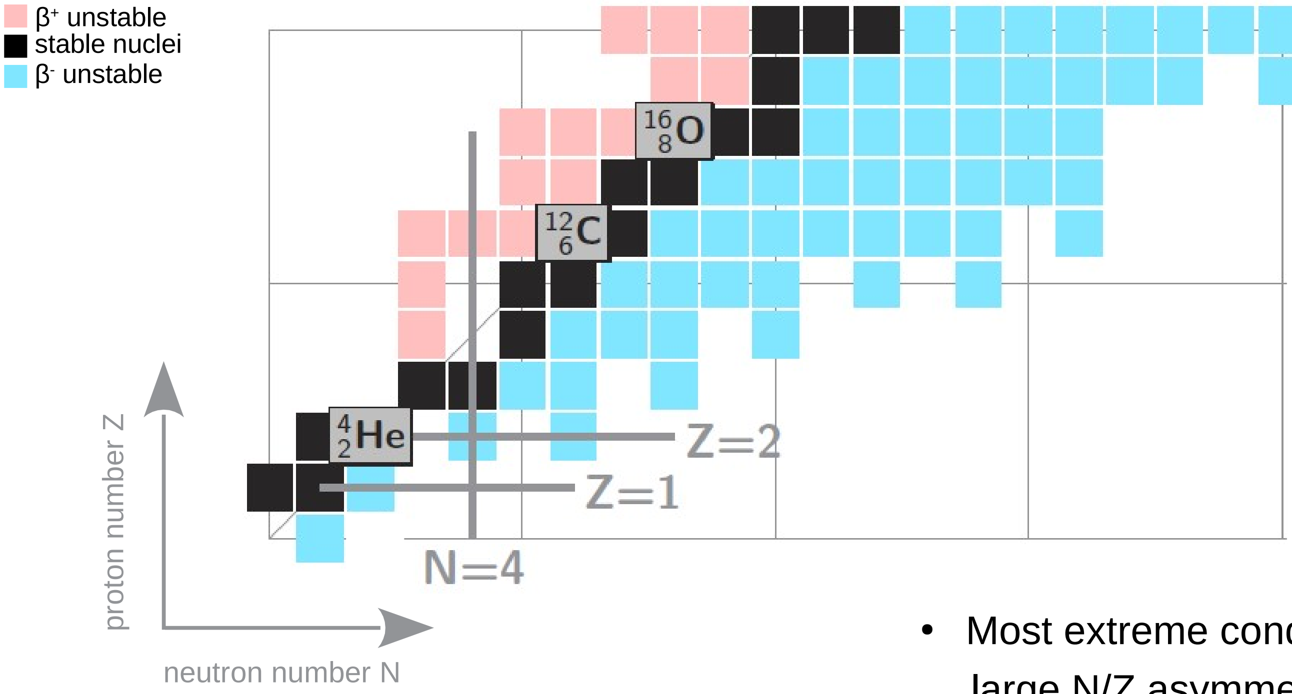
Free system of four correlated neutrons

Meytal Duer, TU Darmstadt

CLUSHIQ2022
November 3rd, 2022

At and beyond the neutron drip-line



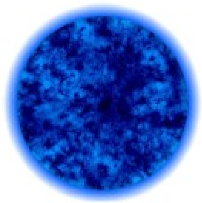


Figure from Marqués, EPJP 136 (2021)

- Most extreme conditions:
  large N/Z asymmetry and low-density
- Neutron halo/skin
- **Correlations: di-neutron, neutron droplets**
- Neutron matter
- ...

At and beyond the neutron drip-line

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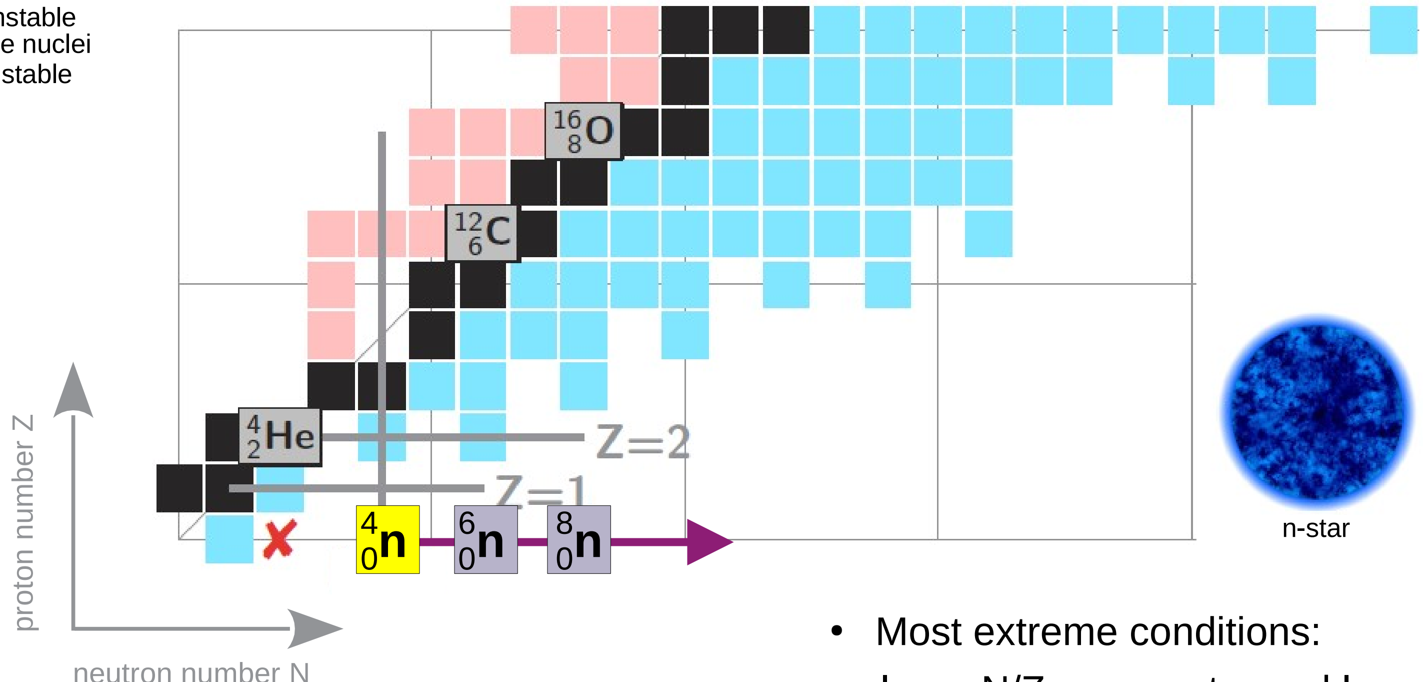

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Outline

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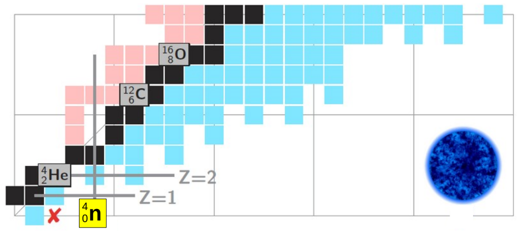
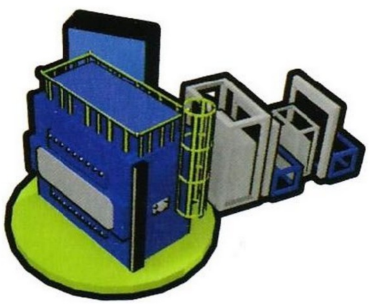
❶ **The tetra-neutron context**

- experimental quest
- theoretical predictions





❷ **4n experiment at SAMURAI: quasi-free α-knockout reaction**

- experimental method
- results and discussion

❸ **Future perspectives**

next-generation experiments

A 60-year quest

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XX century:

- fission of uranium
  e.g. Schiffer & Vandenbosch, Phys. Lett. 5 (1963)

Volume 5, number 4 PHYSICS LETTERS 15 July 1963

SEARCH FOR A PARTICLE-STABLE TETRA NEUTRON *

J. P. SCHIFFER and R. VANDENBOSCH
Argonne National Laboratory, Argonne, Illinois

Received 7 June 1963

As in most experiments of this sort, however, a negative result cannot be regarded as conclusive and further experiments are needed to give additional weight to our result.

- transfer reactions
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- double-charge-exchange $^4He(\pi^-,\pi^+)$ reaction
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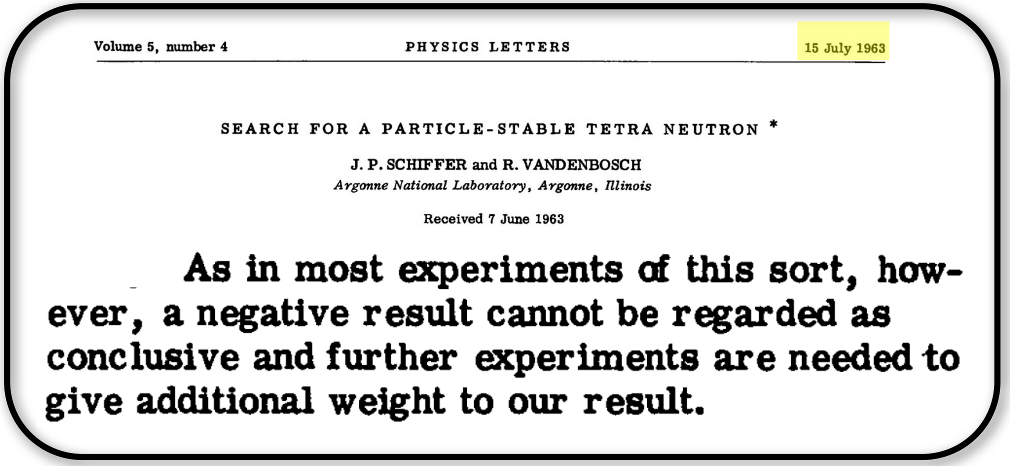

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XXI century:

