WPCF, Resonance Workshop 2023
Catania, Italy

UNIVERSITY of York

Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

Observation of a correlated free four-neutron system and future perspectives

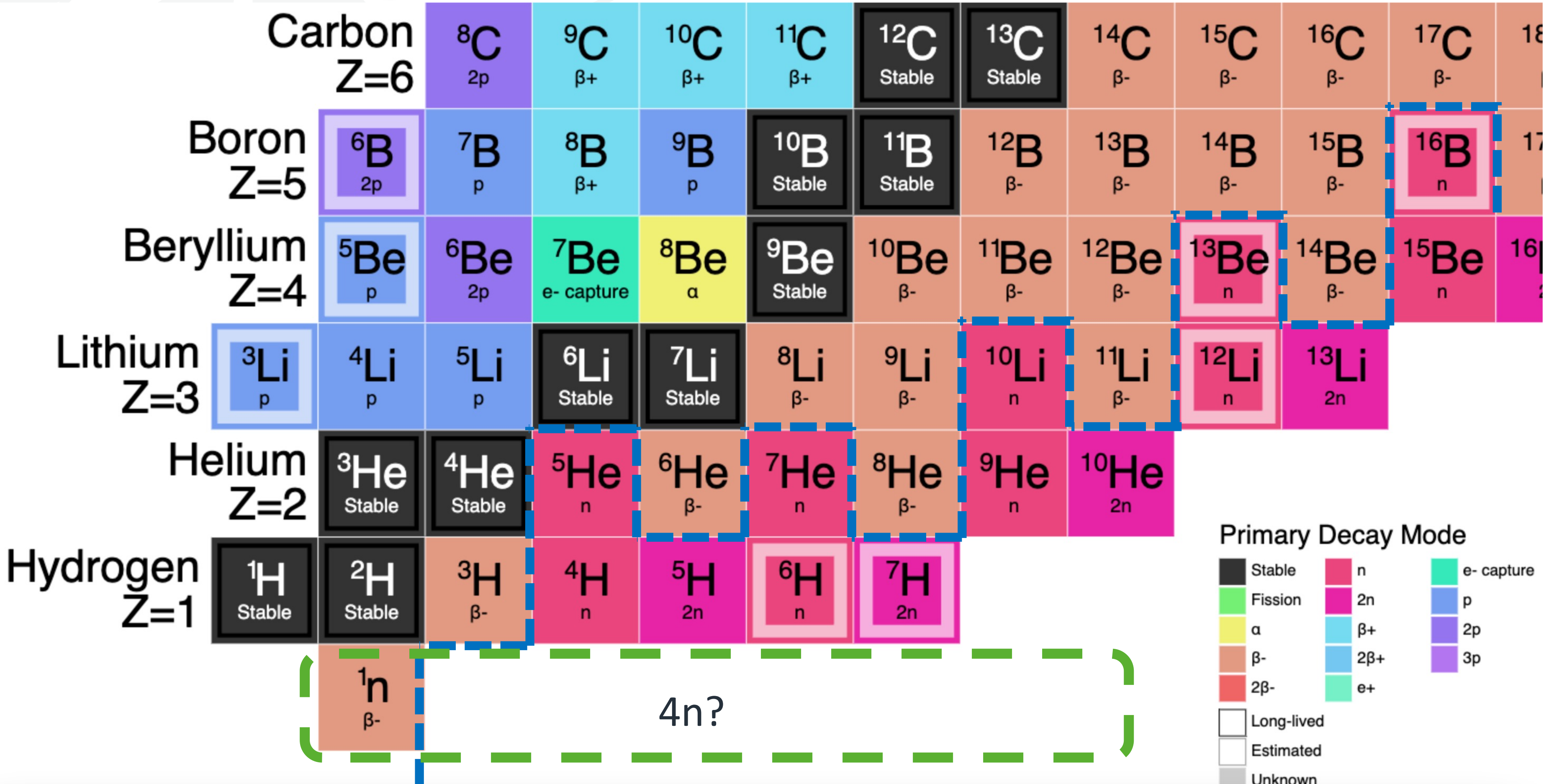
+++ Accepted RIBF proposal, SAMURAI74
Kenjiro Miki & Meytal Duer

Stefanos Paschalis

RIKEN
SAMURAI
DFG Deutsche Forschungsgemeinschaft
TECHNISCHE UNIVERSITÄT DARMSTADT
Bundesministerium für Bildung und Forschung
SFB 1245
HIC for FAIR Helmholtz International Center
UKRI Science and Technology Facilities Council

