Pure-neutron Nuclei – Current and Future

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Contents

- Pure-neutron nuclei (multi-neutron systems)
  Multi-neutron cluster (multi-neutron system in a nucleus)
- Recent 4n experiments
- ^{11}Li(p,2p)^{10}He experiment
- Future Perspectives

Pure-neutron nuclei

(Z=0 element, multi-neutron systems, neutron droplets)

Are there any nuclei made only of neutrons?

Dineutron

$\tau \sim 10^{-22} s$

Decay into n+n

No bound states

No resonance

Tetra-neutron

$\tau \sim ?$

Bound ?

Resonance ?

Hexa-neutron

$\tau \sim ?$

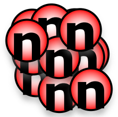
Bound ??

Resonance ??

More stable than ^4n?

Never Measured

…



^An (A>6)

$\tau \sim ?$

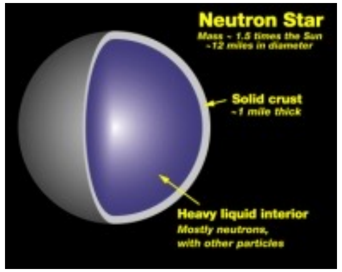
Bound ??

Resonance ??

New Magicity?

Never Measured

…



Neutron Star

$\tau = \infty$

Bound

R_{NS}?, max(M_{NS})?

Compositions?

Not yet established

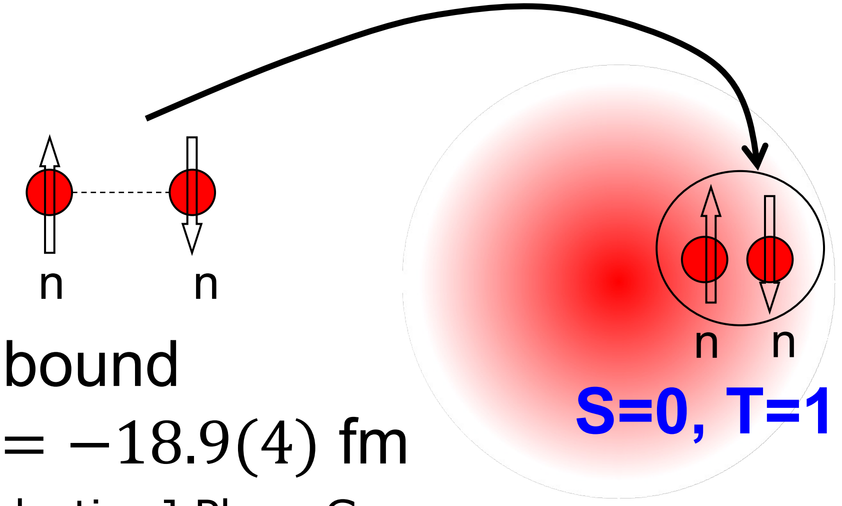
⇨ nnn, nnnn interactions
Multi-neutron correlations
Magic numbers of ^An

⇨ Ab-inito Calc.
Lattice QCD

⇨ EoS of neutron matter
Neutron star
Universal features of fermionic systems

Multi-neutron system in a nucleus
→ Multi-neutron cluster

Dineutron in nuclei?

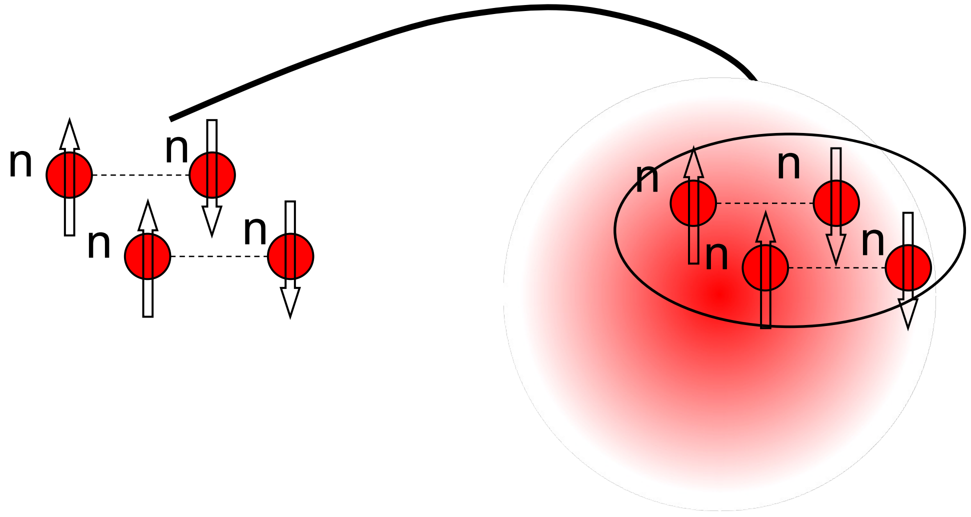


Unbound

$a_s = -18.9(4)$ fm

A.Gårdestig, J.Phys. G,
Nucl. Part Phys. 36, 053001 (2009).

Tetra neutron in nuclei?



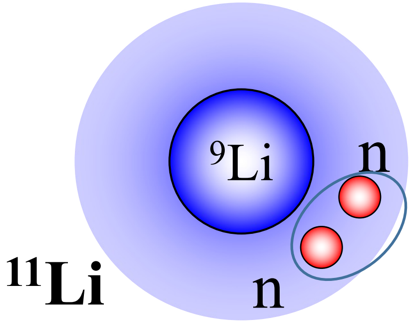
A.B.Migdal

Strongly correlated "dineutron"
on the **surface** of a nucleus

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

➢ Possible "dineutron" site

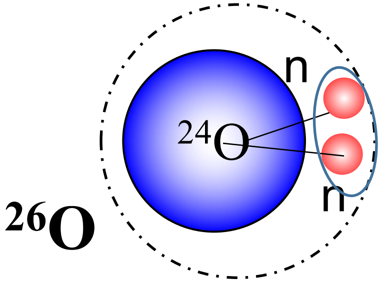
2n Halo Nuclei?



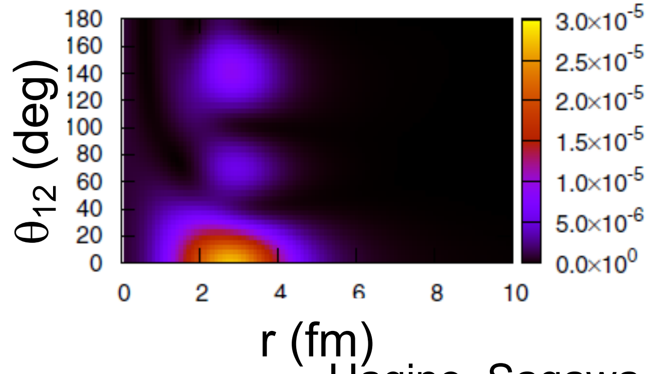
S_{2n}=0.37MeV

TN et al., PRL96, 252502 (2006).
Y. Kubota et al., PRL 125, 252501 (2020).

2n weakly-unbound nuclei?



S_{2n}= –0.018(5) MeV
Y.Kondo, TN et al., PRL116,102503(2016).

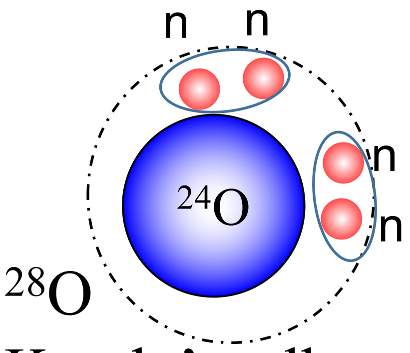


Hagino, Sagawa, PRC93,034330(2016)

^{16}Be : B Monteagudo et al., PRL **132**, 082501 (2024).

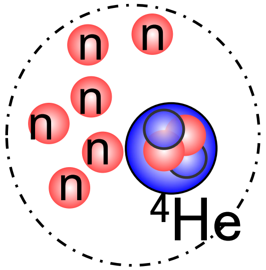
➢ Possible "tetra-neutron" site

4n weakly-unbound nuclei?



