エキゾチック核子多体系で紐解く物質の階層構造（B02班）

Exotic nuclei for investigating hierarchical structure of matter (Grp-B02)

中村隆司

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Kickoff Symposium, “Clustering as a window on the hierarchical structure of quantum systems”,
O-Okayama Campus, Tokyo Institute of Technology, Nov. 19-20, 2018

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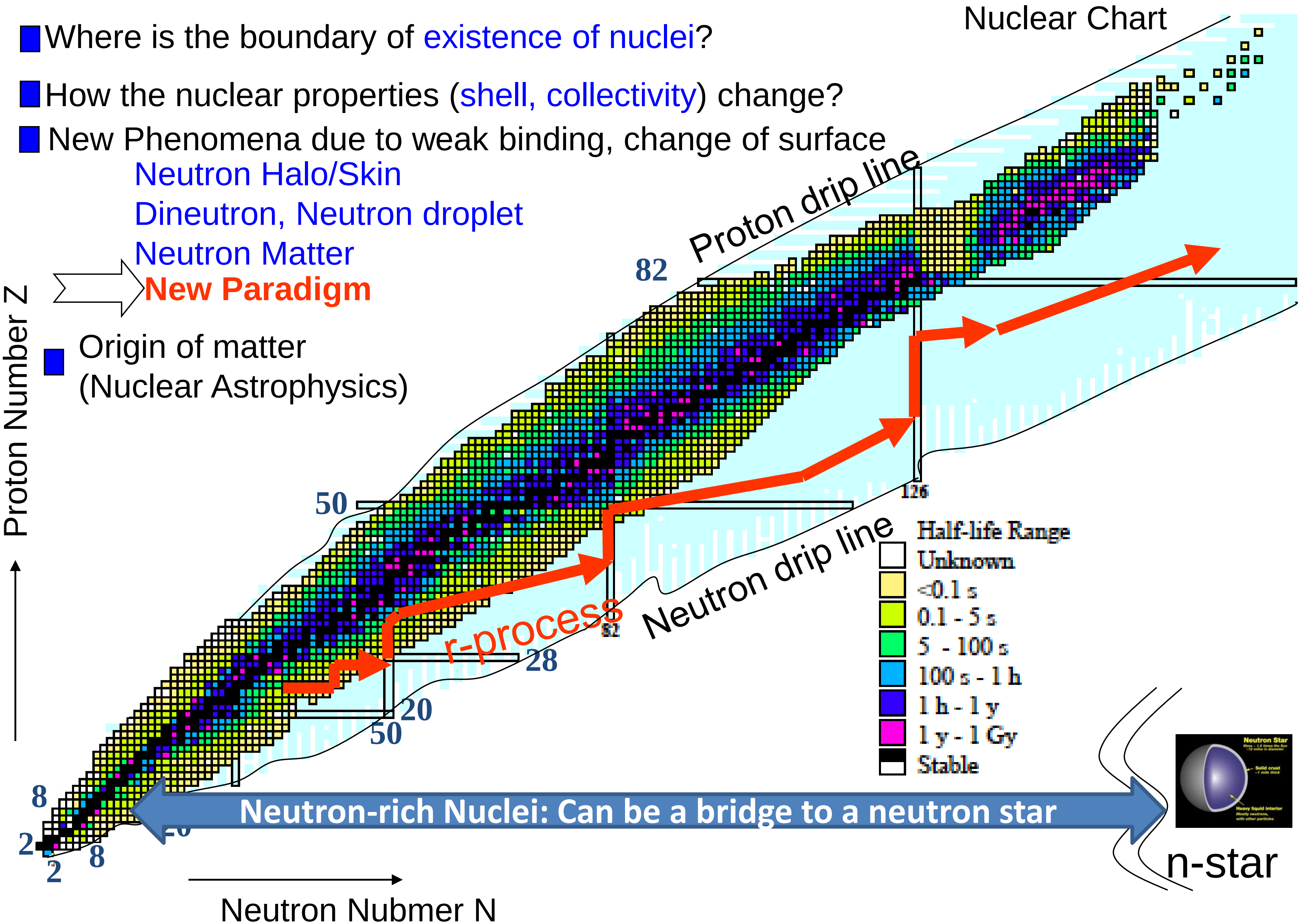
- Introduction
- Dineutron Cluster
- Semi-hierarchy at the neutron-rich limit
- Spectroscopy of Oxygen isotopes
- Planned Experiments – Multi-neutron cluster
- Summary and perspectives

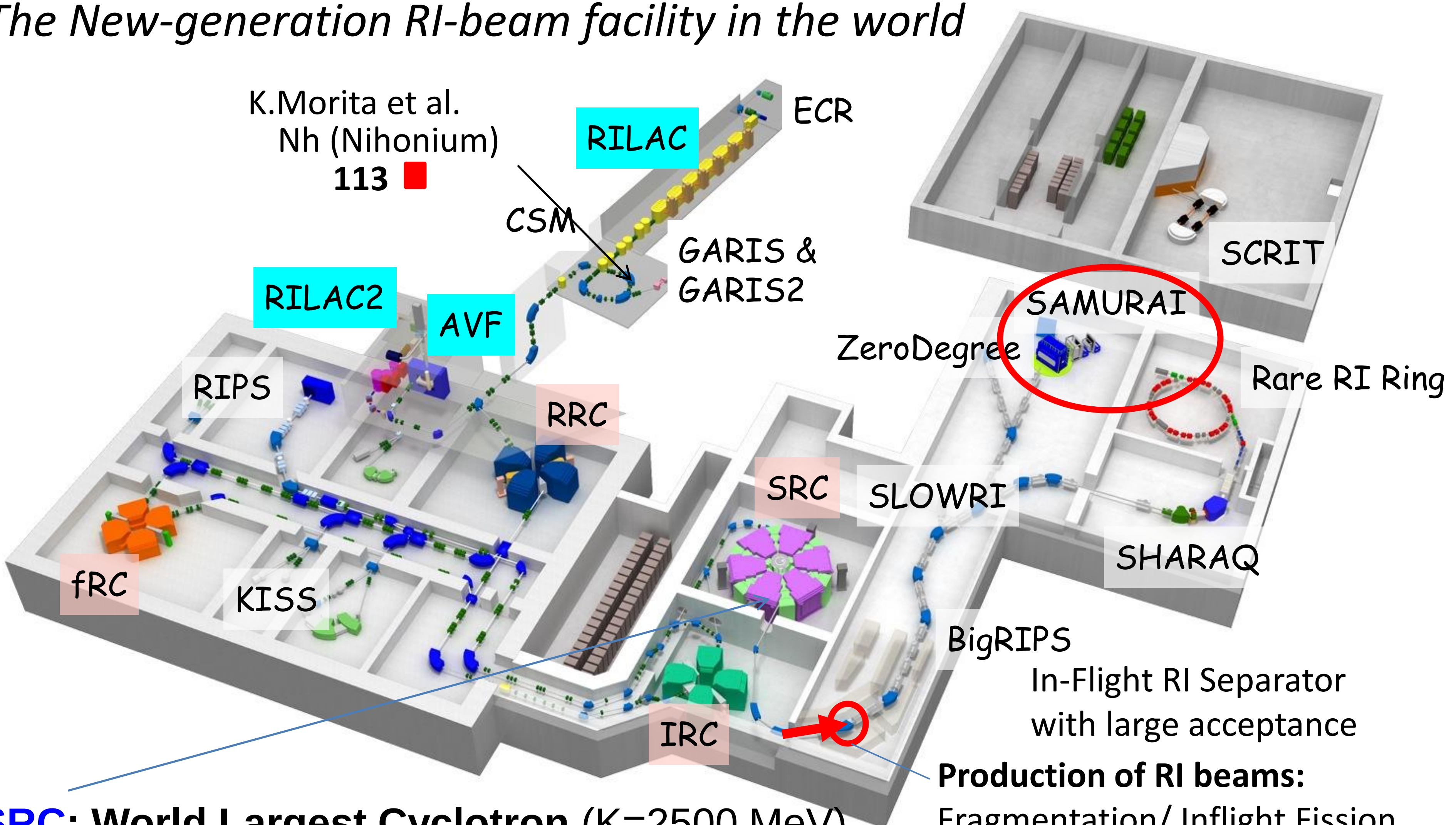
Towards the neutron-rich limit

- Where is the boundary of existence of nuclei?
- How the nuclear properties (shell, collectivity) change?
- New Phenomena due to weak binding, change of surface
  - Neutron Halo/Skin
  - Dineutron, Neutron droplet
  - Neutron Matter
  - **New Paradigm**
- Origin of matter (Nuclear Astrophysics)



RI Beam Factory (RIBF) at RIKEN 2007~

The New-generation RI-beam facility in the world



SRC: World Largest Cyclotron (K=2500 MeV)

