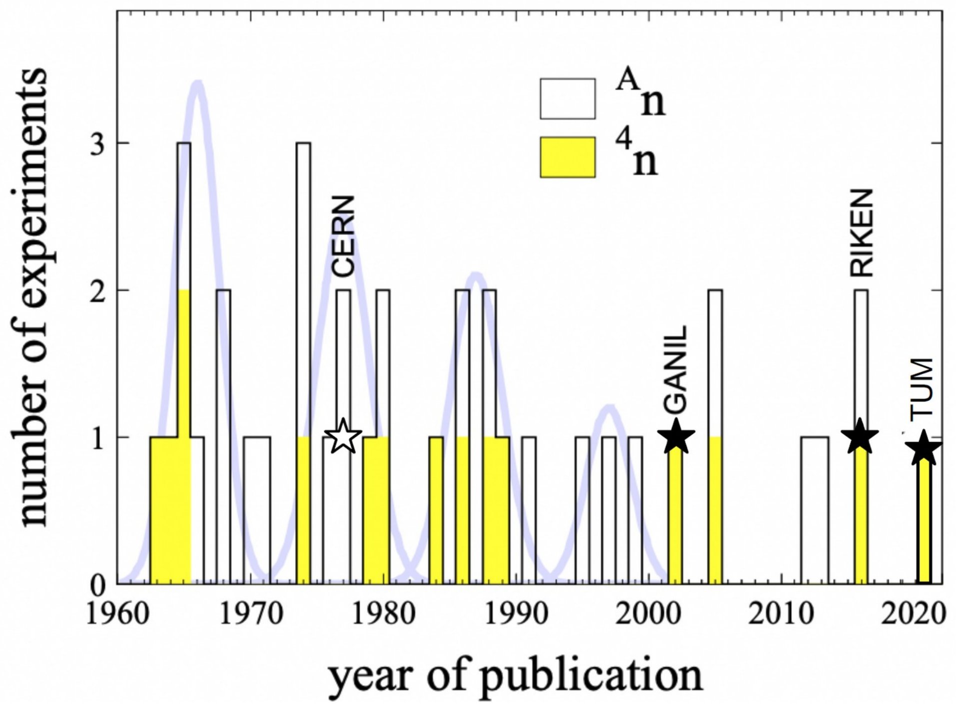
A four-neutron system probed via alpha knockout from ^{8}He

Meytal Duer

July 7th, ECT* Trento, Italy

"Observation of a correlated free four-neutron system"
MD et al., Nature 606, 678 (June 2022)

A 60-year quest



XX century:

- fission of uranium
  e.g. Schiffer & Vandenbosch, Phys. Lett. 5 (1963)
- transfer reactions
  e.g. Cerny et al., Phys. Lett. 53B (1974)
- double-charge-exchange $^4He(\pi^-,\pi^+)$ reaction
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Modified from Marqués & Carbonell, EPJA 57 (2021)

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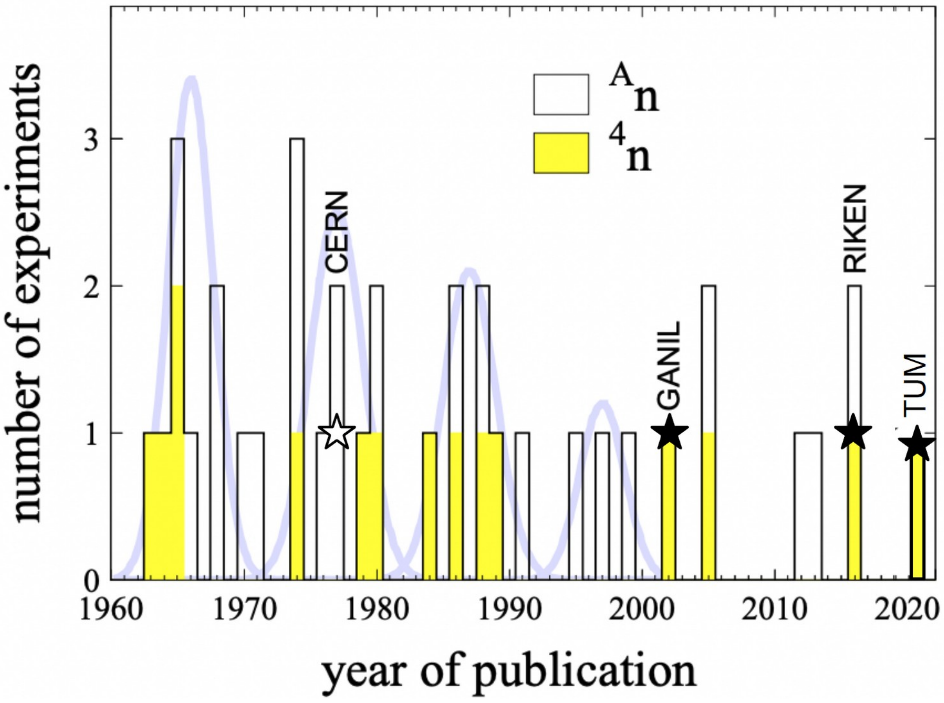

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XXI century:

- radioactive-ion beams
  - 3 positive signals:
    ★ GANIL 2002, RIKEN 2016, Munich 2022

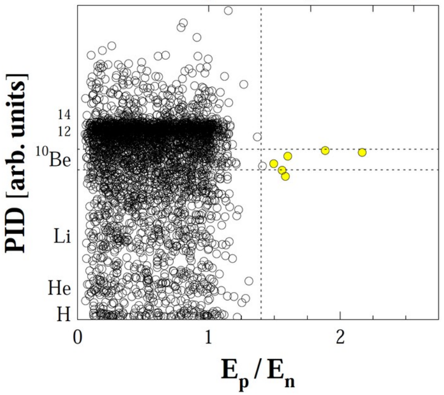
Indications for a tetra-neutron

TECHNISCHE UNIVERSITÄT DARMSTADT

GANIL 2002

Breakup on a C target:

$^{14}Be \rightarrow {}^{10}Be + {}^{4}n$



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

2σ significance

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Double-charge-exchange:

$^8He(^4He,^8Be)$

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

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Kisamori et al., PRL 116 (2016)

Munich 2022

Multi-nucleon transfer:

$^7Li(^7Li,^{10}C)$

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

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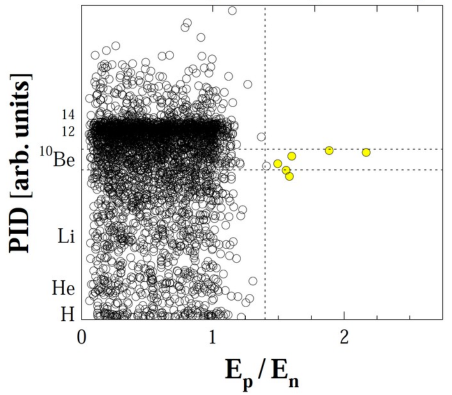

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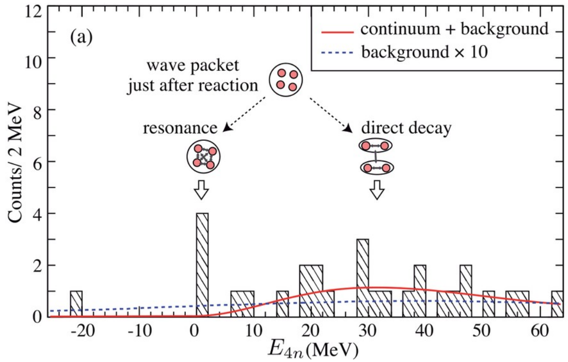

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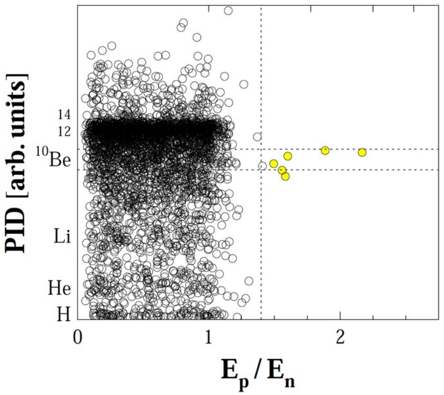

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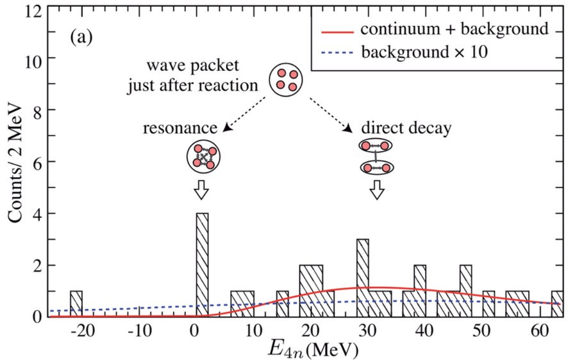

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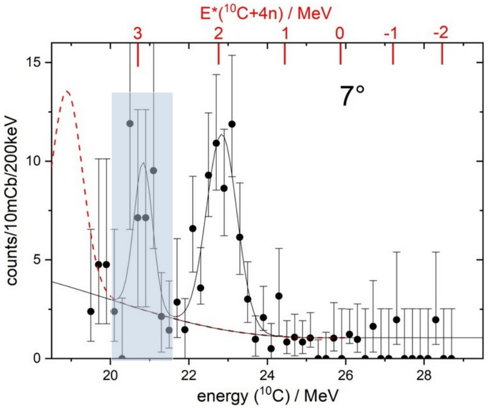

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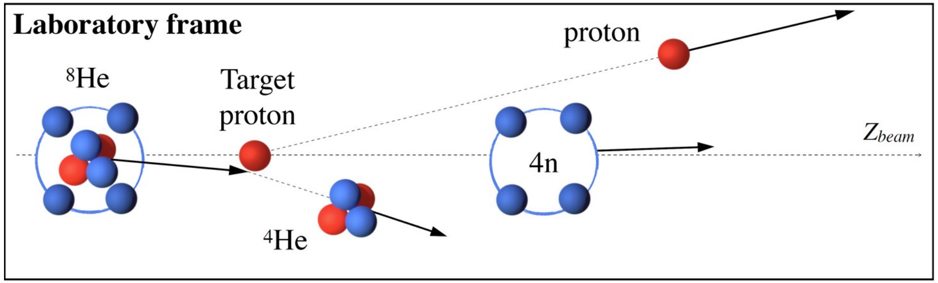
Present experimental work

TECHNISCHE UNIVERSITÄT DARMSTADT

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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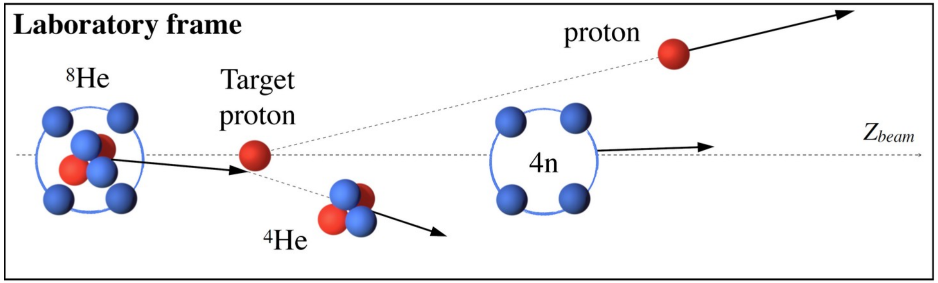

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  - pronounced α-core structure
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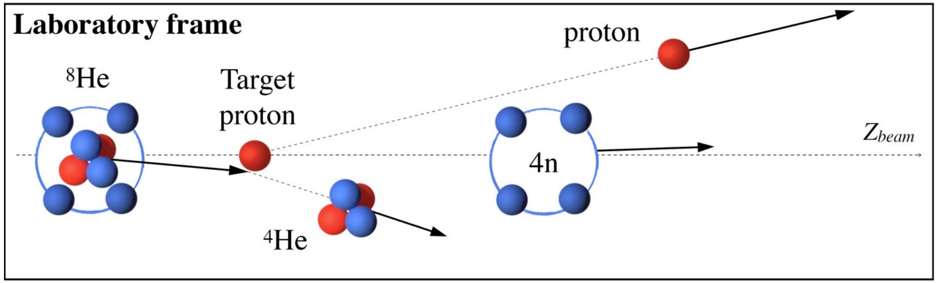

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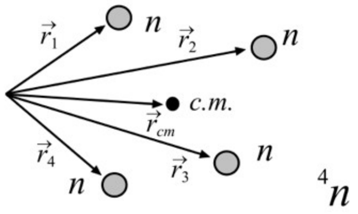
"sudden removal of an α-particle from ^{8}He"

- Five-body (^{4}He+4n) COSMA model:
  - initial structure (^{8}He)
  - reaction mechanism
  - + final-state interaction (FSI)
    overlap probability ~30%



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

Present experimental work

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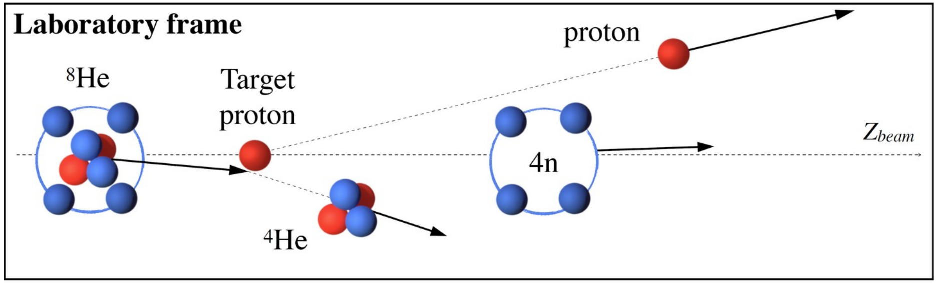
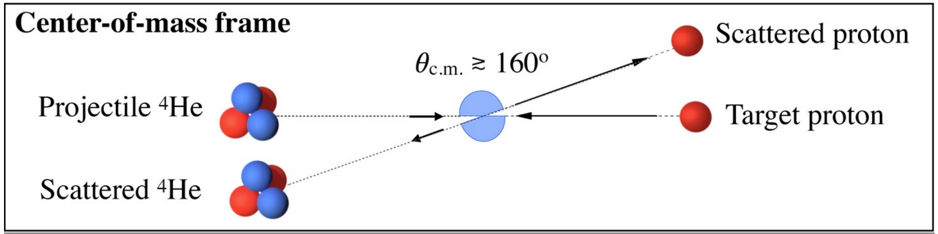
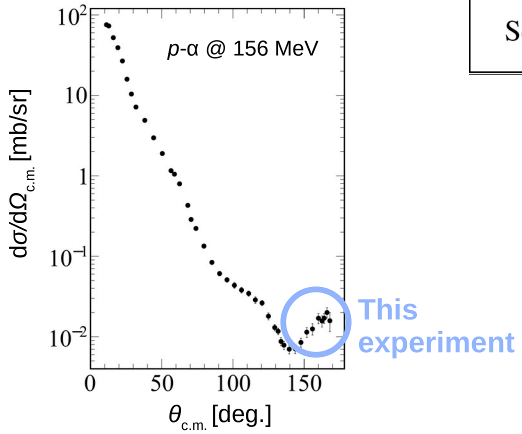
Method: $^{8}He(p,p^{4}He)$ quasi-elastic knockout

- High-energy 156 MeV/nucleon
- 4n energy spectrum via missing mass: precise measurement of **charged particles**
- Large momentum transfer
  - “recoil-less” production
- p-α elastic scattering known

  V. Comparat et al., PRC (1975)







RIKEN: ^{18}O campaign at SAMURAI

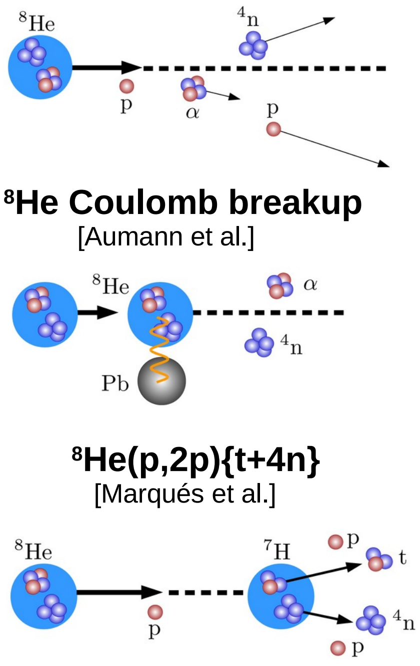
❶ Superconducting Ring Cyclotron (SRC)

