TECHNISCHE UNIVERSITÄT DARMSTADT

A06. Strong interactions beyond the neutron dripline:

Free system of four correlated neutrons

Meytal Duer, TU Darmstadt

October 6th 2022, SFB 1245 Annual workshop

The elusive tetra-neutron

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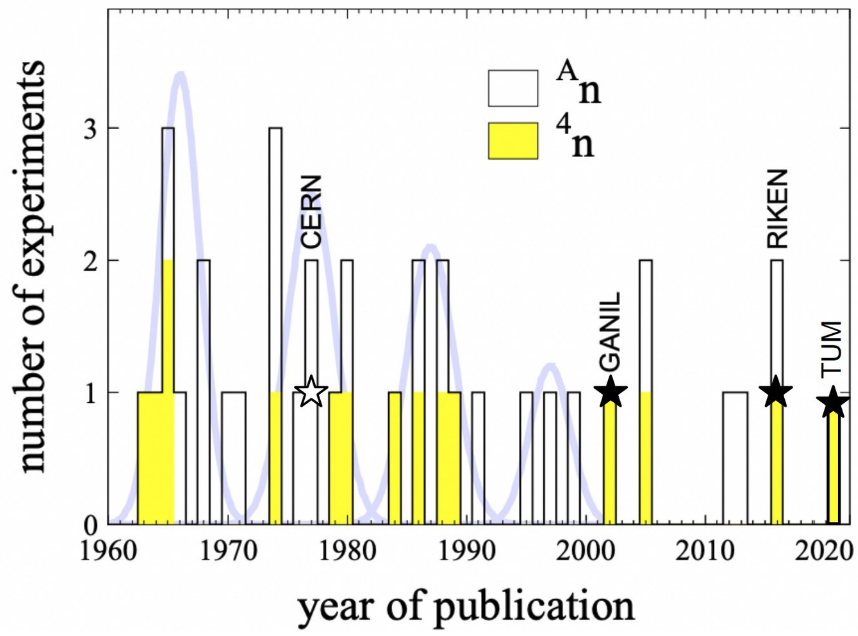
A long-standing quest



Modified from Marqués & Carbonell, EPJA 57 (2021)

XX century:

- fission of uranium e.g. Schiffer, PL 5 (1963)
- transfer reactions e.g. Cerny, PL 53B (1974)
- double-charge-exchange (π^-,π^+) reaction e.g. Ungar, PLB (1984)

➢ no indication

XXI century:

★ first positive signals

- radioactive-ion beams GANIL 2002, RIKEN 2016
- stable beam TUM 2022

The elusive tetra-neutron: indications

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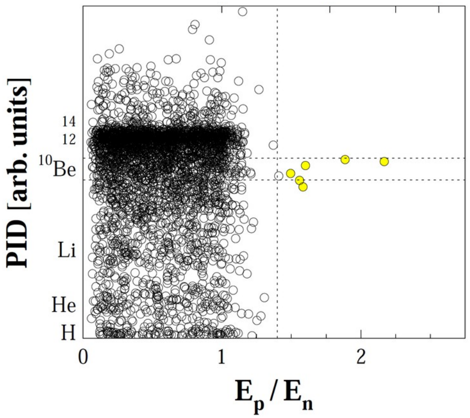
GANIL 2002

Breakup on a C target:
$^{14}Be \rightarrow {}^{10}Be+4n$



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

2σ significance

Marqués *et al.*, PRC 65 (2002)
Marqués *et al.*, arXiv:nucl-ex/0504009 (2005)

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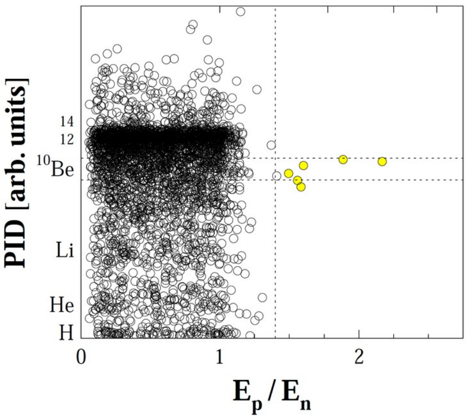

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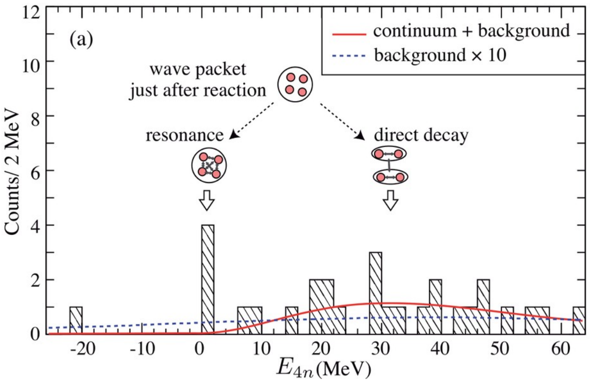
RIKEN 2016

Double-charge-exchange:
$^{8}He(^{4}He,^{8}Be)4n$



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

4.9σ significance

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

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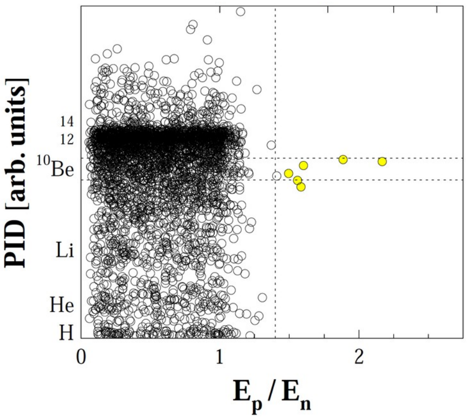

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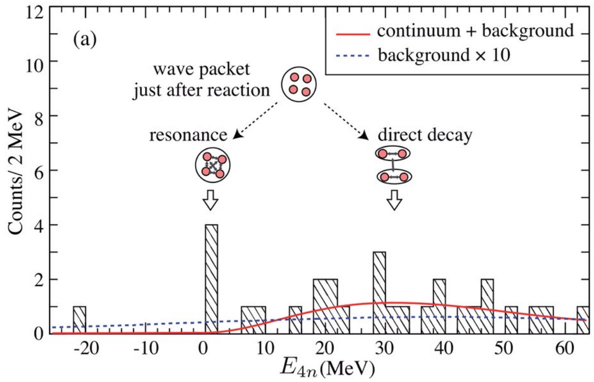

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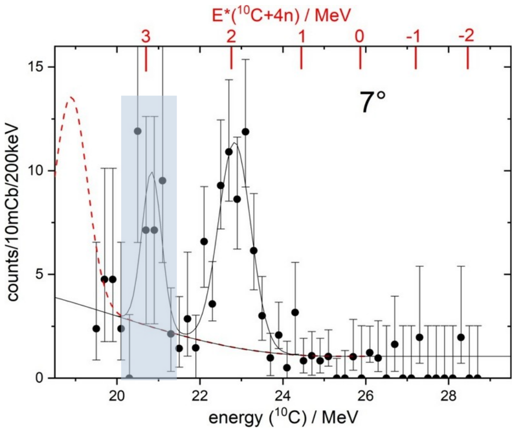
TUM 2022

Multi-nucleon transfer:
$^7Li(^7Li,^{10}C)4n$



~10 candidates for bound ^4n:
BE=0.42±0.16 MeV

3σ significance

Faestermann *et al.*, PLB 824 (2022)

The elusive tetra-neutron: indications

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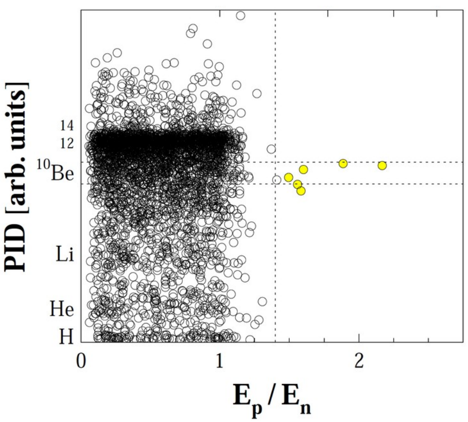

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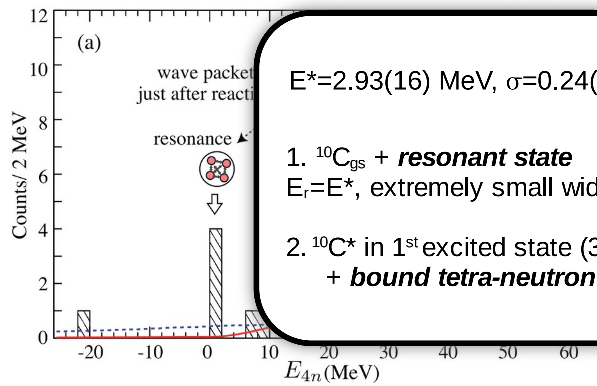