High-Intense Heavy Ion Beams up to ^{238}U at 345MeV/u

eg. ^{48}Ca: ~700pnA (~4x10^{12}pps) *~10 times compared to 2008*

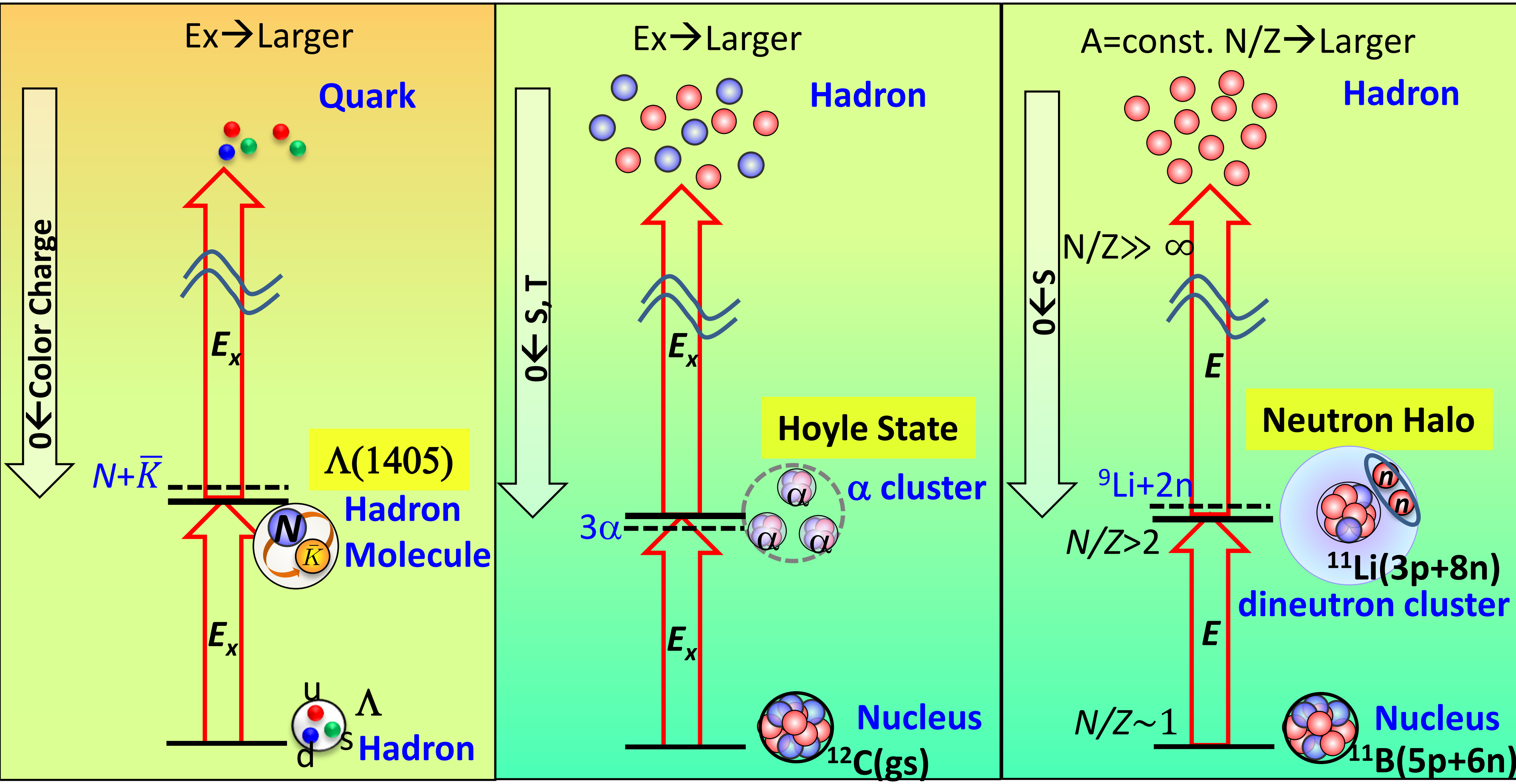
^{238}U: ~70pnA (~4x10^{11} pps) *~10^{3} times compared to 2007*

“Dineutron cluster” in neutron-rich nuclei

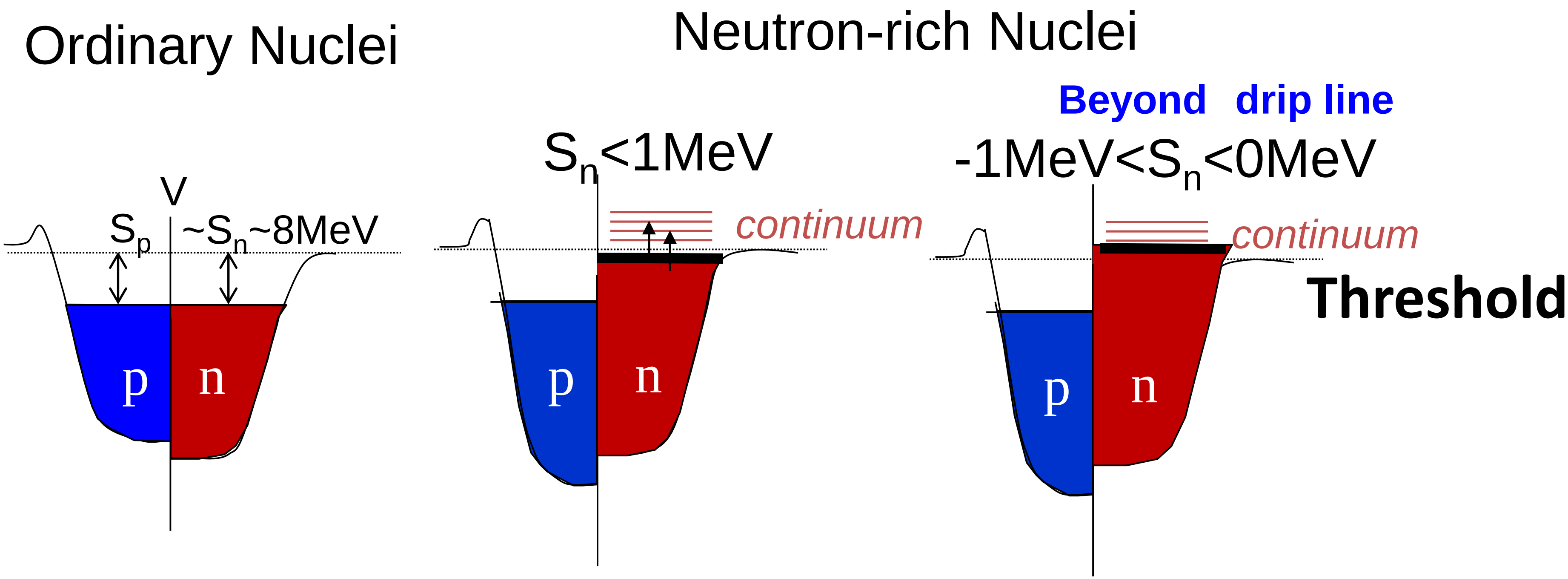
Dineutron exists in Nuclei?
“dineutron”-states can be semi-hierarchy?

Clustering and Hierarchical Structure of Matter

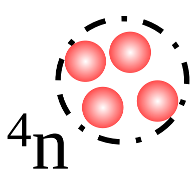
- ✓ Threshold: **Clustering near Threshold → Semi-Hierarchy**
- ✓ Degree of Freedom : **Neutralization of Charge, Spin(S), Isospin(T)**
- ✓ Degree of Separation: **Compositeness, Spectroscopic factor**



Multi-neutron correlation (neutron cluster) near drip line

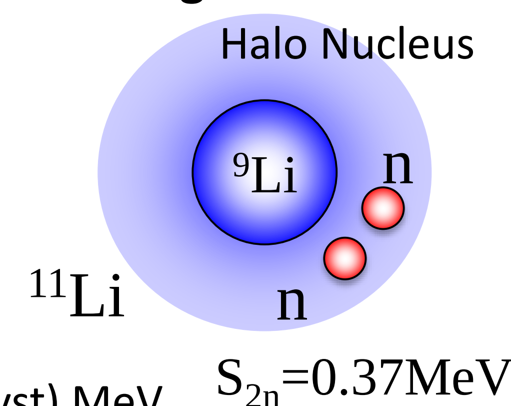


Weakly bound/unbound nuclei --- Threshold (*Unitary limit*)→ Clustering



Halo Nuclei

Weakly Unbound Nuclei



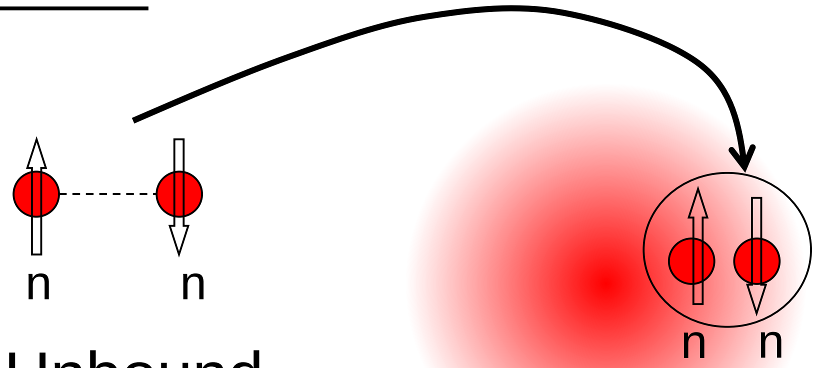
^{4}n: **"Tetra neutron"** $E_{4n}=0.83\pm0.65(\mathrm{stat})\pm1.25(\mathrm{syst})$ MeV

K.Kisamori et al., PRL116, 052501 (2016)

^{26}O: **"Weakly Unbound 2n"** ^{24}O+2n E_{2n}= 0.018±0.003(stat)±0.004(syst) MeV

Y.Kondo et al., PRL116,102503(2016).