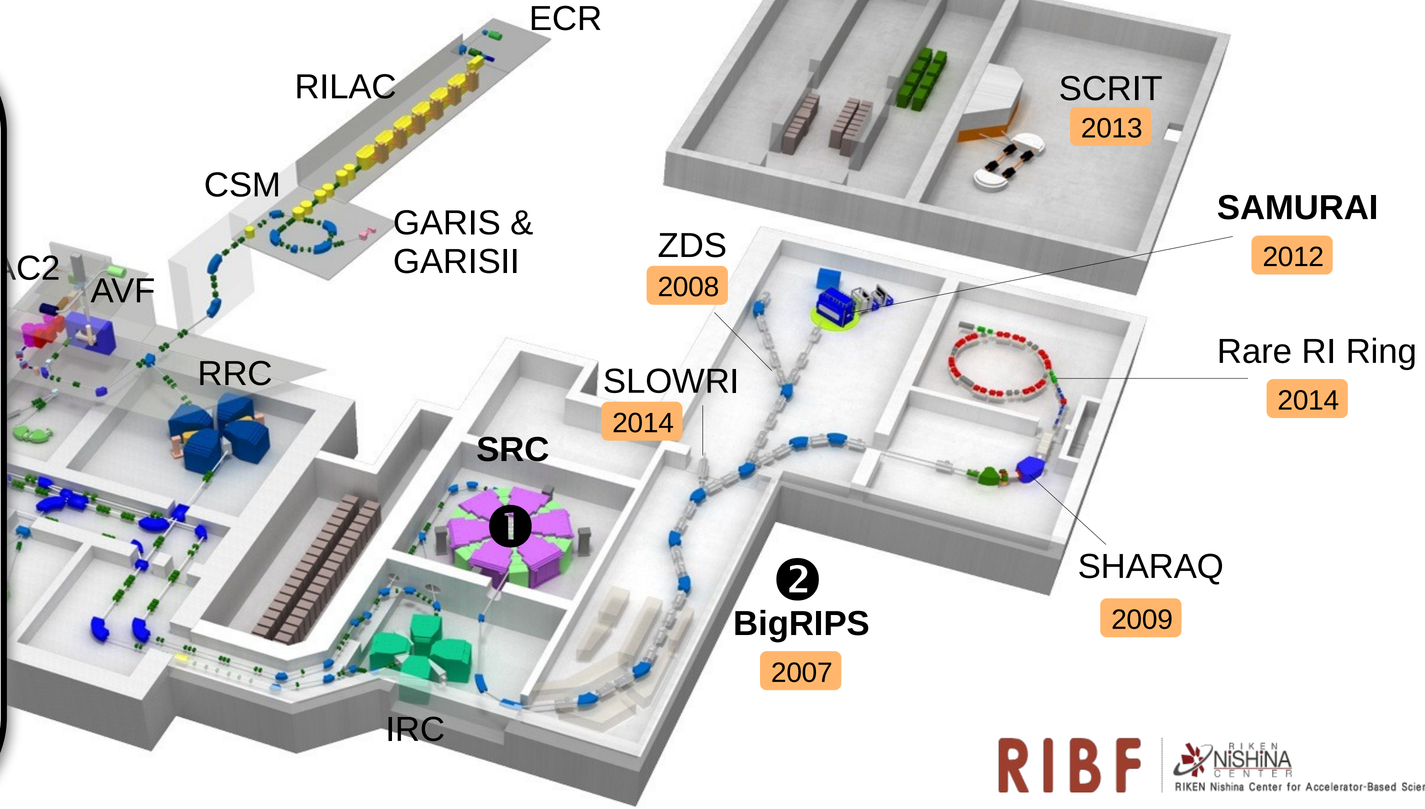
- primary ^{18}O beam

^{8}He(p,p^{4}He)
[Paschalis et al.]

^{8}He Coulomb breakup
[Aumann et al.]

^{8}He(p,2p){t+4n}
[Marqués et al.]





RIKEN: ^{18}O campaign at SAMURAI

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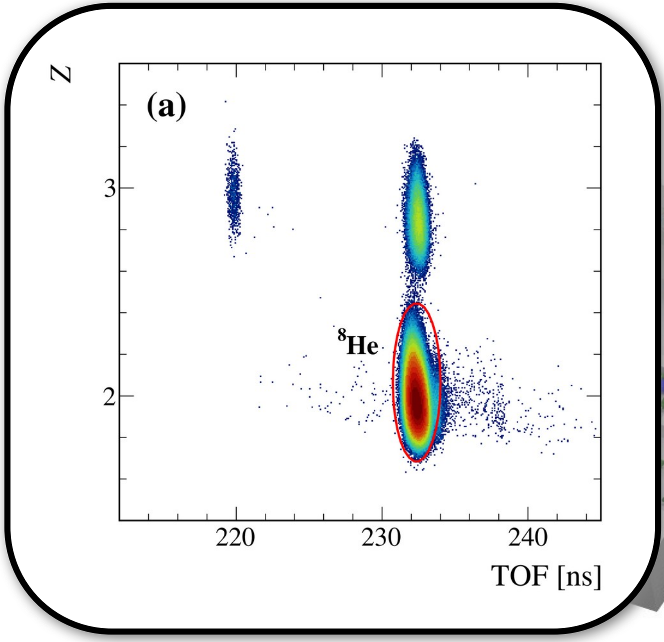
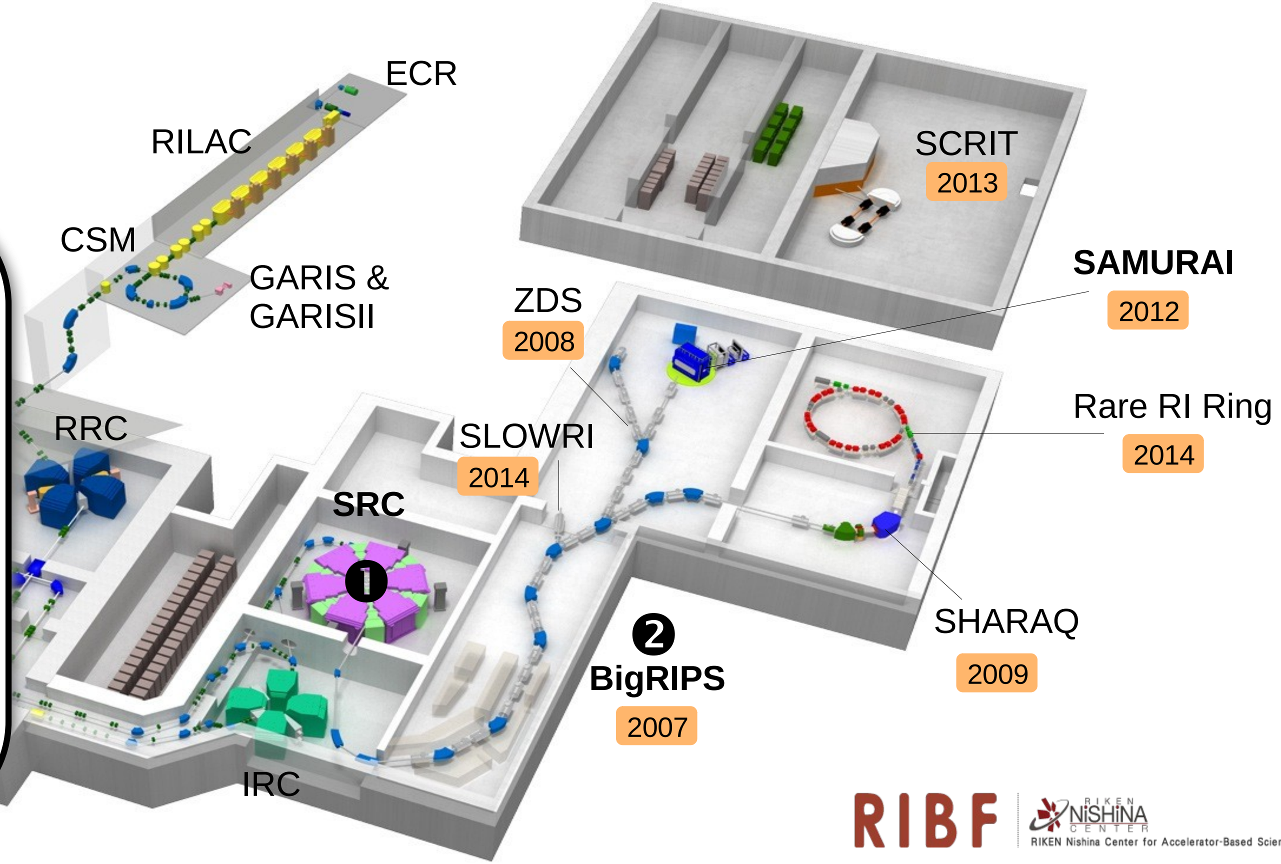
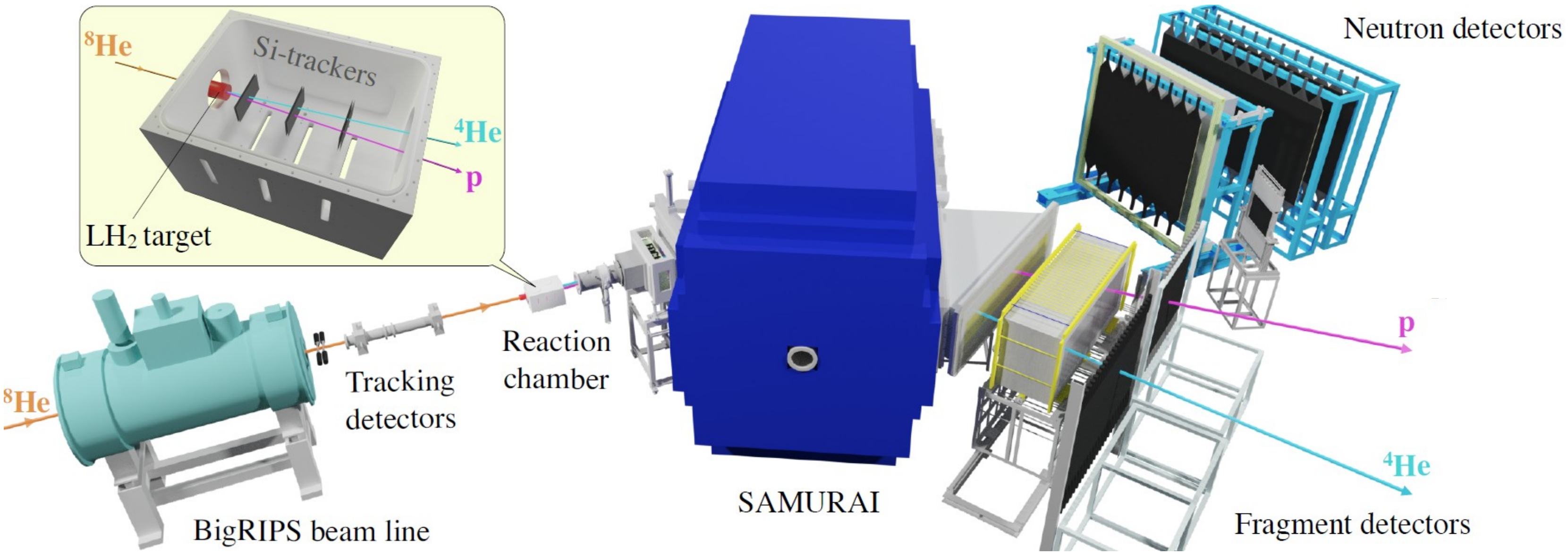
- primary ^{18}O beam

❷ BigRIPS fragment separator
- secondary ^{8}He beam



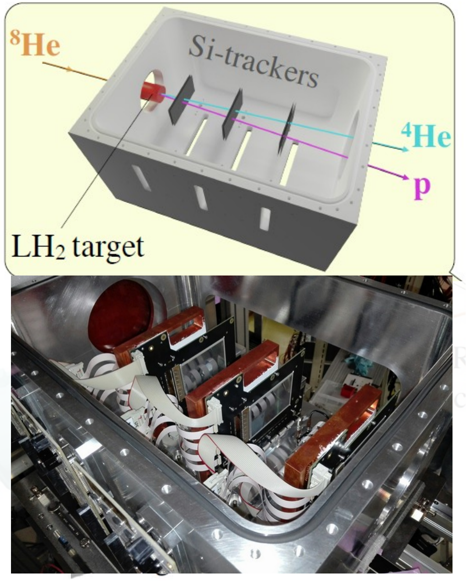


Experimental setup

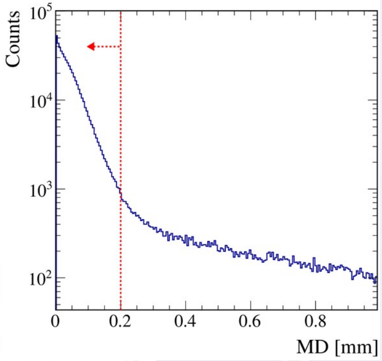


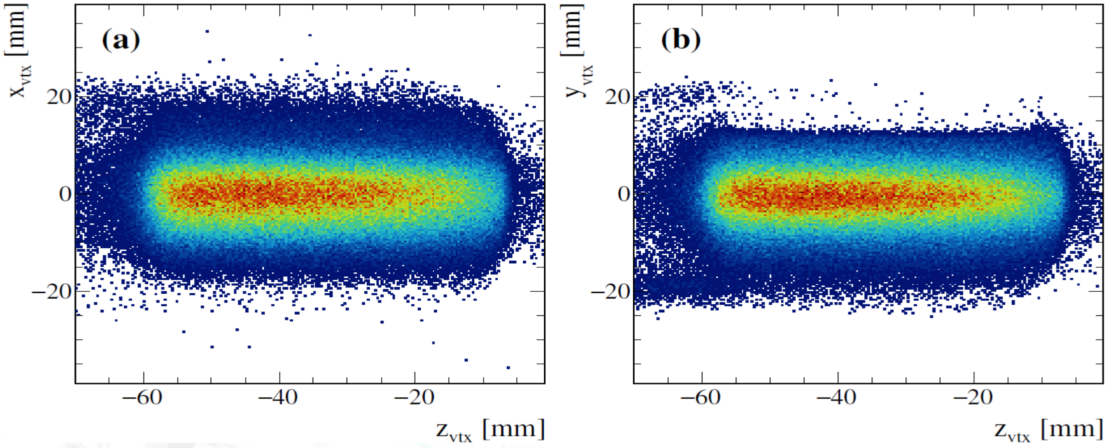
A dedicated silicon tracker

minimum distance → reaction vertex reconstruction



100 µm thick strips





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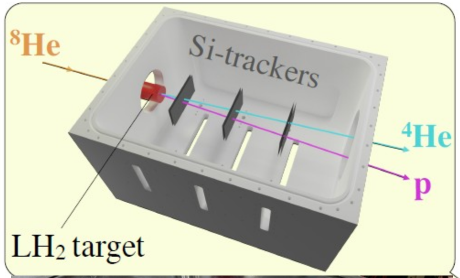

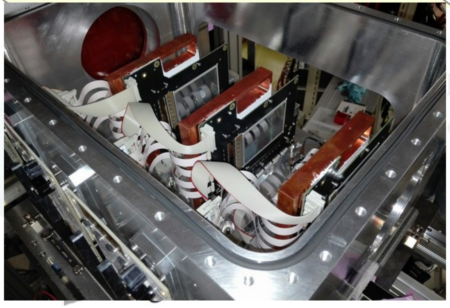

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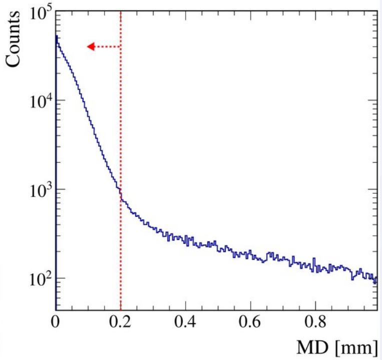