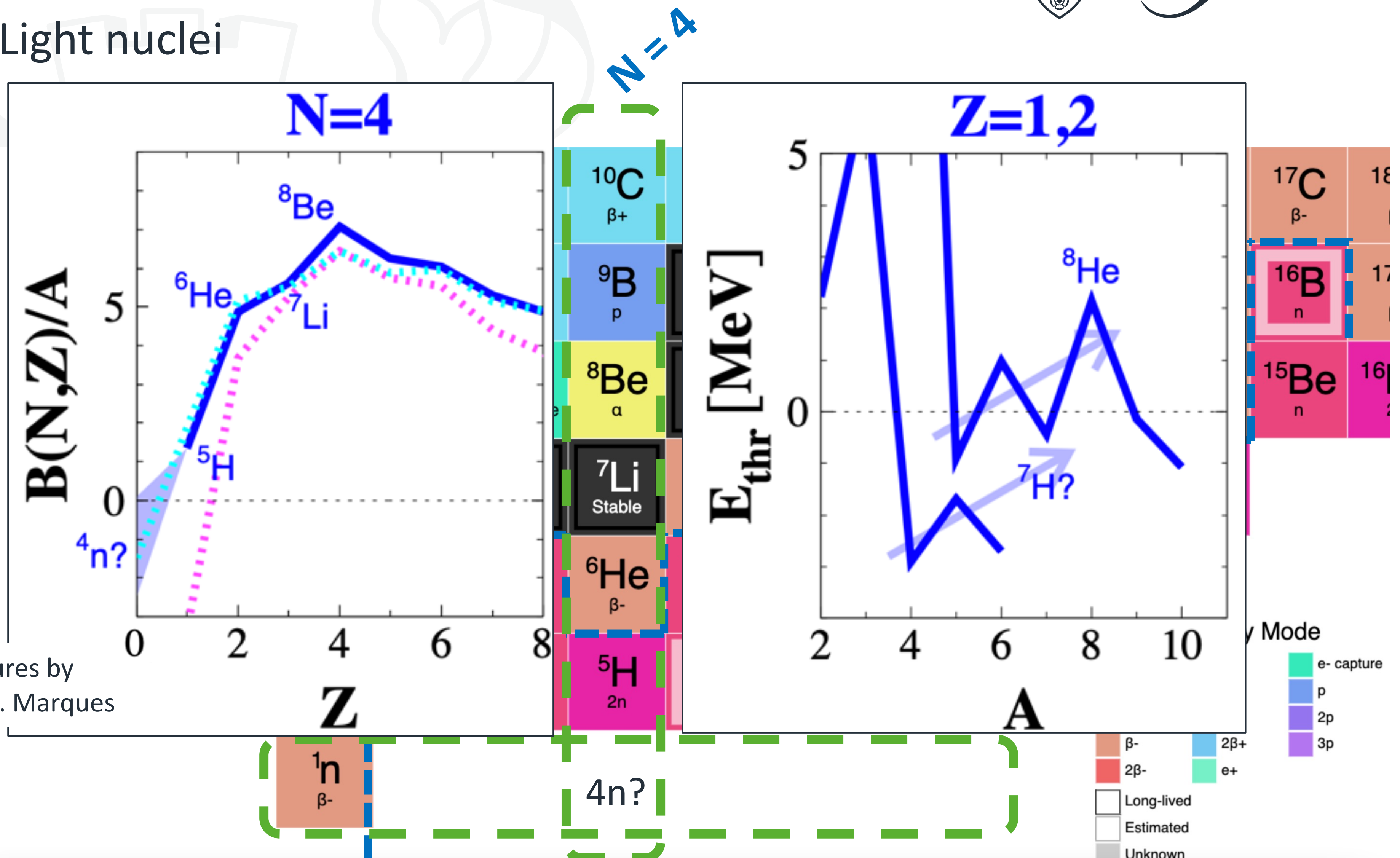
Nuclear landscape

Light nuclei



Nuclear landscape

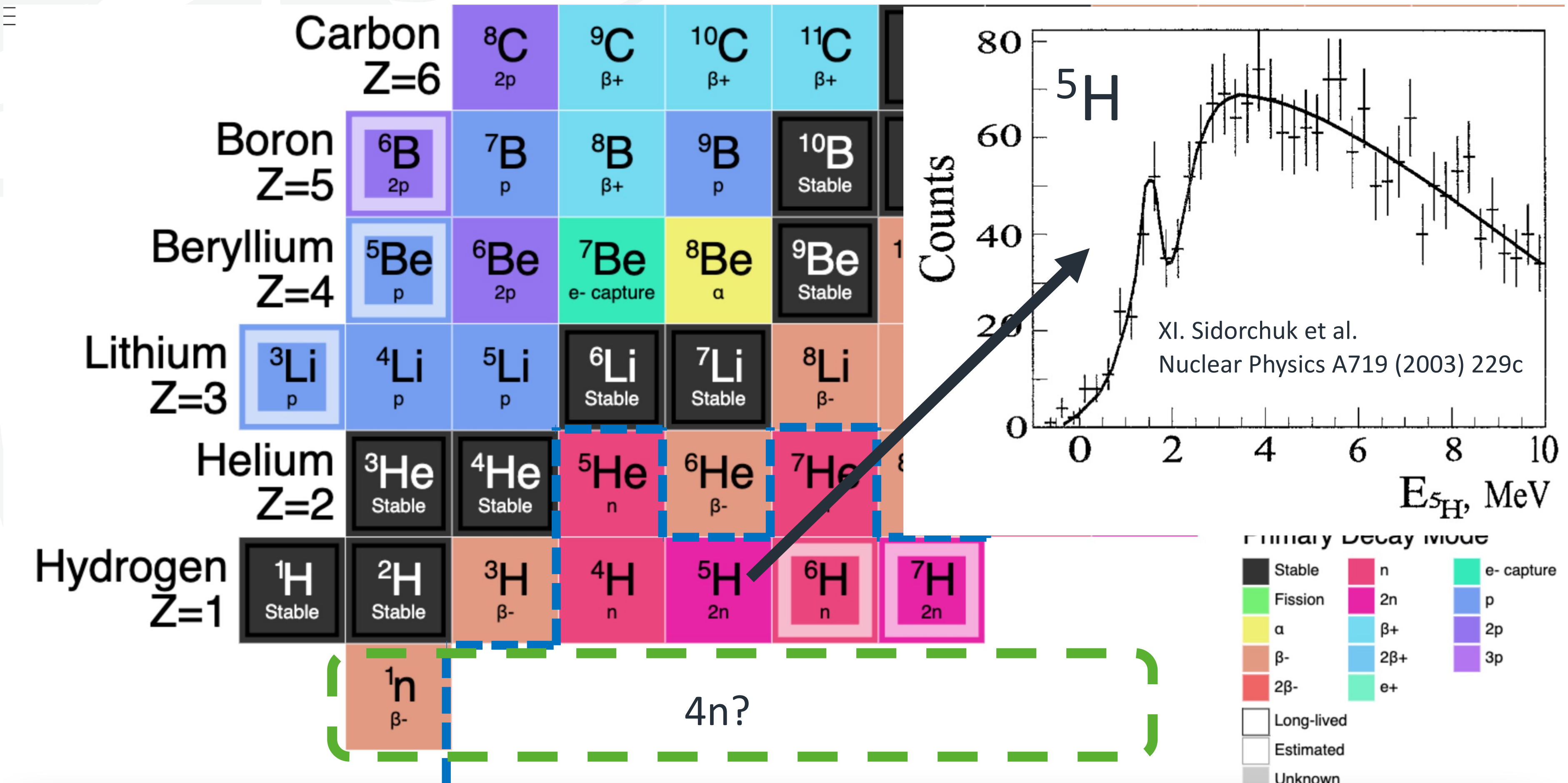
Light nuclei



Figures by
F.M. Marques

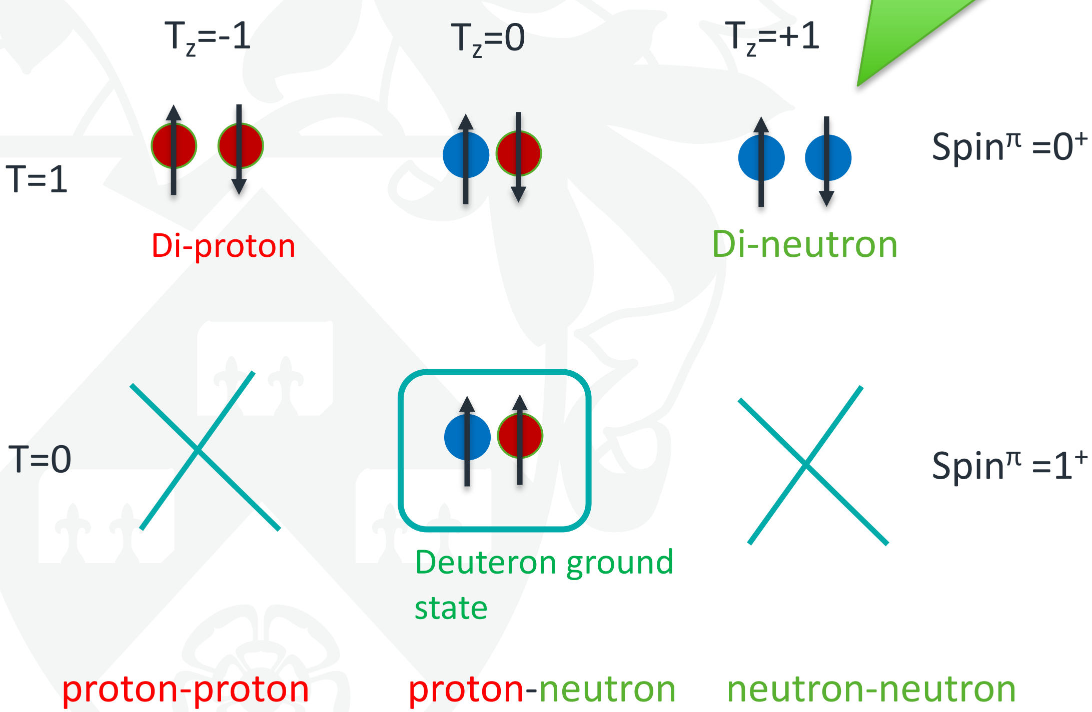
Nuclear landscape

Light nuclei



Nuclear Forces

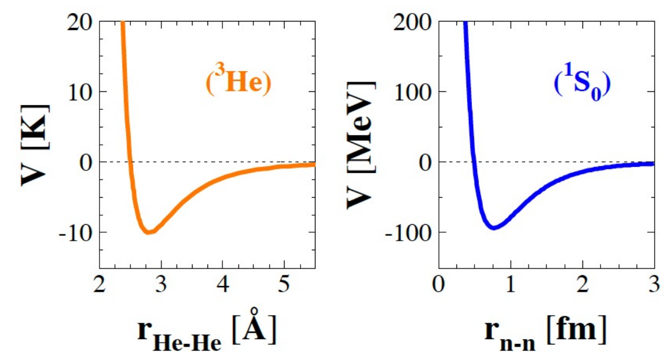
<u>Two-nucleon Systems:</u>



is known to be just unbound by only about 100 keV

R. Guardiola, PRL 84, 1144 (2000)

- $(^3\text{He})_2$ (✗) $\cdots$ $(^3\text{He})_N$ (✓): $N \sim 30$



- few-body fermionic systems
- T = 3/2 component of 3N forces
- coupling to the continuum

A 60-year quest of multi-neutron systems

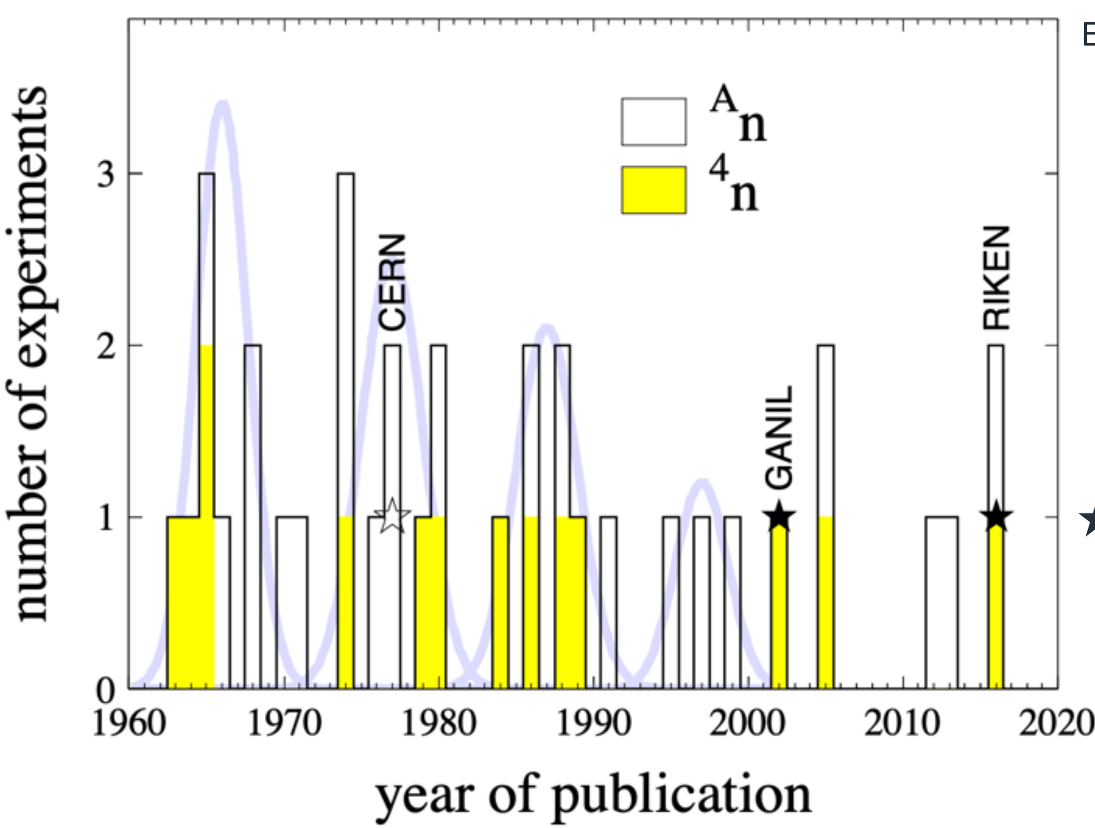
A 60-year quest

Experimental work – throughout the decades

For a recent, comprehensive review see: **The quest for light multineutron systems**

F. Miguel Marqués[1] and Jaume Carbonell[2]

EPJ A 57, 105 (2021)



★★

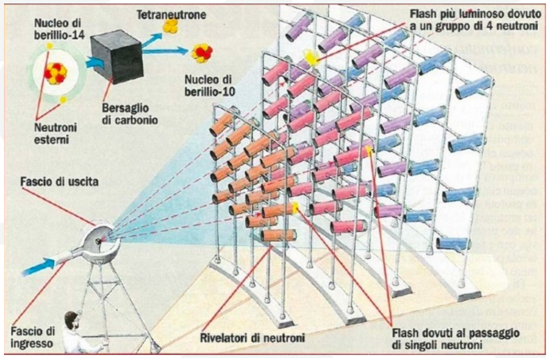
36+ experiments searching for multi-neutrons!!

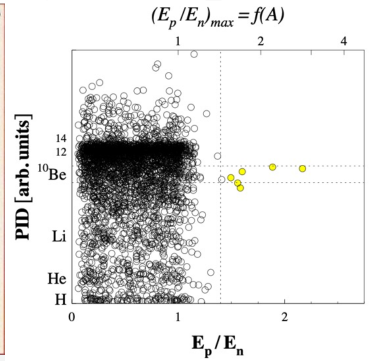
A 60-year quest

Experimental work

GANIL – 2002

C (^{14}Be, ^{10}Be) 4n





➢ 6 events consistent with bound 4n or a low-energy resonance (E(4n) < 2 MeV)

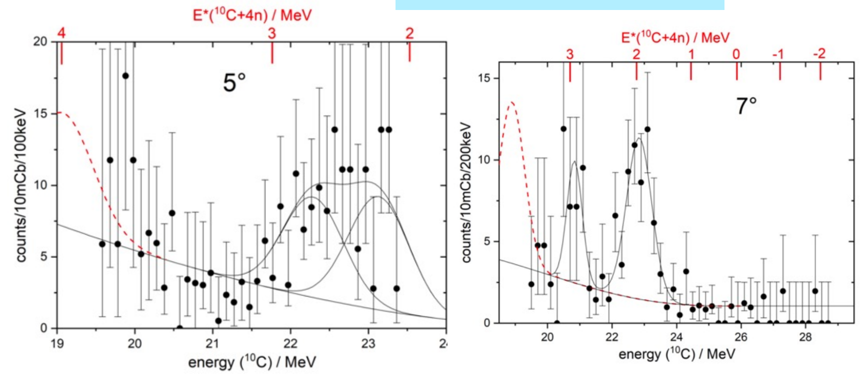
F.M. Marques et al., PRC 65, 044006 (2002) and arXiv:nucl-ex/0504009

Thomas Faestermann et al., PLB 824 (2022) 136799

TUM – 2022

Multi-nucleon transfer

^{7}Li(^{7}Li,^{10}C) ^{4}n



➢ 4n resonance E(4n) = 2.93 MeV, Γ < 0.24 MeV

or

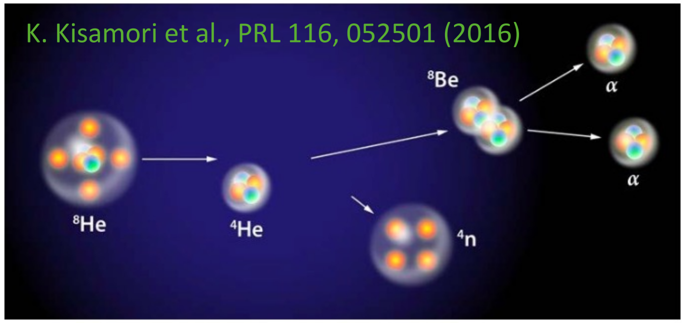
➢ 4n bound by 0.42(16) MeV & ^{10}C in 1st excited state

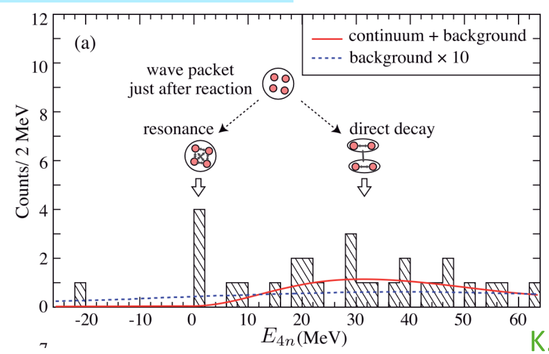
RIKEN – SHARAQ/RIBF – 2016

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

Double charge exchange reaction

K. Kisamori et al., PRL 116, 052501 (2016)





➢ 4 events consistent with 4n resonance:

E(4n) = 0.8 ± 1.3 MeV, Γ < 2.6 MeV

K. Kisamori et al., PRL 116, 052501 (2016)

A 60-year quest

Theoretical calculations

Binding Energy of a Neutron Gas

K. A. Brueckner
University of California, La Jolla, California

John L. Gammel
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

AND

Joseph T. Kubis
Princeton University, Princeton, New Jersey

(Received December 28, 1959)

We conclude that a neutron gas is not bound at any density….