E*=2.93(16) MeV, σ=0.24(9) MeV:

1. $^{10}C_{gs}$ + ***resonant state***
E_r=E*, extremely small width

2. $^{10}C^*$ in 1st excited state (3.35 MeV)
+ ***bound tetra-neutron***

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

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TUM 2022

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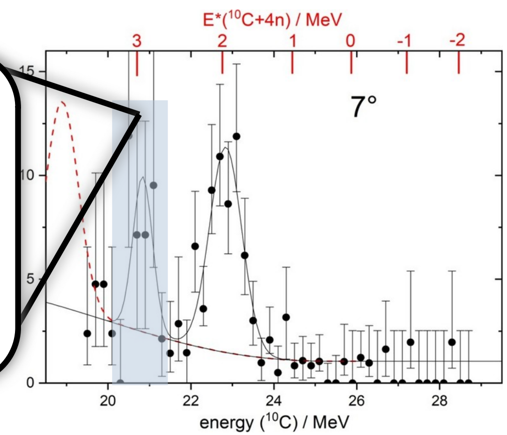

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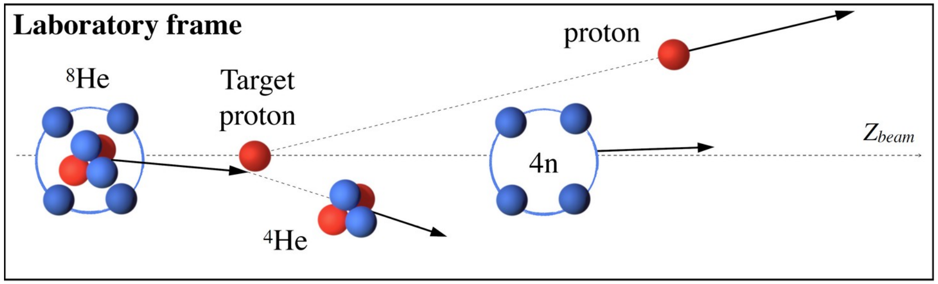
Present experimental work

Method: ^{8}He(p,p^{4}He) quasi-elastic knockout

- high-energy 156 MeV/nucleon
- 4n energy spectrum via missing mass: precise measurement of **charged particles**



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TECHNISCHE UNIVERSITÄT DARMSTADT

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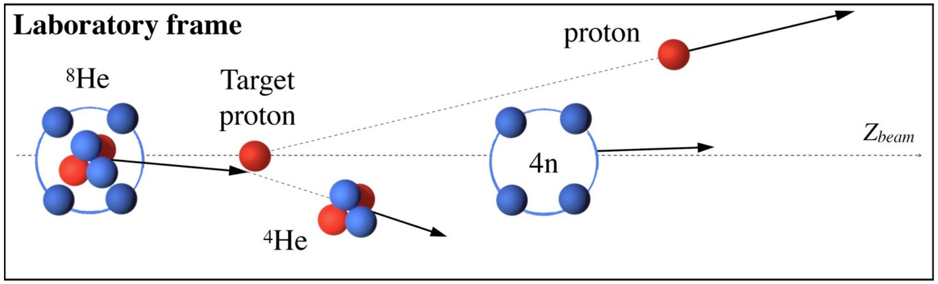
  - **large overlap ⟨^{8}He|α⊗4n⟩**



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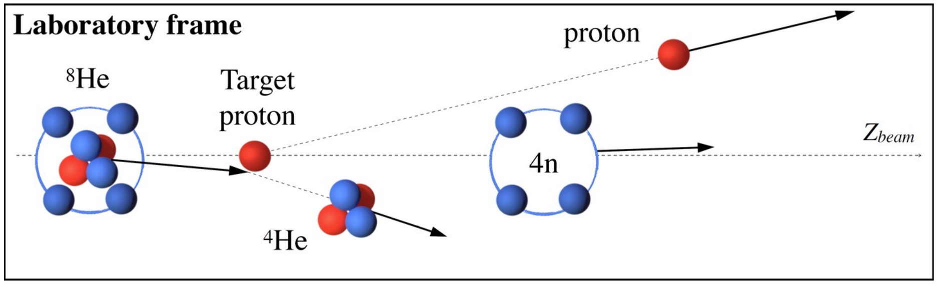
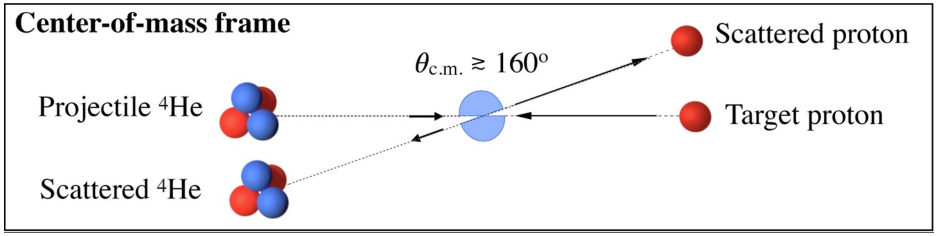
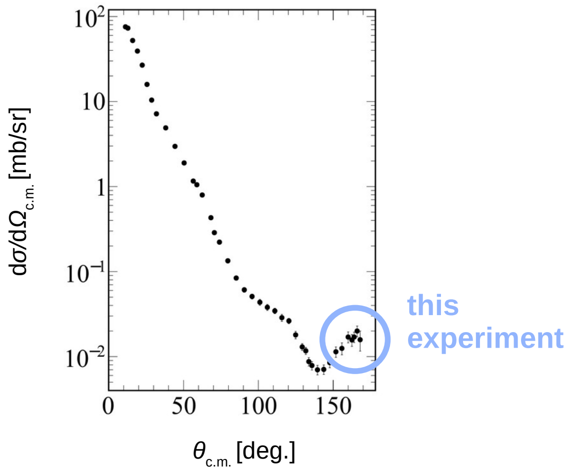
- Large momentum transfer
  - "recoil-less" production







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

Experimental setup at SAMURAI

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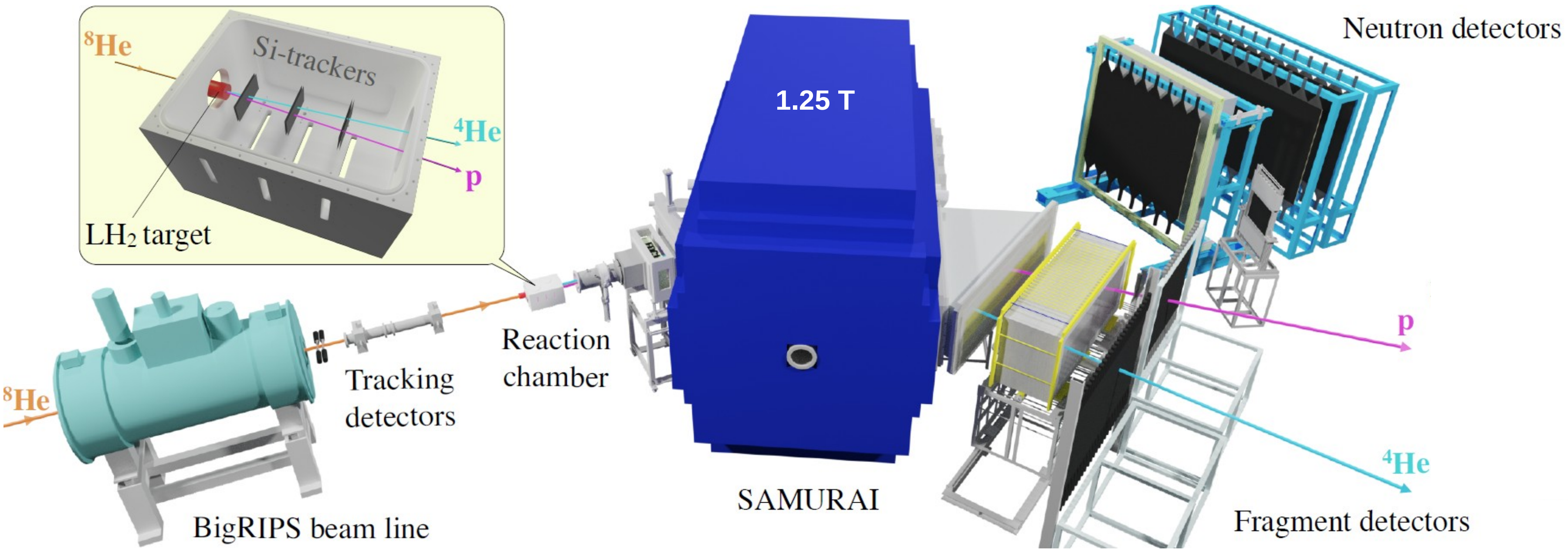