Kondo's talk

➢ Possible "hexa-neutron" site



^{10}He

Neutron drops in an external field –ab-initio theory

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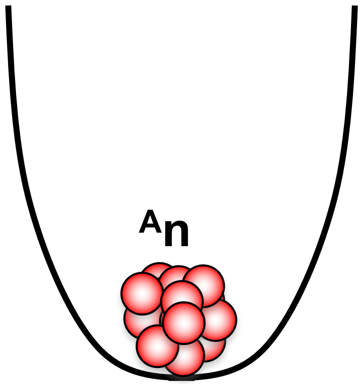
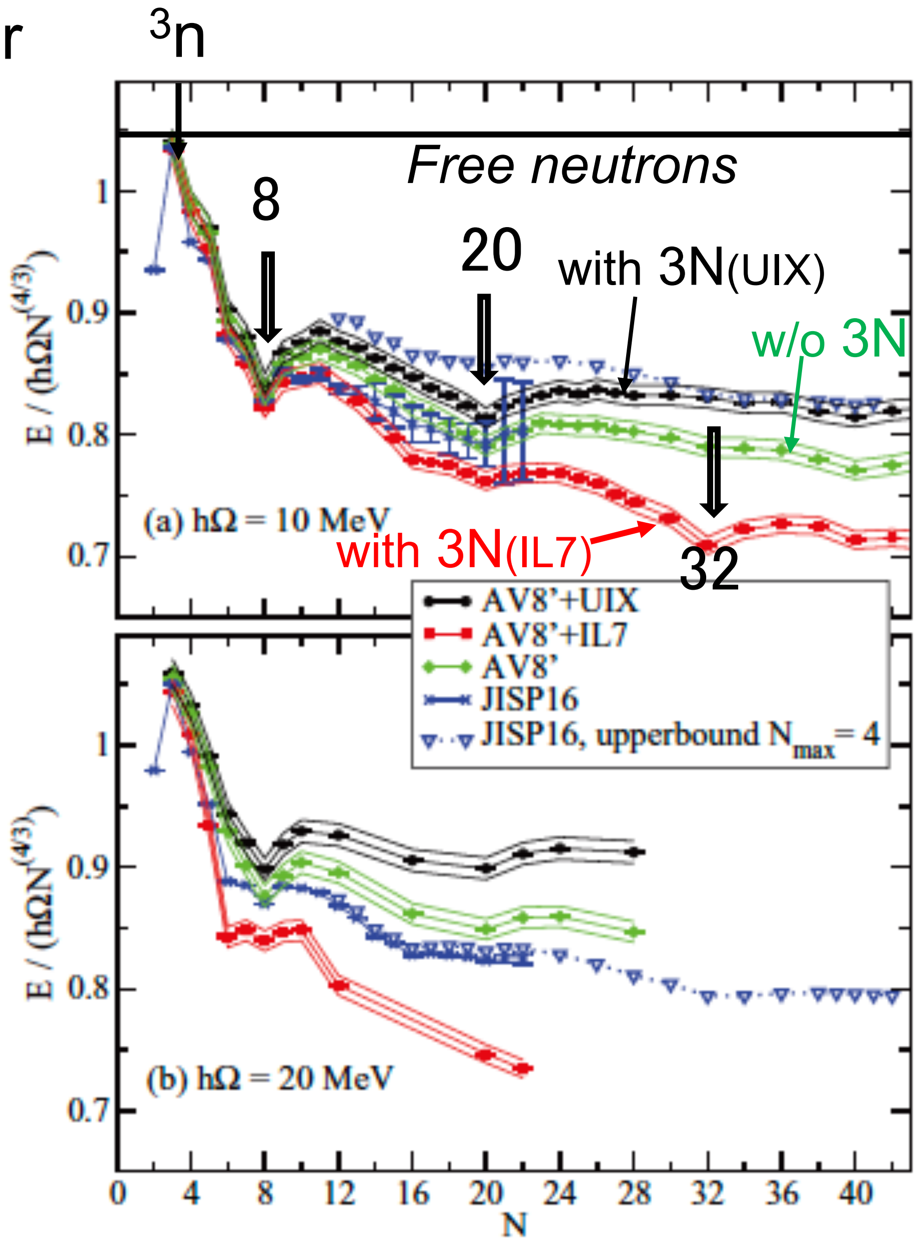
P.Maris J.P.Vary, S.Gandolfi, J.Carlson, S.C.Pieper
PRC87, 054318(2013).