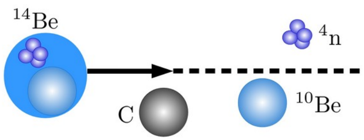
radioactive-ion beams

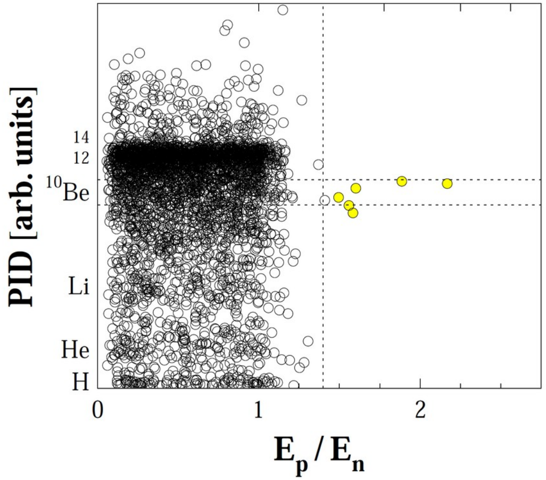
➢ first positive signals

The elusive tetra-neutron

GANIL 2002

Breakup on a C target:





6 candidates: bound ^{4}n or
low-energy resonance (E_r<2 MeV)

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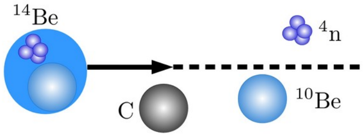

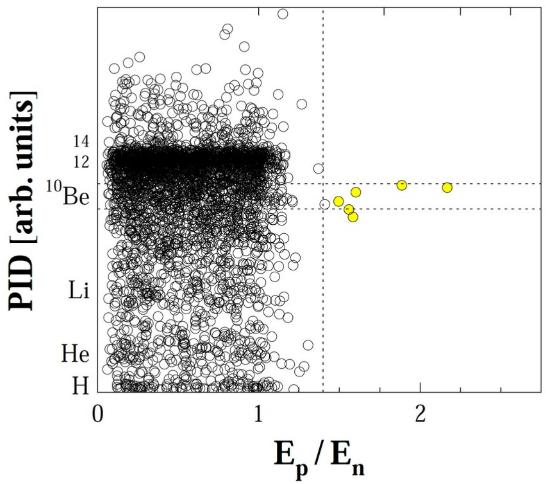

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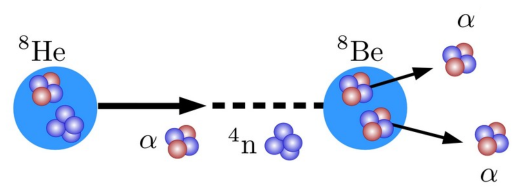

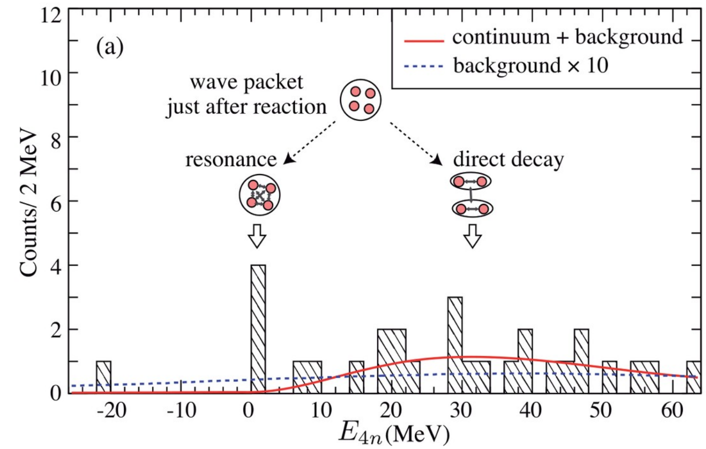

4 candidates for ^{4}n resonance: E_r=0.8±1.4 MeV, Γ<2.6 MeV

Kisamori *et al.*, PRL 116 (2016)

Can a bound tetra-neutron exist?

Overall historical consensus: **no bound tetra-neutron**

unrealistic modifications of V_{nn}

Glöckle PRC 18, 1978; Offermann, NPA 318, 1979...

Pieper PRL 90, 2003:

$$H = \sum_{i=1}^{A} T_i + \sum_{i<j=1}^{A} V_{ij} + \sum_{i<j<k=1}^{A} V_{ijk}$$

- ab initio Green's function Monte Carlo calculations
- using modern realistic NN and NNN potentials
- good description for light nuclei

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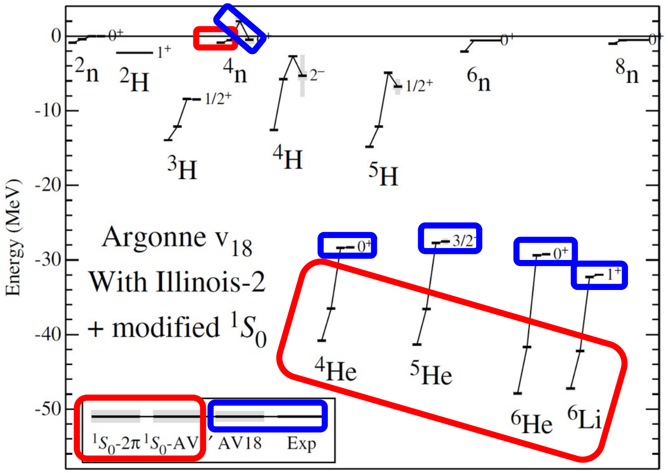
"it does not seem possible to change modern nuclear Hamiltonians to bind a tetraneutron without destroying many other succesful predictions... our understanding of nuclear forces will have to be significantly changed"



What about a resonance ?

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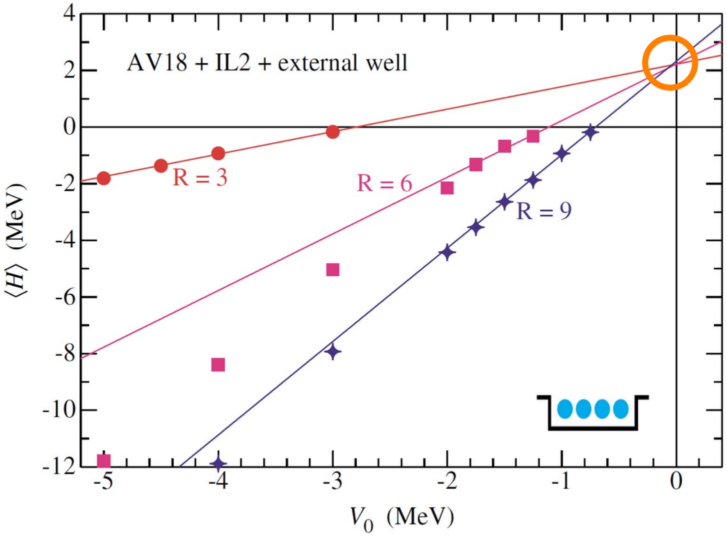
- neutrons trapped in Woods-Saxon potential with radius R and depth V_0
- resonance energy by extrapolation to $V_0 \to 0$
- **possible resonance around 2 MeV**



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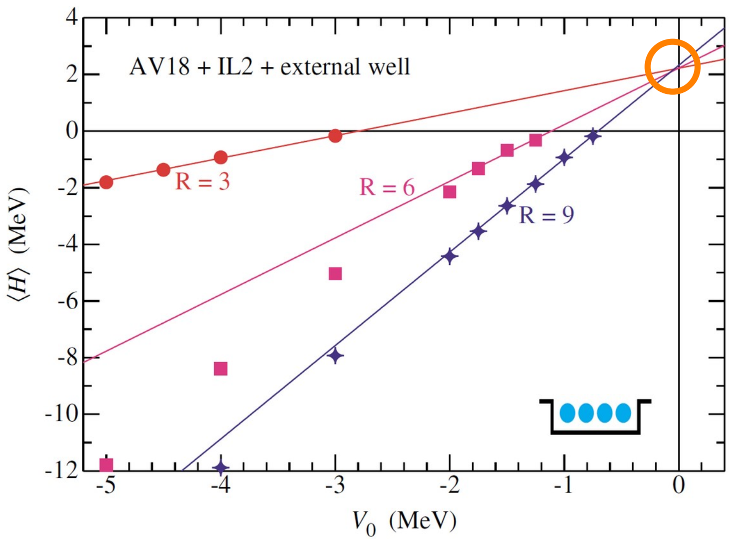
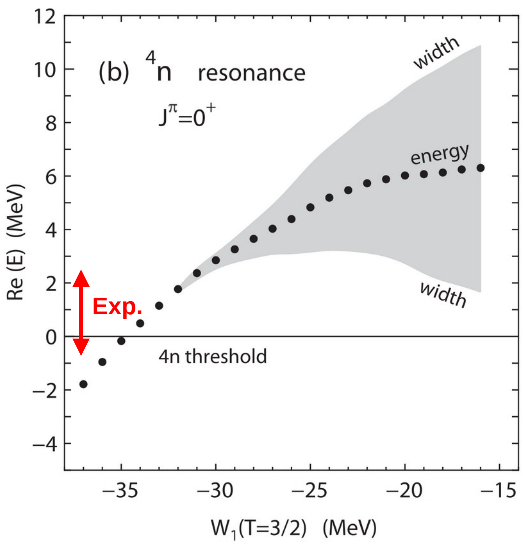
Hiyama *et al.*, PRC 93, 2016:

Full treatment of continuum

- absence of a four-neutron resonance
- resonance behaviour only for **remarkably (unrealistic) attractive 3N force in T=3/2 channel**
  - 15 times larger than T=1/2
  - inconsistent with known light nuclei





What about a resonance ?