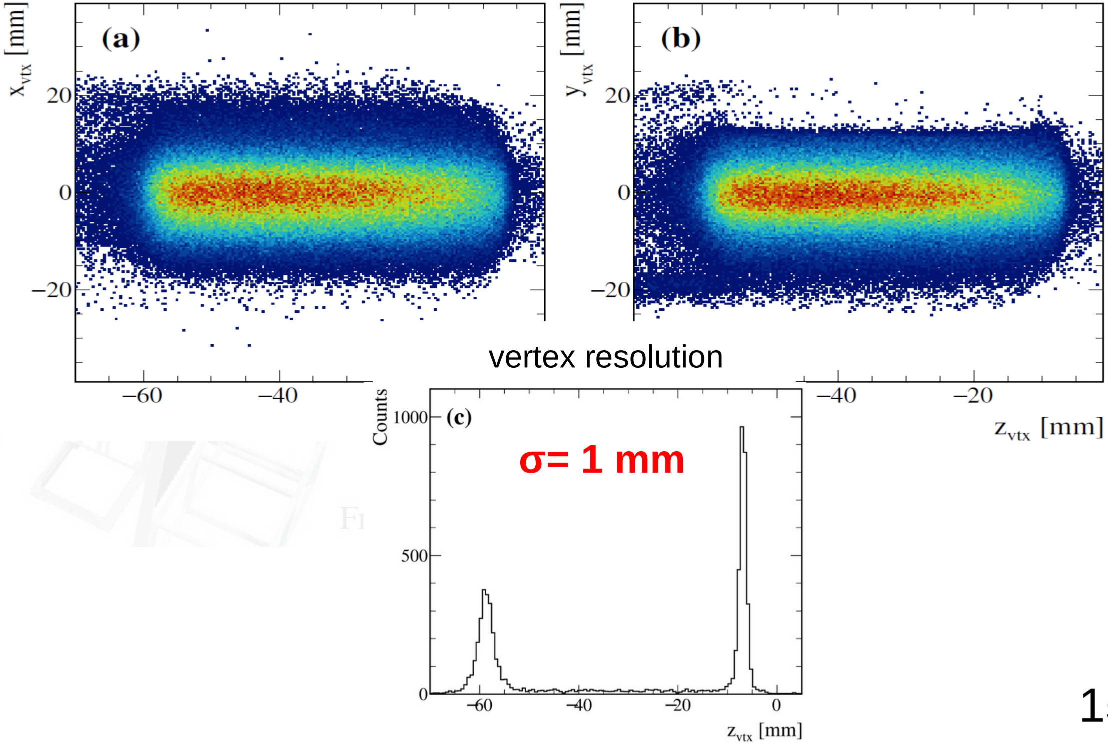

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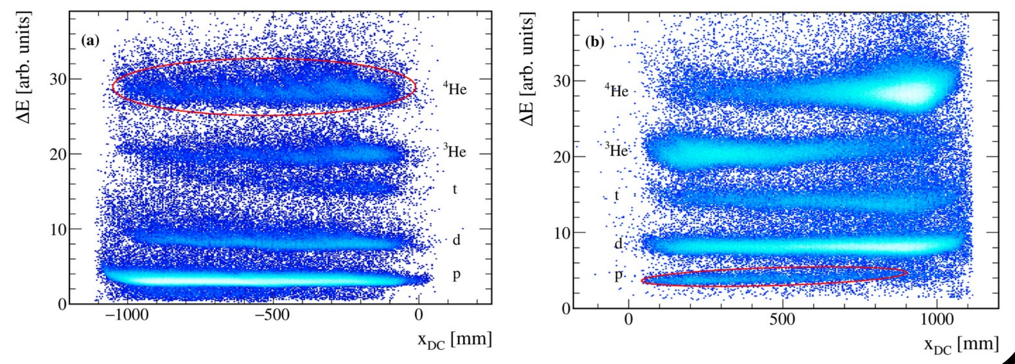

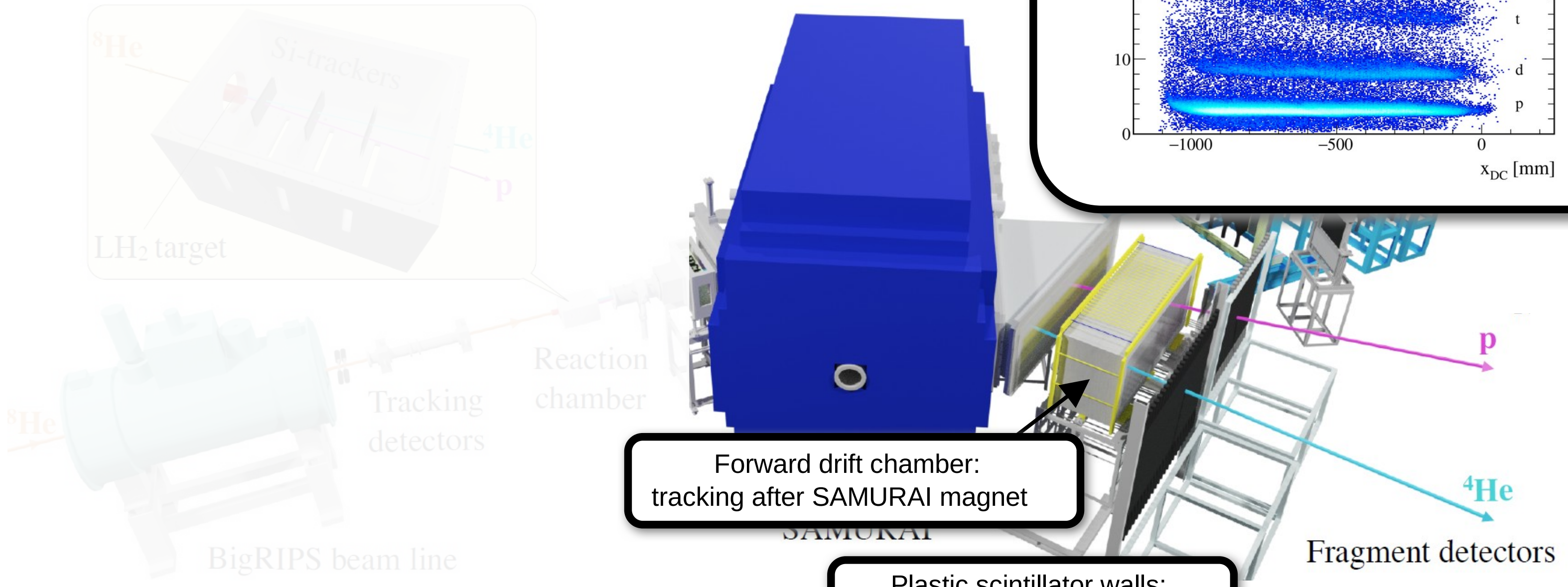

Forward drift chamber:
tracking after SAMURAI magnet

Plastic scintillator walls:
energy-loss and TOF

Experimental setup

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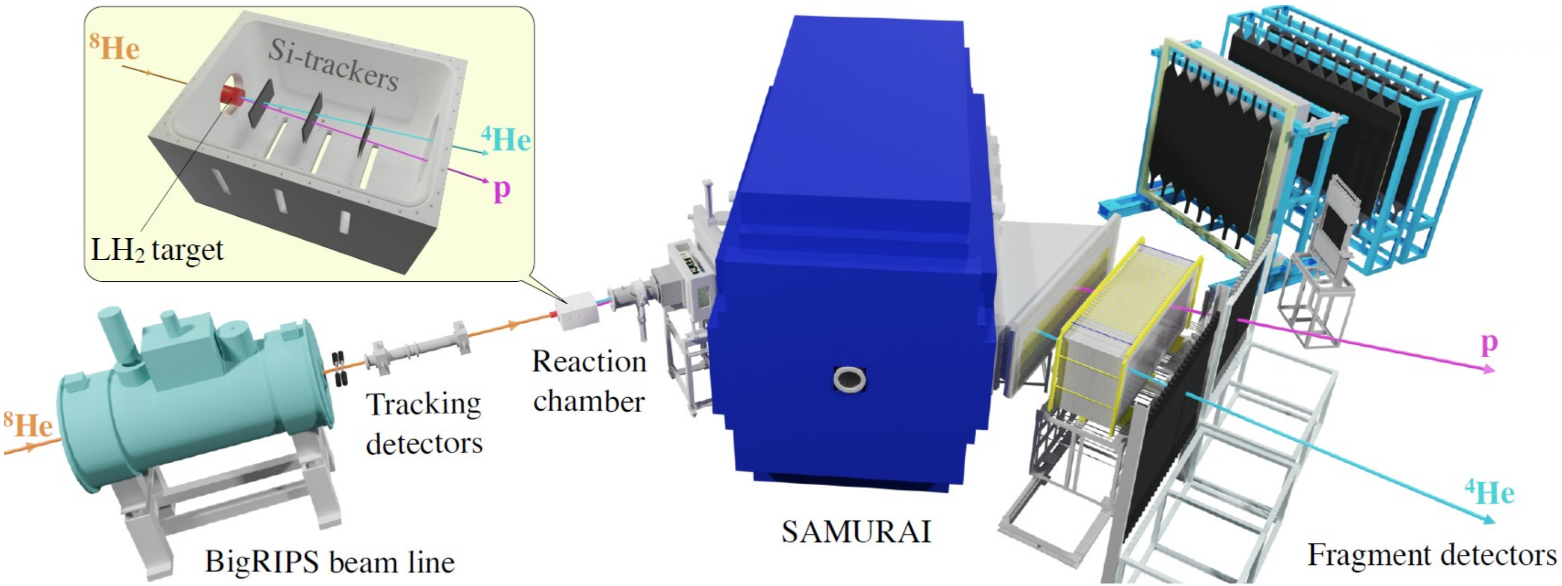
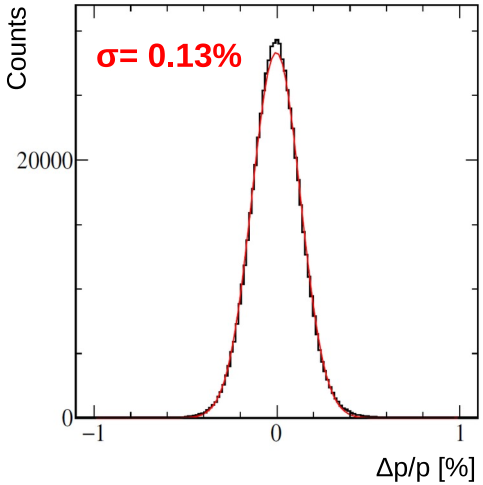


relative momentum precision



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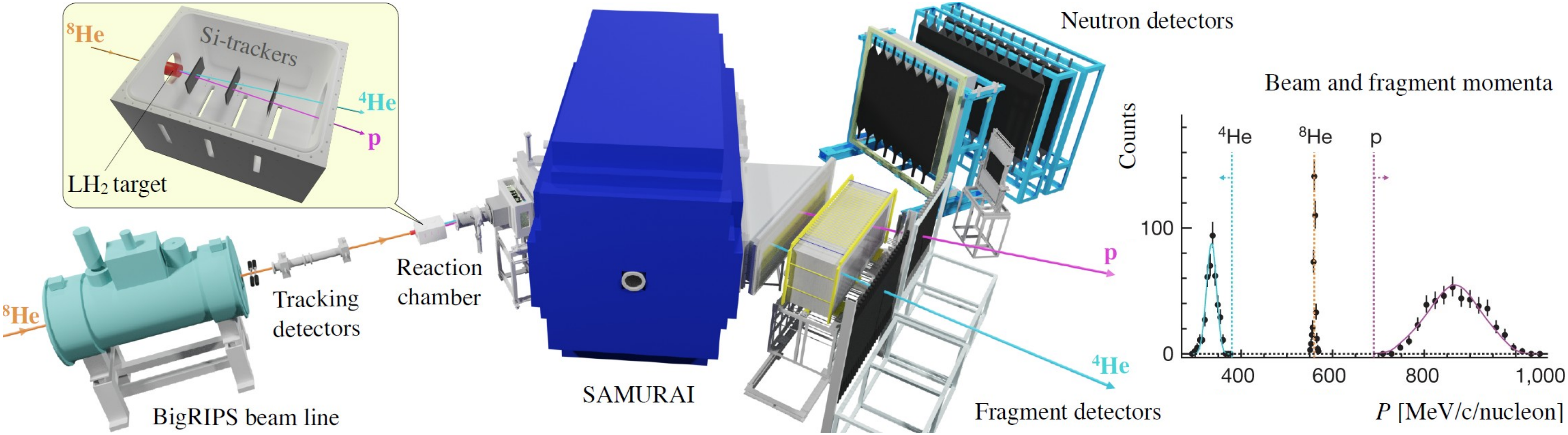
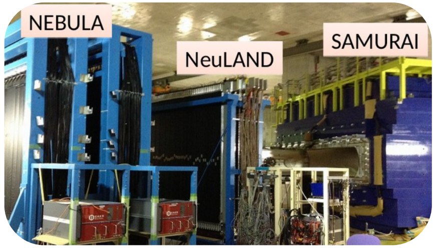


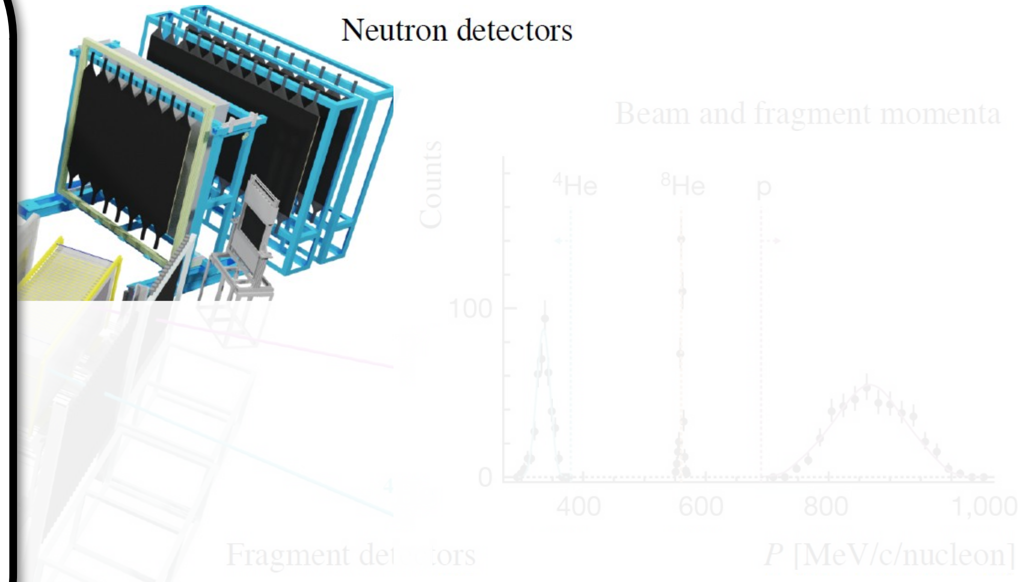
SAMURAI

Experimental setup

NeuLAND demonstrator (R^{3}B/GSI) +NEBULA

Successful experimental campaign (2015-2017)





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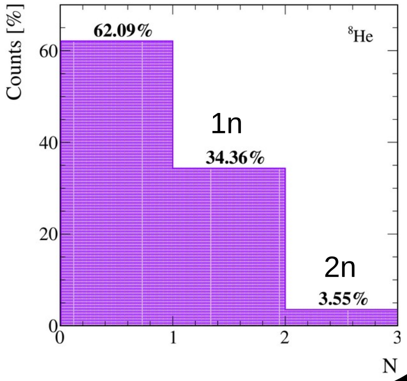
small p-^{4}He cross section ~1 µb

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



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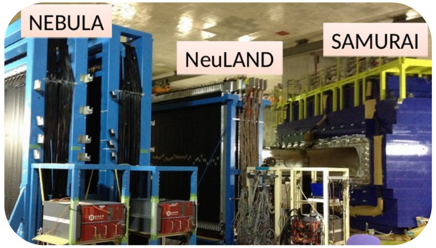

