Exploring multi-neutron decay nuclei

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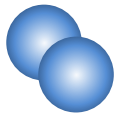
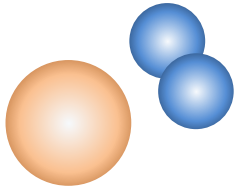
International Symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2022)

Oct.31 – Nov.3, 2022, Sendai, Japan

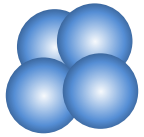
What structure do many neutrons have?



- 2n system (di-neutron)
  - Unbound in free space
  - Di-neutron correlation appears in nuclei (^{6}He, ^{11}Li, ^{19}B)

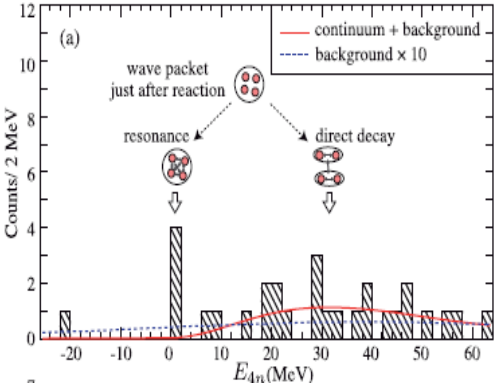


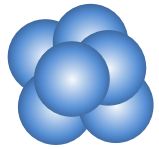
Y. L. Sun et al., Phys. Lett B**814**, 136072 (2021)
T. Nakamura et al., Phys.Rev.Lett.**96**, 252502(2006)
Y. Kubota et al., Phys.Rev.Lett.**125**, 252501(2020)
K. J. Cook et al., Phys.Rev.Lett.**124**, 212503(2020)



- 4n system (tetra-neutron)
  - Resonance?
  - 4n cluster or 2x2n clusters in n-rich nuclei?

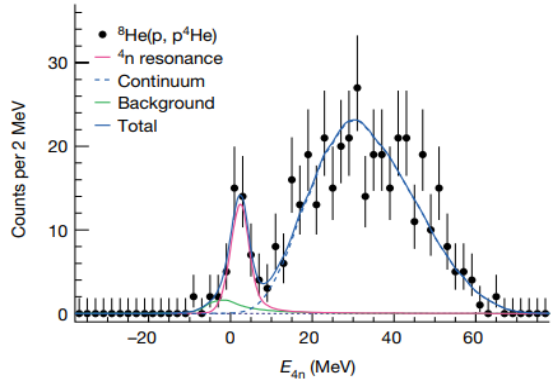
K. Kisamori et al., Phys.Rev.Lett. **116**,052501(2016)





- 6n system (hexa-neutron)

M.Duer et al., Nature **606,** 678-682(2022)

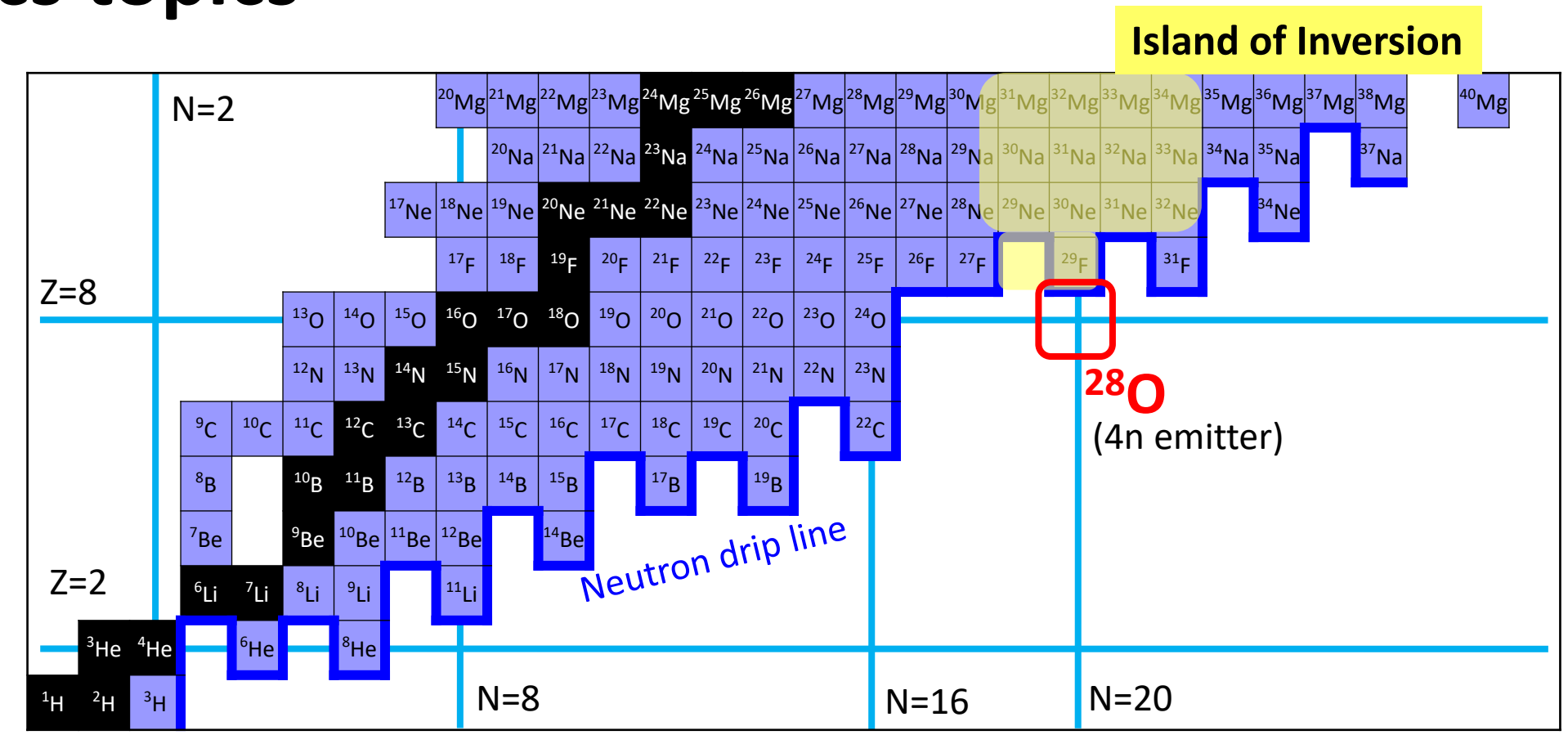


Expected to appear in very neutron-rich nuclei

Contents

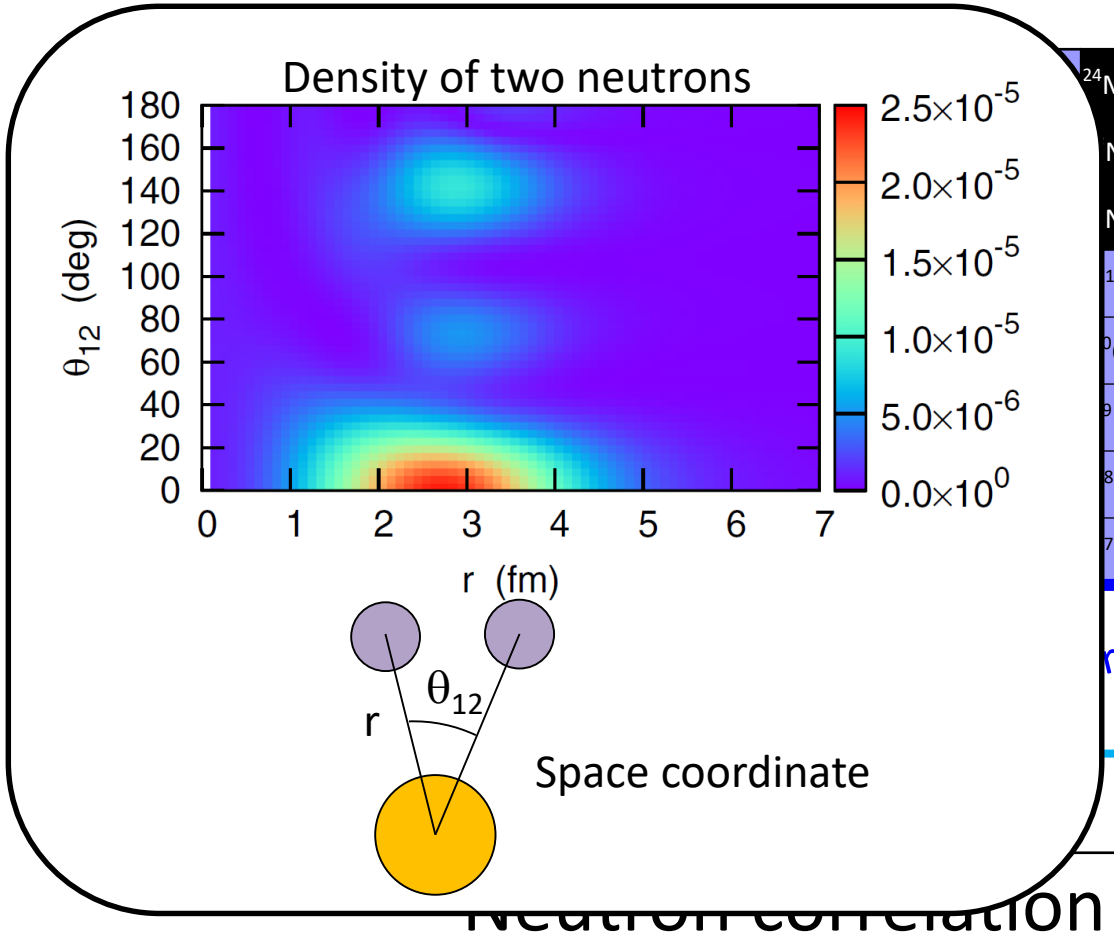
- Study of extremely neutron-rich nuclei ^{27,28}O
- Search for multi-neutron cluster in ^{10}He