All studies agree on:

- dominance of V_{nn} ($^1S_0$) in multi-neutron systems
- negligible contribution of 3N force

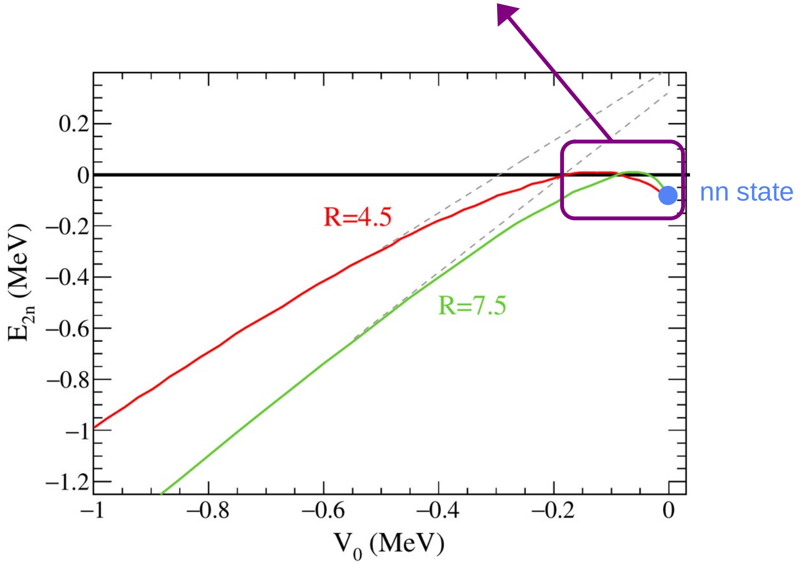
Contradictory results:

- do not origin from different interactions
- **methods to solve the few-neutron problem and/or treatment of the continuum**

From bound state to the continuum

example: 2n ($^1S_0$) confined in a trap

Importance of near threshold region
(Analytic Continuation on the Coupling Constant Method)



Modified from Deltuva & Lazauskas, PRL 123 (2019)

The elusive tetra-neutron

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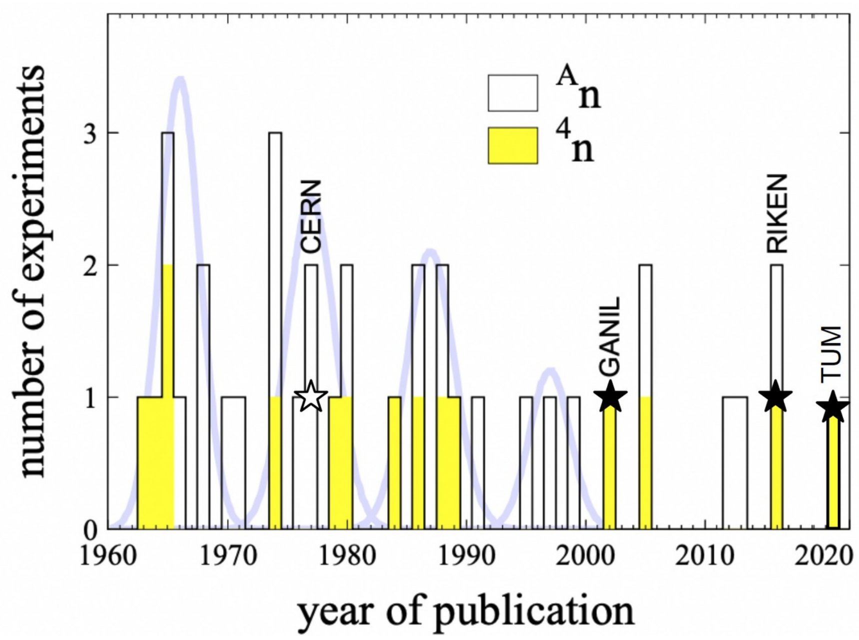

Modified from Marqués & Carbonell, EPJA 57 (2021)

Experiment:

- a long-standing quest for tetra-neutron system
- so far, three (weak) positive signals:
  - ★ GANIL 2002, RIKEN 2016, TUM 2022
  - ➢ indications for bound / unbound

Theory:

- no bound tetra-neutron
- no consensous about a resonant state

Outline

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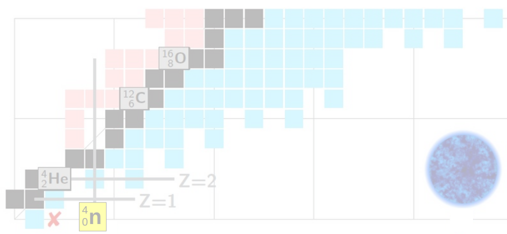
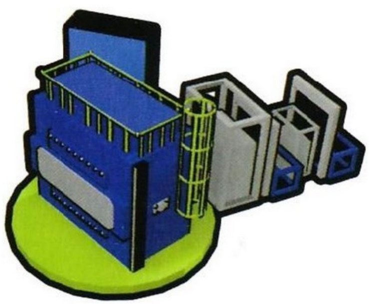
➊ The tetra-neutron context

- experimental quest
- theoretical predictions





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- results and discussion

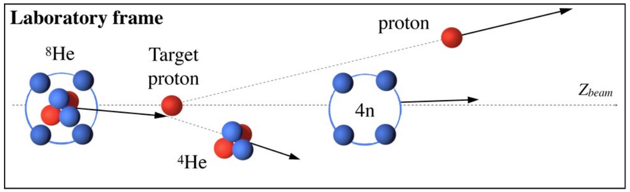
➌ Future perspectives

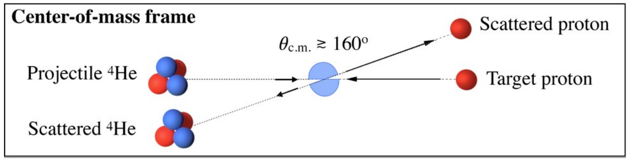
next-generation experiments

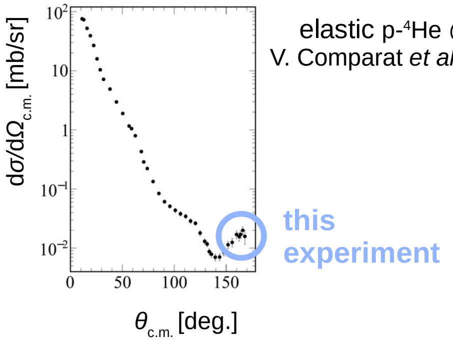
Present experimental work

QFS knockout $^8He(p,p^4He)$ at 156 MeV/nucleon

- Large momentum transfer p-^{4}He
  - “recoil-less” production
  - minimizes final-state interactions (FSI) between neutrons and charged particles







elastic p-^{4}He @ 156 MeV
V. Comparat *et al.*, PRC (1975)

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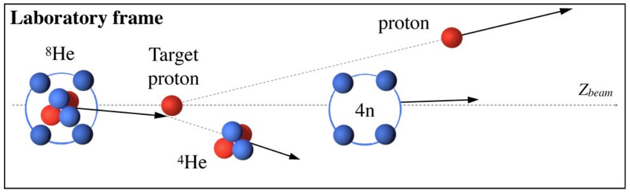
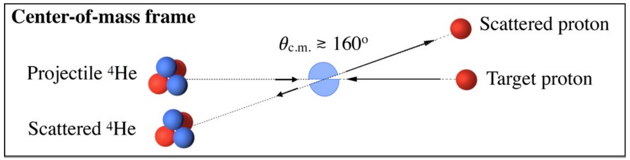
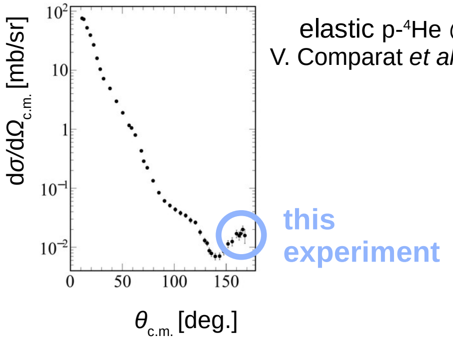
  - **large overlap ⟨^{8}He|α⊗4n⟩**







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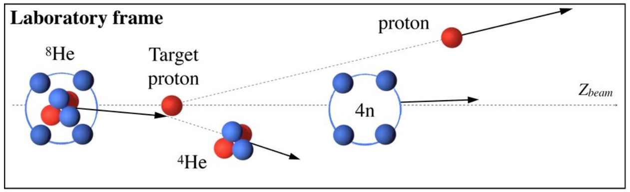
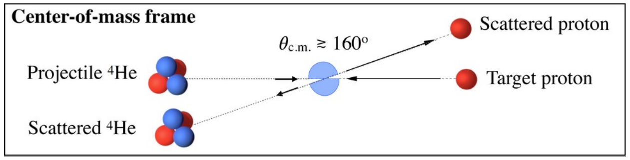
  - minimizes final-state interactions (FSI) between neutrons and charged particles
- ^{8}He is a good starting point:
  - pronounced α-core structure
  - **large overlap $\langle ^{8}He | \alpha \otimes 4n \rangle$**
- 4n energy spectrum via **missing mass**
  - precise measurement of charged particles

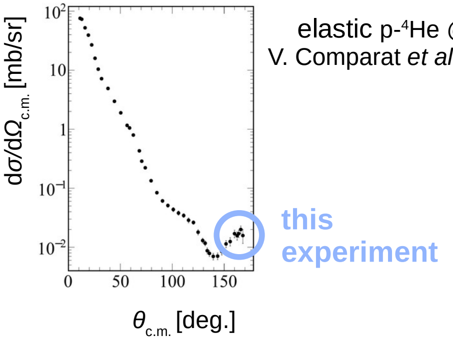
$$P_{miss} = P_{^{8}He} + P_{p(tgt)} - P_{^{4}He} - P_{p}$$

$$E_{4n} = \sqrt{E_{miss}^{2} - \boldsymbol{P}_{miss}^{2}} - 4\,m_{n}$$

$E_{4n} < 0$: bound $\quad E_{4n} > 0$: unbound







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The Radioactive Ion Beam Factory