EXISTENCE OF THE TRINEUTRON

A. N. Mitra
and
V. S. Bhasin
Department of Physics and Astrophysics, University of Delhi, Delhi, India

(1965)

NONEXISTENCE OF THE TETRANEUTRON*

Y. C. Tang and B. F. Bayman
School of Physics, University of Minnesota, Minneapolis, Minnesota

(Received 17 June 1965)

Here again, we find that there is neither a bound nor a resonant 4n system.

A 60-year quest

Theoretical calculations

UNIVERSITY of York

VOLUME 90, NUMBER 25 PHYSICAL REVIEW LETTERS week ending 27 JUNE 2003

Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?

Steven C. Pieper*

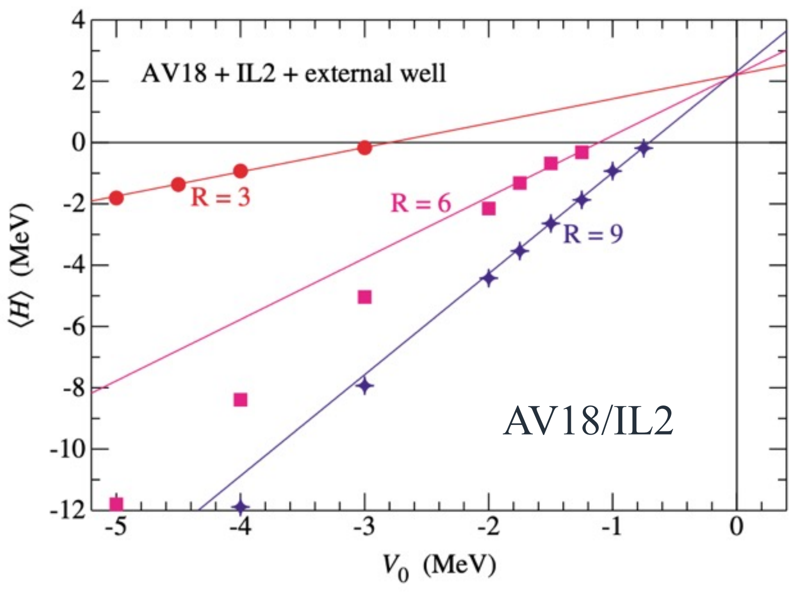


FIG. 1 (color online). Energies of ^4n in external wells versus the well-depth parameter V_0.

Regarding a bound ^{4}n:
"… our current very successful understanding of nuclear forces would have to be severely modified in ways that, at least to me, are not at all obvious."

Regarding a ^{4}n resonance state:
"This suggests that there might be a ^{4}n resonance near 2 MeV, but since the GFMC calculation with no external well shows no indication of stabilizing at that energy, the resonance, if it exists at all, must be very broad. In any case, the AV18/IL2 model does not produce a bound ^{4}n."

A 60-year quest

UNIVERSITY of York

Theoretical calculations, resonance or not?

(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF
(4n) Lazauskas, PRC 72 (2005) 034003 : 4NF
(3,4n) Hiyama, PRC 93 (2016) 044004 : 3NF(T =3/2)

→ No, 3n/4n

Shirokov, PRL 117 (2016) 182502
Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501
Li, PRC 100 (2019) 054313

→ Yes, 3n/4n

Deltuva, PRL 123 (2019) 069201
Deltuva, PRC 100 (2019) 044002
Ishikawa, PRC 102 (2020) 034002

→ No, 3n/4n

Deltuva, PLB 782 (2018) 238
Higgins, PRL 125 (2020) 052501

→ non-resonant low-energy enhancement of the density of states in the four-neutron spectrum.

Lazauskas, PRL 130 (2022) 102501

→ non-resonant dineutron-dineutron correlations

"The differences among them must rather be found in the methods used to solve the few-nucleon problem and/or in the way they access the few-neutron continuum": Eur. Phys. J. A (2021) 57:105

Latest Experimental work

SAMURAI at RIBF/RIKEN

"Observation of a correlated free four-neutron system"
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

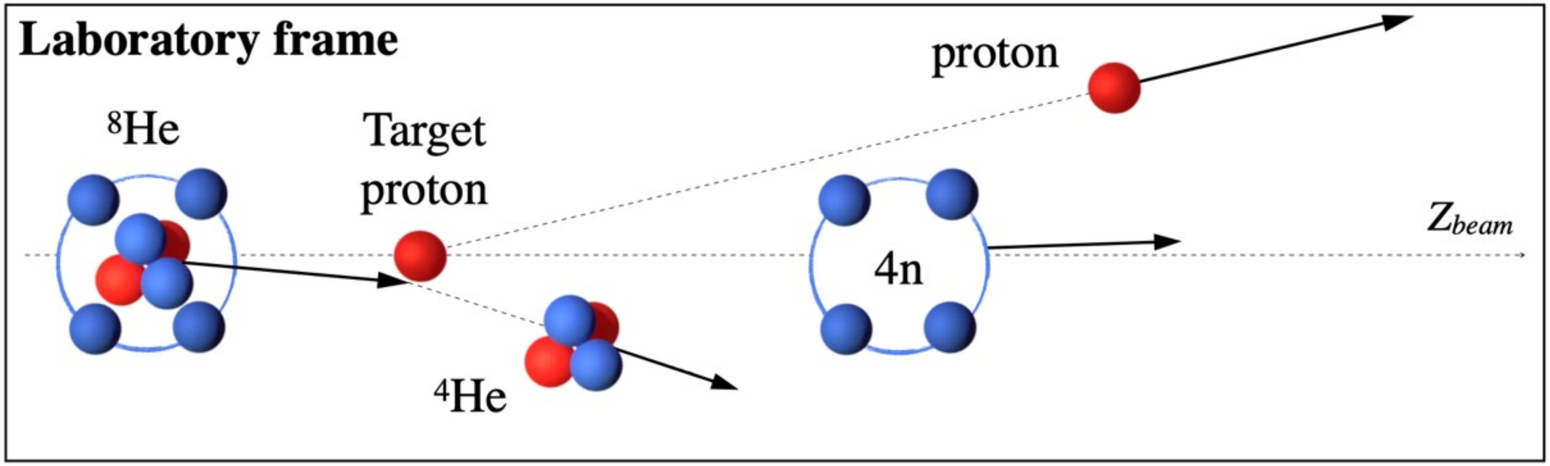
Method

$^{8}He(p,p\alpha)^{4}n$ Quasi-Elastic knockout reaction at large momentum transfer

Reconstruct the energy of the **missing mass** of the ^{4}n system through the precise measurement of the charge particles involved in the reaction (p, α).

Basic principle: Don't touch the neutrons !
(recoilless conditions)

Quasi-elastic scattering of α in ^{8}He



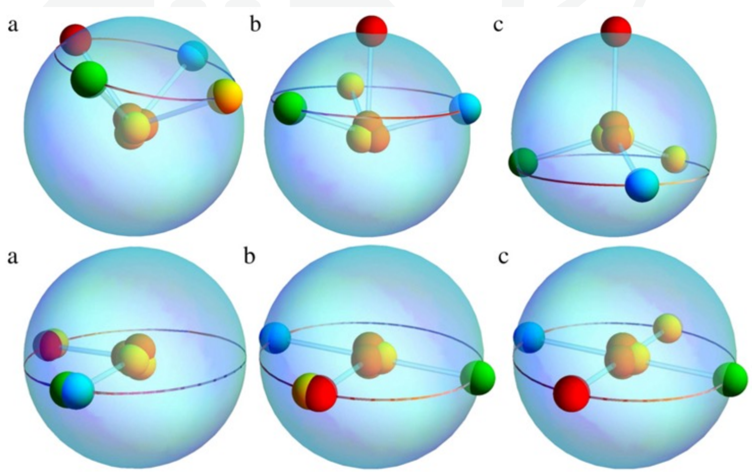
Method

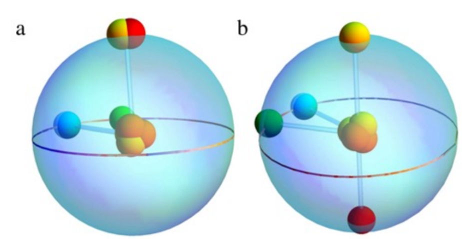
^{8}He(p,pα)^{4}n Quasi-Elastic knockout reaction at large momentum transfer

- ^{8}He a good starting point to populate a 4n system. Highest possible A/Z=4. Well-formed α cluster. Large overlap < ^{8}He | α ⊗ 4n >

Indeed, large alpha SF reported by L.V. Chulkov et al., NPA 759, 43 (2005)

Tetrahedral configurations





Great circle configurations

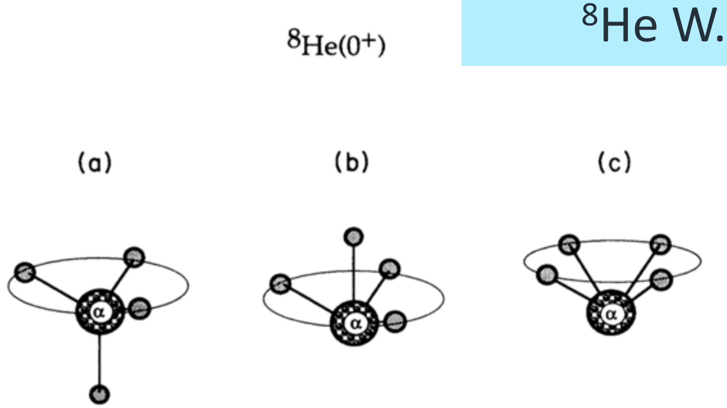
P. Mei, P. Van Isacker , Annals of Physics 327 (2012) 1182–1201

Method

^{8}He(p,pα)^{4}n Quasi-Elastic knockout reaction at large momentum transfer

- ^{8}He a good starting point to populate a 4n system. Highest possible A/Z=4.

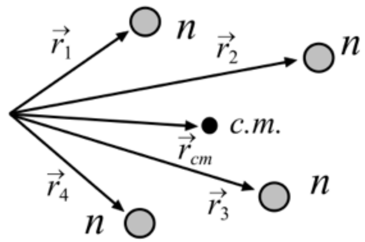
  $< \alpha \otimes 4n \,|\, ^8He >$ → $< \alpha \otimes 4n \,|\hat{O}|\, ^8He >$ involves a transition operator



^{8}He W.F. in the COSMA model

I. initial structure
II. reaction mechanism, and
III. final-state interaction (FSI)

^4n



Two of the three most probable configurations found in ^{8}He can be associated with a ^{4}n system. The probability for each of them is approx. 30%.
M.V. Zhukov, PRC 50, R1 (1994)

"Sudden removal of the α-particle from ^{8}He"
The exact case of interest is studied within the COSMA model.
L.V. Grigorenko et al., EPJA 19, 187 (2004)

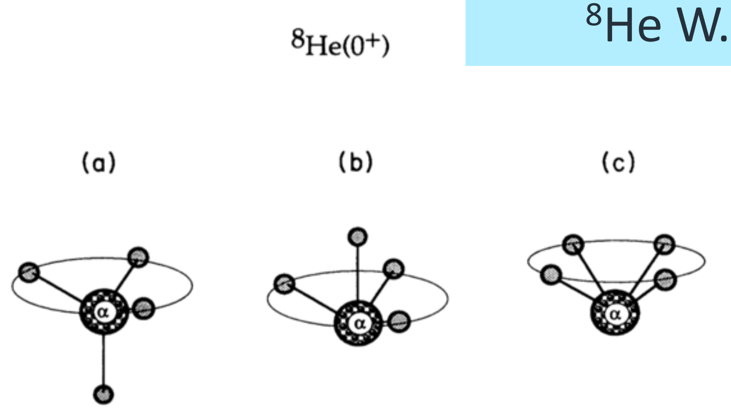
Method

^{8}He(p,pα)^{4}n Quasi-Elastic knockout reaction at large momentum transfer

- ^{8}He a good starting point to populate a 4n system. Highest possible A/Z=4.

