



Extremely neutron-rich nuclei probed by breakup reactions with rare-isotope beams

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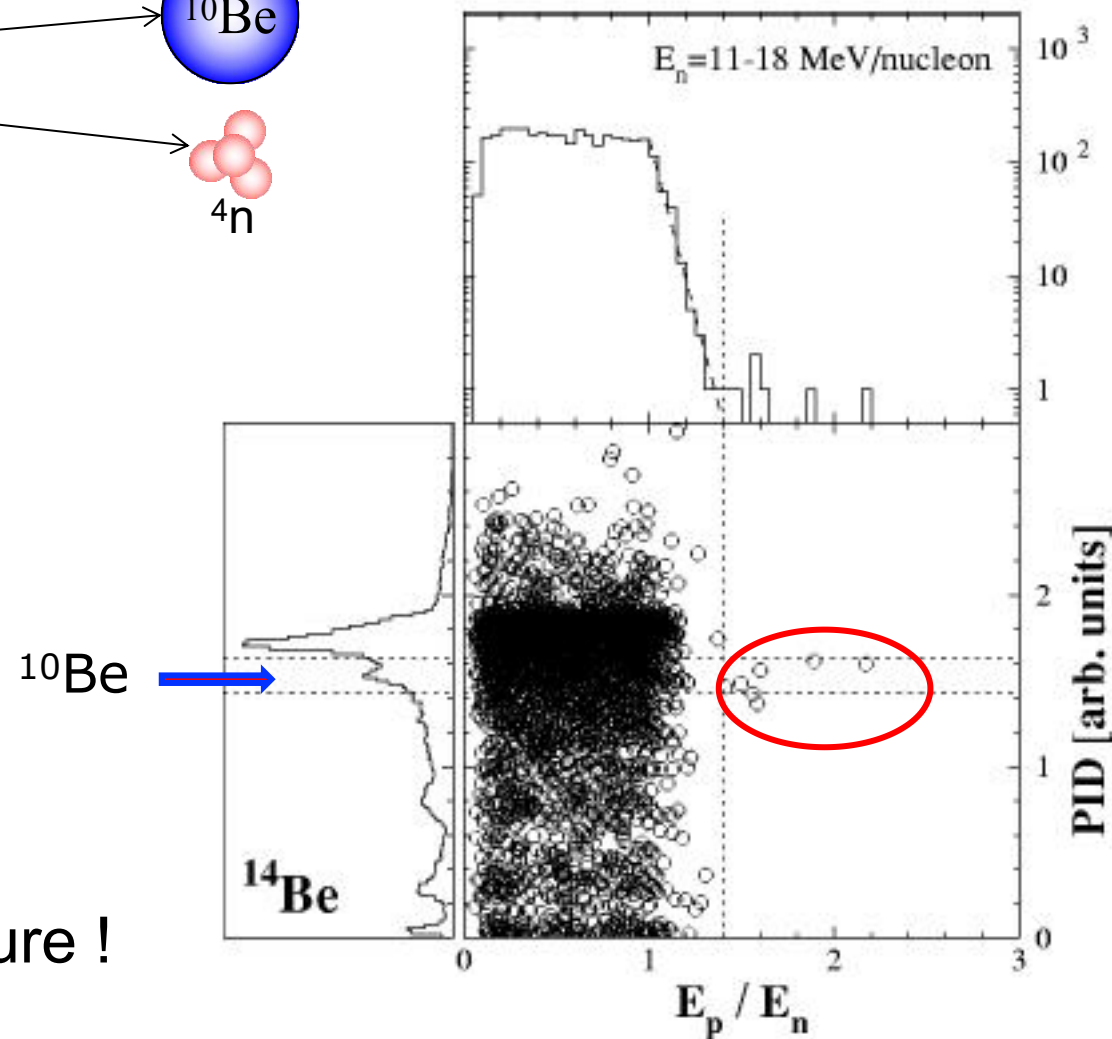
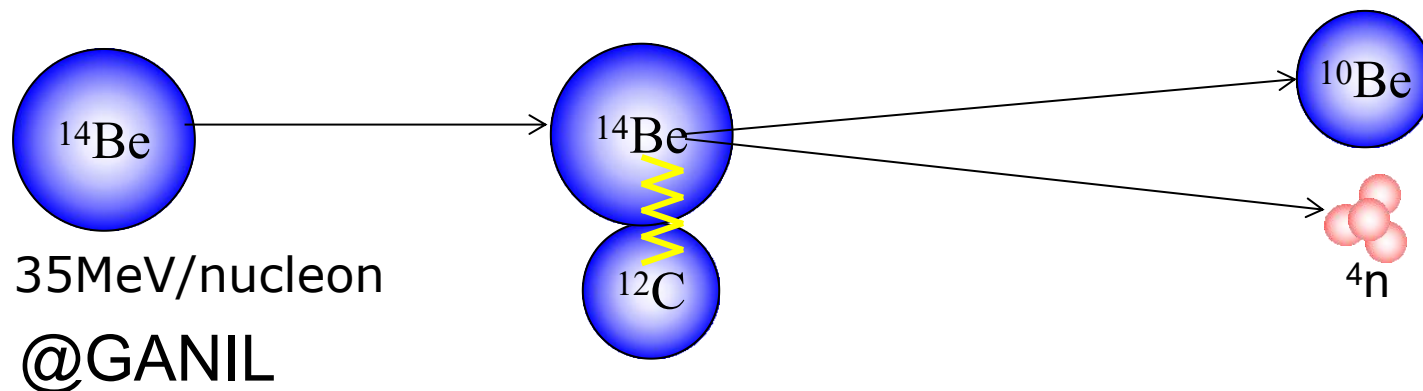
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 - Clusters near the neutron drip line
 - Neutron Halo nuclei—Basics
 - Three Signals of Neutron Halo
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- Lecture-II: Coulomb breakup of Neutron Halo Nuclei and Soft E1 Excitation
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 - Coulomb breakup
 - Coulomb breakup of one-neutron halo nuclei $\rightarrow {}^{11}\text{Be}, {}^{19}\text{C}, {}^{31}\text{Ne}$
 - Coulomb breakup of two-neutron halo nuclei $\rightarrow {}^{11}\text{Li}, {}^{19}\text{B}, {}^6\text{He}$
- Lecture-III: Multi-neutron states using quasi-free scattering
 - Tetra-neutron
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Tetra-Neutron

--Status and Perspectives

Tetra-neutron

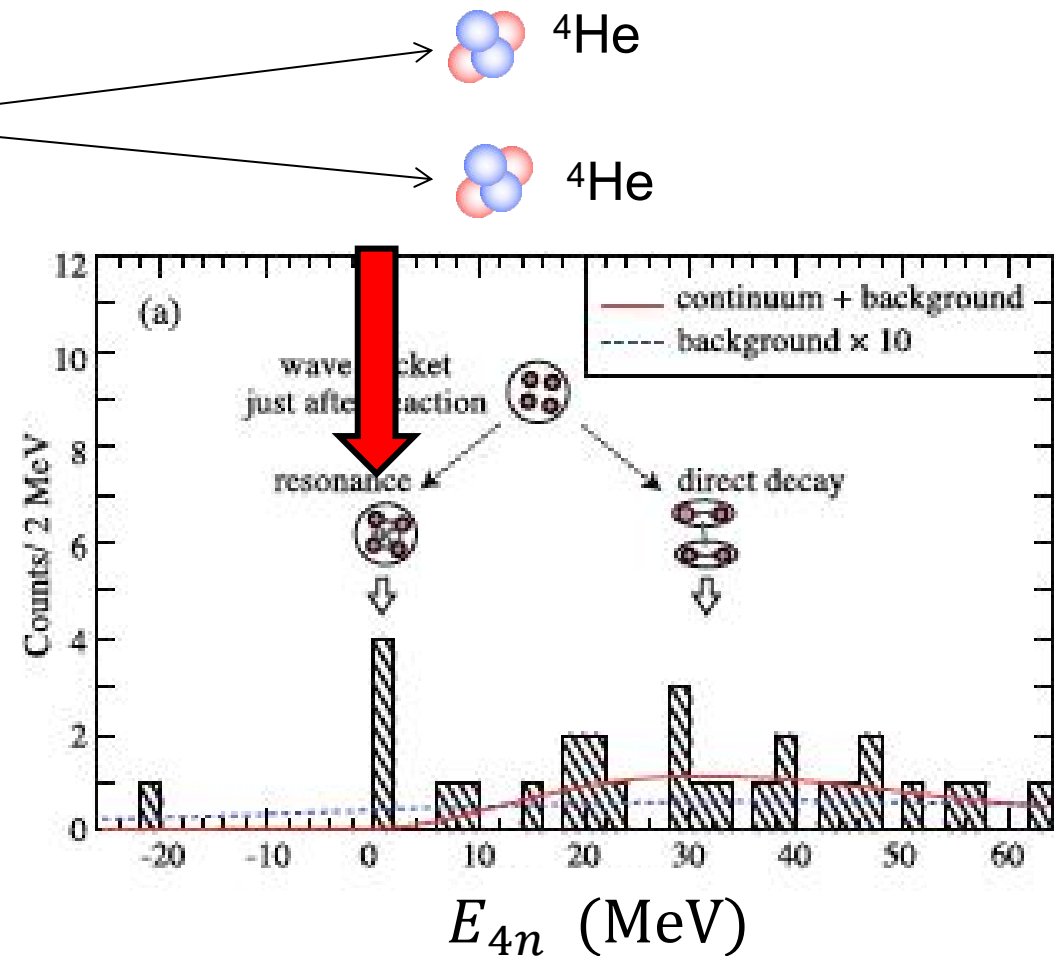
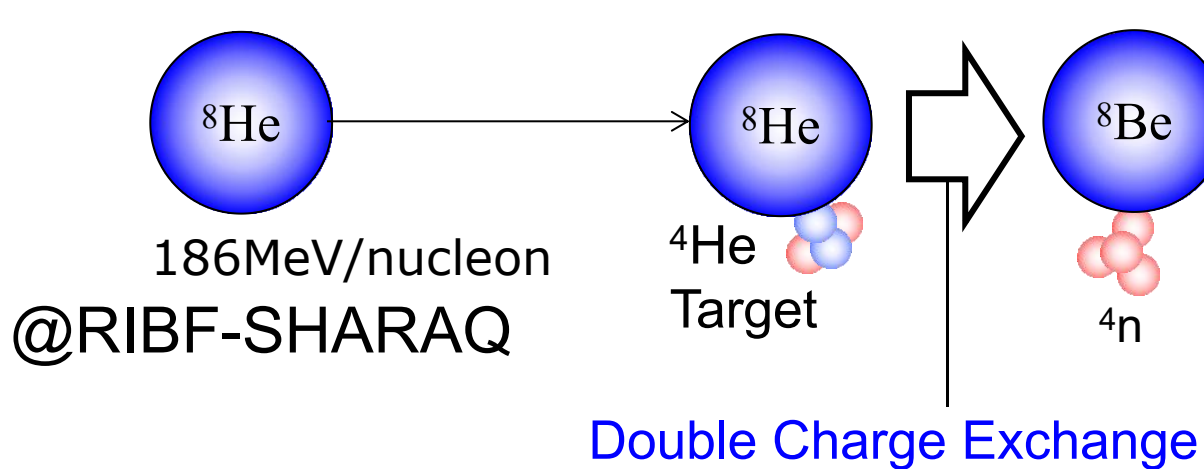
2002 Marqu  z (PRC65, 044006 (2002))



The confirmation experiments were not successful (technically) →
Confirmation should be done in the near future !