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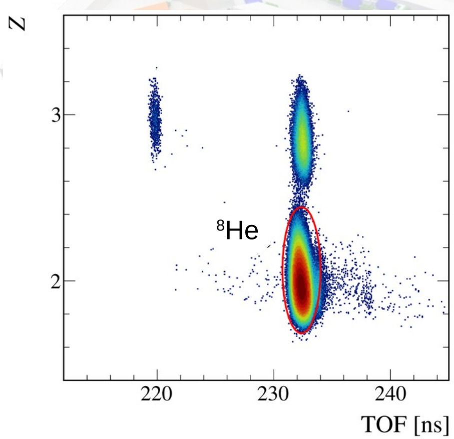
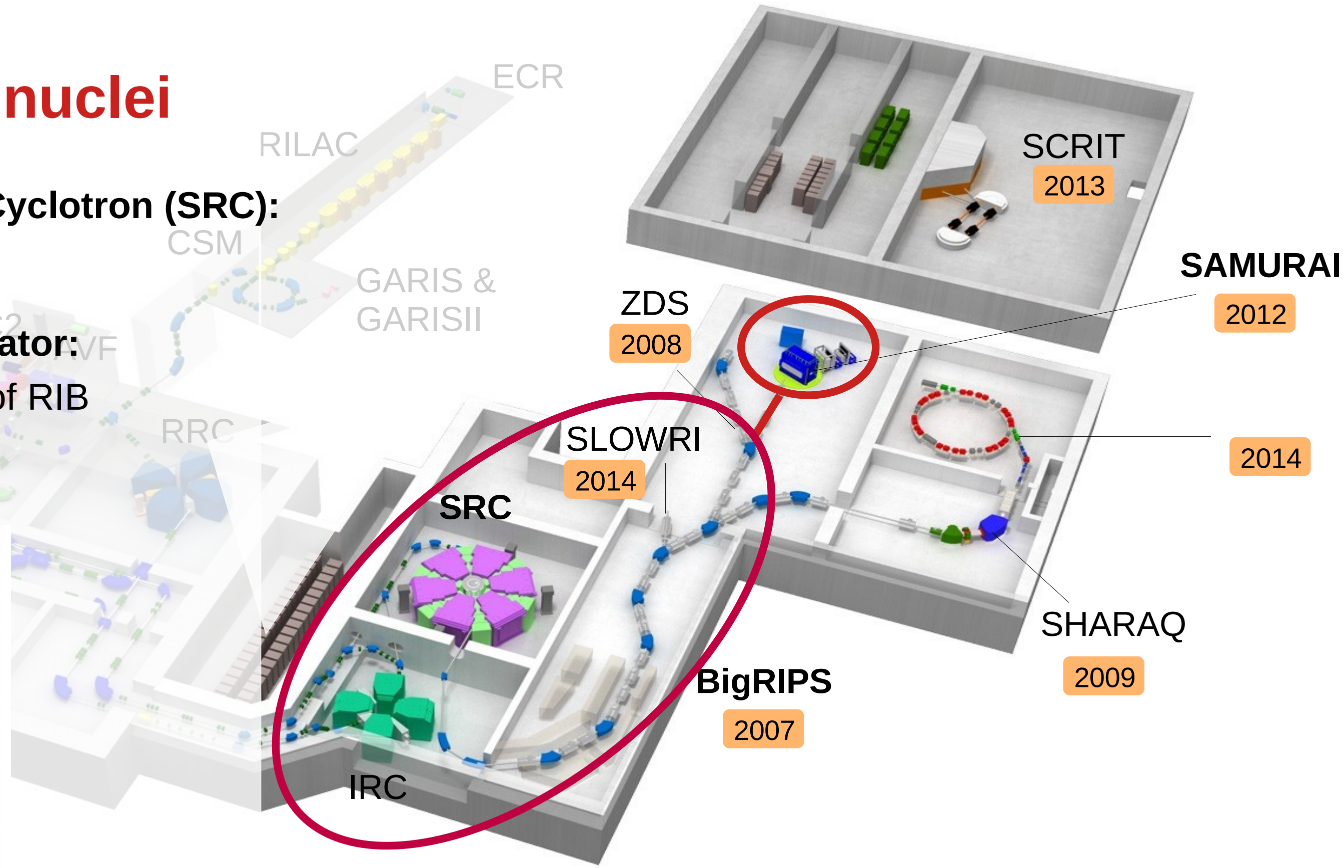
Access to exotic nuclei

- **Superconducting Ring Cyclotron (SRC):** primary ^{18}O beam
- **BigRIPS fragment separator:** production and selection of RIB

➢ **SAMURAI setup**





RIBF | RIKEN NiSHiNA CENTER | RIKEN Nishina Center for Accelerator-Based Science

SAMURAI setup at the RIBF

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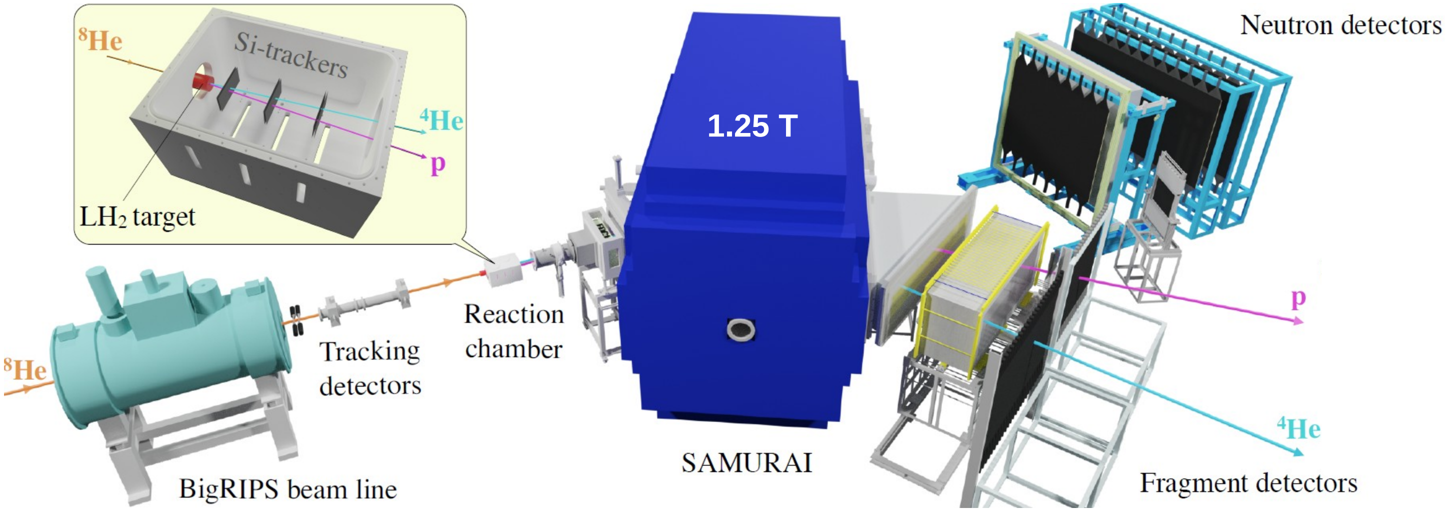
SAMURAI dipole magent: up to 3 T (1.25 T)

Tracking & identification of **secondary beam (^{8}He)**

Tracking & identification of **fragments (p, ^{4}He)**

Neutrons (not possible in this experiment)



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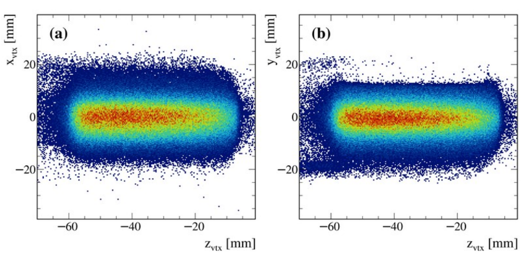
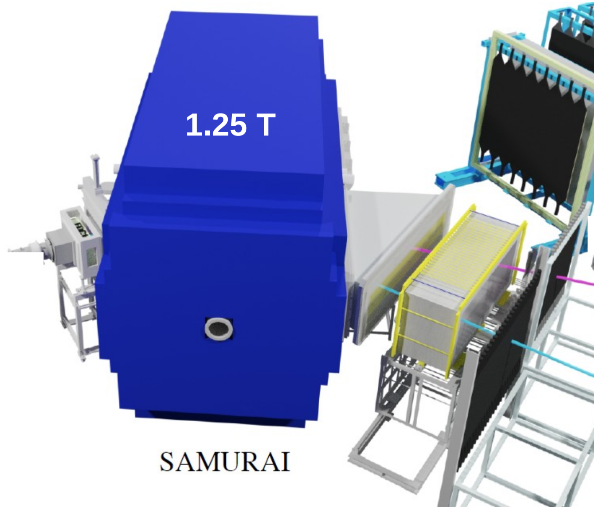
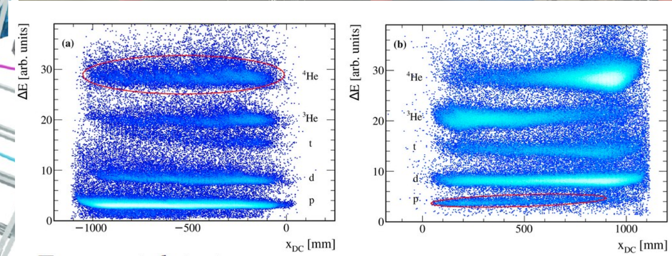
Reaction vertex reconstruction at target







Fragment detectors

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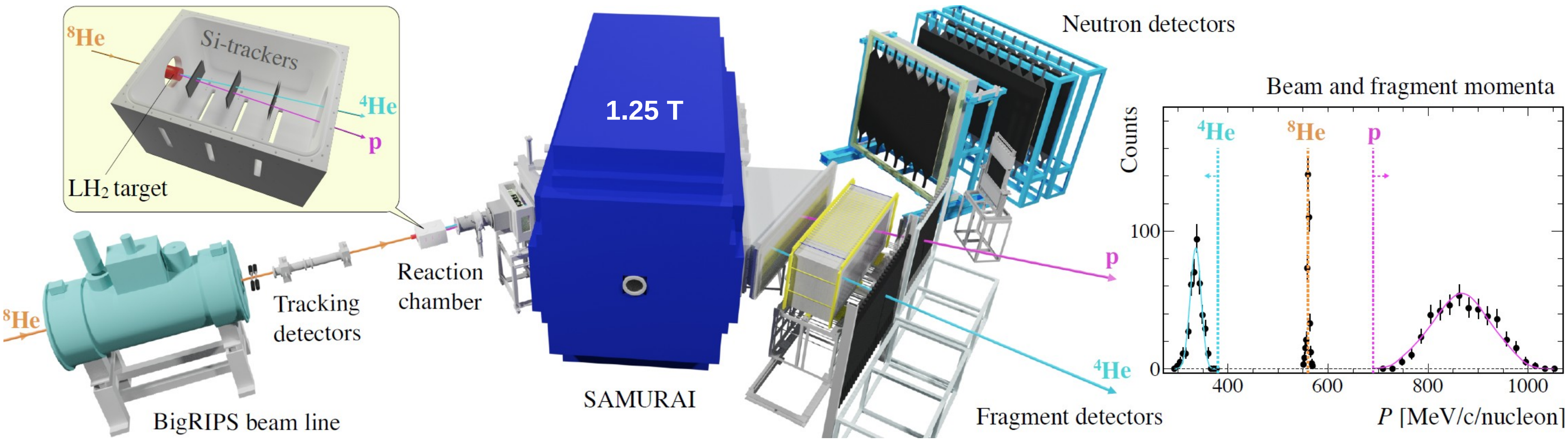