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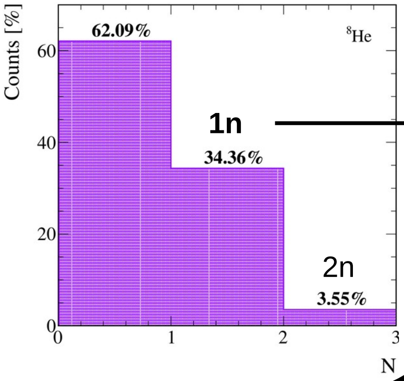
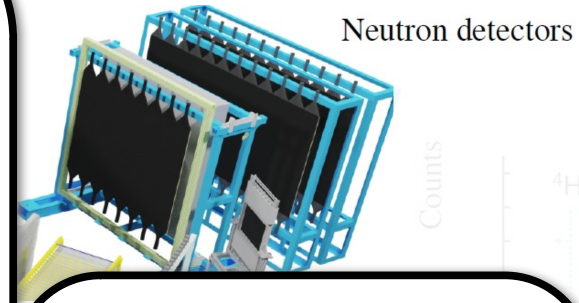
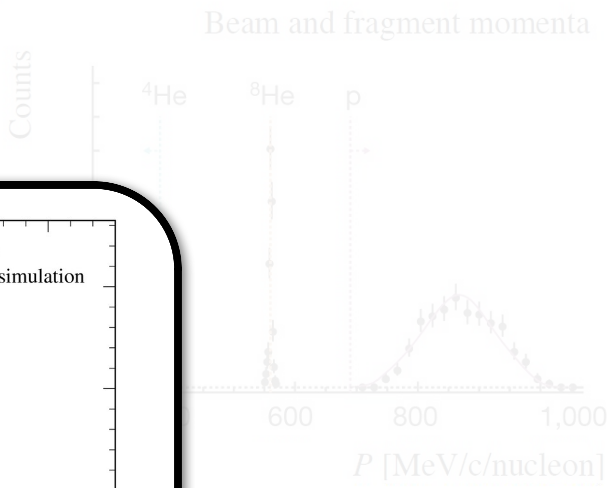
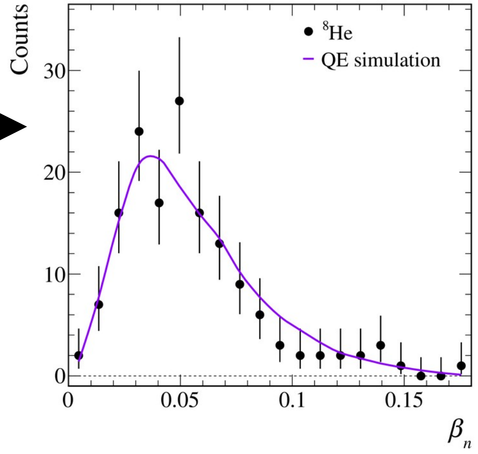




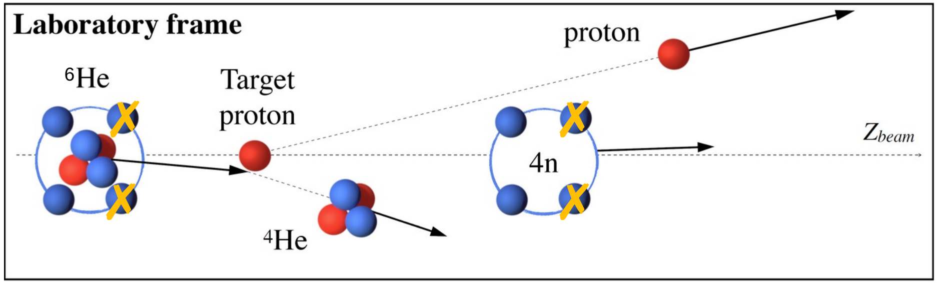




Benchmark measurement

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

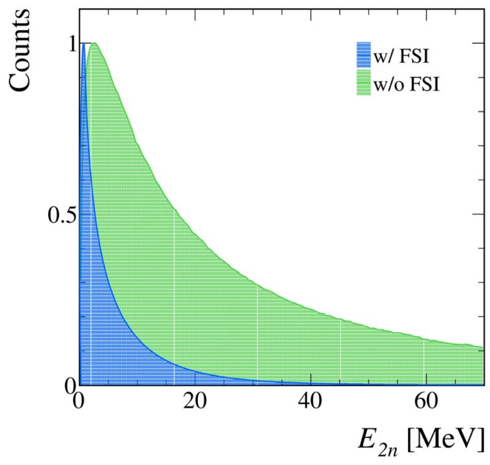
- Two-neutron relative-energy spectrum is expected to be well described by thoery
- Di-neutron is known to be unbound by ~100 keV



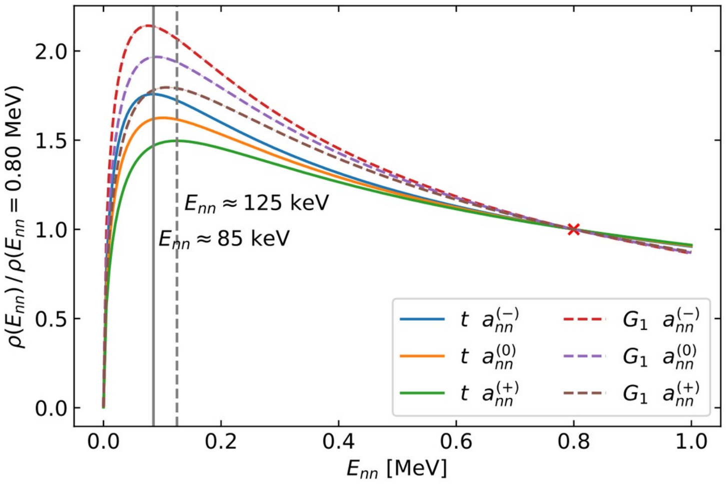
Theoretical input:

- **w/o FSI:** three-body (^{4}He+2n) cluster model for ground-state wavefunction
- **w/ FSI:** + nn final-state interaction

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



Interlude: neutron-neutron scattering length



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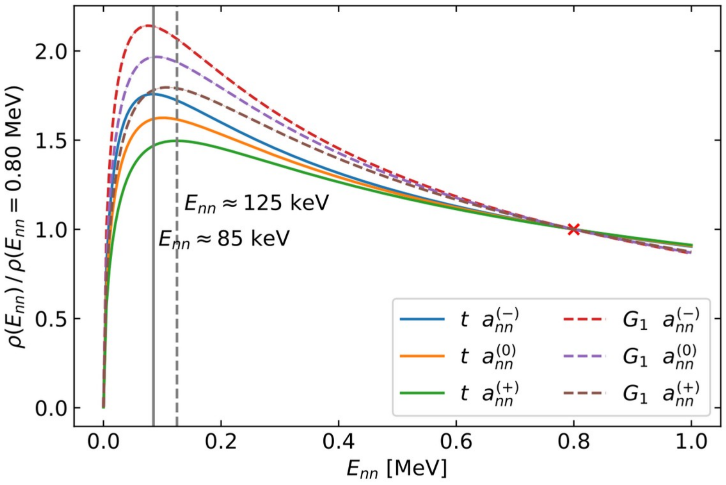

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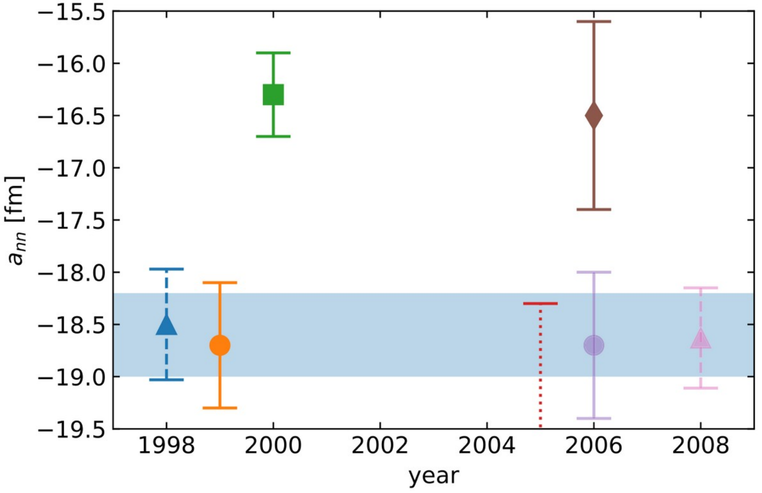
experimental data



dashed: $d + \pi^- \rightarrow \gamma + n + n$
solid: $d + n \rightarrow p + n + n$
dotted: $d + d \rightarrow {}^2\text{He} + n + n$

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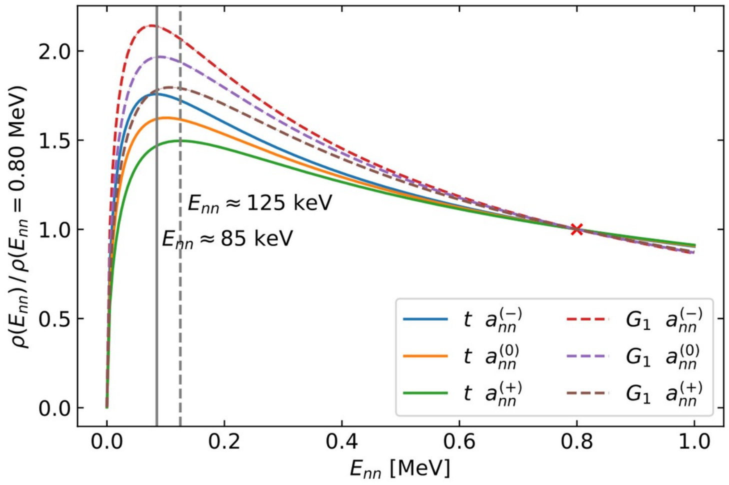

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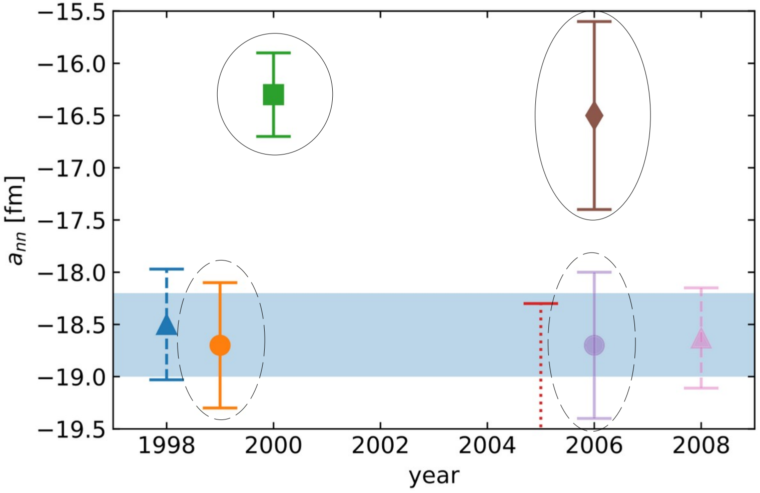

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Bonn
TUNL

Interlude: neutron-neutron scattering length

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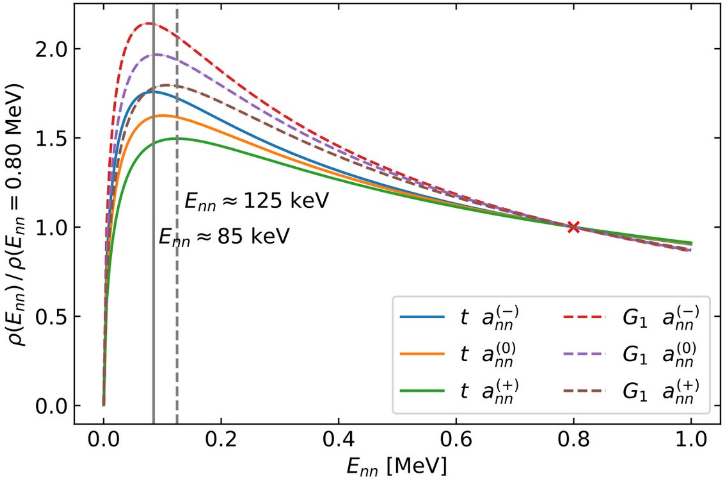

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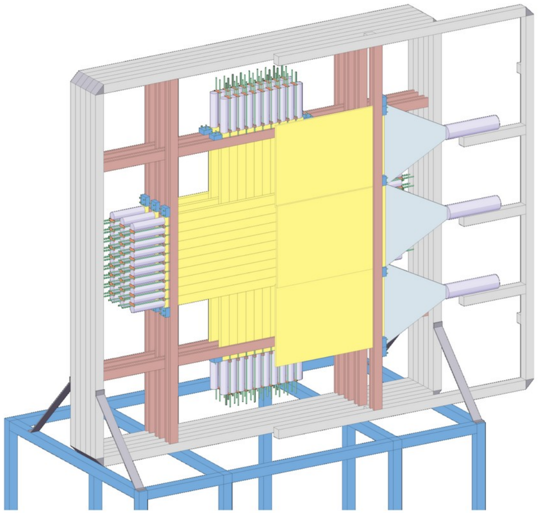
Determination of the nn scattering length

[T. Aumann et al., NP2012-SAMURAI55R1]

HIME: HIgh-resolution detector for Multi-neutron Events

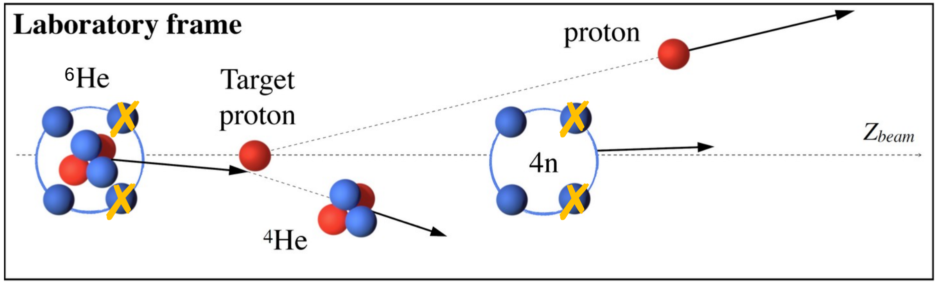
- 100 (length) X 4 (width) X 2 (depth) cm^3 bars
- Demonstrator 40X40 cm^2 (T. Nakamura et al.)
- Full detector 100X100 cm^2 (being built at TUDa)
- Resolution:
  - timing: 100 ps (rms)
  - energy: **better than 25 keV** (for E_{nn}<100 keV)
- Goal: overall uncertianty of ~1%
  - **determination of a_{nn} within $\pm$0.2 fm**



Benchmark measurement

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

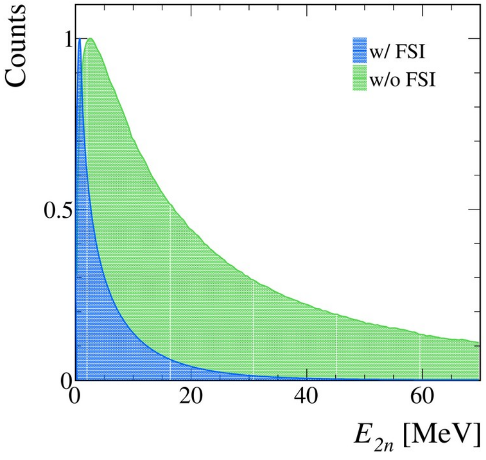
- Two-neutron relative-energy spectrum is expected to be well described by thoery
- Di-neutron is known to be unbound by ~100 keV



Theoretical input:

- **w/o FSI:** three-body (^{4}He+2n) cluster model for ground-state wavefunction
- **w/ FSI:** + nn final-state interaction

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



Simulation of quasi-elastic reaction

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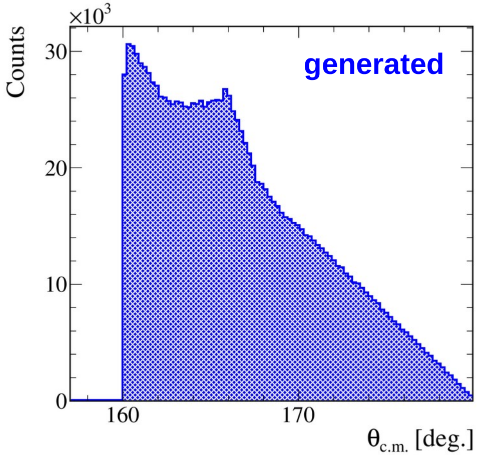
❶ Generate QE $^{6}He(p,p^{4}He)$ events