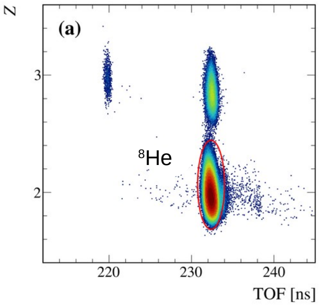

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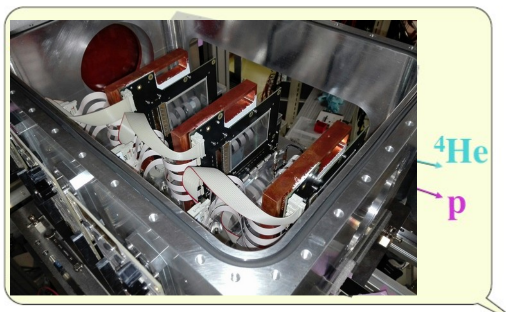
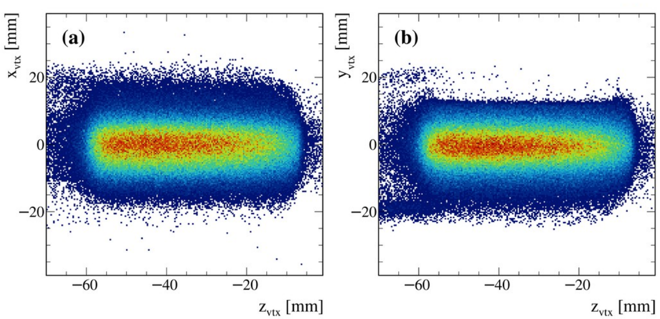
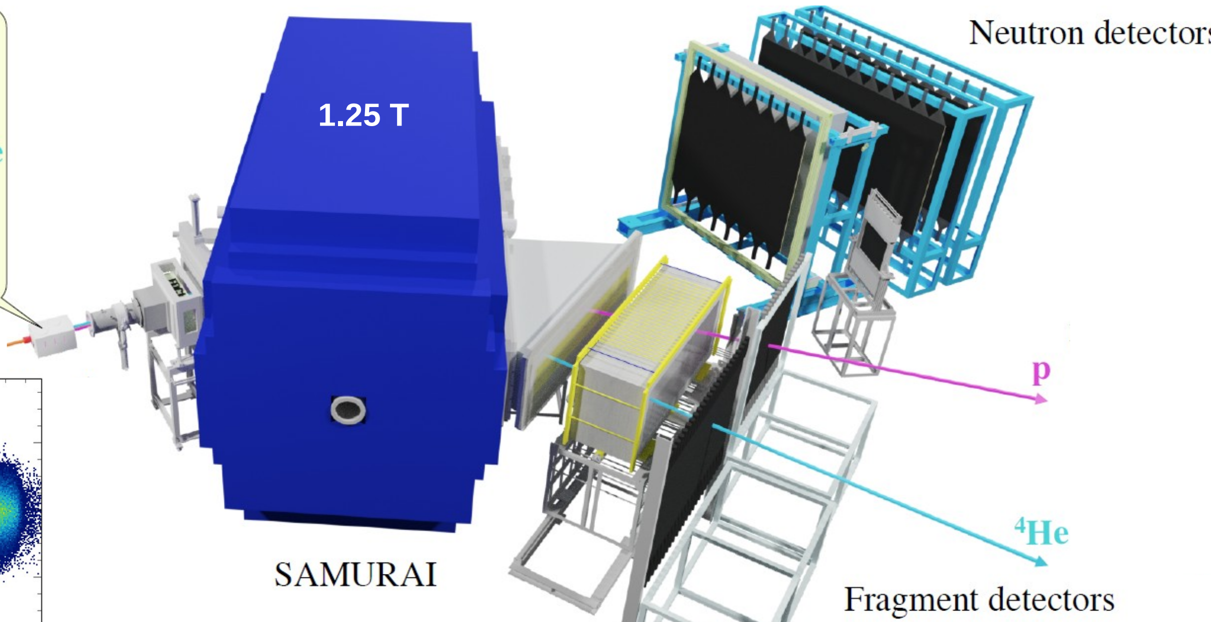


Reaction vertex reconstruction





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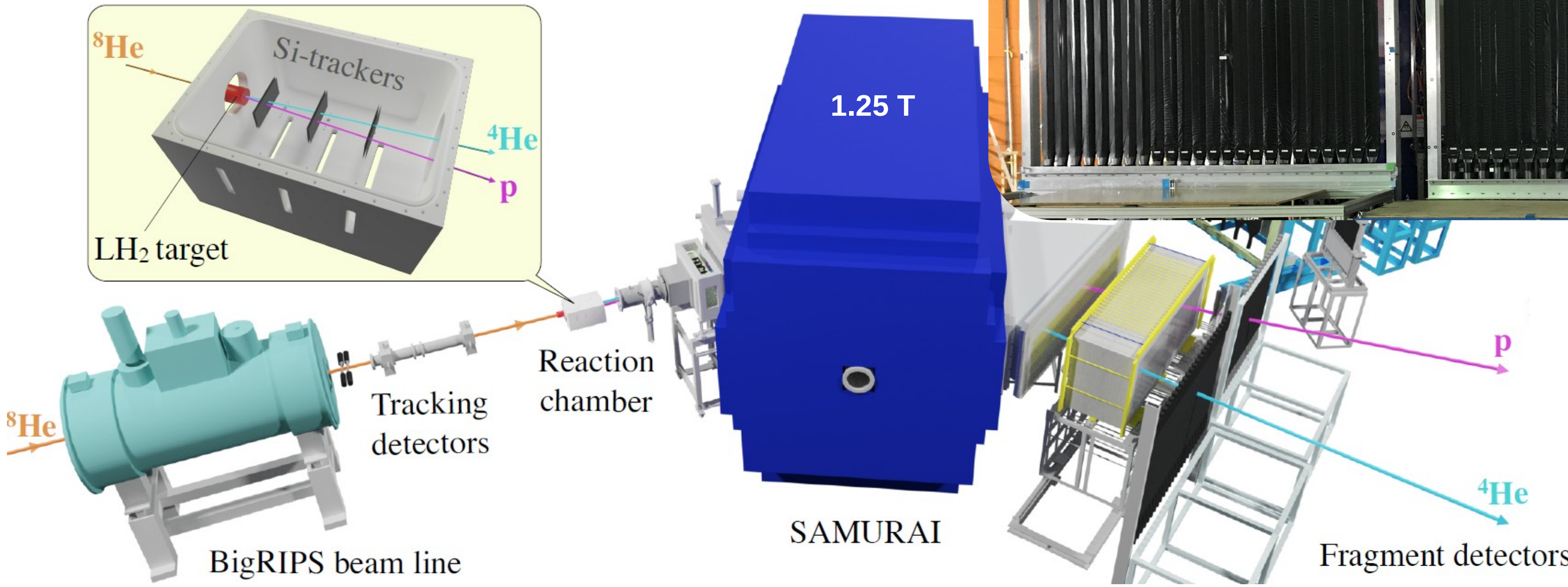

