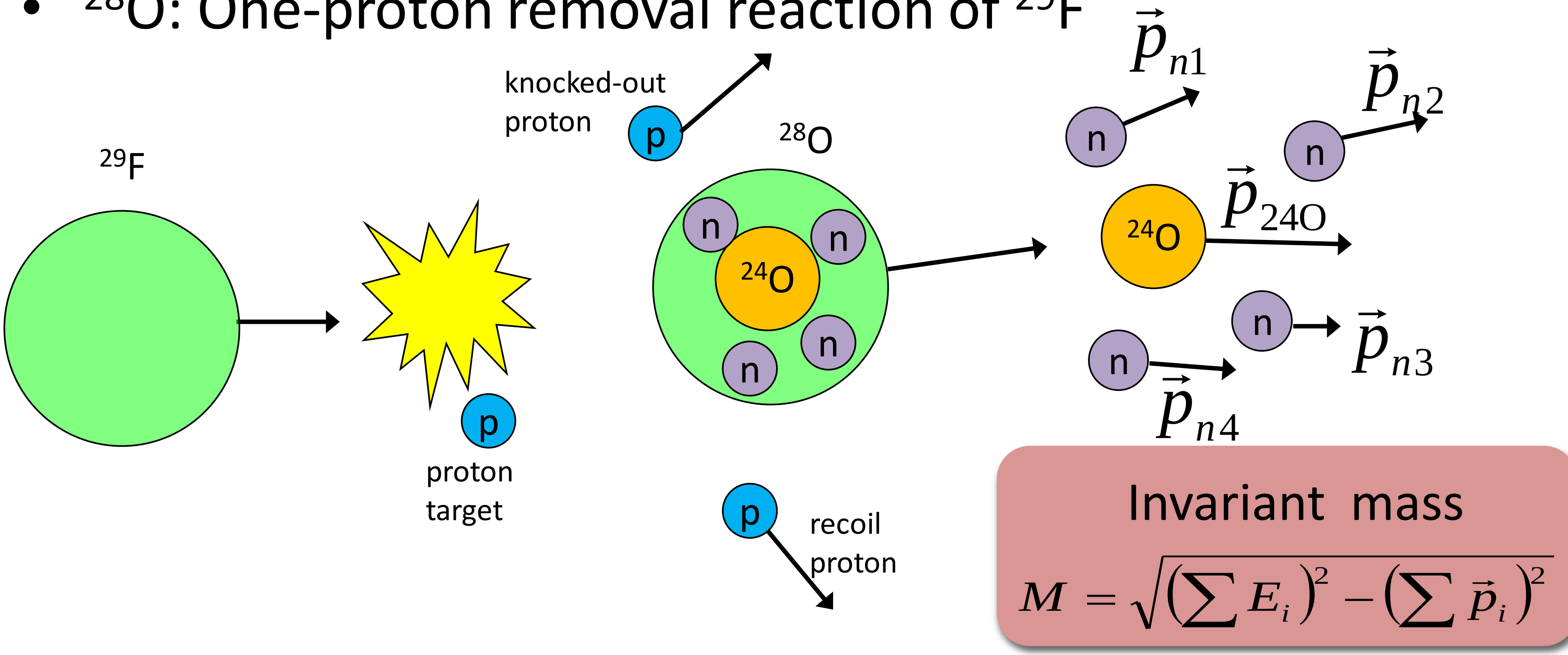
Excited states of N=19 nuclei



- Single-hole state → shell structure

How to study ^{27}O and ^{28}O?