Quantum Monte-Carlo (QMC) for AV8'
No-Core Full Configuration (NCFC) for JISP16

Ab-initio calculations for
Neutron drops in an external field

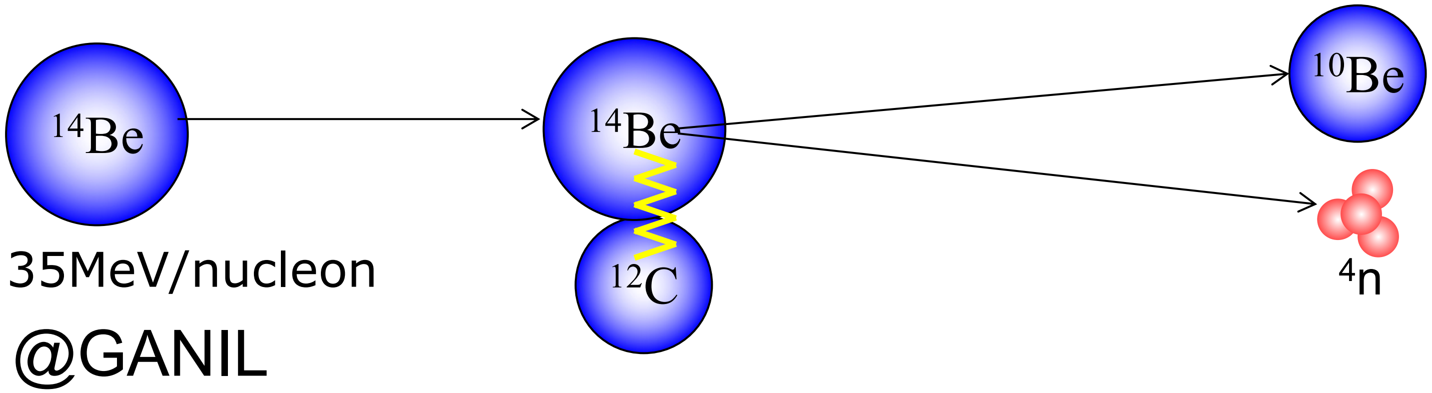


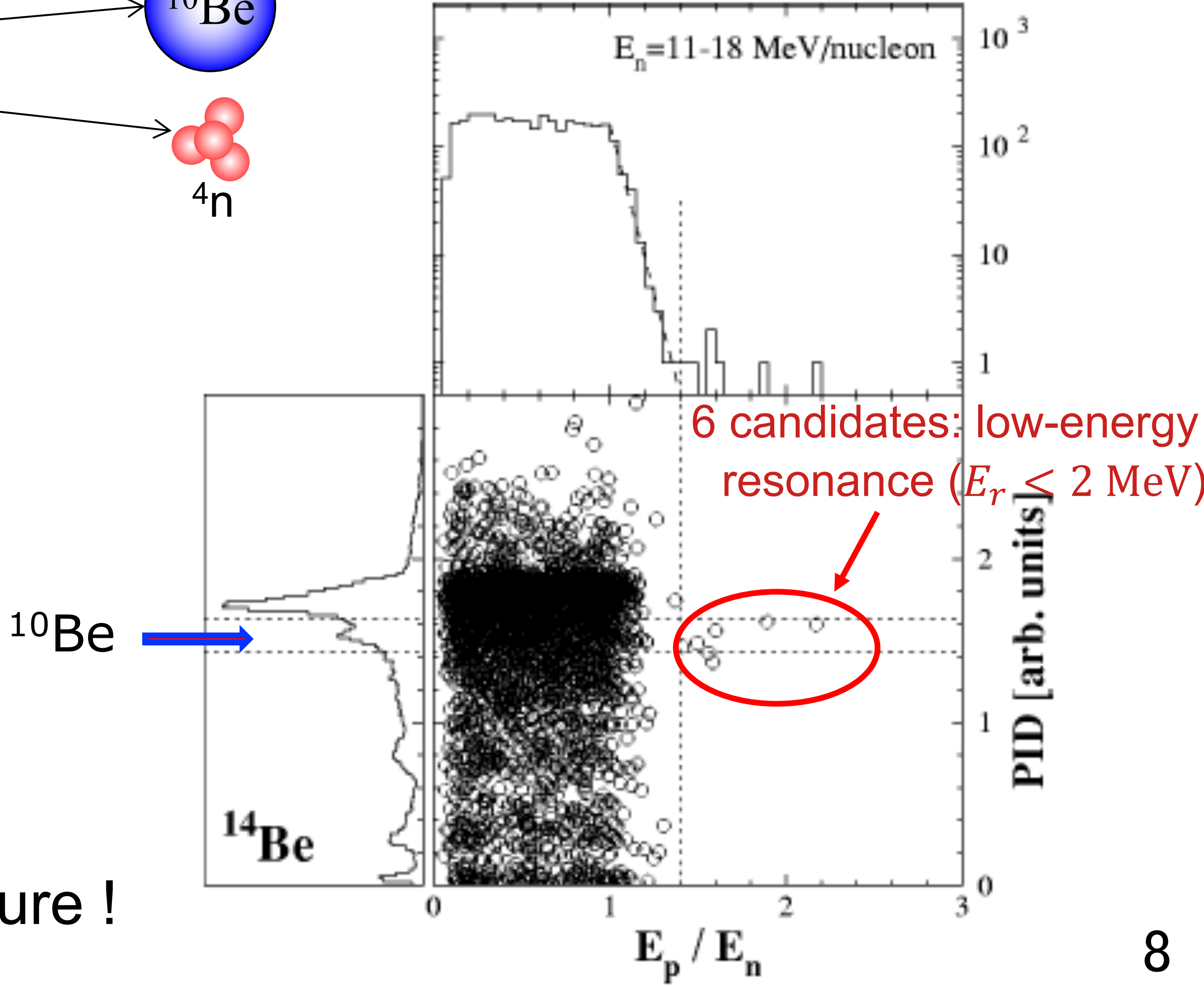


Recent Experiments on Tetra-Neutron

Tetra-neutron by Breakup

2002 Marquéz (PRC65, 044006 (2002). arXiv:nucl-ex/0504009(2005))

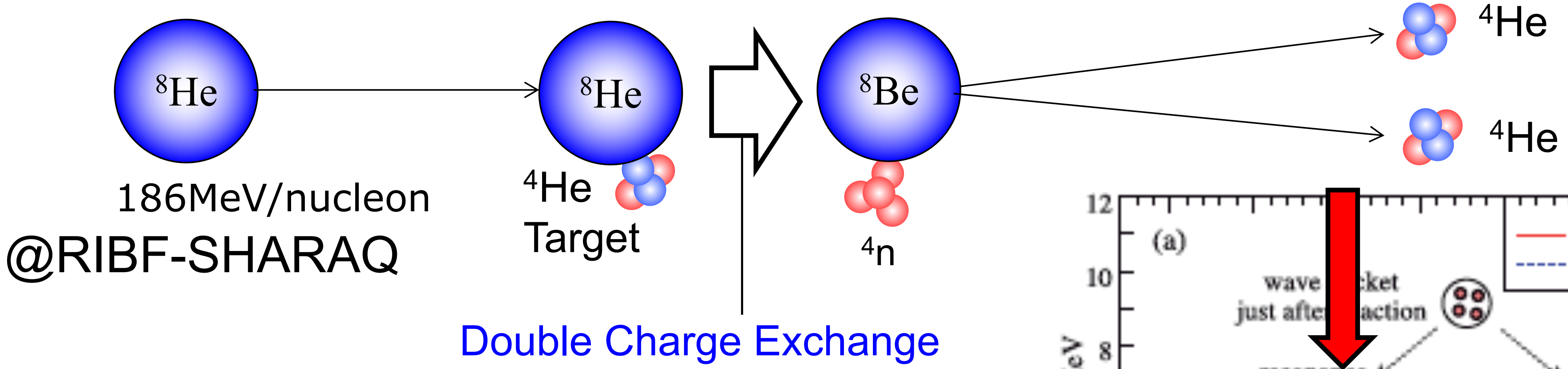


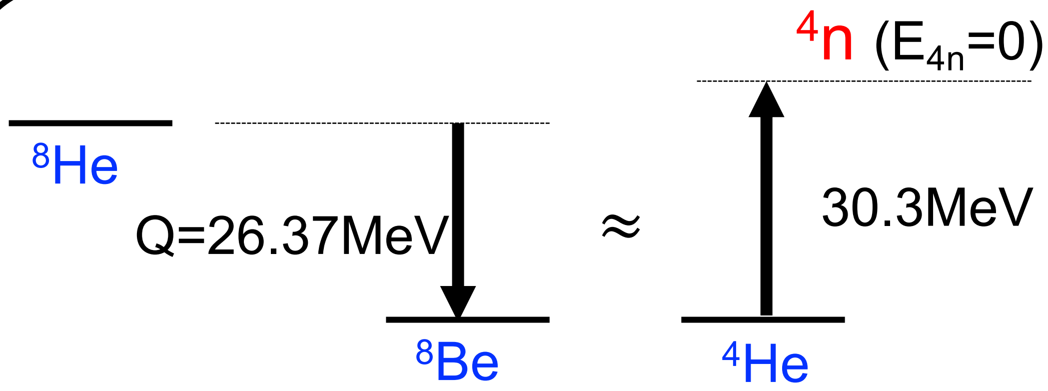


Confirmation should be done in the near future !

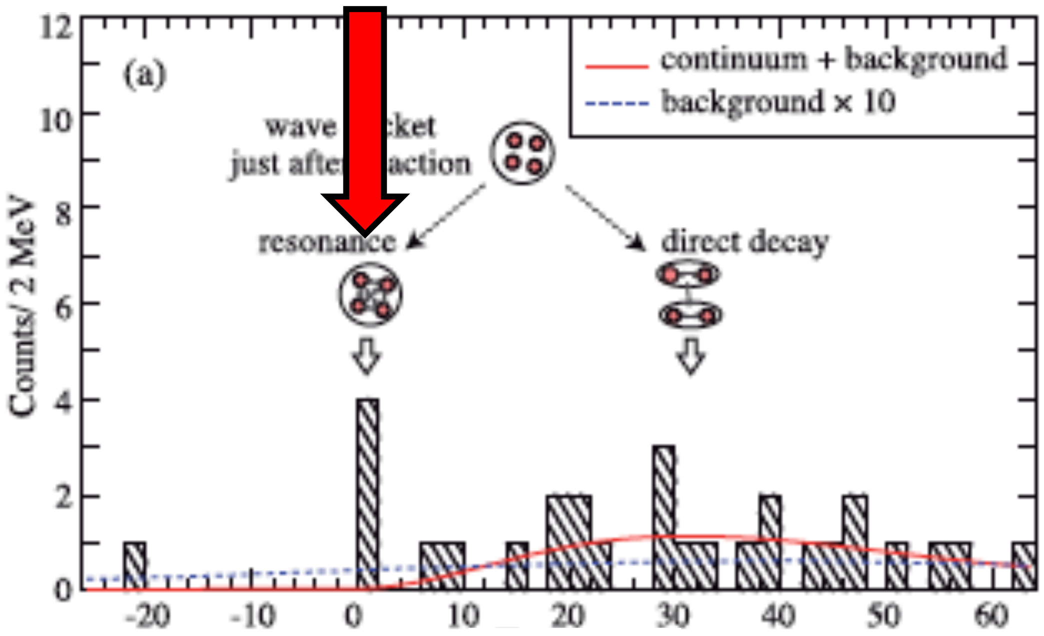
Tetra-neutron by Double Charge Exchange

2016 K.Kisamori, S.Shimoura (PRL116, 052501 (2016))





→Momentum transfer $\Delta \boldsymbol{q} \sim 0$



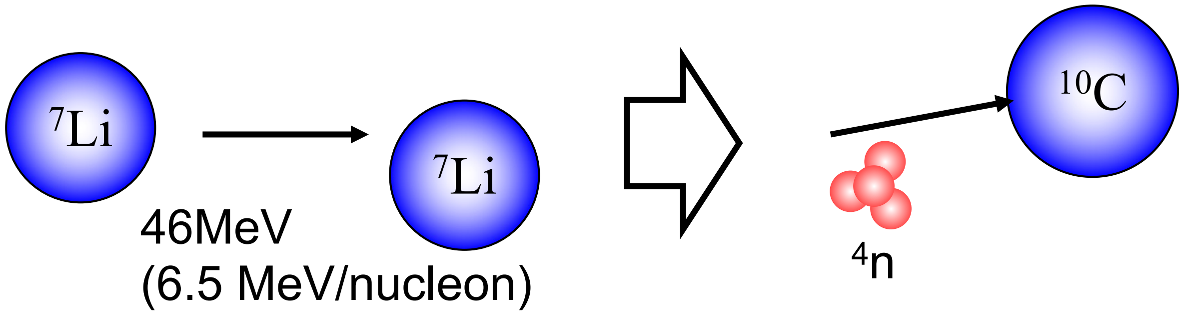
E_{4n} (MeV)

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

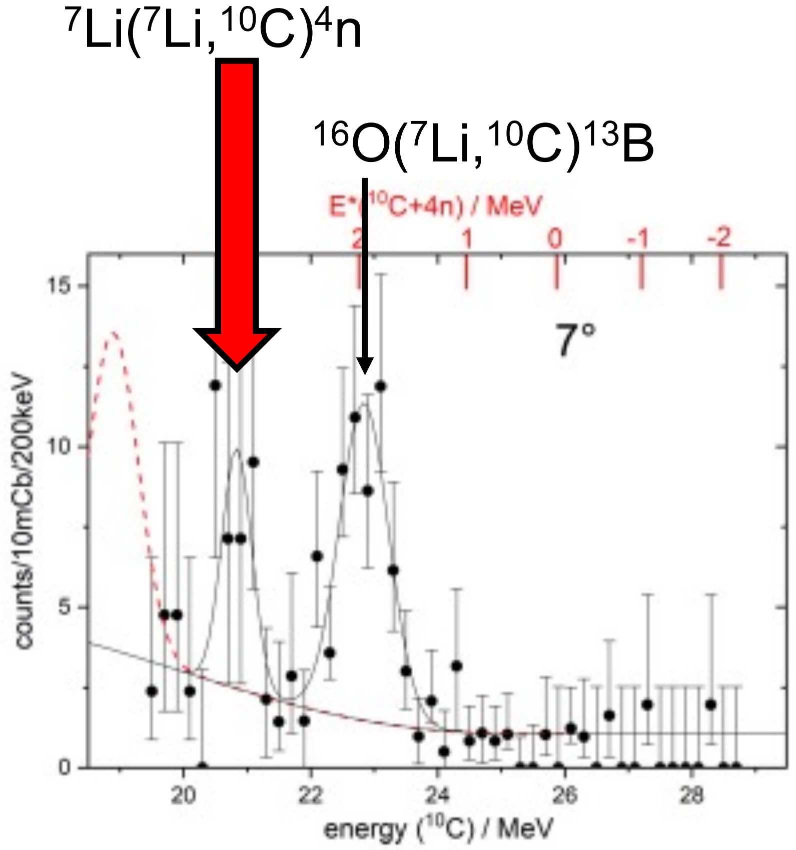
$\Gamma < 2.6$ MeV(FWHM)