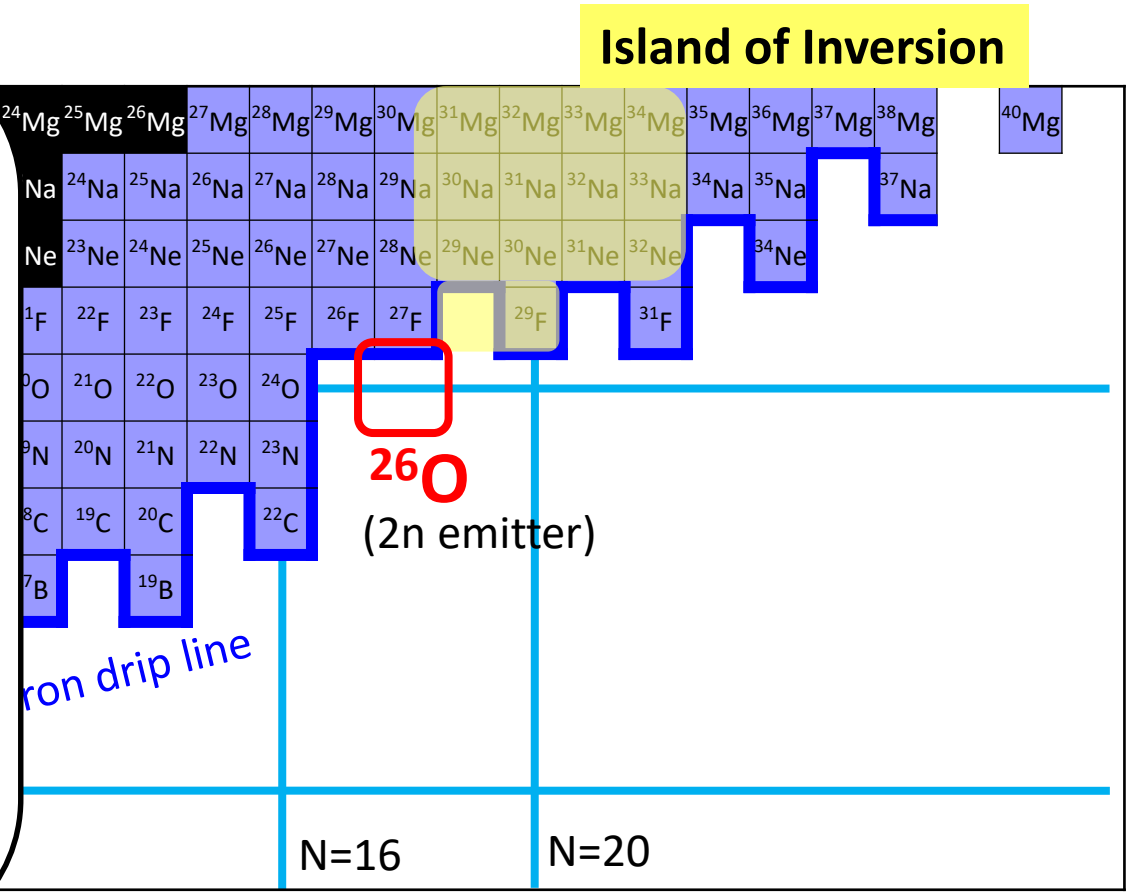
Physics topics



- Neutron correlation
- Island of inversion
- Sudden change of neutron drip line (Oxygen anomaly)

Di-neutron correlation



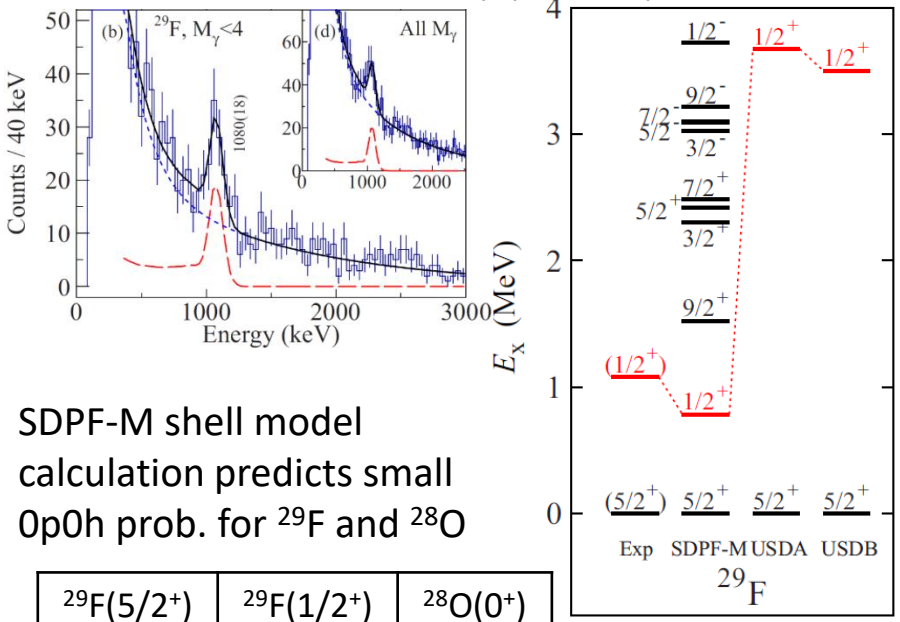


Neutron correlation

- Di-neutron correlation is predicted in ^{26}O
  - K. Hagino et al., PRC89, 014331 (2014)
- What's happen in ^{28}O?

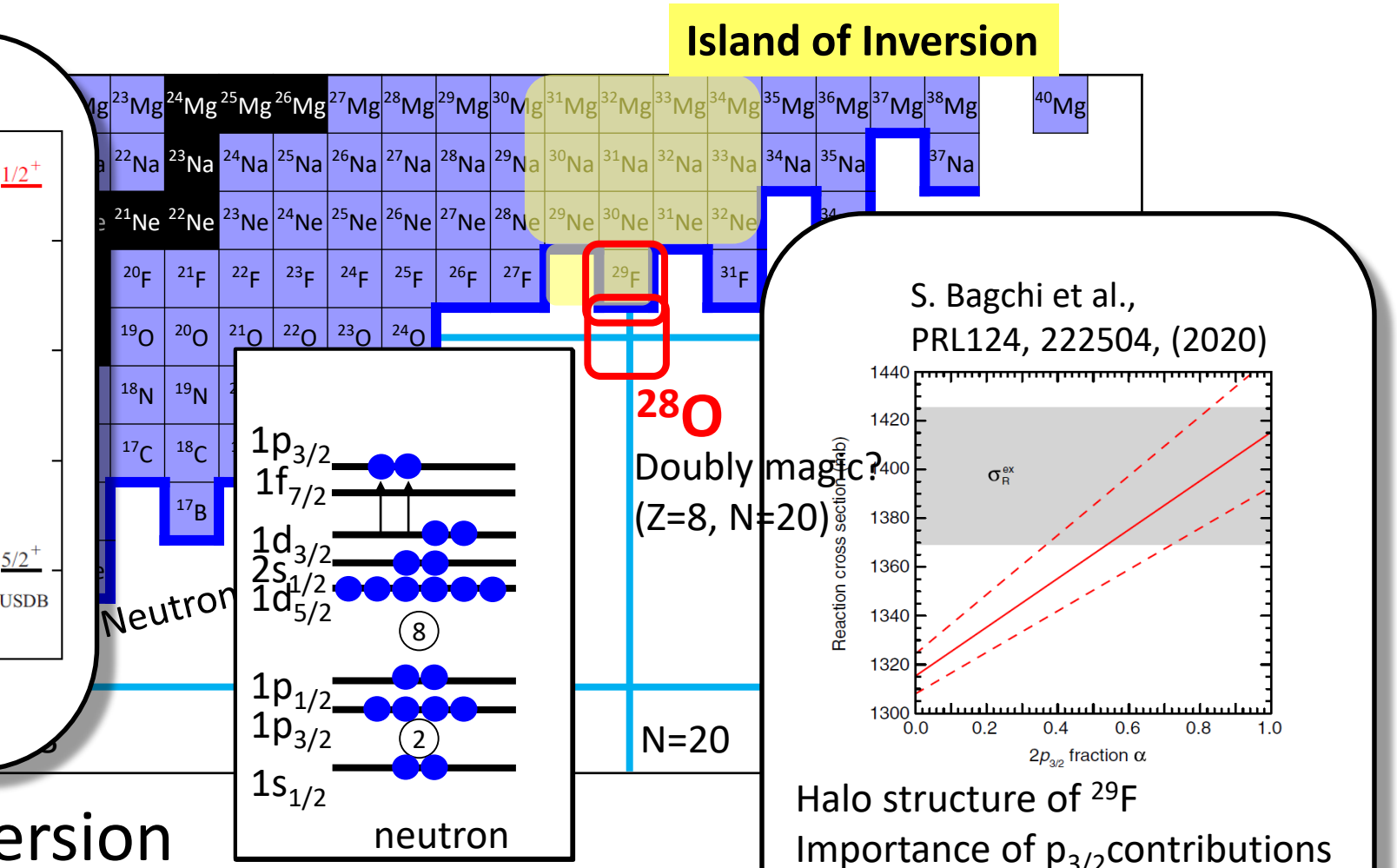
Island of inversion

P. Doornenbal, Y.K et al.,
PRC95, 041301(R), (2017)



SDPF-M shell model calculation predicts small 0p0h prob. for ^{29}F and ^{28}O

^{29}F(5/2$^+$)	^{29}F(1/2$^+$)	^{28}O(0$^+$)
7.9%	1.0%	10.9%



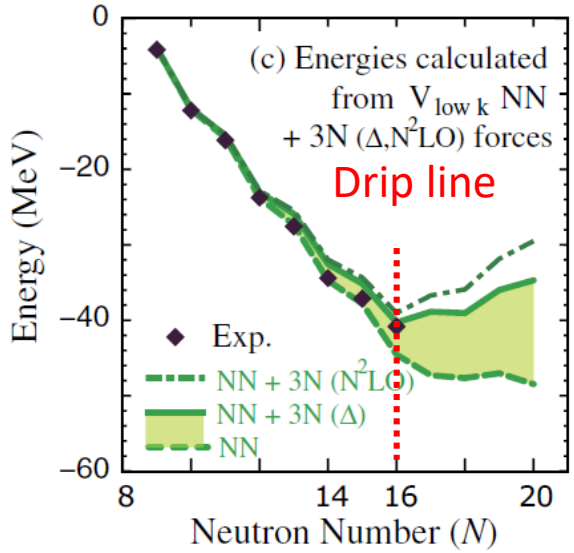
S. Bagchi et al.,
PRL124, 222504, (2020)

Halo structure of ^{29}F
Importance of $p_{3/2}$contributions
→ Disappearance of N=28 shell closure

- Island of inversion
  - Where is the south boundary?
  - Is ^{28}O doubly magic?

Oxygen anomaly

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



3NF plays an important role in binding of oxygens

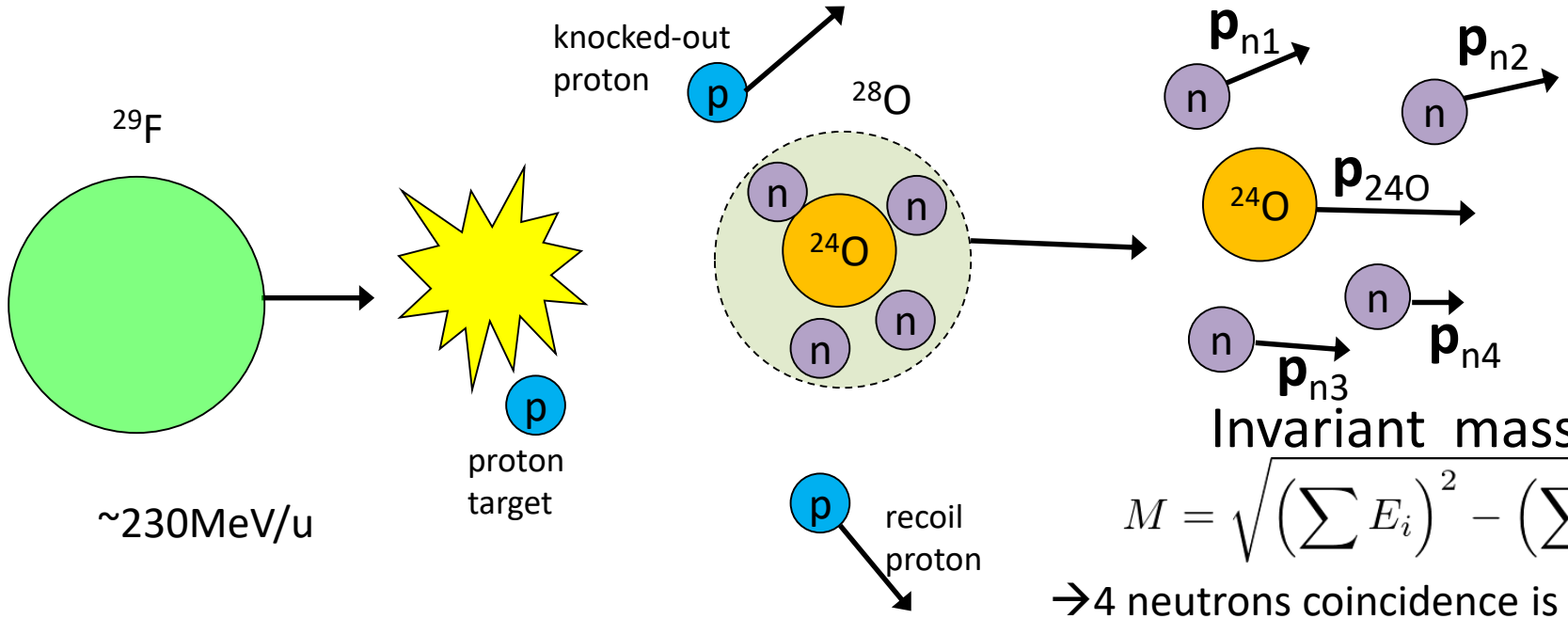
G. Hagen et al., PRL108, 242501 (2012)
J. Holt et al., Eur.Phys. J.A49, 39 (2013)

neutron drip line (Oxygen anomaly)

– What is the origin?

