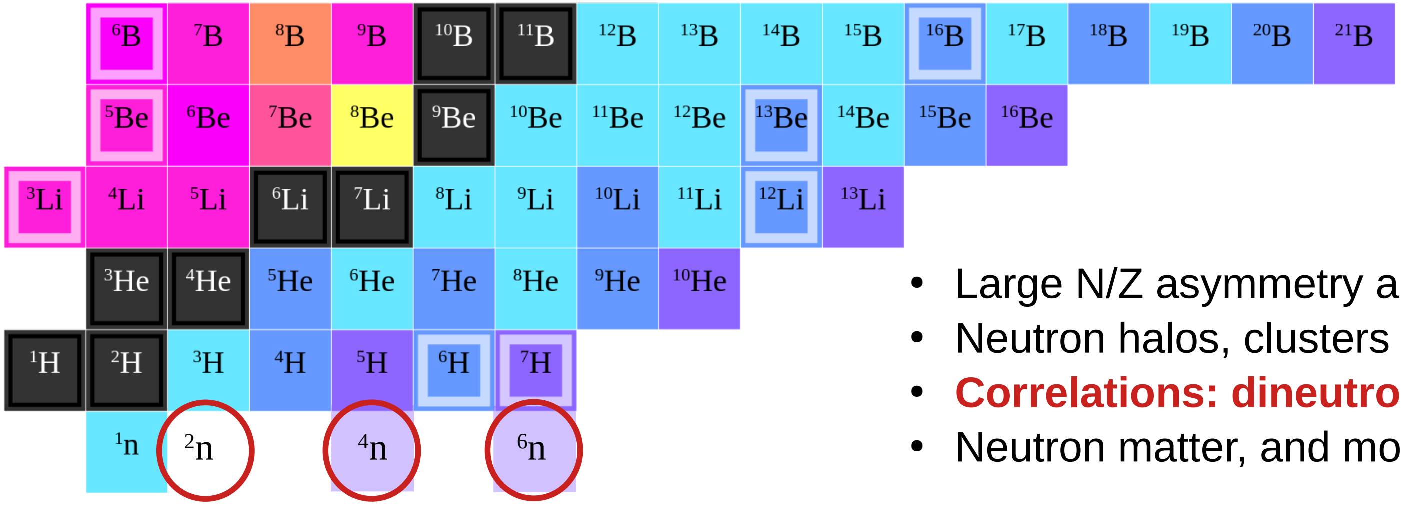
FREE SYSTEM OF FOUR CORRELATED NEUTRONS

Meytal Duer, TU Darmstadt

August 1st, 2023

AT AND BEYOND THE NEUTRON DRIPLINE



- Large N/Z asymmetry and low-density
- Neutron halos, clusters
- **Correlations: dineutron, neutron droplets**
- Neutron matter, and more..

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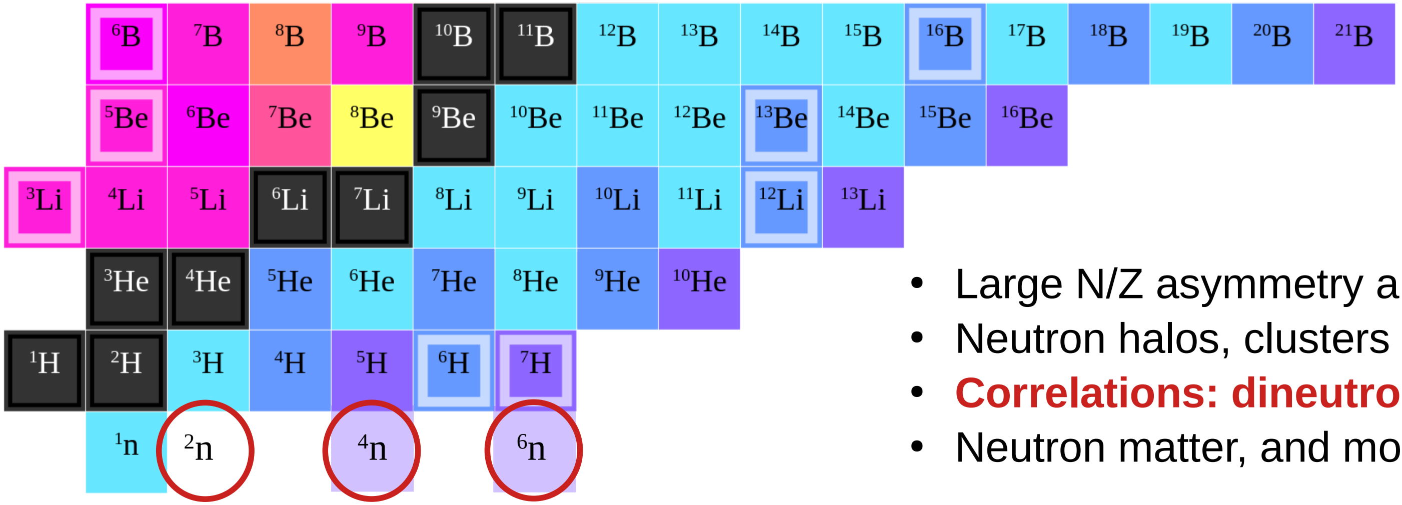

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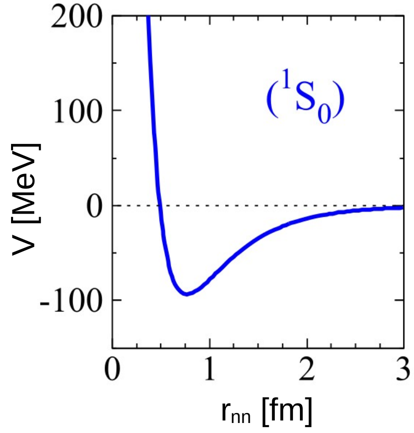
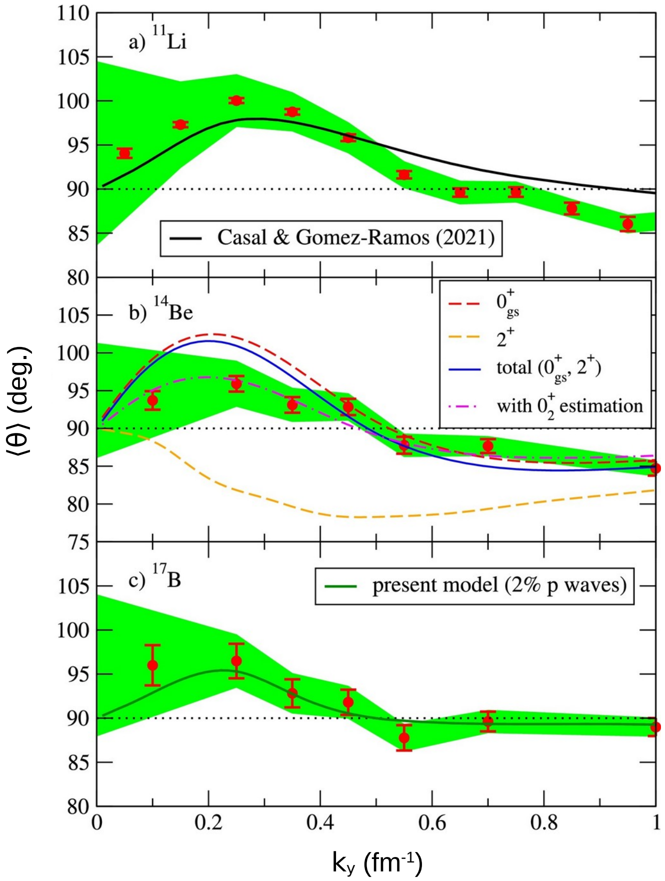
- Low-density nuclear matter:
  nn interactions dominated by attractive *S*-wave
  - dineutron unbound by ~100 keV
  - large scattering length: a_{nn}=-18.9(4) fm
  - **strong correlations even at very low-density**



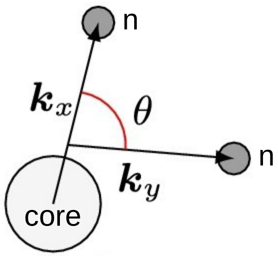
Marqués, EPJP 136 (2021)

DINEUTRON CORRELATION

- Borromean halo nuclei ^{11}Li, ^{14}Be, ^{17}B
- (p,pn) knockout reaction at the RIBF facility



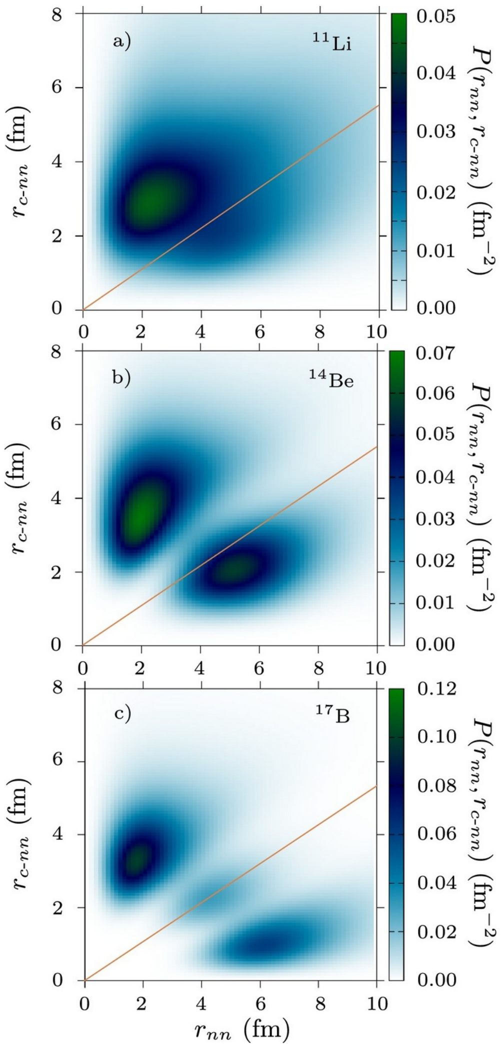
Corsi et al., Phys. Lett. B 840 (2023)



opening angle between 2n:

90° ⇒ non-correlated case

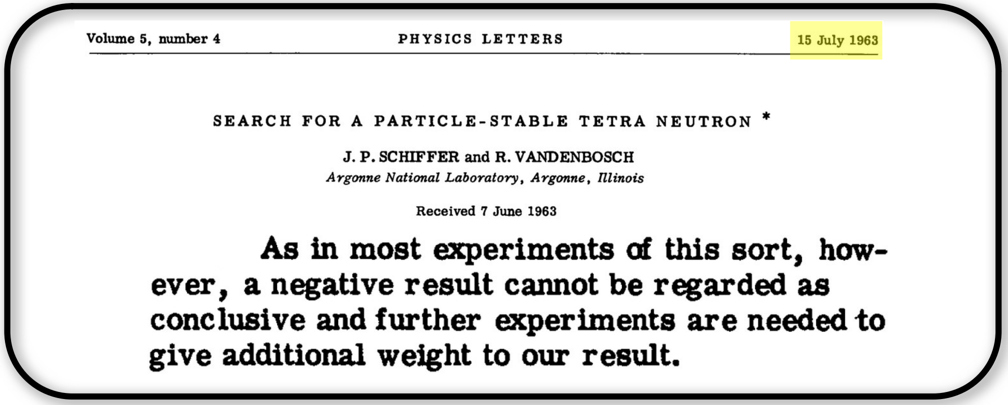
>90° ⇒ spatial correlation



LONG-STANDING QUEST FOR MULTI-NEUTRON SYSTEMS

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
  e.g. Cerny et al., Phys. Lett. 53B (1974)
- double-charge exchange (π^-,π^+) reaction
  e.g. Ungar et al., Phys. Lett. B 144 (1984)