- ^{28}O: One-proton removal reaction of ^{29}F

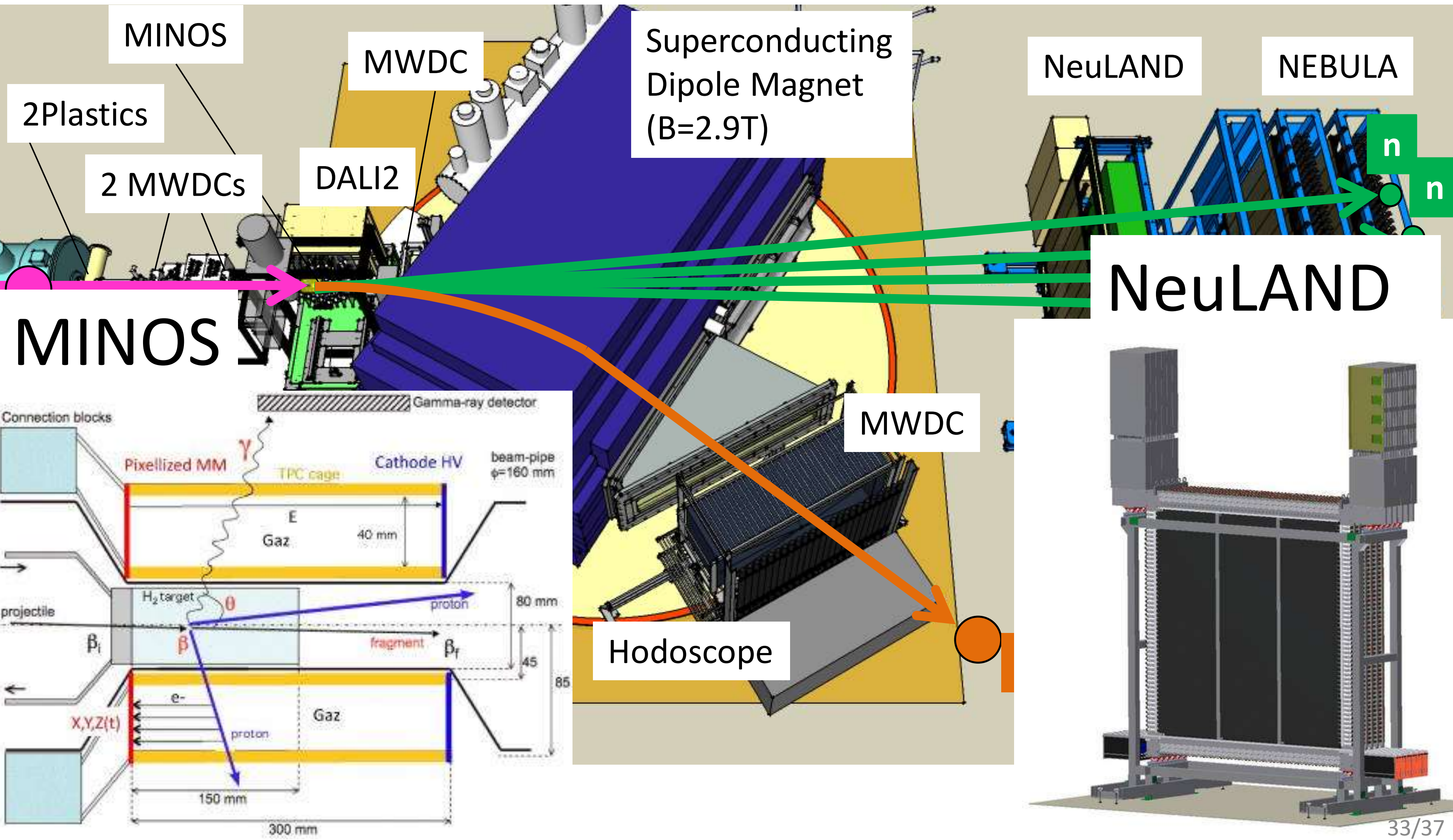


$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