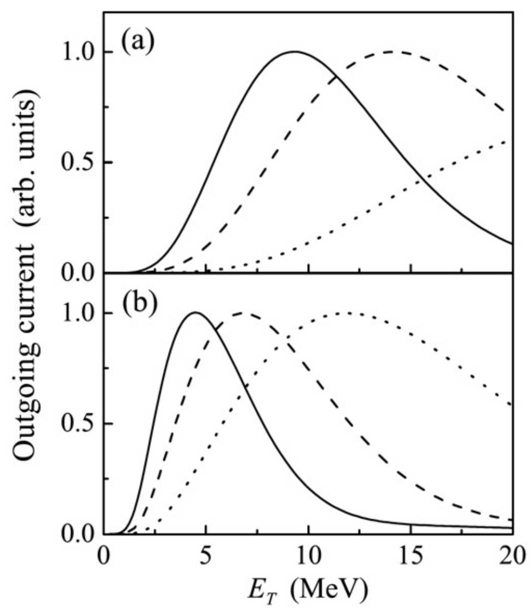
  $< \alpha \otimes 4n \,|\, {}^8He >$ → $< \alpha \otimes 4n \,|\hat{O}|\, {}^8He >$ involves a transition operator

^{8}He W.F. in the COSMA model



I. initial structure
II. reaction mechanism,
III. final-state interaction

4



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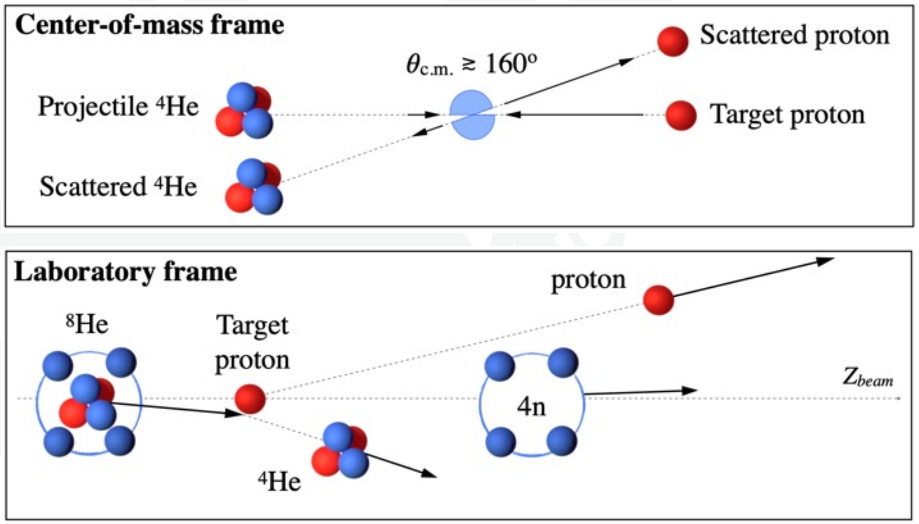
"Sudden remova
The exact case
the COSMA moc
L.V. Grigorenko e

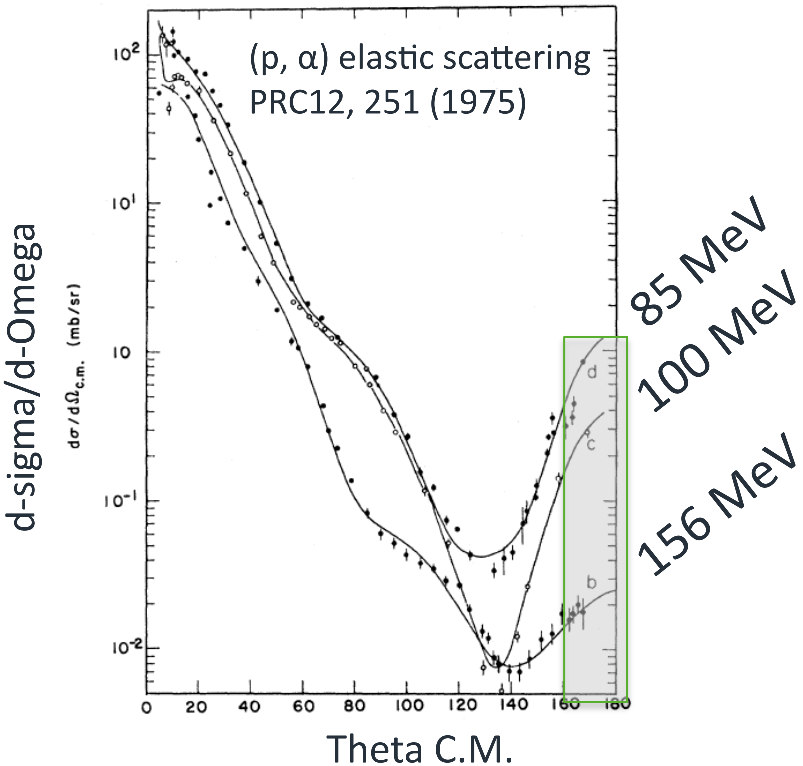
Method

$^{8}He(p,p\alpha)^{4}n$ Quasi-Elastic knockout reaction at large momentum transfer

- (p, α) elastic scattering data is well known.

Quasi-elastic scattering of α in ^{8}He

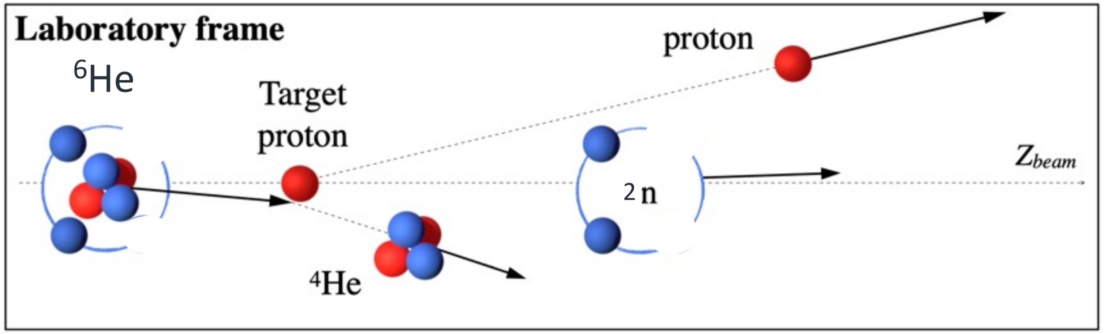


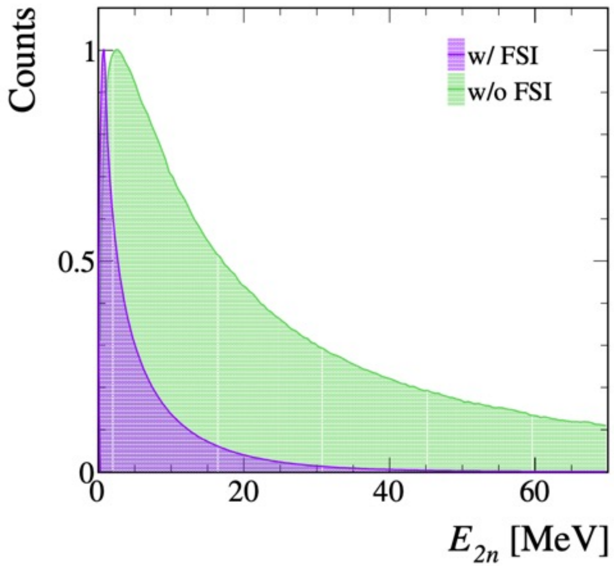


Method

$^{8}He(p,p\alpha)^{4}n$ Quasi-Elastic knockout reaction at large momentum transfer

- Helium beams allow for a "control case" to be employed **$^{6}He(p,p\alpha)^{2}n$** !!

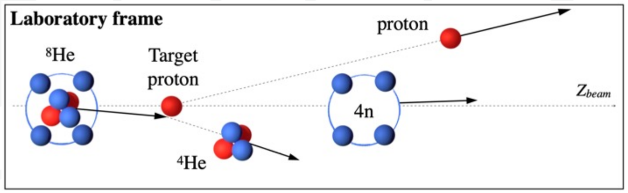


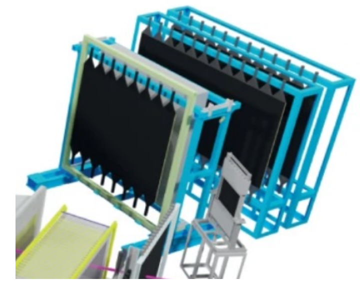


Theory:
Göbel, M. et al., "Neutron-neutron scattering length from the $^{6}He(p, p\alpha)nn$ reaction"
PRC 104, 024001 (2021).