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

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



Invariant mass

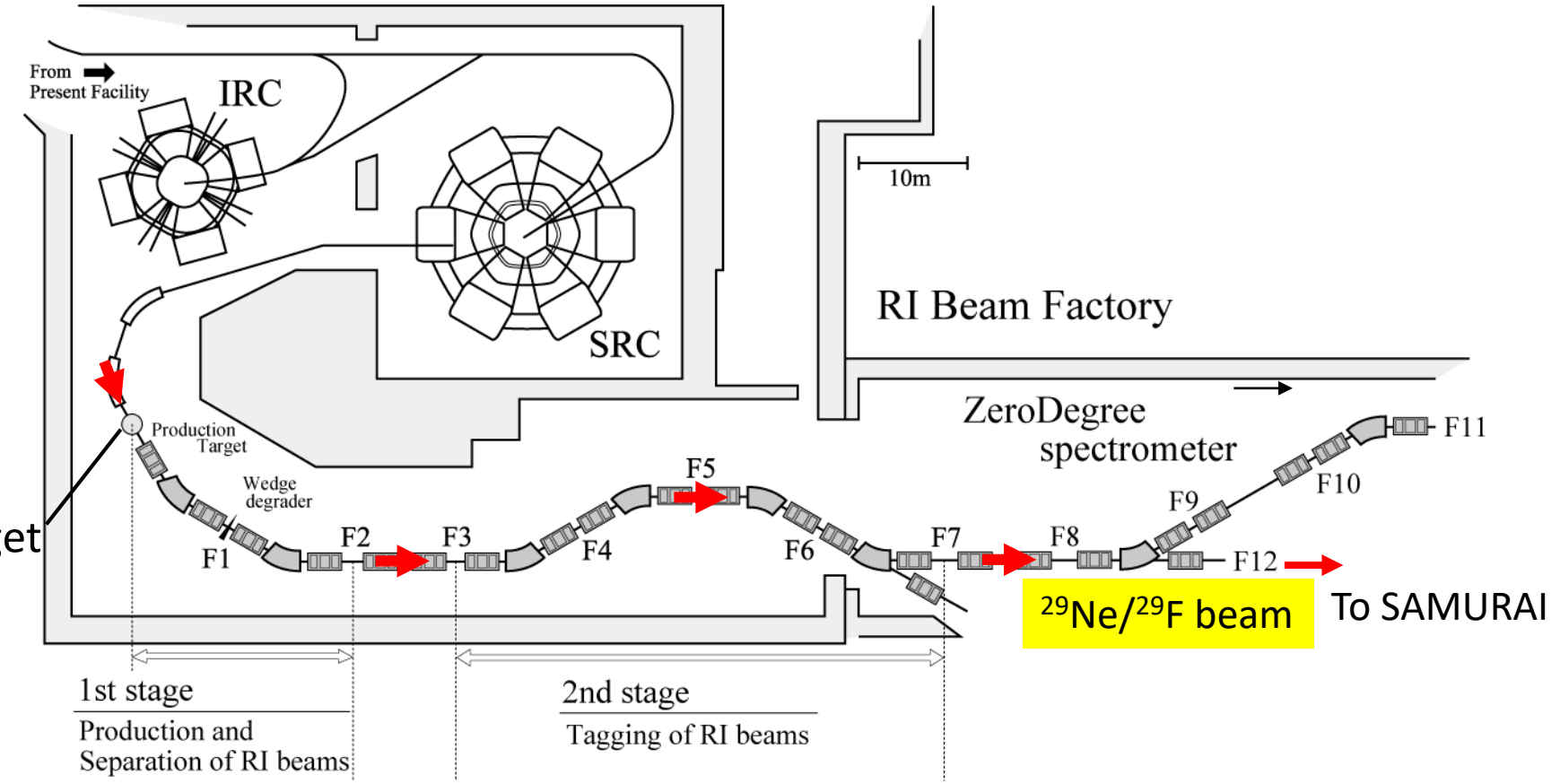
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \mathbf{p}_i\right)^2}$$