→ **no indication for a tetra-neutron**

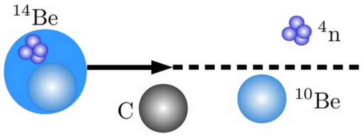
XXI century:

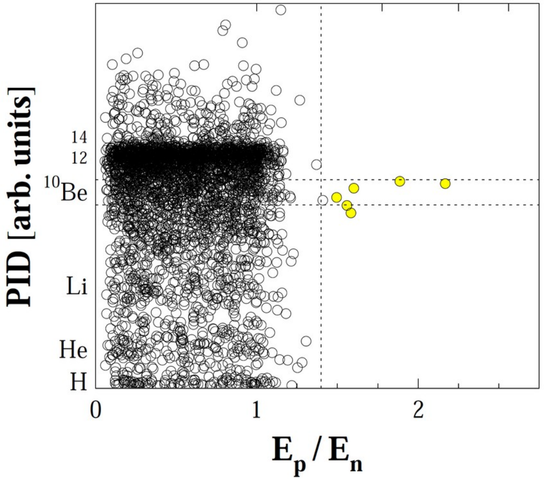
- radioactive-ion beams
  → **first positive signals**

THE ELUSIVE TETRA-NEUTRON

GANIL 2002

breakup reaction





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

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

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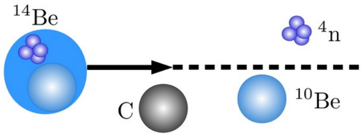

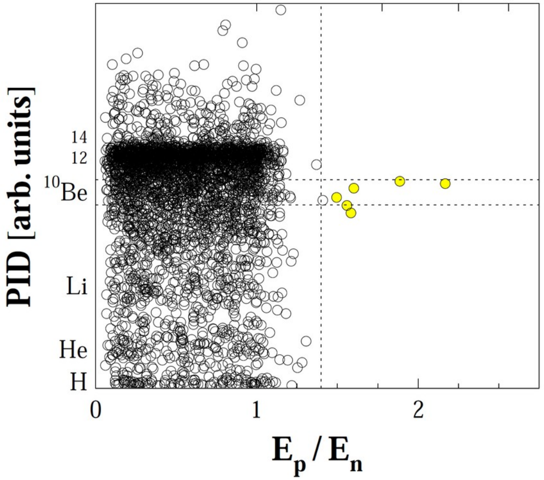

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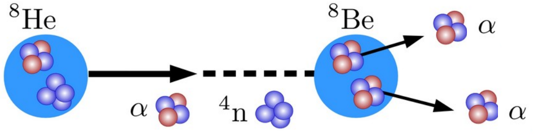
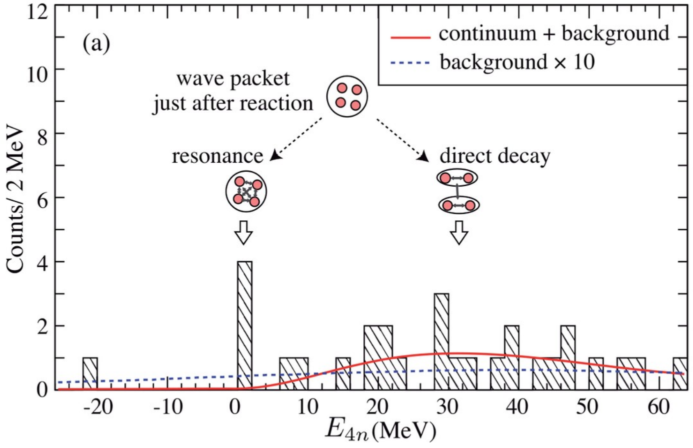
RIKEN 2016

double-charge exchange





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?

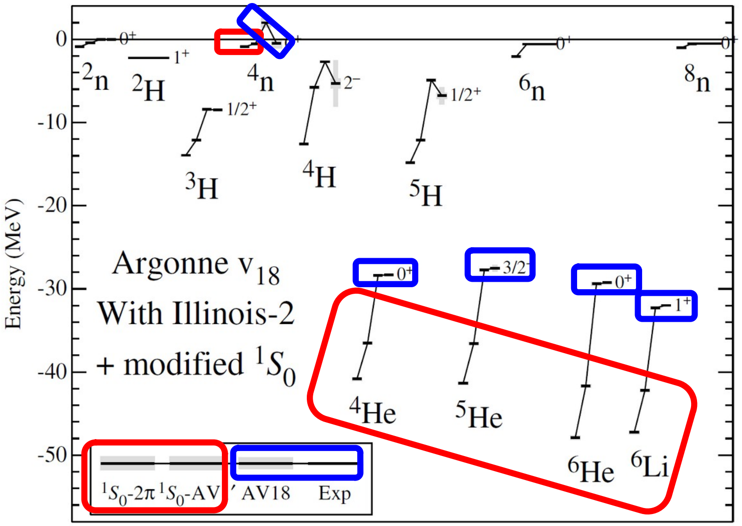
Historical consensus: **no bound tetra-neutron can exist**

Pieper PRL 90, 2003:

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

- ab initio Green’s function Monte Carlo
- using modern realistic NN and NNN potentials

“it does not seem possible to change modern nuclear Hamiltonians to bind a tetra-neutron without destroying many other successful predictions... our understanding of nuclear forces will have to be significantly changed”

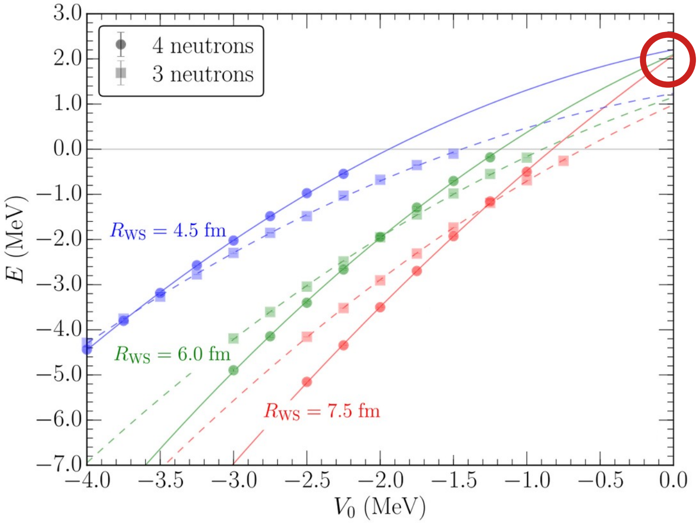


A TETRA-NEUTRON RESONANCE?

Quantum Monte Carlo calculation:

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

- 4n confined in Woods-Saxon potential radius R_{WS}, depth V_0
- extrapolation to $V_0 \to 0$
- **possible resonance at 2.1(2) MeV**



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

A TETRA-NEUTRON RESONANCE?

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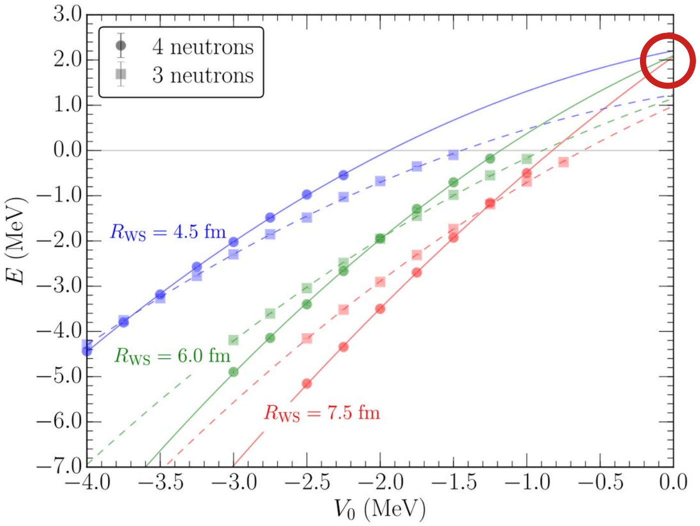


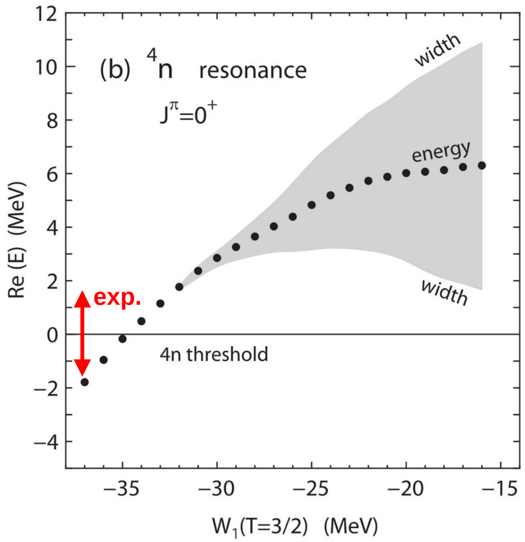
S. Gandolfi et al., PRL 118 (2017)

Full treatment of continuum:

- **no tetra-neutron resonance can exist**

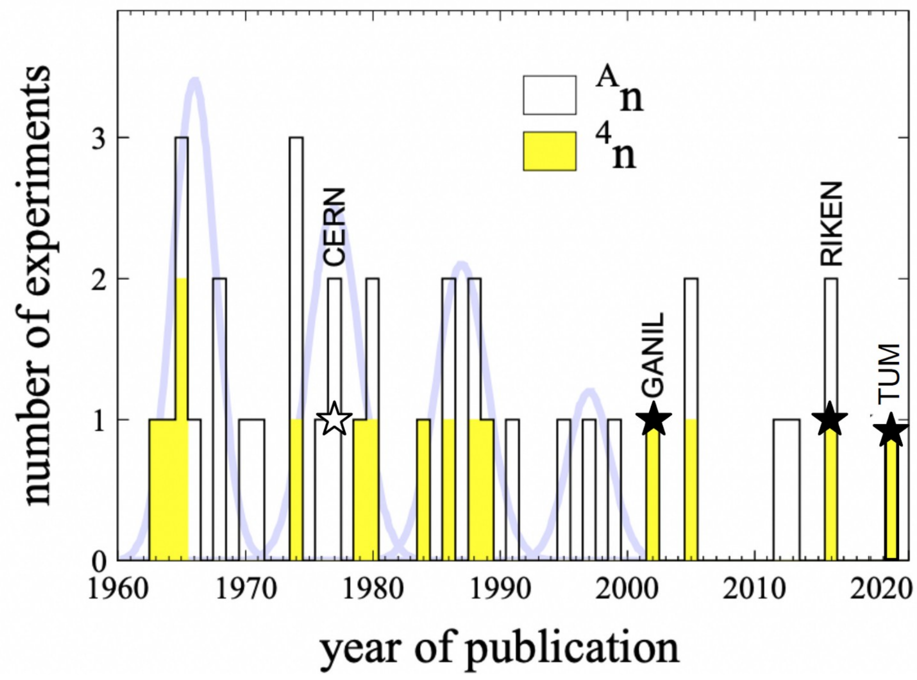
  “the four-neutron system is studied using exact continuum equations... This indicates the absence of an observable 4n resonance, in contrast to a number of earlier works.” Deltuva, PLB 782 2018