Tetra-neutron by Multi-nucleon Transfer

2022 T.Faestermann (PLB824, 136799 (2022))



MP Tandem accelerator
@Garching near Munich



$$E_x(^{10}\mathrm{C} + {}^4n) = 2.93 \pm 0.16\ \mathrm{MeV}$$
$$\Gamma < 0.24\ \mathrm{MeV}$$

⇨

Width: too narrow to be a resonance

→ ^{10}C:1st excited state (Ex=3.354 MeV)

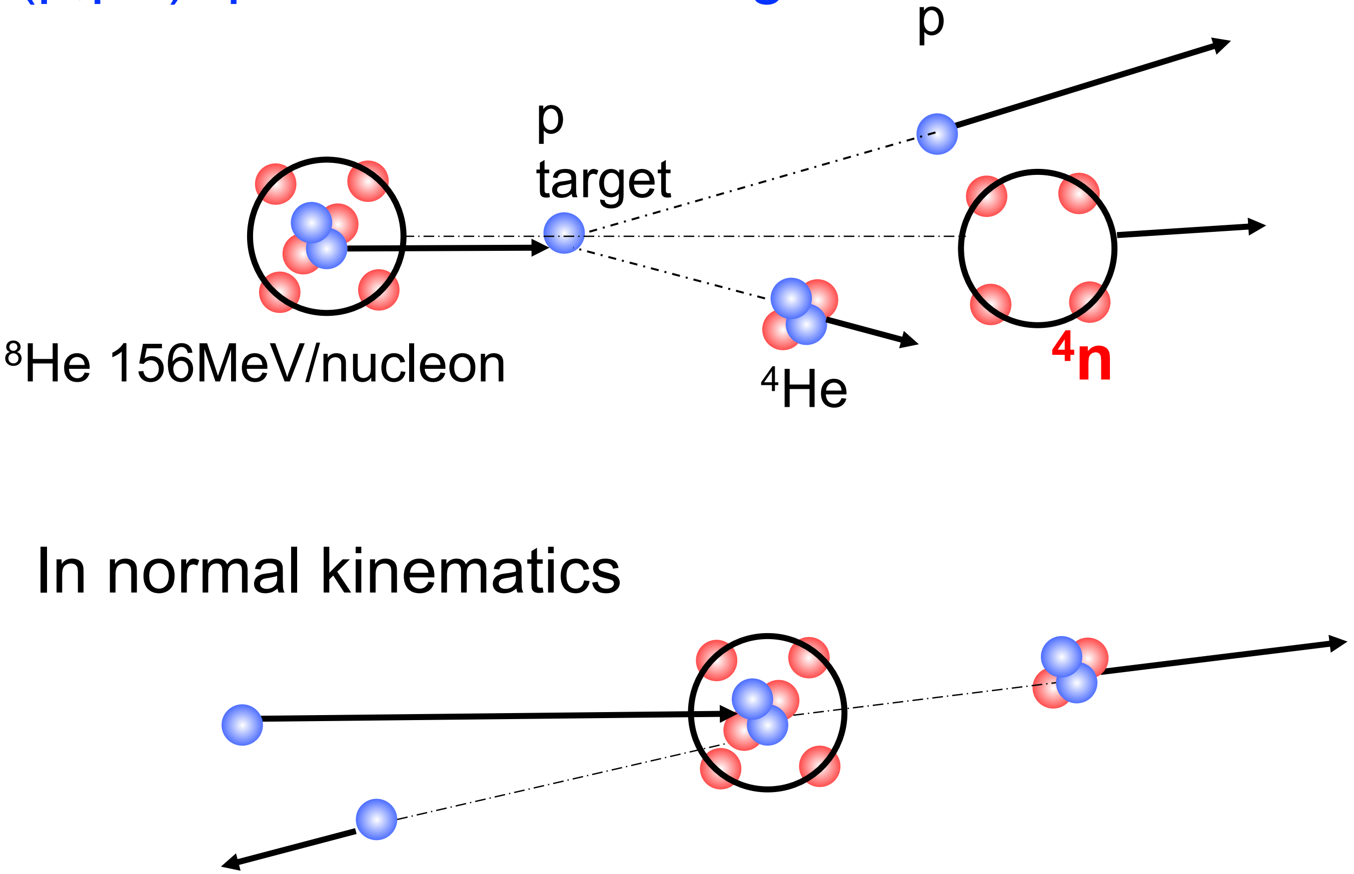
→$E_{4n} = -0.42 \pm 0.16$ MeV (**Bound state!**)

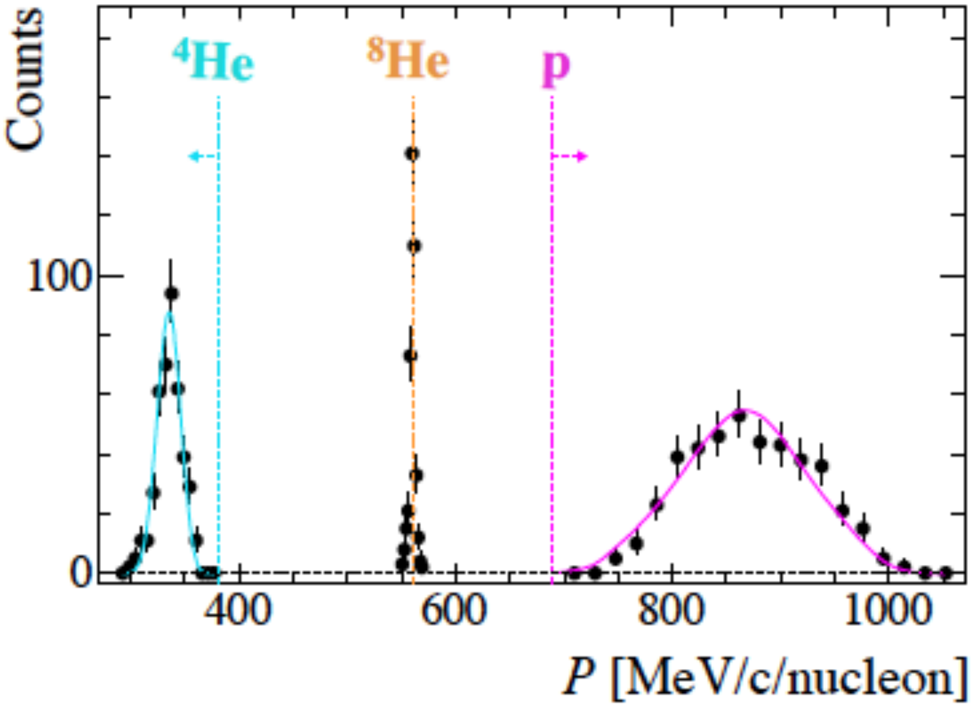
$\tau \sim 450\ s$ (1st forbidden β decay)