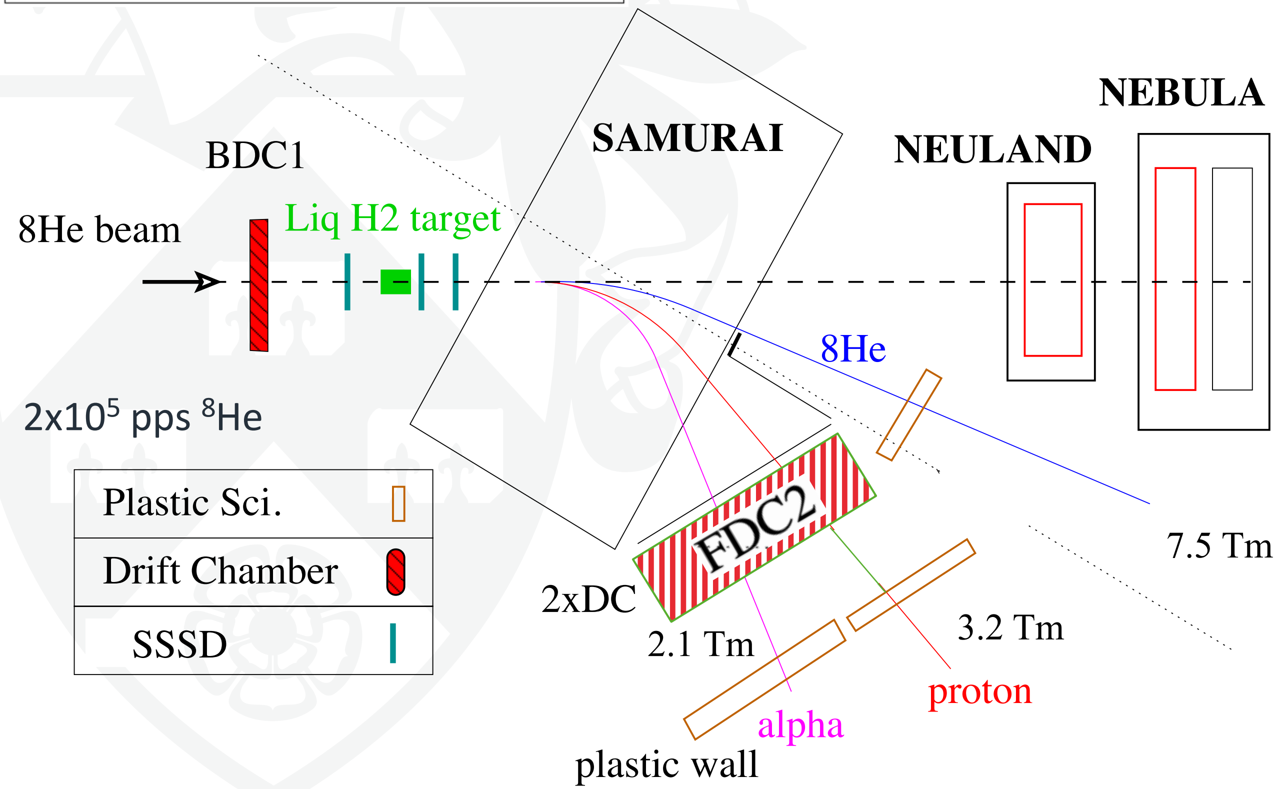
Experimental setup

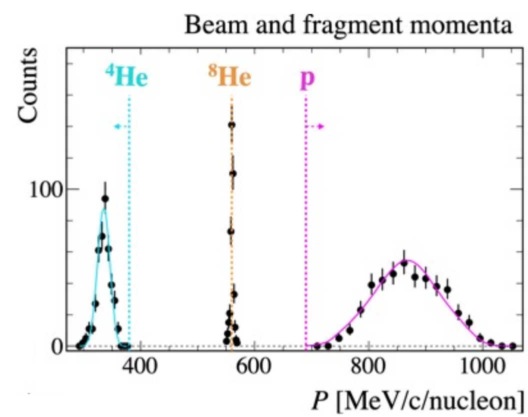
SAMURAI at RIBF/RIKEN





400 + 120 scintillator bars

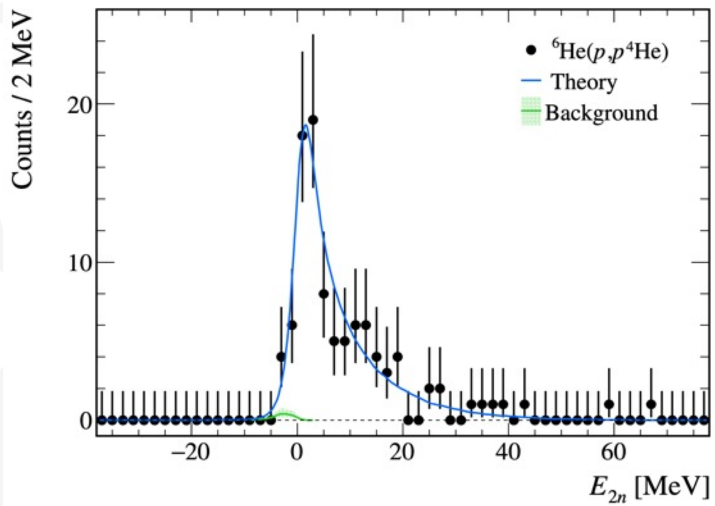




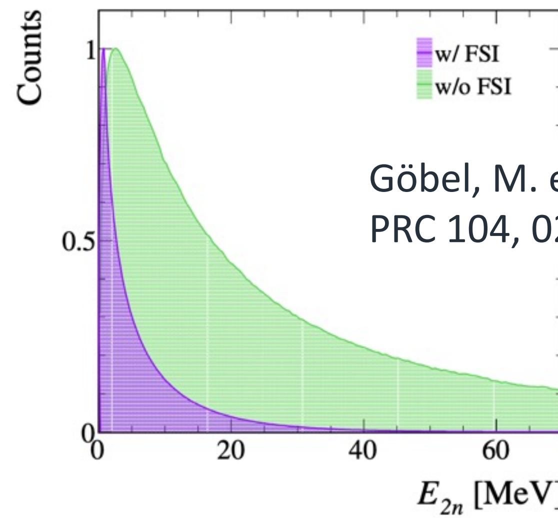
Results:
Missing-mass spectra

Control reaction - ^{6}**He(p,pα)^{2}n**

two-neutron system



Theory:
Göbel, M. et al., "Neutron-neutron scattering length from the ^{6}He(p, pα)nn reaction"
PRC 104, 024001 (2021).



Göbel, M. et al.,
PRC 104, 024001 (2021)

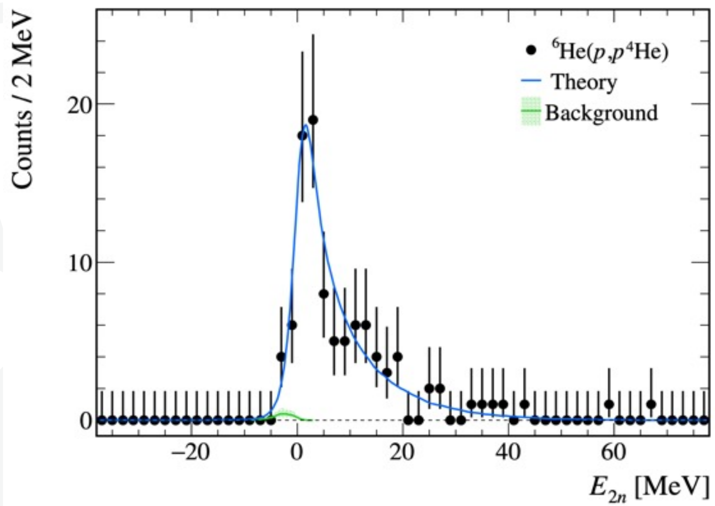
Confirming the expected low-energy structure for of di-neutron

"Observation of a correlated free four-neutron system"
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

Results:
Missing-mass spectra

Control reaction - ^{6}**He(p,pα)^{2}n**

two-neutron system

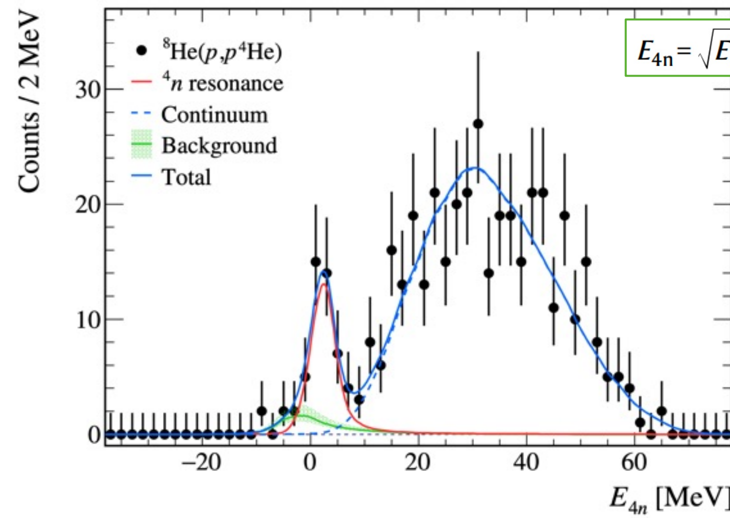


Confirming the expected low-energy structure for of di-neutron

^{8}He(p,pα)^{4}n

four-neutron system

$$E_{4n} = \sqrt{E^2_{miss} - \mathbf{P}^2_{miss}} - 4m_n$$

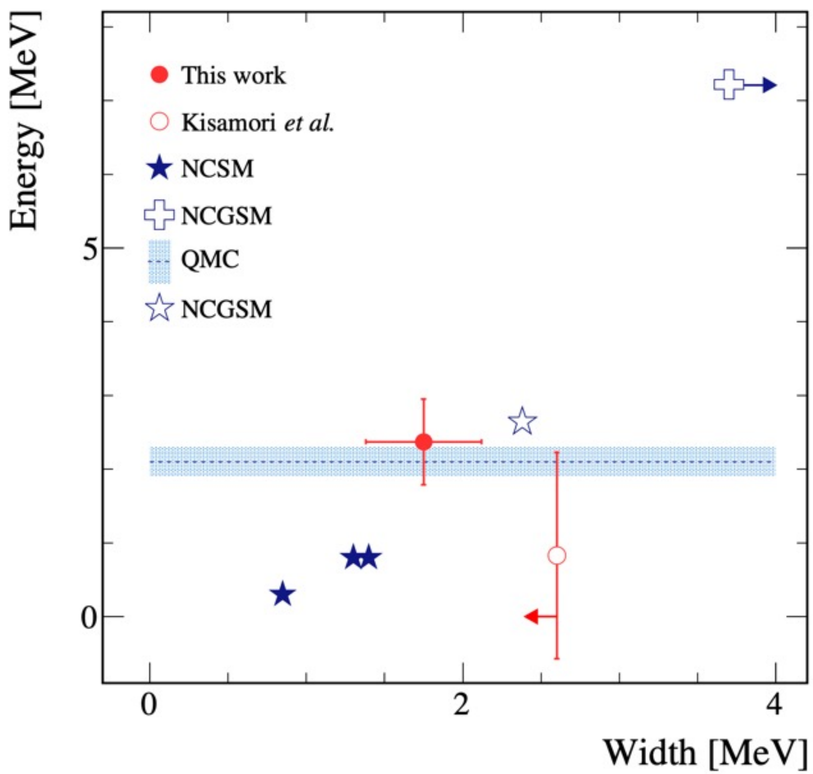


A near-threshold resonance-like structure:
E_r = 2.37 ± 0.38(stat.) ± 0.44(sys.) MeV

Γ = 1.75 ± 0.22(stat.) ± 0.30(sys.) MeV

"Observation of a correlated free four-neutron system"
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

Comparison of experimental results with theory predictions



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

Γ = 1.75 ± 0.22(stat.) ± 0.30(sys.) MeV

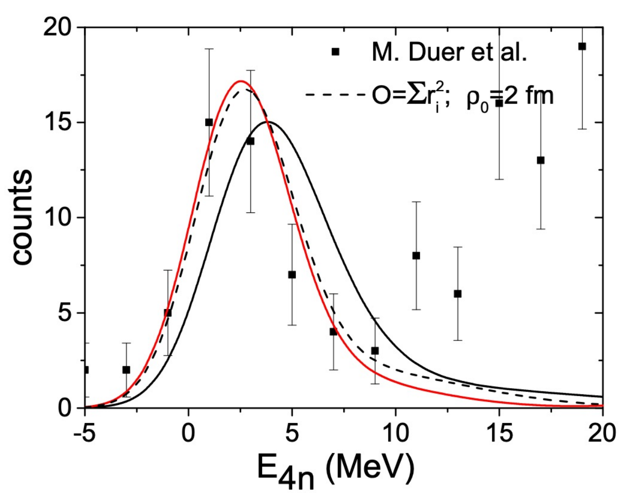
- No-Core Shell Model (**NCSM**)
  PRL 117, 182502 (2016)
- No-Core Gamow Shell Model (**NCGSM**)
  PRC 100, 054313 (2019)
  PRL 119, 032501 (2017)
  (where the blue arrow indicates that the width is predicted to be larger than 3.7 MeV)
- Quantum Monte Carlo (**QMC**)
  PRL 118, 232501 (2017)

Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

"Low Energy Structures in Nuclear Reactions with 4n in the Final State"

Lazauskas, PRL 130 (2023) 102501

"We show that these experimental results find a natural explanation in terms of the ***dineutron correlations in the final state****, if the four neutrons are weakly bound in the initial projectile, forming a broad wave function."*



strong sensitivity of the response function to the neutrons' initial distribution inside ^{8}He

Dependency on how we populate & how we measure four neutrons

Requires two-dineutron correlations as well as the presence of pre-existing two-dineutron clusters in the initial ^{8}He state

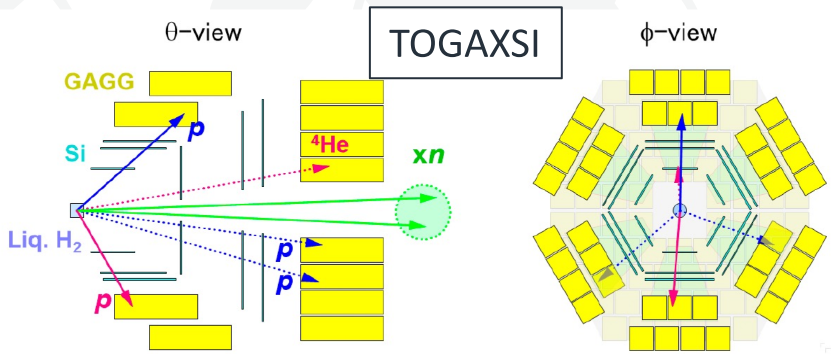
- Measuring the relative momentum amongst the neutrons should help resolve this