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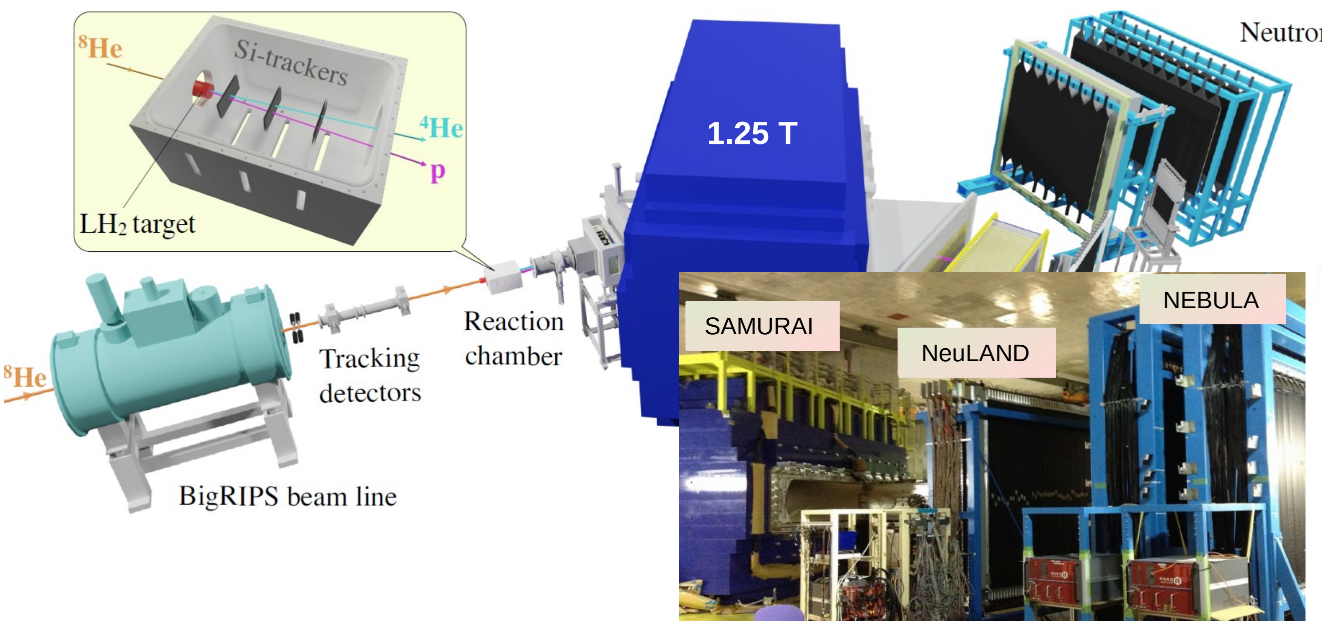
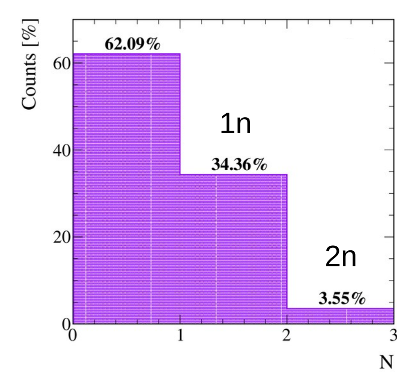


In this measurement:

small p-^{4}He cross section ~1 µb

- relatively low statistics ^{8}He(p,p^{4}He)
- 4n detection impossible



Benchmark measurement

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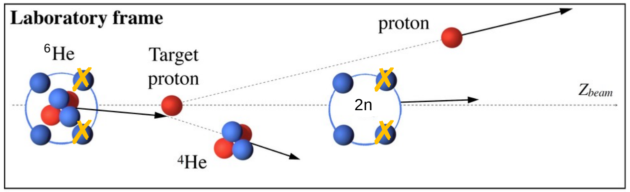
- 2n relative-energy spectrum is expected to be well described by theory
- di-neutron is unbound by ~100 keV



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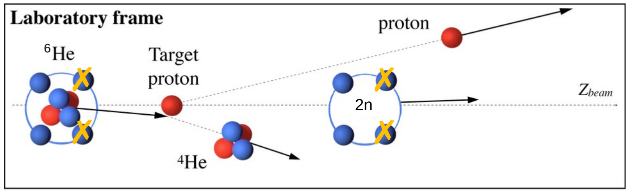
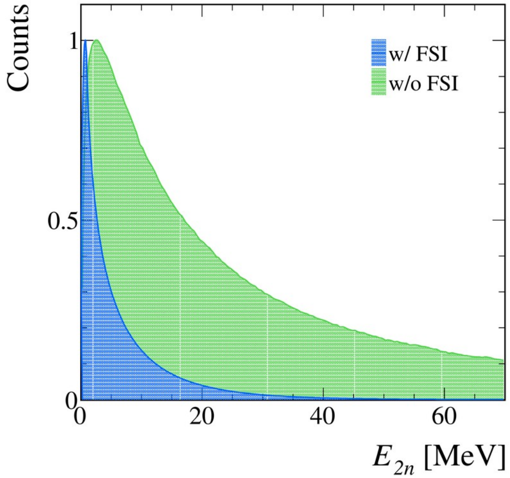


Theoretical input:

- w/o FSI: 3-body (^{4}He+n+n) cluster model
  - nn interaction in $^1S_0$ wave
  - nα interactions in s-, p-, d-wave
  - phenomenological 3-body force
- w/ FSI: nn final-state interaction
  - t-matrix approach



M. Göbel *et al.*, "*Neutron-neutron scattering length from the ^{6}He(p,pα)nn reaction*", PRC 104 (2021)

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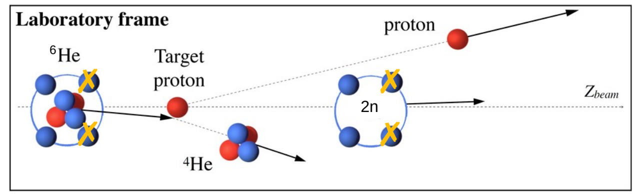

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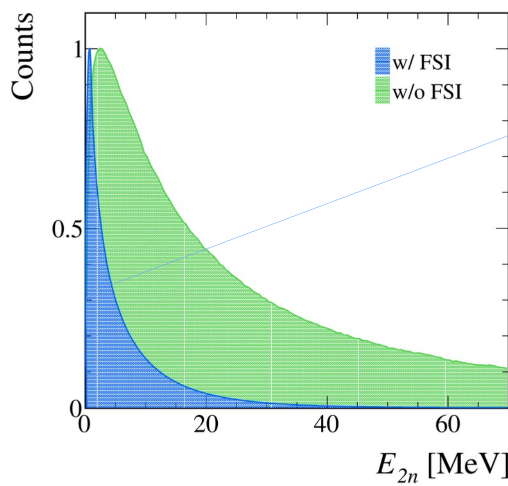
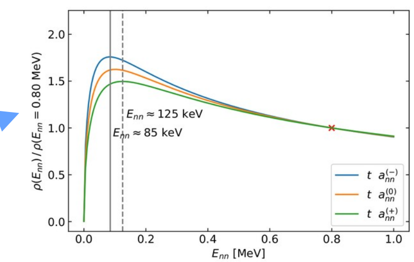


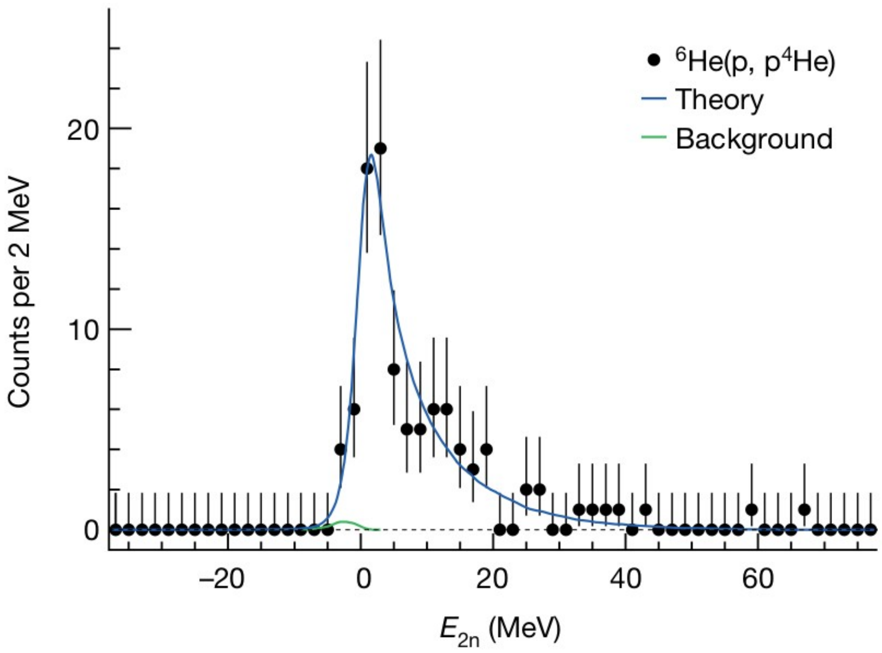


$a_{nn}=-18.7$ fm
wide energy range E_{2n}>>1 MeV
$a_{nn}\pm 2$ → <2% deviation

M. Göbel *et al*., "*Neutron-neutron scattering length from the ^{6}He(p,pα)nn reaction*", PRC 104 (2021)

Results: missing-mass spectra

$^{6}He(p,p^{4}He)2n$



confirms the expected di-neutron low-energy peak ~100 keV

MD *et al.*, Nature 606, 678 (2022)