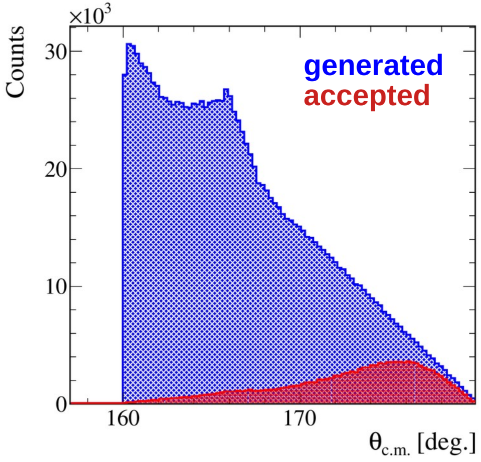


② Run through full detector simulation

③ Smear simulated data by internal resolutions

④ Analyze same way as experimental data

Simulation of quasi-elastic reaction



❶ Generate QE $^{6}He(p,p^{4}He)$ events

❷ Run through full detector simulation

❸ Smear simulated data by internal resolutions

❹ Analyze same way as experimental data

Simulation of quasi-elastic reaction

TECHNISCHE UNIVERSITÄT DARMSTADT

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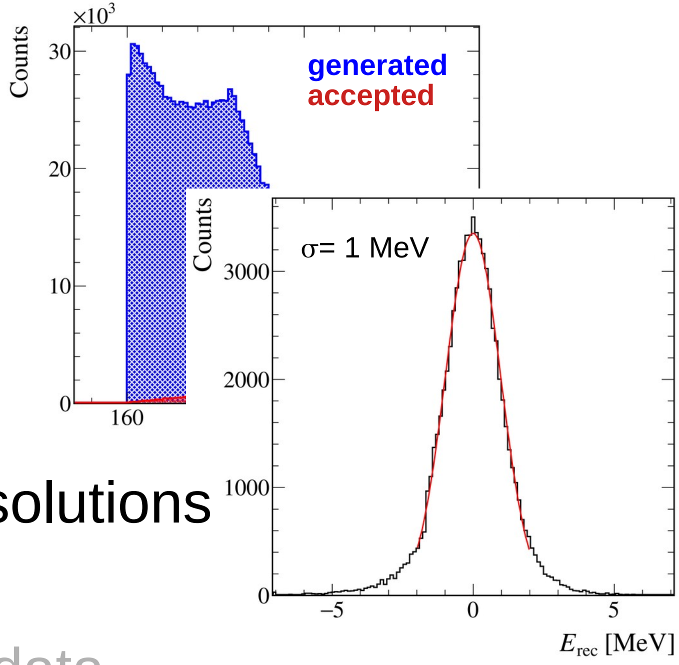

Simulation of quasi-elastic reaction

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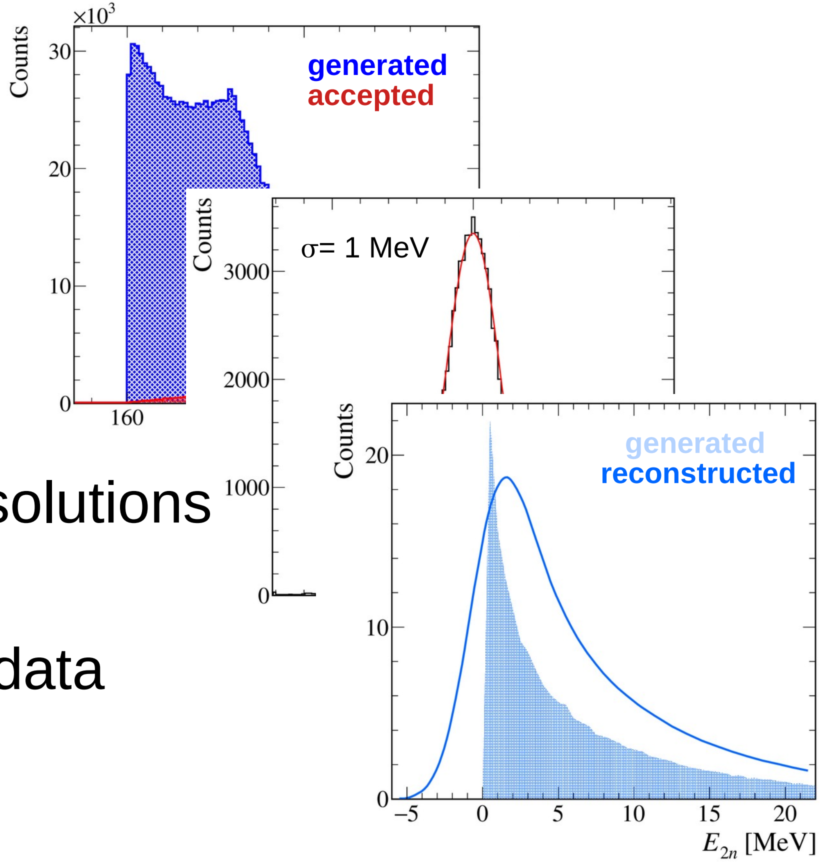
❶ Generate QE $^{6}He(p,p^{4}He)$ events

❷ Run through full detector simulation

❸ Smear simulated data by internal resolutions

❹ Analyze same way as experimental data



Results: ^{6}He missing mass spectrum

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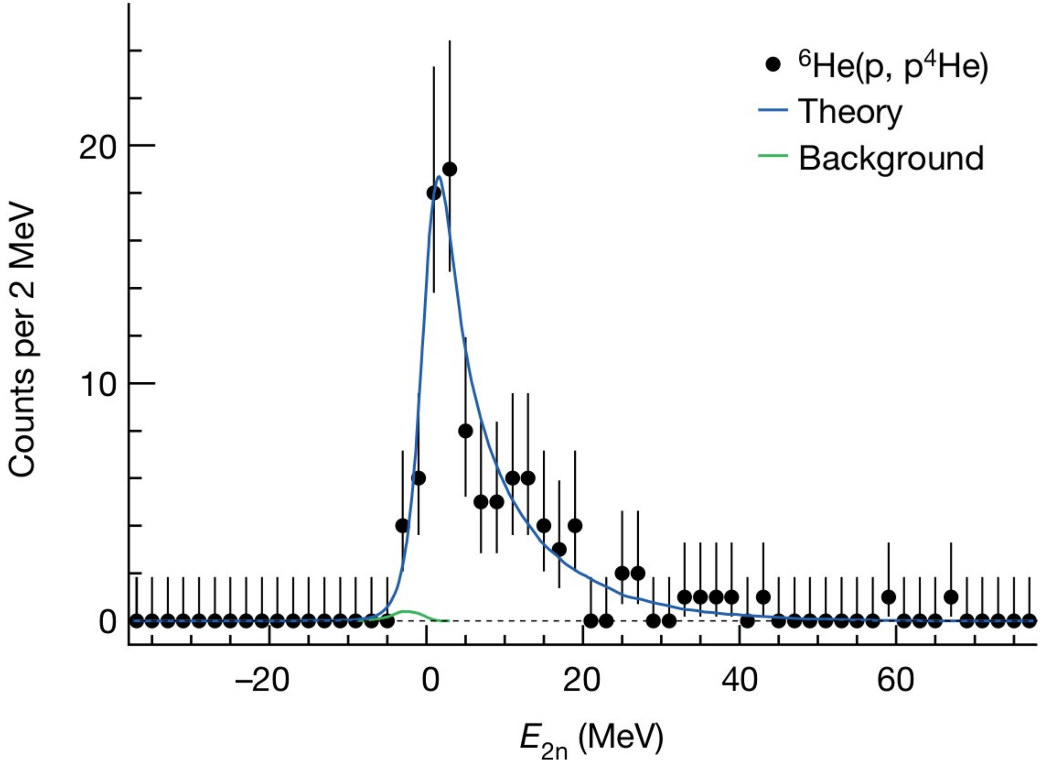
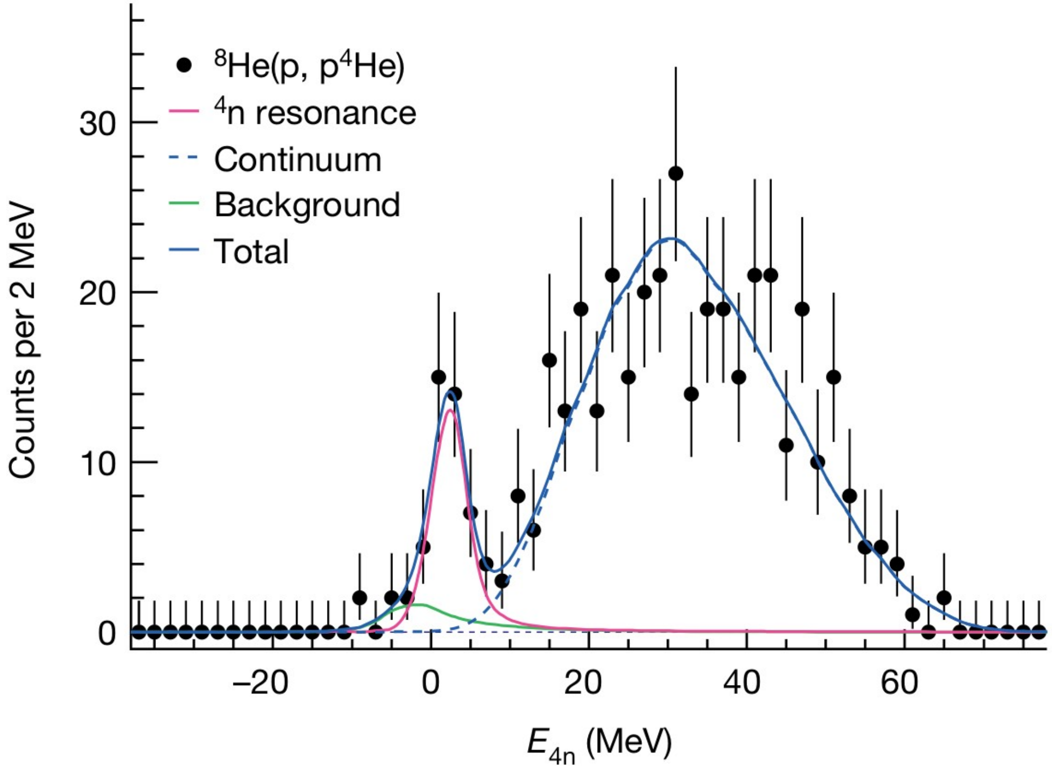


MD et al., Nature 606, 678 (2022)

- Very good agreement:
  - confirms the expected di-neutron low-energy peak ~100 keV
  - systematic uncertainty - 0.4 MeV (energy) 0.3 MeV (width)
- No events in unphysical region
- Very low background contribution ~1%

Results: ^{8}He missing mass spectrum

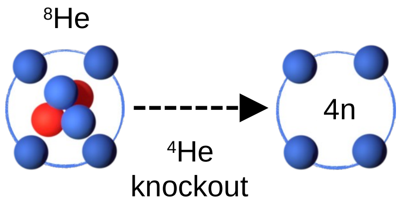


MD et al., Nature 606, 678 (2022)

Two components:

- low-energy peak !
- broad distribution at higher energies – continuum from direct decay

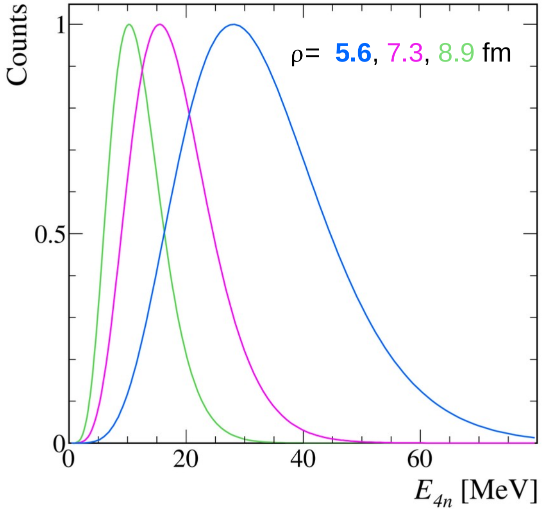
Direct decay part

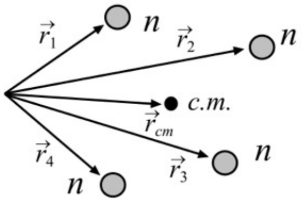


Four-body continuum response

- Five-body (^{4}He+4n) COSMA model:
  - source term depends on ^{8}He strcuture
  - sensitive to the hyperradius ρ
    - **5.6 fm reproduces ^{8}He radius**
    - wide distribution centered ~30 MeV