→4 neutrons coincidence is needed

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

Experiment @ RIKEN-RIBF

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



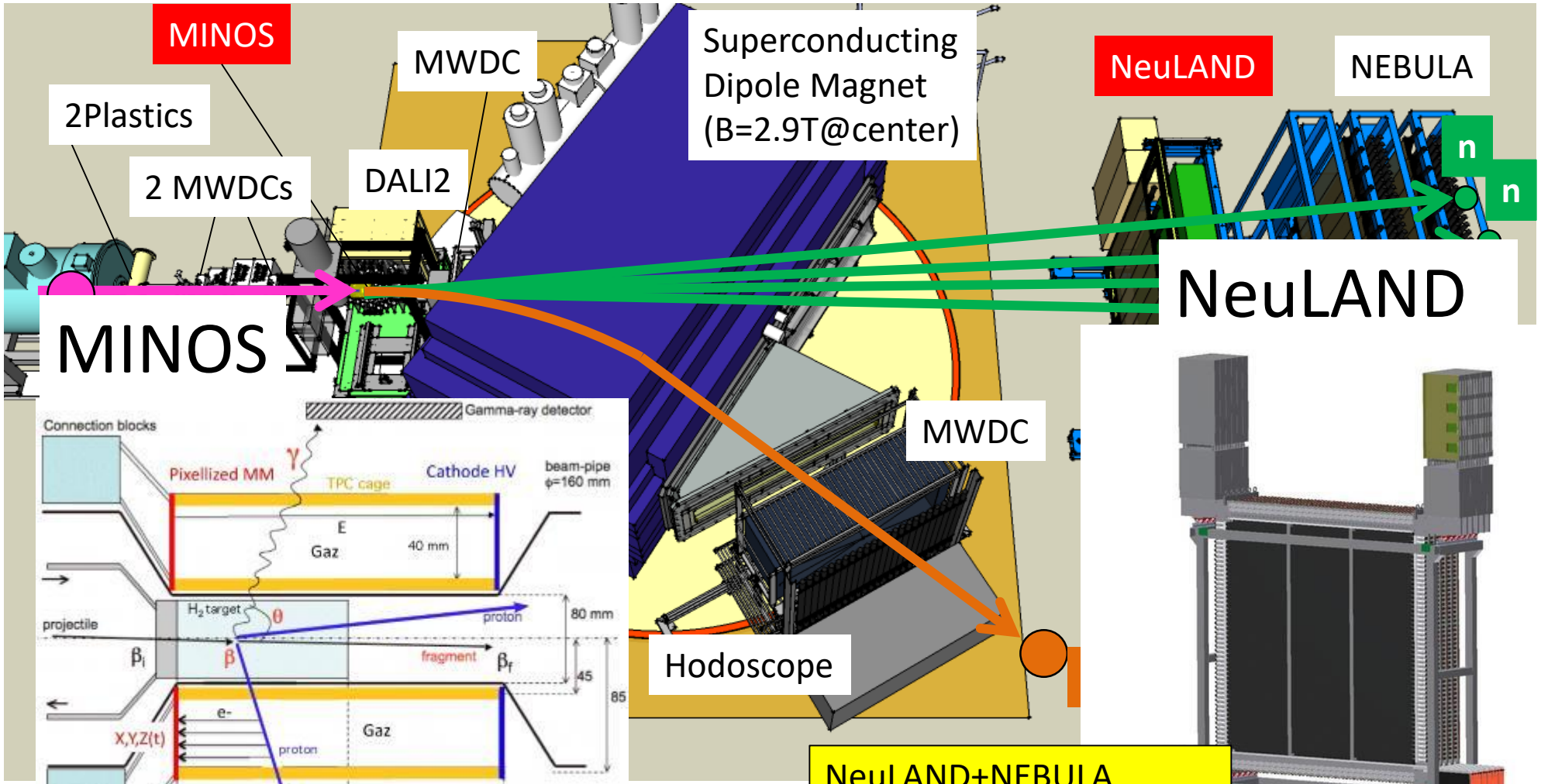
^{9}Be target

^{29}Ne/^{29}F beam

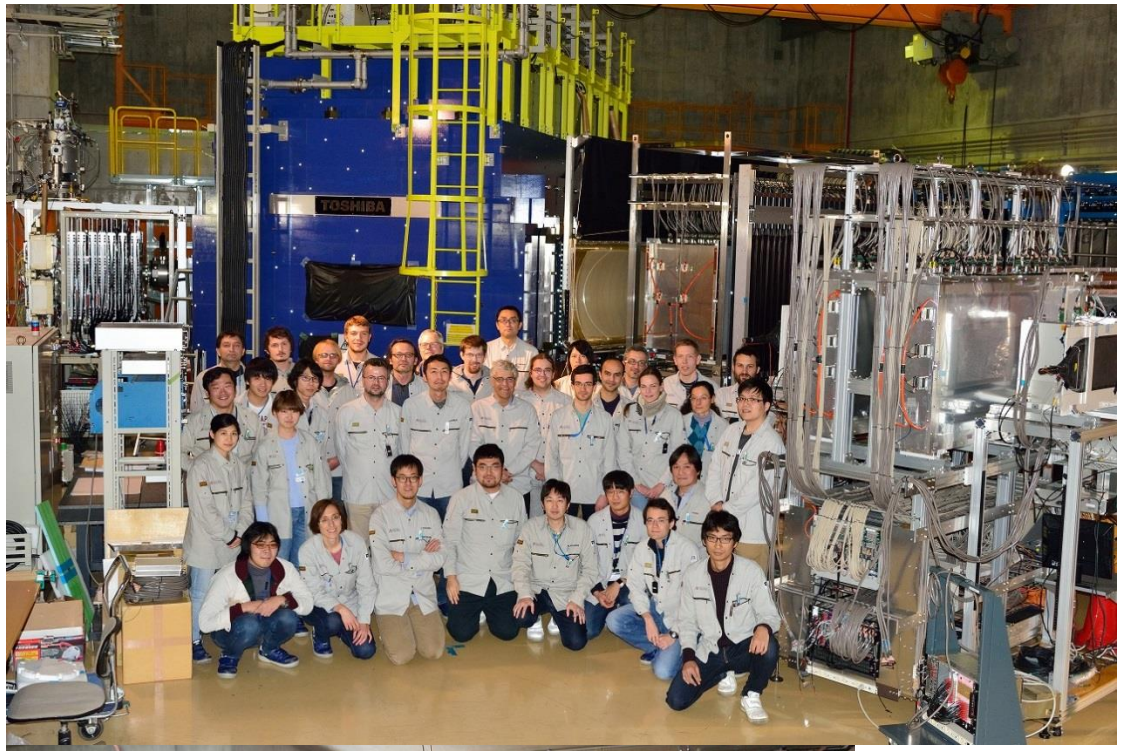
To SAMURAI

BigRIPS Selection/identification of secondary beam

^{28}O measurement @ RIBF-SAMURAI



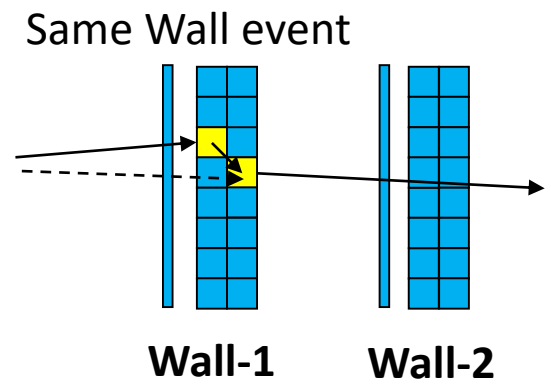
SAMURAI21 collaboration

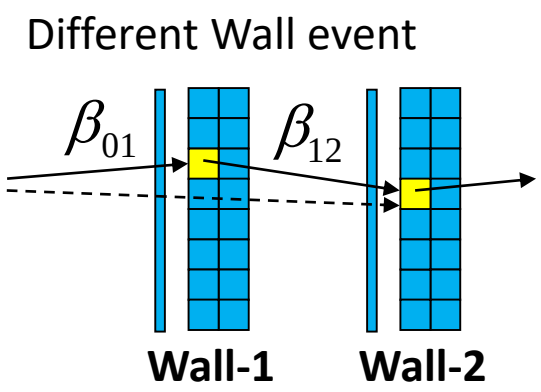


Y.Kondo, T.Nakamura, N.L.Achouri, H.Al Falou, L.Atar, T.Aumann, H.Baba, K.Boretzky, C.Caesar, D.Calvet, H.Chae, N.Chiga, A.Corsi, H.L.Crawford, F.Delaunay, A.Delbart, Q.Deshayes, Zs.Dombrádi, C.Douma, Z.Elekes, P.Fallon, I.Gašparić, J.-M.Gheller, J.Gibelin, A.Gillibert, M.N.Harakeh, A.Hirayama, C.R.Hoffman,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

Neutron crosstalk



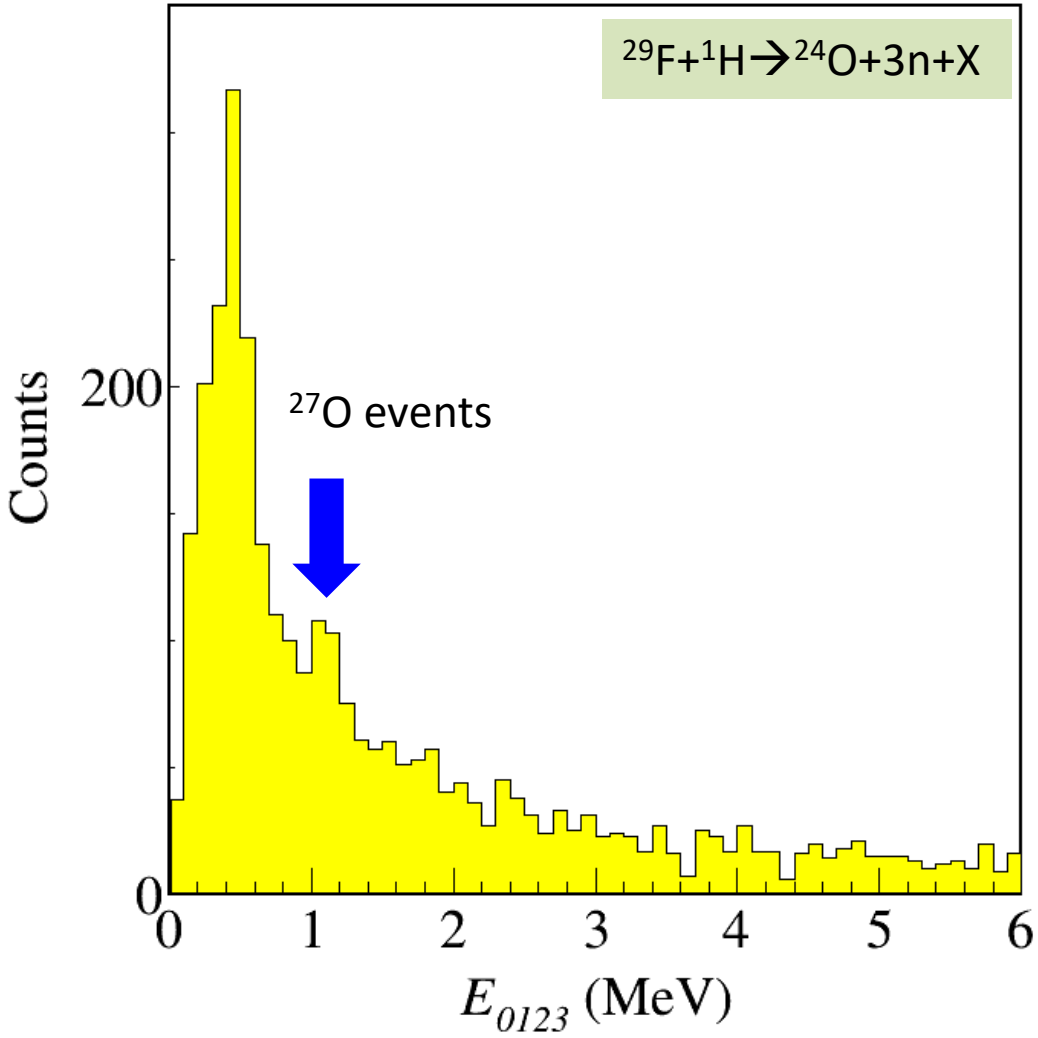


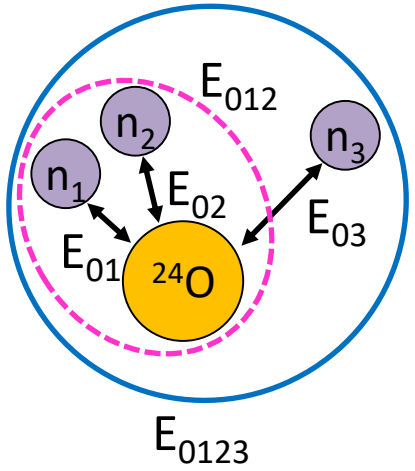
hit detector

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

T. Nakmura et al., Nucl. Instrum. Methods B**376**,156 (2016)
Y. Kondo et al., Nucl. Instrum. Methods B**463**, 173 (2020)

Decay energy spectrum (^{24}O+3n coincidence)

