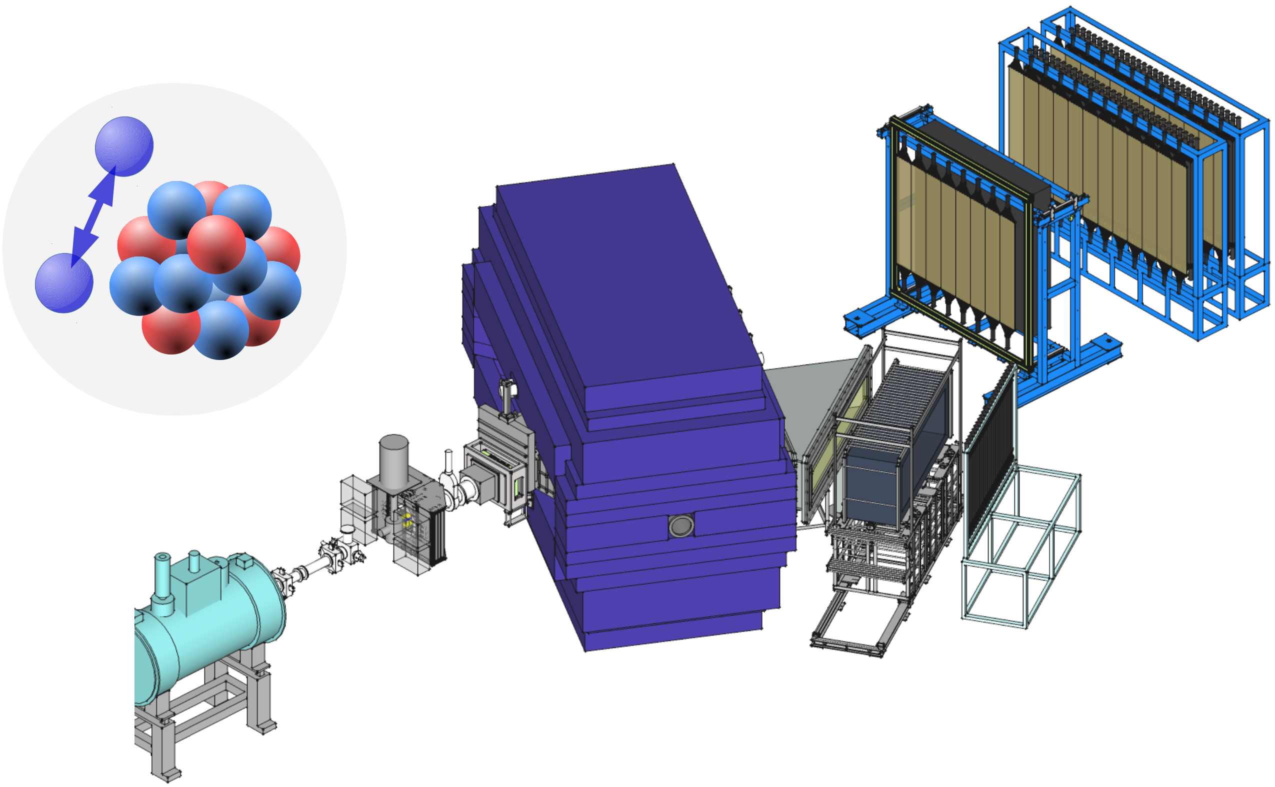
Neutron decays beyond the drip line studied at SAMURAI

Workshop CRC 1245
Mainz, 4 July 2018

Julian Kahlbow, T. Aumann, D. Rossi for project A06



Outline

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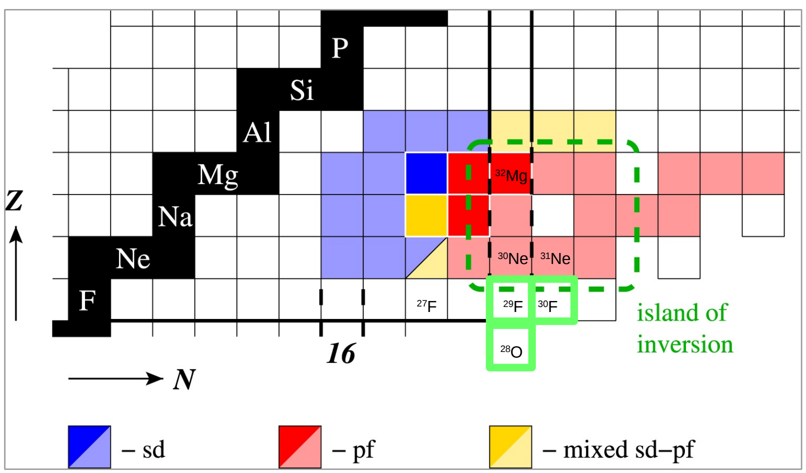
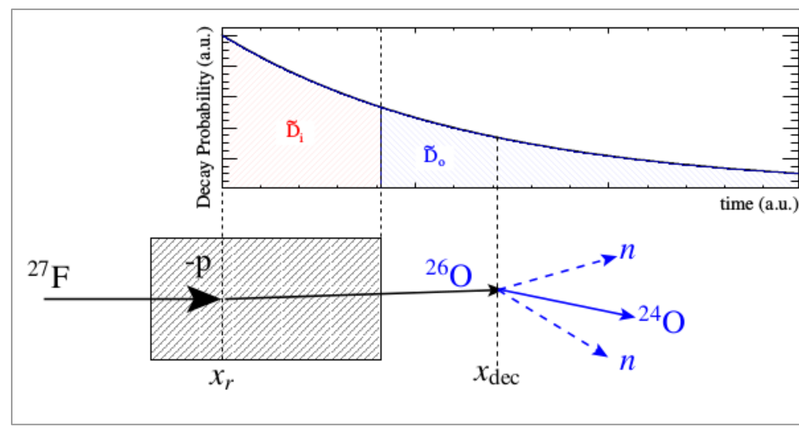
Spectroscopy at the low-*Z* shore of the island of inversion

Invariant-mass spectroscopy of the heaviest, neutron-unbound oxygen & fluorine isotopes



Neutron-decay lifetime of ^{26}O(g.s.)

New technique to measure the lifetime in picosecond range of a nucleus that decays in-flight via neutron emission



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Spectroscopy at the low-*Z* shore of the island of inversion

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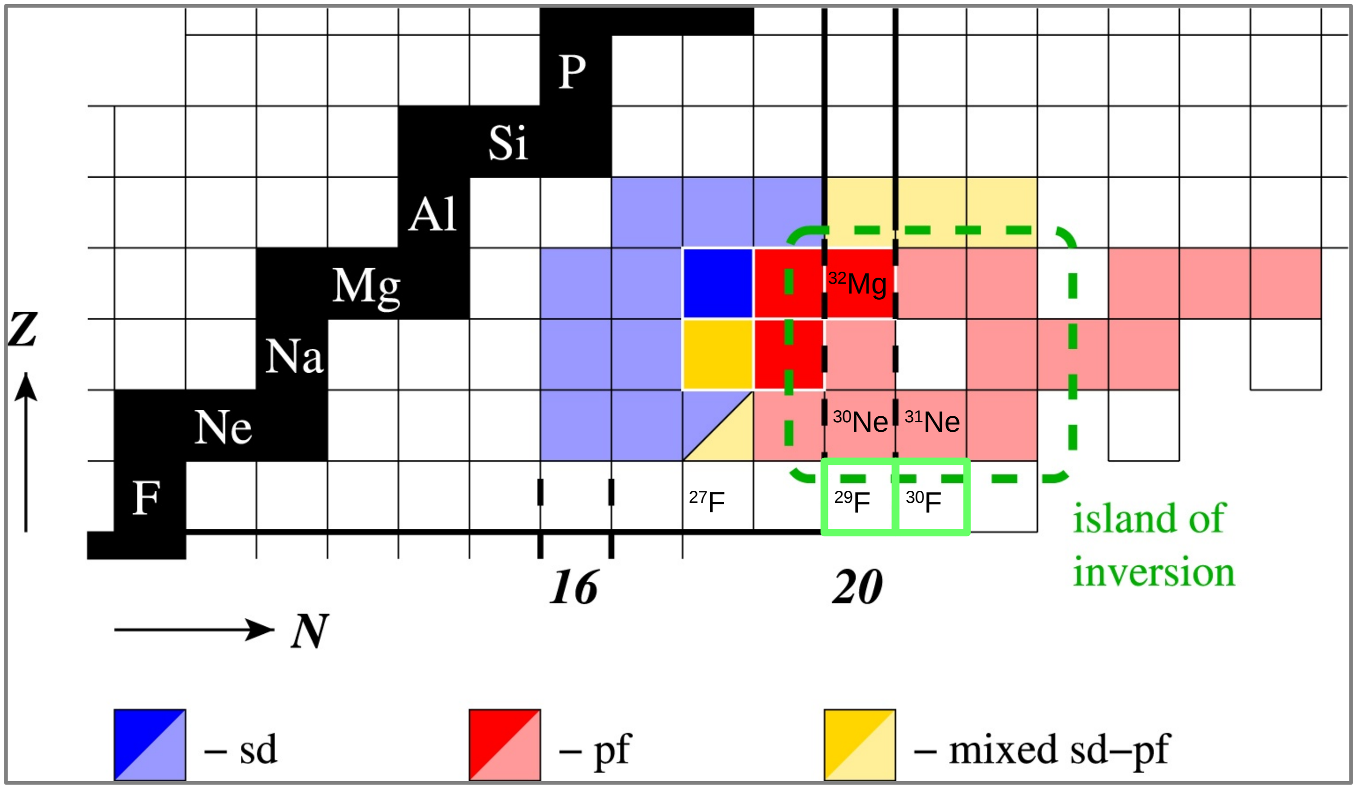

P.A. Butler et al., J. Phys. G: Nucl. Part. Phys. 44 (2017)

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Invariant-Mass Spectroscopy of ^{28}O & ^{27}O