Results: missing-mass spectra

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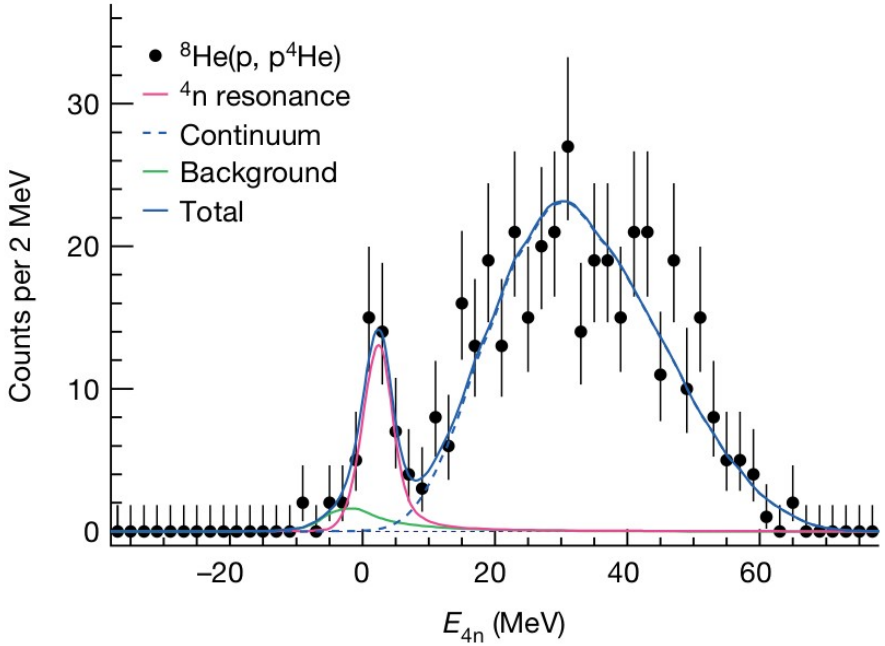
$^{8}He(p,p^{4}He)4n$



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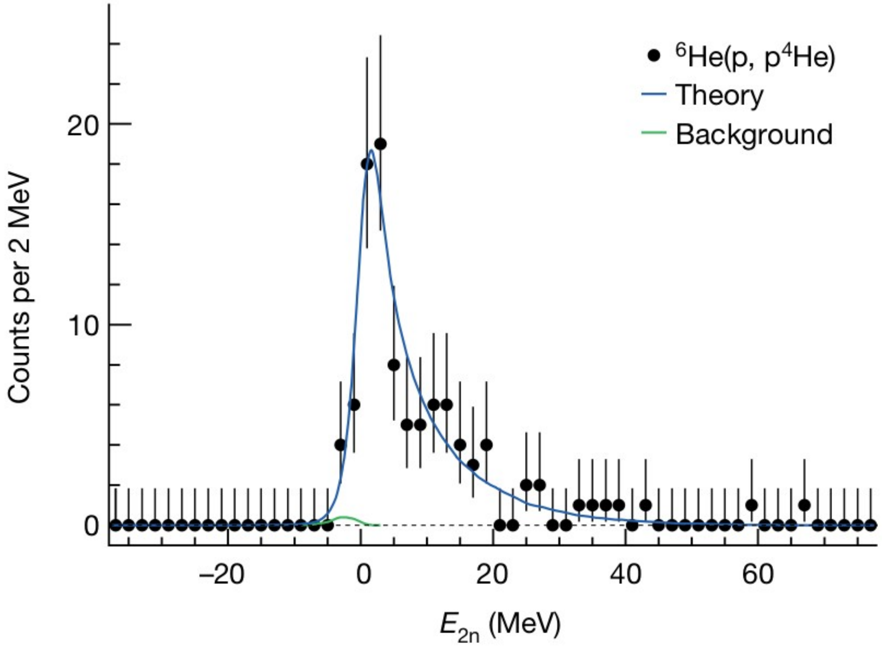

confirms the expected di-neutron low-energy peak ~100 keV

MD *et al.*, Nature 606, 678 (2022)

Continuum component

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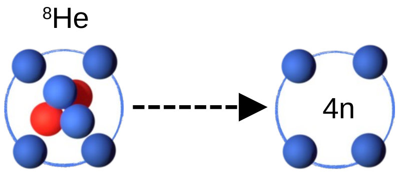
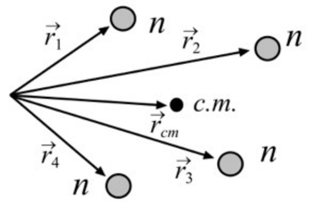


"sudden removal of an α-particle from ^{8}He"

- Five-body (^{4}He+4n) COSMA model

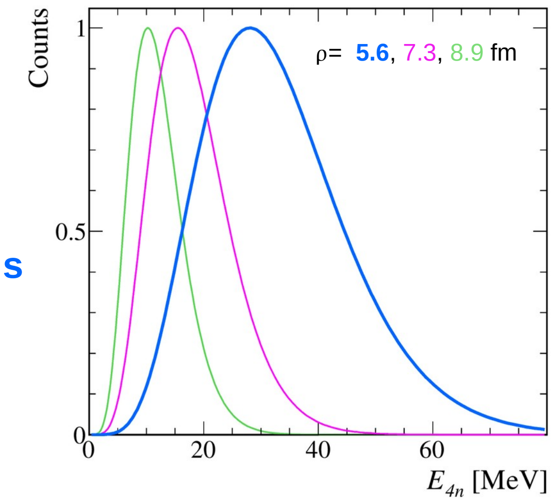
  A source term for the reaction mechanism:
  - initial structure (^{8}He)
  - sensitive to the hyperradius of the source ρ
  - **5.6 fm reproduces experimental ^{8}He radius**



^4n

$$\sum_{i=1,4} r_i^2 = \rho^2 + 4r_{\text{cm}}^2$$

continuum spectrum w/o FSI



Zhukov *et al.*, PRC (1994); Grigorenko *et al.*, EPJA (2004)

Results: missing-mass spectra

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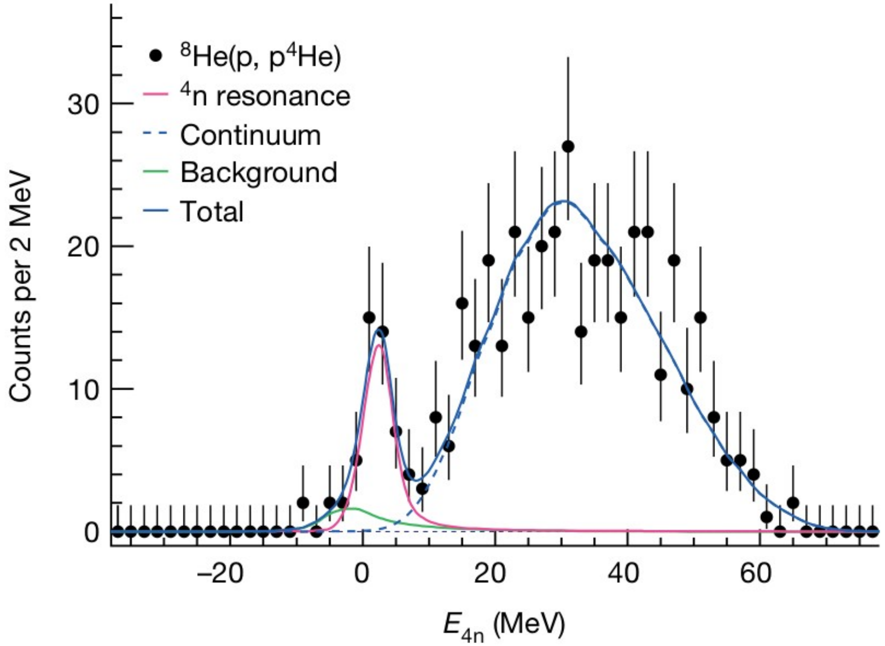
^{8}He(p,p^{4}He)4n

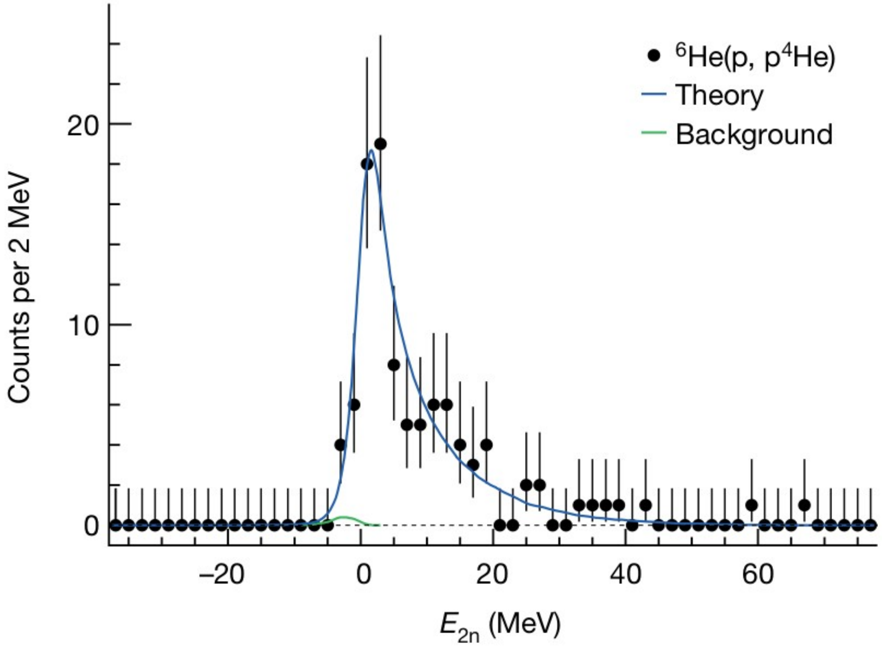


resonance like-structure:

E_r = 2.37±0.38(stat.)±0.44(sys.) MeV

Γ = 1.75±0.22(stat.)±0.30(sys.) MeV

^{6}He(p,p^{4}He)2n



confirms the expected di-neutron low-energy peak ~100 keV

MD *et al.*, Nature 606, 678 (2022)

A tetra-neutron correlation?