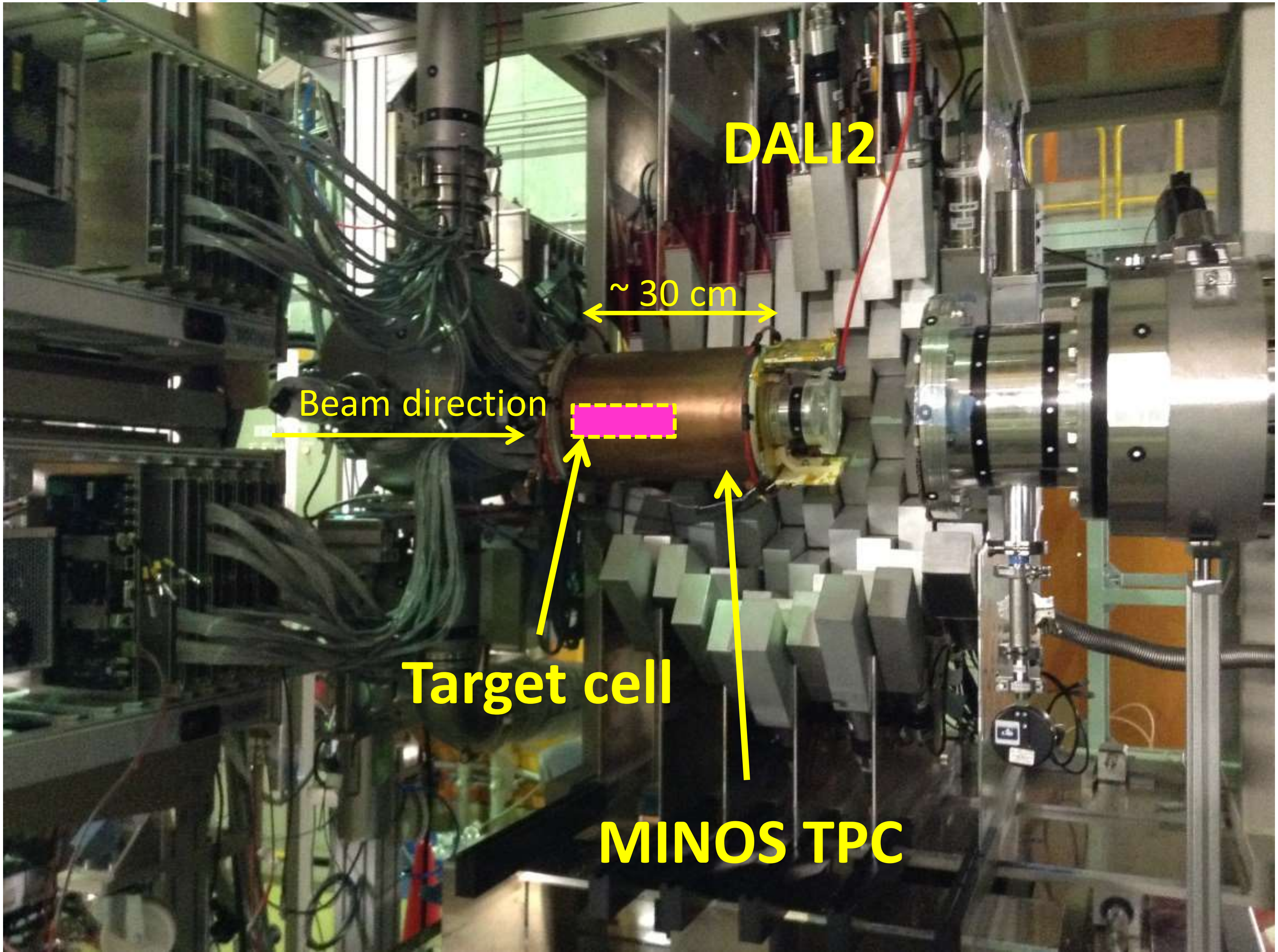
- ^{27}O: two-proton removal reaction of ^{29}Ne
  - ^{28}F is unbound
  - ^{28}F can also be studied with the same setup