- resonance behaviour only for unrealistic 3N force



Hiyama et al., PRC 93 (2016)

LONG-STANDING QUEST FOR MULTI-NEUTRON SYSTEMS



Modified from Marqués & Carbonell, EPJA 57 (2021)

Experiment:

- until recently three (weak) positive signals:
  ★ GANIL 2002, RIKEN 2016, TUM 2022
  indications for bound / unbound

Theory:

- no bound 4n
- no consensus about a resonant state

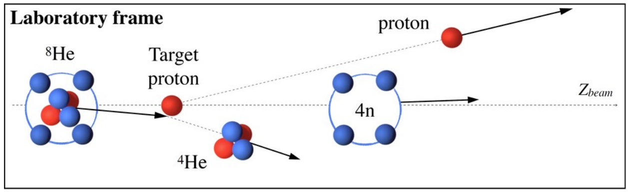
PRESENT EXPERIMENTAL WORK

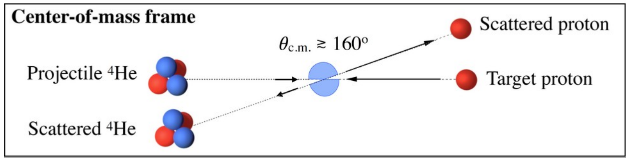
Quasi-free knockout ^{8}He(p,p^{4}He) at 156 AMeV, RIBF

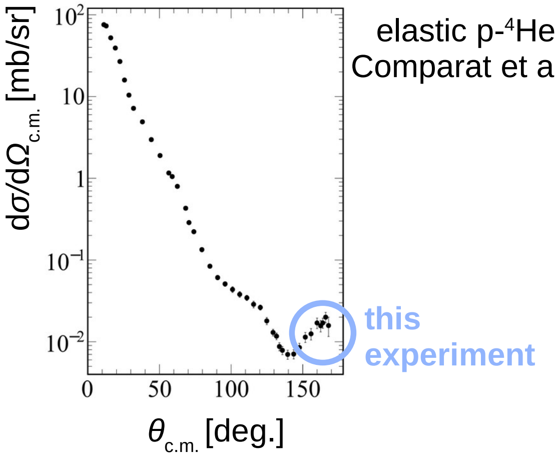
- large momentum transfer
  - ➔ sudden removal of an α-particle from ^{8}He
  - ➔ 4n as spectators

- four-neutron energy spectrum via **missing-mass**
  - ➔ precise measurement of charged particles

$$\bar{P}_{miss} = \bar{P}_{^8He} + \bar{P}_{p(tgt)} - \bar{P}_{^4He} - \bar{P}_p \rightarrow E_{4n} = \sqrt{E^2_{miss} - \boldsymbol{P}^2_{miss}} - 4m_n$$



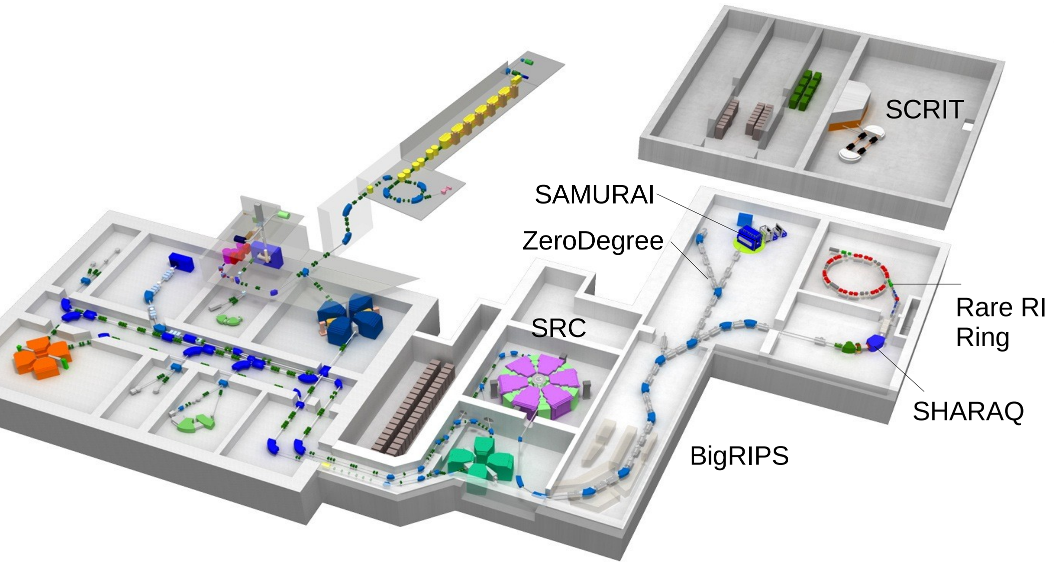


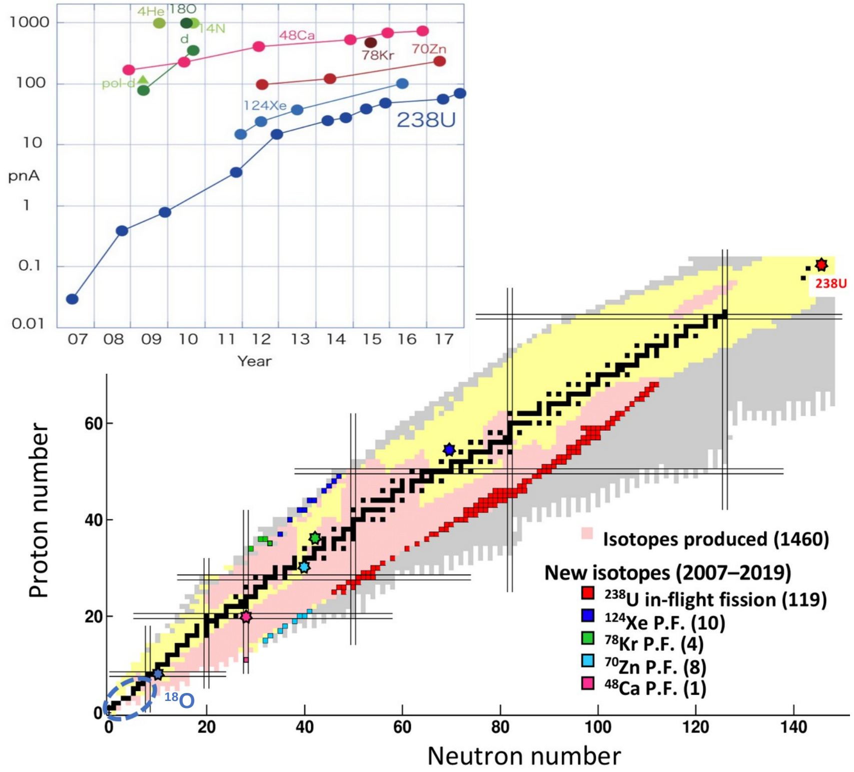


elastic p-^{4}He at 156 MeV
Comparat et al., PRC (1975)

THE RADIOACTIVE ION BEAM FACTORY (RIBF)

- Primary stable beams accerelated up to 345 AMeV
- High intensities of 1 pμA for light- medium-mass beams, 100 pnA for ^{238}U
- Access to exotic nuclei: projectile fragmentation / in-flight fission





Okuno et al., J. Phys. Conf. Ser. 1401 (2020)

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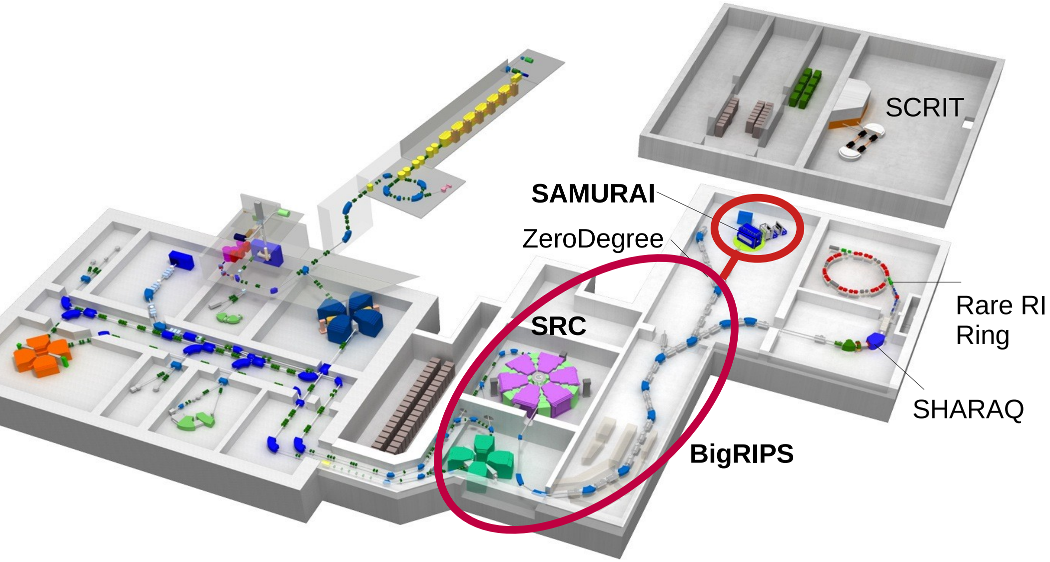
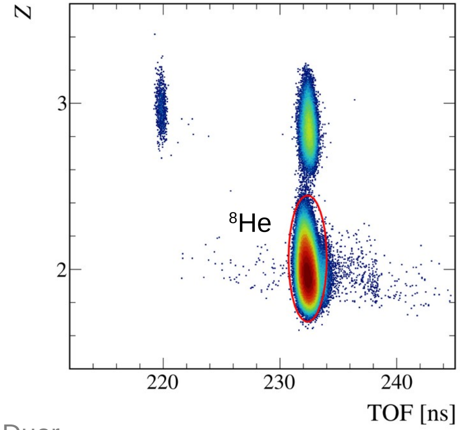
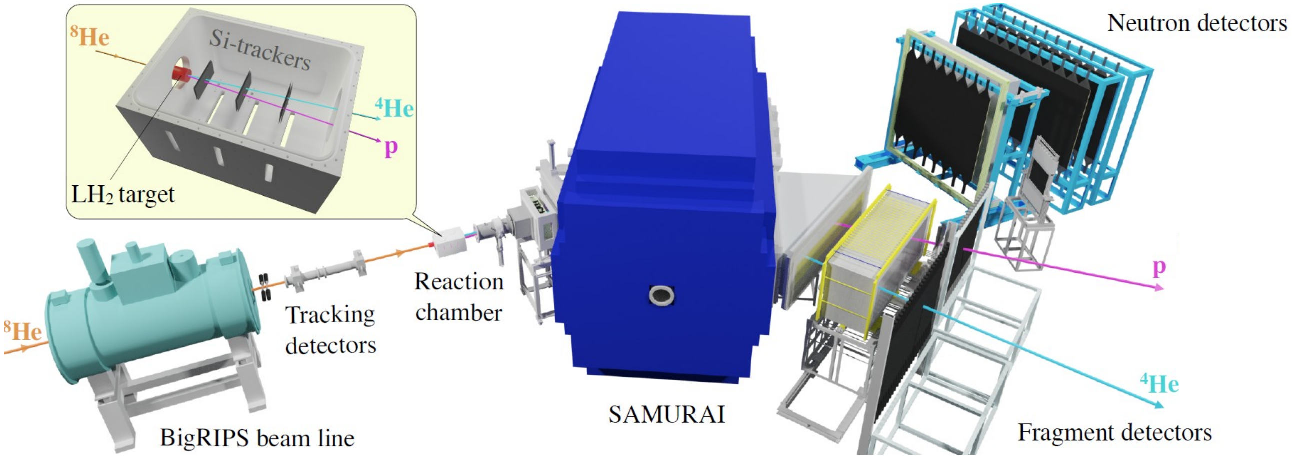