Tetra-neutron

2016 Kisamori, Shimoura (PRL116, 052501 (2016))

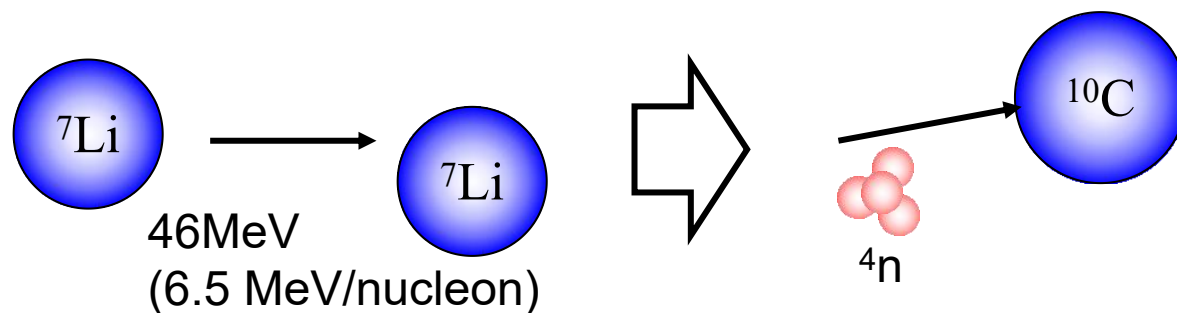


$$E_{4n} = 0.83 \pm 0.65(\text{stat}) \pm 1.25(\text{syst})\text{MeV}$$

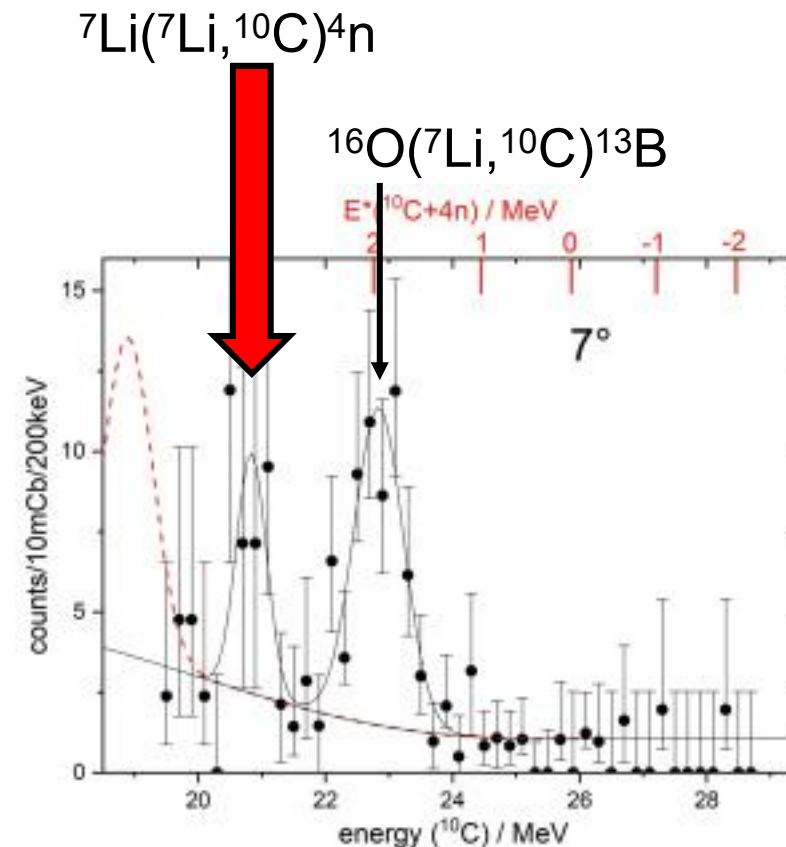
$$\Gamma < 2.6 \text{ MeV (FWHM)}$$

Tetra-neutron

2022 Faestermann (PLB824, 136799 (2022))

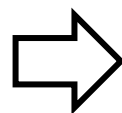


MP Tandem accelerator
@Garching near Munich



$$E_x({}^{10}\text{C} + 4n) = 2.93 \pm 0.16 \text{ MeV}$$

$$\Gamma < 0.24 \text{ MeV}$$

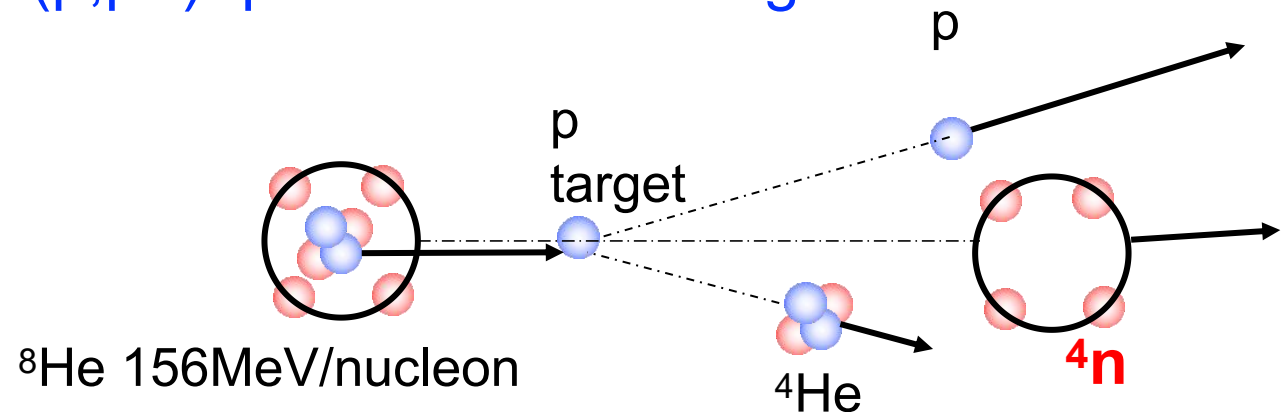


Width: too narrow to be a resonance
 $\rightarrow {}^{10}\text{C}$: 1st excited state ($E_x = 3.354 \text{ MeV}$)
 $\rightarrow E_{4n} = -0.42 \pm 0.16 \text{ MeV}$ (Bound state)
 $\rightarrow 0.145 \text{ s}$ (1st independent decay)

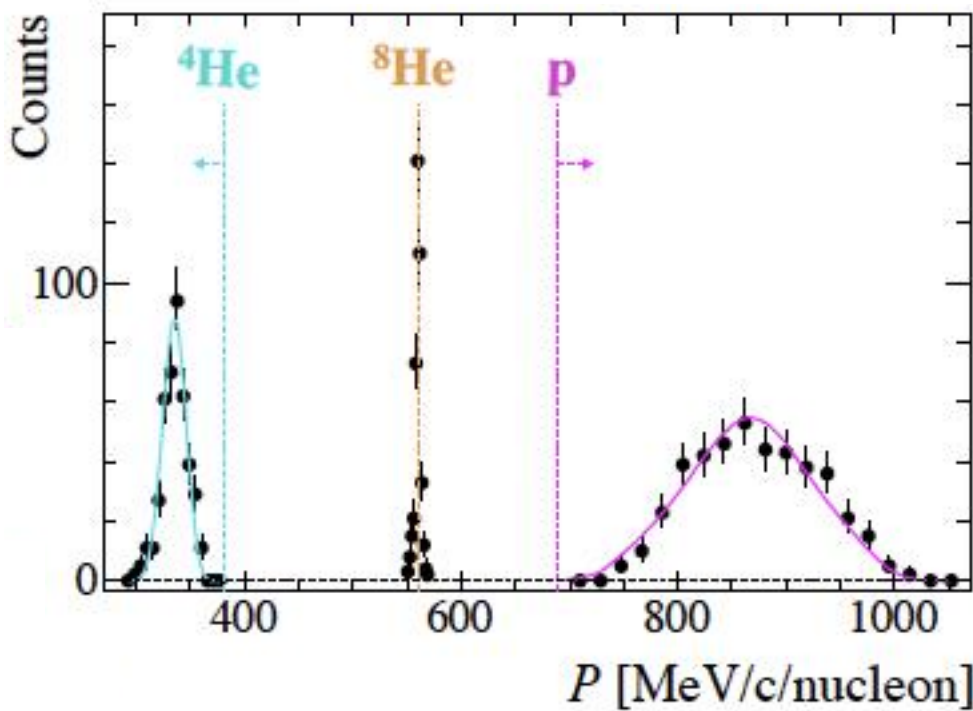
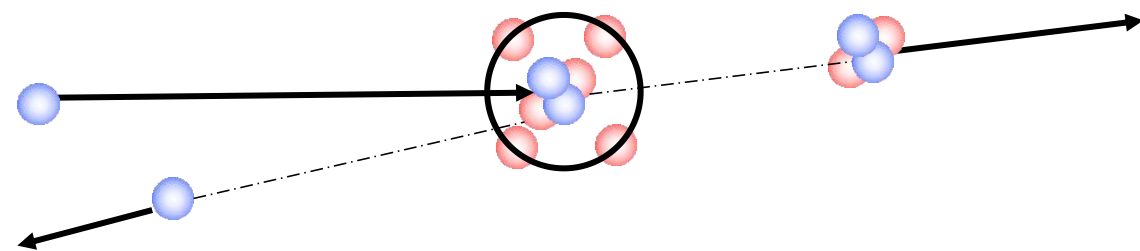
Tetra-neutron at SAMURAI-RIBF