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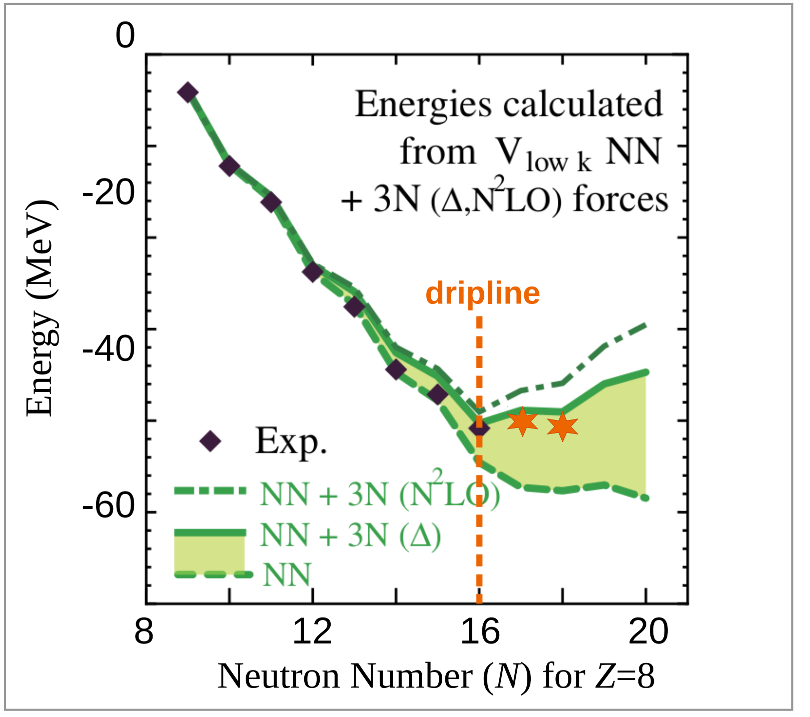
- Spokesperson: Yosuke Kondo (TITech)
- Solving the "Oxygen Anomaly":

  fluorine can bind min. 6 more neutrons than oxygen
- ^{29}F(p,2p)^{28}O → ^{24}O + **$4n$**
- ^{29}Ne(p,3p)^{27}O → ^{24}O + **$3n$**
- Is ^{28}O a doubly magic nucleus?

First invariant-mass analysis with 4 coincident neutrons to determine the decay energy

T. Otsuka, A. Schwenk et al., Phys. Rev. Lett. 105, 032501 (2010)



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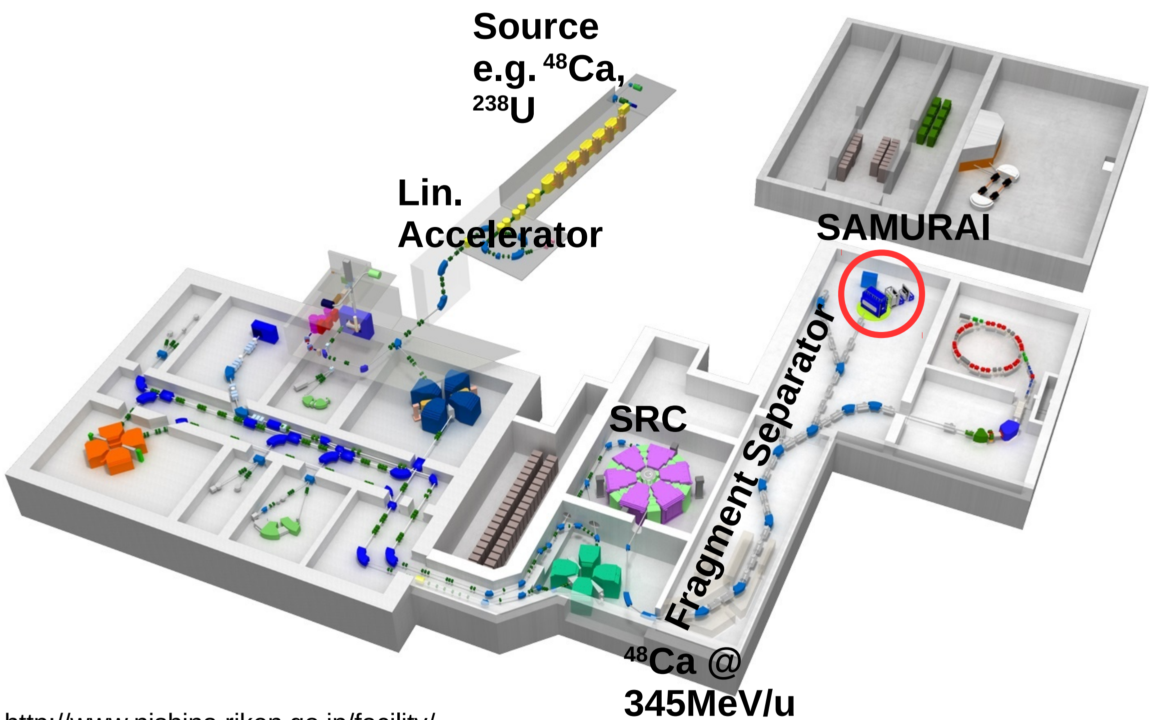
Invariant-Mass Spectroscopy at SAMURAI (RIBF)

RI-Beam Factory



http://www.nishina.riken.go.jp/facility/

Invariant-Mass Spectroscopy at SAMURAI (RIBF)
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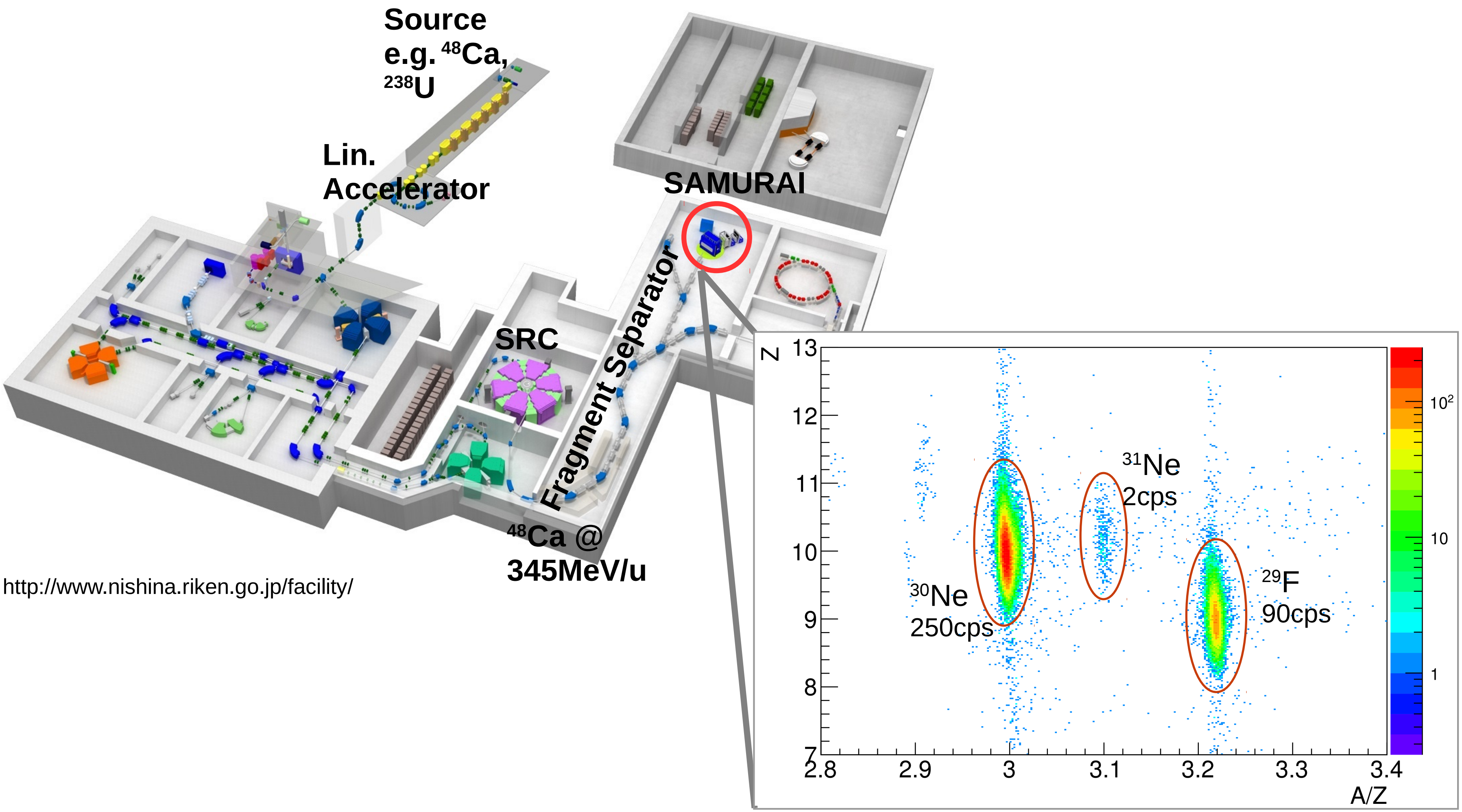