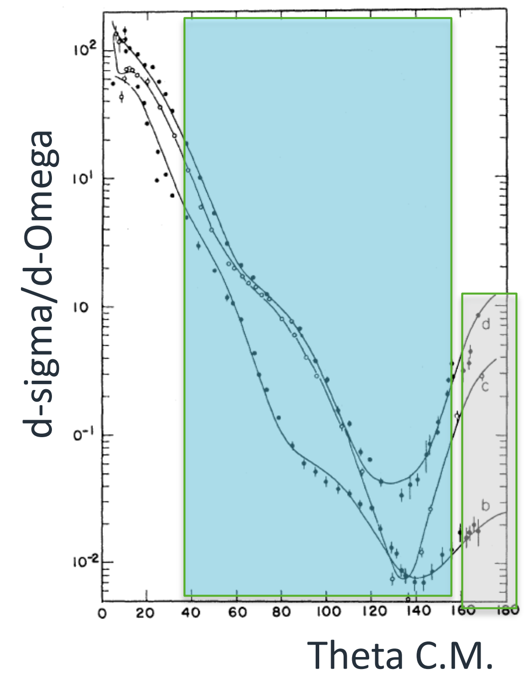
→ New experiment

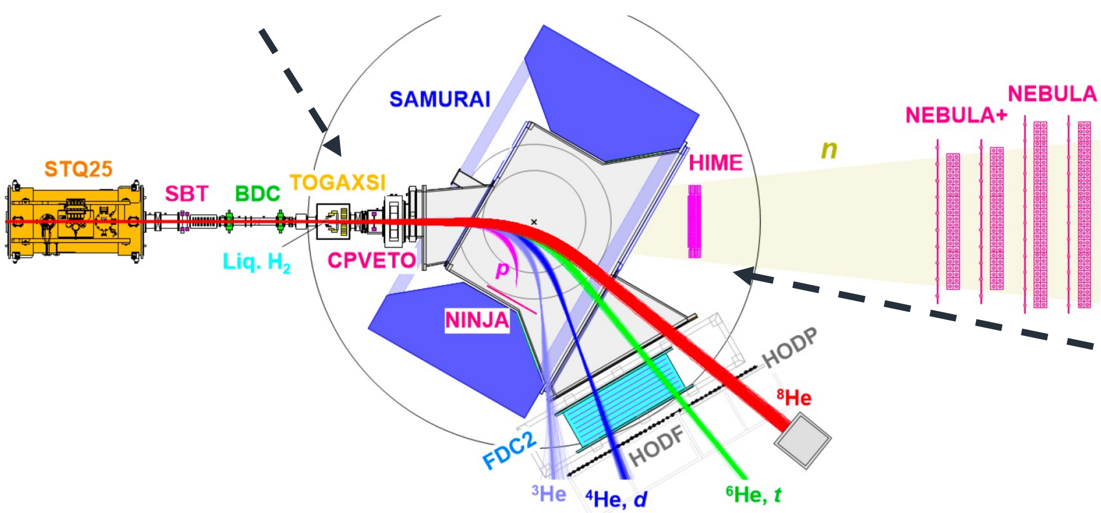
Accepted RIBF proposal SAMURAI74 (Kenjiro Miki & Meytal Duer)

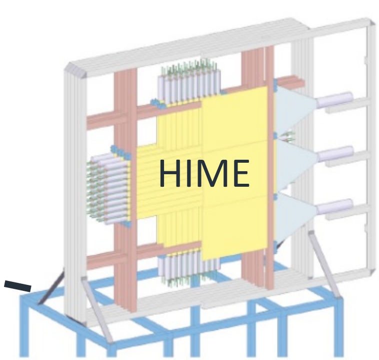
- $^{8}He(p, p\alpha)4n$
- $^{6}He(p, 3p)4n$ and $^{8}He(p, 3p)6n$

➢ complementary reactions & 4n in coincidence for direct relative momentum measurement









HIME
NEBULA
NEBULA+

4n detection Eff. ~ 0.9%

Summary and Conclusions

UNIVERSITY of York

- experimental observation of a four-neutron resonance-like structure near threshold.

- ^{8}He beam and a quasi-elastic (p,pa) reaction at large momentum transfer in inverse kinematics enabled access to the ^{4}n system in a recoil-less way.

- The finely tuned experimental apparatus (SAMURAI setup) and the high intensity radioactive beams provided by RIBF enabled a high-resolution measurement yielding a low-energy peak with a statistical significance well beyond the 5σ level.

- Next generation experiments approved - where four neutron system is accessed in different ways and where all four neutrons are detected in coincidence.

- elaborate nuclear theories accounting fully for the effect of the continuum and modelling the exact nuclear reaction are essential to understand the observed low-energy peak.

Observation of a correlated free four-neutron system

M. Duer,[1,*] T. Aumann,[1,2,3] R. Gernhäuser,[4] V. Panin,[5,2] S. Paschalis,[6,1] D. M. Rossi,[1] N. L. Achouri,[7] D. Ahn,[5] 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,[14,1,5] 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,[16,1] 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] and M. V. Zhukov[20]

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Thank you !!

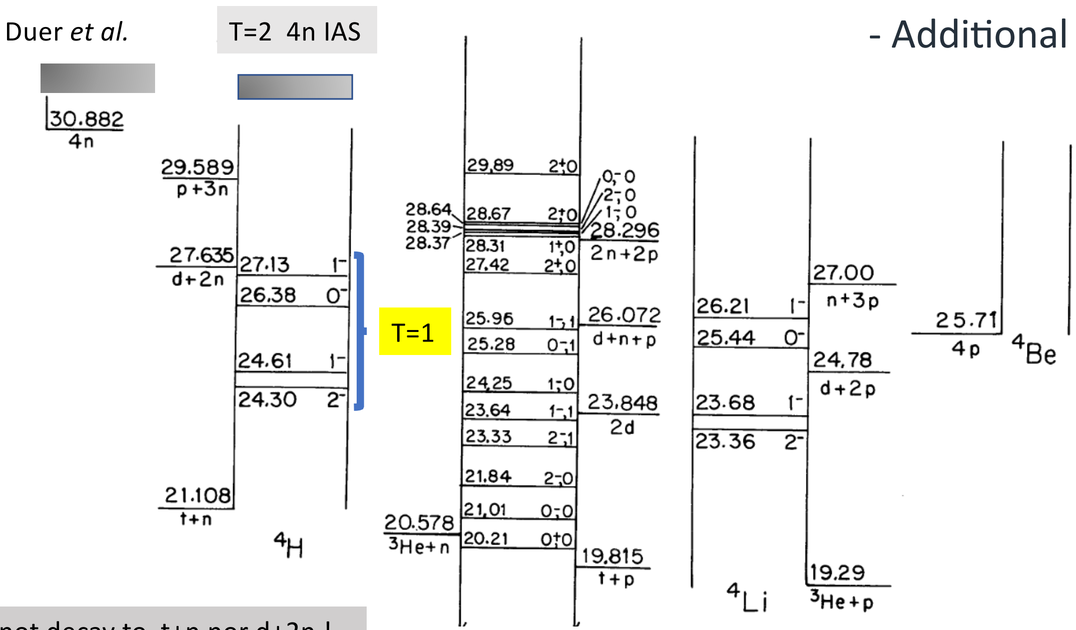
Backup slides

Accepted **GANIL** proposal
The tetra-neutron Isobaric Analog State in ^{4}H
(Augusto Macchiavelli & Marlène Assié)

UNIVERSITY of York

- LISE beam line
  - CATS multiwire proportional chambers
  - MUGAST array covering from 5 to 30 degrees
  - Additional MUST2 detector at 0 degree

^{6}He(p,^{3}He)^{4}H ΔT=0,1



T=2 state cannot decay to t+n nor d+2n !

p + 3n

Look at ^{6}He coming in and ^{3}He plus a proton coming out

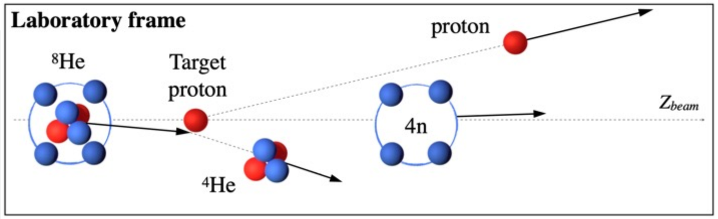
Populate the IAS of the n^{4} in ^{4}H via the ^{6}He(p,^{3}He)^{4}H reaction

ΔT =0,1 changes are allowed

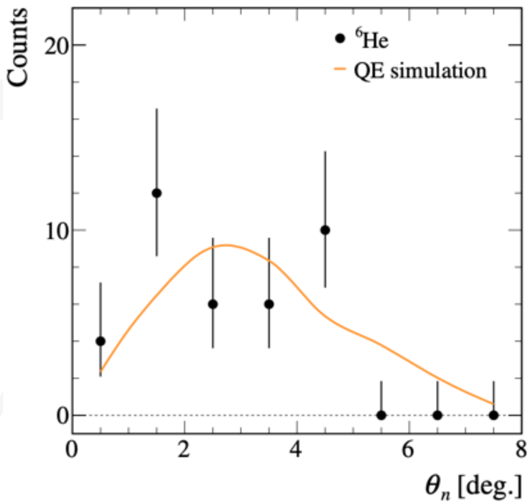
Selective ^{3}He + p (from ^{4}H decay) trigger due to isospin selection rules

Neutron detection

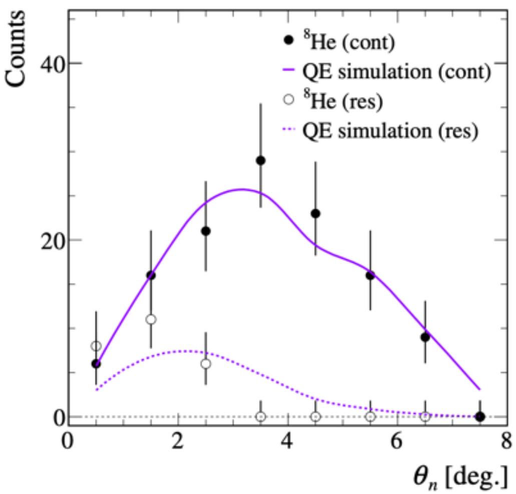
Events with **one neutron in coincidence** are consistent with expected distributions



^{6}He(p,pα)^{2}n



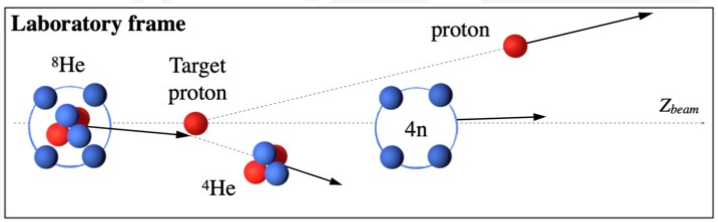
^{8}He(p,pα)^{4}n



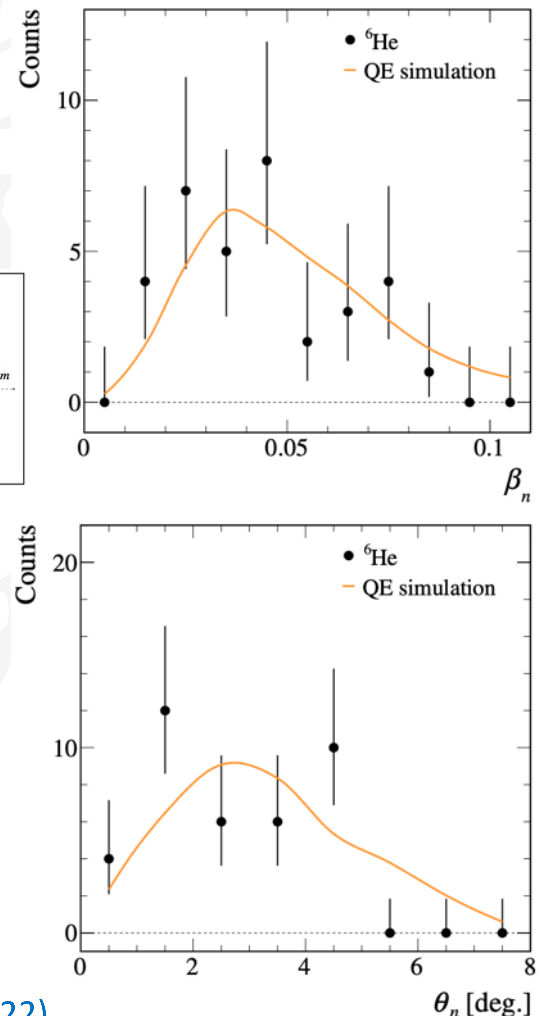
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