- **Superconducting Ring Cyclotron**
  primary ^{18}O beam
- **BigRIPS fragment separator**
  production and selection of ^{8}He
- **SAMURAI setup**



SAMURAI SETUP AT RIBF

SAMURAI dipole magent: 1.25 T (max. 3 T)
Tracking & PID of **^{8}He beam**
Tracking & PID of **fragments (p, ^{4}He)**
Neutrons (not possible in this experiment)



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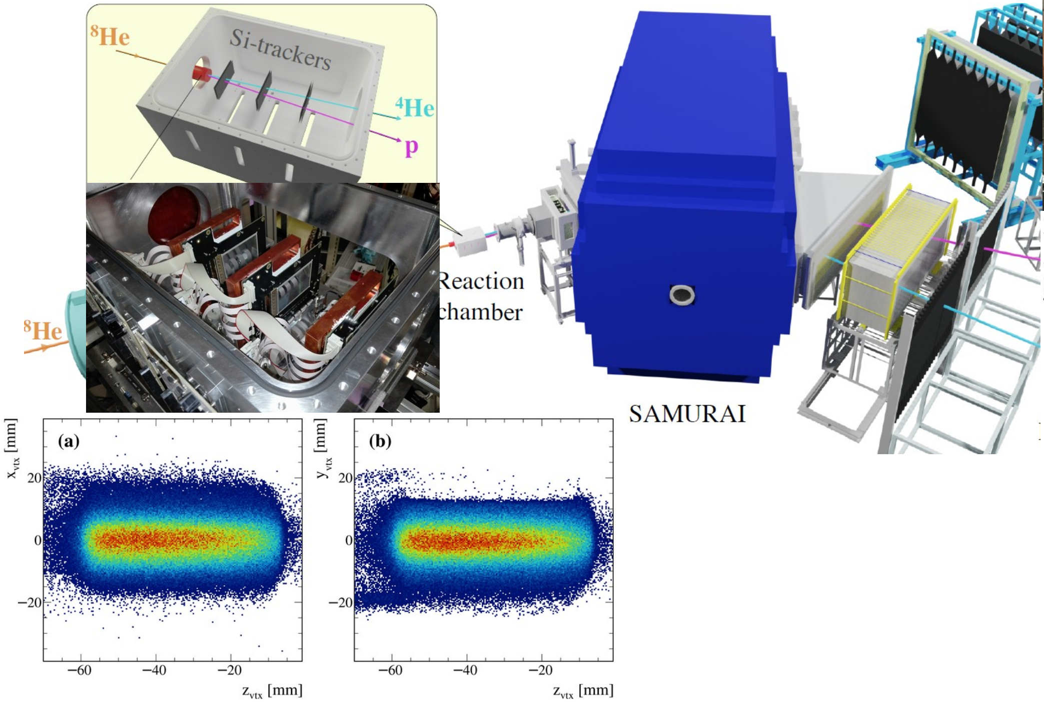

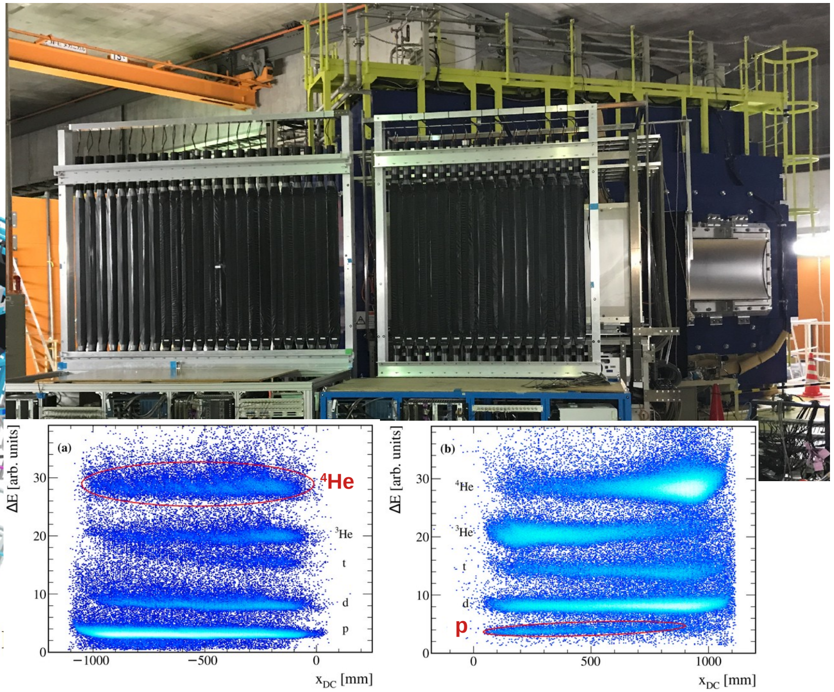

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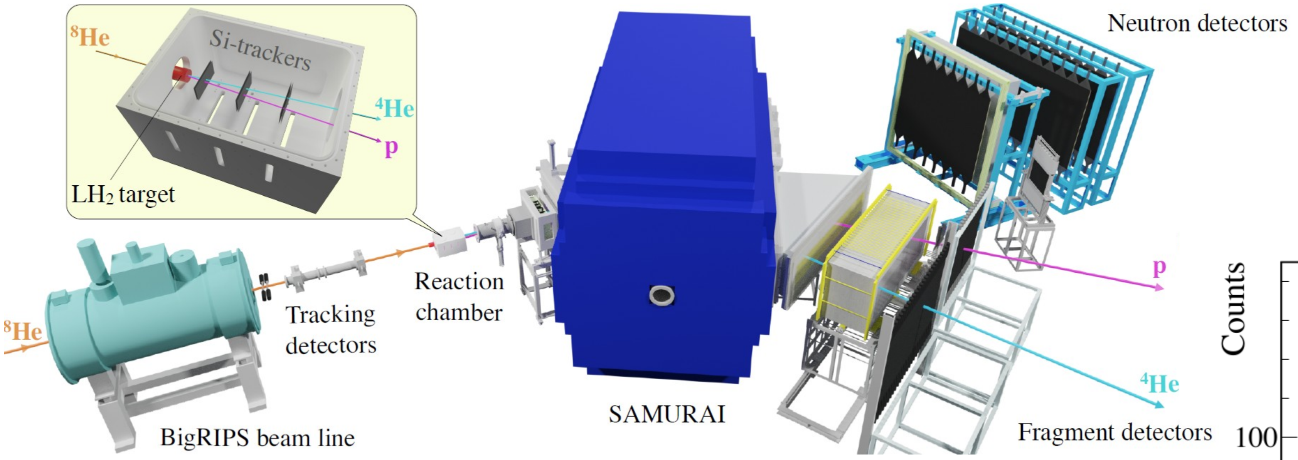
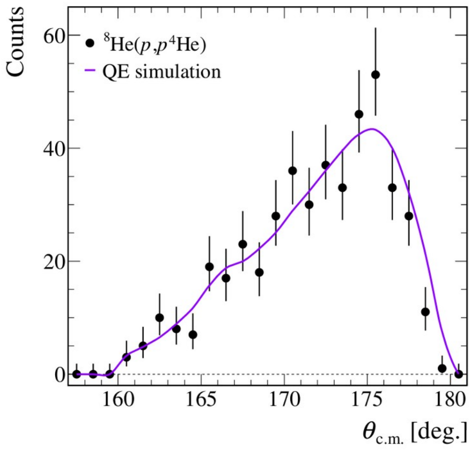
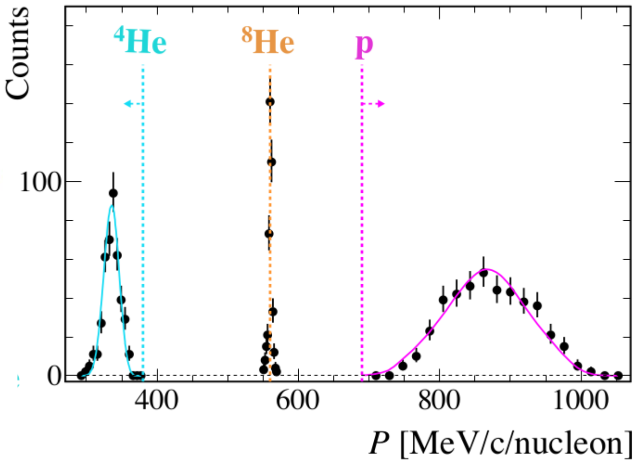




Beam and fragment momenta



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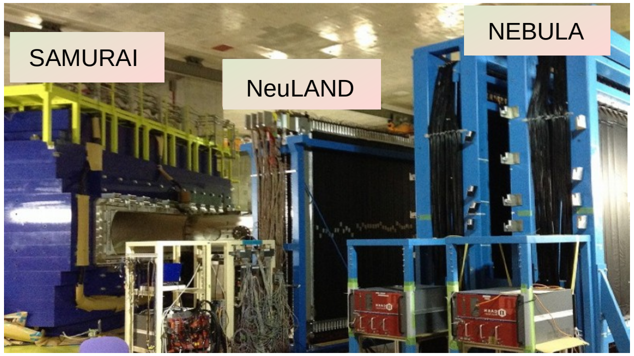
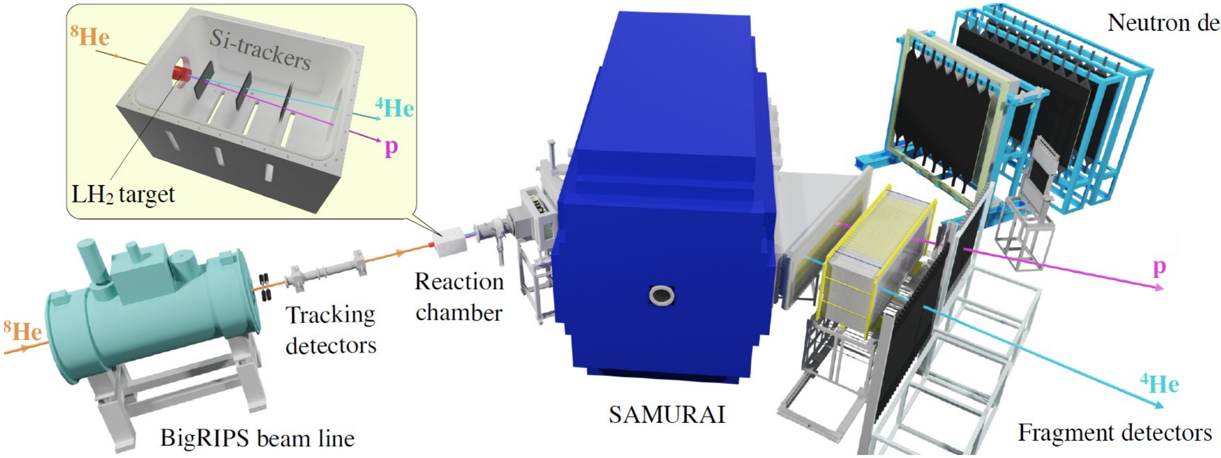