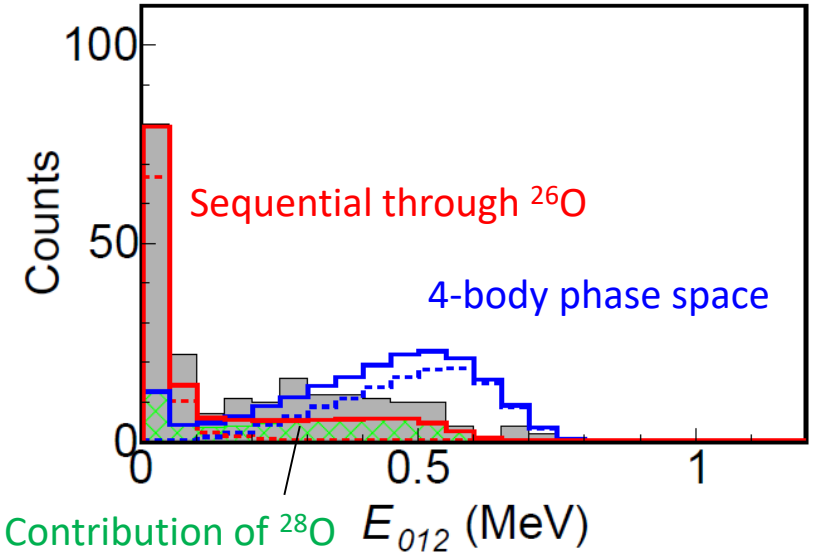


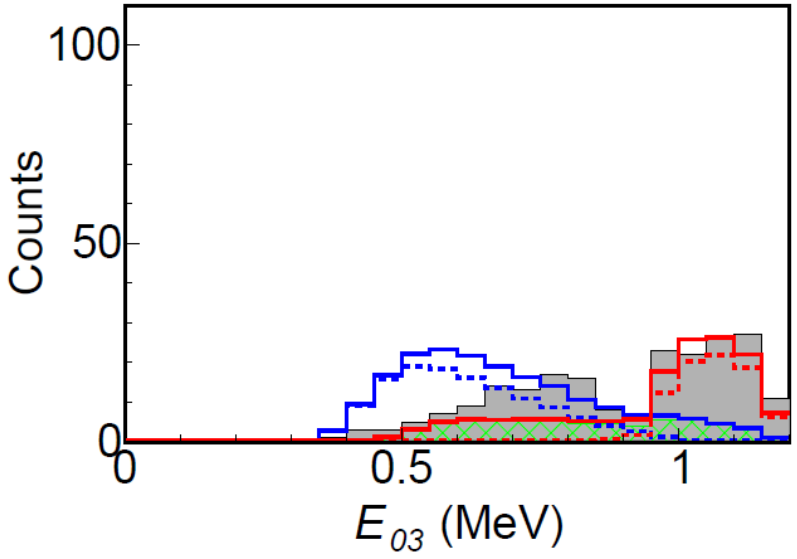


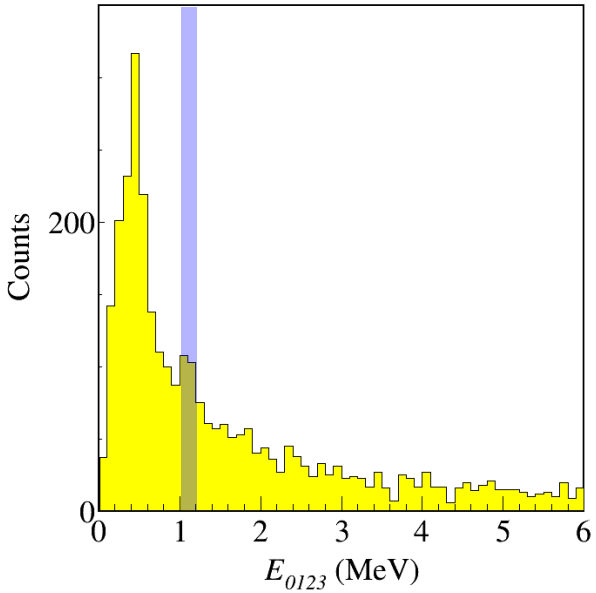
$E_{01}<E_{02}<E_{03}$

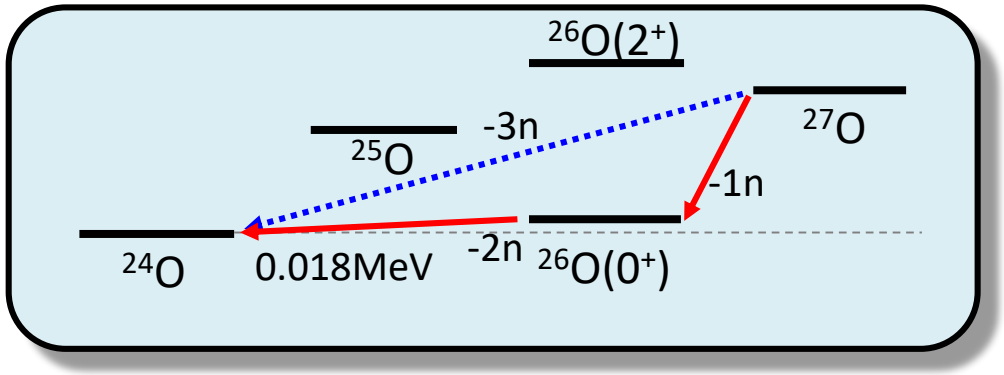
Correlation in ^{27}O decay

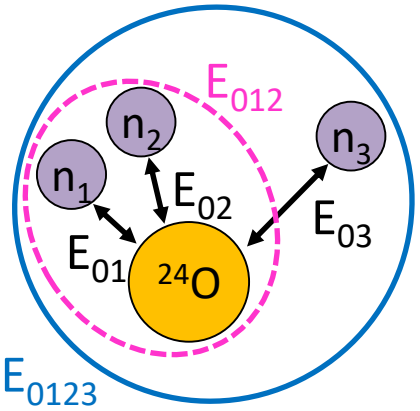
1.0 MeV < E_{0123} < 1.2 MeV





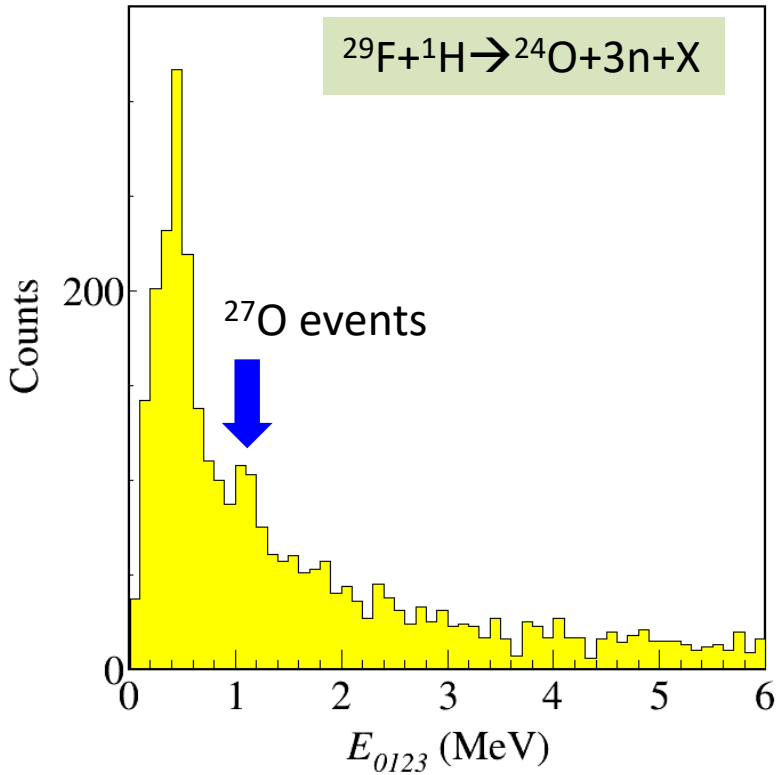


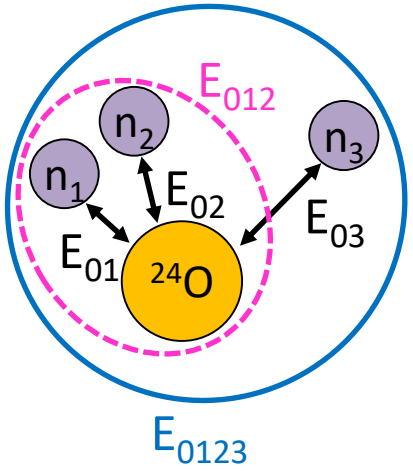




E_{01}<E_{02}<E_{03}

Decay energy spectrum (^{24}O+3n coincidence)





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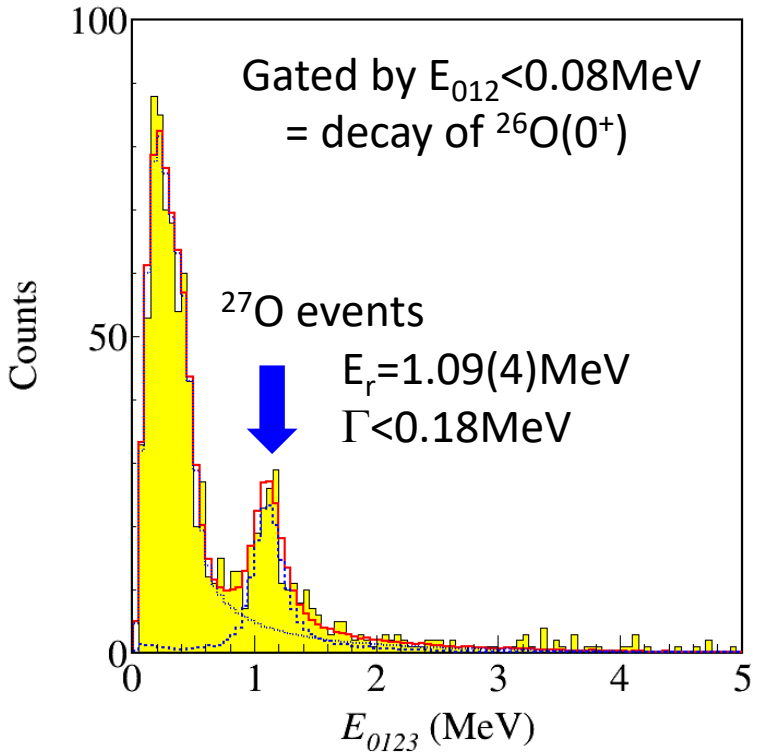
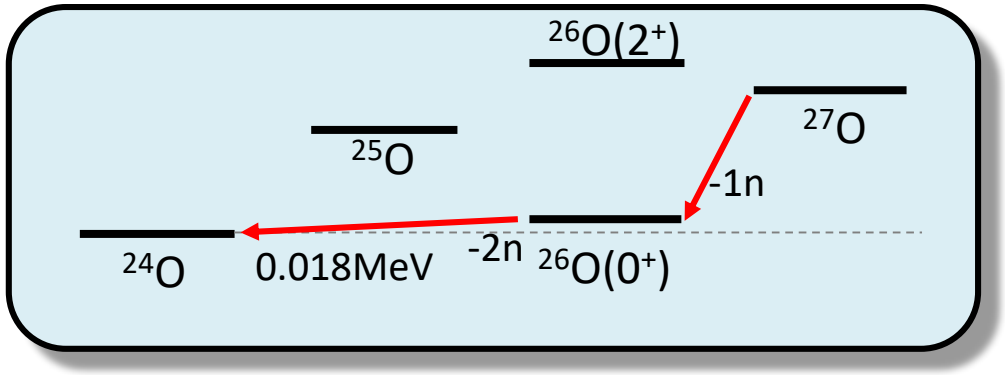




Systematic error of E_r : 0.02MeV

Decay energy spectrum (^{24}O+4n coincidence)

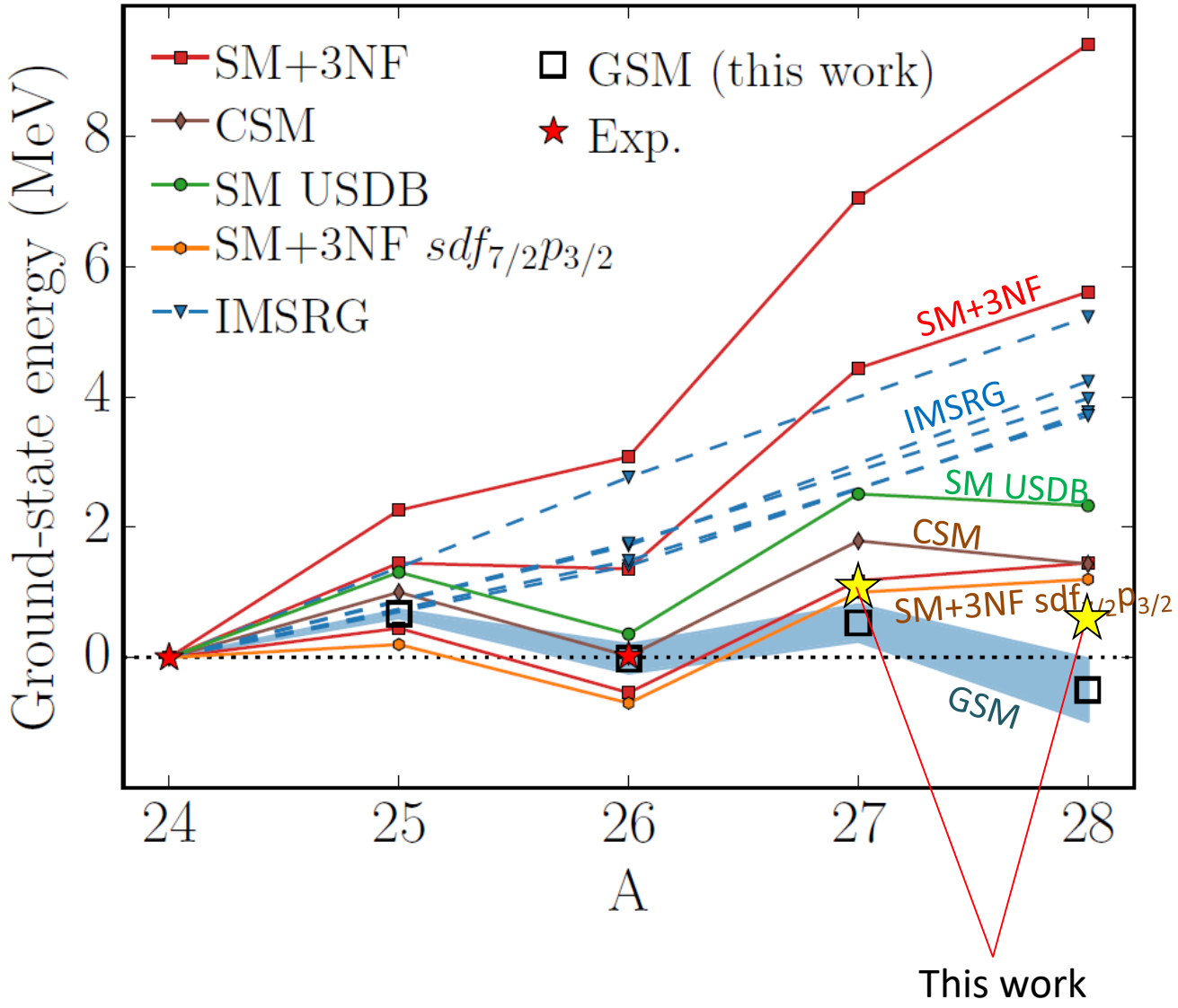
$^{29}F+^{1}H \rightarrow ^{24}O+4n$

^{28}O ground state

Success of 4n coincidence detection!