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

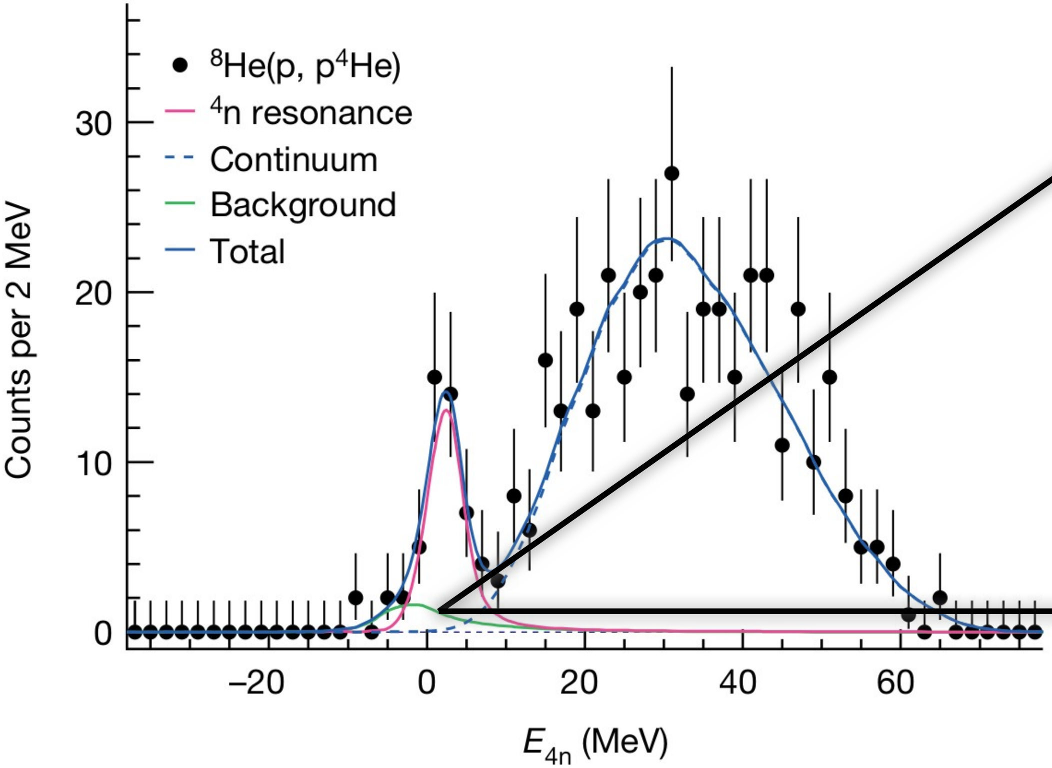


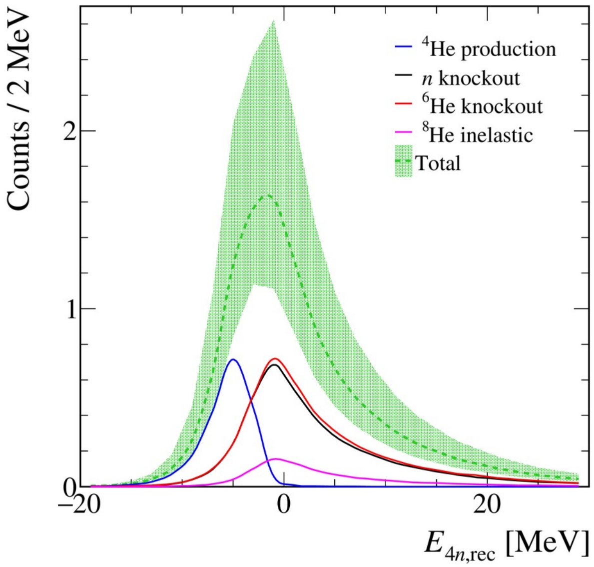


^4n

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

Background contribution





* total contribution of 2.6%

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

Background contribution

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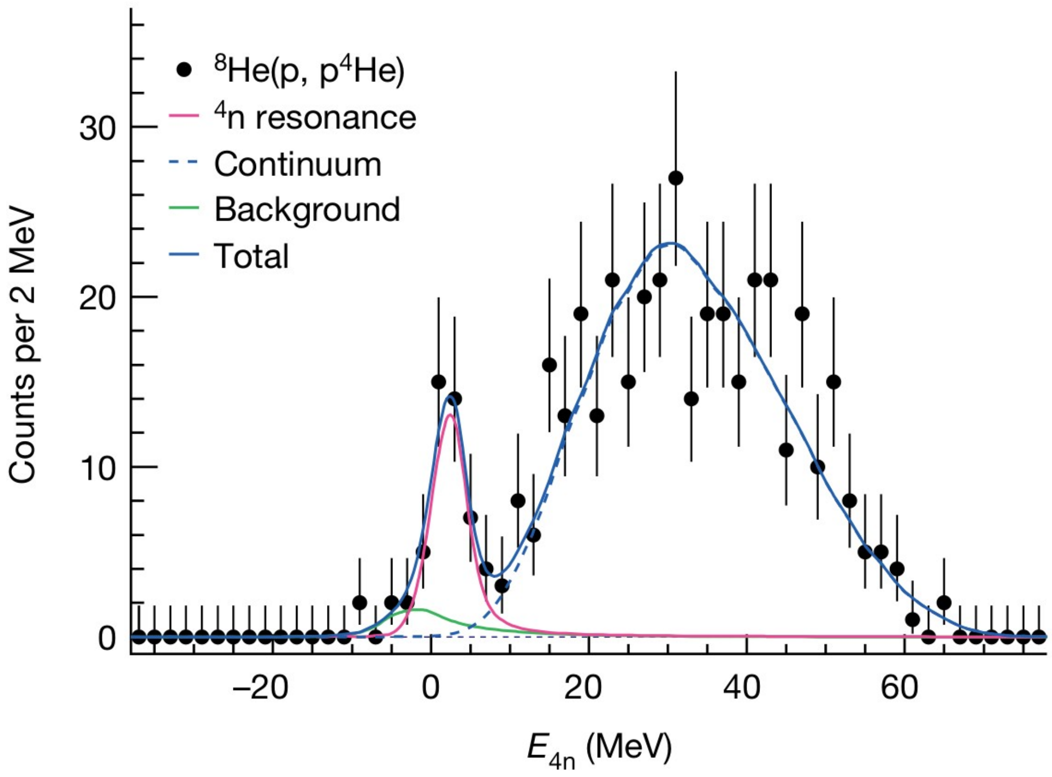
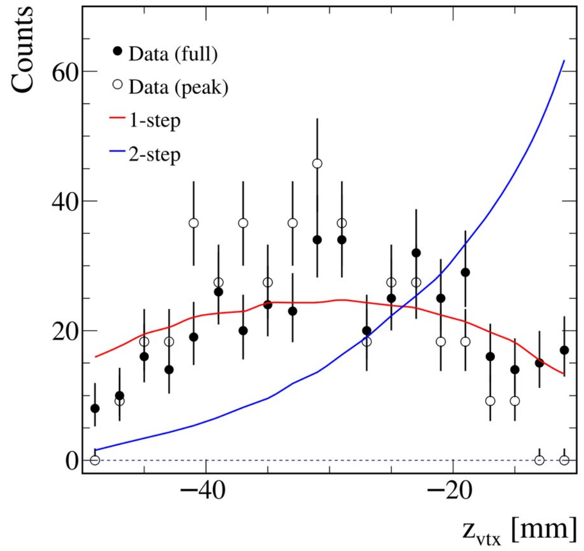


MD et al., Nature 606, 678 (2022)

One-step vs. two-step reactions



Results: ^{8}He missing mass spectrum

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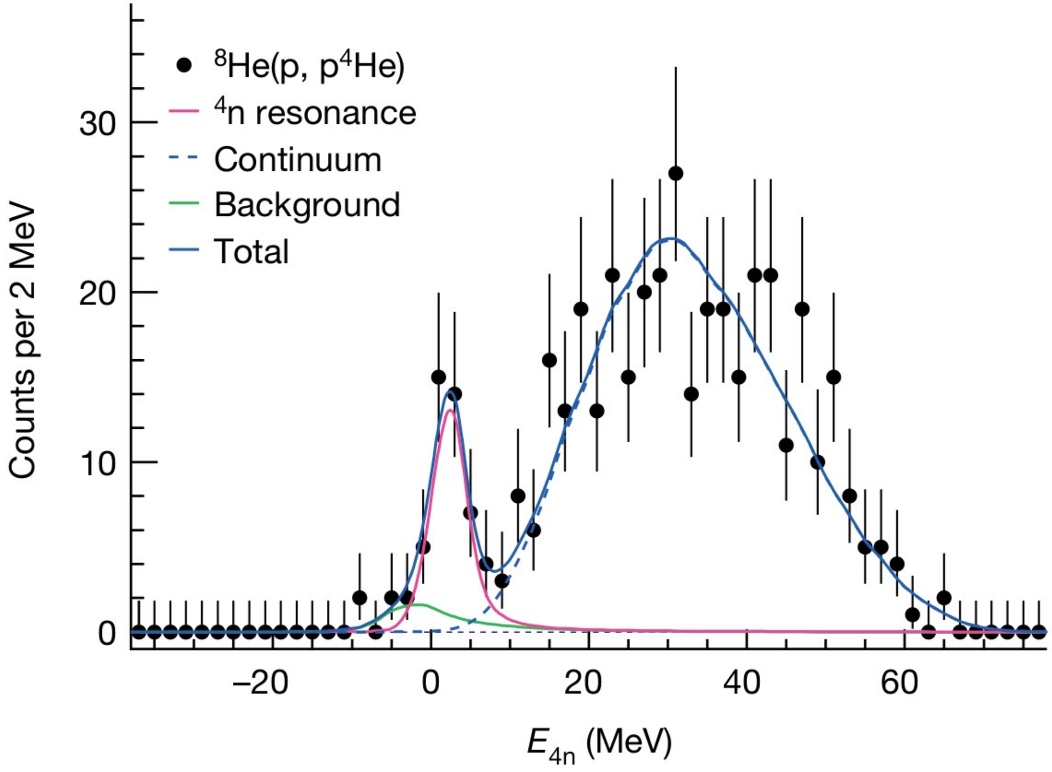

MD et al., Nature 606, 678 (2022)

- Fit energy spectrum with continuum from direct decay & experimental background
- **Resonance like-structure** consistent with a tetra-neutron state near threshold

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

  Γ = 1.75±0.22(stat.)±0.30(sys.) MeV

- Low-energy peak with significance well beyond 5σ

What do theories say ?

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DARMSTADT

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

PHYSICAL REVIEW LETTERS
week ending
27 JUNE 2003

Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?

Steven C. Pieper*

"our current very successful understanding of nuclear forces would have to be severly modified in ways that, at least to me, are not at all obvious"

What do theories say ?

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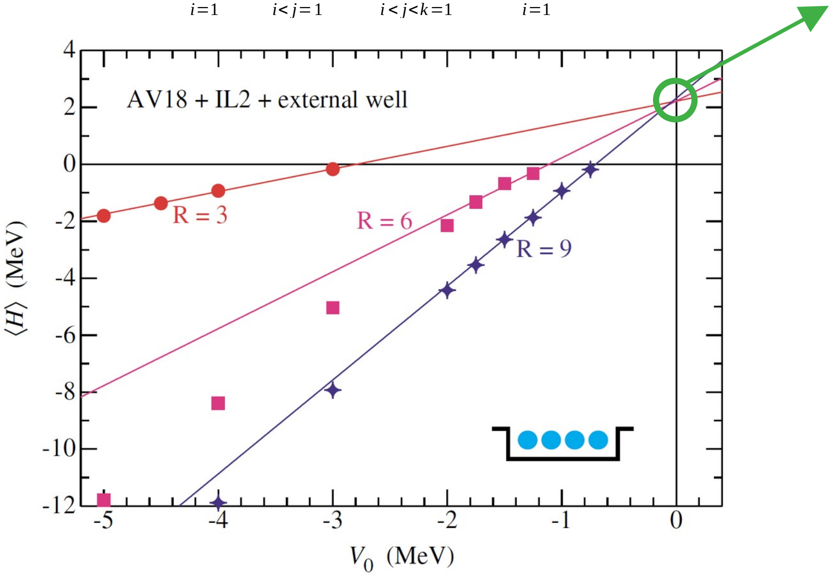
Overall consensus: **no bound tetra-neutron**

What about a resonance?

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



"there might be a ^{4}n resonance near 2 MeV, ... must be very broad"

S. Pieper, PRL 90 (2003)

What do theories say ?

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

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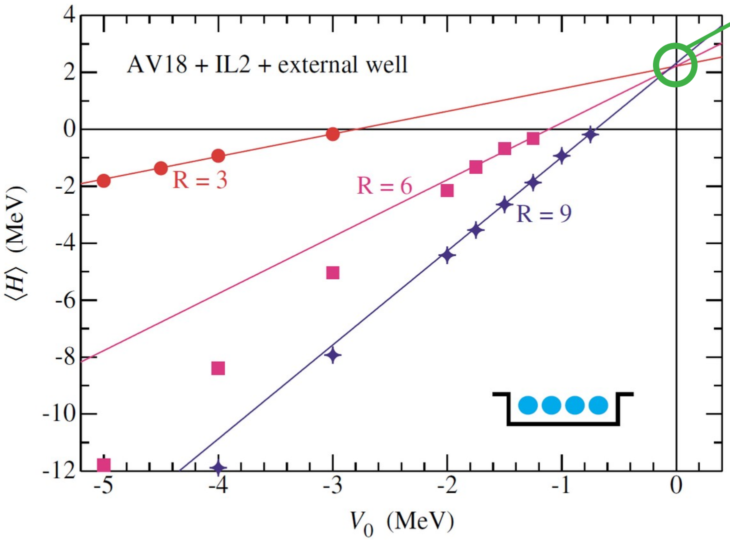


S. Pieper, PRL 90 (2003)

"there might be a ^{4}n resonance near 2 MeV, ... must be very broad"

Predictions for a resonance:

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

No resonant state:

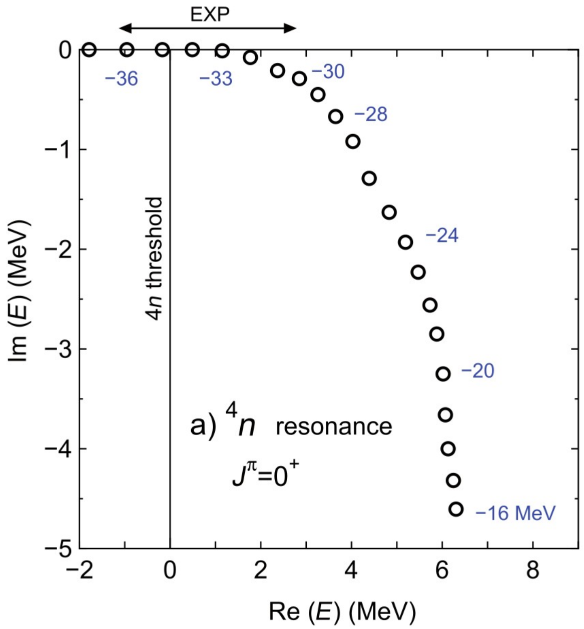
Sofianos JPG 23 (1997); Deltuva PRL 123 (2019);
Hiyama PRC 93 (2016); Lazauskas PTEP 073 (2017); 3-body force (T=3/2)
Lazauskas PRC 72 (2005); 4-body force
Deltuva PLB 782 (2018); Higgins PRL 125 (2020); QM enhancements
...

What do theories say ?

TECHNISCHE UNIVERSITÄT DARMSTADT

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

What about a resonance?



- AV8 NN interaction + phenomenological 3-body force:

$$V_{ijk}^{3N} = \sum_{T=1/2}^{3/2} \sum_{n=1}^{2} W_n(T) \exp\left(-(r_{ij}^2 + r_{jk}^2 + r_{ki}^2)/b_n^2\right) \mathcal{P}_{ijk}(T),$$

with $T = 1/2$, $T = 3/2$ and strength parameters: W_1 (attractive) W_2 (repulsive)

- Adjust only the attractive $W_1(T = 3/2)$ channel
  - ➔ **huge strength parameter** $W_1 \in [-36, -30]\,\text{MeV}$
  - ➔ 15 times larger than for $T = 1/2$, $-2.04\ \text{MeV}$
  - ➔ inconsistent with data of light nuclei

Lazauskas et al., PTEP 073 (2017)

What do theories say ?

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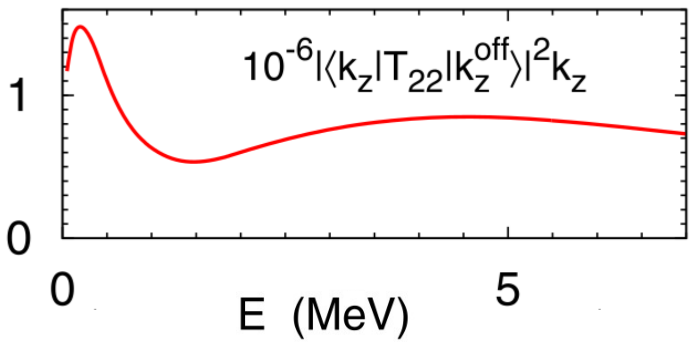
Overall consensus: **no bound tetra-neutron**

What about a resonance?

Rigorous continuum calculation:

- AGS equations in momentum-space
- transition operator method for the 4→4 process
  - absence of any ^{4}n resonance
  - **low-energy enhancement** of some $T_{\beta\alpha}$ transition operators
- might explain the signal in ^{8}He(^{4}He,^{8}Be) reaction? (RIKEN 2016)
- depends on the specific kinematical configuration



Deltuva, PLB 782 (2018)

Experiment - theory comparison

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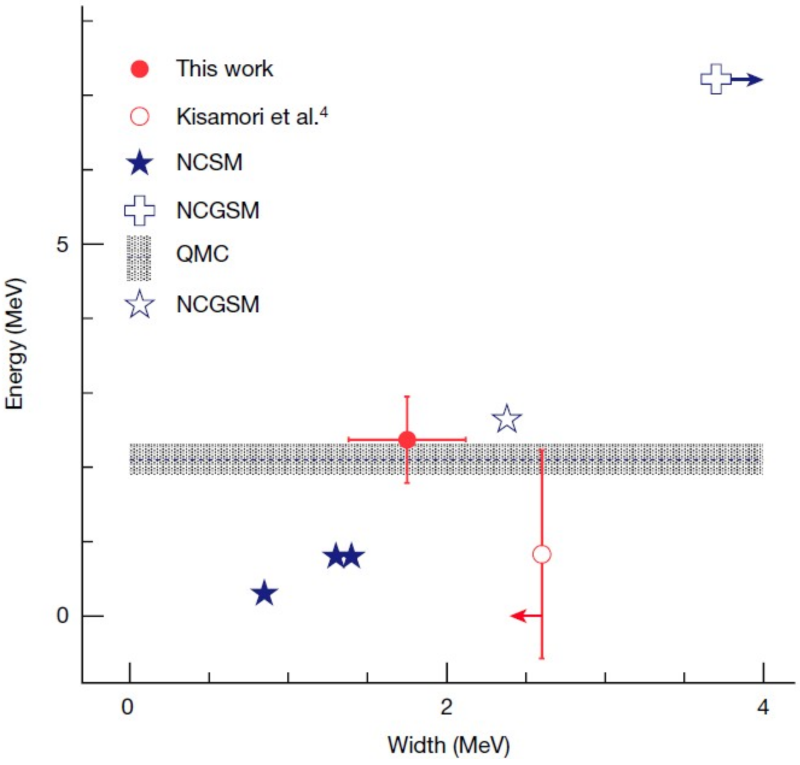

MD et al., Nature 606, 678 (2022)

Predictions for a resonance:

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- No-core Gamow shell model (NCGSM): Fossez PRL 119 (2017)
- Quantum Monte Carlo (QMC): Gandolfi PRL 118 (2017)
- ☆ NCGSM: Li PRC 100 (2019)

Pieper PRL 90 (2003): *"might be a ^{4}n resonance near 2 MeV... must be very broad"*

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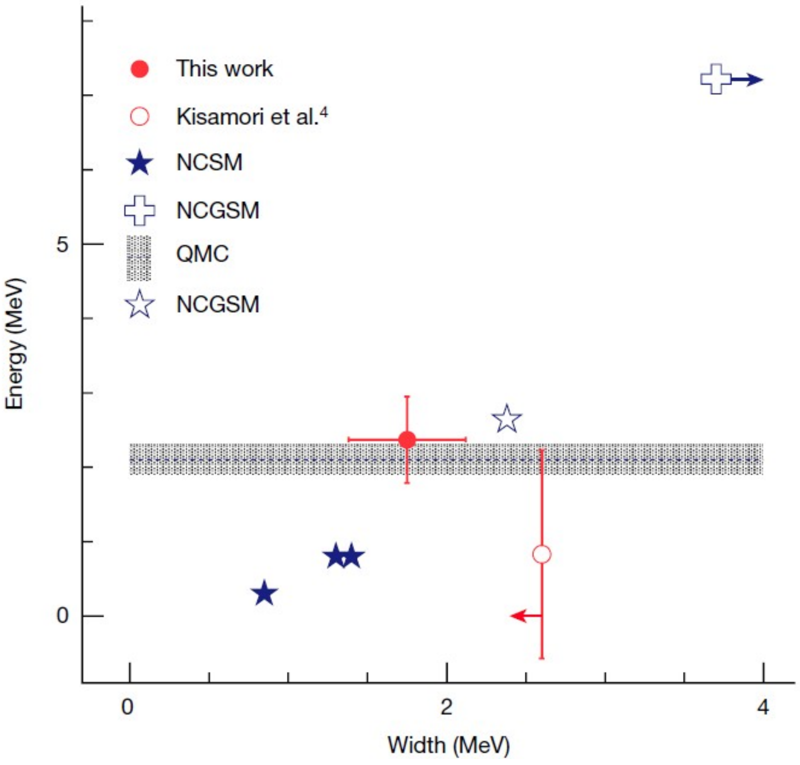

MD et al., Nature 606, 678 (2022)

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Lazauskas PRC 72 (2005); 4-body force

Deltuva PLB 782 (2018); Higgins PRL 125 (2020); QM enhancement

...