Tetra-neutron by alpha-knockout

2022 M. Duer, SAMURAI collaboration, (Nature **606**, 678 (2022))

(p,pα) quasi-free scattering in inverse kinematics

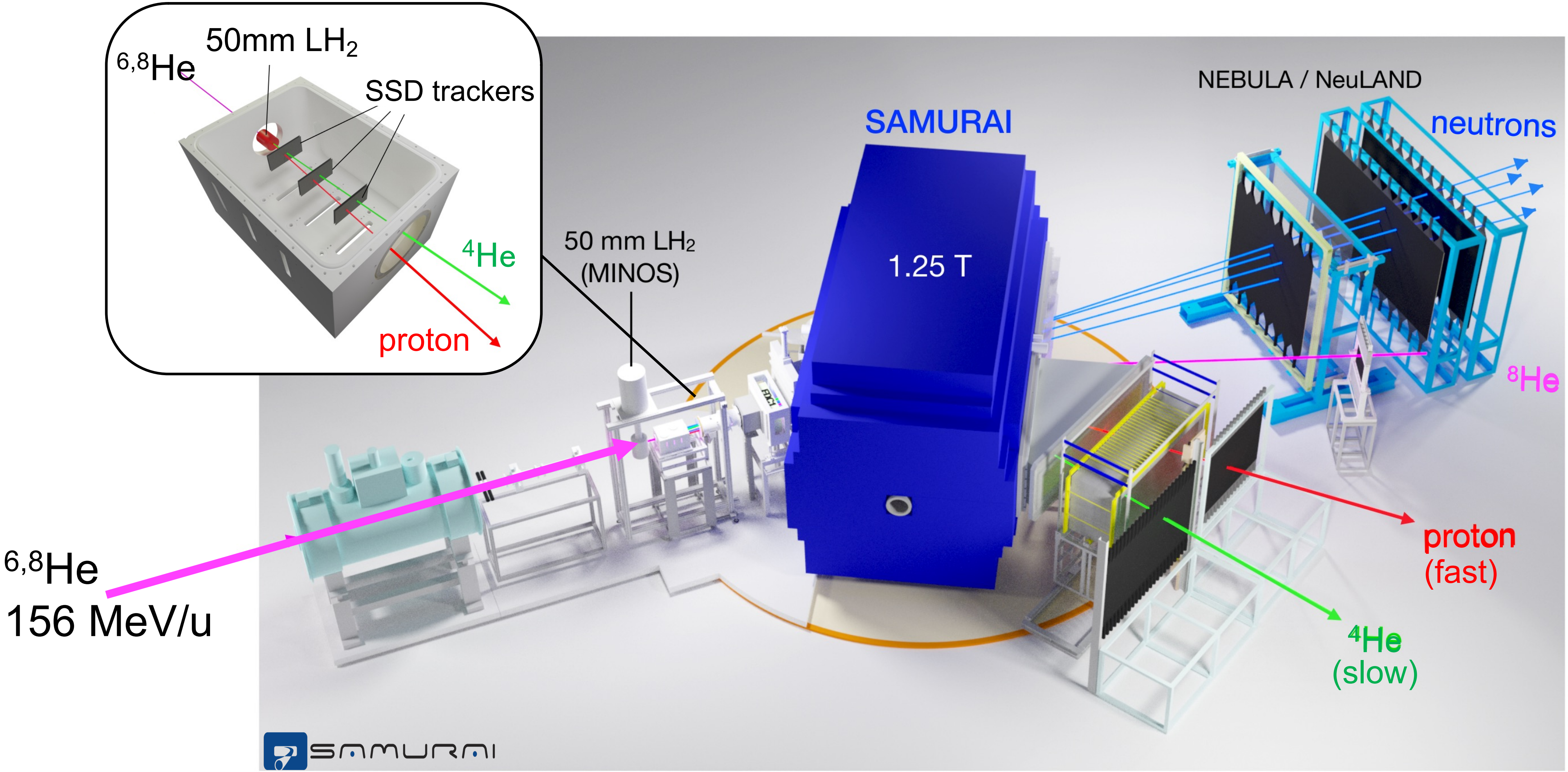




Backward scattering → Large momentum transfer $\Delta q > P_F$

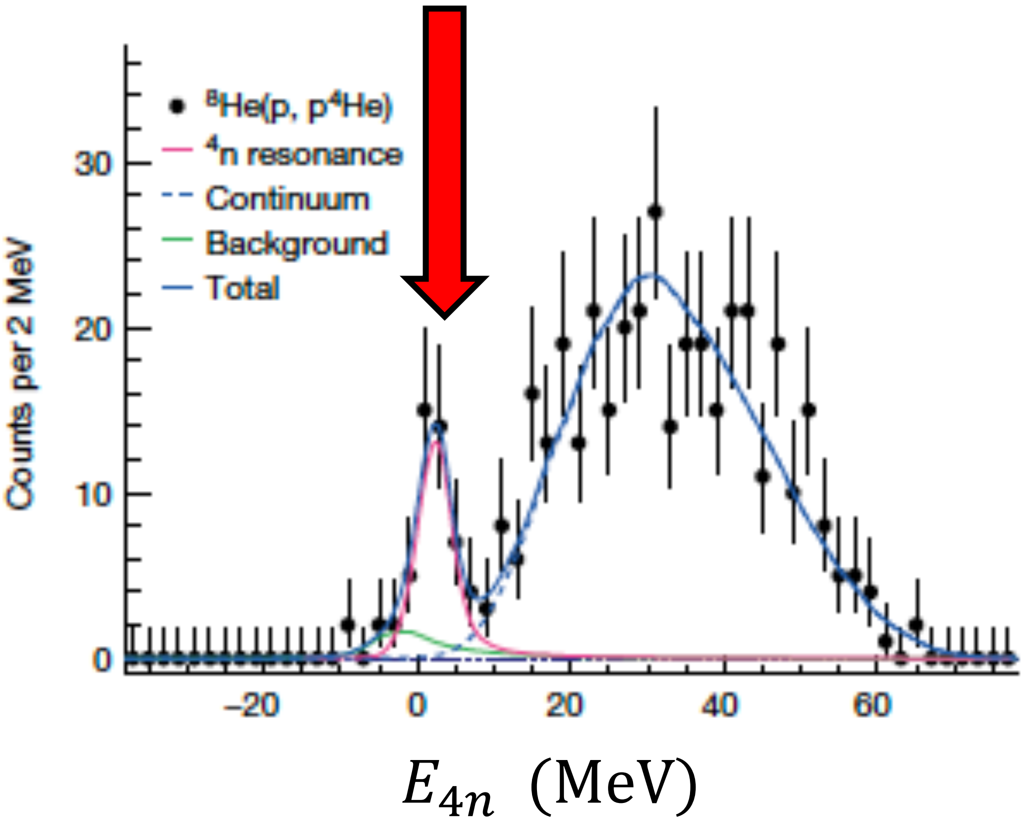
→ Minimize Final State Interactions

SETUP AT SAMURAI

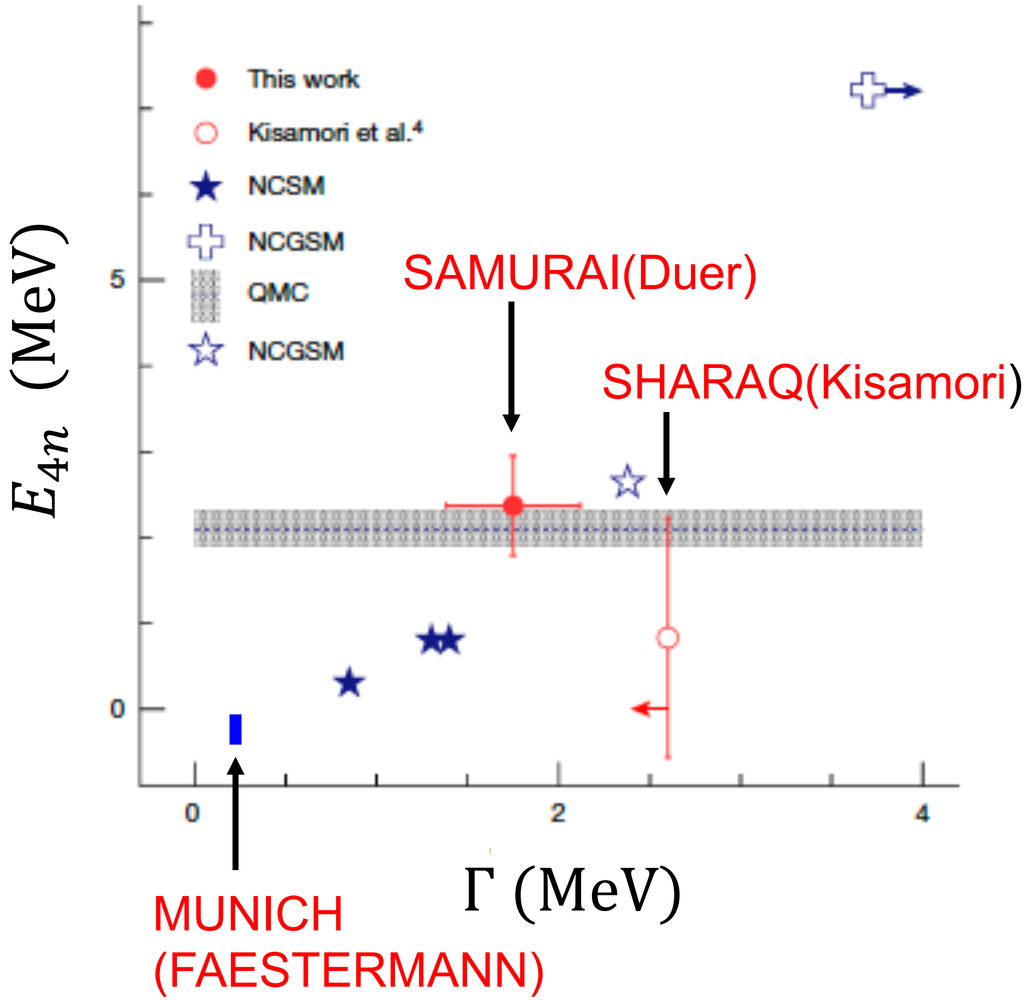


Tetra-neutron at SAMURAI-RIBF

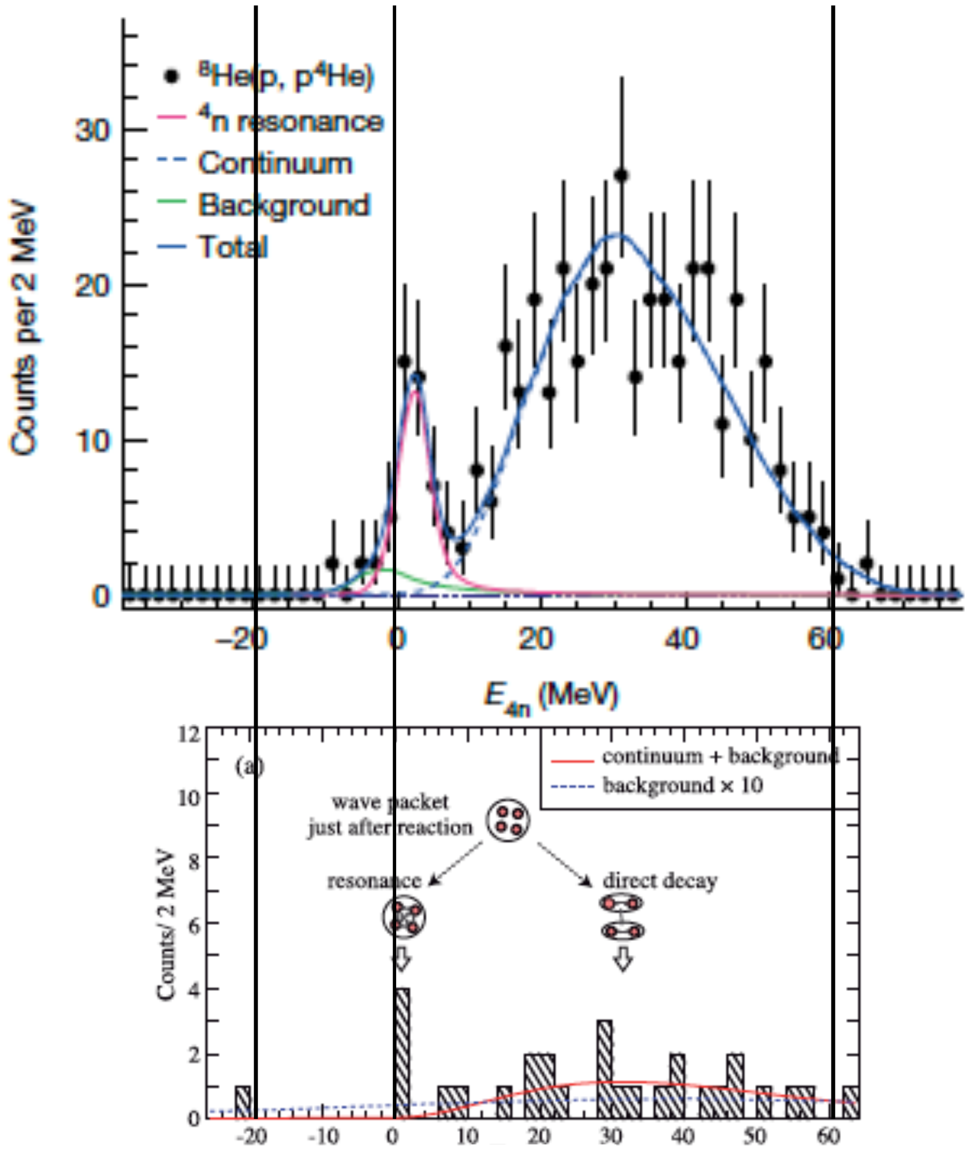
Nature **606**, 678 (2022).



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



$^{8}He(p,p\ \alpha)\ ^{4}n$ vs. $^{4}He(^{8}He,\ ^{8}Be)\ ^{4}n$



E_{4n} (MeV)

Nearly Identical Spectra? Why?

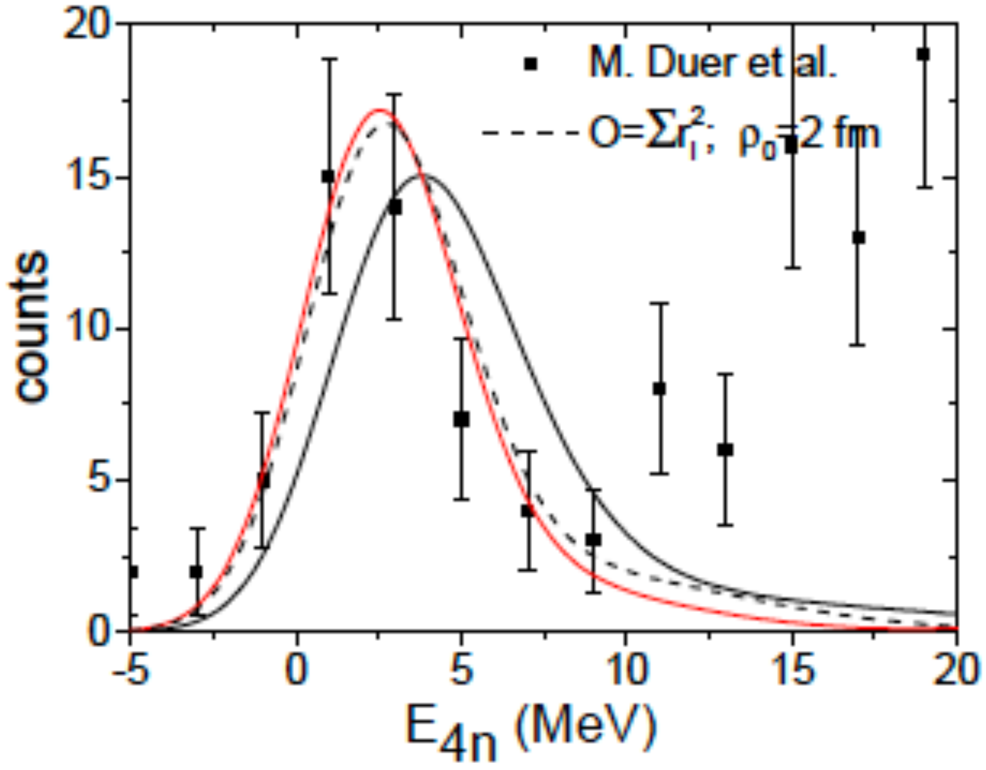
$^{8}He(p,p\alpha)^{4}n$ in inv. kinematics
@SAMURAI-RIBF
M.Duer et al. Nature 2022

$^{4}He(^{8}He,\ ^{8}Be)\ ^{4}n$
@SHARAQ-RIBF
Kisamori et al., PRL 2016

Tetra-neutron: Resonance or?

R.Lazauskas, E.Hiyama, J.Carbonell, Phys. Rev. Lett. **130**, 102501(2023).

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 ^{8}He.



Next Step

- Energy spectrum with better E resolution
- 4 Neutron coincidence measurements

→4n Decay Scheme

Remark for $^3n, ^3p$

K.Miki et al.

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Accepted Paper