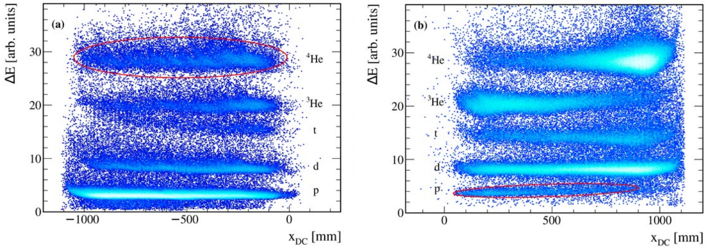

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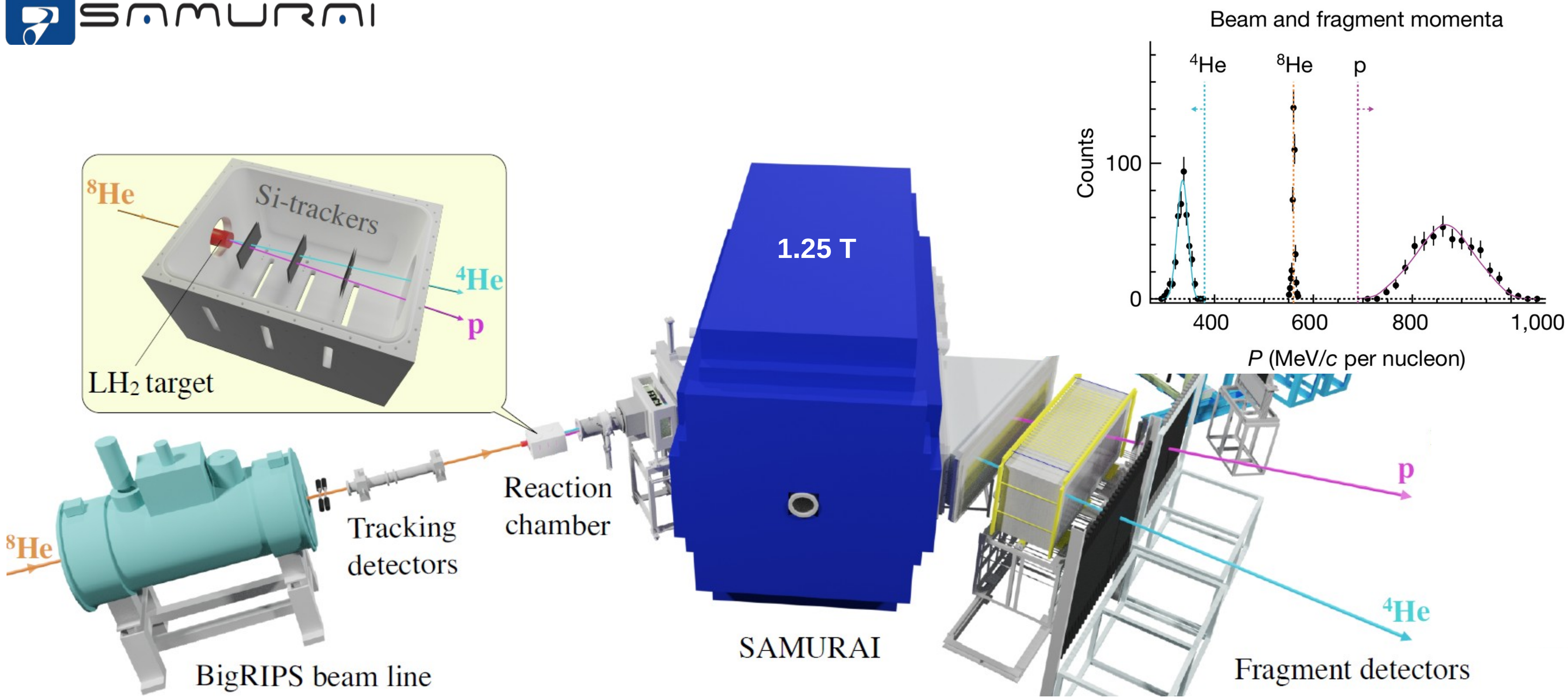

Experimental setup at SAMURAI

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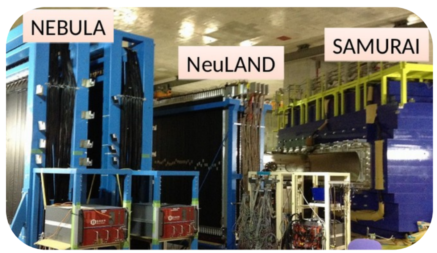
SAMURAI

NeuLAND demonstrator (R³B/GSI) + NEBULA

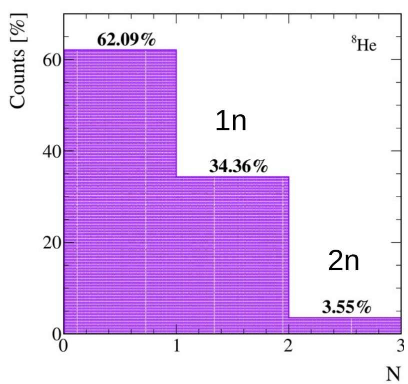
successful experimental campaign (2015-2017)

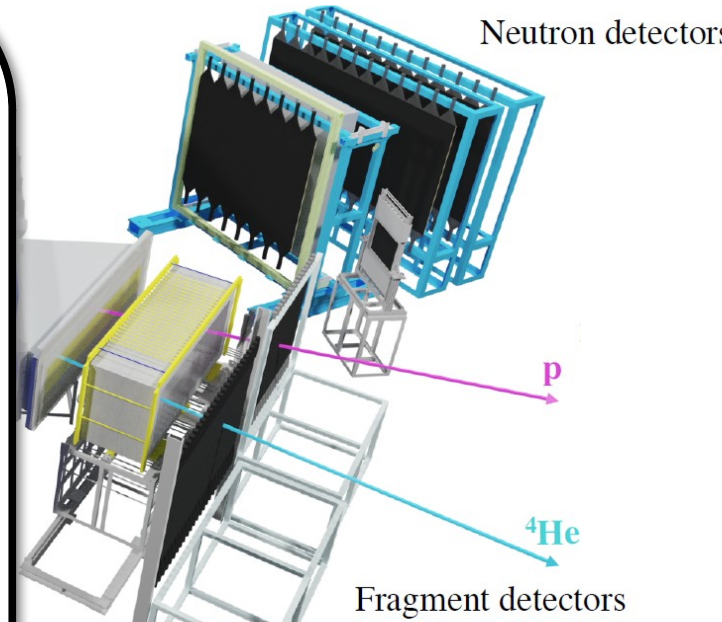


In this experiment:

small p-^{4}He cross section ~1 µb

- ~400 ^{8}He(p,p^{4}He) events
- four-neutron detection impossible
- only consistency check of the recoil-less production

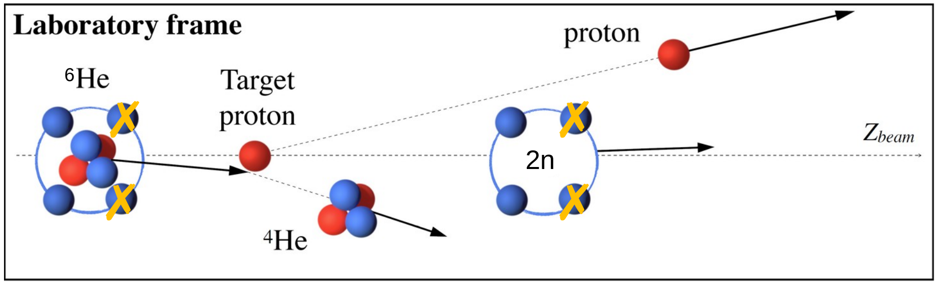




Benchmark measurement

^{6}He(p,p^{4}He) quasi-elastic knockout

- two-neutron relative-energy spectrum is expected to be well described by theory
- dineutron is known to be unbound by ~100 keV



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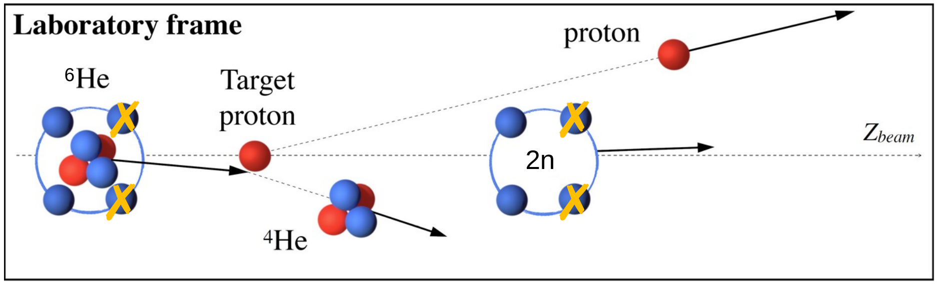
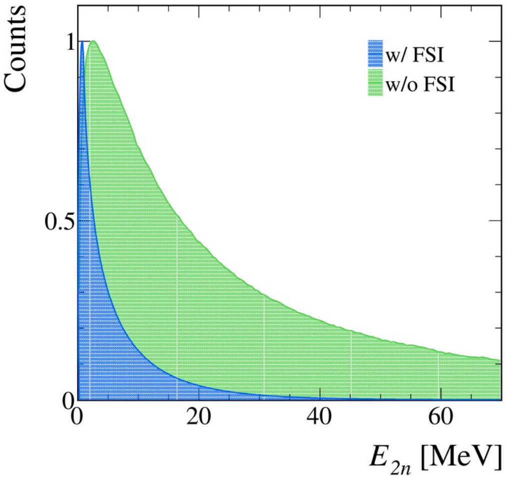


Theoretical input:

- **w/o FSI:** three-body (^{4}He+2n) cluster model
  - nn, nα interactions: ℓ-dependent Gaussian potentials
  - 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)