Dineutron?



S=0, T=1

Unbound

a= -18.7 fm

s-wave scattering length

A.B.Migdal

Strongly correlated “dineutron”

on the **surface** of a nucleus

Sov.J.Nucl.Phys.238(1973).

Dineutron:

@ **Low-dense** Neutron skin/halo?

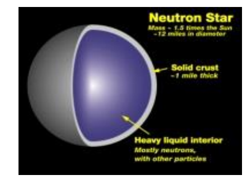
/Inner crust of Neutron star?

M.Matsuo

PRC73,044309(2006).

A.Gezerlis, J.Carlson,

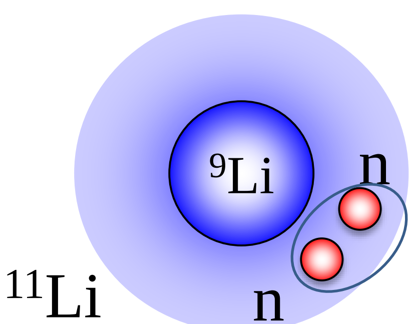
PRC81,025803(2010)



neutron-star

Possible dineutron site

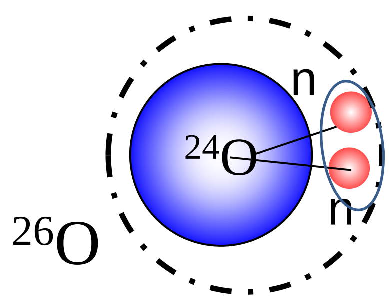
2n Halo Nuclei?

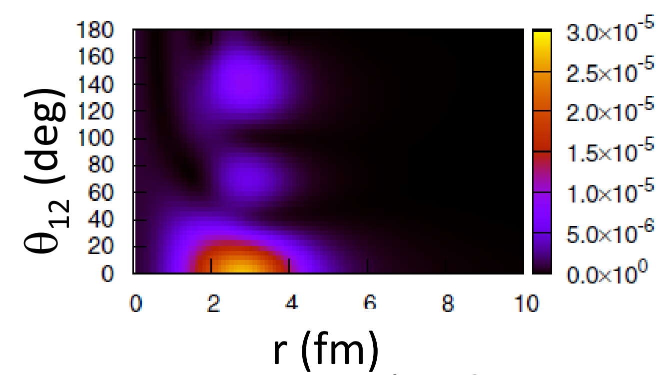


S_{2n}=0.37MeV

T.Nakamura PRL96, 252502 (2006).

2n weakly-unbound nuclei?



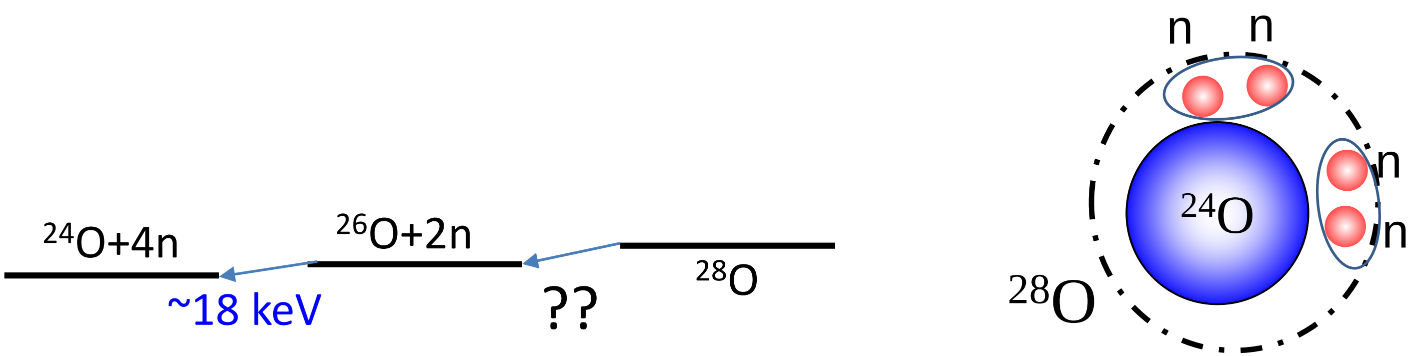


S_{2n}= –0.018(5) MeV

Hagino, Sagawa, PRC93,034330(2016)

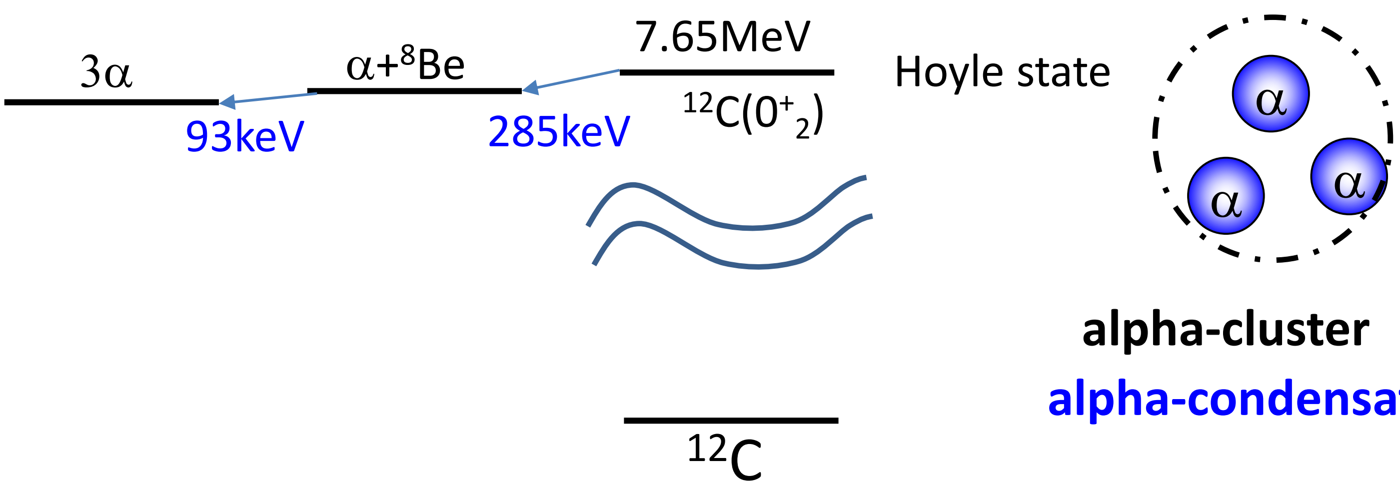
Kondo, TN et al., PRL116,102503(2016).

What happens if there are 'multiple' dineutrons?



Dineutron-cluster?

Dineutron-condensation?



alpha-cluster

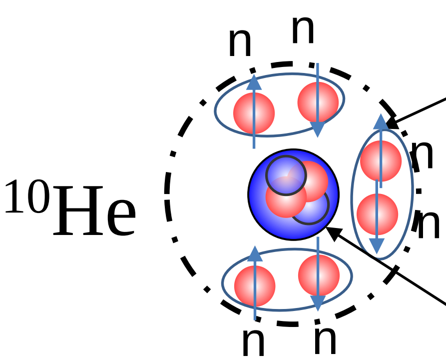
alpha-condensation?

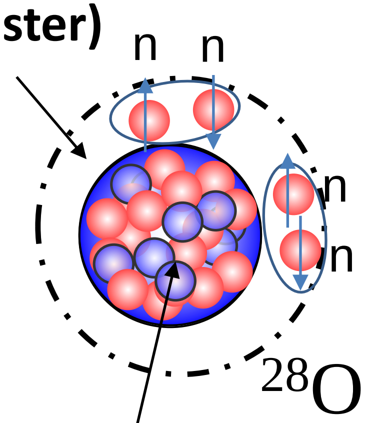
A.Tohsaki, H.Horiuchi, P.Schuck,G.Ropke, PRL 87, 192501 (2001).

Dineutron Clustering & Hierarchy

Naïve Picture

Surface-region:
Dineutron-cluster hierarchy
(made of dineutron-cluster)





Core-region:
Normal nuclear hierarchy
(made of nucleons)

Dineutron-cluster hierarchy: **Semi-hierarchy?**

Evolution Towards the Stability Limit

Where is the neutron drip line?

What are characteristic features of drip-line nuclei?

How does nuclear structure evolve towards the drip line?