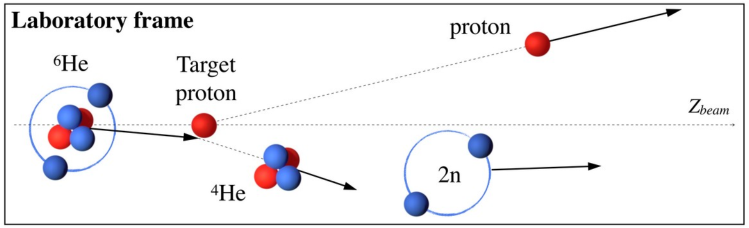
Small p-^{4}He cross section (~1 μb) at the specific kinematics

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

RESULTS:
MISSING-MASS SPECTRUM

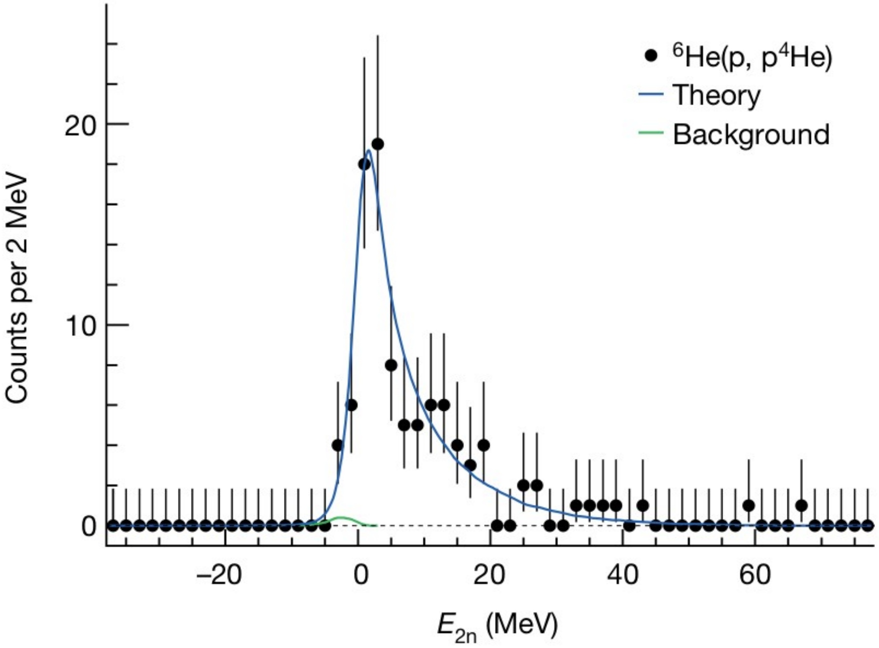
Benchmark measurement:

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



- 2n relative-energy spectrum expected to be well described by theory
- theoretical input M. Göbel et al., PRC 104 (2021)
  - 3-body (^{4}He+2n) cluster model
  - nn final-state interaction (FSI)

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



confirms the expected dineutron low-energy peak ~100 keV

RESULTS: MISSING-MASS SPECTRUM

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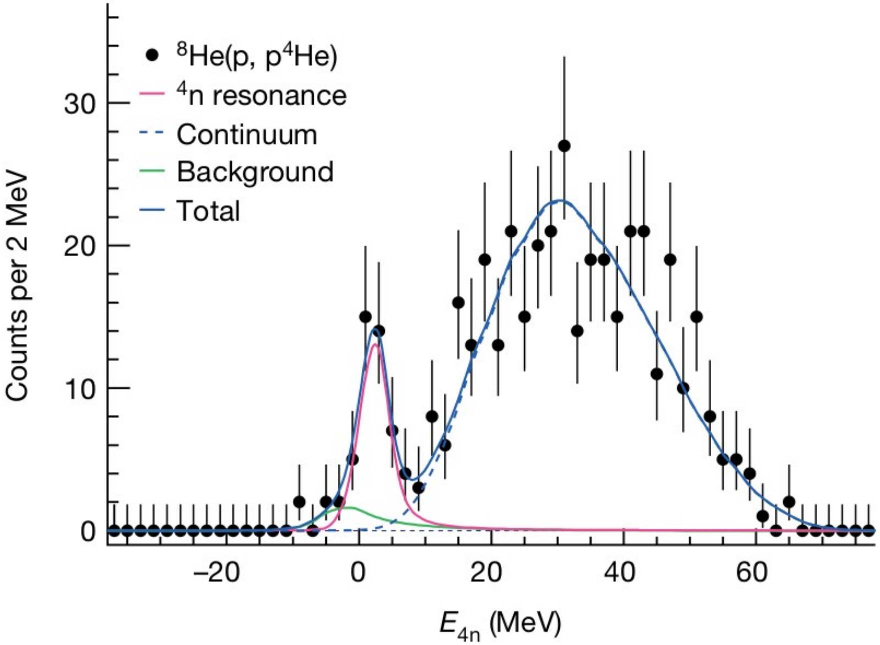
^{8}He(p,p^{4}He)4n



evidence of free correlated four neutrons

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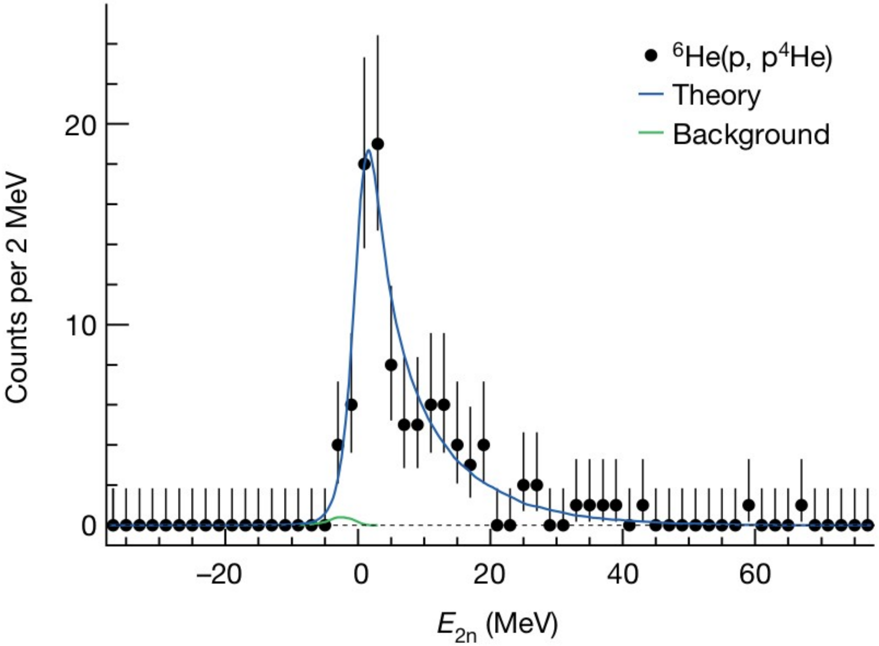

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MD et al., Nature 606, 678 (2022)

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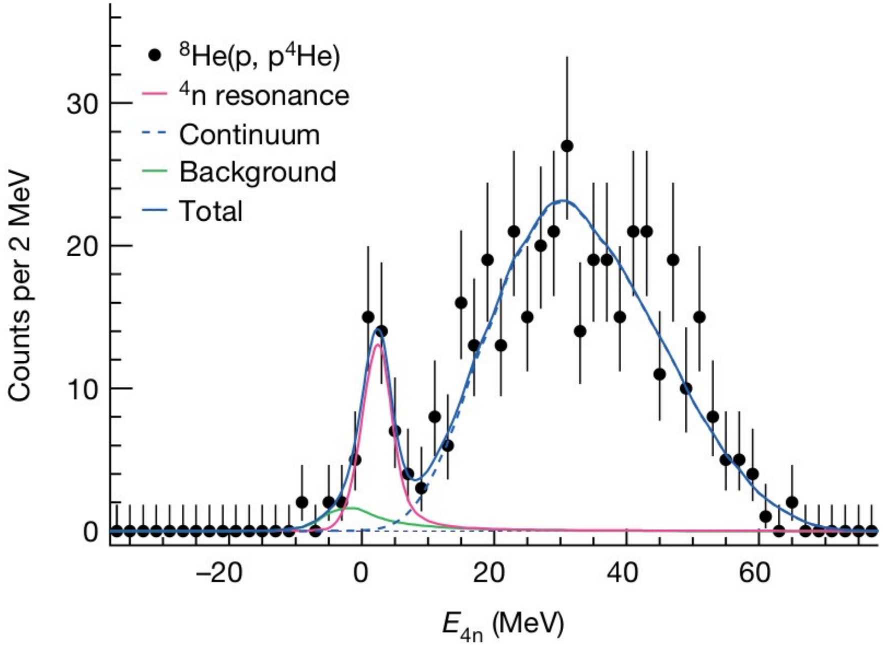
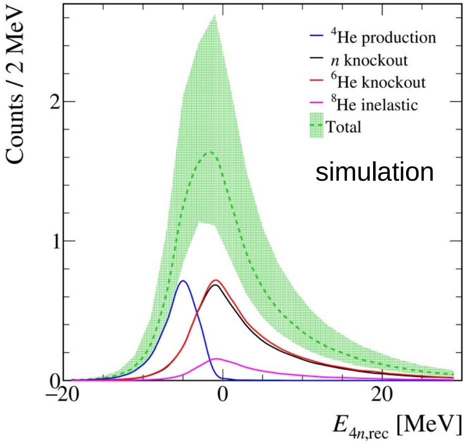


evidence of free correlated four neutrons

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

- Continuum component:
  five-body (^{4}He+4n) COSMA model
  Zhukov et al., PRC (1994); Grigorenko et al., EPJA (2004)

- Background estimate:
  two-step reactions (~3%)

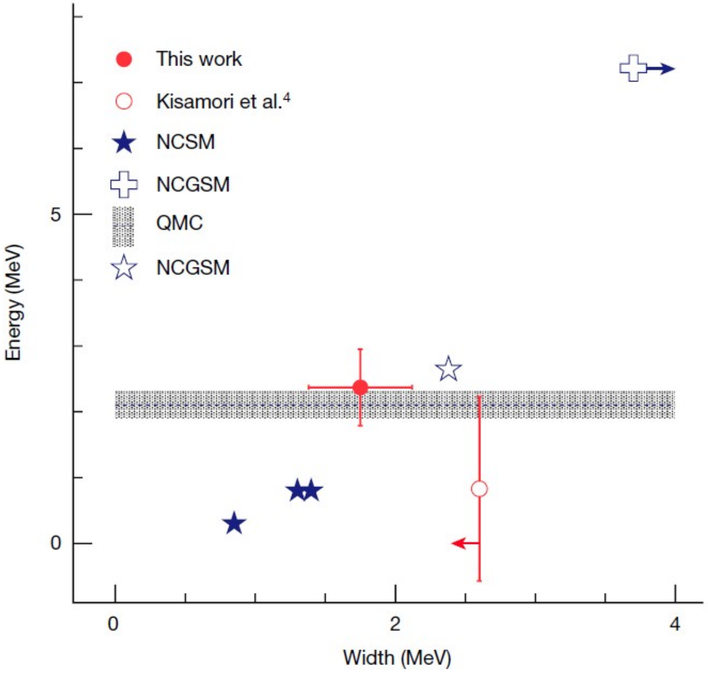


- Resonance-like structure:
  E_r = 2.37±0.38(stat.)±0.44(sys.) MeV
  Γ = 1.75±0.22(stat.)±0.30(sys.) MeV

A CORRELATED 4N SYSTEM

Resonance or non-resonant FSI among the neutrons and reaction mechanism?