Precise spectroscopy of the $3n$ and $3p$ systems via the $^3H(t,^3He)3n$ and $^3He(^3He,t)3p$ reactions at intermediate energies

Phys. Rev. Lett.

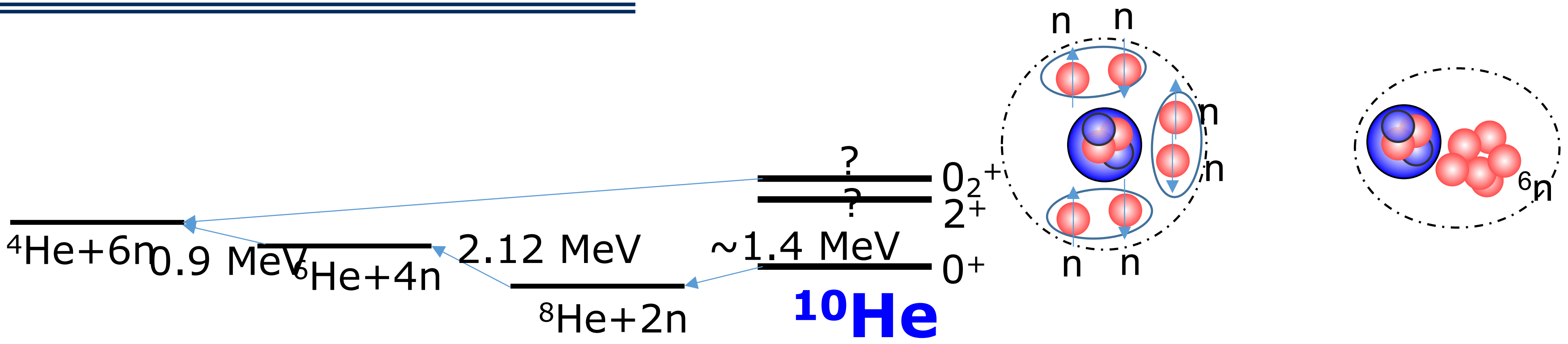
ABSTRACT

To search for low-energy resonant structures in isospin $T = 3/2$ three-body systems, we have performed the experiments \$\trit\trihe 3n\$ and \$\he\hetri 3p\$ at intermediate energies. For the $3n$ experiment, we have newly developed a thick Ti-\$\trit\$ target, which has the largest tritium thickness among targets of this type ever made. The $3n$ experiment for the first time covered the momentum-transfer region as low as 15 MeV/c, which provides ideal conditions for producing fragile systems. However, in the excitation-energy spectra we obtained, we did not observe any distinct peak structures. This is in sharp contrast to tetraneutron spectra. The distributions of the $3n$ and $3p$ spectra are found to be similar, except for the displacement in energy due to Coulomb repulsion. Comparisons with theoretical calculations suggest that three-body correlations exist in the $3n$ and $3p$ systems, although not enough to produce a resonant peak.

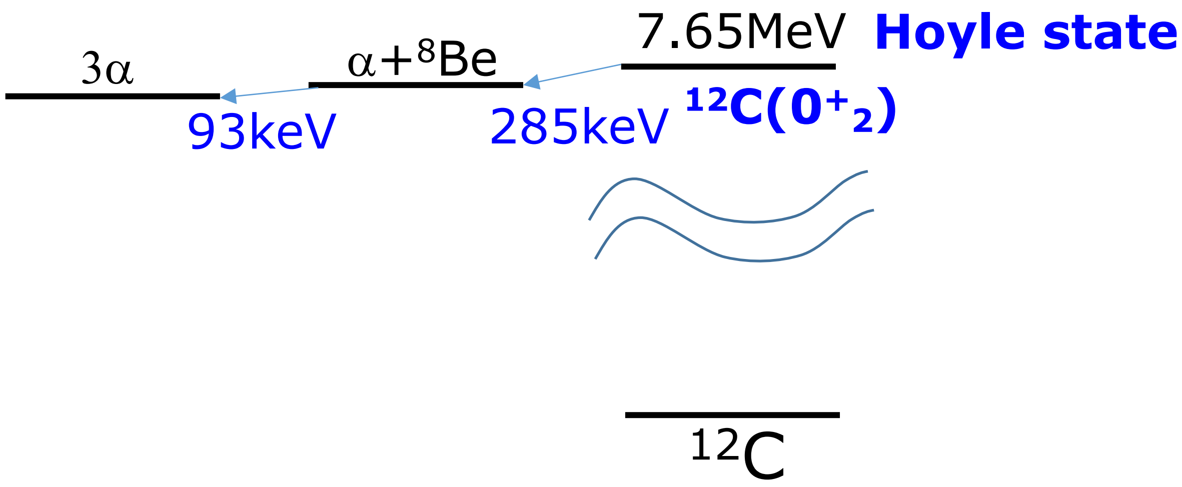
Multi-neutron clusters in $^{10}He^{*}$?