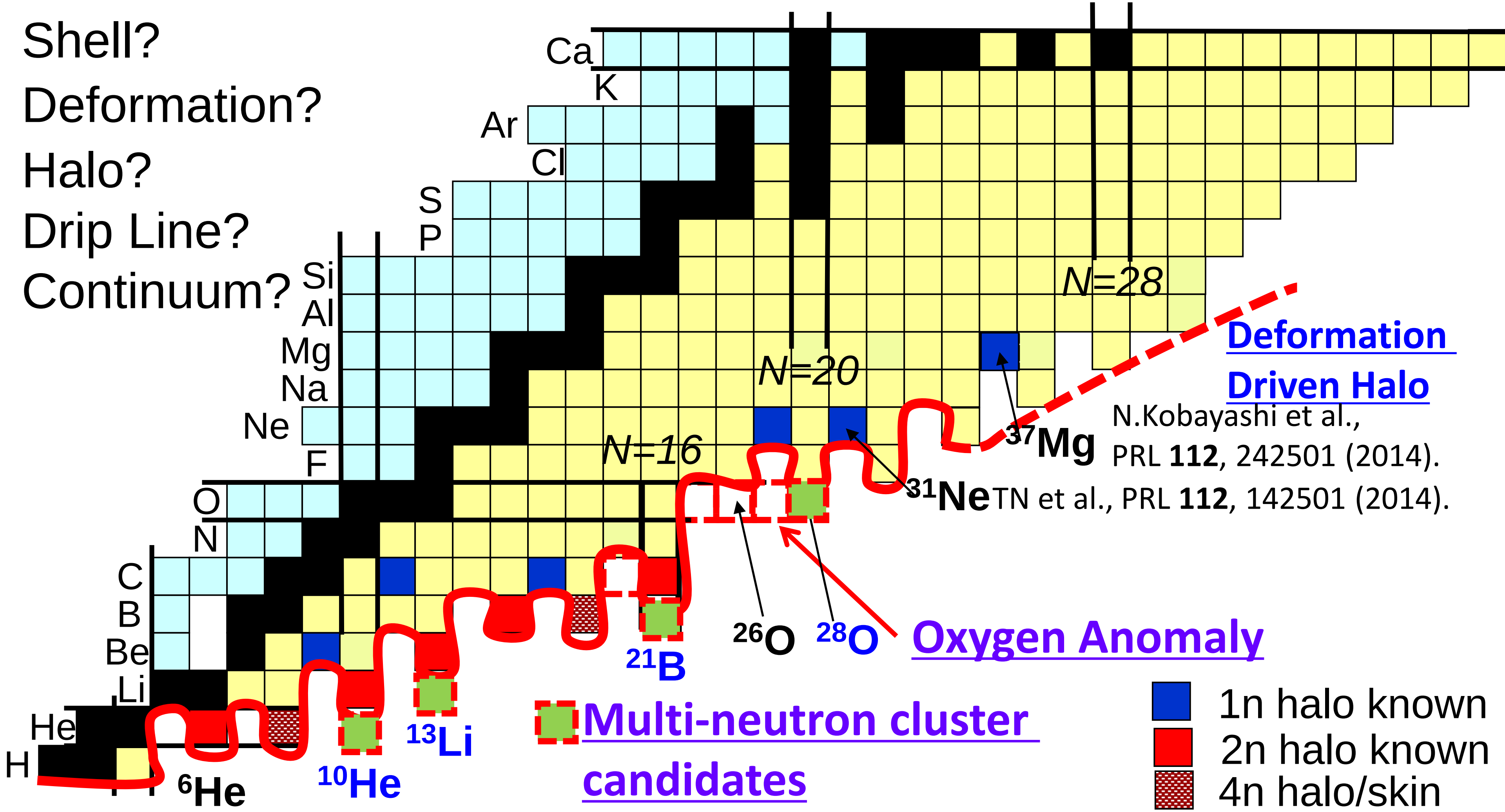
Shell?

Deformation?

Halo?

Drip Line?

Continuum?



Previous Experiments 我々の先行研究

Spectroscopy of Super-heavy oxygen isotopes

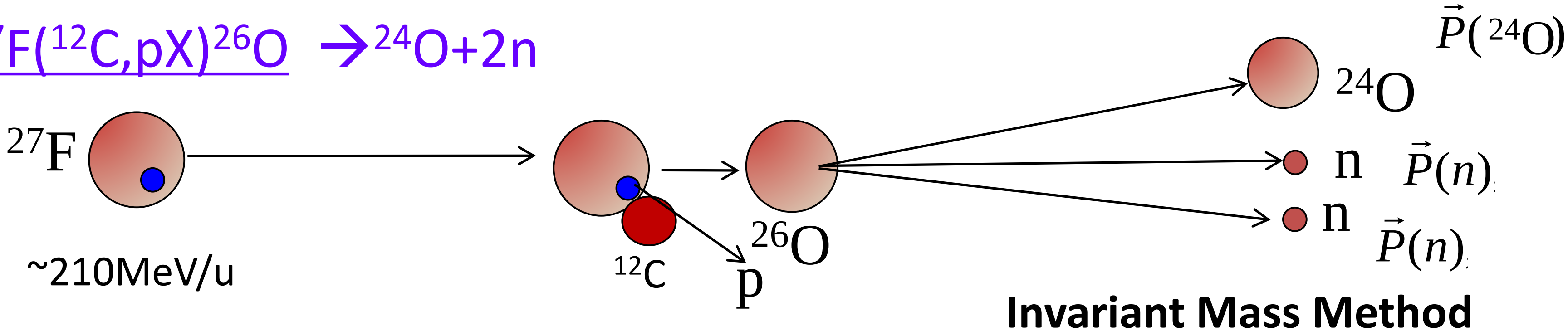
--Barely Unbound 2n emitter ^{26}O

& 4n emitter ^{28}O

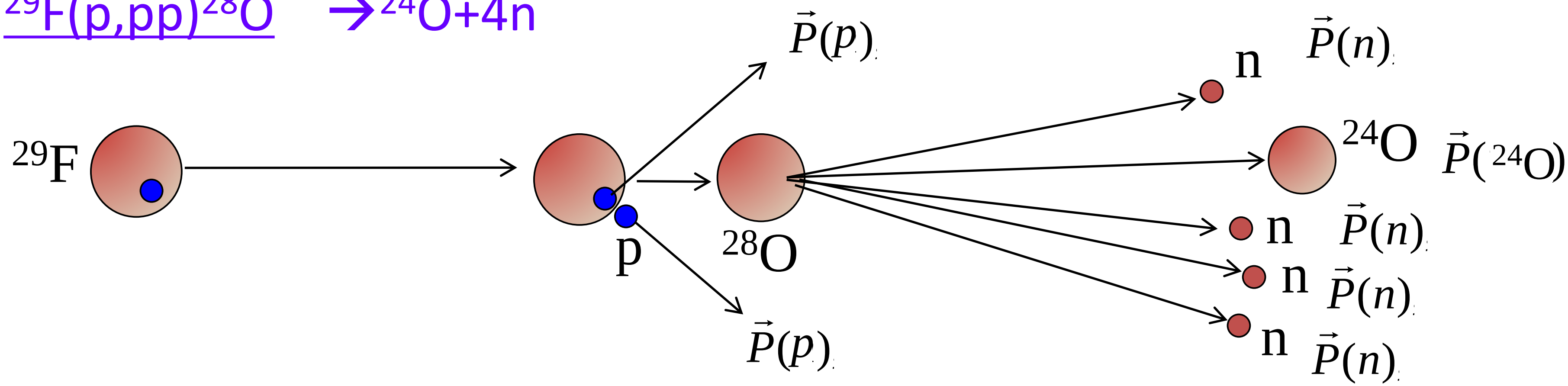
Yosuke Kondo, TN et al.