Predictions for a tetra-neutron



★ Shirokov PRL (2016); ░ Gandolfi PRL (2017);
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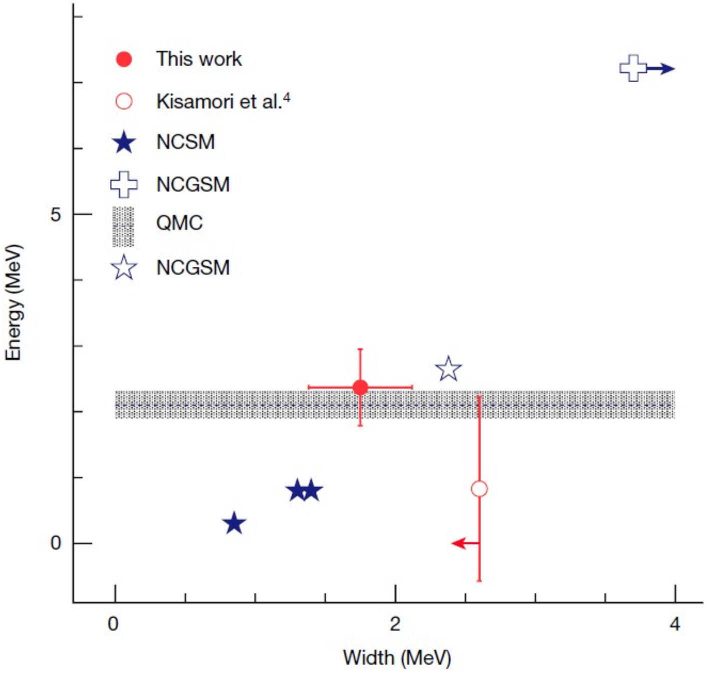

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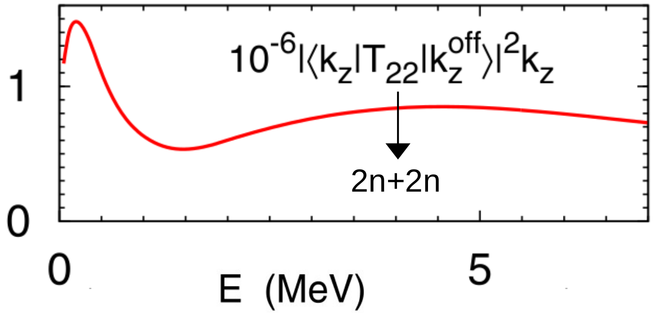
Full treatment of continuum → no tetra-neutron

Recent review: Marqués & Carbonell, EPJA 57 (2021)

Low-energy structures

"even without an observable resonance the transition operators exhibit pronounced low-energy peaks. They may be seen also in more complicated reaction such as ^{8}*He(*^{4}*He,*^{8}*Be) with the 4n subsystem in the final state"*



Deltuva, PLB 782 (2018)

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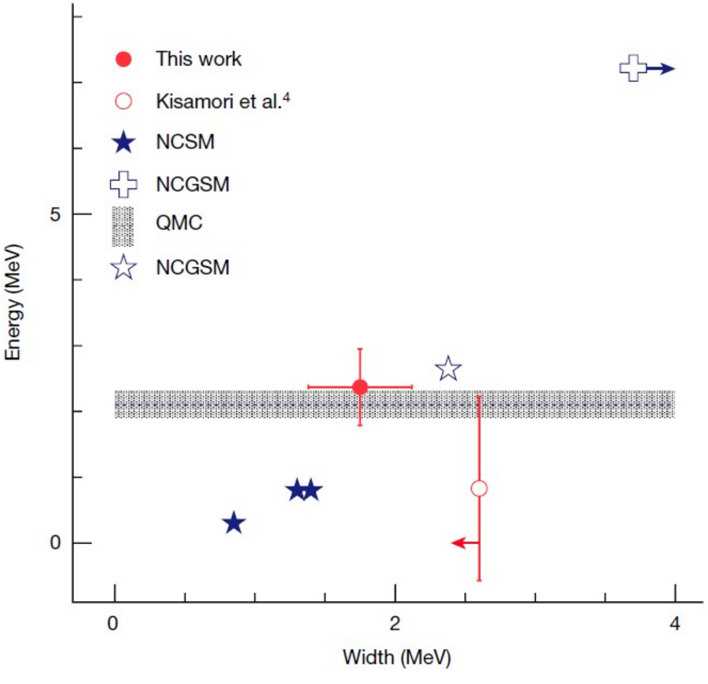

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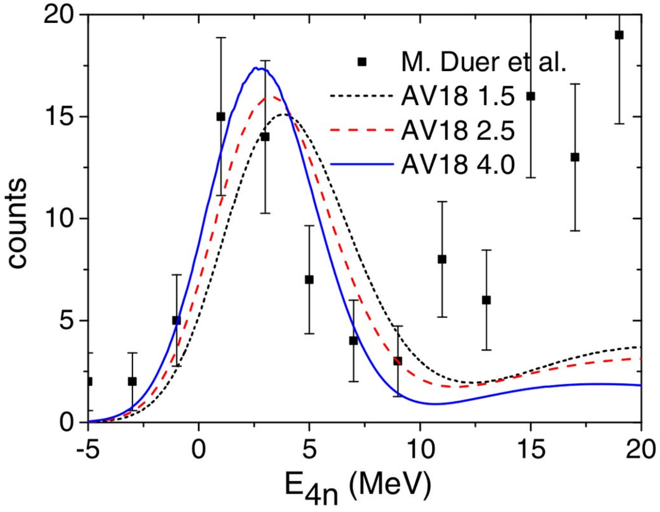
Low-energy structures

“we propose a natural explanation for the low energy structure: it emerges as a consequence of final state interaction among the 4n and the -important- presence of four neutrons in the periphery of the ^{8}He projectile”



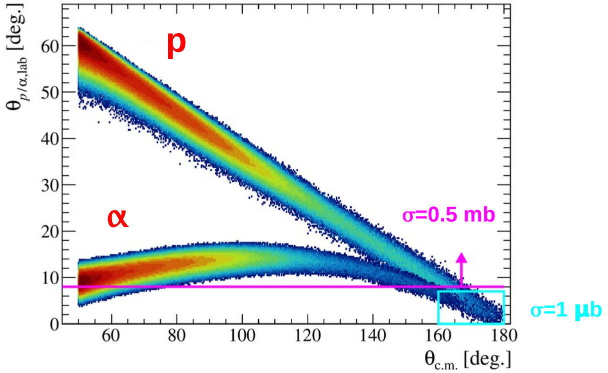
Laszauskas et al., PRL (2023)

FUTURE PERSPECTIVES

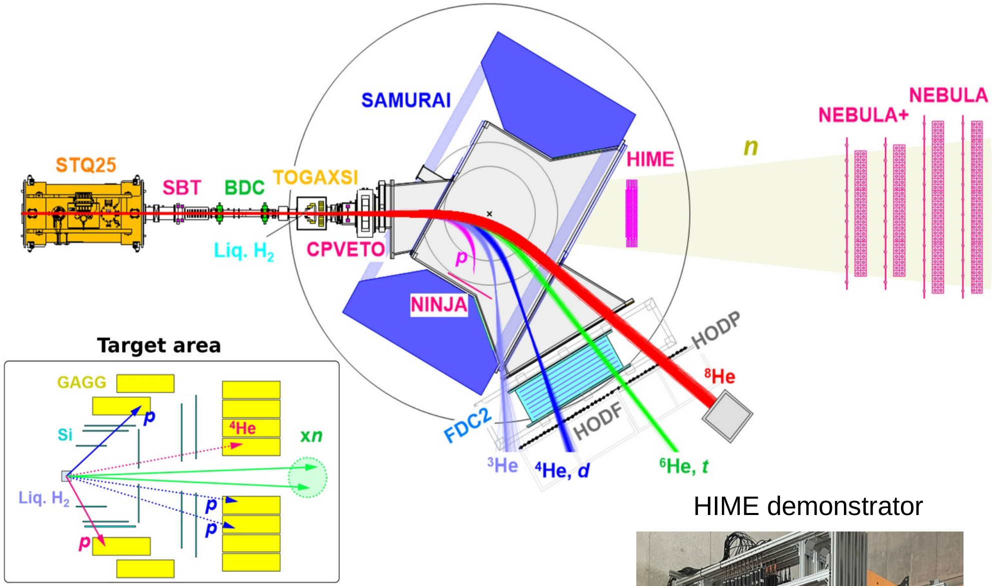
Correlations in multi-neutron systems

K. Miki, MD et al. (SAMURAI74), accepted proposal 2022

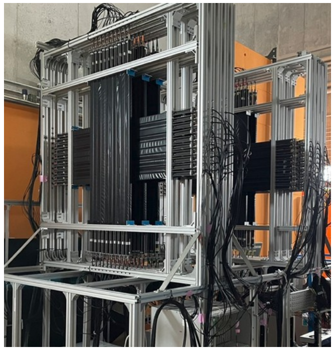
- properties of the 4n system:
  correlations among **4n in coincidence**
  - ➔ exclusive ^{8}He(p,pα)4n knockout



  - ➔ **reaction mechanism:** ^{6}He(p,3p)4n knockout
- search for **6n correlation** via missing-mass ^{8}He(p,3p) measurement



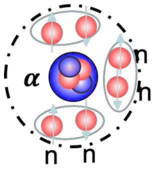
HIME demonstrator



FUTURE PERSPECTIVES

Multi-neutron decays of ^{10}He

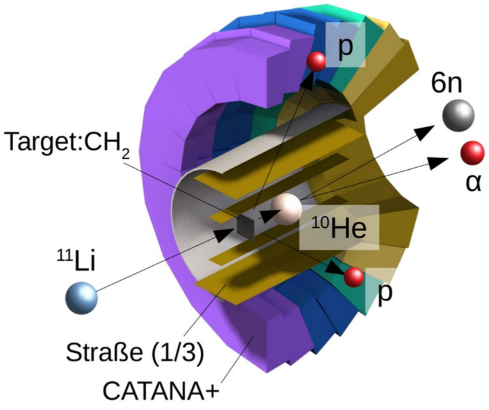
T. Nakamura et al. (SAMURAI47), 2023

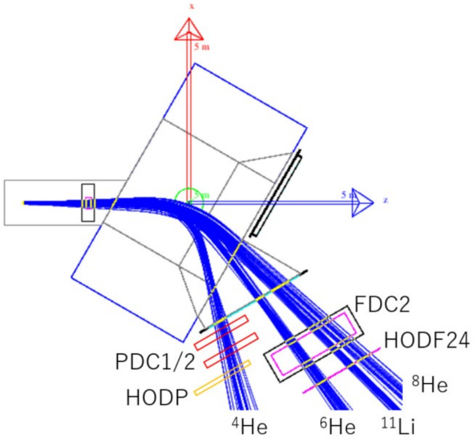


- ^{11}Li(p,2p) knockout:

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

  - mainly missing-mass: (p,2p) + fragment
  - 2n in coincidence to study nn correlations





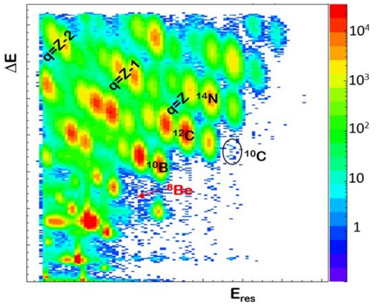
Thank you!