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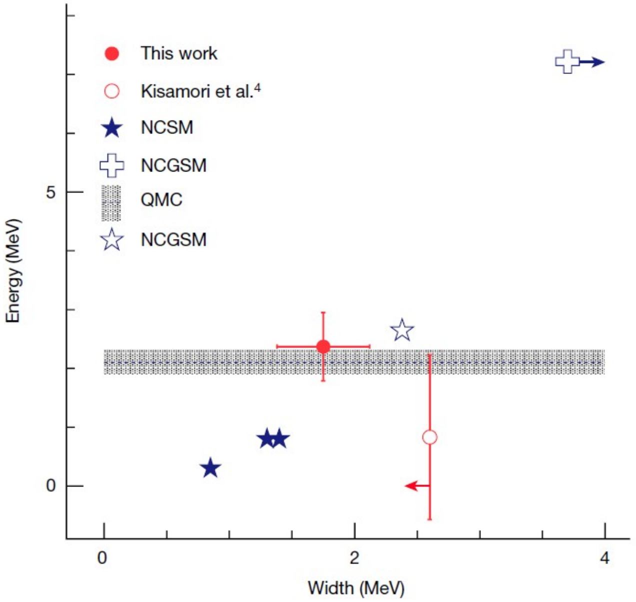
Predictions for a tetra-neutron



★ Shirokov PRL 117 (2016); Gandolfi PRL 118 (2017);
Fossez PRL 119 (2017); ☆ Li PRC 100 (2019);

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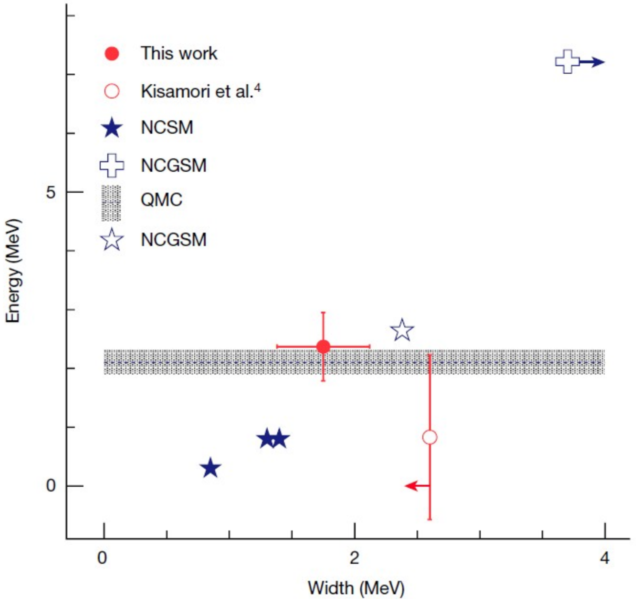

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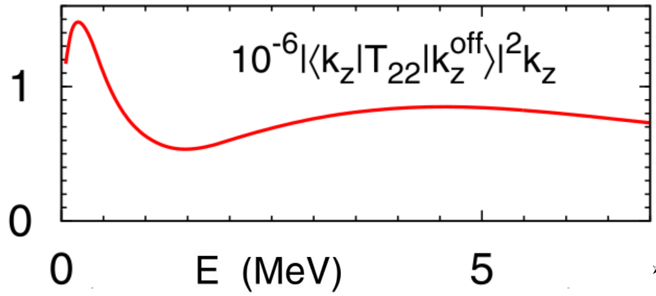
Full treatment of continuum → ***No tetra-neutron***

A recent overview: Marqués & Carbonell, EPJA 57 (2021)

Low-energy structures

"the four-neutron system is studied using exact continuum equations for transition operators... This indicates the absence of an observable 4n resonance, in contrast to a number of earlier works. ***Even without an observable resonance the transition operators exhibit pronounced low-energy peaks****"*



Deltuva, PLB 782 (2018)

- may be seen in nuclear reactions
- must be combined with reaction mechanism

A tetra-neutron correlation?

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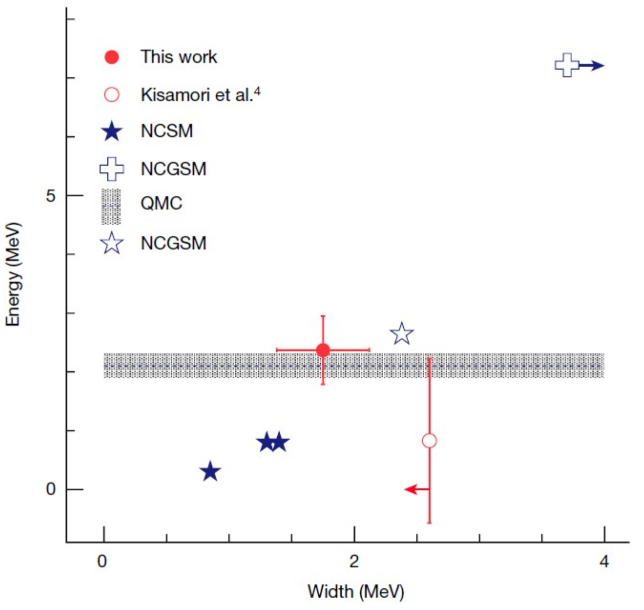
Predictions for a tetra-neutron



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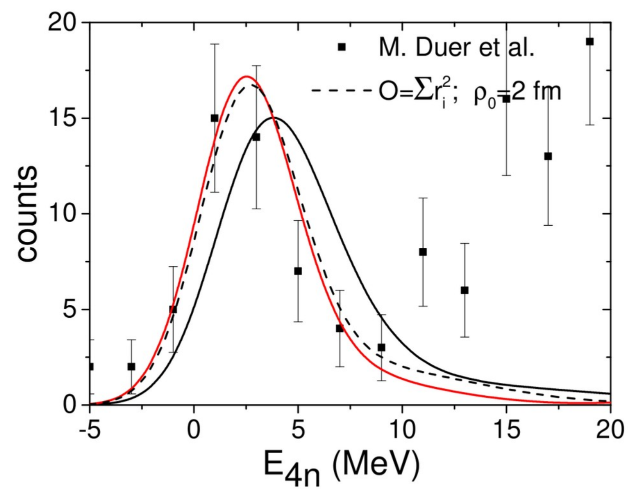
Full treatment of continuum → ***No tetra-neutron***

A recent overview: Marqués & Carbonell, EPJA 57 (2021)

Low-energy structures

- Reaction model to describe the sudden removal of α-core from ^{8}He: transition from (^{4}He+4n) initial state and 4 interacting neutrons in the final state



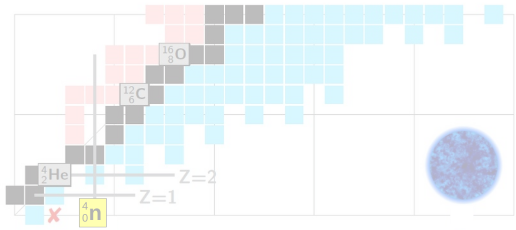
- Consequence of: two-dineutron FSI and presence of dineutron clusters in ^{8}He

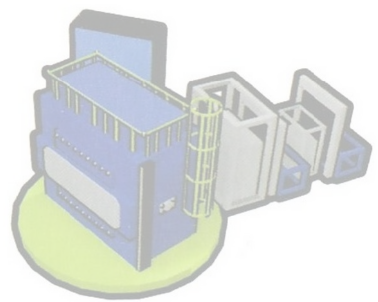
Laszauskas, Hiyama, Carbonell, arXiv:2207.07575 [nucl-th] (2022)

Outline

➊ **The tetra-neutron context**

- experimental quest
- theoretical predictions





➋ **4n experiment at SAMURAI: quasi-free α-knockout reaction**

- experimental method
- results and discussion

➌ **Future perspectives**

next-generation experiments

Future perspectives

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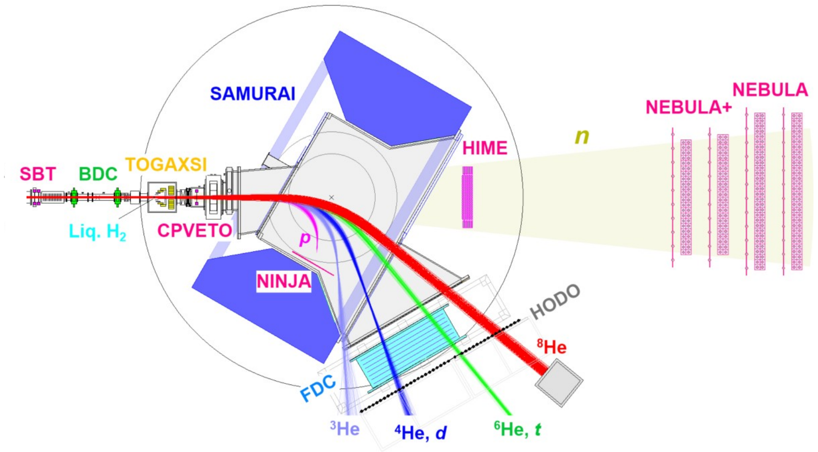
Correlations in multi-neutron systems [Proposal 2022, K. Miki, MD, T. Uesaka *et al.*]

- **Neutron detection: ^{8}He(p,pα)4n with all four neutrons in coincidence**



Future perspectives

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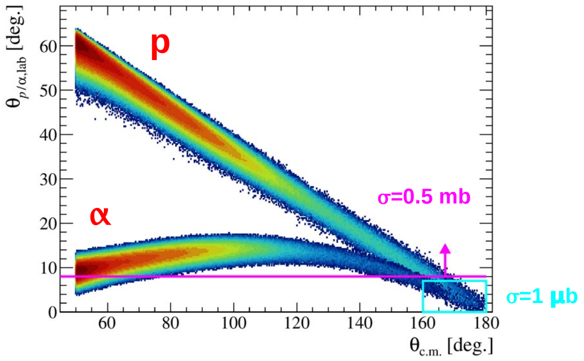
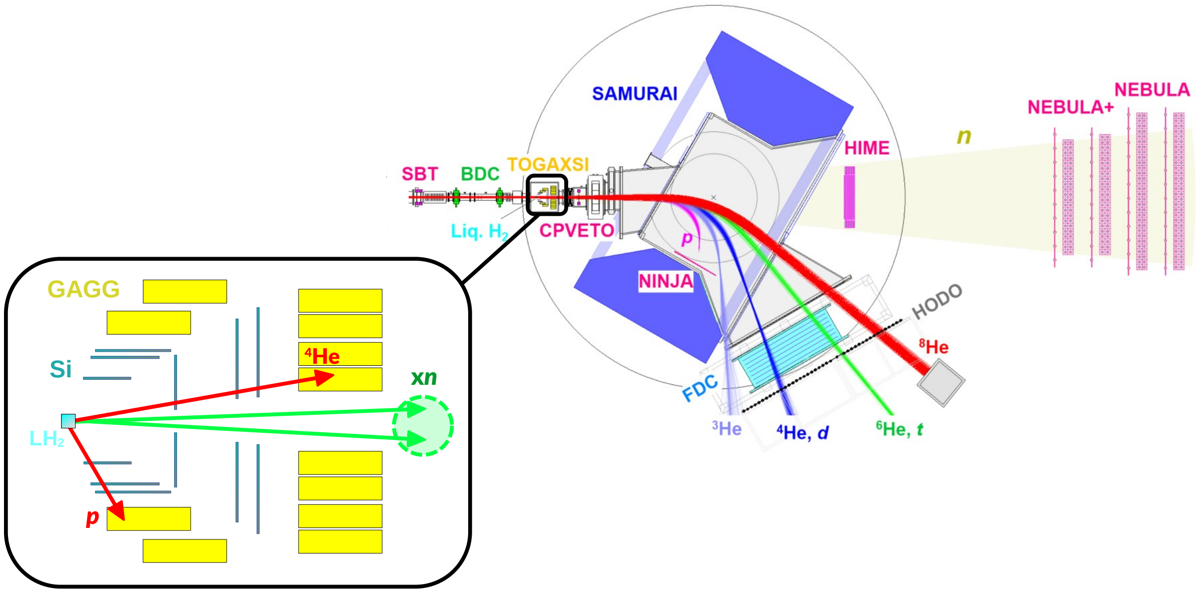