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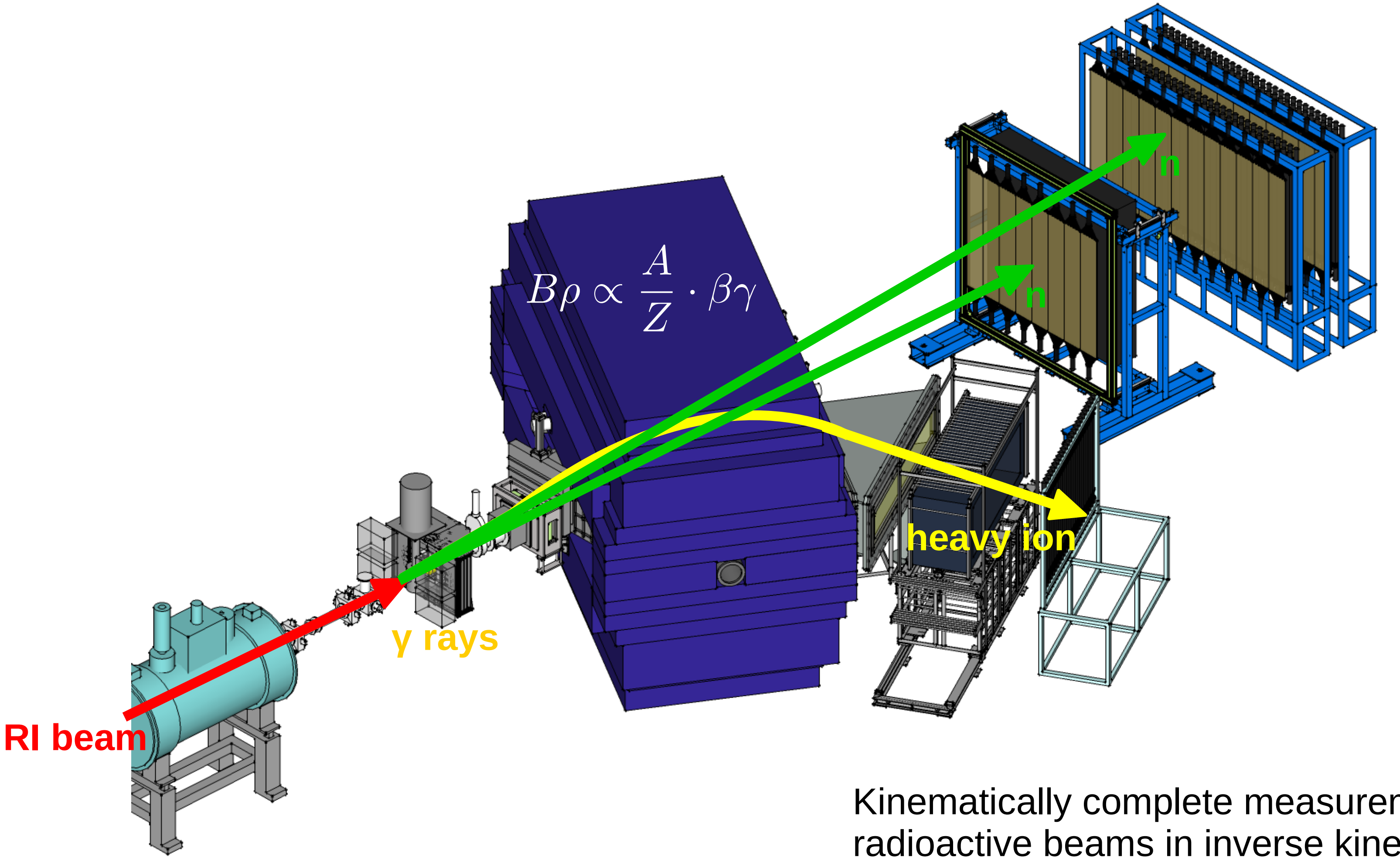
SAMURAI Experimental Setup

Superconducting **A**nalyzer for **Mu**lti-particles from **Ra**dio **I**sotope Beams

(SAMURAI + MINOS + DALI2 + NeuLAND + NEBULA)



Kinematically complete measurements with radioactive beams in inverse kinematics

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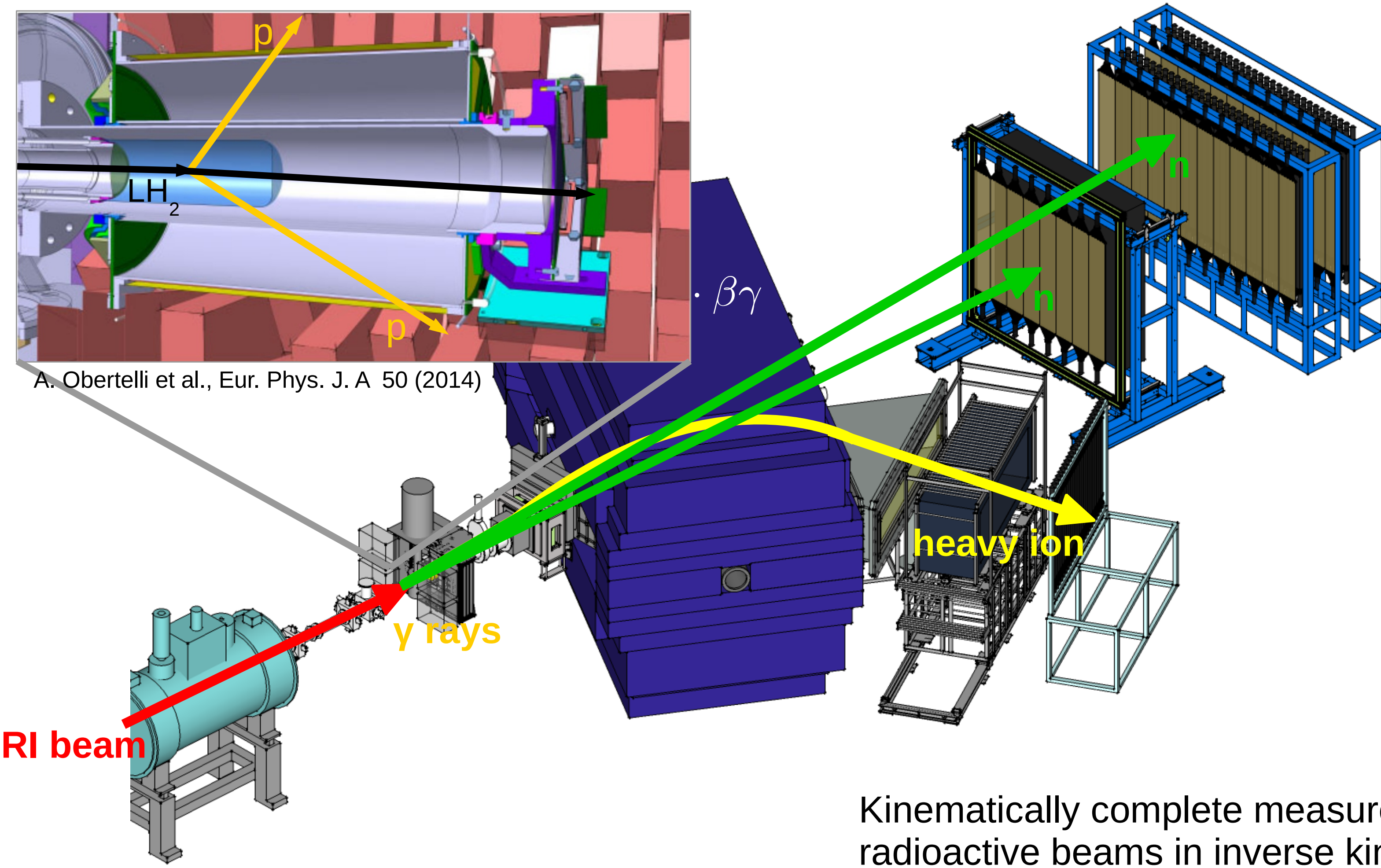


Kinematically complete measurements with radioactive beams in inverse kinematics

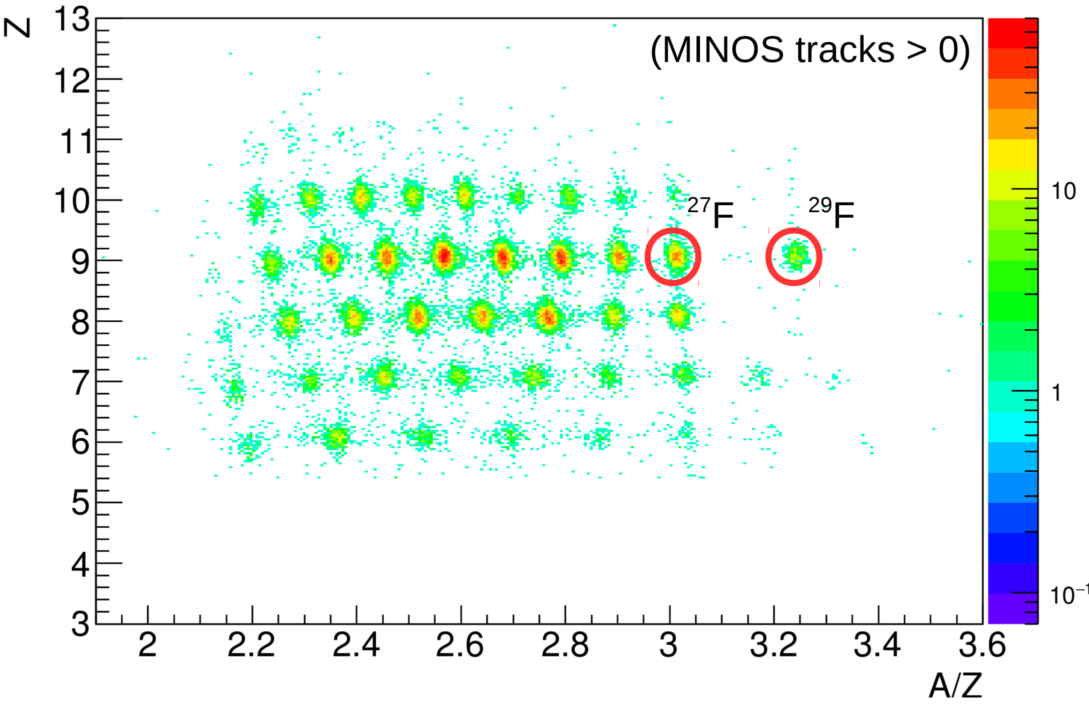
Invariant-Mass Spectroscopy at SAMURAI (RIBF)

Reaction-channel Identification

- Quasi-free scattering reaction to populate:

$$^{30}\mathrm{Ne}(p,2p)^{29}\mathrm{F}^* \longrightarrow {}^{27}\mathrm{F} + 2n$$

$$^{31}\mathrm{Ne}(p,2p)^{30}\mathrm{F} \longrightarrow {}^{29}\mathrm{F} + n$$



- Excellent resolution of the setup
  Momentum: p/Δp = 800

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Reaction-channel Identification