Knockout Reaction/Quasi-Free Reaction

$^{27}F(^{12}C,pX)^{26}O$ → $^{24}O+2n$



$^{29}F(p,pp)^{28}O$ → $^{24}O+4n$

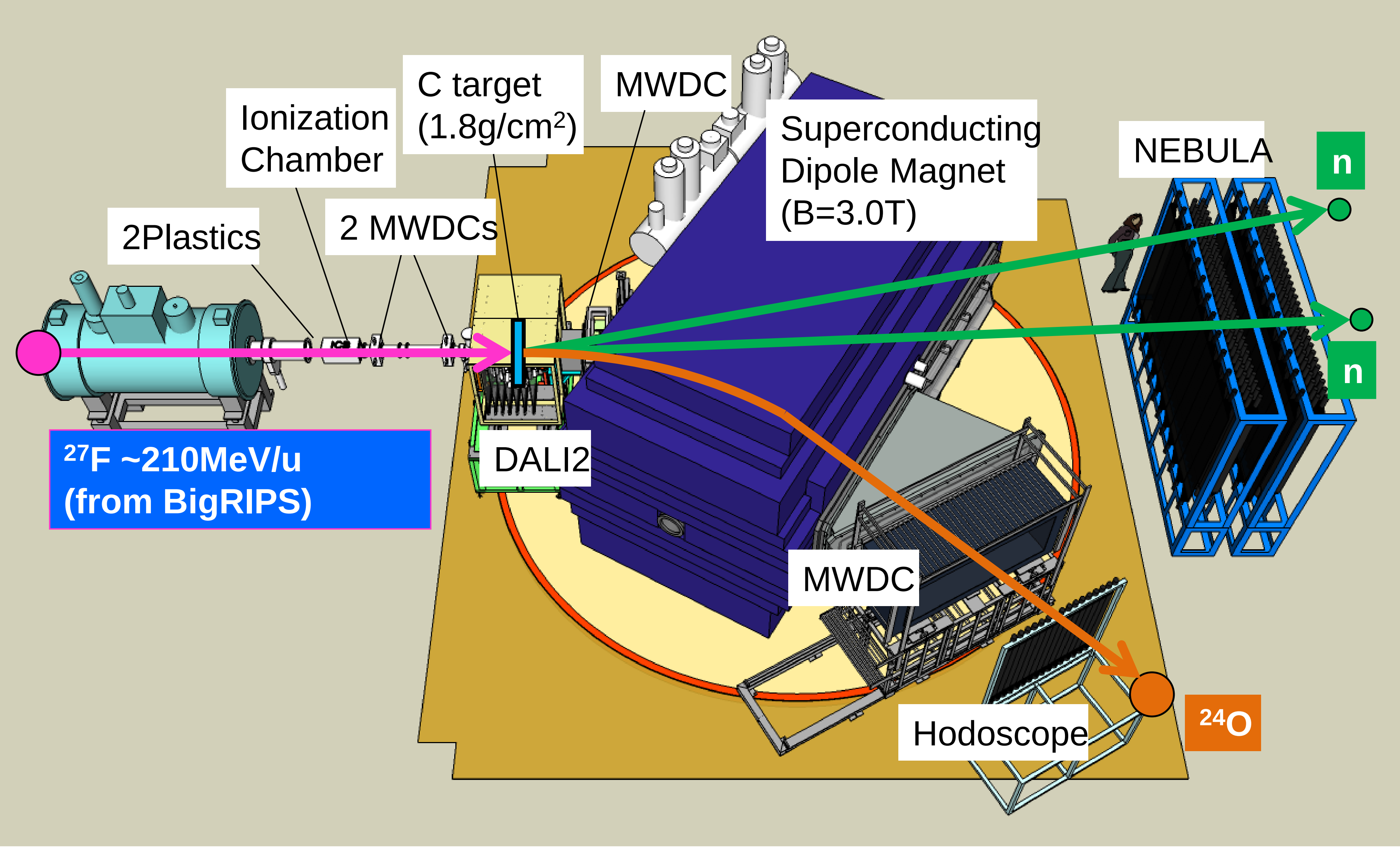


Invariant Mass Method: **+ High Yield, + Good Resolution ~ a few 100 keV**
- Require Measurement of All the Decay Particles

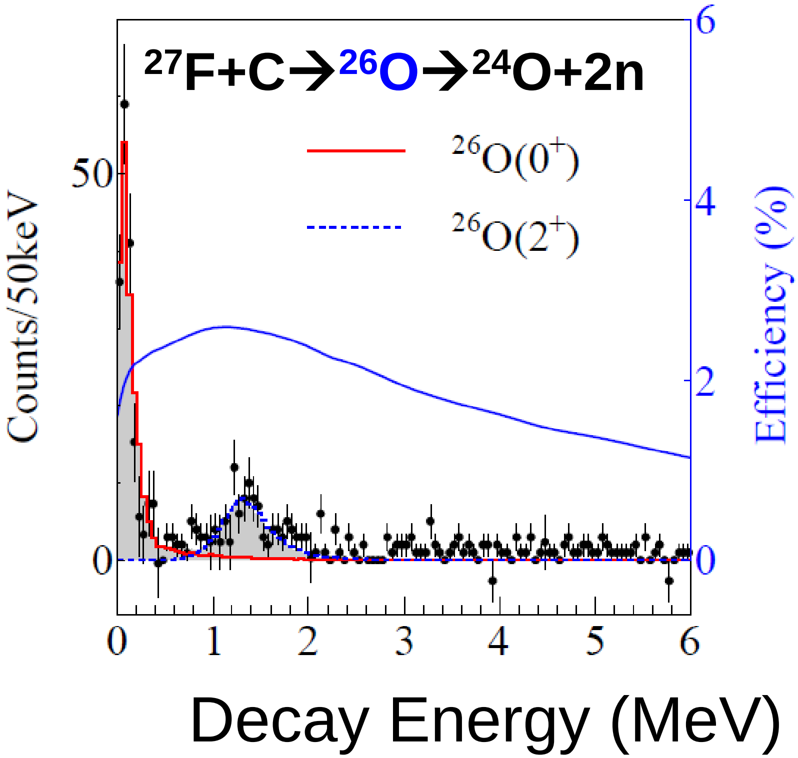
Missing Mass Method: - Low Yield, - Worse Resolution ~ a few MeV
+ Measurement of projectile and recoil protons only

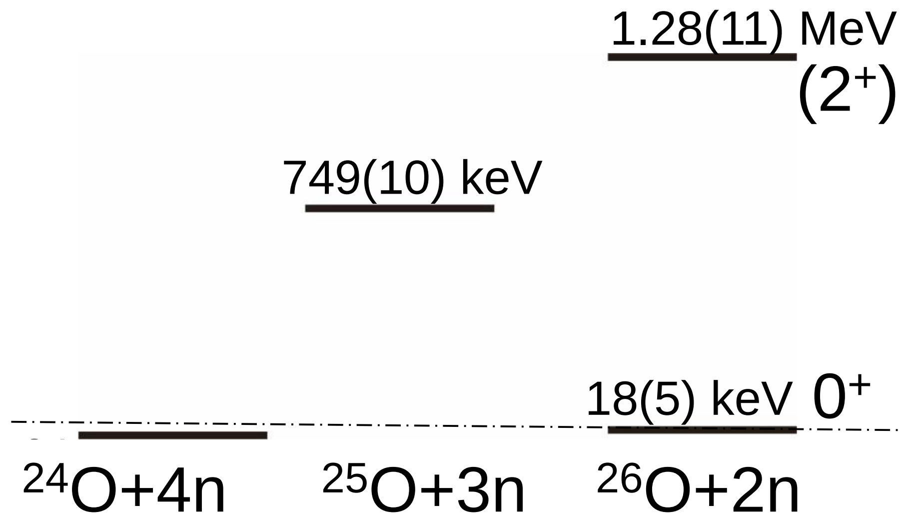
Review: T.Nakamura, H.Sakurai, H.Watanabe, Prog. Part. Nucl. Phys. 97, 53 (2017).

Experimental Setup at SAMURAI at RIBF



Result of ^{26}O





Ground state (0^+)

5 times higher statistics than previous study

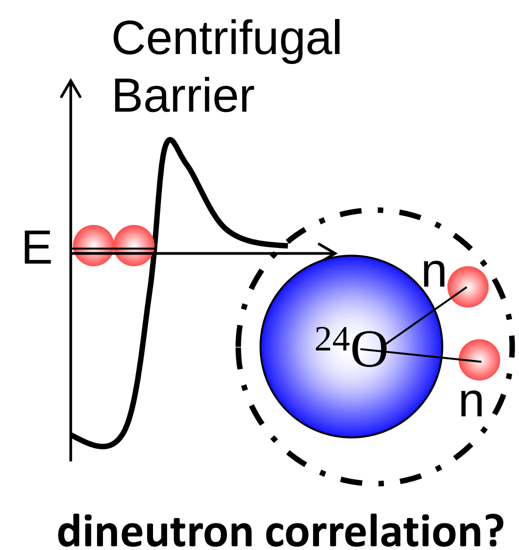
18±3(stat)±4(syst)keV

Finite value is determined for the first time

1st excited state (2^+)