Theoretical predictions towards ^{28}O

K. Fossez et al., PRC 96, 024308 (2017)



SM USDB: B. A. Brown, Int. J. Mod. Phys. E26, 1740003 (2017)

SM+3NF: T. Otsuka et al., PRL105, 032501 (2010)

SM+3NF $sdf_{7/2}p_{3/2}$:

CSM: A. Volya et al., PRL94, 052501 (2005), A. Volya et al., PRC74, 064314, (2006)

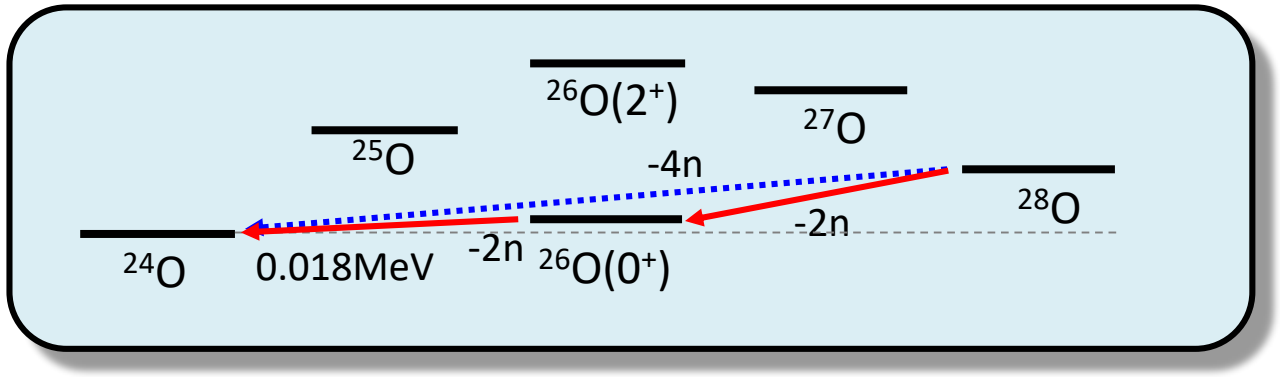
IMSRG: V. Lapux et al., PRL117, 052501, (2016), H. Hergert, private communication

Correlation in ^{28}O decay

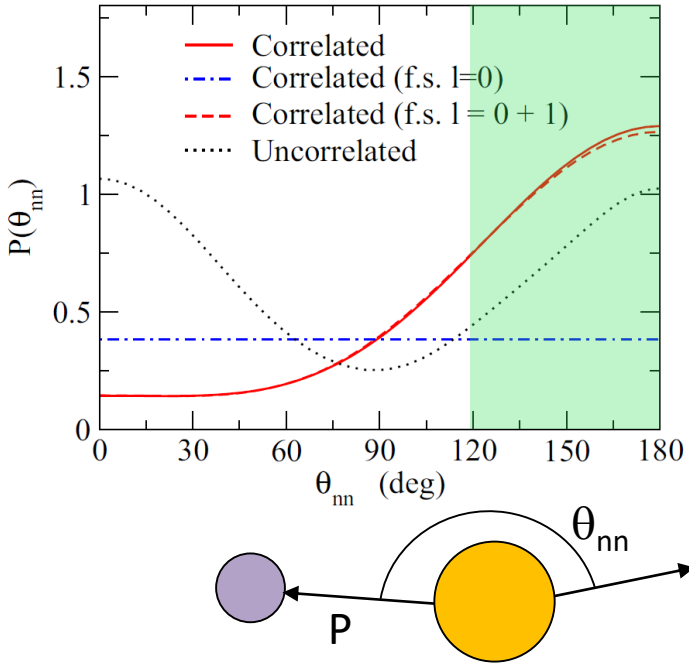
E_{01234} < 1.0 MeV

Sequential through ^{26}O

5-body phase space



K. Hagino et al., PRC89, 014331 (2014)
Opening angle of momentum vectors in ^{26}O decay



Dineutron correlation enhances back-to-back 2n emission

Future perspectives

Study of opening angle

→ di-neutron correlation in ^{26,28}O?

Contents

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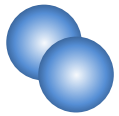
Multi-neutron system and multi-neutron cluster structure



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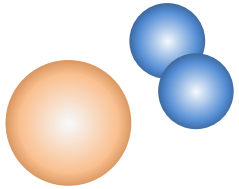
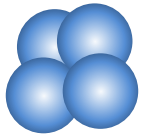
  - Di-neutron correlation appears in nuclei (^{6}He, ^{11}Li, ^{19}B)



Y. L. Sun et al., Phys. Lett B**814**, 136072 (2021)
T. Nakamura et al., Phys.Rev.Lett.**96**, 252502(2006)
Y. Kubota et al., Phys.Rev.Lett.**125**, 252501(2020)
K. J. Cook et al., Phys.Rev.Lett.**124**, 212503(2020)



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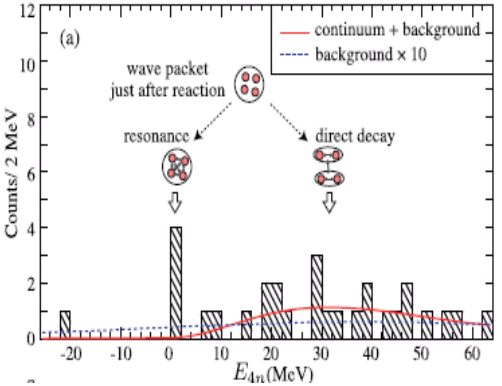
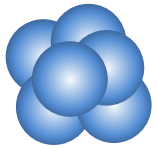
K. Kisamori et al., Phys.Rev.Lett. **116**,052501(2016)





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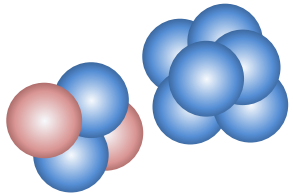
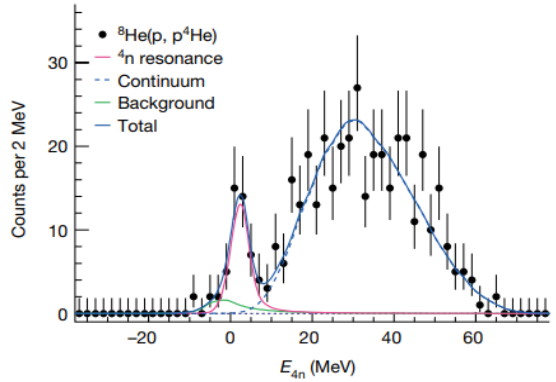
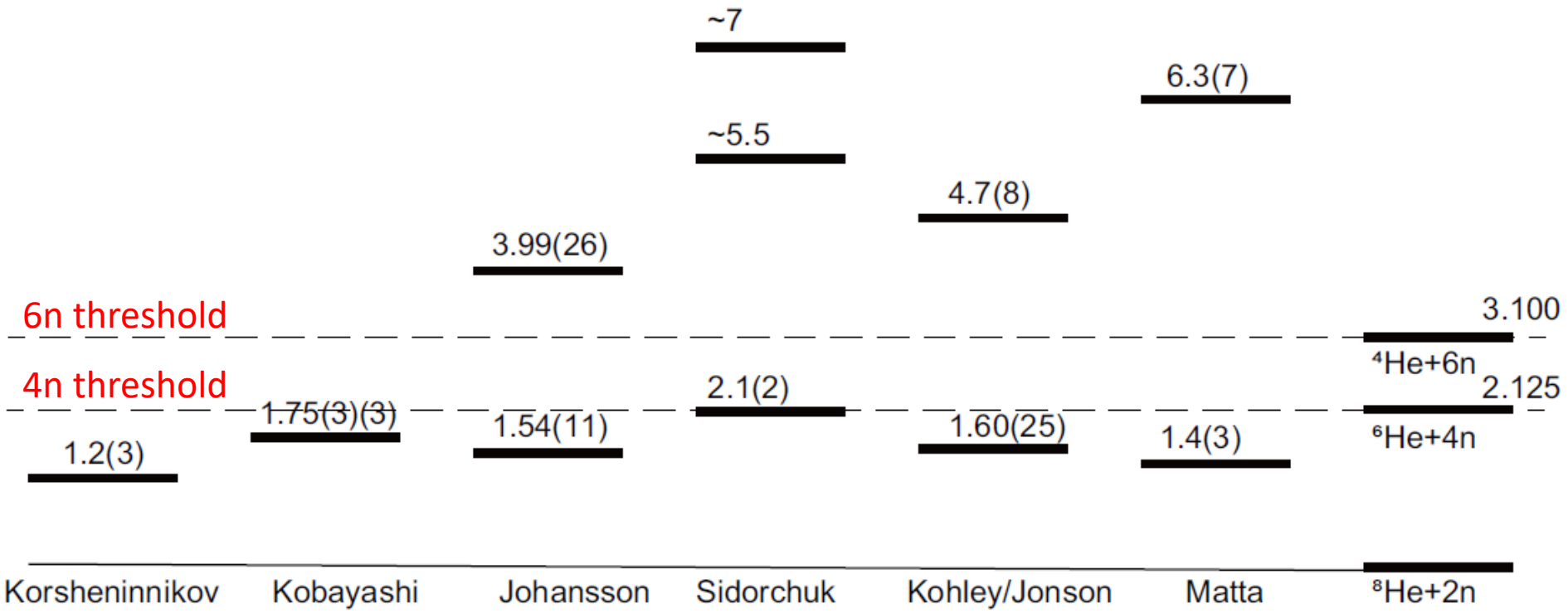


^{10}He (^{4}He+6n)

M.Duer et al., Nature **606,** 678-682(2022)