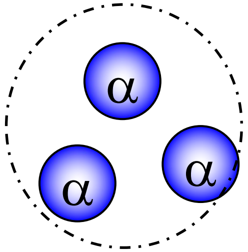
$^{11}Li(p,2p)^{10}He$ experiment at SAMURAI-RIBF

What happens if there are multiple dineutrons?



triple-dineutron or “^{6}n” ?





alpha-cluster

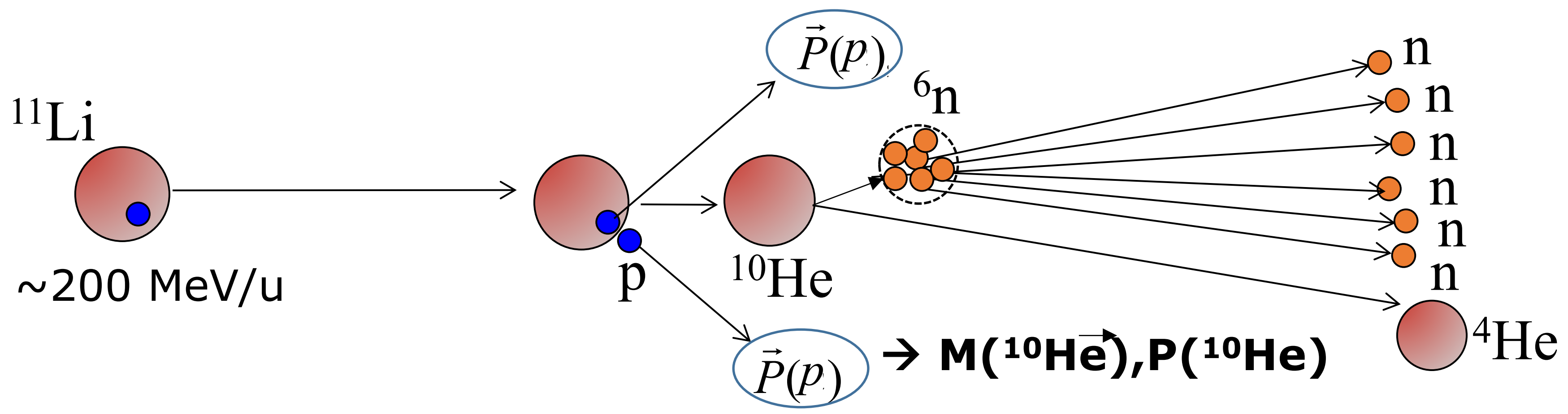
alpha-condensation

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

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

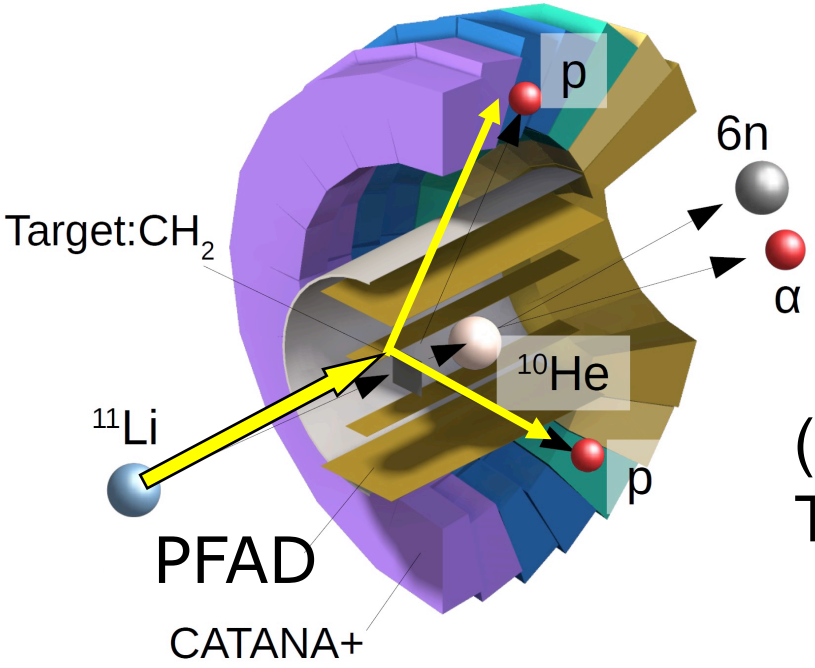
^{11}Li(p,2p)^{10}He*
^{10}He*→^{8}He+2n, ^{6}He+4n, ^{4}He+6n