Observed for the first time

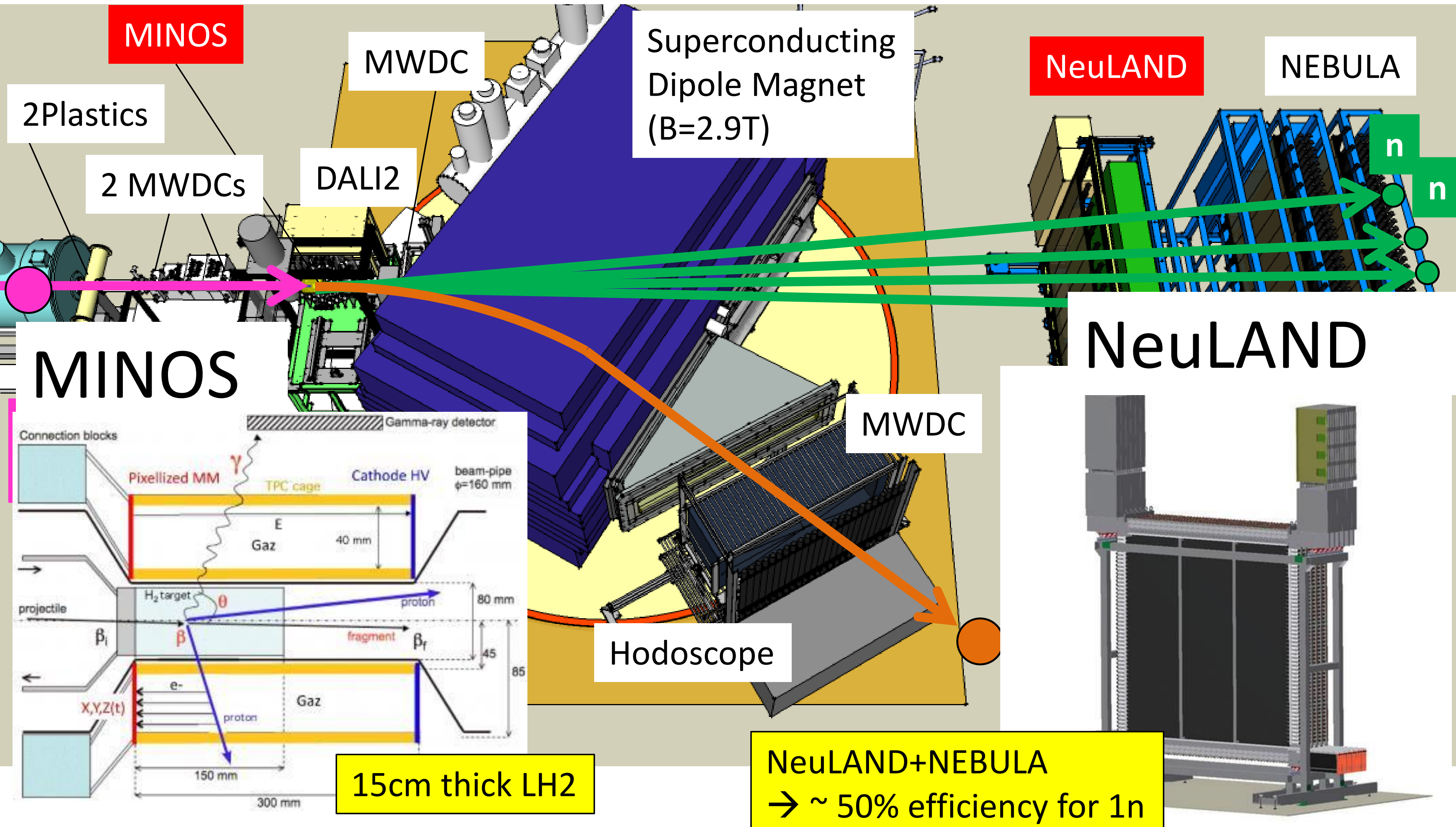
$1.28^{+0.11}_{-0.08}$MeV



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

Towards ^{28}O (doubly magic nucleus?)

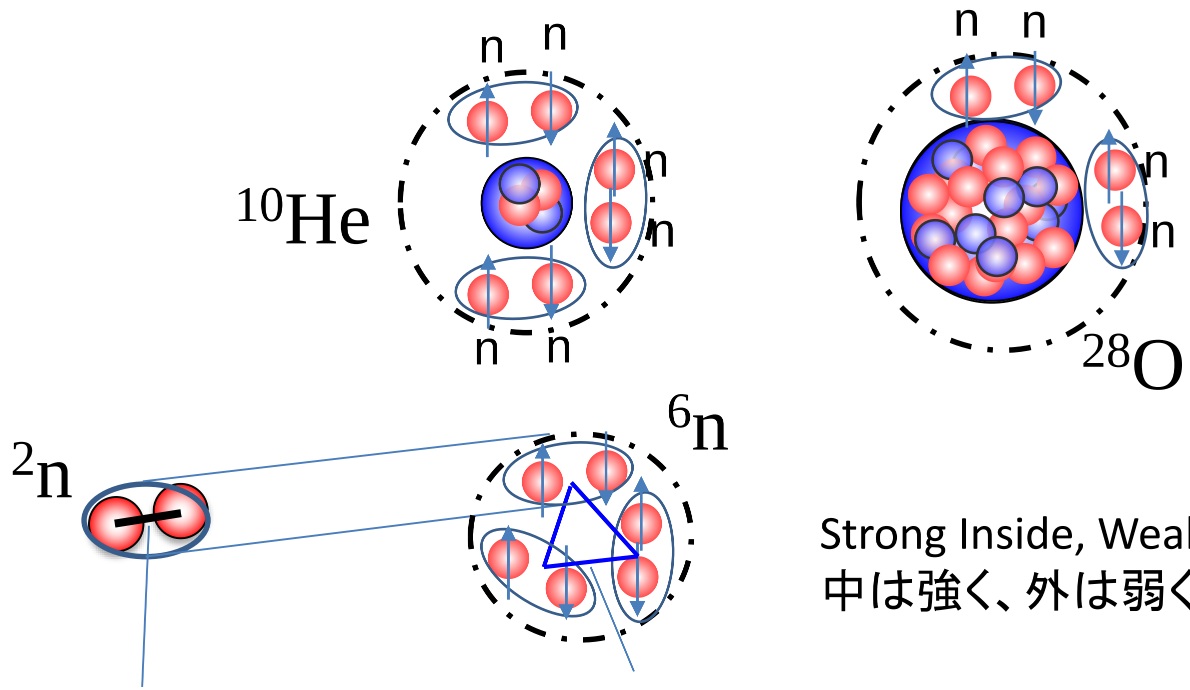
^{28}O measurement @ RIBF-SAMURAI



Planned Experiments in this project

Multi-neutron 4n and 6n states in extremely neutron-rich nuclei beyond the neutron drip line

RI-beam→ ^{10}He, ^{21}Be, ^{28}O →^{4}n,^{6}n



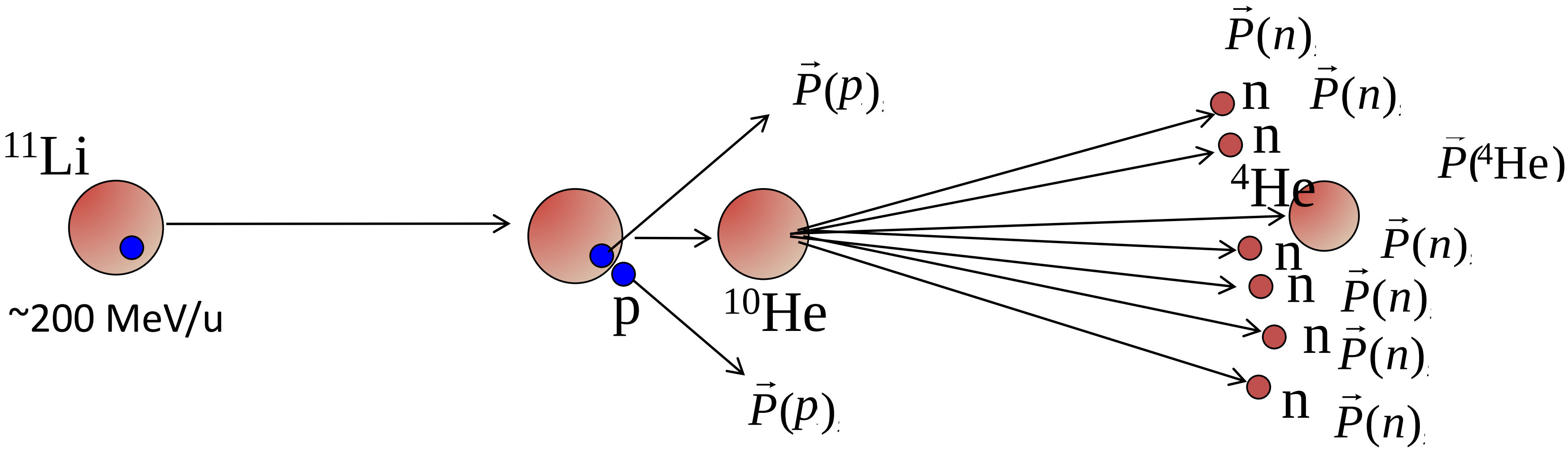
Strong Inside, Weak outside?
中は強く、外は弱く?

nn interaction >> ^{2}n-^{2}n interaction →(Semi)-Hierarchy
(Strong Inside) (Weak Outside)

First exp. Focusing on ^{10}He: 6n states

^{11}Li(p,pp)^{10}He*

^{10}He* → ^{8}He+2n, ^{6}He+4n, ^{4}He+2n



Invariant Mass Method: + High Yield, + Good Resolution ~ a few 100 keV

- Require Measurement of All the Decay Particles

Missing Mass Method: - Low Yield, - Worse Resolution ~ a few MeV

+ Measurement of projectile and recoil protons only

"6n" mass can be also extracted

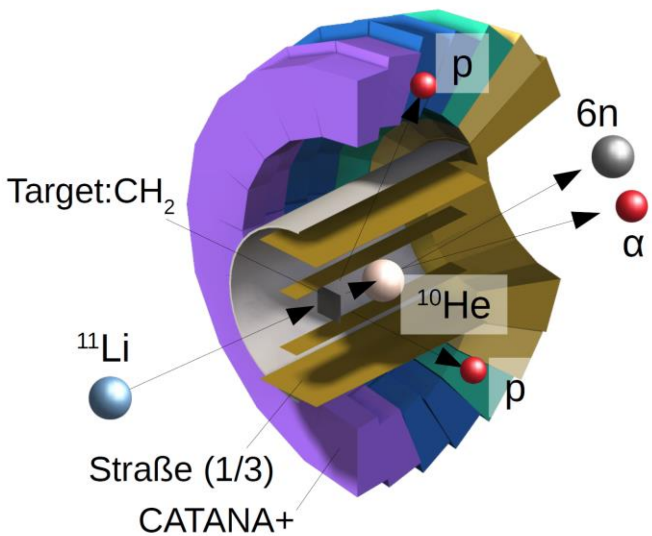
Submitted to RIBF NP-PAC in Oct.