A05: talk by Marco Knösel

Results: missing-mass spectra

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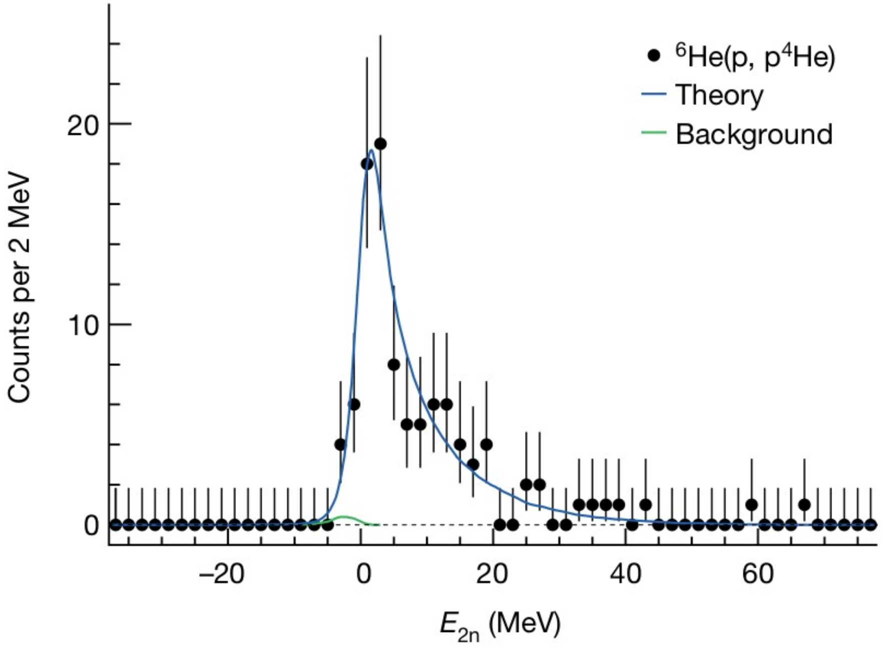
$^{6}He(p,p^{4}He)2n$



confirms the expected dineutron low-energy peak ~100 keV

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

Results: missing-mass spectra

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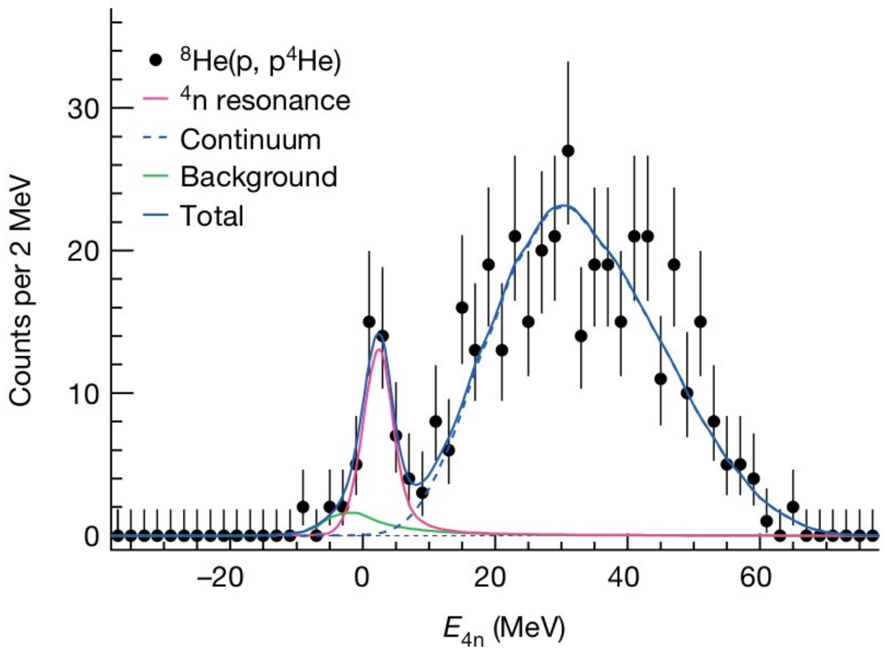

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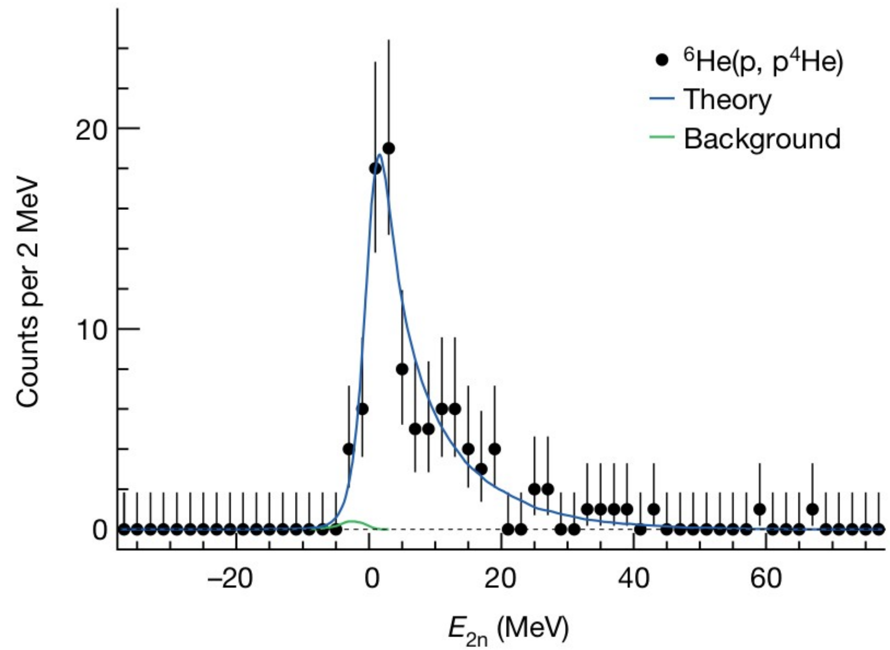

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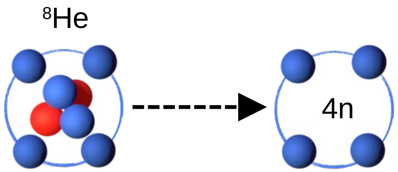
Direct decay part



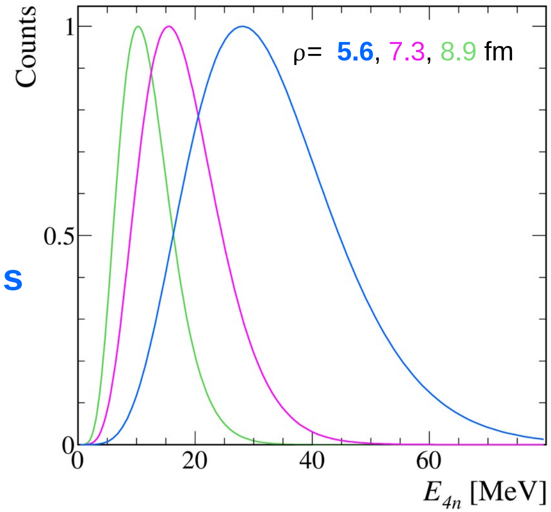
"sudden removal of an α-particle from ^{8}He"

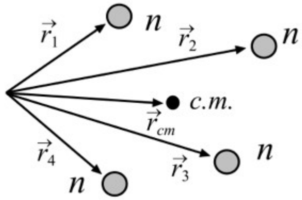
- Five-body (^{4}He+4n) COSMA model

  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**

continuum spectrum w/o FSI





^4n

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

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

Results: missing-mass spectra

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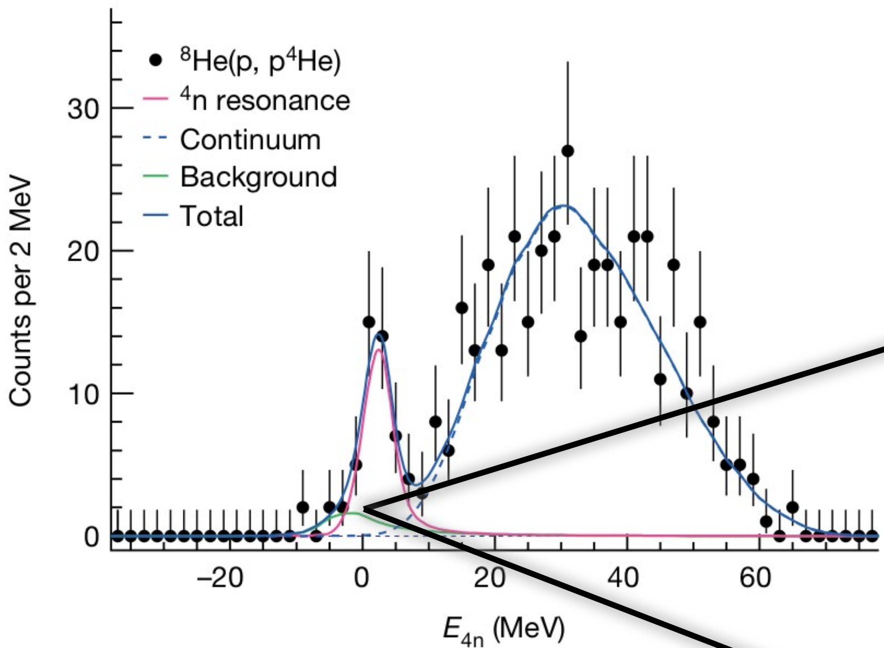
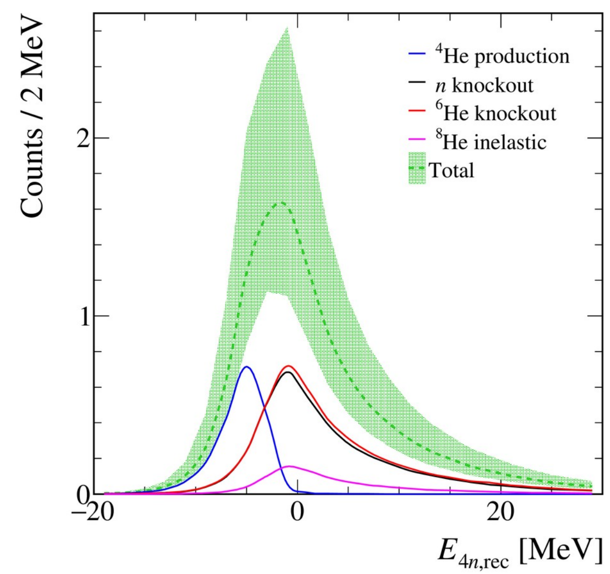