2022 M. Duer, SAMURAI collaboration, (Nature **606**, 678 (2022))
(p,p α) quasi-free scattering in inverse kinematics



In normal kinematic (順運動学)

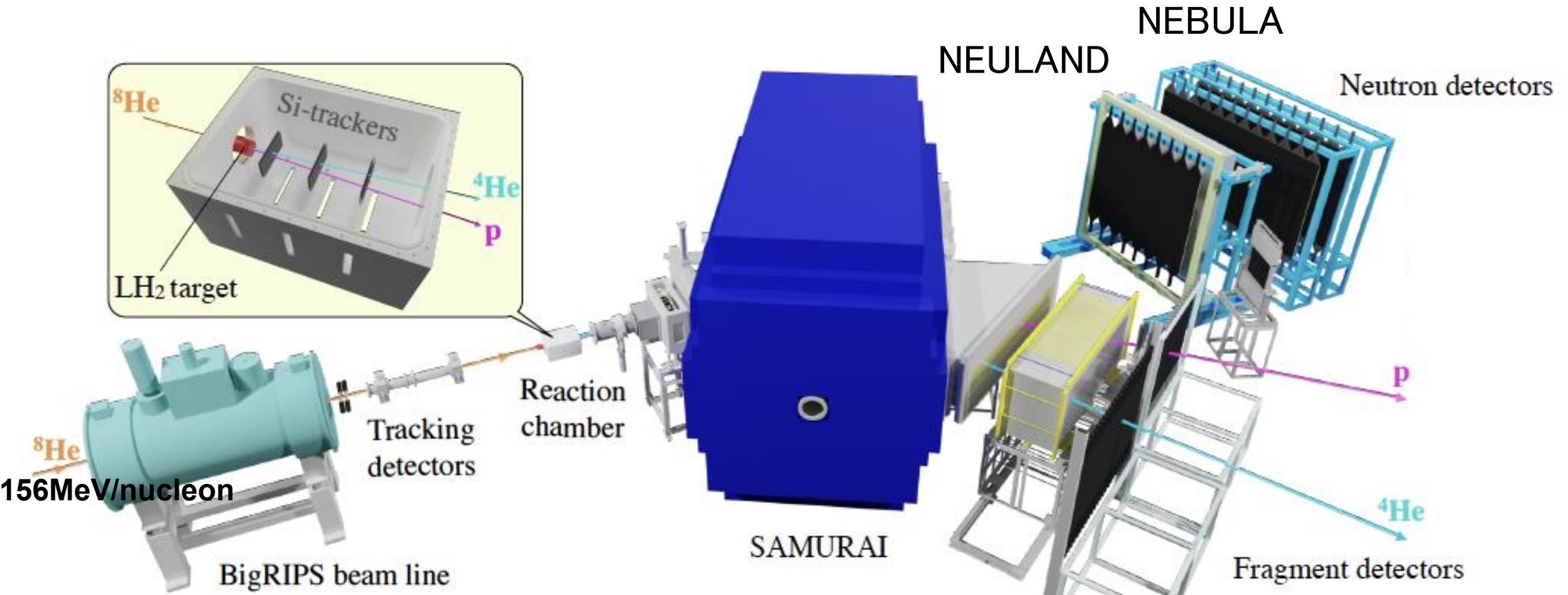


Backward scattering \rightarrow Large momentum transfer $\Delta q > P_F$
 \rightarrow Minimize Final State Interactions

Tetra-neutron at SAMURAI-RIBF

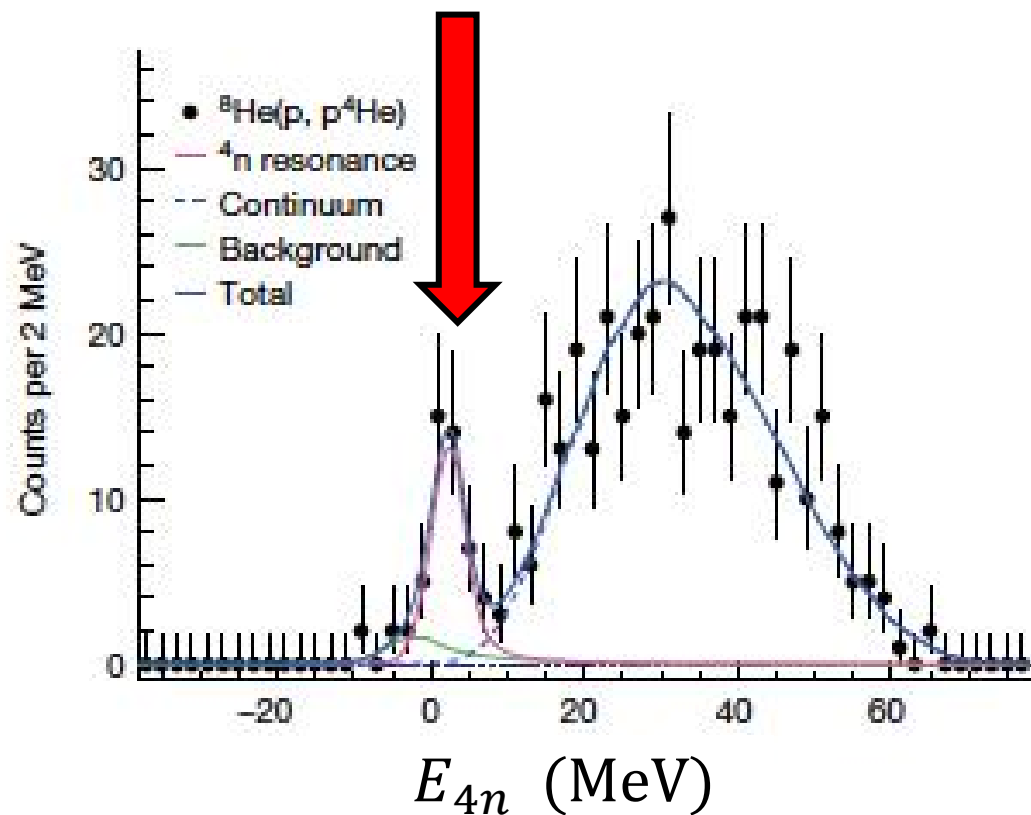
Nature **606**, 678 (2022).

Experimental Setup

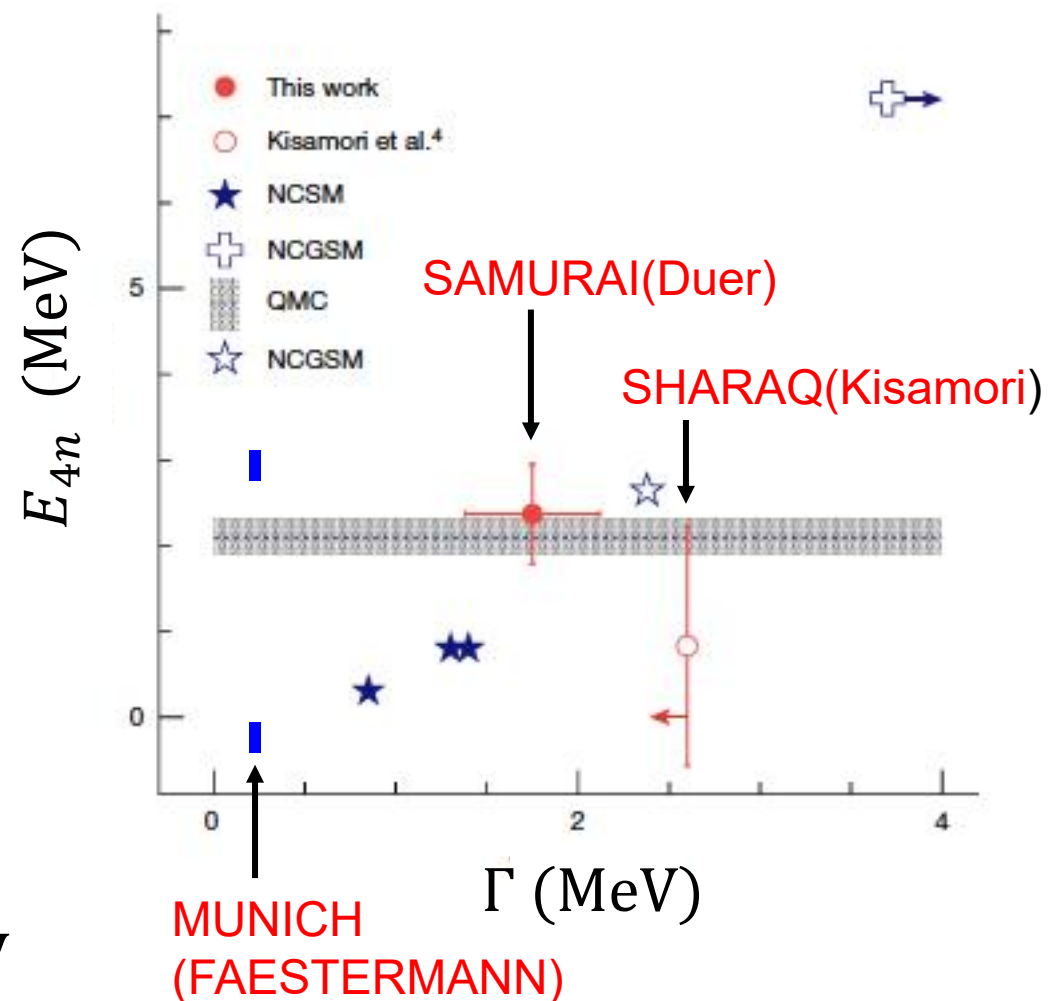


Tetra-neutron at SAMURAI-RIBF

Nature **606**, 678 (2022).



$$E_{4n} = 2.37 \pm 0.38(\text{stat}) \pm 0.44(\text{syst})\text{MeV}$$
$$\Gamma = 1.75 \pm 0.22(\text{stat}) \pm 0.30(\text{syst})\text{MeV}$$