Neutron detection

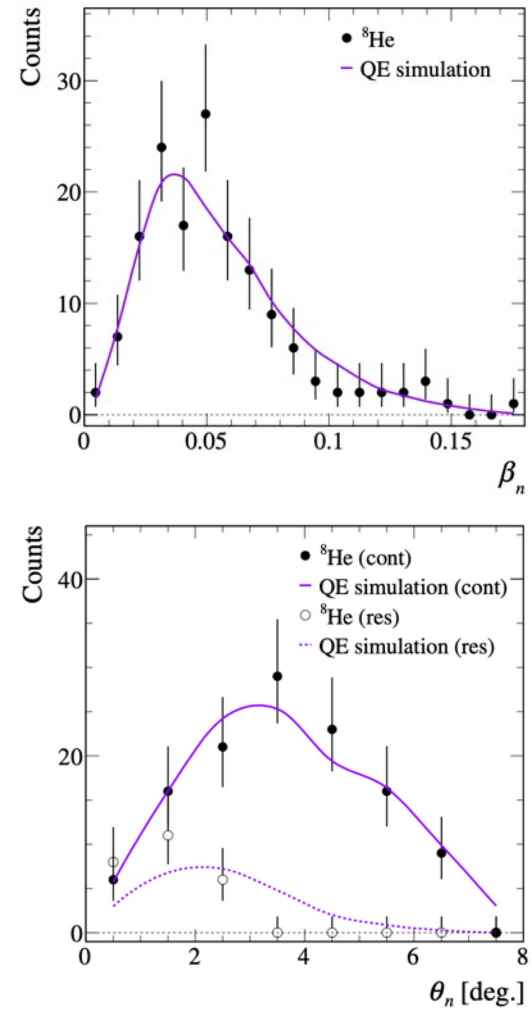
Events with one detected neutron are consistent with expected distributions



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

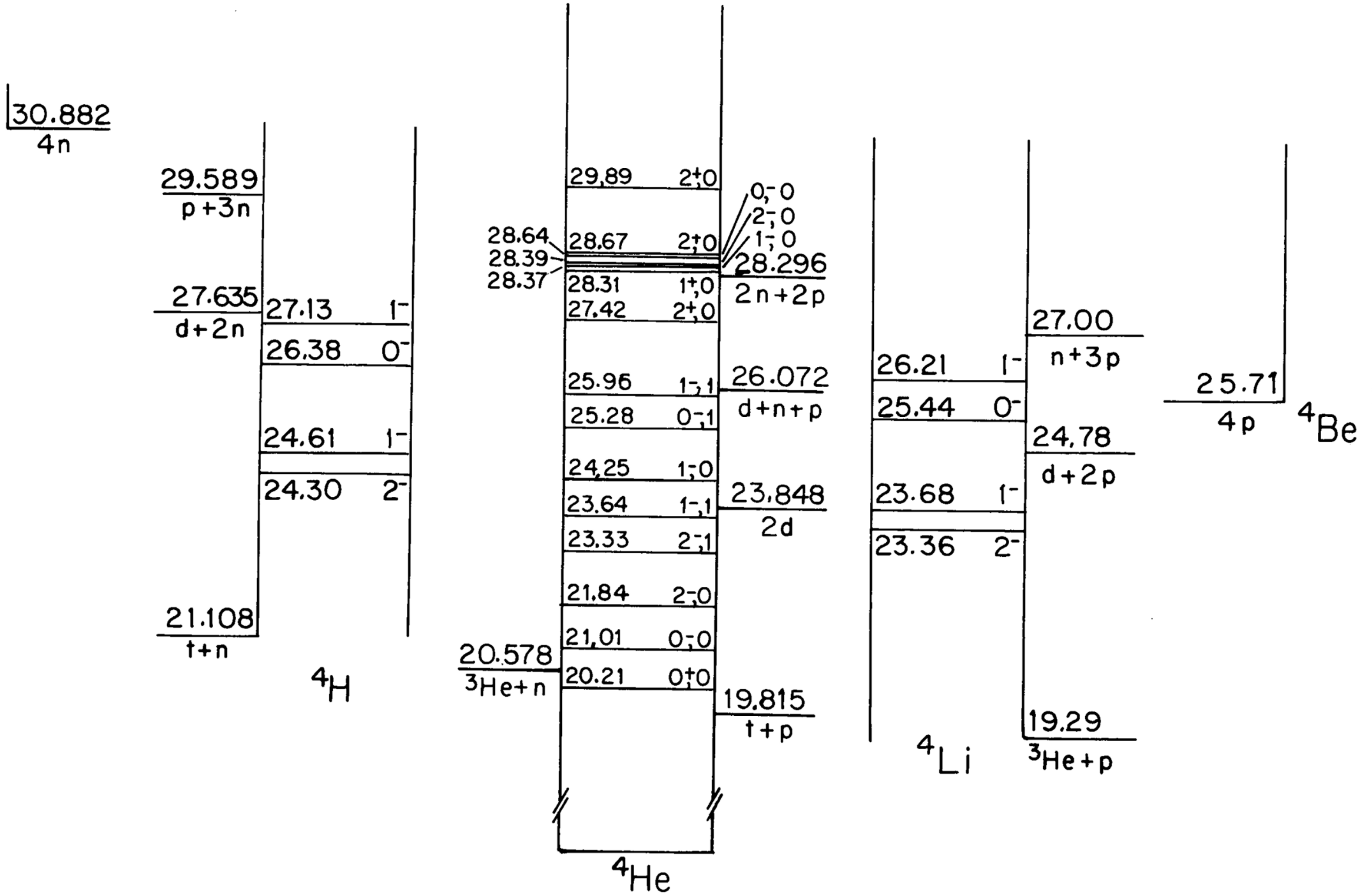


$^{8}He(p,p\alpha)^{4}n$



Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

A=4 Isobaric Analog States - IAS



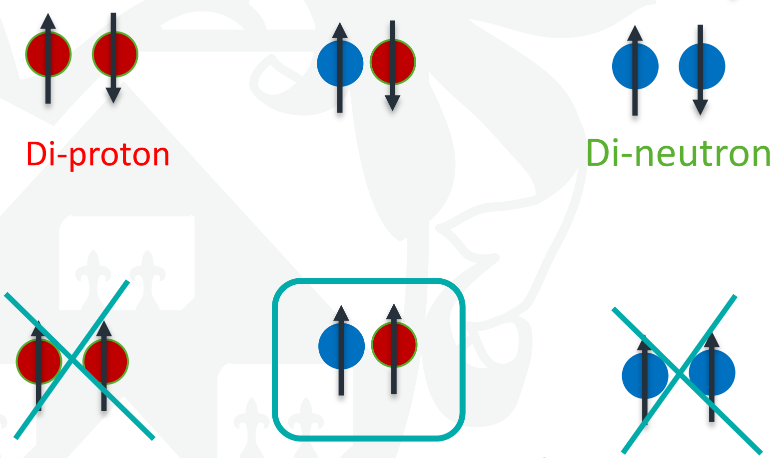
Nuclear Forces

Two-nucleon Systems:

T_z=-1 T_z=0 T_z=+1

is known to be just unbound by only about 100 keV

T=1



Di-proton

Di-neutron

Spin$^\pi$ =0$^+$

T=0

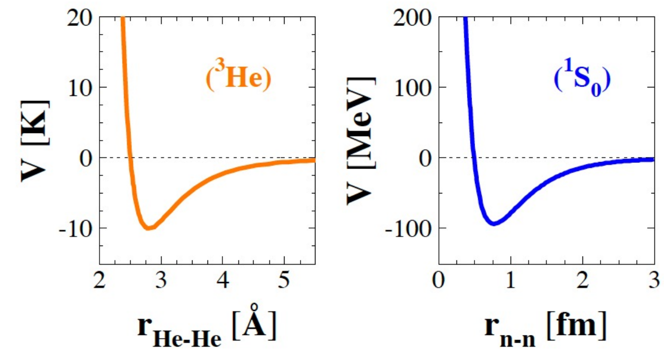
Spin$^\pi$ =1$^+$

Deuteron ground state

proton-proton proton-neutron neutron-neutron

R. Guardiola, PRL 84, 1144 (2000)

- $(^3He)_2$ (✘) ··· $(^3He)_N$ (✔): N ~ 30



- few-body fermionic systems
- T = 3/2 component of three-nucleon forces
- coupling to the continuum

Low Energy Structures in Nuclear Reactions with 4n in the Final State

Lazauskas, PRL 130 (2022) 102501

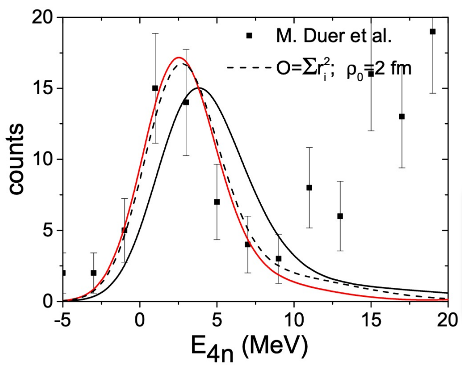
UNIVERSITY of York

"complement the analysis of the $^{8}He(p, p^{4}He)4n$ reaction, by addressing shortcomings of the COSMA model in three essential ways":

i. implementing a realistic description of the 8He valence neutron distribution,
ii. implementing a rigorous dynamics for the four-neutron break-up, and
iii. considering the interaction between valence neutrons in full extent and retaining consistency between the multineutron Hamiltonians before and after the α-particle removal.

We show that these experimental results find a natural explanation in terms of the dineutron correlations in the final state, if the four neutrons are weakly bound in the initial projectile, forming a broad wave function.