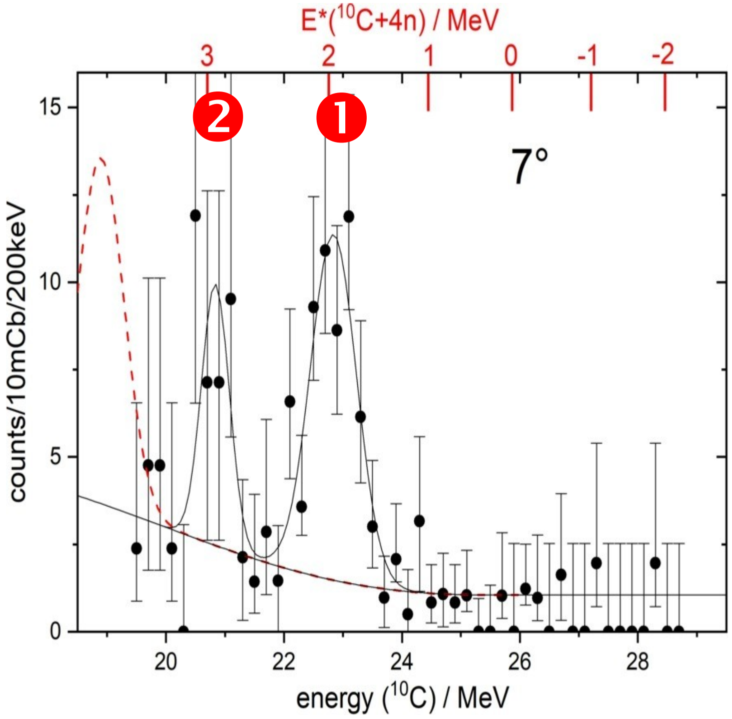
SAMURAI19 experiment: M. Duer, T. Aumann, R. Gernhäuser, V. Panin, S. Paschalis, D. M. Rossi, N. L. Achouri, D. Ahn, H. Baba, C. A. Bertulani, M. Böhmer, K. Boretzky, C. Caesar, N. Chiga, A. Corsi, D. Cortina-Gil, C. A. Douma, F. Dufter, Z. Elekes, J. Feng, B. Fernández-Domínguez, U. Forsberg, N. Fukuda, I. Gasparic, Z. Ge, J. M. Gheller, J. Gibelin, A. Gillibert, K. I. Hahn, Z. Halász, M. N. Harakeh, A. Hirayama, M. Holl, N. Inabe, T. Isobe, J. Kahlbow, N. Kalantar-Nayestanaki, D. Kim, S. Kim, T. Kobayashi, Y. Kondo, D. Körper, P. Koseoglou, Y. Kubota, I. Kuti, P. J. Li, C. Lehr, S. Lindberg, Y. Liu, F. M. Marqués, S. Masuoka, M. Matsumoto, J. Mayer, K. Miki, B. Monteagudo, T. Nakamura, T. Nilsson, A. Obertelli, N. A. Orr, H. Otsu, S. Y. Park, M. Parlog, P. M. Potlog, S. Reichert, A. Revel, A. T. Saito, M. Sasano, H. Scheit, F. Schindler, S. Shimoura, H. Simon, L. Stuhl, H. Suzuki, D. Symochko, H. Takeda, J. Tanaka, Y. Togano, T. Tomai, H. T. Törnqvist, J. Tscheuschner, T. Uesaka, V. Wagner, H. Yamada, B. Yang, L. Yang, Z. H. Yang, M. Yasuda, K. Yoneda, L. Zanetti, J. Zenihiro, and M. V. Zhukov.

“Indications for a bound tetraneutron”

^{7}Li(^{7}Li,^{10}C) at 46 MeV, MP Tandem of Garching, Germany

Target: 100 µg/cm2, 7Li2O deposited on 20 µg/cm C foils. Targets were quite hygroscopic after vapor deposition-> also H2O and possibly CO2.





Faestermann et al., PLB 824 (2022)

❶ Other target component (H, Li, C, O)

→ ^{7}Li(^{16}O,^{10}C)^{13}B

❷ E* = 2.93(16) MeV, σ= 0.24(9) MeV:

- ^{7}Li(^{7}Li,^{10}C$_{gs}$) – ***tetraneutron resonance***
  E$_r$=2.93(16) MeV & extremely small width
  (0.24 MeV upper limit, eloss of C in tgt uncertainty)
- ^{7}Li(^{7}Li,^{10}C*) – ^{10}C in 1st excited state 3.354 MeV
  + ***bound tetraneutron*** BE = 0.42(16) MeV

~10 events → statistical significance 3σ

Red curve: ^{7}Li(^{16}O,^{10}C*)^{13}B case;
Solid: phase space of 4n + constant bkg.

Continuum component

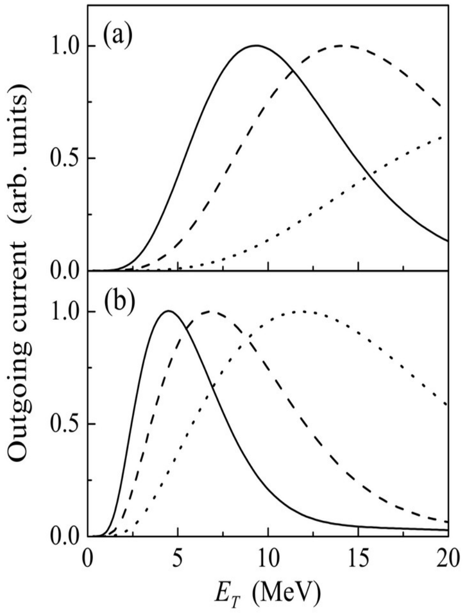
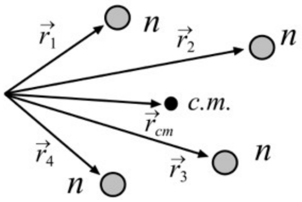


Fig. 11. Continuum response of the ^{4}n system in the MWS with a "Gaussian" source (13). Solid, dashed and dotted curves correspond to rms hyperradius $\langle\rho_{\mathrm{sour}}\rangle$ of the source equal to 8.9, 7.3, and 5.6 fm, respectively. Panels are calculated with (a) no final-state interaction, (b) RT potential (the correct *n*-*n* scattering length). All calculations are normalized to unity at the peak.

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

A source term for the reaction mechanism:

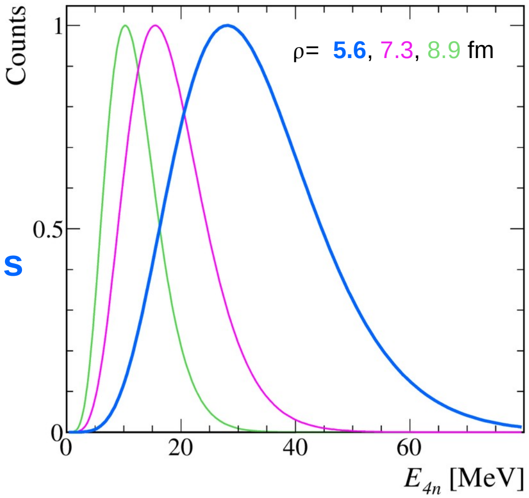
- initial structure (^{8}He)
- sensitive to the hyperradius of the source ρ
- **5.6 fm reproduces experimental ^{8}He radius**



^4n

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

continuum spectrum w/o FSI



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

BENCHMARK MEASUREMENT

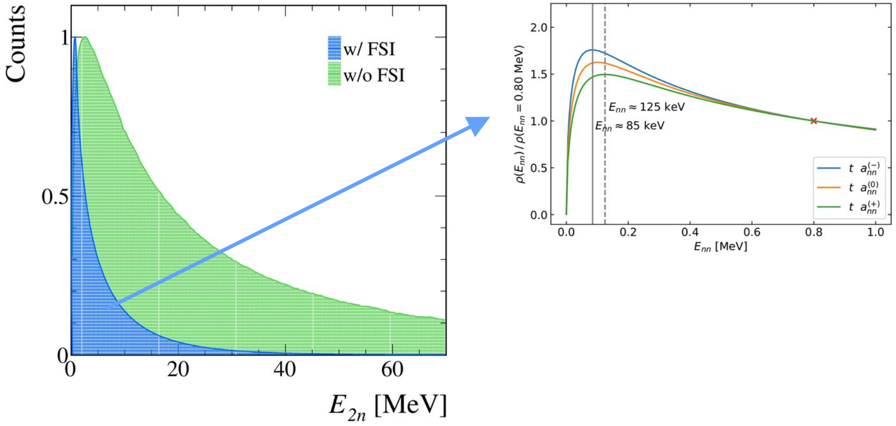
Quasi-free knockout ^{6}He(p,p^{4}He)

- 2n relative-energy spectrum is expected to be well described by theory

Theoretical input:

- **w/o FSI:** 3-body (^{4}He+n+n) cluster model
  - nn interaction $^1S_0$ 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.*, PRC 104 (2021)