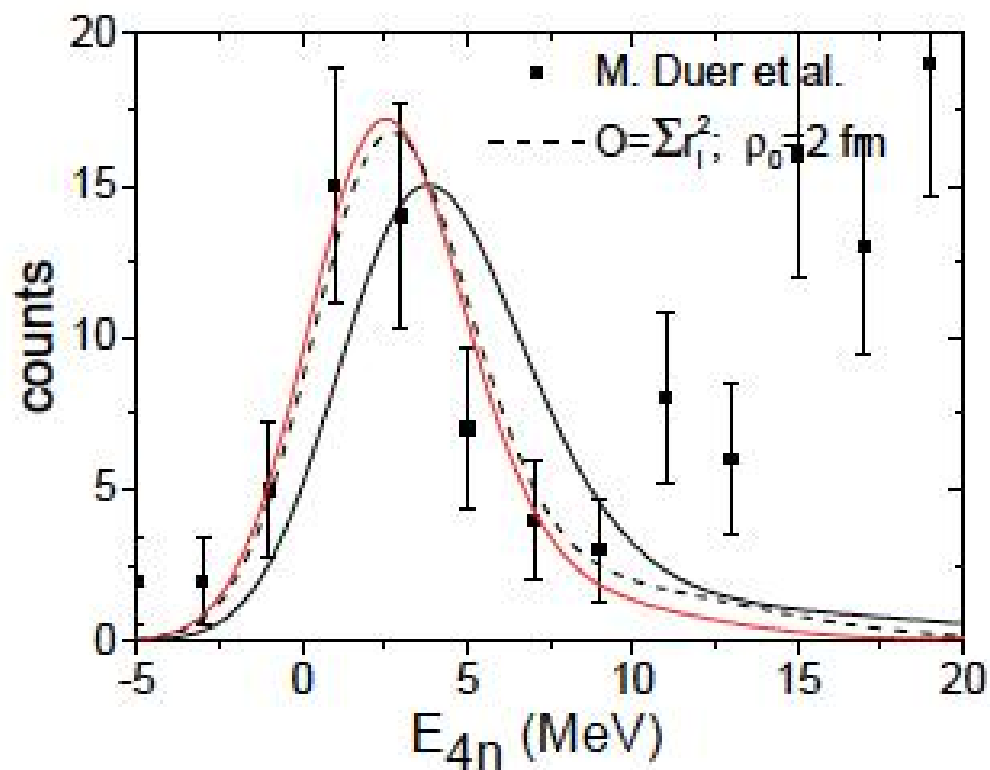


Tetra-neutron: Resonance or?

Lazauskas, Hiyama, Carbonell, PRL in press (arXiv:2207.07575v1)

Resonance due to Tetra-neutron does not exist.

Spectrum in RIBF-SAMURAI: reproduced by “dineutron+dineutron” emission from the neutron density distribution just after 4n removal from ^8He .



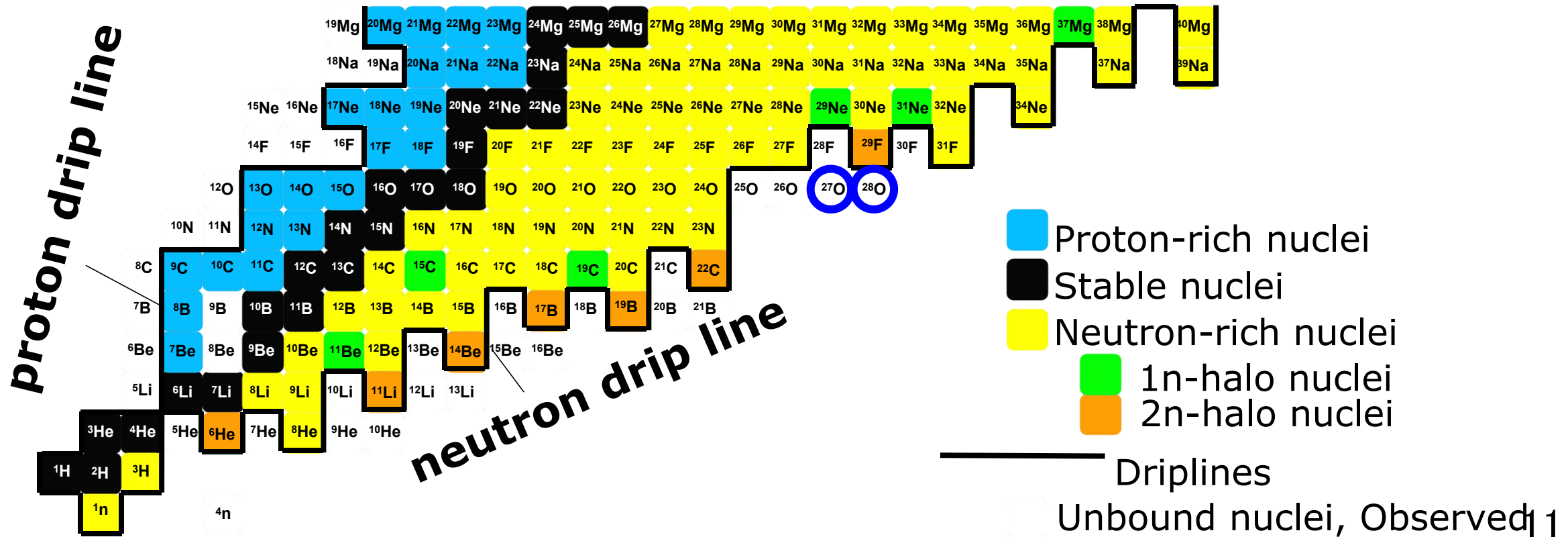
Next Step

- Energy spectrum with better E resolution
- 4 Neutron coincidence measurements
- ➔ 4n Decay Scheme

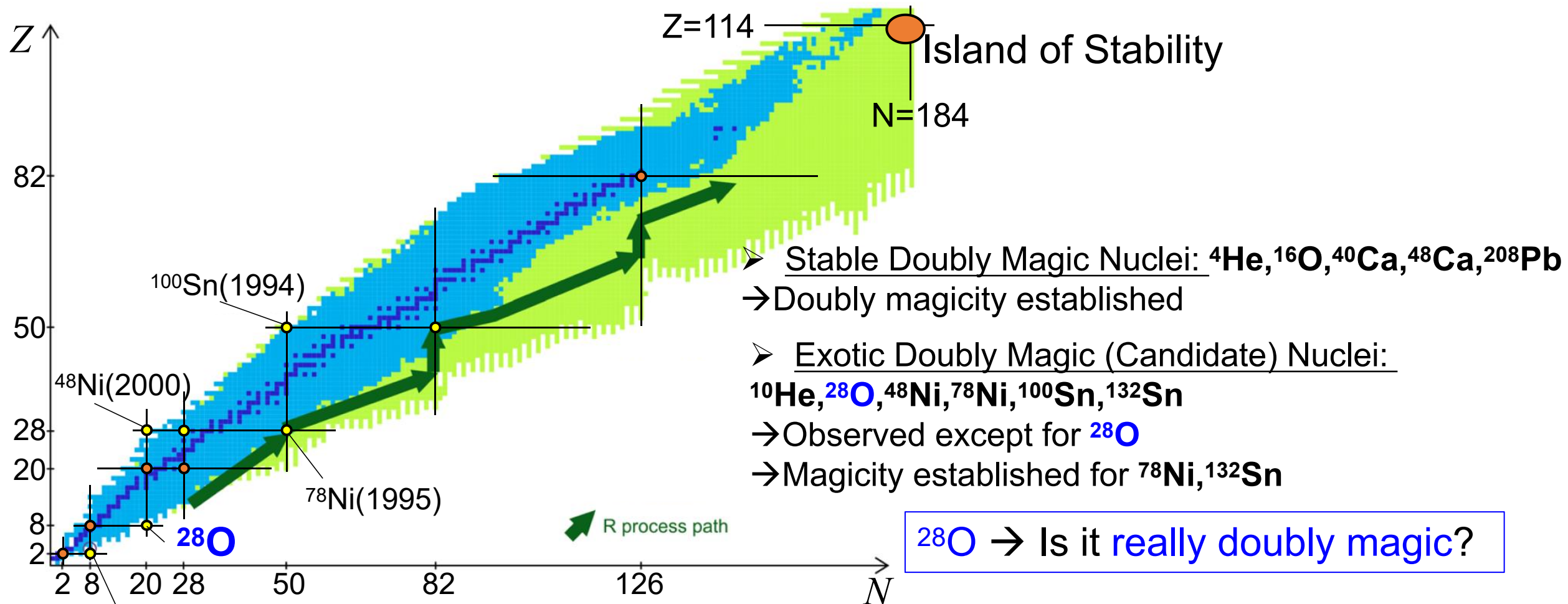
Why ^4He double-charge-exchange result (Kisamori) coincides with $^8\text{He}(-^4\text{He})$ (Duer) ?

“multi-neutron cluster” in Nuclei

➤ Spectroscopy of ^{27}O and ^{28}O



Why ^{28}O ? -- Doubly Magic Nucleus by Mayer-Jensens view



(modified from) T.Otsuka et al., Rev. Mod. Phys. 92, 015002 (2020).