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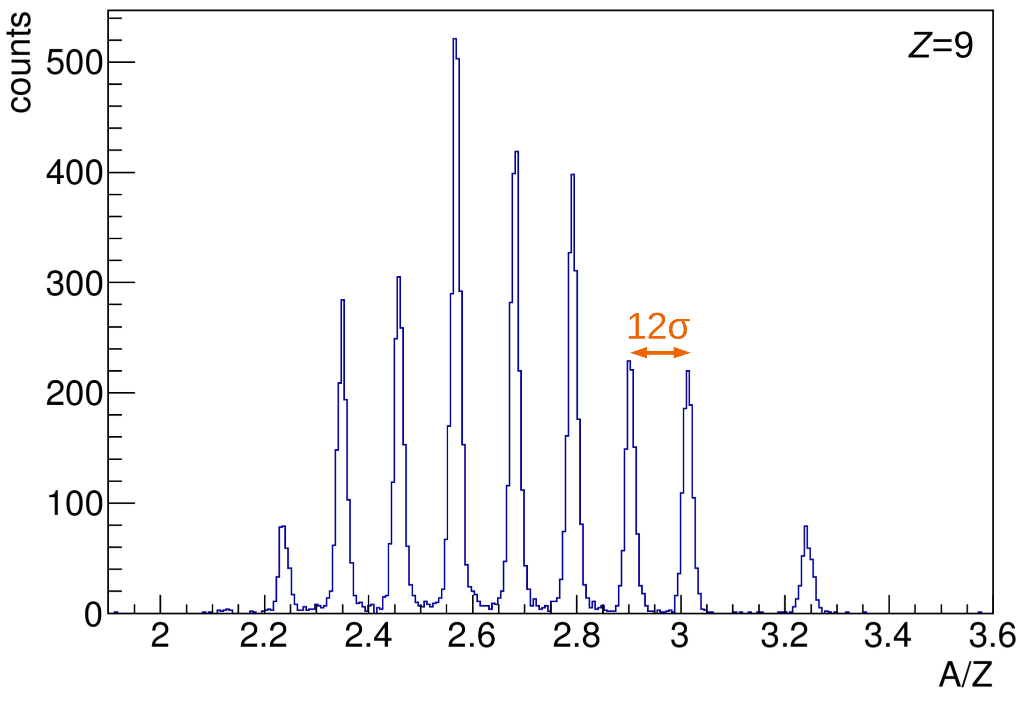

- Excellent resolution of the setup
  Momentum: p/Δp = 800

^{29}F at the low-*Z* shore of the island of inversion

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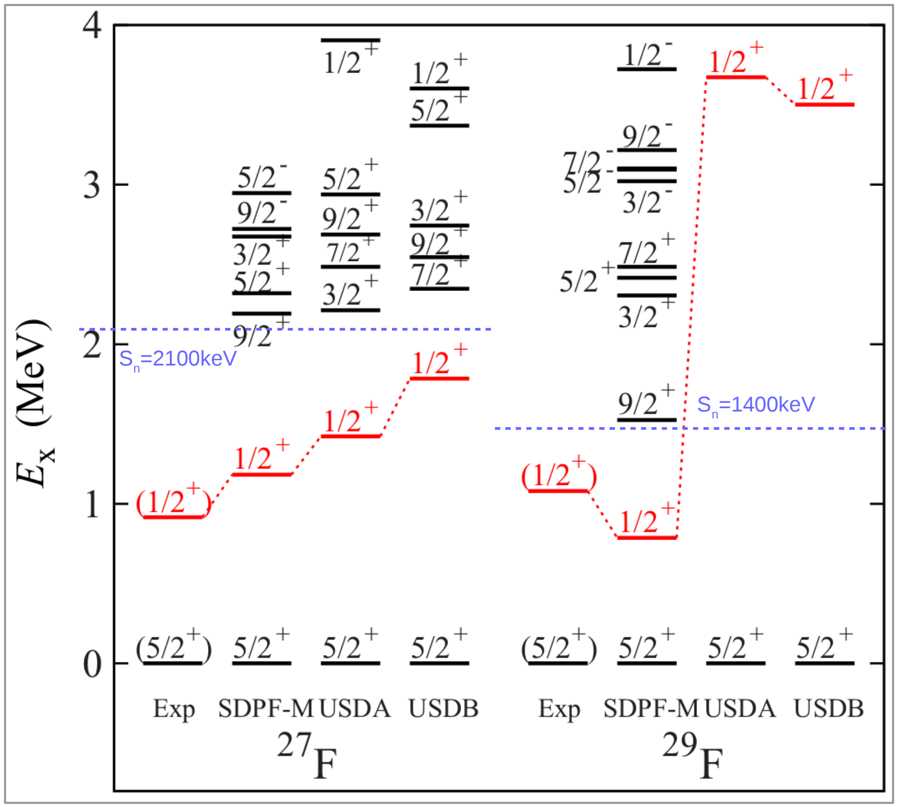
P. Doornenbal, H. Scheit et al., Phys. Rev. C 95 (2017)



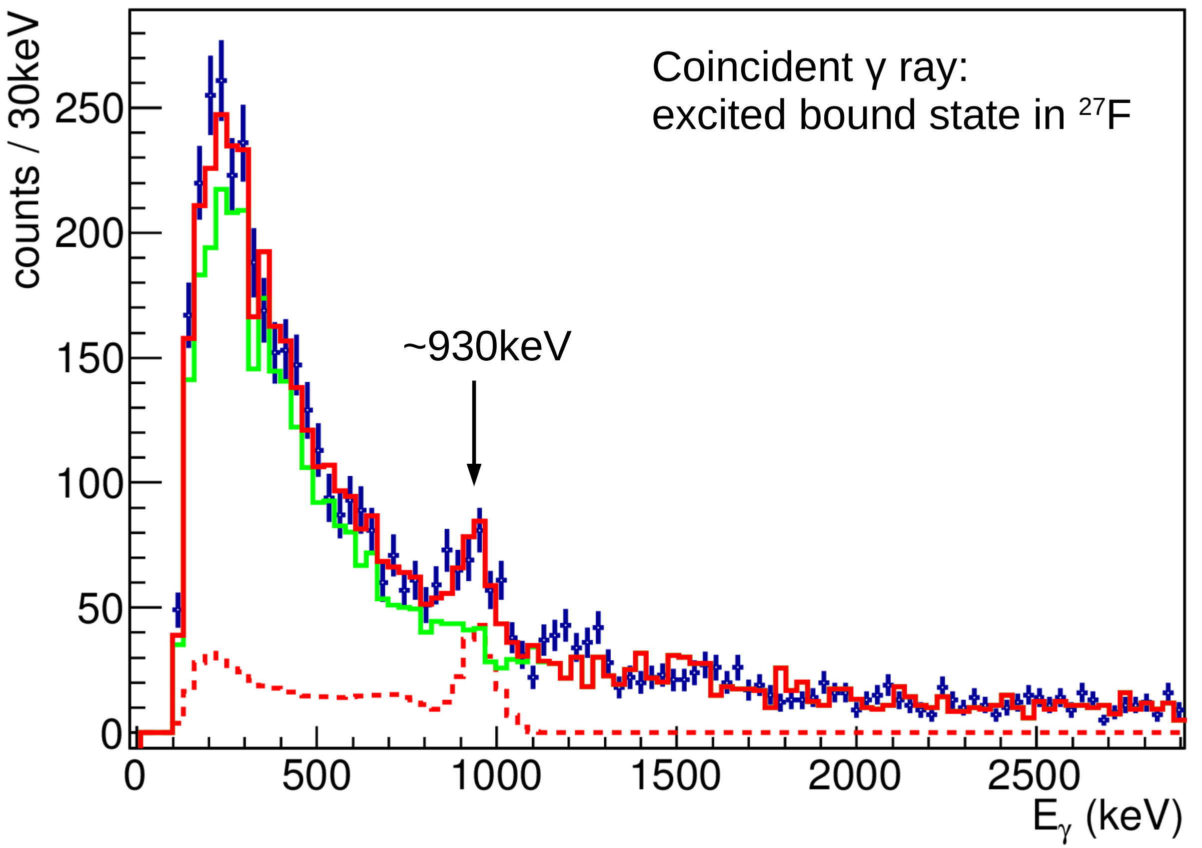
- In-beam gamma spectroscopy: *N*=20 shell gap quenched at ^{29}F
- 2p2h & 4p4h *pf*-shell configurations are crucial (in g.s.)
- Interplay:
  Oxygen ↔ Fluorine ↔ Island of Inversion

Invariant-Mass Spectroscopy of ^{29}F*

$$E_{rel} = |\sum_i P_i| - \sum_i m_i$$

$$^{30}\mathrm{Ne}(p,2p)^{29}\mathrm{F}^* \longrightarrow \boxed{^{27}\mathrm{F} + 2n}$$

Invariant-Mass Spectroscopy of $^{29}F^*$

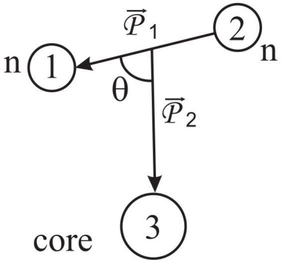


Outlook

2-neutron correlations studied in Jacobi coordinates

$$^{30}\mathrm{Ne}(p,2p)^{29}\mathrm{F}^{*} \longrightarrow {}^{27}\mathrm{F} + 2n$$

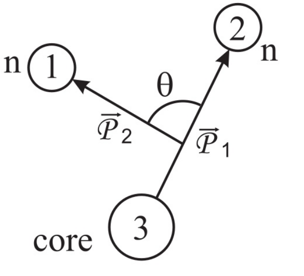
T System



$E_{rel}(^{29}F) < 0.8$MeV

1.1MeV < $E_{rel}(^{29}F) < 1.5$MeV

Y System



Invariant-Mass Spectroscopy of ^{30}F

$$^{31}\mathrm{Ne}(p,2p)^{30}\mathrm{F} \longrightarrow \boxed{^{29}\mathrm{F} + n}$$