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

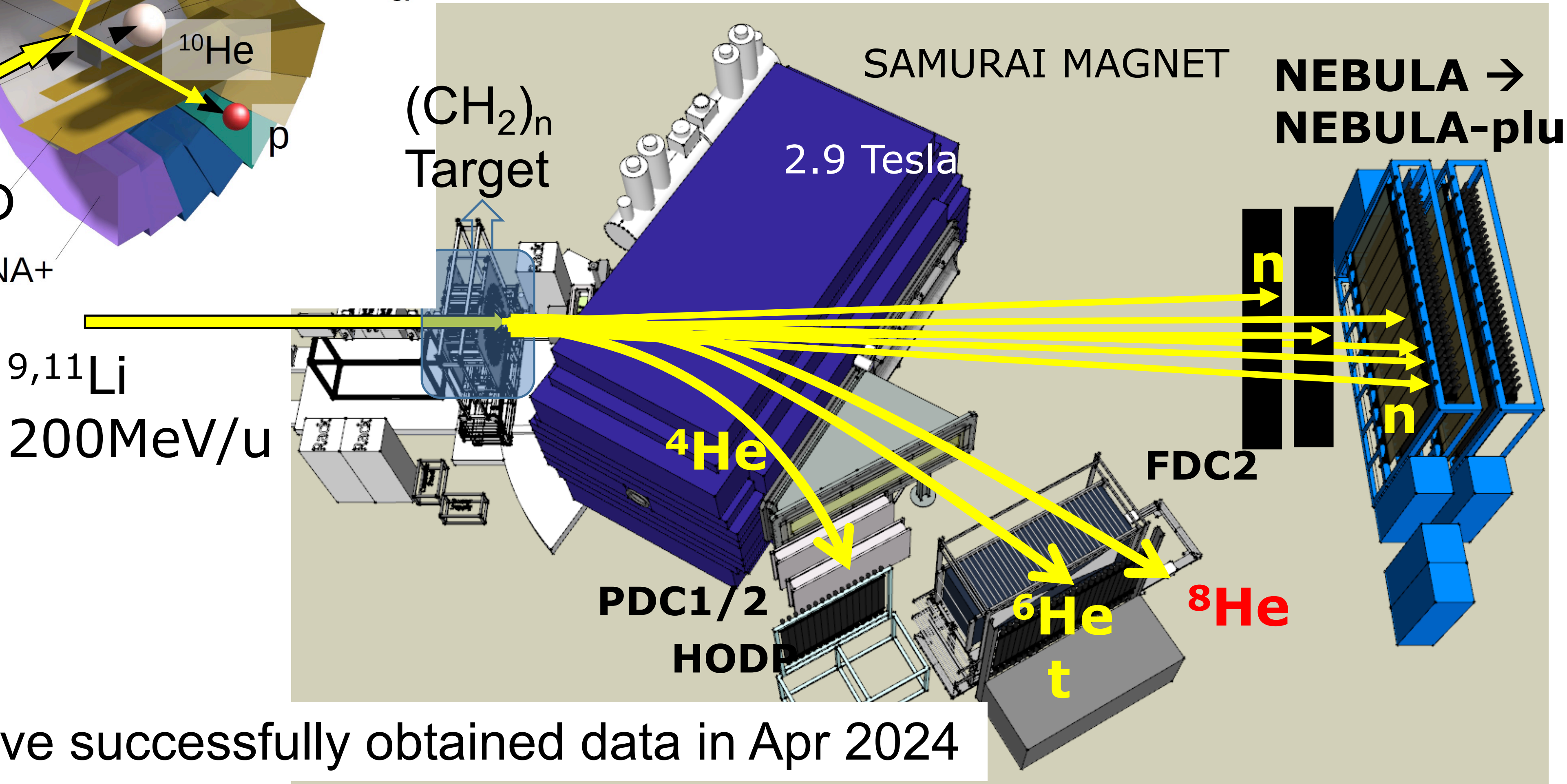


^{9}Li(p,2p)^{8}He*
^{8}He*→^{6}He+2n, ^{4}He+4n

Experimental Setup



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



We have successfully obtained data in Apr 2024

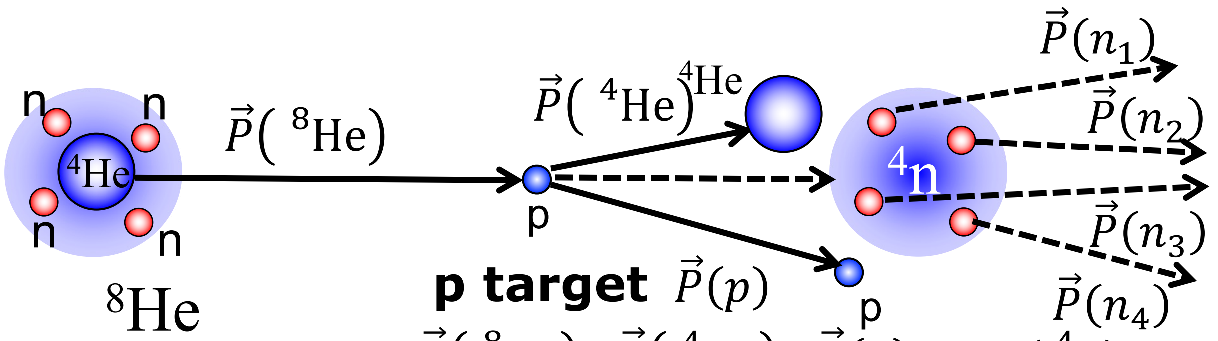
Perspectives:

Next Step for pure-neutron nuclei at SAMURAI-RIBF

Missing mass method→Invariant Mass Method

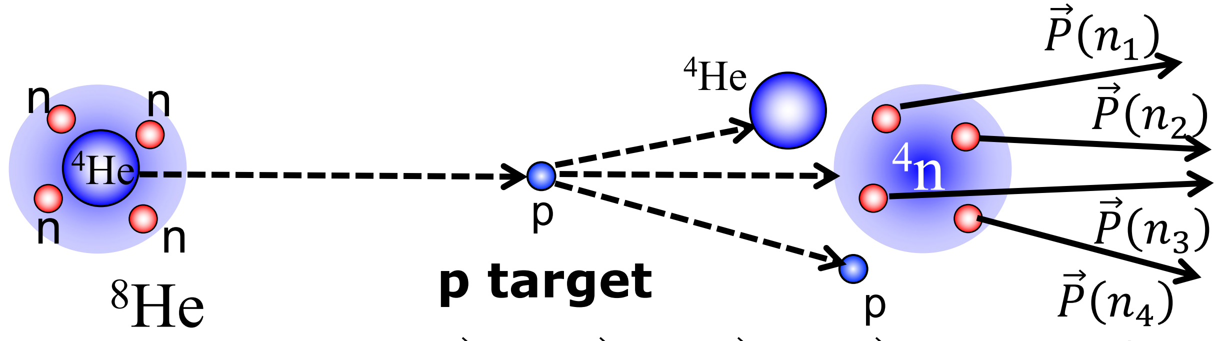
Missing Mass

M.Duer Nature 2022



$\vec{P}(^8\mathrm{He}),\ \vec{P}(^4\mathrm{He}),\ \vec{P}(p) \rightarrow M(^4n)$

Invariant Mass



$\vec{P}(n_1), \vec{P}(n_2), \vec{P}(n_3), \vec{P}(n_4) \rightarrow M(^4n)$

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

😄 **No need of neutron detections**

😩 **Worse mass-resolution: $\Delta M \sim$ 1MeV**

😩 **Decay mode cannot be observed**

😄 **Good mass-resolution: $\Delta E \sim$ 100keV**

😄 **Decay mode can be observed**

😩 **Need of neutron detection**
(M_n>2: it has been nearly impossible)

NEBUA→NEBULA PLUS (Marqués, Orr)+ HIME(TN, Rossi, Duer, Aumann,Knösel)

^{4}n invariant mass exp approved at RIBF: M.Duer, K.Miki, T.Aumann, TN et al.,

4n,6n experiments at RIBF --Miki,Duer et al. Approved at RIBF--

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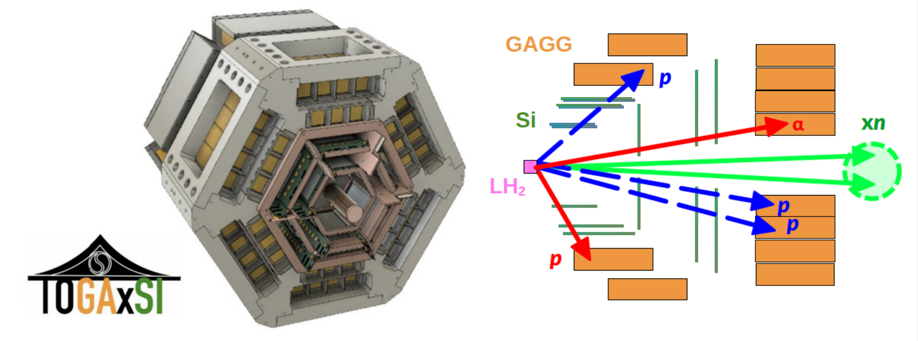
Correlations in multi-neutron systems [K. Miki, MD et al. SAMURAI74, exp. In 2025]:

- properties of the 4n system - correlations among **4n in coincidence**
  - → exclusive $^{8}He(p,p\alpha)4n$ knockout
  - → **reaction mechanism:** $^{6}He(p,3p)4n$ knockout
- search for **6n correlations** via missing-mass $^{8}He(p,3p)$ measurement

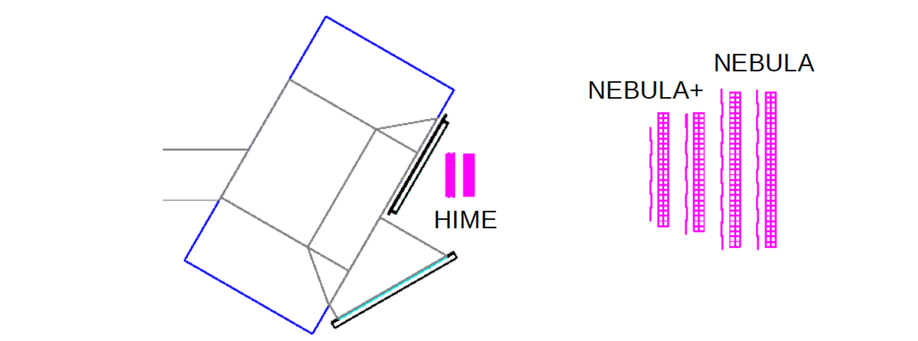
Charged particles: TOGAXSI

Tanaka et al., NIMB 542 (2023)



- Wide range of c.m. angles $50^{\circ} \leq \theta_{c.m.} \leq 165^{\circ}$
  - → $\sigma_{p\text{-}\alpha}=0.5$ mb
  - → $\sigma_{3p}=1$ mb (INCL calculation)

Neutrons: upgraded detection setup
HIME + NEBULA-Plus + NEBULA



- Total estimated 4n detection efficiency 1.1% (E_{4n}<6.5 MeV)

Slide by M.Duer

NEOLITH(NEutrOn detector array for muLtI-neutron systems using Tracking tecHnology)

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The figure has been removed as this is an on-going project

JSPS KAKENHI, Grant-in-Aid for Specially Promoted Science

Simulation Results (by Y. Kondo)

Position resolution(σ) ~2mm
E_{rel} resolution(σ): 30~50 keV@1MeV

The figures have been removed as this is an on-going project

- ✓ Compared to the NEBULA-Plus setup, Efficiency is smaller, but S/N and Mass resolutions are better by a factor of ~3
- ✓ With high-intense beam such as $^{6,8}He$, experiments are feasible

Summary

- ✓ Pure Neutron Nuclei (Multi-neutron systems)
  - ➢ 4n, 6n … → 3N, 4N force/correlations → Basis for N-star physics
    →Unique Neutral Fermionic Systems
- ✓ Mutli-neutron clusters What happens when pure-neutron nuclei in a nucleus
- ✓ Recent Tetra Neutron Experiments
  - ➢ Four experiments: Breakup/DCX/a knockout/multi-nucleon transfer
  - ➢ ^{8}He(p,pα)4n reaction in inverse kinematics at SAMURAI at RIBF
    →Resonance-like structure (~40 events) at $E = 2.37 \pm 0.38(stat.) \pm 0.44(sys.)\mathrm{MeV}$
    M.Duer et al., Nature **606**, 678 (2022).
  - ➢ ^{8}He(p,pα)4n & 4He(8He,8Be)4n provides similar spectra
  - ➢ ^{3}n by K.Miki
- ✓ Multi-neutron clusters in highly exited ^{8}He/^{10}He? → RIBF experiment ^{9,11}Li(p,2p)^{8,10}He

Perspectives

- ➢ Missing Mass → Invariant mass spectroscopy for ^{4}n, ^{6}n
- ➢ ^{4}n Invariant mass with TOGAXI+HIME+NEBULAPLUS ~2025
- ➢ NEOLITH (Next generation neutron detector array) ^{4}n,^{6}n Invariant mass ~2028

Collaboration of tetra-neutron at SAMURAI

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

Article

Observation of a correlated free four-neutron system

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

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Check for updates

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SAMURAI47 Collaboration (^{11}Li(p,2p)^{10}He*)

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