Background estimation:

✗ **direct reactions – kinematically rejected**
e.g. ^{8}He(p,p^{6}He*)2n; ^{6}He* → ^{4}He+2n

✔ **two-step reactions – only background source**
e.g. (i) ^{8}He(p,p^{6}He), (ii) ^{6}He(p,p^{4}He)2n

simulated two-step reactions



total contribution of 2.6%

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Results: missing-mass spectra

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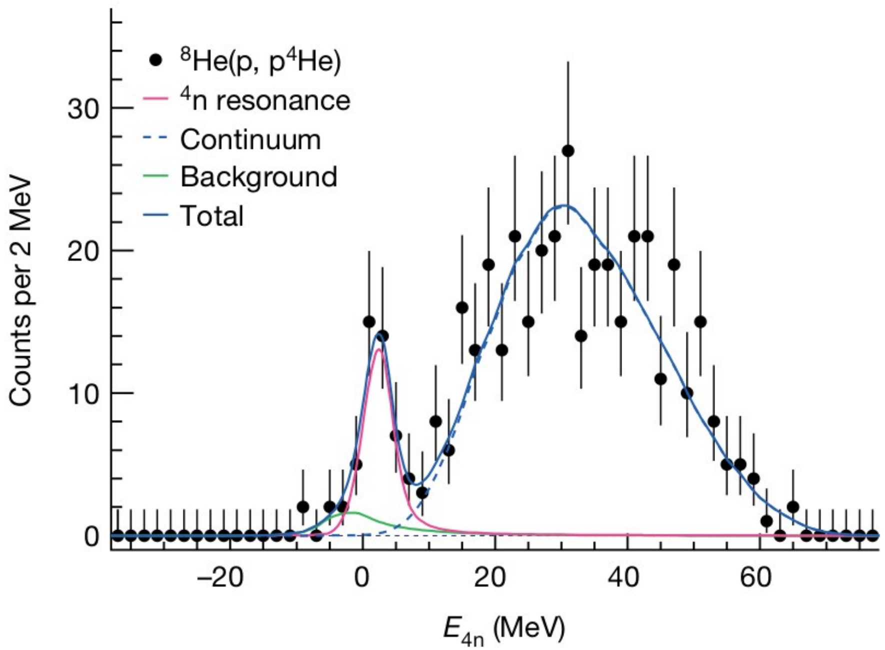

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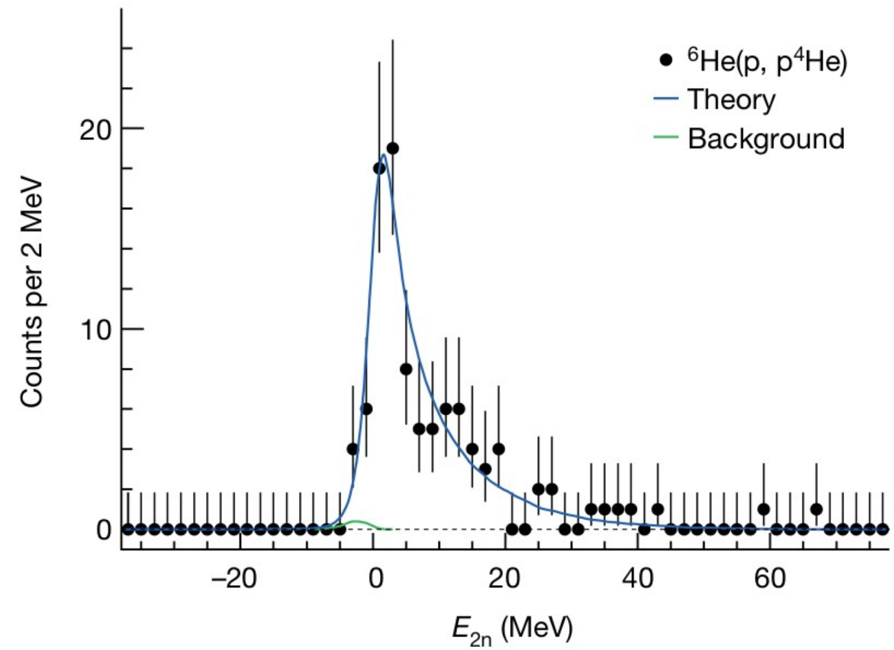

resonance like-structure:

E_r = 2.37±0.38(stat.)±0.44(sys.) MeV,

Γ = 1.75±0.22(stat.)±0.30(sys.) MeV

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

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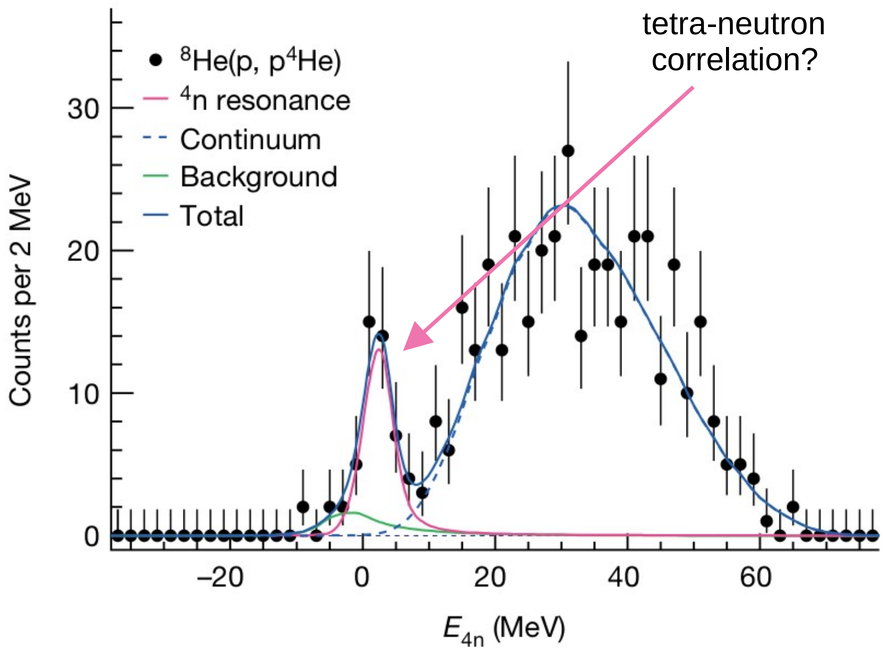

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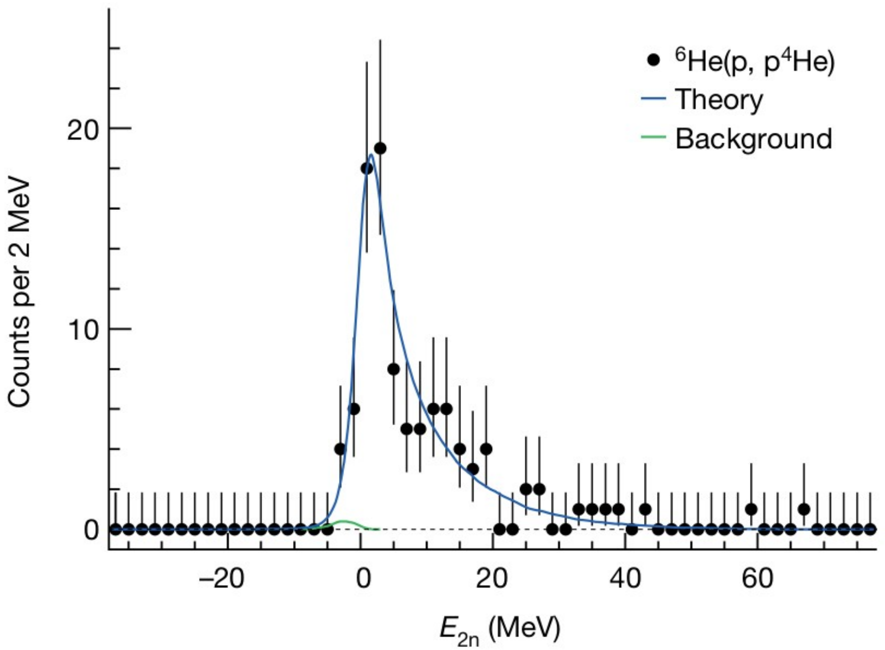