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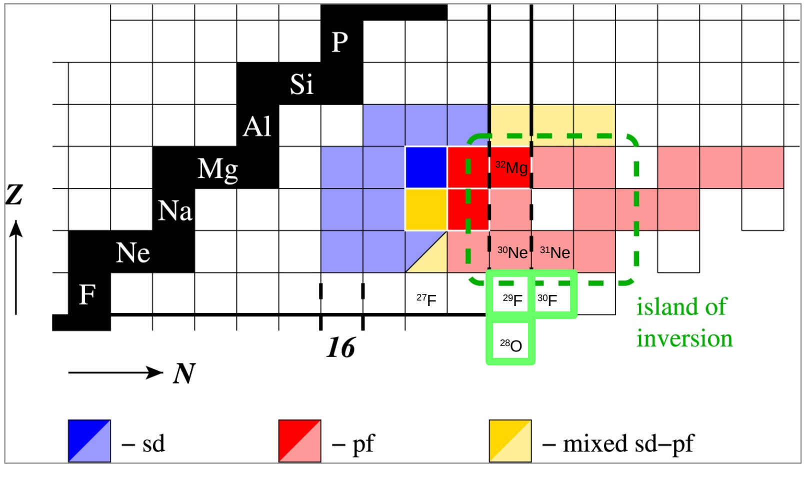

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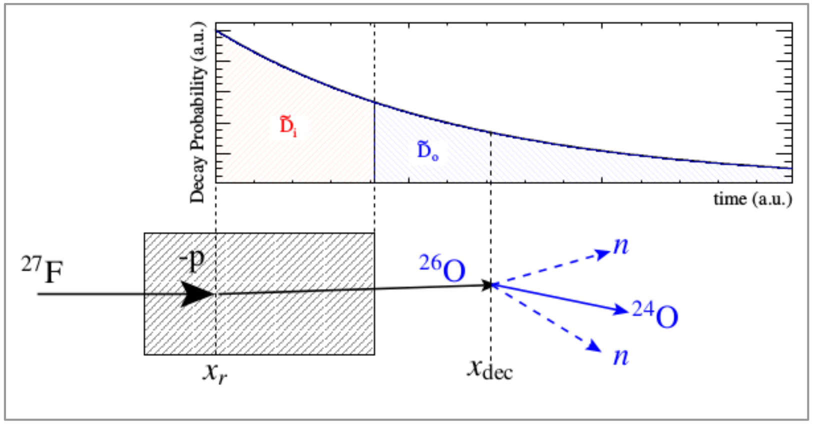

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^{26}O – A barely unbound system

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

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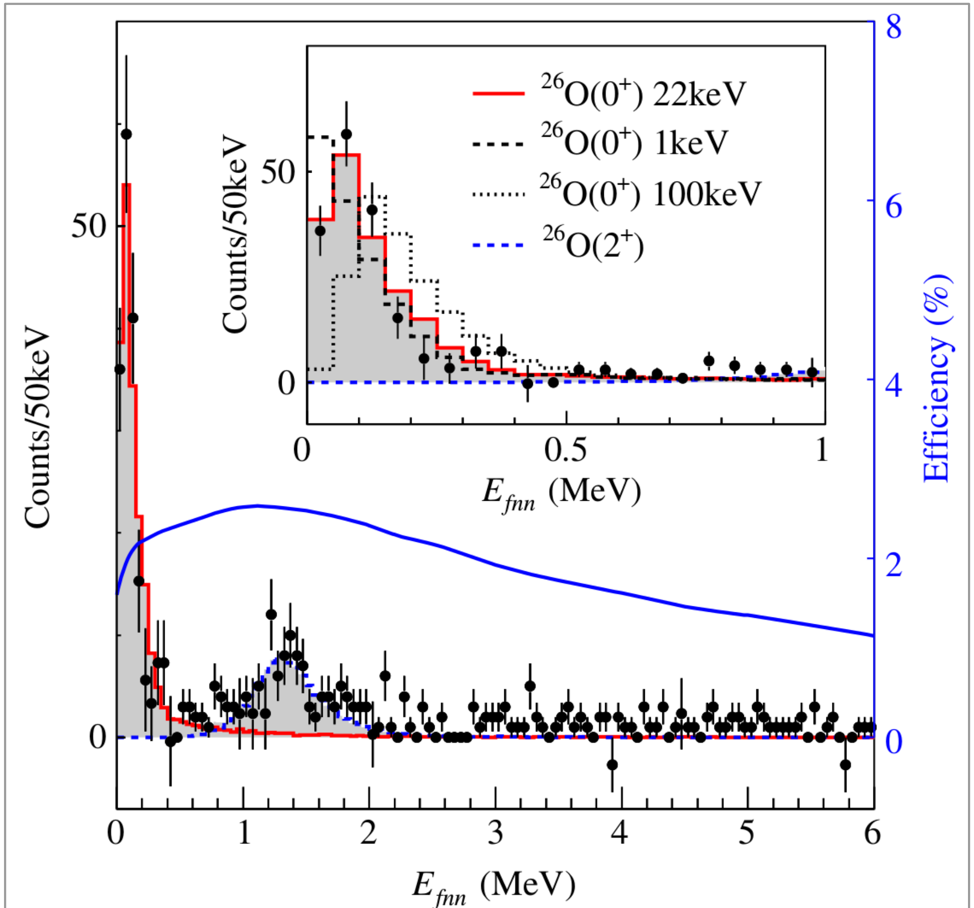


Experiment at SAMURAI

$$^{27}\mathrm{F} \xrightarrow{-p} {}^{26}\mathrm{O}^* \longrightarrow {}^{24}\mathrm{O} + 2n$$

Invariant-mass analysis
to reconstruct the decay energy

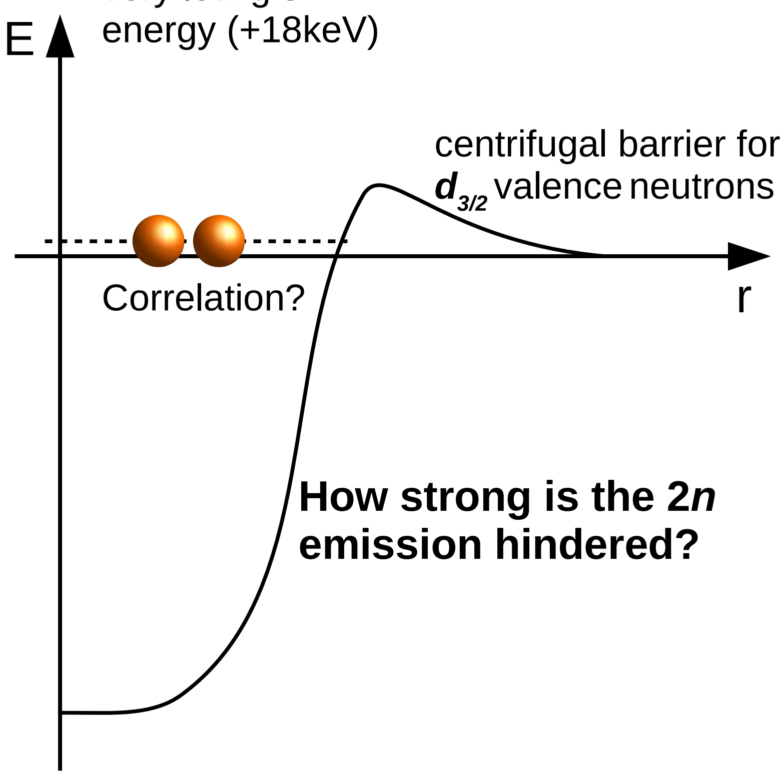
$$E_{\mathrm{dec}} = 18 \pm 3(\mathrm{stat}) \pm 4(\mathrm{syst})\,\mathrm{keV}$$

$$E_{\mathrm{dec}}(2^+) = 1.28^{+0.11}_{-0.08}\,\mathrm{MeV}$$

→ **true 2*n* decay:**
^{25}O(g.s.) higher in energy

$$E_{\mathrm{dec}} = 749 \pm 10\,\mathrm{keV}$$

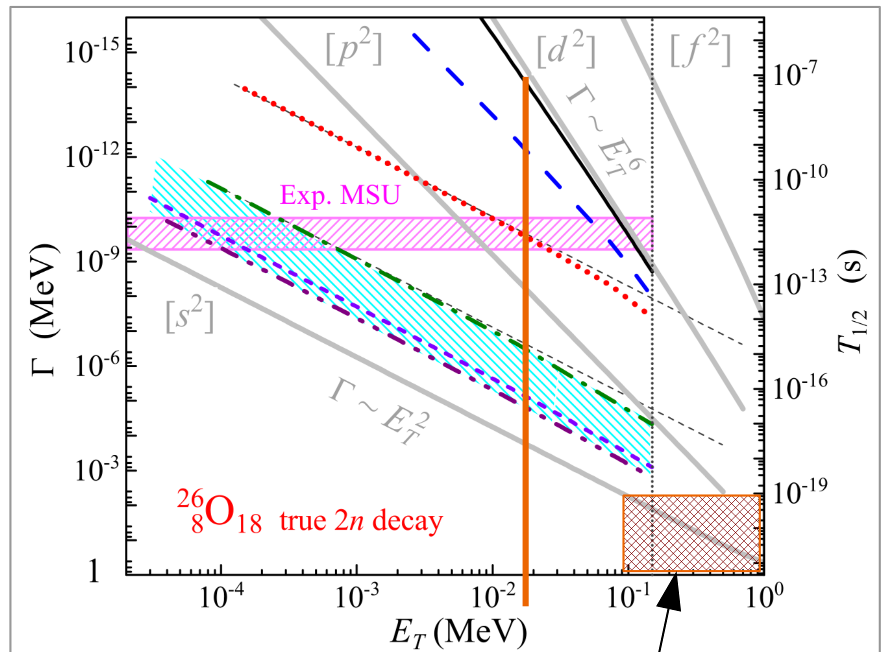
^{26}O – A barely unbound system



How strong is the 2*n* emission hindered?