- Further calculations are needed to understand the low-energy peak observed and its origin

Article

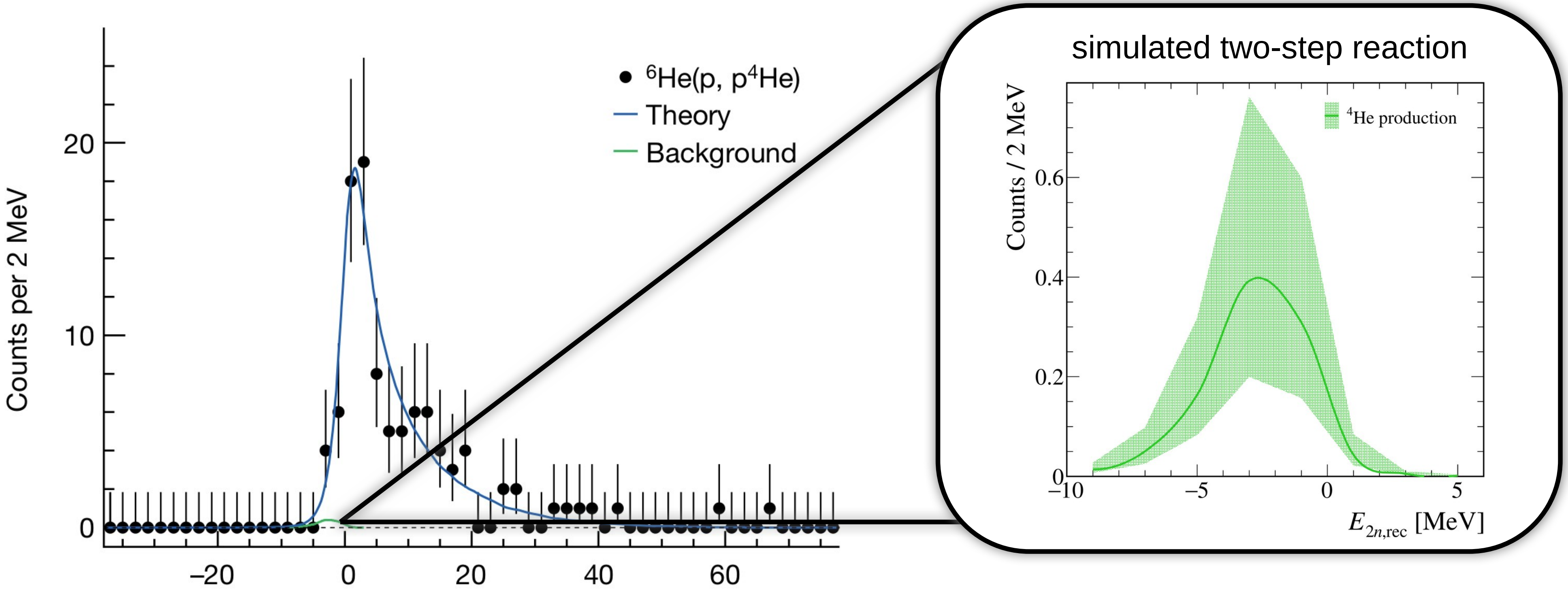
Observation of a correlated free four-neutron system

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]

678 | Nature | Vol 606 | 23 June 2022

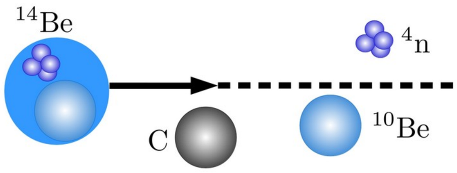
Thank you!

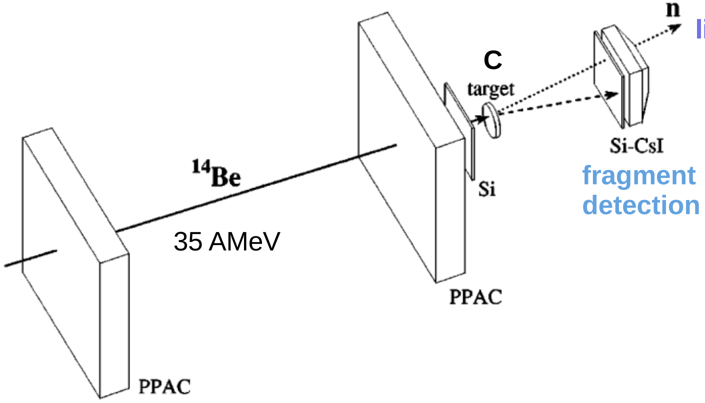
Missing mass: $^6He(p,p^4He)$



The GANIL 2002 result

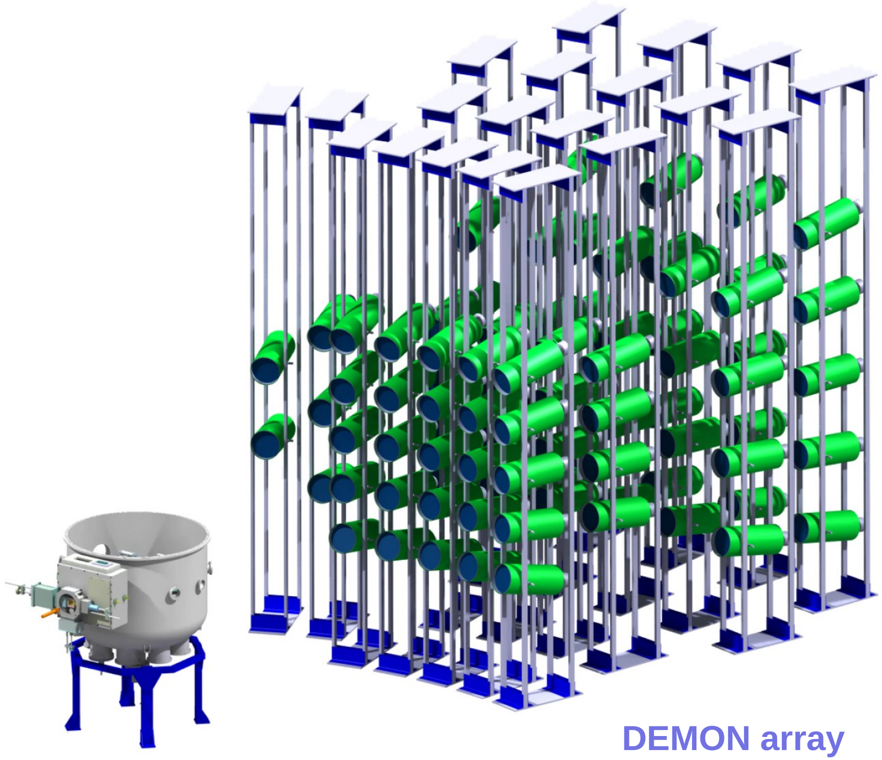
Breakup of ^{14}Be:





fragment detection

DEMON:
liquid scintillator array



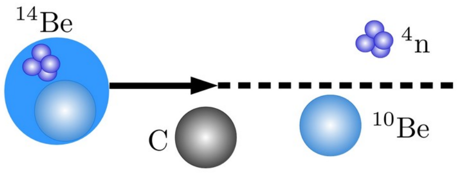
DEMON array

Marqués PRC 65 (2002)

Marqués arXiv:nucl-ex/0504009 (2005)

The GANIL 2002 result

Breakup of ^{14}Be:



Principle of measurement:

- E_p: recoil energy of proton from n-p elastic scattering
- E_n: energy per nucleon from time-of-flight measurement
- For 1n $E_p/E_n \leq 1.4$ (>1 due to detector resolutions)

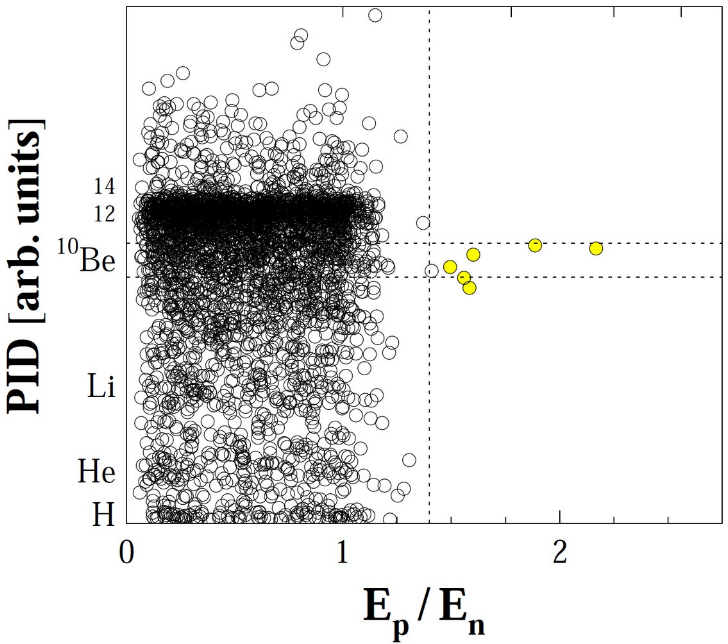
6 candidates:

possible scenarios

- bound ^4n

  OR
- low-energy resonance $E_r \leq 2$ MeV

statistical significance 2σ



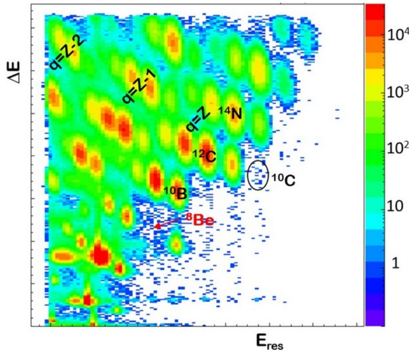
Marqués PRC 65 (2002)

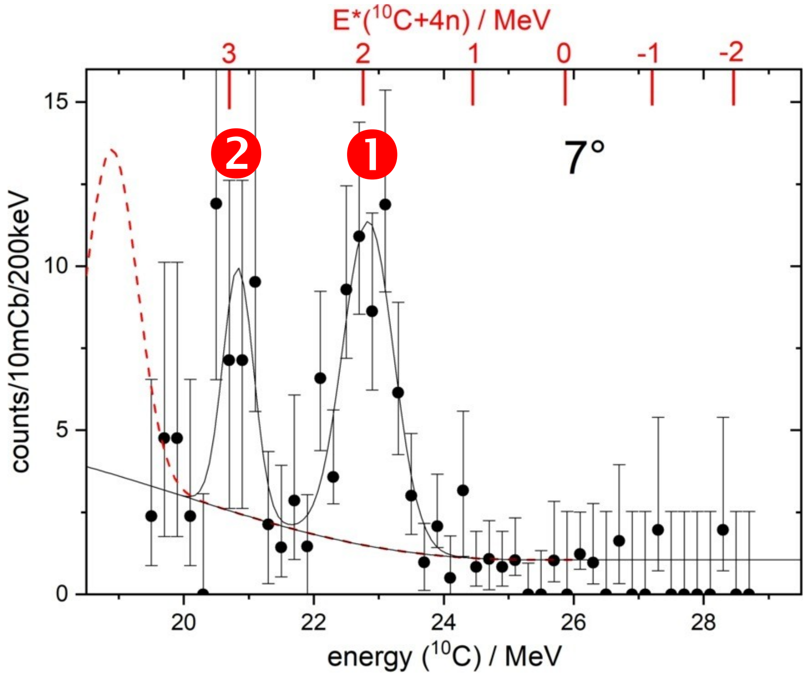
Marqués arXiv:nucl-ex/0504009 (2005)

“Indications for a bound tetraneutron”

TECHNISCHE UNIVERSITÄT DARMSTADT

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





❶ Concentration of other elements

→ ^{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

- ^{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

Faestermann et al., PLB 824 (2022)

Cluster Orbital Shell Model Approximation

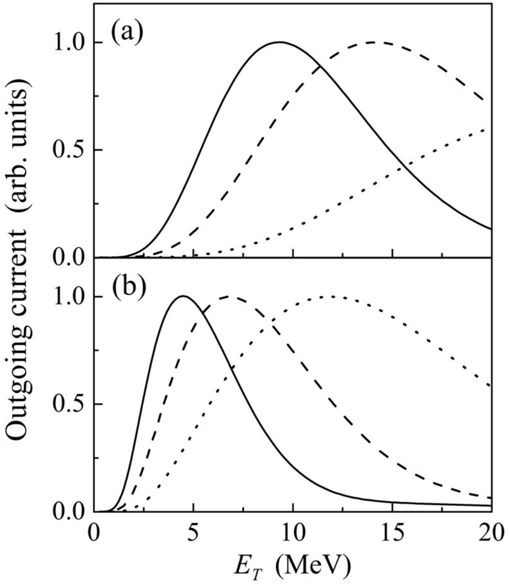
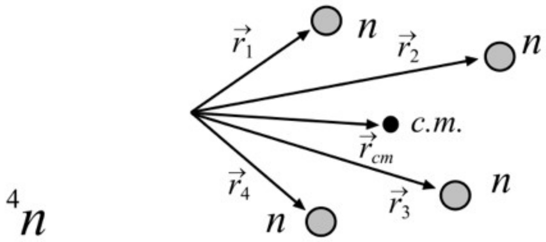