Previous experiments for ^{10}He



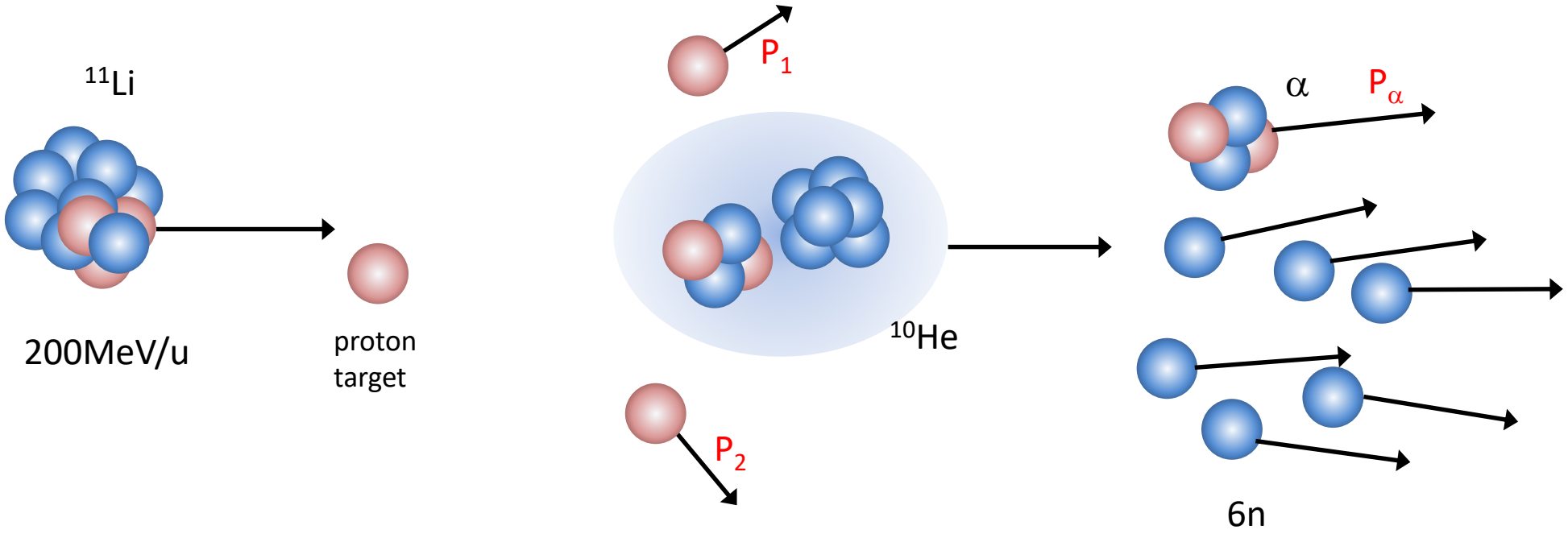
No conclusive data for excited states

Close to the 4He+6n threshold

→ <u>6n cluster structure</u>

A. Korsheninnikov *et al*, Phys. Lett. B **326**, 31 (1994).
T. Kobayashi *et al*, Nucl. Phys. A **616**, 223c (1997).
H.T. Johansson *et al*, Nucl. Phys. A **842** 15 (2010).
H.T. Johansson *et al*, Nucl. Phys. A **847** 66 (2010).
S.I. Shidochuk *et al.*, Phys. Rev. Lett. **108** 202502 (2012)
Z. Kohley *et al*, Phys. Rev. Lett. **109**, 232501 (2012).
M.D. Jones *et al.*, Phys. Rev. C **91**, 044312 (2015).
A. Matta *et al.*, Phys. Rev. C **92**, 041302(R) (2015).

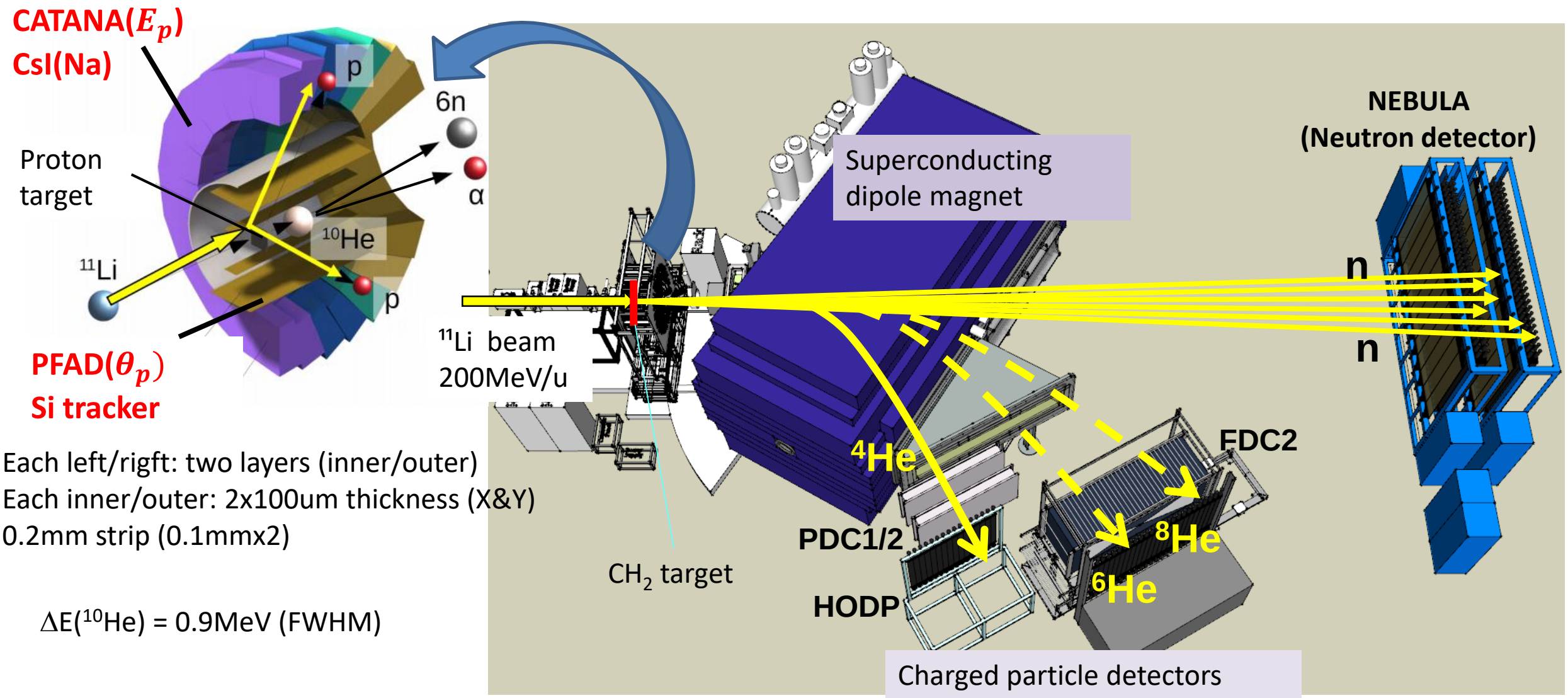
Missing mass method in ^{11}Li(p,2p) reaction



$$(M_{^{10}He})^2 = \left(\sqrt{(M_{^{11}\mathrm{Li}})^2 + (\vec{\mathrm{P}}_{^{11}\mathrm{Li}})^2} + M_p - \sqrt{(M_p)^2 + (\vec{P_1})^2} - \sqrt{(M_p)^2 + (\vec{P_2})^2}\right)^2 - (\vec{\mathrm{P}}_{^{11}\mathrm{Li}} - \vec{P_1} - \vec{P_2})^2$$

$$(M_{6n})^2 = \left(\sqrt{(M_{^{10}\mathrm{He}})^2 + (\vec{\mathrm{P}}_{^{10}\mathrm{He}})^2} - \sqrt{(M_\alpha)^2 + (\vec{P_\alpha})^2}\right)^2 - (\vec{\mathrm{P}}_{^{10}\mathrm{He}} - \vec{P_\alpha})^2$$

Experimental setup (RIBF, RIKEN)

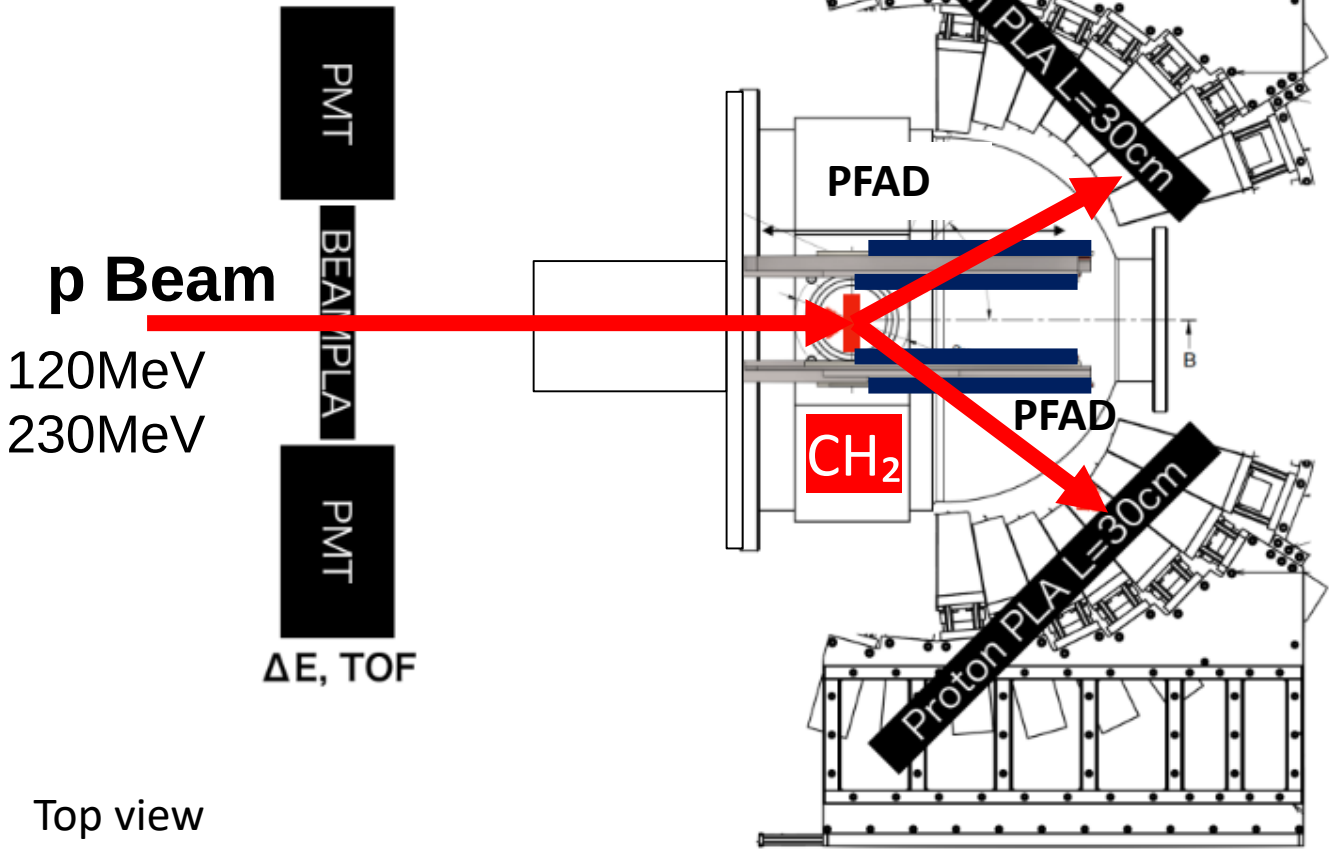


Each left/rigft: two layers (inner/outer)
Each inner/outer: 2x100um thickness (X&Y)
0.2mm strip (0.1mmx2)