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MD *et al.*, Nature 606, 678 (2022)

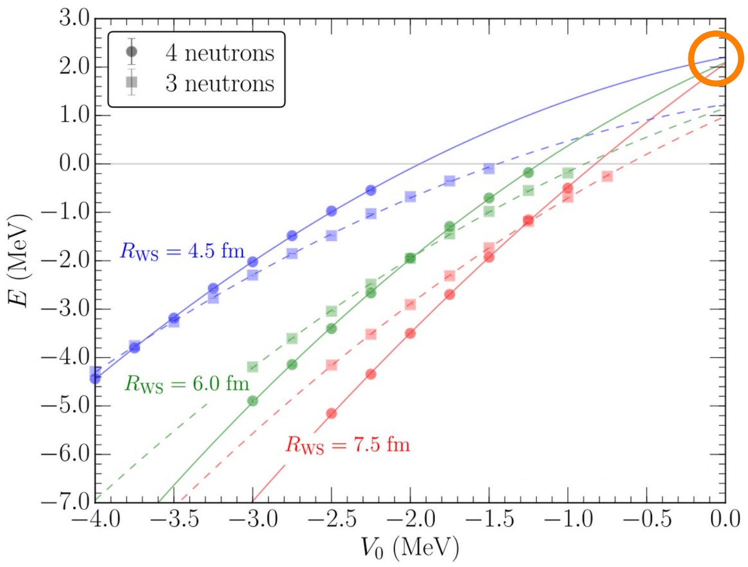
What do theories say ?

- Overall consensus: no bound tetra-neutron
- What about a resonance?

Quantum Monte Carlo calculations

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

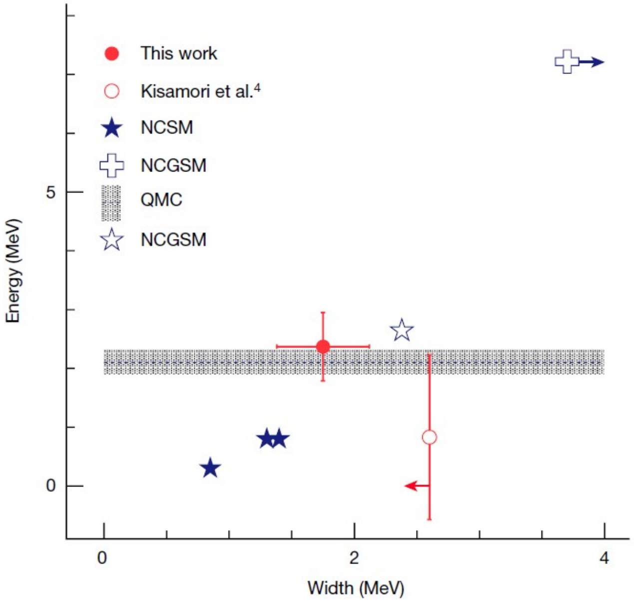
- 2- and 3-body chiral EFT interactions
- neutrons trapped in Woods-Saxon potential with radius R_{WS} and depth V_0
- resonance energy from extrapolation to $V_0 \to 0$
  - **possible resonance at 2.1(2) MeV**



S. Gandolfi *et al.*, PRL 118 (2017)

A tetra-neutron correlation?

Predictions for a tetra-neutron



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

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

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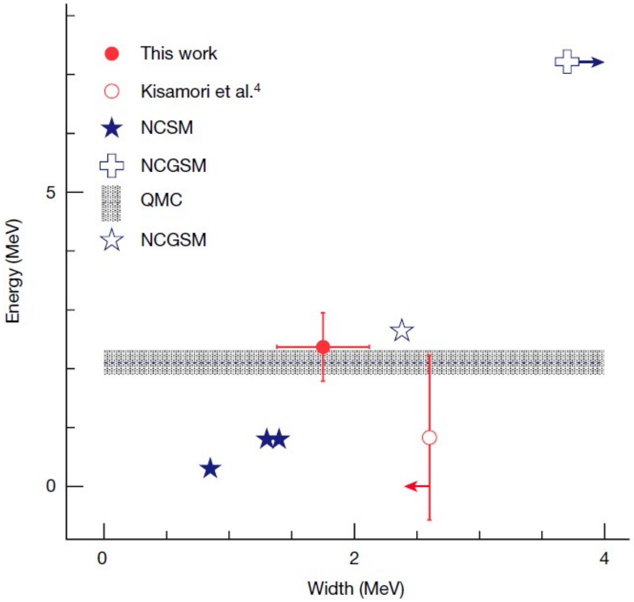

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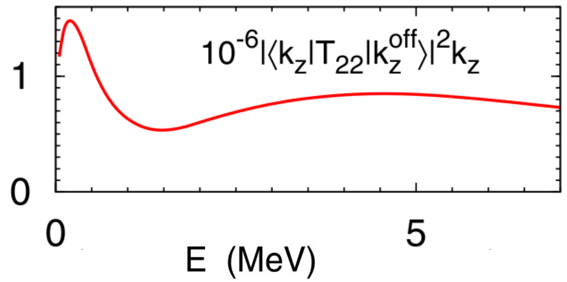
Full treatment of continuum → ***No tetra-neutron***

Sofianos JPG 23 (1997); Lazauskas PRC 72 (2005); Hiyama PRC 93 (2016); Lazauskas PTEP 073 (2017); **Deltuva PLB 782 (2018);** Deltuva PRL 123 (2019); Higgins PRL 125 (2020); ...



- transition operator method:
  - absence of any resonance
  - **low-energy enhancement** of some transition operators
- explain RIKEN '16 signal in ^{8}He(^{4}He,^{8}Be) reaction?
- must be combined with reaction mechanism

A tetra-neutron correlation?

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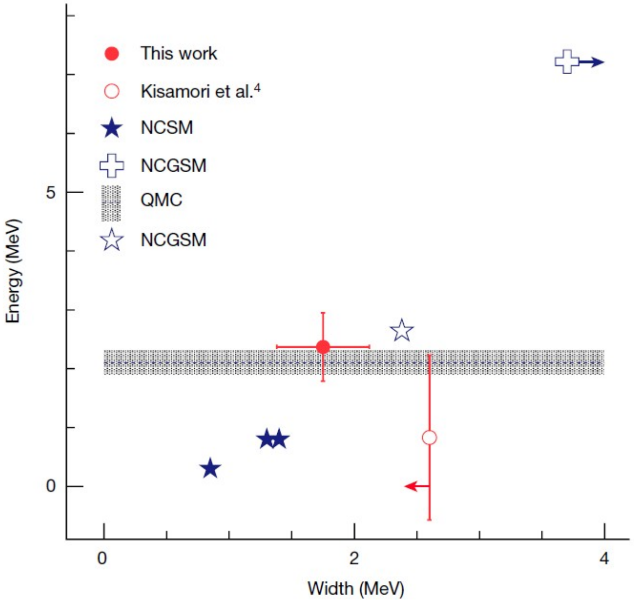
Predictions for a tetra-neutron



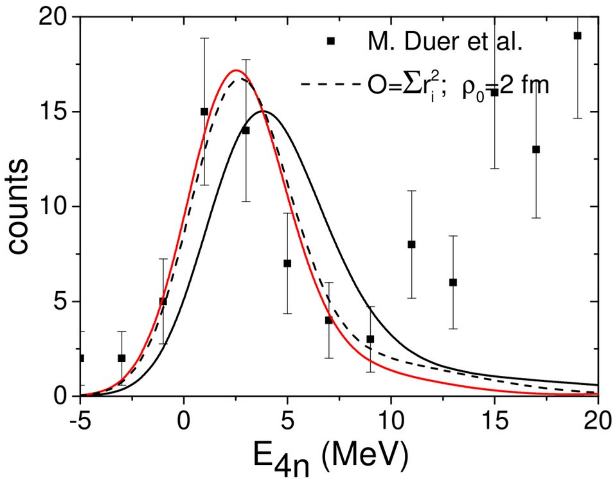
MD *et al.*, Nature 606, 678 (2022)

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

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

Sofianos JPG 23 (1997); Lazauskas PRC 72 (2005); Hiyama PRC 93 (2016); Lazauskas PTEP 073 (2017); Deltuva PLB 782 (2018); Deltuva PRL 123 (2019); Higgins PRL 125 (2020); ...