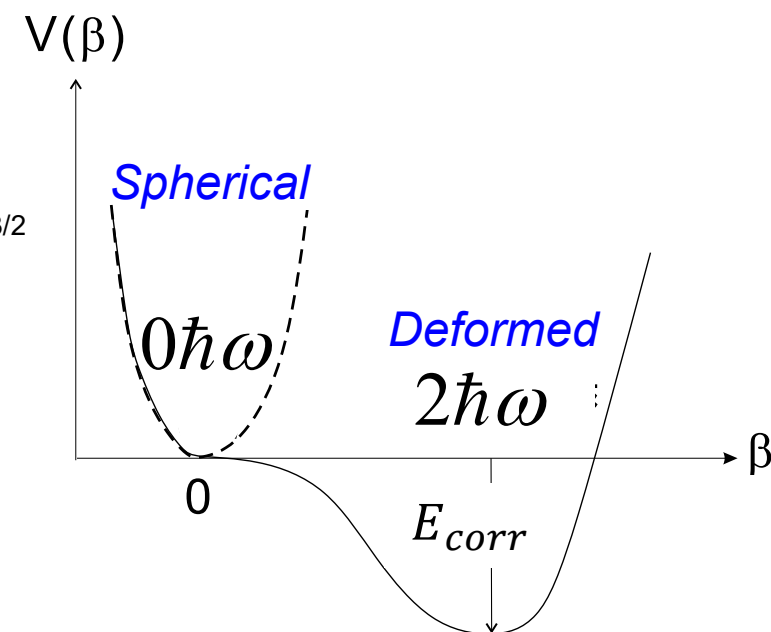
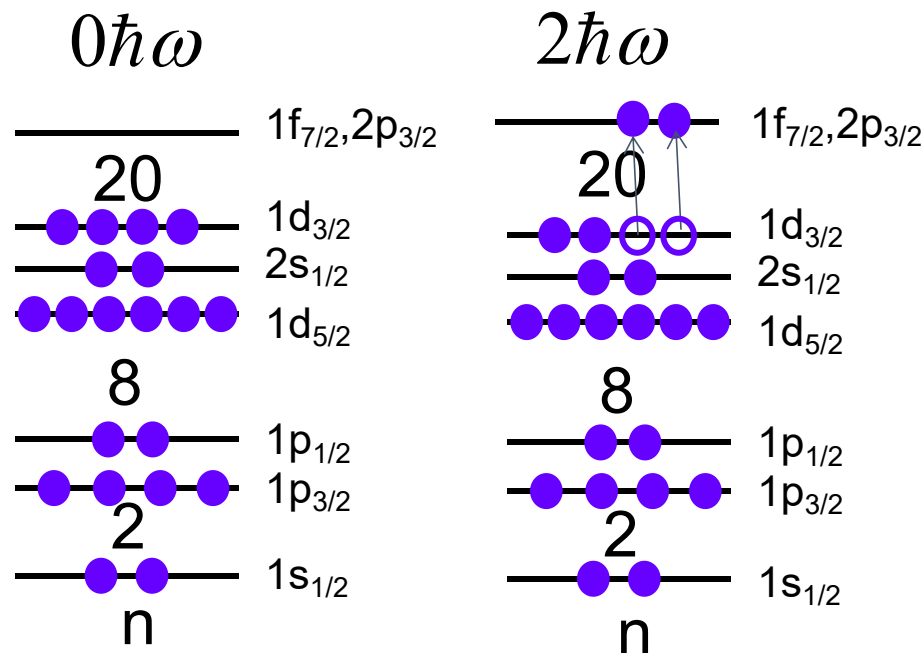
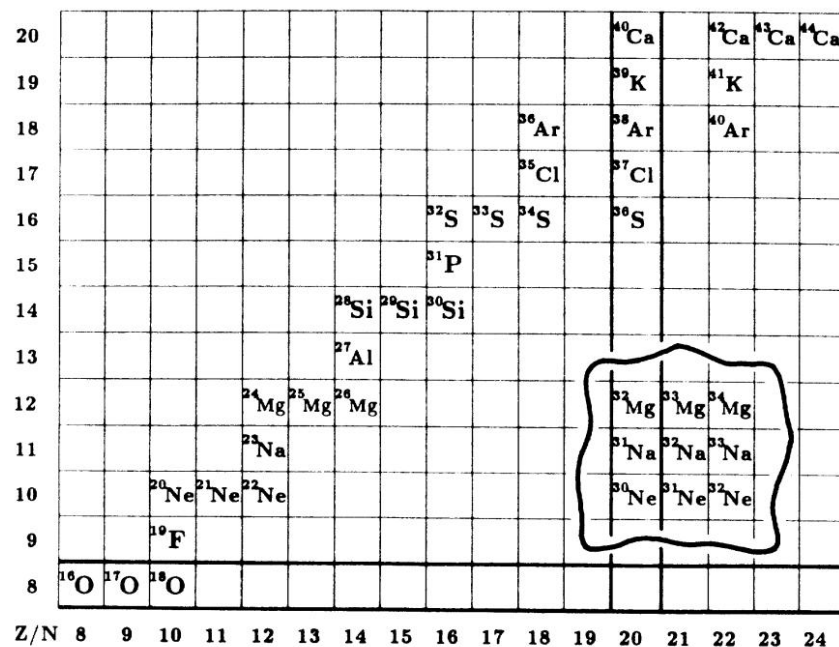
Island of Inversion in a nutshell

E.K. Warburton, J.A.Becker, B.A.Brown, PRC41, 1147 (1990).

Further evidence for the presence of an anomaly in binding energies for the “island of inversion” centered at $Z=11$, $N=21$ is obtained by comparison of shell-model calculations to experiment.

...

It is found that for $Z=10-12$, $N=20-22$ (and possibly $N > 22$) nuclei the lowest $2\hbar\omega$ state is more bound than the $0\hbar\omega$ ground state.



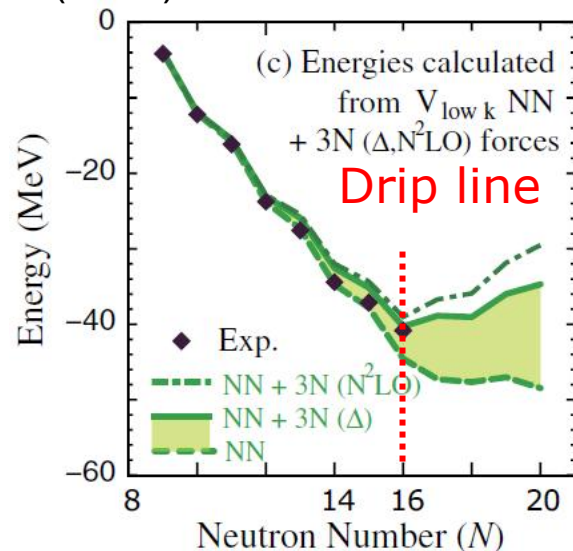
$$E_{corr} = 2E_x(\hbar\omega) - E(nn) < 0$$

Island of Inversion: $E(0\hbar\omega) > E(2\hbar\omega)$

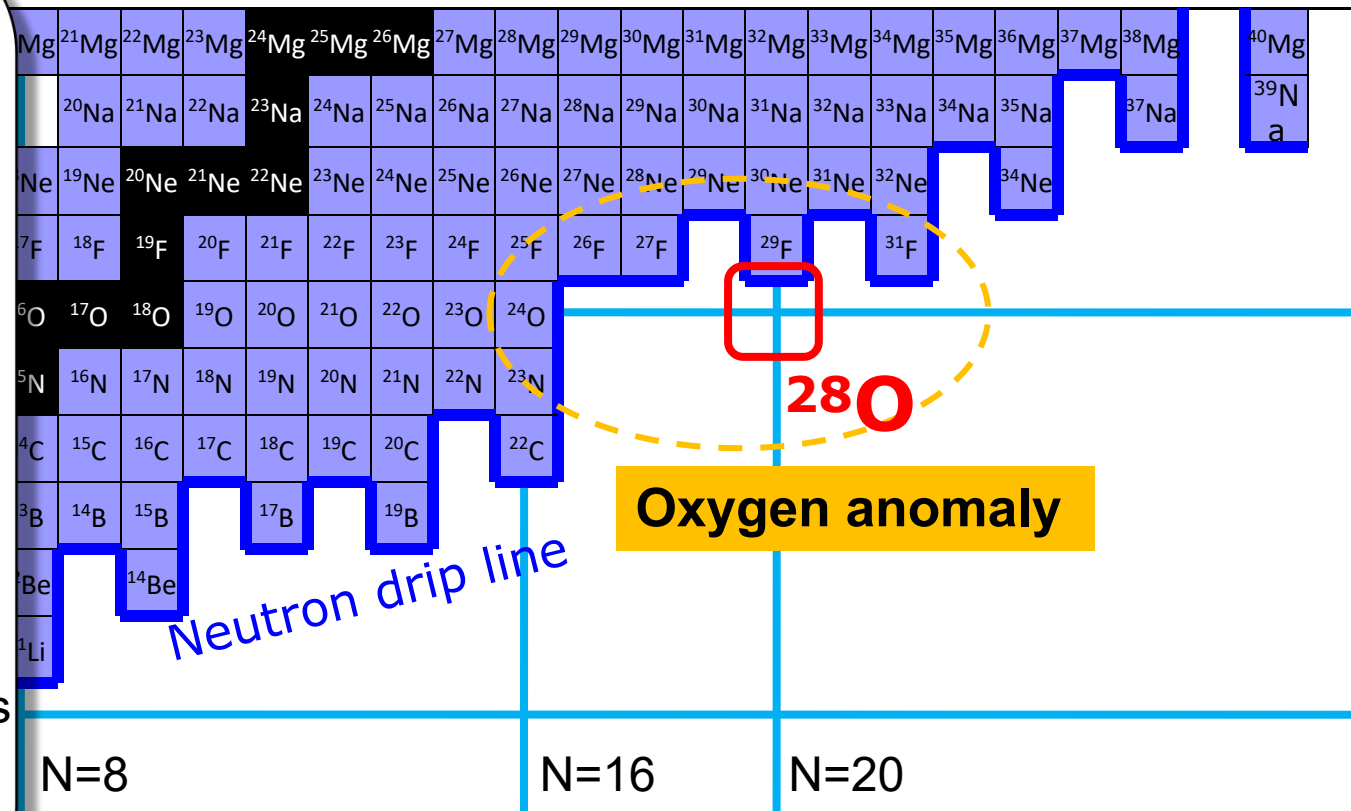
Weakly Bound Effect
Jahn Teller Effect → Deformation
Monopole Migration...