- Cross section:
  > two orders of magnitude larger
- Detection efficiency for 4n: 0.9%



Future perspectives

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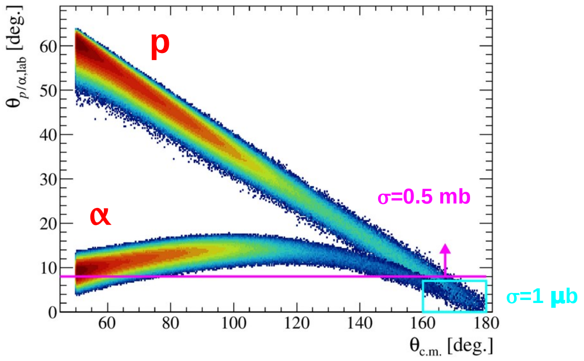

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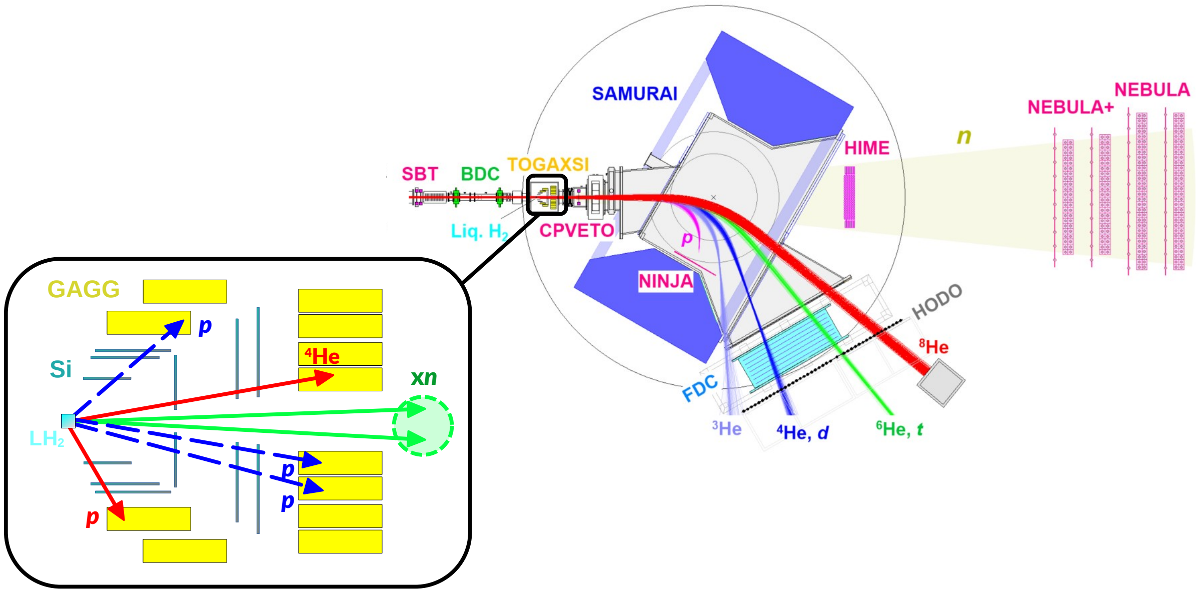

- **Reaction mechanism: ^{6}He(p,3p)4n knockout reaction**
  - (p,3p) cross sections measured for heavy nuclei
  - two sequential p-p collisions A. Frotscher *et al.*, PRL 125 (2020)

Future perspectives

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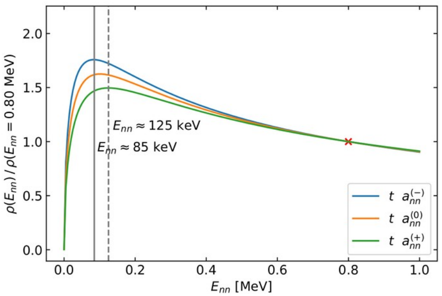
nn scattering length from ^{6}He(p,pα)nn reaction

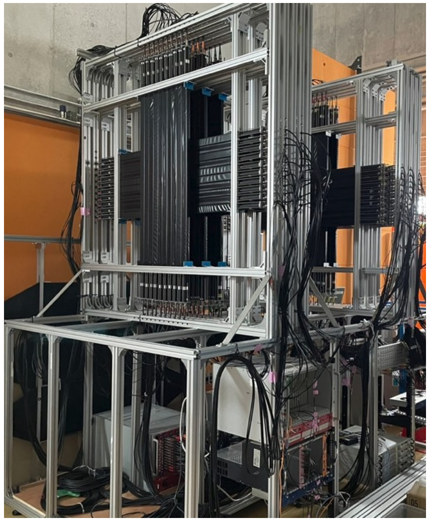
[T. Aumann et al. SAMURAI55R1]

- nn scattering length not known precisely experimentally
- HIME neutron detector → a_{nn} within $\pm$0.2 fm



M. Göbel *et al*., PRC 104 (2021)

HIME demonstrator



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Future perspectives

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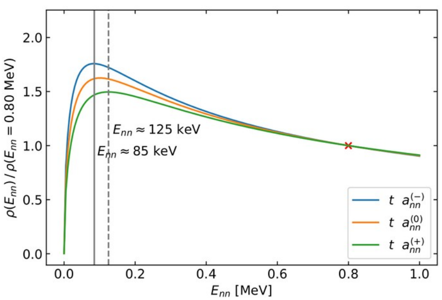
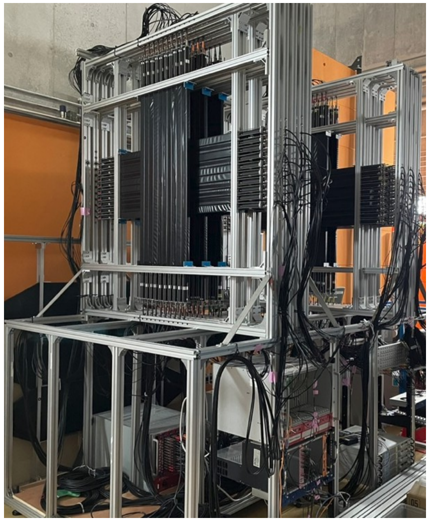
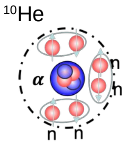


M. Göbel *et al.*, PRC 104 (2021)

HIME demonstrator

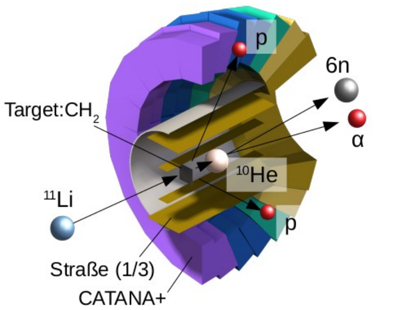


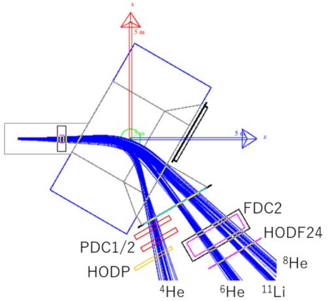
Multi-neutron ^{4}n and ^{6}n states in extremely n-rich nuclei [T. Nakamura *et al.* SAMURAI47, Jan. 2023]



- ^{11}Li(p,2p) knockout reaction:

  ^{10}He → ^{8}He + 2n / ^{6}He + 4n / ^{4}He + 6n
- Mainly missing-mass: **(p,2p)** + **fragment**
- two neutrons in coincidence
  - nn correlations





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Article

Observation of a correlated free four-neutron system

M. Duer[1✉], T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1], N. L. Achouri[7], D. Ahn[5,16], H. Baba[5], C. A. Bertulani[8], M. Böhmer[4], K. Boretzky[2], C. Caesar[1,2,5], N. Chiga[5], A. Corsi[9], D. Cortina-Gil[10], C. A. Douma[11], F. Dufter[4], Z. Elekes[12], J. Feng[13], B. Fernández-Domínguez[10], U. Forsberg[6], N. Fukuda[5], I. Gasparic[1,5,14], Z. Ge[5], J. M. Gheller[9], J. Gibelin[7], A. Gillibert[9], K. I. Hahn[15,16], Z. Halász[12], M. N. Harakeh[11], A. Hirayama[17], M. Holl[1], N. Inabe[5], T. Isobe[5], J. Kahlbow[1], N. Kalantar-Nayestanaki[11], D. Kim[16], S. Kim[1,16], T. Kobayashi[18], Y. Kondo[17], D. Körper[2], P. Koseoglou[1], Y. Kubota[5], I. Kuti[12], P. J. Li[19], C. Lehr[1], S. Lindberg[20], Y. Liu[13], F. M. Marqués[7], S. Masuoka[21], M. Matsumoto[17], J. Mayer[22], K. Miki[1,18], B. Monteagudo[7], T. Nakamura[17], T. Nilsson[20], A. Obertelli[1,9], N. A. Orr[7], H. Otsu[5], S. Y. Park[15,16], M. Parlog[7], P. M. Potlog[23], S. Reichert[4], A. Revel[7,9,24], A. T. Saito[17], M. Sasano[5], H. Scheit[1], F. Schindler[1], S. Shimoura[21], H. Simon[2], L. Stuhl[16,21], H. Suzuki[5], D. Symochko[1], H. Takeda[5], J. Tanaka[1,5], Y. Togano[17], T. Tomai[17], H. T. Törnqvist[1,2], J. Tscheuschner[1], T. Uesaka[5], V. Wagner[1], H. Yamada[17], B. Yang[13], L. Yang[21], Z. H. Yang[5], M. Yasuda[17], K. Yoneda[5], L. Zanetti[1], J. Zenihiro[5,25] & M. V. Zhukov[20]

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Thank you!