3 or 4 neutrons have to be detected

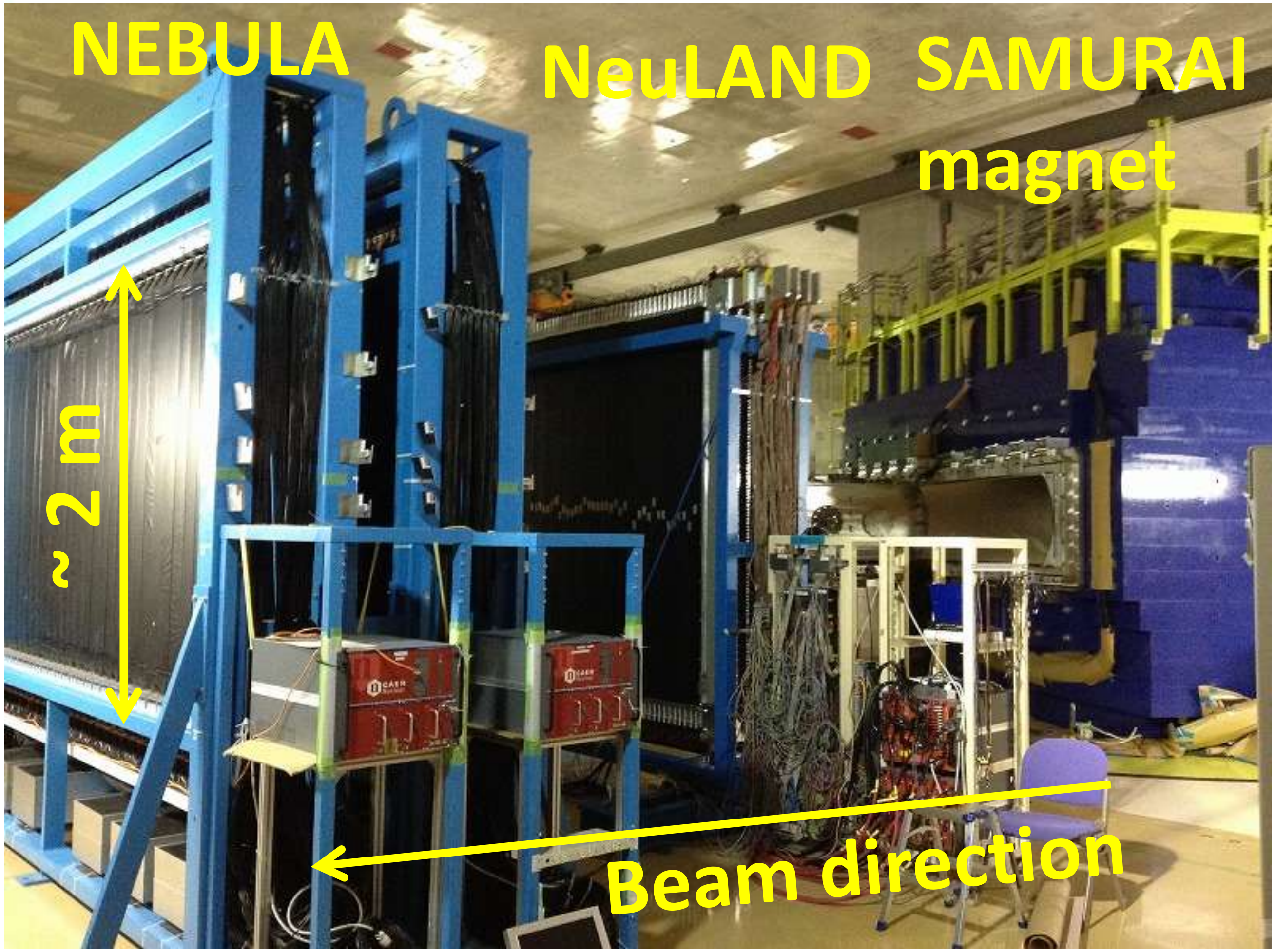
^{28}O measurement (November-December 2015)