Dineutron correlations?



- Reaction model:
  sudden removal of α-core from ^{8}He
  - (^{4}He+4n) initial state
  - four interacting neutrons in the final state
- solving the Faddeev-Yokubovsky equations
  → strong dominance of 2n-2n correlations

Low-energy structure:

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

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

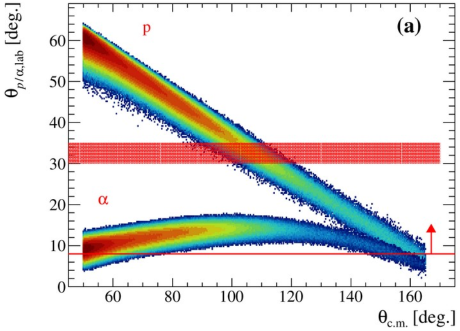
Future perspectives

TECHNISCHE UNIVERSITÄT DARMSTADT

1. Correlations in multi-neutron systems Proposal 2022, K. Miki (Tohoku), MD, T. Uesaka (RNC) *et al.*

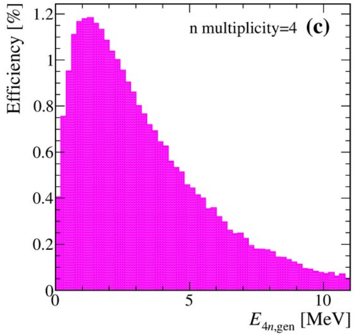
- **Neutron detection:** ^{8}He(p,pα)4n in complete kinematics

  detect all four neutrons in coincidence

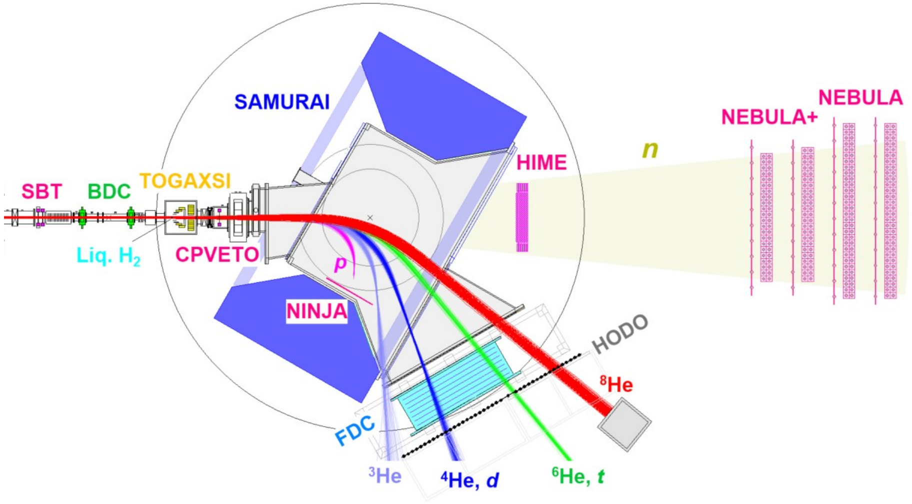


σ=0.5 mb vs. 1 μb ($\theta_{c.m.}$>160°)

> two orders of magnitude larger



detection efficiency for 4n: **0.89%**



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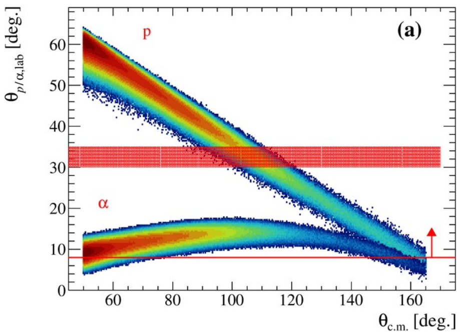

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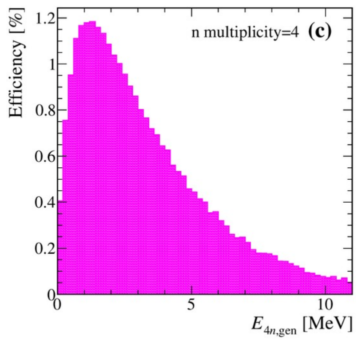

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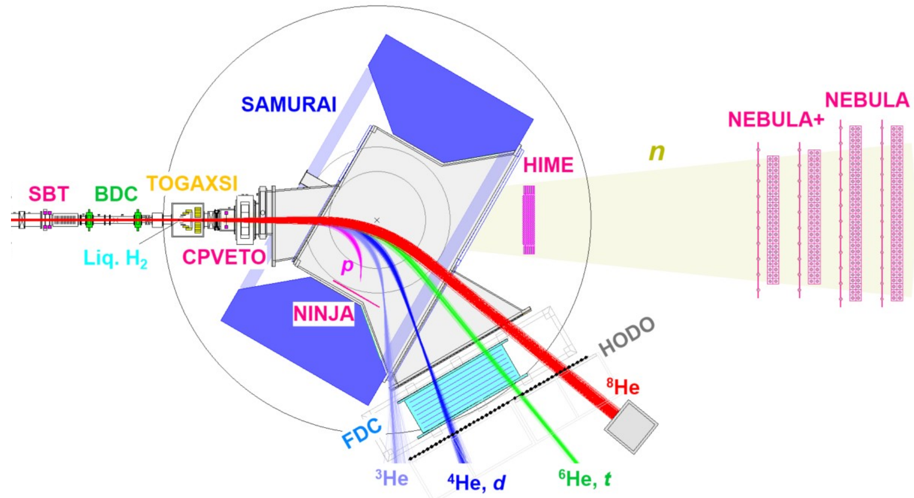

- **Reaction mechanism:** ^{6}He(p,3p)4n knockout reaction
  - (p,3p) cross sections measured for heavy nuclei (A03)
  - two sequential p-p collisions A. Frotscher *et al.*, PRL 125 (2020)

Future perspectives

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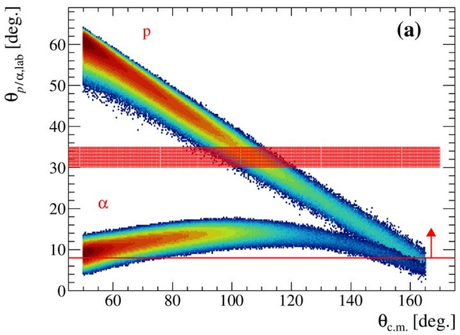

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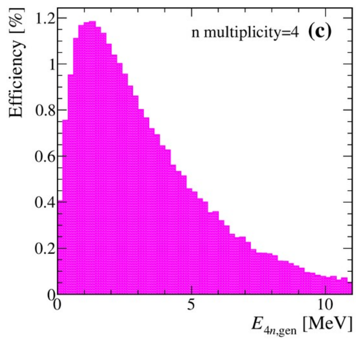

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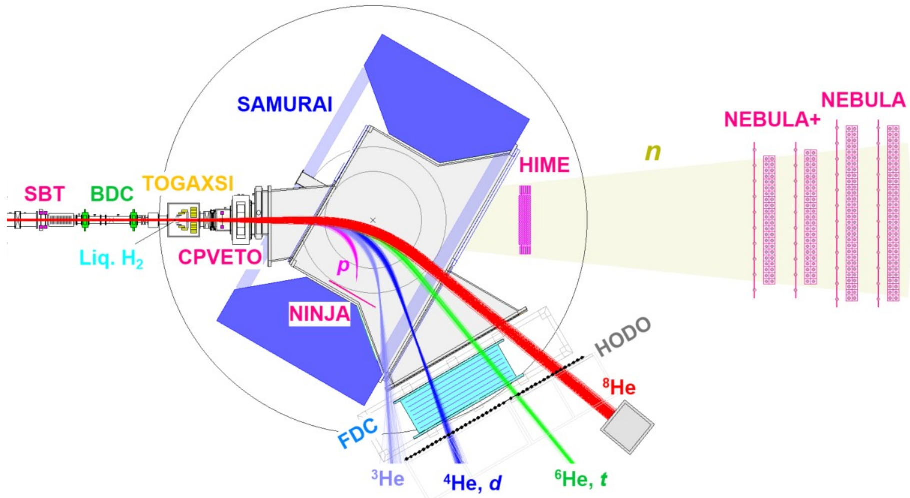

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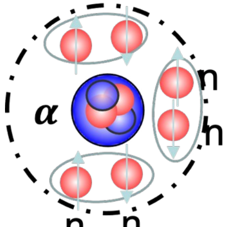
2. nn correlations from ^{10}He decay

multi-neutron ^{4}n and ^{6}n states in extremely neutron-rich nuclei (SAMURAI47 T. Nakamura *et al.*, Dec. 2022)

- ^{11}Li(p,2p)^{10}He knockout reaction
- data analysis from neutron detectors (NEBULA+,NEBULA)



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!