Oxygen anomaly (Dripline anomaly)

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

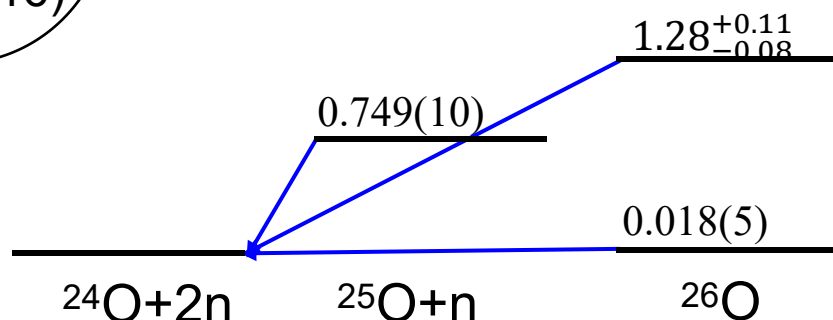
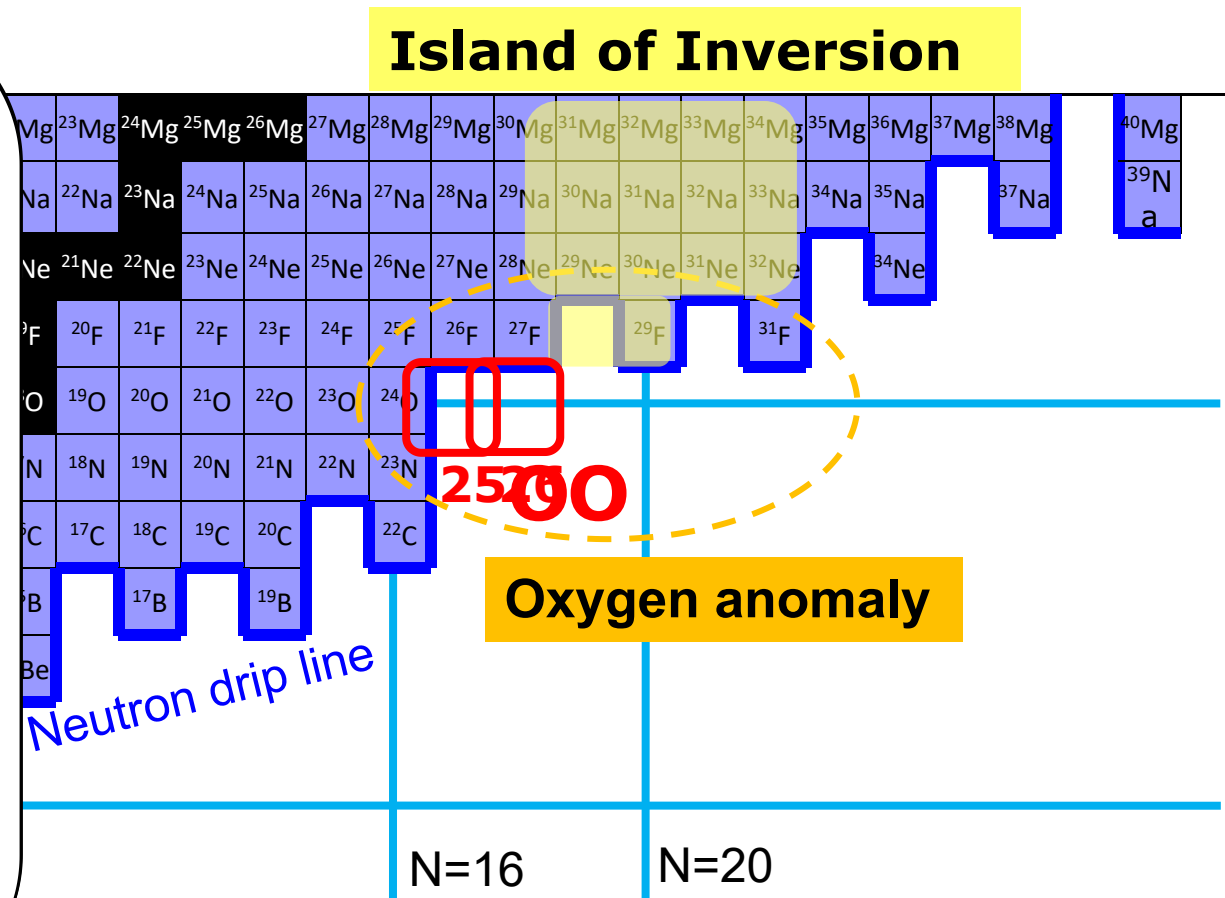
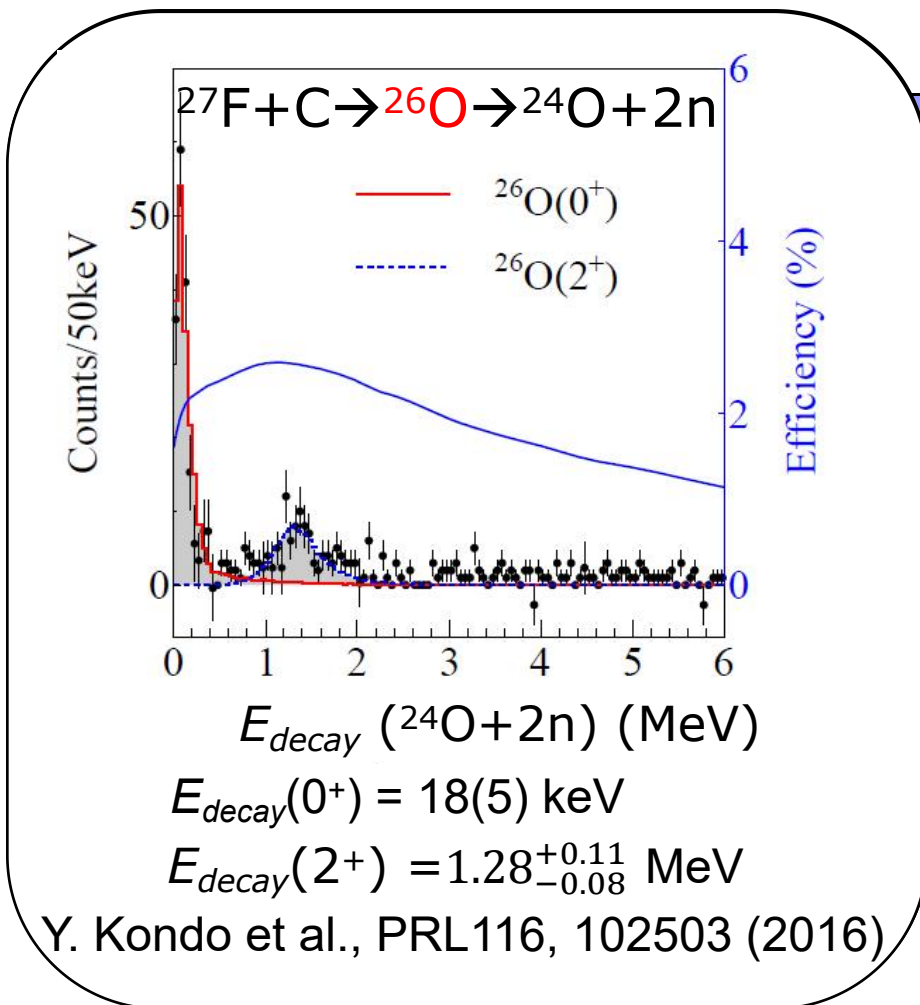


Three-Nucleon Force (**3NF**):
Important role in binding oxygens
G. Hagen et al., PRL108, 242501 (2012)
J. Holt et al., Eur.Phys. J.A49, 39 (2013)



- Sudden change of neutron drip line (Oxygen anomaly)
 - What is the origin?

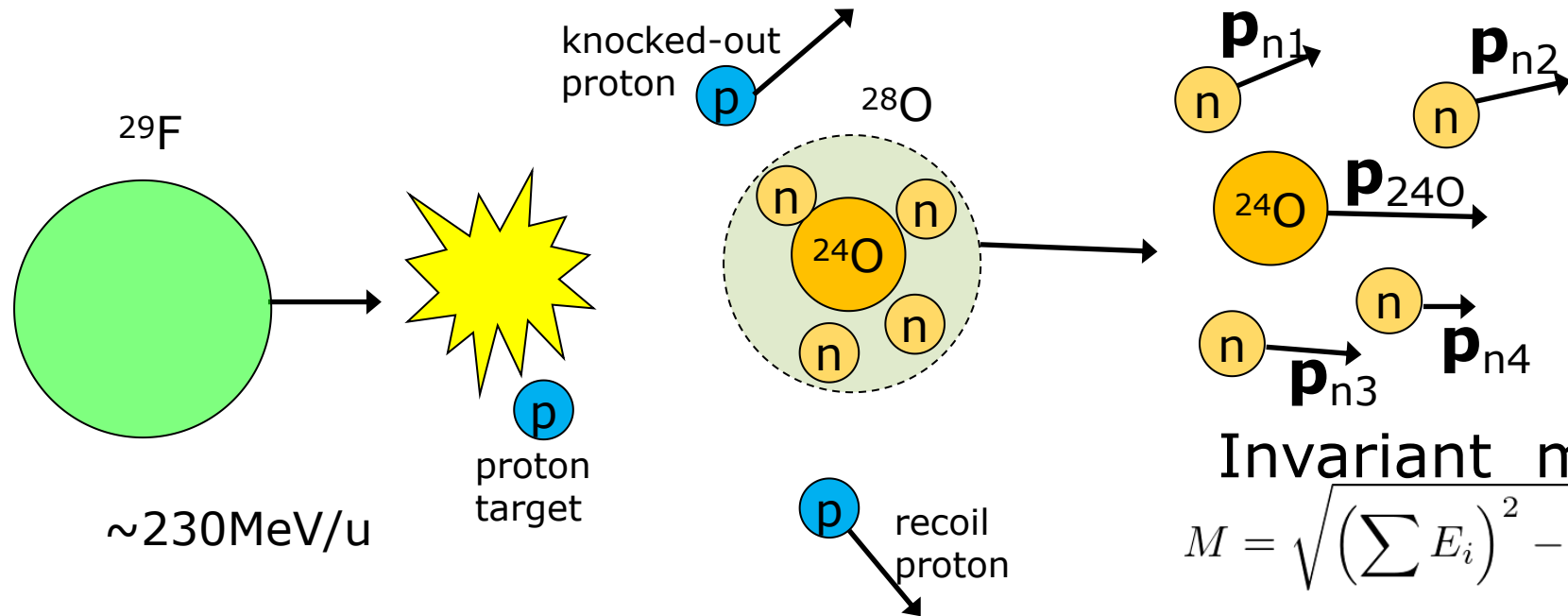
What is known for neutron-rich oxygen isotopes?