$a_{nn}^{(0)}$=-18.7 fm

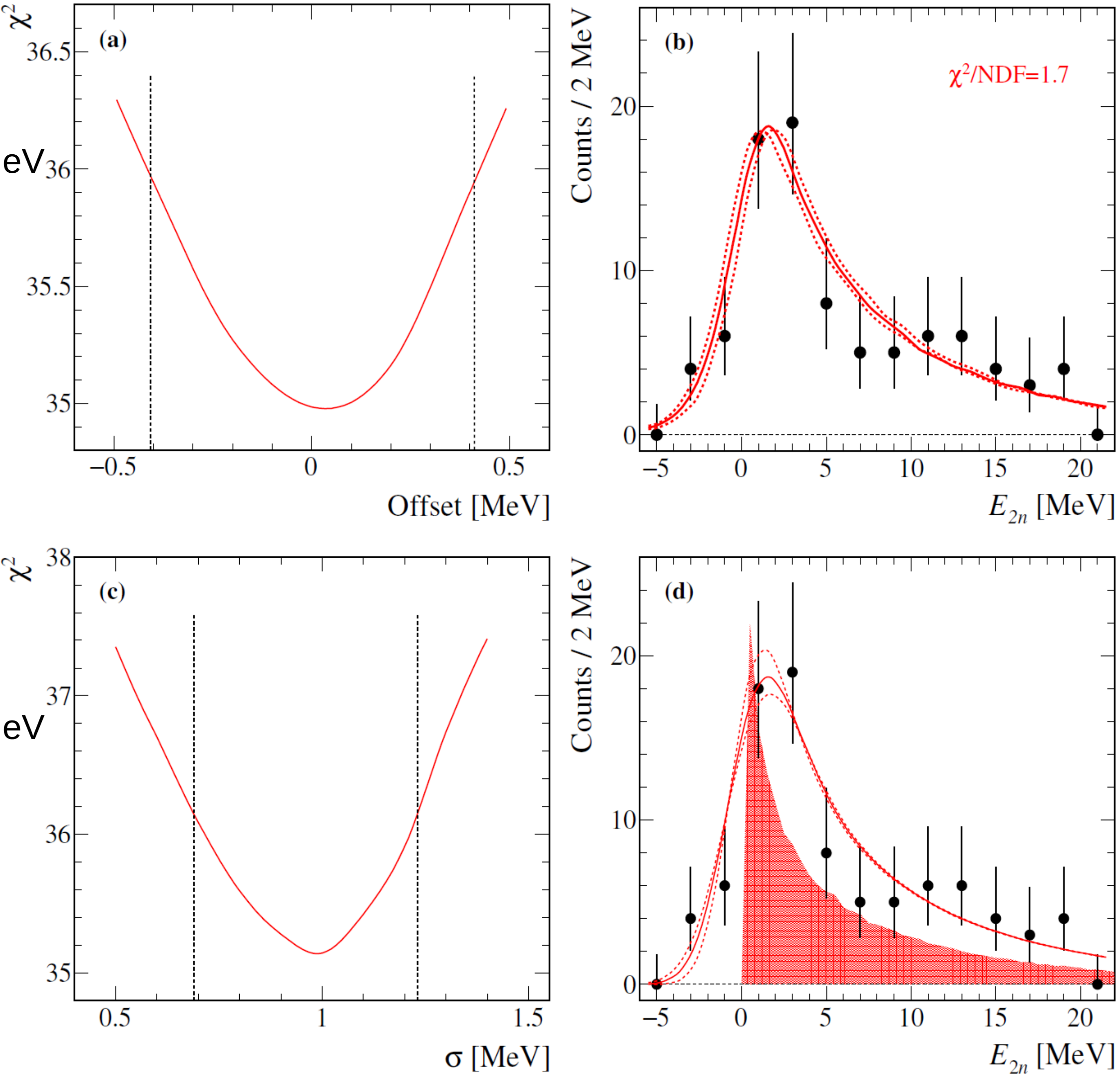
$a_{nn}^{(-)}$=$a_{nn}^{(0)}$-2 fm

$a_{nn}^{(+)}$=$a_{nn}^{(0)}$+2 fm

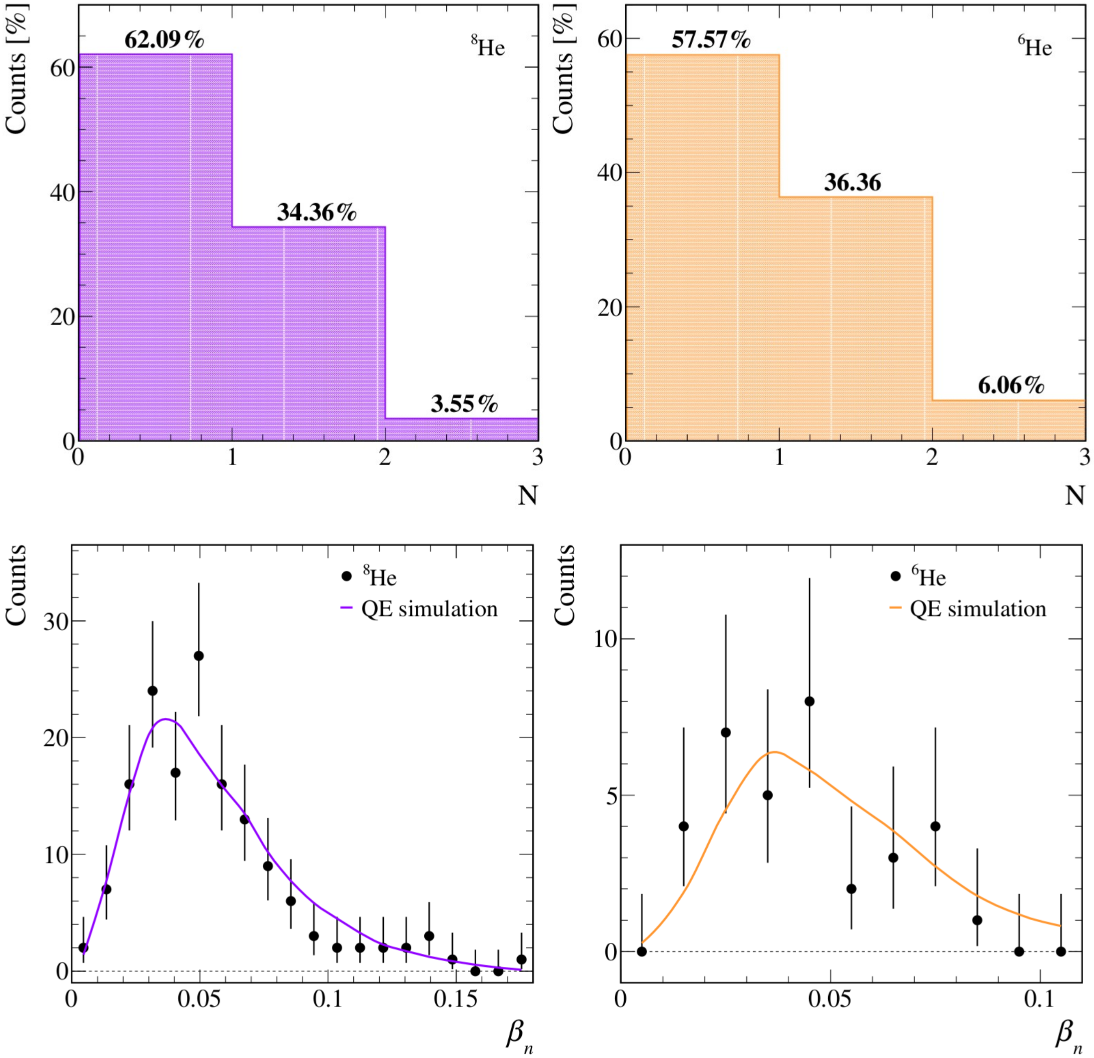
Experimentally:

- commonly used value from π^- capture **-18.6(4) fm**
- contradictory results from d(n,pn)n reaction:
  - Bonn: **-16.3(4) fm** Huhn et al., PRL 85 (2000)
  - TUNL: **-18.7(7) fm** Gonzalez et al., PRC 73 (2006)

systematic uncertainty 0.4 MeV

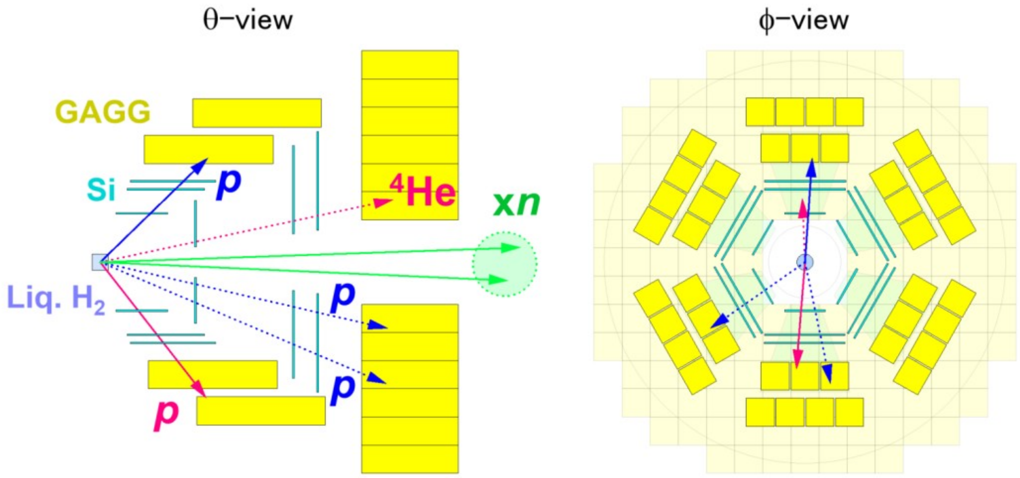


systematic uncertainty 0.3 MeV



Simulated det. eff:
1n – 39%
2n – 5%
3n - <0.5%
4n – 0.06% total (peak 0.5%)

Future perspectives

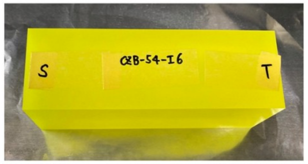


(p,pa) 80% acc. theta + 60% acc. phi + 20% loss eff.
-> 40%
For (p,3p) 1%

Missing-mass reso. ~1.5 MeV

GAGG
$Gd_3Al_2Ga_3O_{12}$
6.63 g/cm^3

Thickness: 70 mm^t (typ.)



$$\mathrm{N_{events/day}} = \mathrm{N_{proj}} \times \sigma(\mathrm{b}) \times d(\mathrm{g/cm^2}) \times 0.6(\mathrm{Avogadro})/\mathrm{A} \times \epsilon_{p-\alpha} \times \epsilon_{4n} \times f(E_{4n})$$
$$= (10^6 \cdot 24 \cdot 3600 \cdot 0.5) \times (0.5 \cdot 10^{-3}) \times 0.142 \times 0.6 \times 0.4 \times 0.0089 \times 0.15 \simeq 1{,}000 \ \mathrm{events/day}.$$

$$\mathrm{N_{events/day}} = \mathrm{N_{proj}} \times \sigma(\mathrm{b}) \times d(\mathrm{g/cm^2}) \times 0.6(\mathrm{Avogadro})/\mathrm{A} \times \epsilon_{3p} \times \epsilon_{4n} \times f(E_{4n})$$
$$= (10^6 \cdot 24 \cdot 3600 \cdot 0.5) \times (1 \cdot 10^{-3}) \times 0.142 \times 0.6 \times 0.010 \times 0.0089 \times 0.15 \simeq 50 \ \mathrm{events/day},$$

By products:

- ${}^{6(8)}\mathrm{He}(p, 2p)^{5(7)}\mathrm{H}$
- ${}^{6(8)}\mathrm{He}(p, pn)^{5(7)}\mathrm{He}$
- ${}^{6(8)}\mathrm{He}(p, p^3\mathrm{He})^{3(5)}n.$