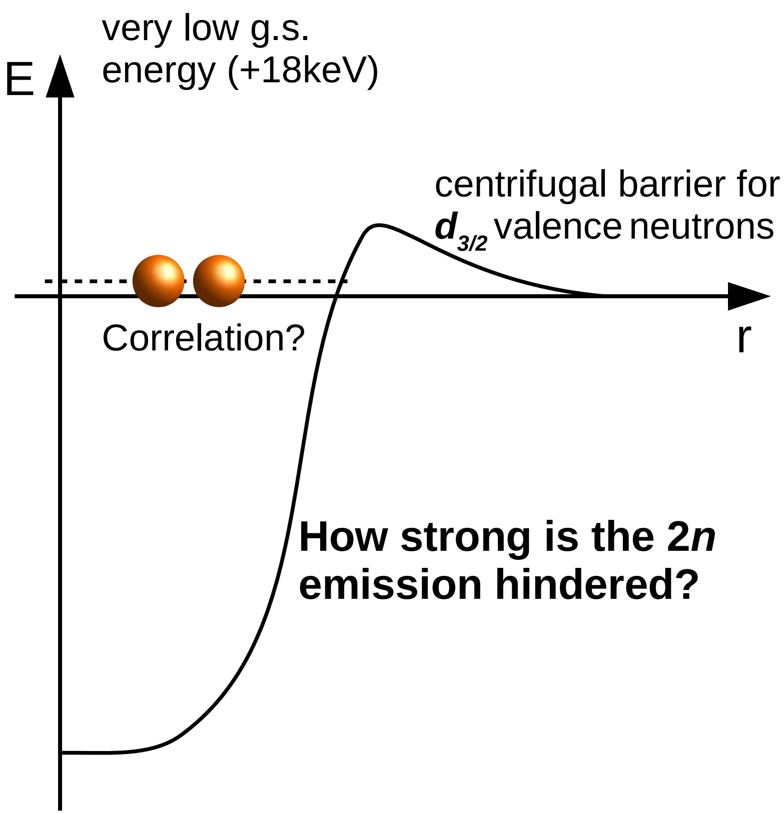
Lifetime Prediction:

L.V. Grigorenko, I.G. Mukha, M.V. Zhukov, Phys. Rev. Lett, 111, 042501 (**2013**)



typical for neutron-unbound states

^{26}O – A barely unbound system



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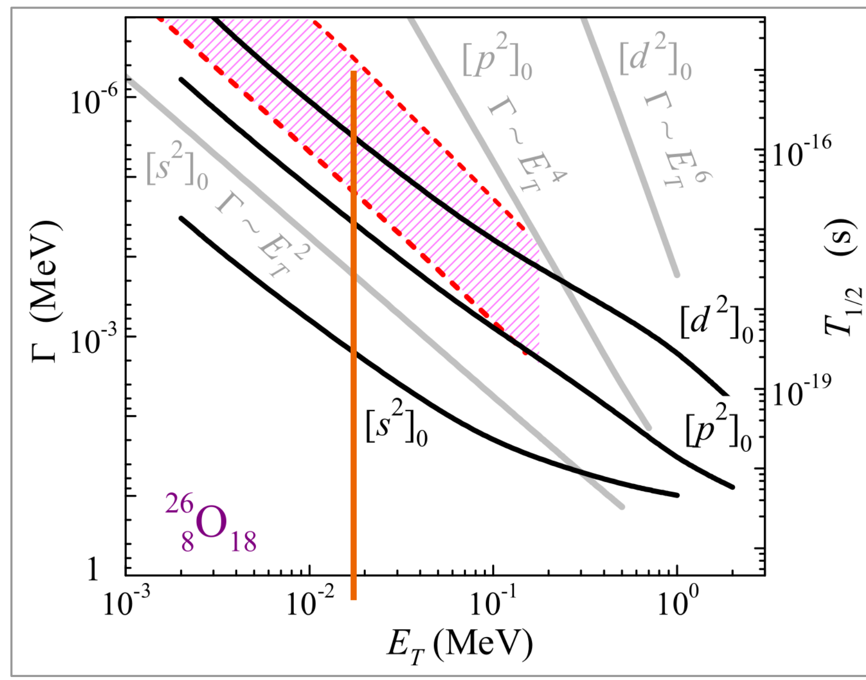
L.V. Grigorenko, J.S. Vaagen, M.V. Zhukov, Phys. Rev. C 97, 034605 (**2018**)



^{26}O – A barely unbound system

Experimental evidence for lifetime in picosecond range:

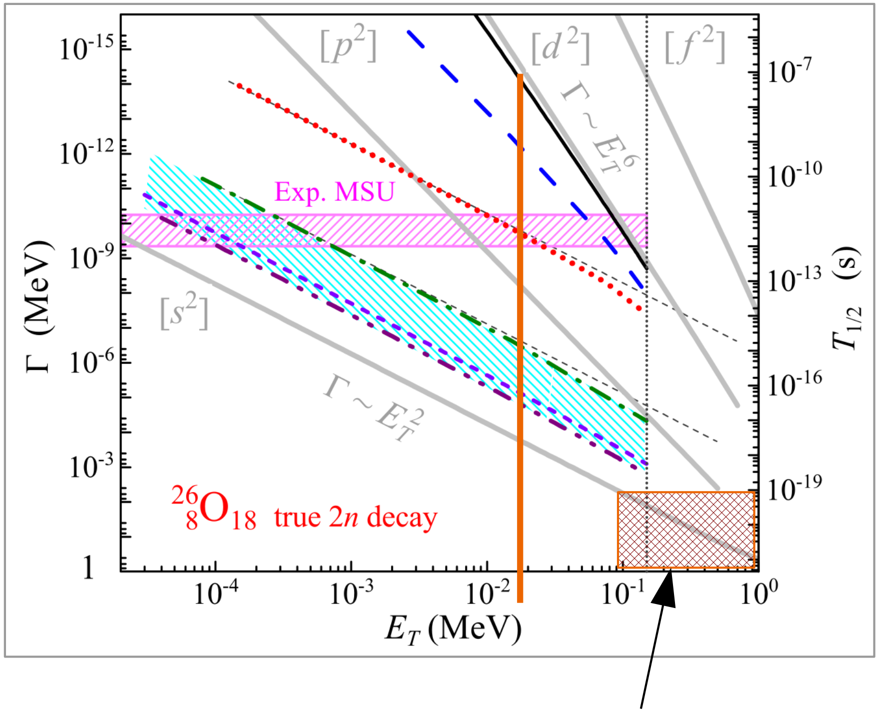
Experiment at NSCL
Z. Kohley et al., PRL 110, 152501 (2013)

$$\tau = 6.5^{+1.6}_{-2.2}(\text{stat}) \pm 4.3(\text{syst})\ \text{ps}$$

Is that a new kind of radioactive decay?

Lifetime Prediction:

L.V. Grigorenko, I.G. Mukha, M.V. Zhukov, Phys. Rev. Lett, 111, 042501 (**2013**)



New experimental technique to measure the *n*-decay lifetime

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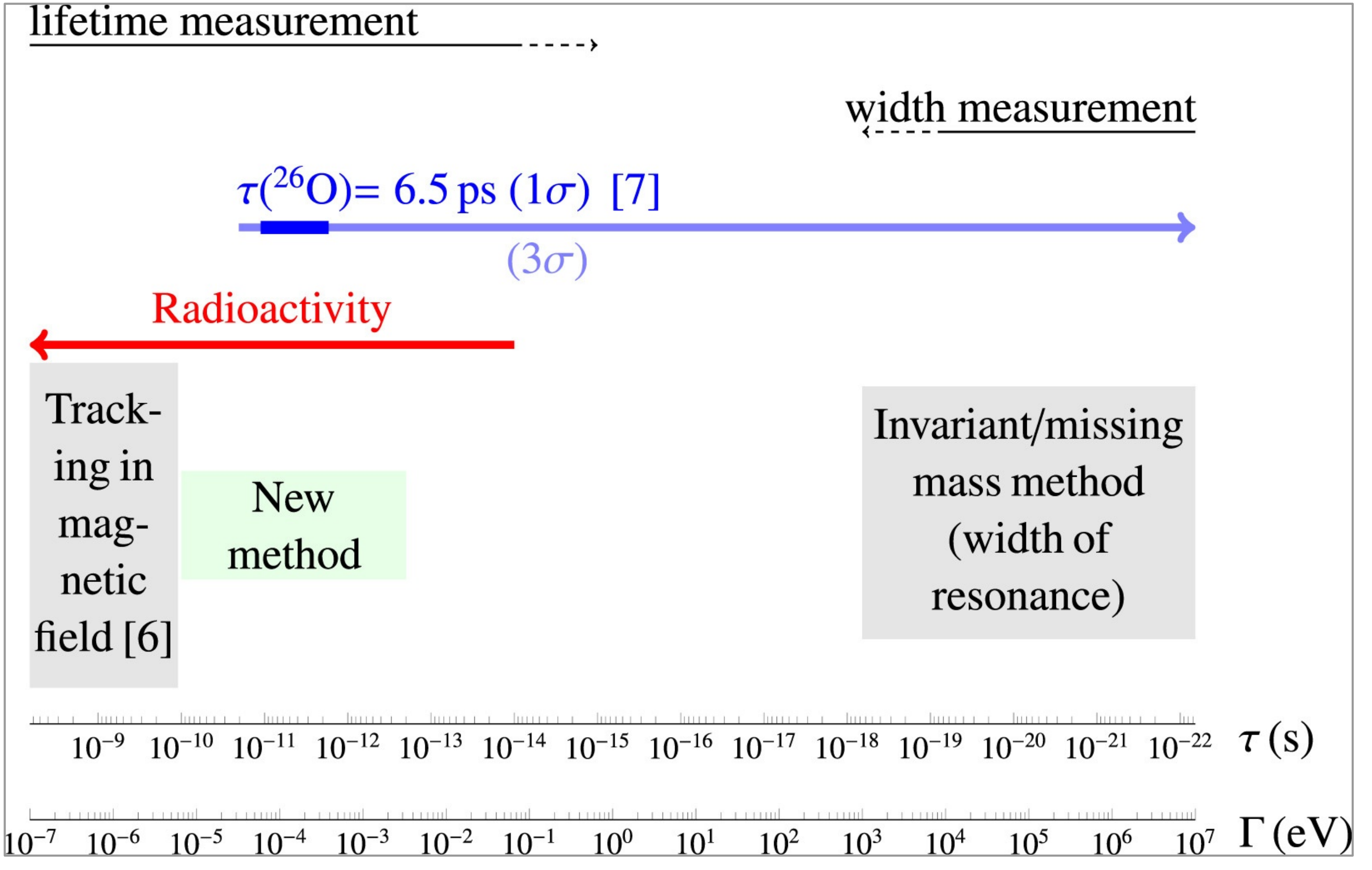
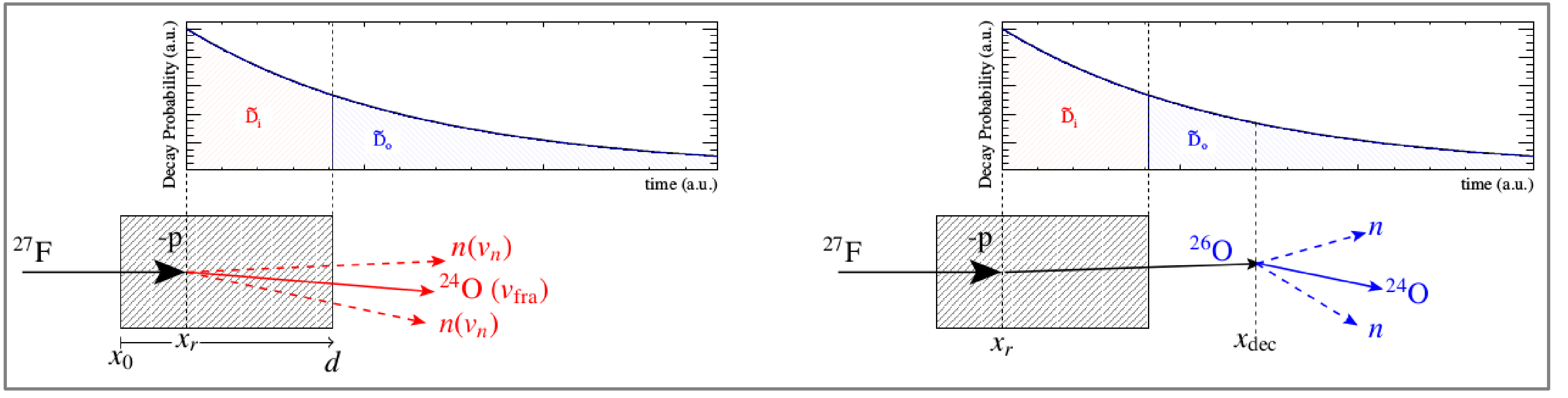