Invariant mass spectroscopy of ^{27}O , ^{28}O

Nature, to be published

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



Invariant mass

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

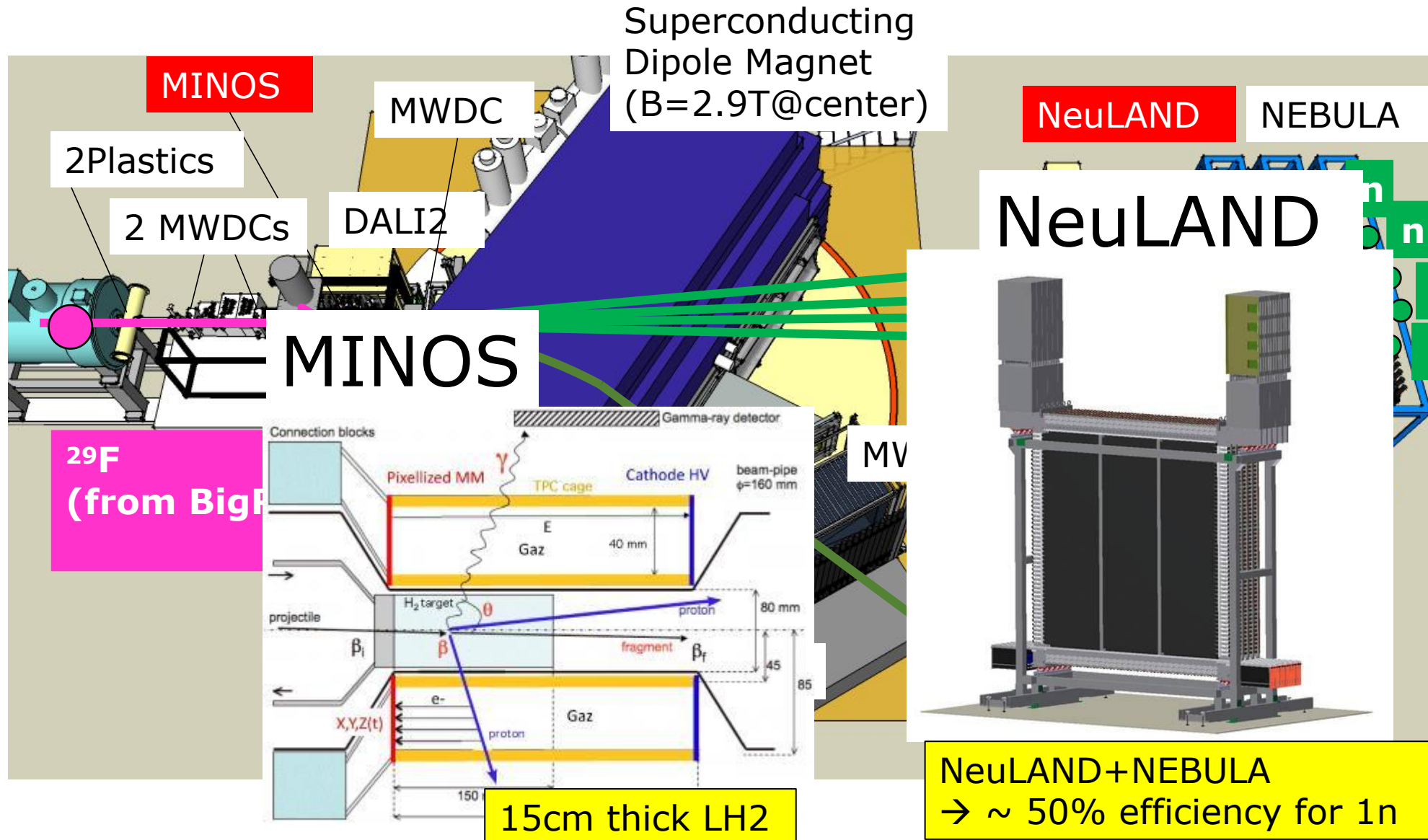
→ **4 neutrons coincidence!**

^{27}O : Two-proton removal reaction of ^{29}Ne
1p1n removal reaction from ^{29}F



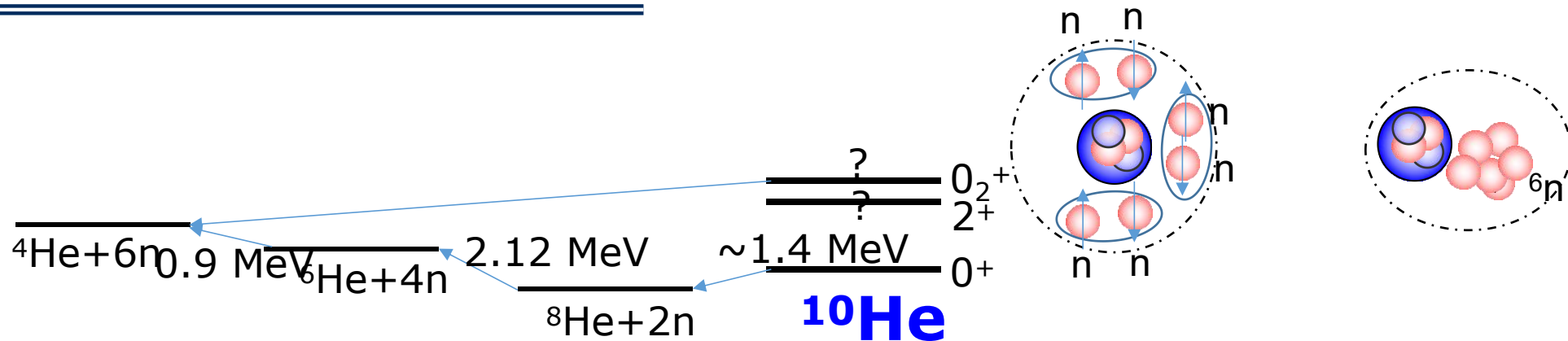
^{28}O measurement @ RIBF-SAMURAI

Nature, to be published

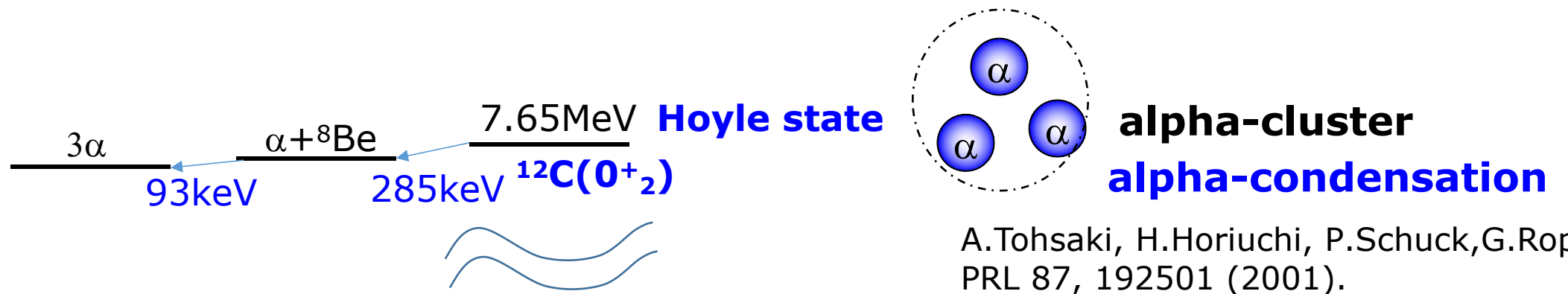


Perspectives

What happens if there are multiple dineutrons?



triple-dineutron or " $6n$ " ?



A.Tohsaki, H.Horiuchi, P.Schuck, G.Ropke, PRL 87, 192501 (2001).