Doctor Thesis of T. Tomai

“Large-acceptance missing mass setup at SAMURAI”

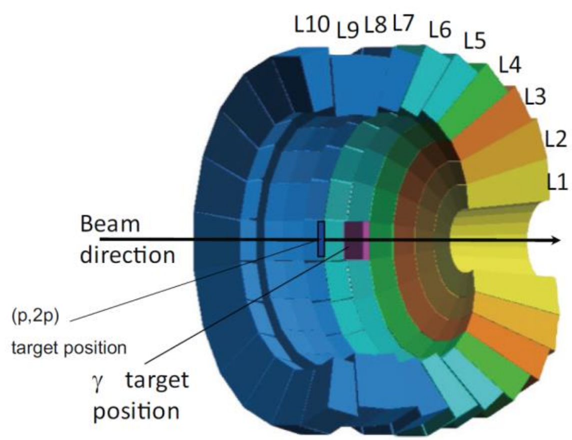
CATANA PLUS and STRAßE

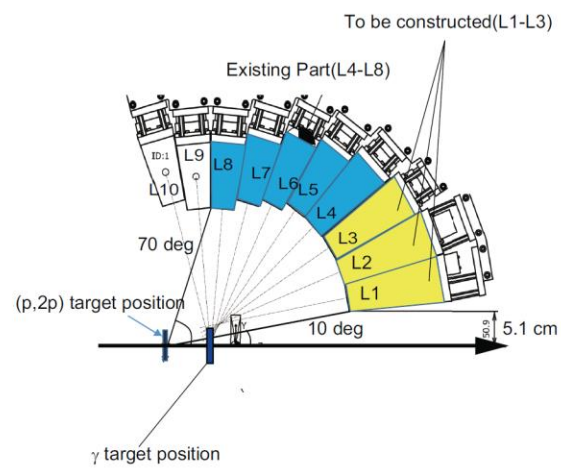
CsI(Na) Scintillators



Si Trackers

CATANA PLUS

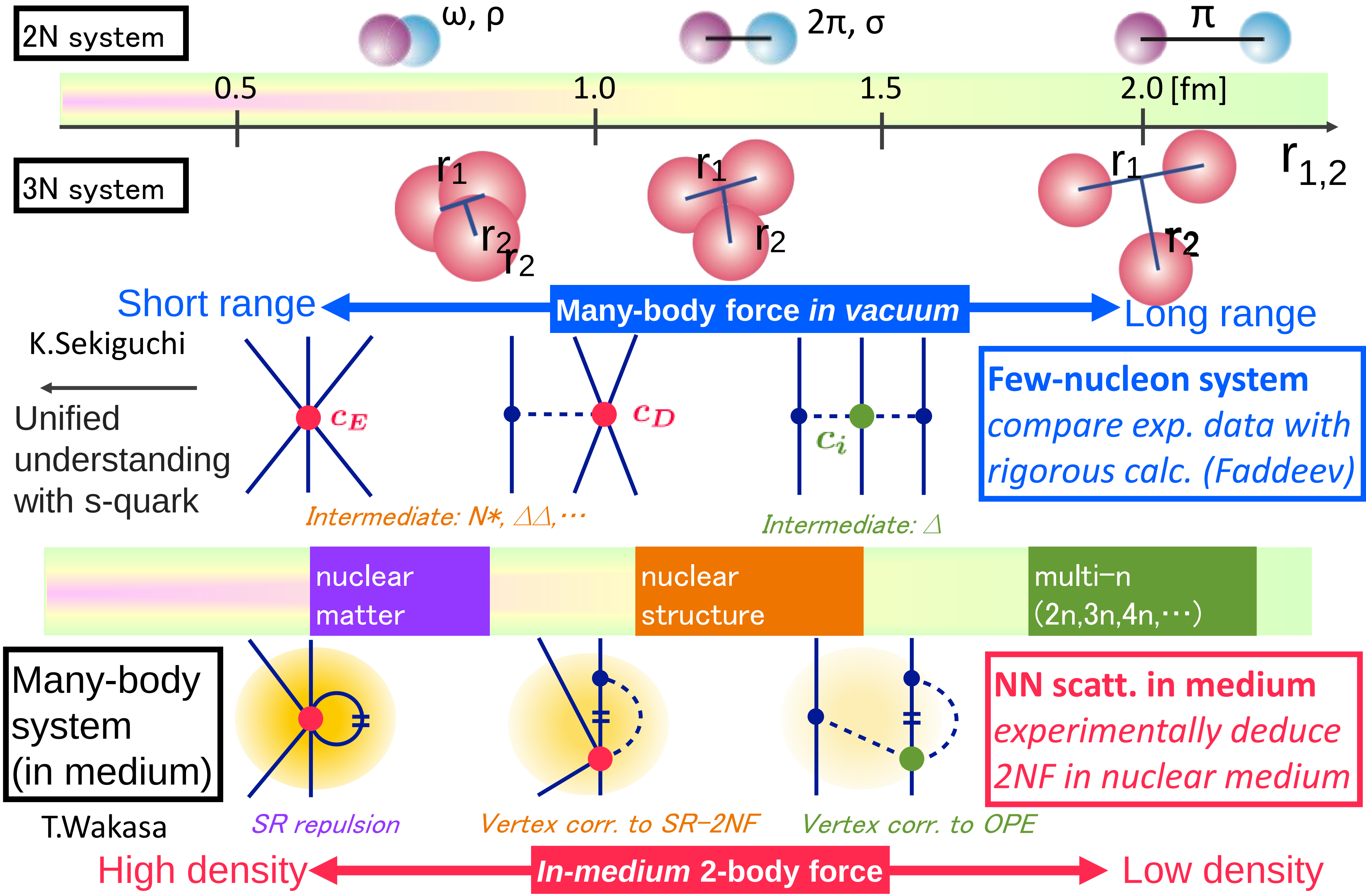




Construction Proposal: Submitted to RIBF NP-PAC in Oct.
TN, A. Obertelli (TU Darmstadt) et al.

Bridge between nuclear/hadron hierarchies & Deeper understanding of nuclear system/hierarchy

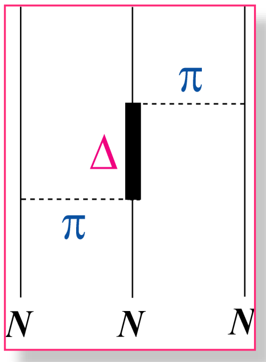
T. Wakasa若狭智嗣
K. Sekiguchi 関口仁子



Three-Nucleon Force (3NF)

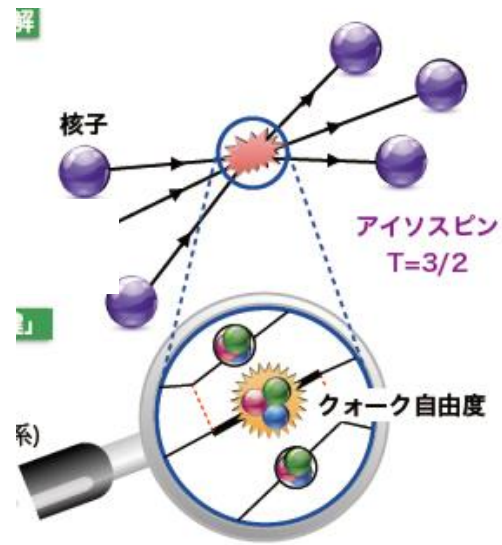
Kimiko Sekiguchi (関口仁子)

Key probe to understand from quark hierarchy to nuclear / hadron hierarchies



Fujita-Miyazawa 3NF (1957)
- most famous picture -

⊗: excited state of nucleon

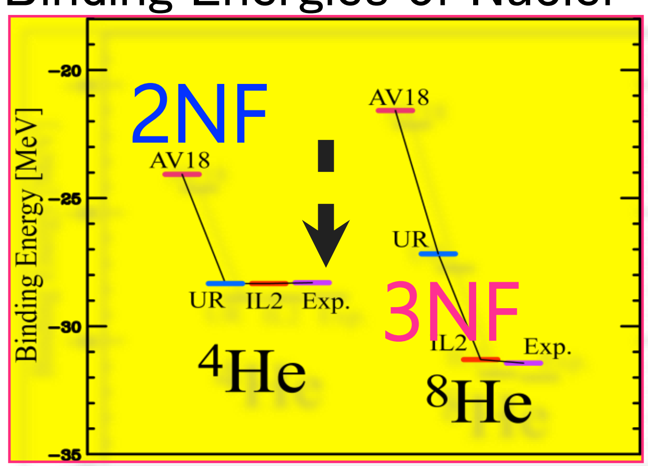


Key element to fully understand nuclear phenomena

- **Iso-spin states of T=3/2 3NFs are expected to be important.**

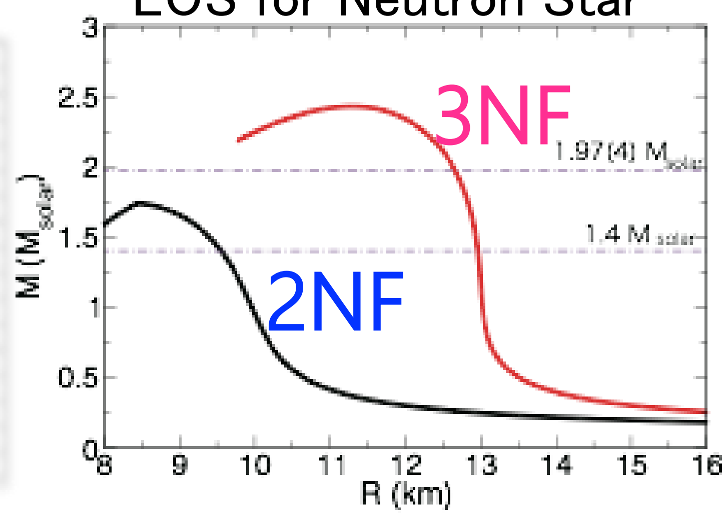
However, not known well.