New experimental technique to measure the n-decay lifetime: Example ^{26}O

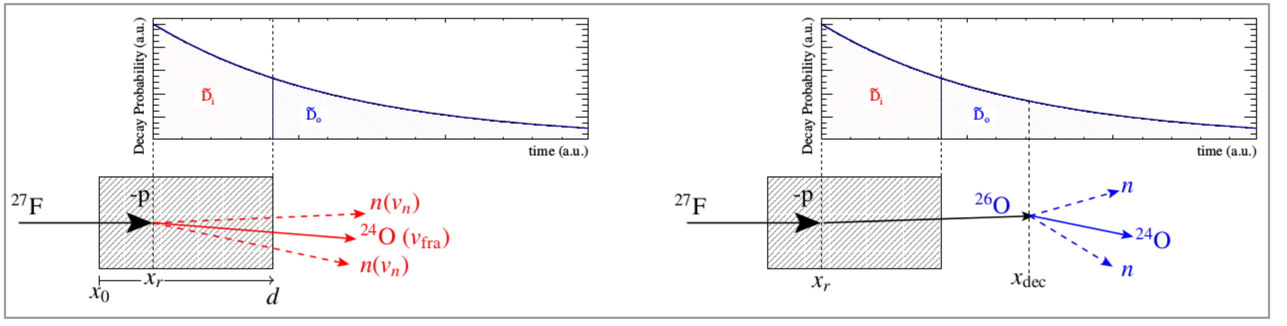
- ^{27}F beam
- Dense and high Z target: high stopping power
- Populate ^{26}O and continuously slow down in target

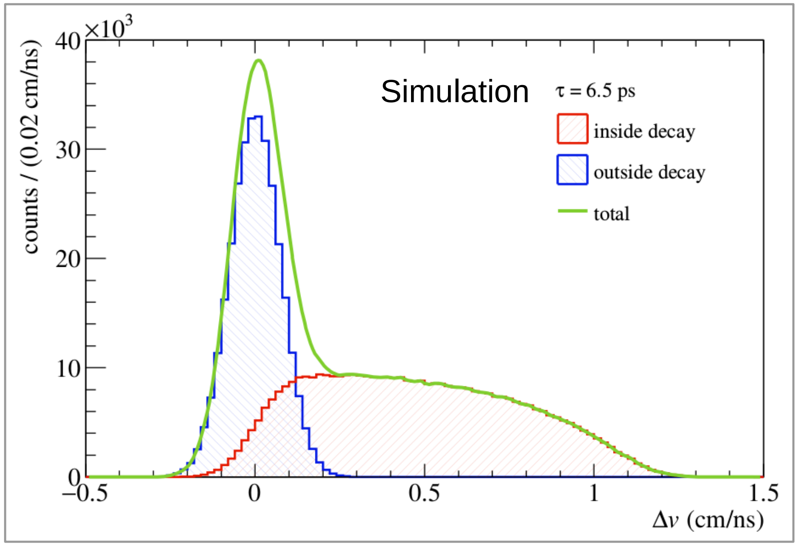


→ the longer the lifetime τ, the more decays happen outside the target

JK, C. Caesar et al., NIM A 866, 265 (2017)

New experimental technique to measure the *n*-decay lifetime: Example ^{26}O





- lifetime τ is sensitive to ratio R of decays in the target to decays outside the target

$$R = \left(\frac{d}{\lambda(1 - e^{-d/\lambda})} - 1 \right)^{-1} \qquad \lambda = \beta\gamma c\tau$$

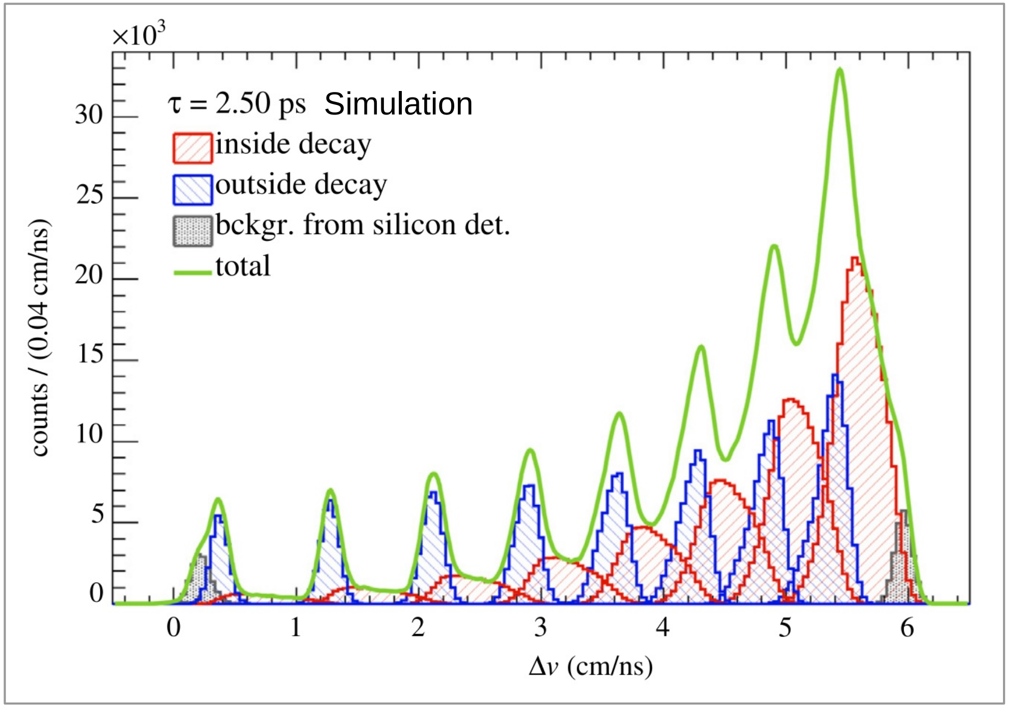
- charged fragment suffers from energy-loss, neutrons do not
- Observable: velocity difference between neutron and fragment (~ $\Delta v = v_n - v_{fra}$)

Sensitivity & Improvements of the Method

Sensitivity to lifetime = choice of:

- Target material
- Target thickness
- Beam energy

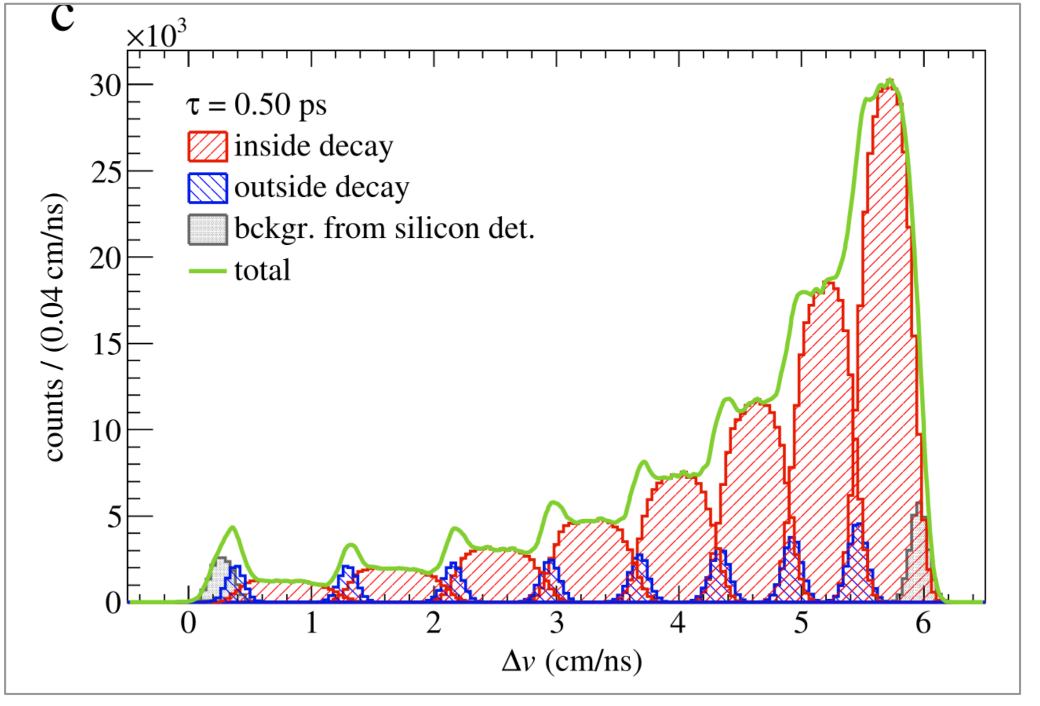
+ use of several targets
in a stack (decreasing in thickness)