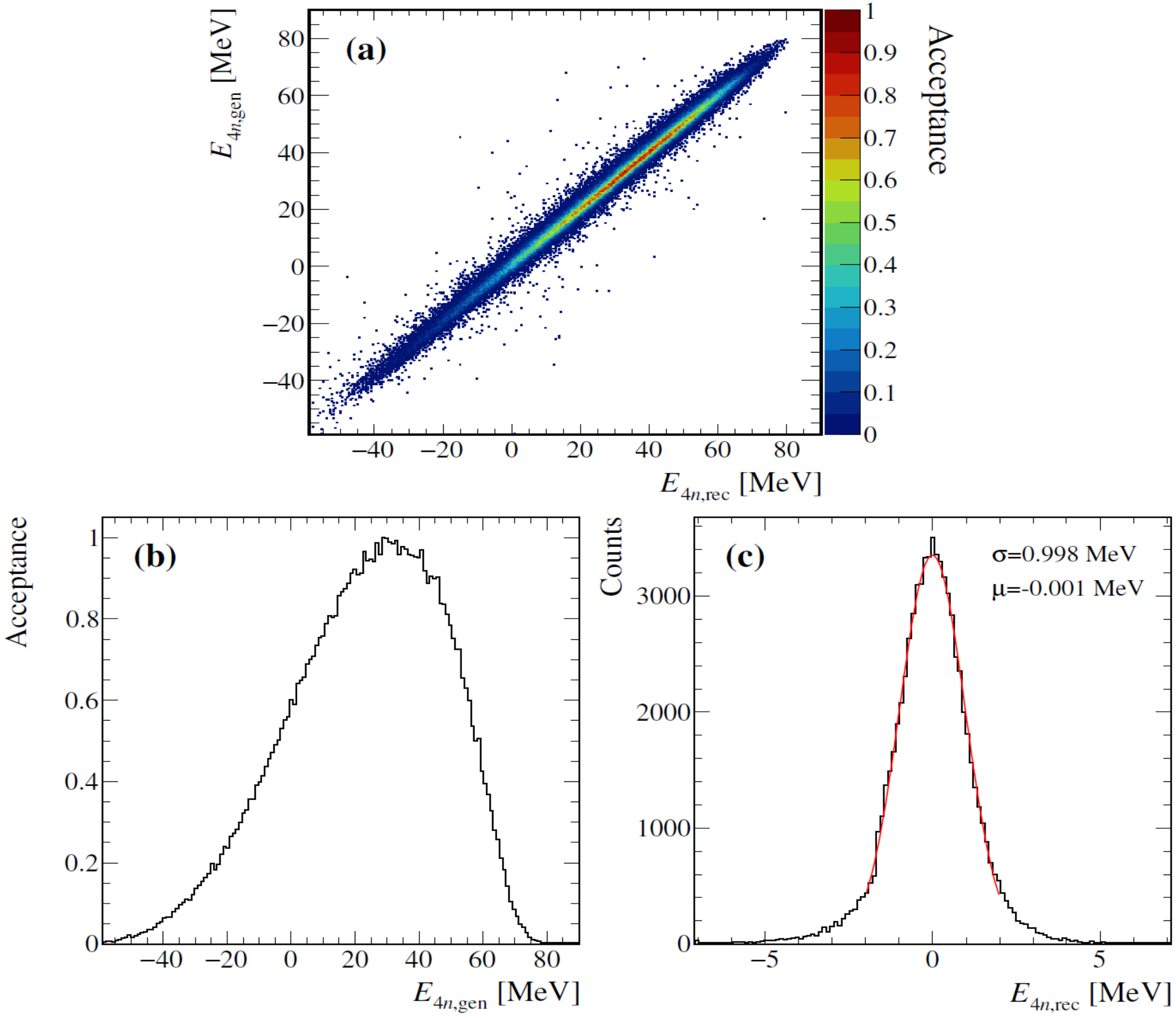
Fig. 11. Continuum response of the ^{4}n system in the MWS with a "Gaussian" source (13). Solid, dashed and dotted curves correspond to rms hyperradius $\langle\rho_{\rm sour}\rangle$ of the source equal to 8.9, 7.3, and 5.6 fm, respectively. Panels are calculated with (a) no final-state interaction,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

Grigorenko et al., EPJA (2004)

Figure 11a shows the continuum responses which could be expected for sources of different sizes if no FSI was present in the ^{4}n system. This is a benchmark case [40] which is mainly determined by the internal structure of the source. To take FSI into account, we used the Reichstein and Tang potential (RT) [41] which provides the correct low-energy behaviour in the n-n channel. The interaction

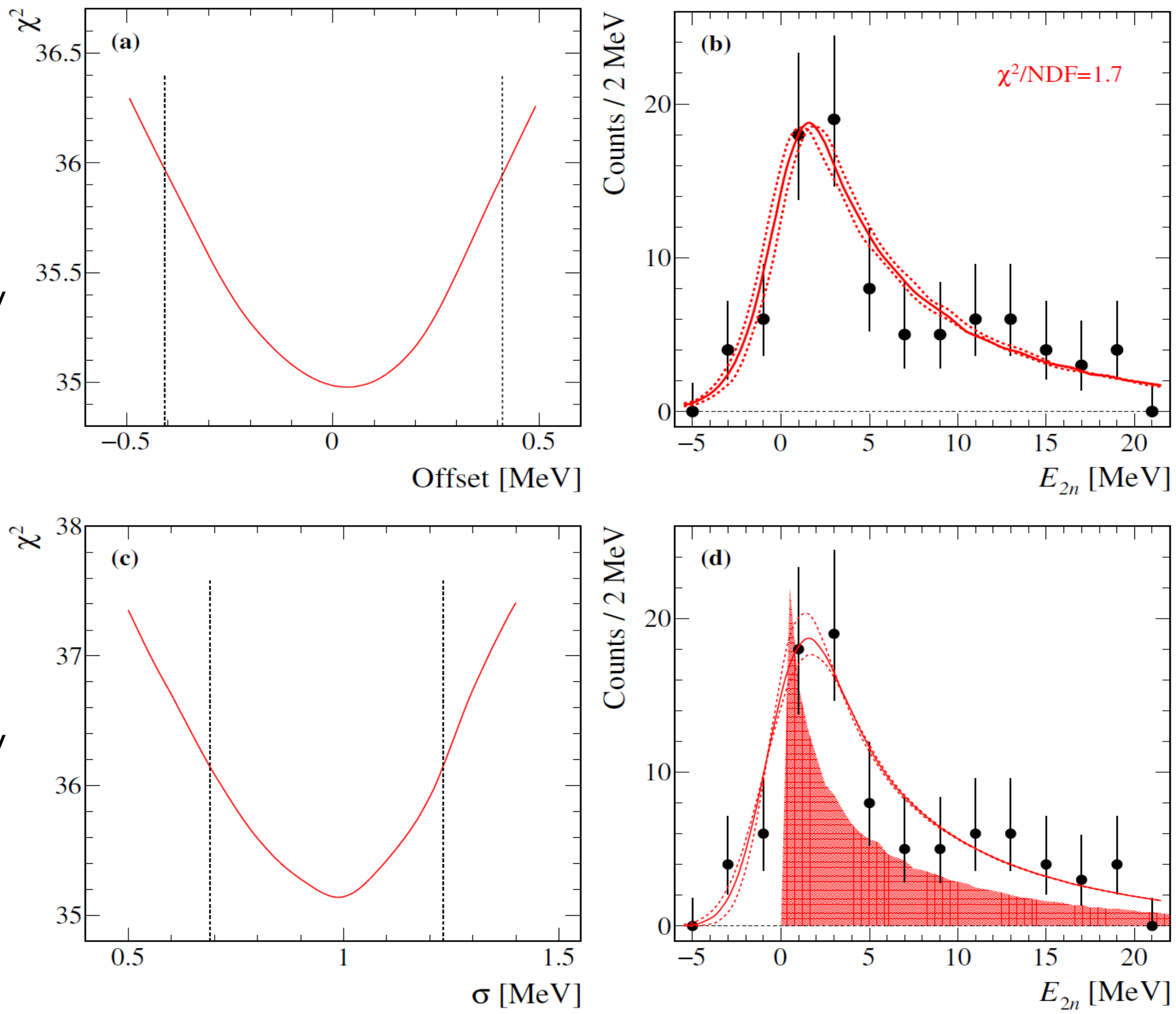


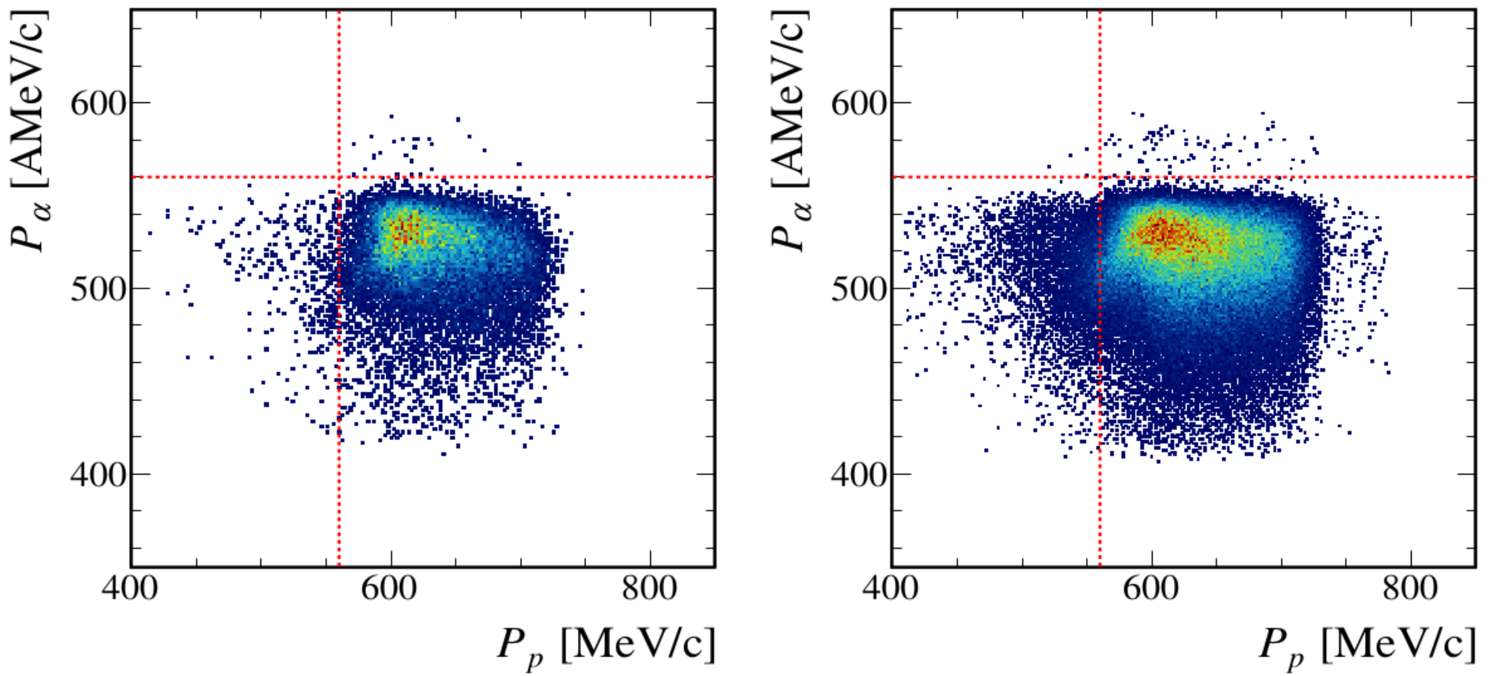
$$\sum_{i=1,4} r_i^2 = \rho^2 + 4r_{\rm cm}^2 \,.$$


(a)
(b)
(c)
Acceptance
Counts
σ=0.998 MeV
μ=-0.001 MeV
$E_{4n,\mathrm{gen}}$ [MeV]
$E_{4n,\mathrm{rec}}$ [MeV]

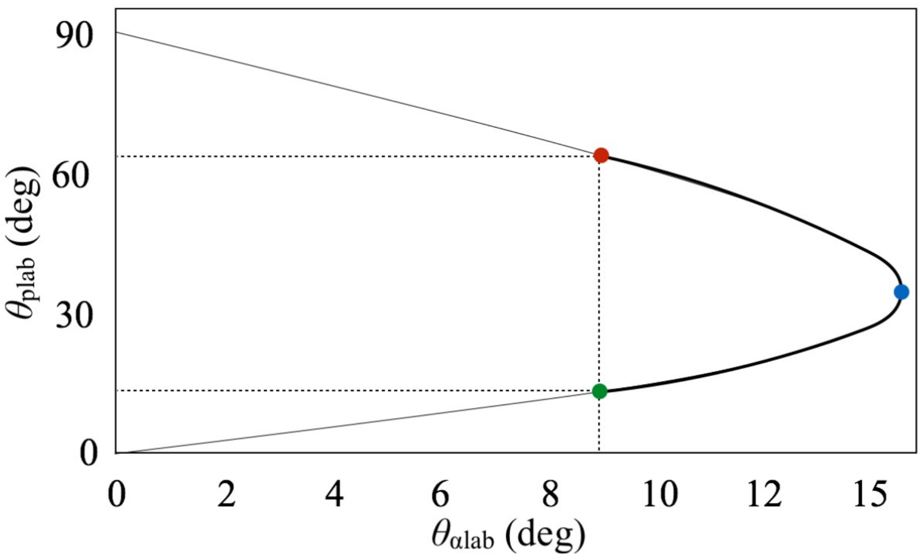
systematic uncertainty 0.4 MeV

systematic uncertainty 0.3 MeV

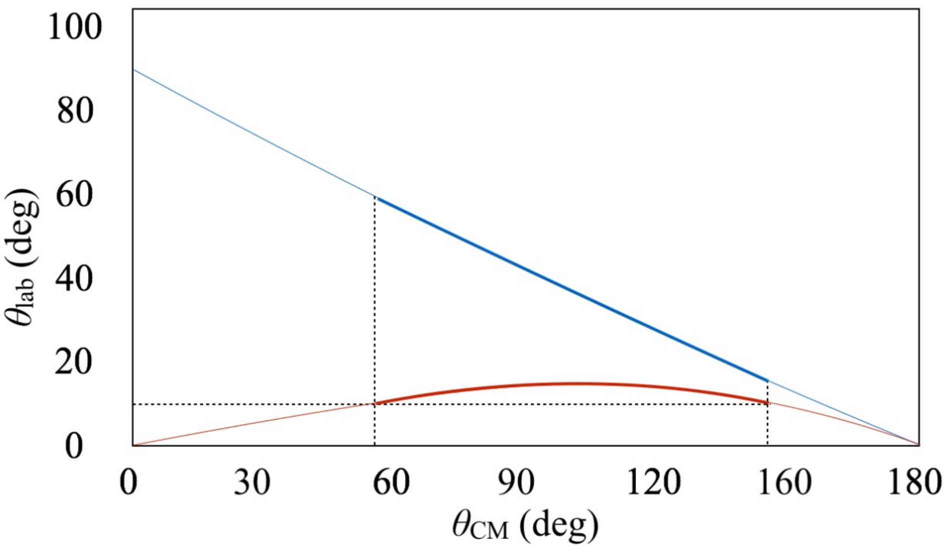




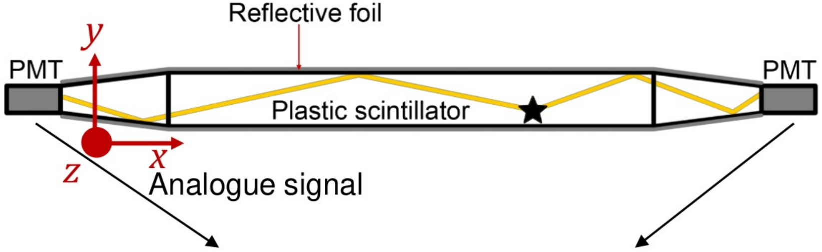
P_α [AMeV/c]
600
500
400
400
600
800
P_p [MeV/c]
P_α [AMeV/c]
600
500
400
400
600
800
P_p [MeV/c]

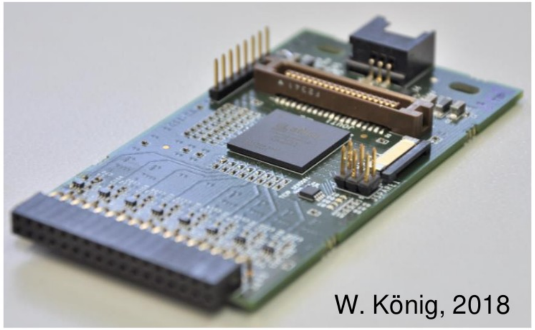


90
60
30
0
θ_{plab} (deg)
0
2
4
6
8
10
12
15
$\theta_{\alpha\text{lab}}$ (deg)

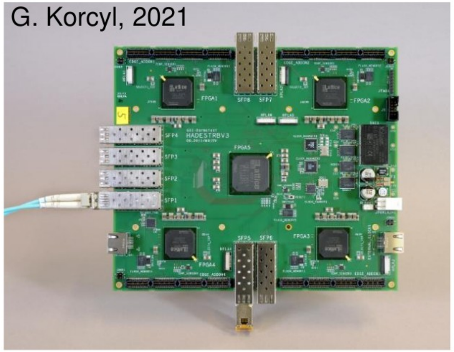


100
80
60
40
20
0
θ_{lab} (deg)
0
30
60
90
120
160
180
θ_{CM} (deg)





Logic signal



Digital data packet

PaDiWa board
→ discriminates the analogue signal

TRB3 board, consisting of 5 **f**ield **p**rogrammable **g**ate **a**rrays (FPGAs → allow programming of logic gates)

- Used for trigger logic
- Better than 20 ps time precision