MINOS & DALI2



NeuLAND is now at RIBF



- NeuLAND (400 detectors) arrived at RIKEN January, 2015

SAMURAI21 collaboration

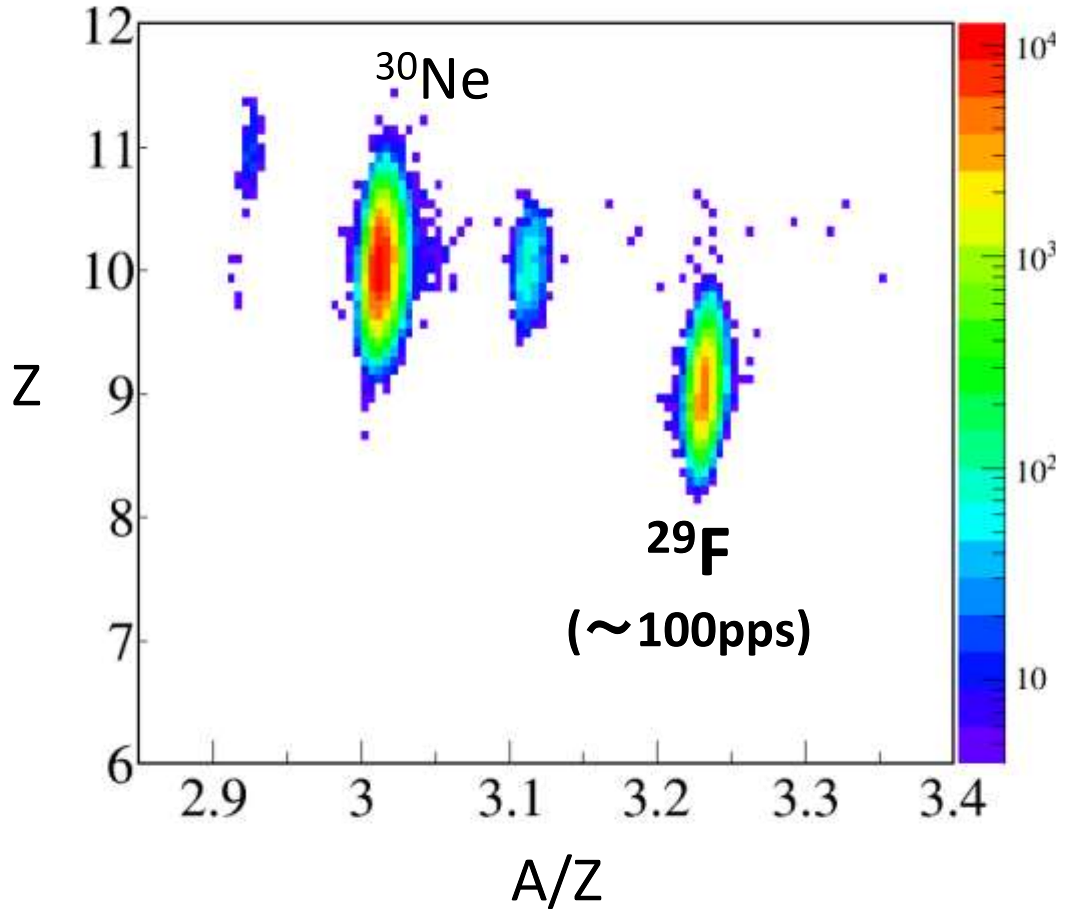
Y.Kondo, T.Nakamura, N.L.Achouri, H.Al Falou, L.Atar, T.Aumann, H.Baba, K.Boretzky, C.Caesar, D.Calvet, H.Chae, N.Chiga, A.Corsi, H.L.Crawford, F.Delaunay, A.Delbart, Q.Deshayes, Zs.Dombrádi, C.Douma, Z.Elekes, P.Fallon, I.Gašparić, J.-M.Gheller, J.Gibelin, A.Gillibert, M.N.Harakeh, A.Hirayama, C.R.Hoffman, 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

Incident beam



^{48}Ca primary beam

- Intensity > 500pnA!!!
  (~140pnA in the first exp)
- Very stable during long beam time (~10days)

High intense & stable ^{29}F beam!
Data analysis is now going on…

Summary

- Invariant mass spectroscopy of ^{25}O, ^{26}O
  - 2n radioactivity of ^{26}O is not likely? (model dependent)
  - First observation of 2^+ state of ^{26}O
    - →3NF, pf shell, continuum are key words
  - Results have been published in PRL116, 102503 (2016)

- Invariant mass spectroscopy of ^{27}O, ^{28}O
  - Successfully done in Nov-Dev, 2015
  - High intense & stable beam
  - Large collaboration (88 participants, 25 Institutes)
  - Analysis is now going on…
  - ^{28}F will also be studied (^{29}F -1n, ^{29}Ne -1p, …)