→ repeating structure, where the last targets are more sensitive to shorter lifetimes

Sensitivity & Improvements of the Method

- Technique: determine *n*-decay time precisely in picosecond range
- Use the simulation to design and analyse (χ^2) the experiment (~ ratio & shape sensitivity)



Sensitivity limit ~0.5ps
for conditions at SAMURAI

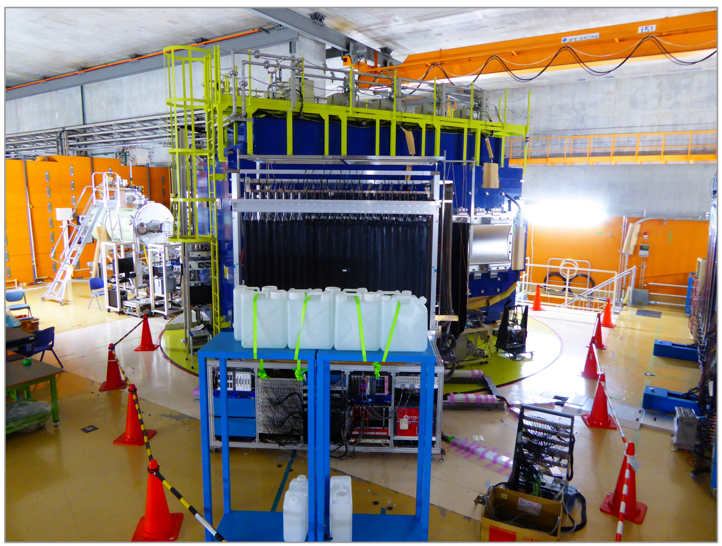
Experiment has been performed at SAMURAI

Spokesperson: C. Caesar

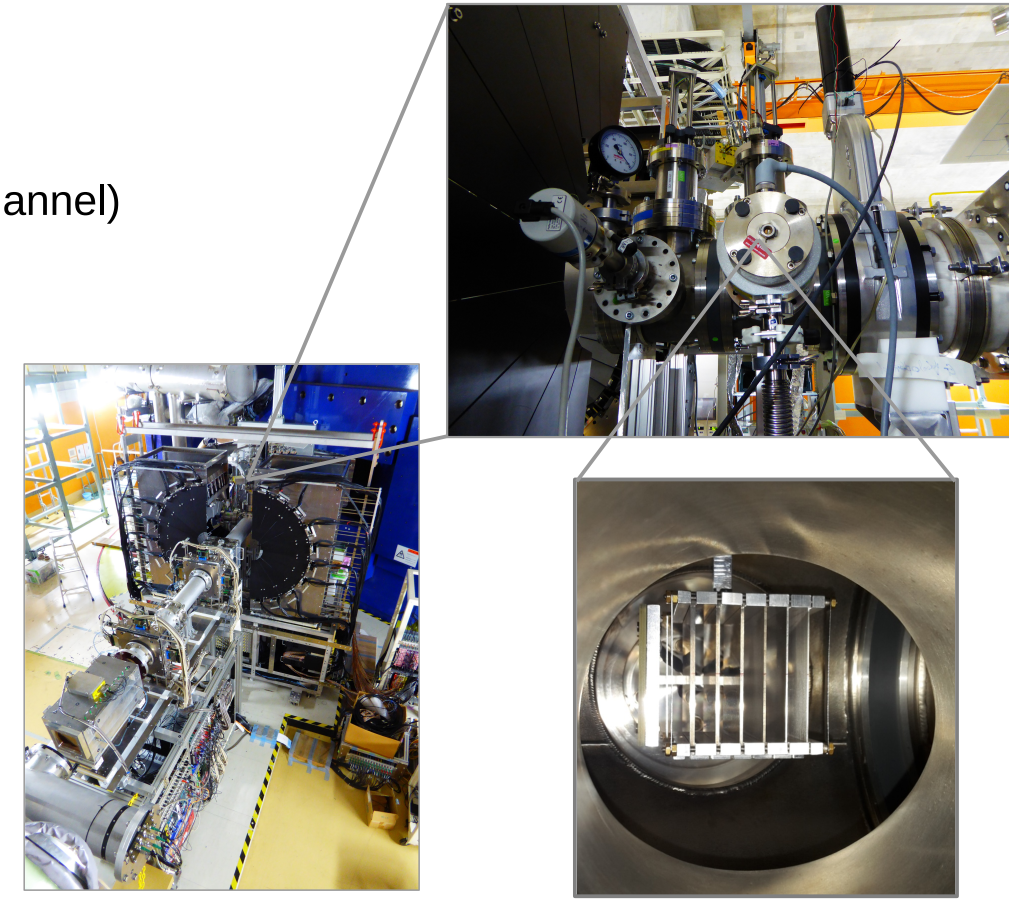
$$^{27}\mathrm{F} \xrightarrow{-p} {}^{26}\mathrm{O} \longrightarrow {}^{24}\mathrm{O} + 2n$$

$$^{26}\mathrm{F} \xrightarrow{-p} {}^{25}\mathrm{O} \longrightarrow {}^{24}\mathrm{O} + n \quad \text{(ref. channel)}$$

Analysis in progress: Sonja Storck



Using the full acceptance of SAMURAI



4 x W + 2 x Pt targets:
14.6g/cm^2

Summary

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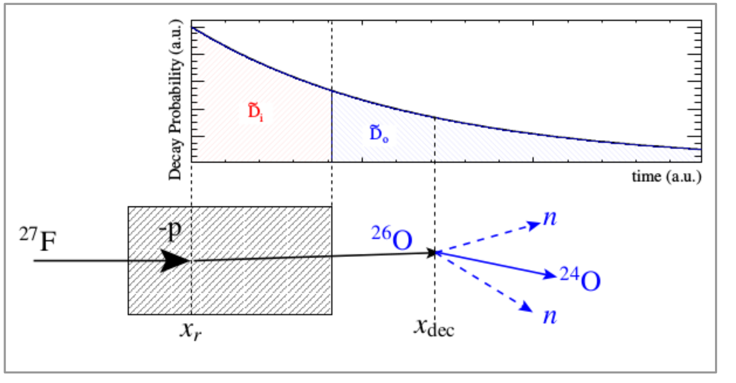
Invariant-mass spectroscopy of the heaviest, neutron-unbound oxygen & fluorine isotopes

Results for ^{28}O (Y. Kondo) & $^{29,30}F$ almost ready

Neutron-decay lifetime of ^{26}O(g.s.)

New technique to measure the lifetime in picosecond range of a nucleus that decays in-flight via neutron emission



First experiment has been performed, analysis is ongoing

Many thanks to the co-authors

Nuclear Inst. and Methods in Physics Research, A 866 (2017) 265–271

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Neutron radioactivity—Lifetime measurements of neutron-unbound states

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[a] Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
[b] GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
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Neutron radioactivity
Neutron spectroscopy
Lifetime measurements
Neutron-rich nuclei
^{26}O

ABSTRACT

A new technique to measure the lifetime τ of a neutron-radioactive nucleus that decays in-flight via neutron emission is presented and demonstrated utilizing MonteCarlo simulations. The method is based on the production of the neutron-unbound nucleus in a target, which at the same time slows down the produced nucleus and the residual nucleus after (multi-) neutron emission. The spectrum of the velocity difference of neutron(s) and the residual nucleus has a characteristic shape, that allows to extract the lifetime. If the decay happens outside the target there will be a peak in the spectrum, while events where the decay is in the target show a broad flat distribution due to the continuous slowing down of the residual nucleus. The method itself and the analysis procedure are discussed in detail for the specific candidate ^{26}O. A stack of targets with decreasing target thicknesses can expand the measurable lifetime range and improve the sensitivity by increasing the ratio between decays outside and inside the target. The simulations indicate a lower limit of measurable lifetime $\tau \sim 0.2$ ps for the given conditions.

Thank You for Your Attention.

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Y.Kondo 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 T.Nakamura 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 **for the SAMURAI21 Collaboration**

C.Caesar J.Kahlbow V.Panin D.S.Ahn L.Atar T.Aumann H.Baba K.Boretzky H.Chae N.Chiga S.Choi M.L.Cortes Sua D.Cortina-Gil Q.Deshayes P.Doornenbal Z.Elekes N.Fukuda I.Gasparic K.I.Hahn Z.Halasz A.Hirayama J.Hwang N.Inabe T.Isobe S.Kim T.Kobayashi D.Körper Y.Kondo Y.Kubota I.Kuti C.Lehr S.Lindberg M.Marques M.Matsumoto T.Murakami I.Murray T.Nakamura T.Nilsson H.Otsu S.Paschalis M.Parlog M.Petri D.Rossi A.Saito M.Sasano H.Scheit P.Schrock Y.Shimizu H.Simon D.Sohler S.Storck L.Stuhl H.Suzuki I.Syndikus H.Takeda H.Törnqvist T.Togano T.Tomai T.Uesaka H.Yamada Z.Yang M.Yasuda K.I.Yoneda **for the SAMURAI20 Collaboration**

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