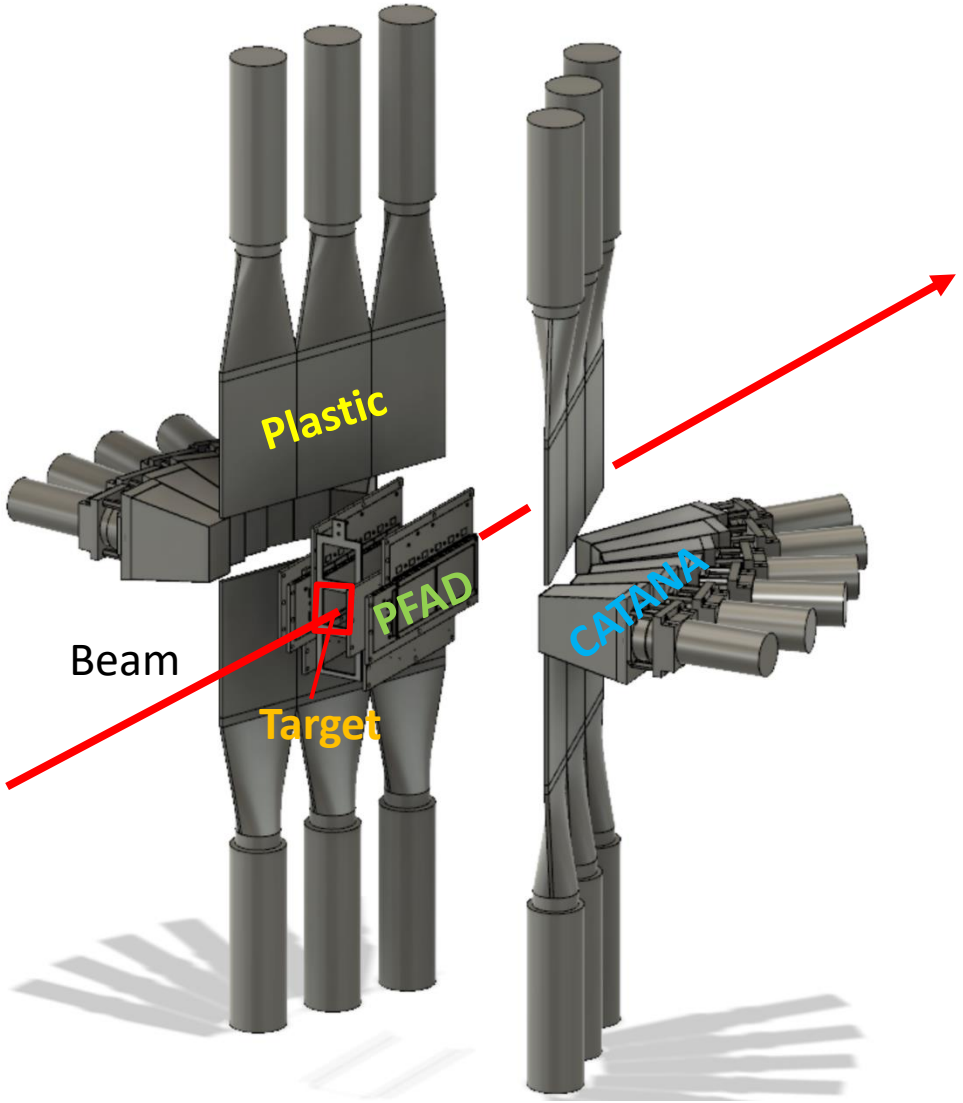
$\Delta E(^{10}He)$ = 0.9MeV (FWHM)

PFAD Test experiment @ HIMAC

東工大理[A], 理研[B], TU Darmstadt[C], LPC Cean[D], 立教大理[E], 北京師範大理[F]
松井智輝[A], 近藤洋介[A], 中村隆司[A], 佐藤義輝[A], 堀川晃太[A], 礒部駆[A], H.Lee[A],
栂野泰宏[B], 笹野匡紀[B], 大津秀暁[B], 田中純貴[B], 王赫[B], P.Doornenbal[B],
V.Alicindor[C], A. Obertelli[C], M. Enciu[C], A. Matta[D], F. Flavigny[D],武重祥子[E], H.**N.** Liu[F]

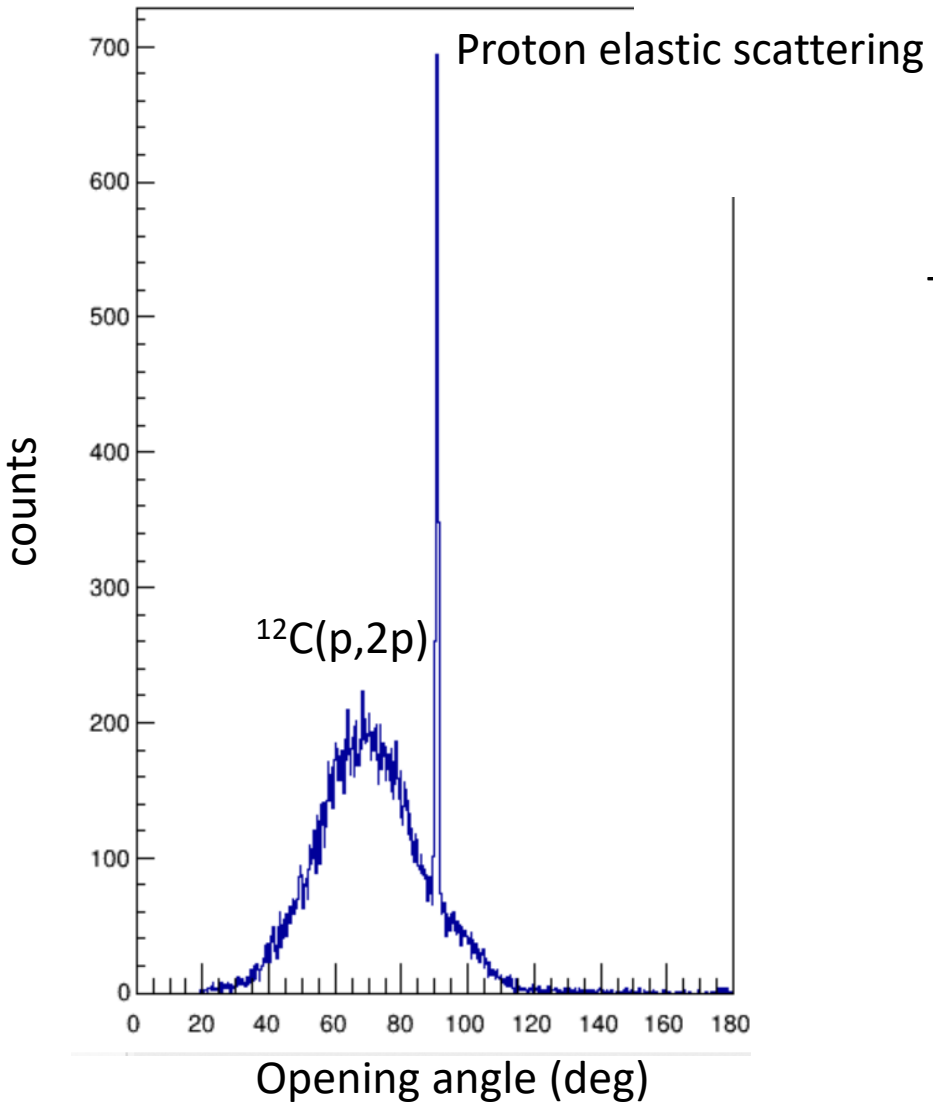


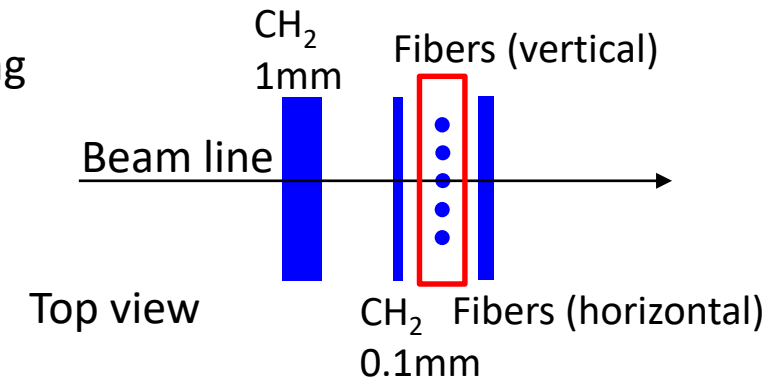
Top view



Analyzed by T. Matsui

Preliminary results of test exp.

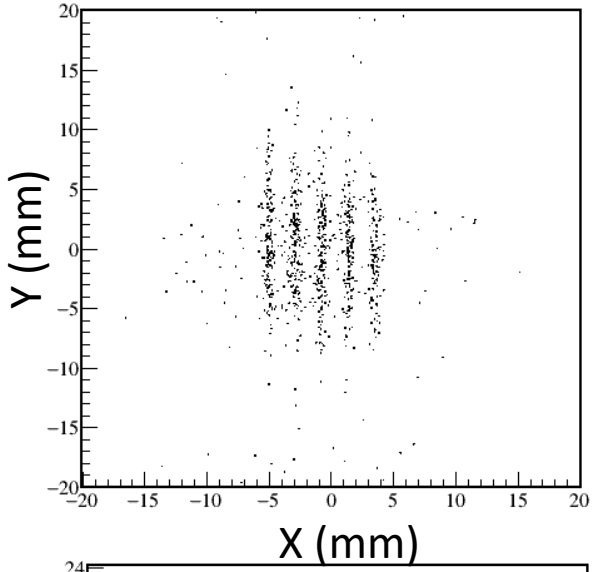


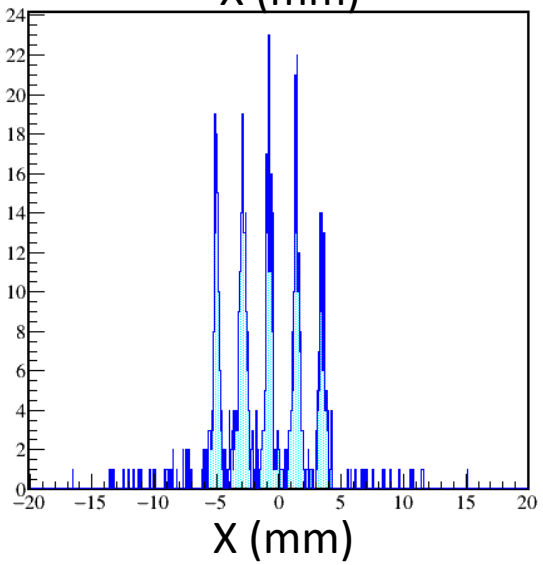


Backside view

Fibers
0.25mm
diameter

Gated by fiber layer
(-5.0mm < Z < -3.5mm)





^{11}Li(p,2p)^{10}He experiment in January

NEBULA → NEBULA Plus (upgrade)

Aug.29

2 Wall config.

120 neutron detectors

→

4 Wall config.

90 new detectors from LPC-CAEN

120+90 neutron detectors

Enables 4 neutron coincidence detection

Oct.04

Setting up is still going on for coming experiment

Summary

- Study of extremely neutron-rich oxygen isotopes
  - First observation of ^{27,28}O
  - Sequential decay through ^{26}O ground state

- Search for 6 neutron cluster in ^{10}He
  - Test of PFAD (Si tracker) @ HIMAC
    - Vertex reconstruction works successfully
  - ^{11}Li(p,2p)^{10}He experiment : Beam time is scheduled in January