Binding Energies of Nuclei



S.C. Pieper PRC 64, 014001(2001)

EOS for Neutron Star



A. Akmal et al., PRC 58, 1804 (1998)

Planned Research

Kimiko Sekiguchi (関口仁子)

Study of **three-proton/neutron force** (iso-spin states of T=3/2) via New Probe of Few-Nucleon Systems

- proton+^{3}He scattering systems
- three-neutron systems : e.g. ^{3}H(^{3}H,^{3}He)3n at RIBF

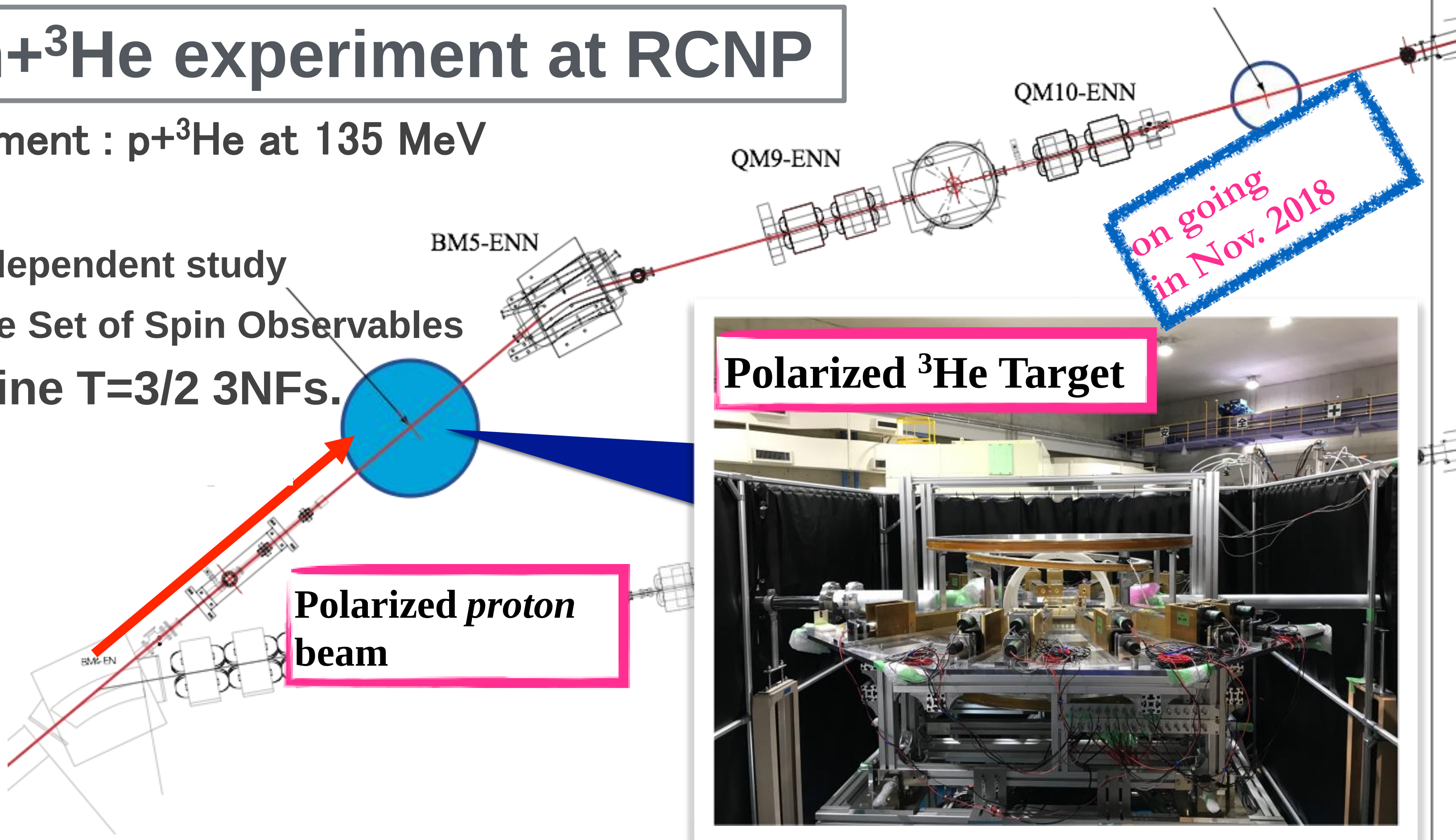
proton+^{3}He experiment at RCNP

First experiment : p+^{3}He at 135 MeV

Next Step

- Energy dependent study
- Complete Set of Spin Observables

=> Determine T=3/2 3NFs.



Summary

- Dineutron → $^{2}n/^{4}n/^{6}n$ **states in medium/vacuum**
  - →**Semi-hierarchy**
- Experimental Plan: 1st experiment: $^{11}Li(p,pp)^{10}He$
- Experiments on 3N force (Sekiguchi)
- Experiments on 2N force in medium (Wakasa→Talk)

Near-future Perspectives

- Construction of CATANA+ : CsI(Na) Arrays: To be constructed 2018-2019
- Silicon tracker (Strasse): 2019-2020 Collaboration with A.Obertelli (TUD)

→Construction Proposal/ Experimental Proposal submitted to RIKEN-PAC

- Next Step: Investigations on Other multi-neutron systems: ^{13}Li, ^{28}O

Collaboration with Other Groups

- Further Inputs from Theories

→Dineutron-decay can be a probe of more correlations?

→Theoretical Investigation on the cluster-relevant reactions

e.g. If $^{11}Li={}^{4}He+t+$"4n": 11Li(p,pp)10He can be considered as t(p,pp)"nn" + 4He+4n?)

- **Universality among Dineutron, Diquark, Ultra-cold atom (unitary limit)** → WS?

Backup

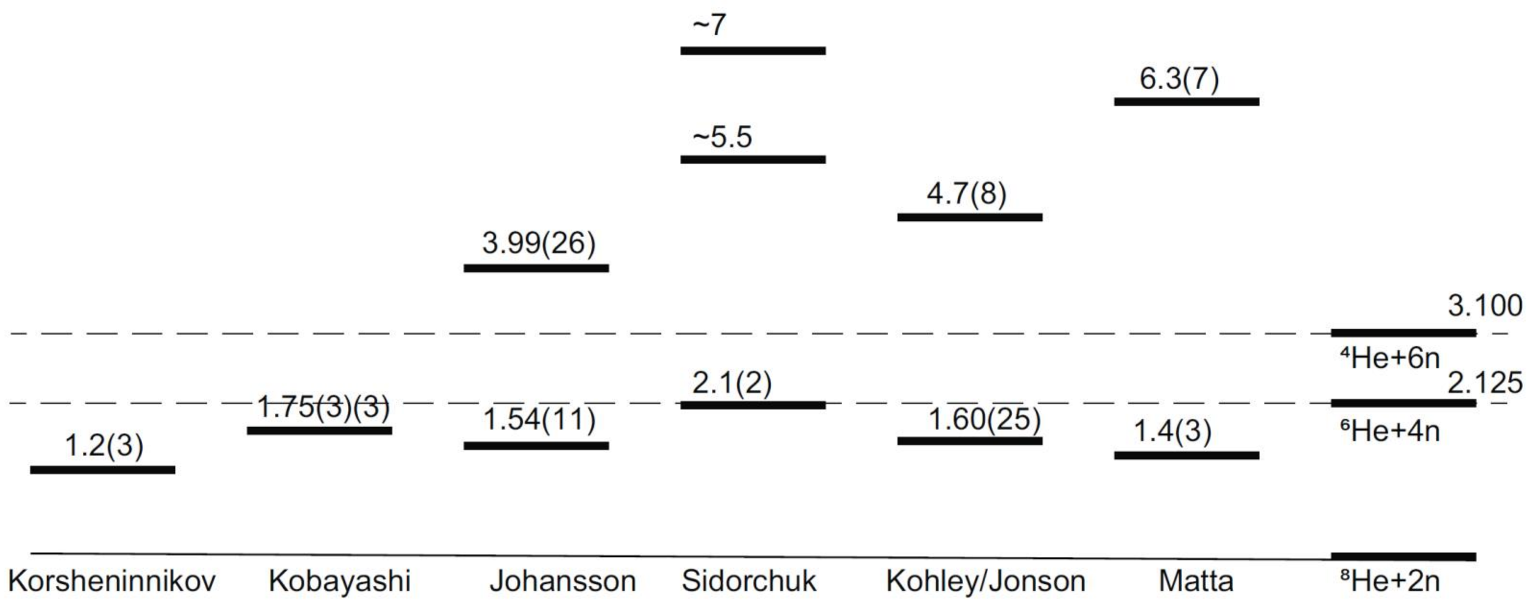


Fig. 1.2: ^{10}He energy levels from the previous experiment with respect to the ^{8}He+2n threshold. The threshold energies for ^{6}He+4n, ^{4}He+6n are shown by dashed lines. Korsheninikov [8] used invariant mass method (IM) for ^{11}Li(d,^{3}He), Kobayashi [9] used missing mass method (MM) for ^{11}Li(p, 2p), Johansson [10] used IM for ^{11}Li(p, 2p), Kohley [11] and Jones [12] used IM for ^{14}Be(CH_2,X), and Matta [13] used MM for ^{11}Li(d,^{3}He).