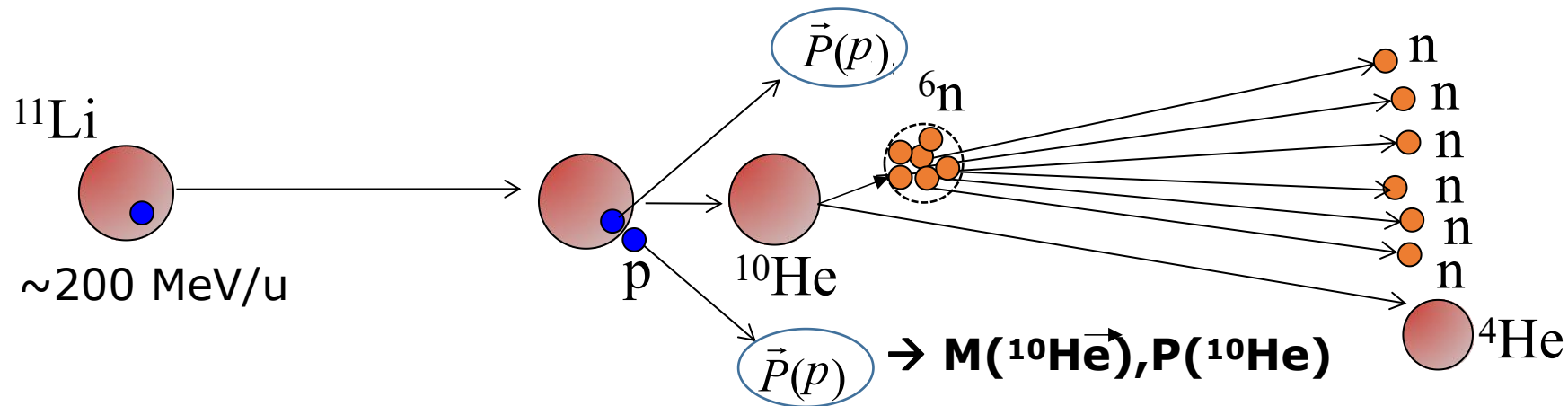
^{12}C

Search for Multi-neutron cluster state in ^{10}He via $^{11}\text{Li}(p,2p)$

+ tagging $^4\text{He}, ^6\text{He}, ^8\text{He}$, t and nn
at forward detectors

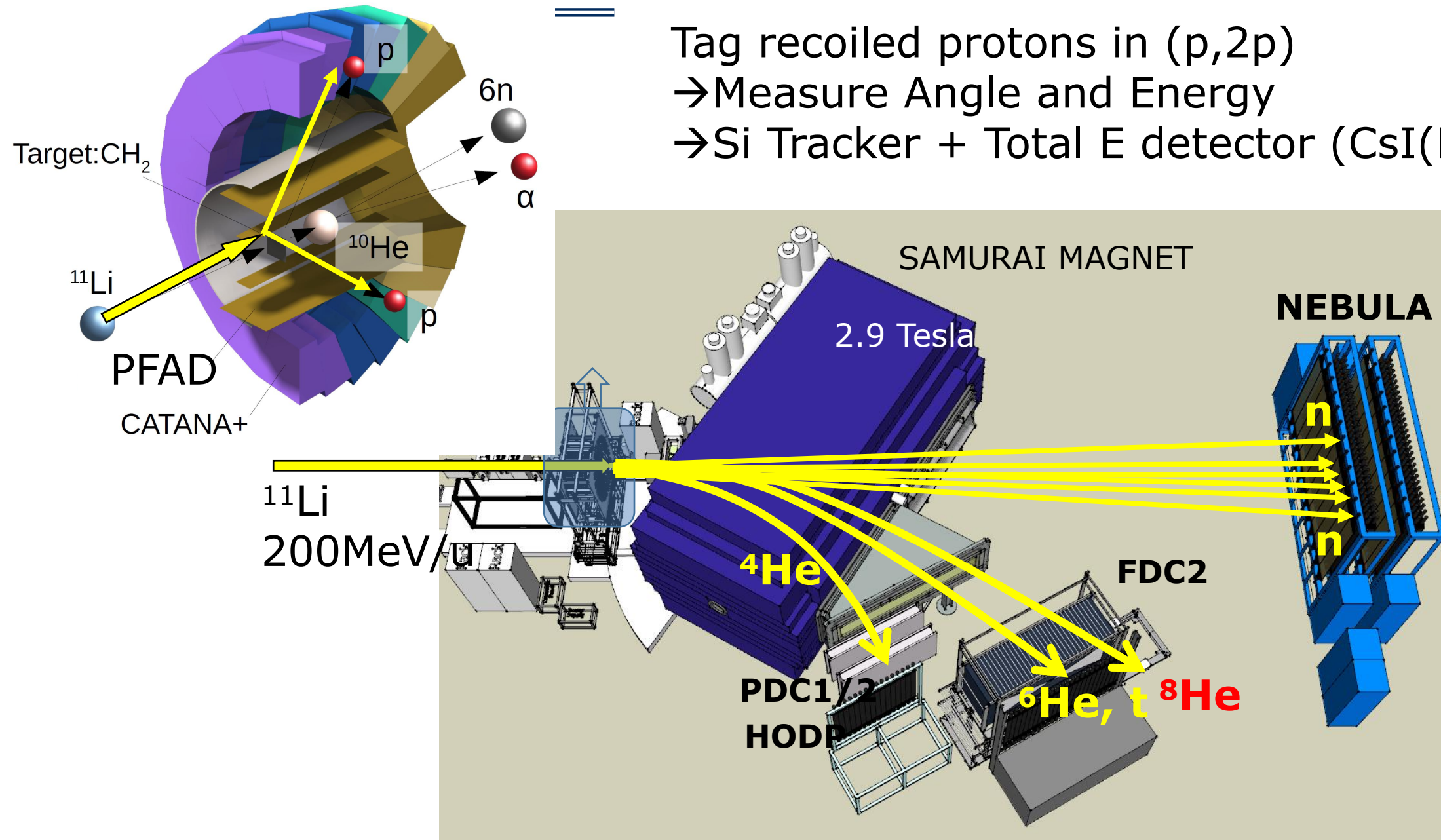
$^{11}\text{Li}(p,2p)^{10}\text{He}^*$

$^{10}\text{He}^* \rightarrow ^8\text{He} + 2n, ^6\text{He} + 4n, ^4\text{He} + 6n$



Planned Experimental Setup

Tag recoiled protons in (p,2p)
 → Measure Angle and Energy
 → Si Tracker + Total E detector (CsI(Na) Array)

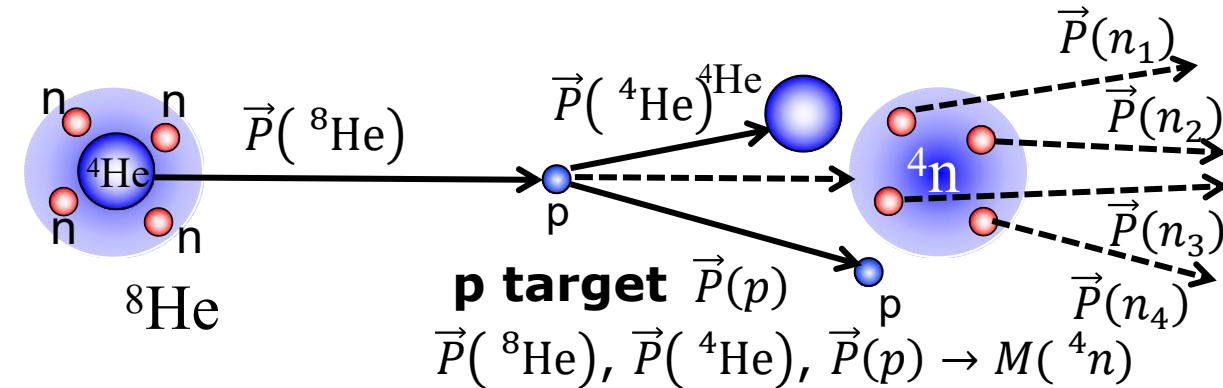


Next Step for multi-neutron systems/clusters

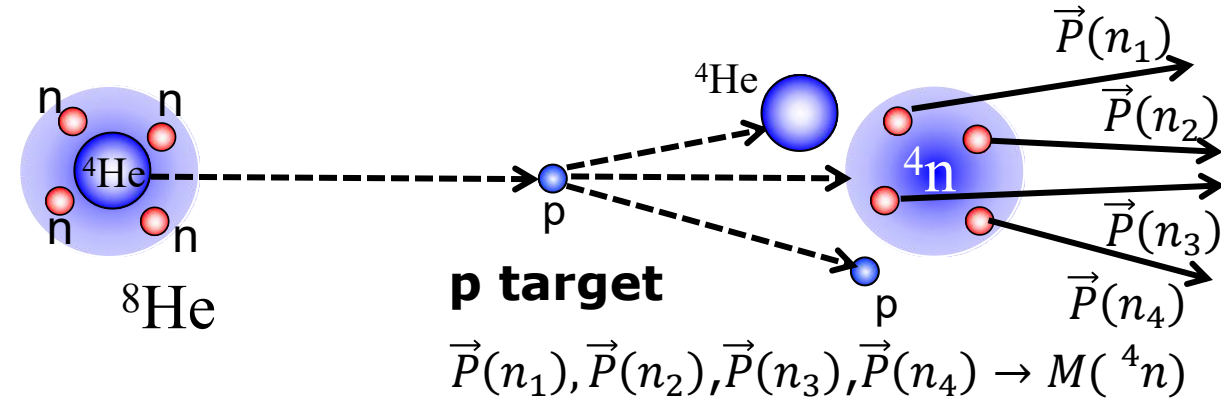
Missing mass method → Invariant Mass Method

Missing Mass

M.Duer Nature 2022



Invariant Mass



$$M(^4n) = \sqrt{\left(\sum_{i=1}^4 E_i\right)^2 - \left|\sum_{i=1}^4 \vec{P}(n_i)\right|^2}$$

- ❖ No need of neutron detections
- ❖ Worse mass-resolution: $\Delta M \sim 1\text{MeV}$
- ❖ Decay mode cannot be observed

- ❖ Good mass-resolution: $\Delta E \sim 100\text{keV}$
- ❖ Decay mode can be observed
- ❖ Need of neutron detection ($M_n > 2$: it is very difficult)

Summary: Lecture-III

✓ Key question: Are there nuclei made of only(mostly) "neutrons"?

✓ Tetra neutron

➤ 2022 Result from SAMURAI, RIBF: →Resonance

M.Duer et al. Nature **606**, 678 (2022).

$$E_{4n} = 2.37 \pm 0.38(stat) \pm 0.44(syst) \text{ MeV}$$

$$\Gamma = 1.75 \pm 0.22(stat) \pm 0.30(syst) \text{ MeV}$$

✓ Multi-neutron cluster beyond the drip line

➤ Super-heavy oxygen isotopes ^{27}O (3n emitter) and ^{28}O (4n emitter) :

Ground states of $^{27}\text{O}, ^{28}\text{O}$: Observed and Masses measured at SAMURAI

Both decay through $^{26}\text{O}_{gs}$

Y. Kondo et al., Submitted for publication

Perspectives

➤ More exotic neutron states: ^{10}He 6n

→Missing mass spectroscopy with PFAD/CATANA: expected to run in June 2023

➤ Missing Mass → Invariant mass spectroscopy for ^4n , ^6n

→Next generation neutron detector array (hopefully soon)

Article

Observation of a correlated free four-neutron system

<https://doi.org/10.1038/s41586-022-04827-6>

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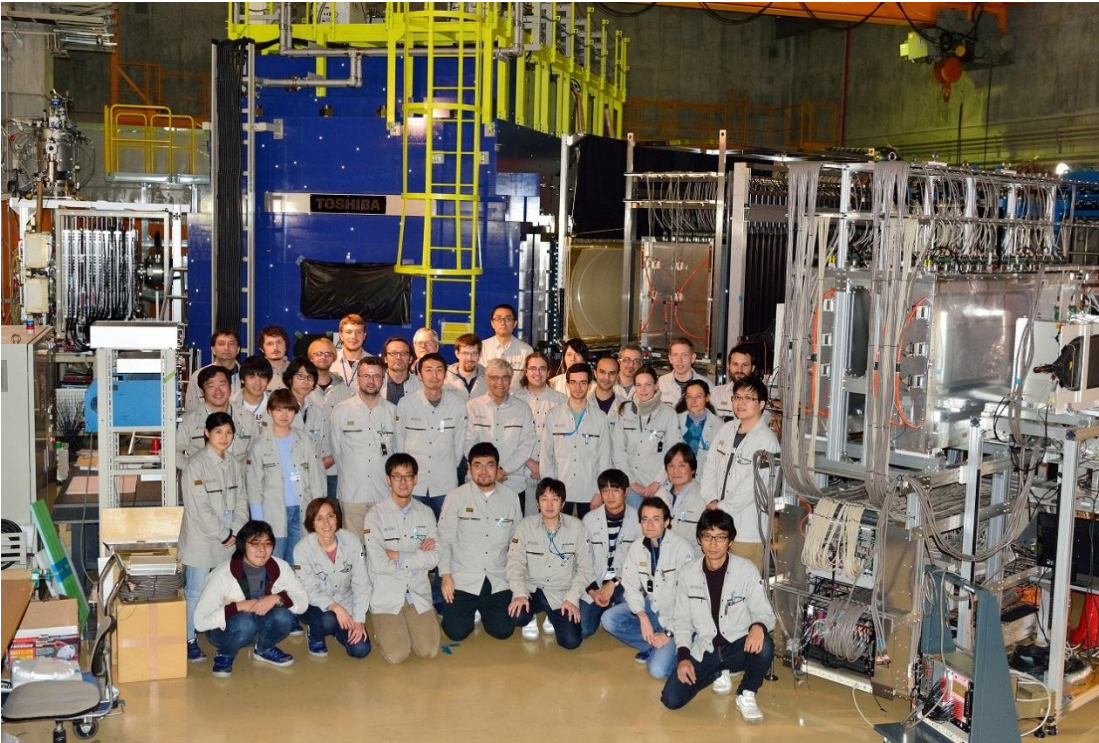
Open access



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SAMURAI21 collaboration—27,280



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, **M.Yasuda**, 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 (+few analysis)

25 Institutes

Backup