"Low energy structures in nuclear reactions with 4n in the final state"



? Dependency on:
how we produce it &
how we measure it

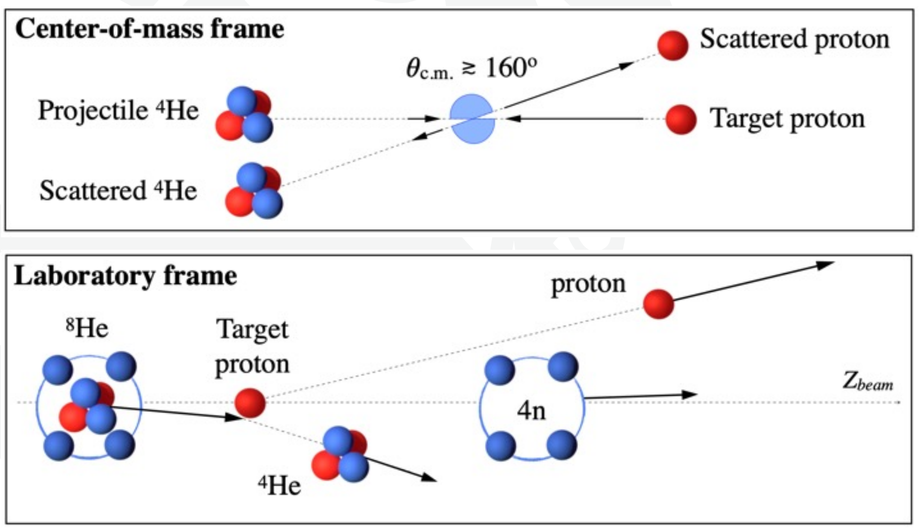
strong sensitivity of the response function to the neutrons' initial distribution inside ^{8}He

Method

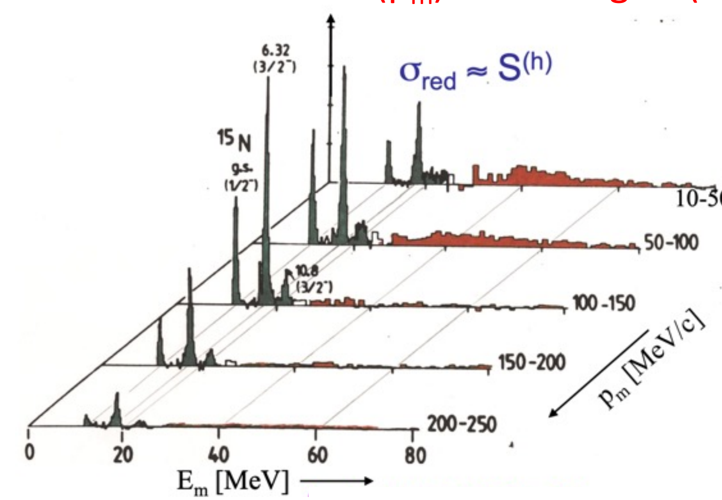
$^{8}He(p,p\alpha)^{4}n$ Quasi-Elastic knockout reaction at large momentum transfer

- Large momentum transfer minimizes final state interactions between the 4n and the (p, α).

Quasi-elastic scattering of α in ^{8}He



Spectral function:
distribution of mom. (p_m) and energies (E_m)



Minimizing FSI at larger mom. transfer: ^{16}O (e,e'p)

J. Mougey, Nucl. Phys. A335 (1980) 35.

Acknowledgements

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BMBF projects No. 05P15RDFN1, 05P15WOFNA, and 05P15WOCIA, by
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by JSPS KAKENHI Grant No. JP16H02177, JP16H02179, and JP18H05404,,
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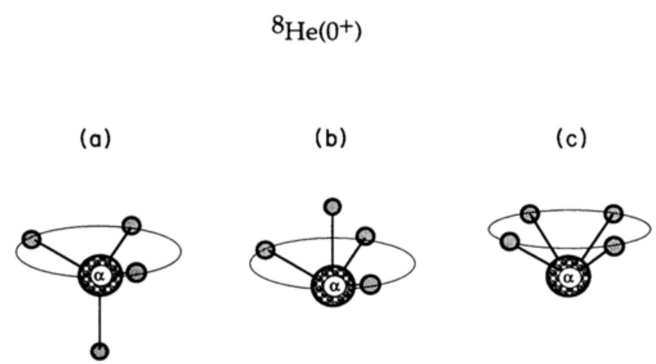
HIC for FAIR and Croatian Science Foundation under projects No. 1257 and 7194. Z. E., Z. H.,
by NKFIH grants No. 114454, 128947 and GINOP-2.3.3-15-2016-00034

Overlap of the ^{4}n wavefunction with that of the residual 4n system emerging from ^{8}He

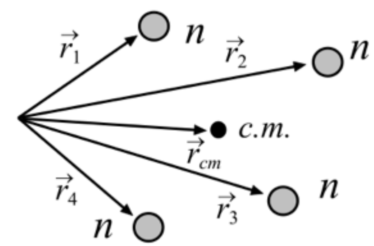
The ^{8}He WF has been considered within the COSMA model:

a simple five-body cluster orbital shell model approximation



I. initial structure
II. reaction mechanism, and
III. final-state interaction (FSI)

^4n



Two of the three most probable configurations found in ^{8}He can be associated with a ^{4}n system. The probability for each of them is approx. 30%.
M.V. Zhukov, PRC 50, R1 (1994)

"Sudden removal of the α-particle from ^{8}He"
The exact case of interest is studied within the COSMA model.
L.V. Grigorenko et al., EPJA 19, 187 (2004)

Overlap of the ^{4}n wavefunction with that of the residual 4n system emerging from ^{8}He

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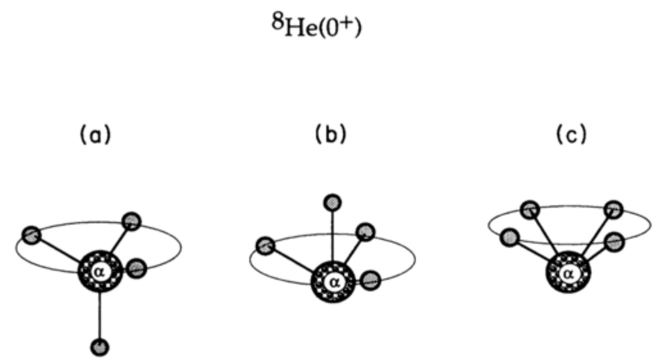
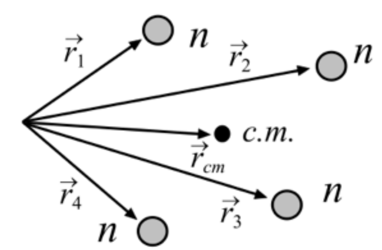


I. initial structure
II. reaction mechanism, and
III. final-state interaction (FSI)

^4n



Two of the three most probable configurations found in ^{8}He can be associated with a ^{4}n system. The probability for each of them is approx. 30%. M.V. Zhukov, PRC 50, R1 (1994)

Transformation of ^{8}He WF into the 4-n c.m. system with proper anti-symmetrization indeed has a significant l = 0 component as the expected for the ^{4}n ground-state configuration.

Overlap of the ^{4}n wavefunction with that of the residual 4n system emerging from ^{8}He

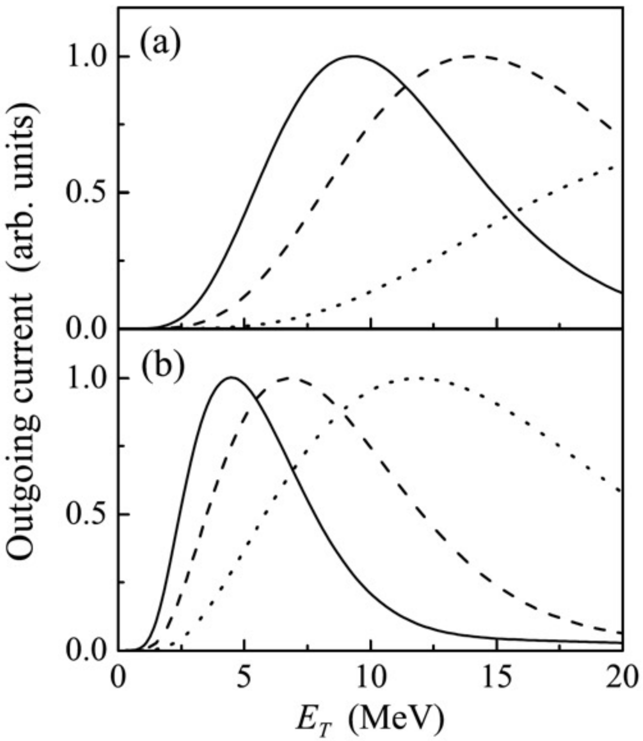
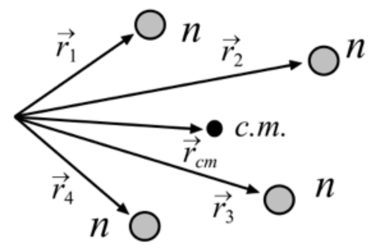


Fig. 11. Continuum response of the ^{4}n system in the MWS with a "Gaussian" source (13). Solid, dashed and dotted curves correspond to rms hyperradius $\langle \rho_{sour} \rangle$ of the source equal to 8.9, 7.3, and 5.6 fm, respectively. Panels are calculated with (a) no final-state interaction, (b)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

source function : overlap between the ^{8}He and α-particle wave functions. The source function results from a representation of the wave function in the internal variables of the four-neutron system (hyperradius of 4n, angles and hyperangles of 4n), and apha-4n relative motion and a proper transformation of the ^{8}He wave function to the valence-neutron c.m. coordinates.

I. initial structure
II. reaction mechanism, and
III. final-state interaction (FSI)

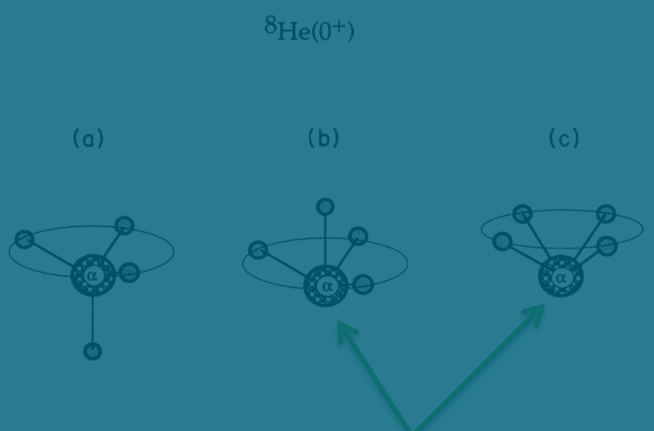


"Sudden removal of the α-particle from ^{8}He"
The exact case of interest is studied within the COSMA model.
L.V. Grigorenko et al., EPJA 19, 187 (2004)

Structure of ^{8}He

five-body Hamiltonian in the Hartree-Fock-Bogoliubov approximation.

The ^{8}He WF has been considered within the COSMA, a simple five-body cluster orbital shell model approximation



Two of the three most probable configurations found in ^{8}He can be associated with a ^{4}n system. The probability for each of them is approx. 30%.
M.V. Zhukov, PRC 50, R1 (1994)

Critisism:

… where the authors constructed the ground state wave function by assuming that the four neutrons occupy the $1p_{3/2}$ state in a harmonic oscillator potential. However, this model is too simplistic, since it completely neglects the pairing correlation and the continuum couplings….

……..pairing leads to strong dineutron structure in ^{8}He

K. Hagino, N. Takahashi, and H Sagawa
PRC 77, 054317 (2008)

recent theoretical studies

Is a trineutron resonance lower
in energy than a tetraneutron resonance?

S. Gandolfi *et al.*,
arXiv:1612.01502v1 [nucl-th] 5 Dec 2016

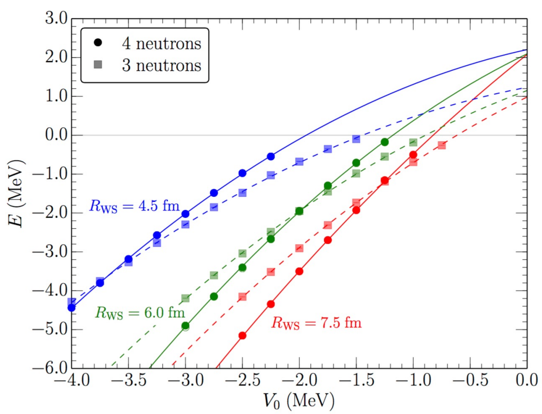


FIG. 1. The energy of three (squares) and four (circles) neutrons in external Woods-Saxon potentials for varying radius R_{WS} as a function of the well depth V_0. The blue/upper lines correspond to $R_{WS} = 4.5$ fm, the green/middle lines to $R_{WS} = 6$ fm, and the red/lower lines to $R_{WS} = 7.5$ fm. In each case, a quadratic fit to the AFDMC results was obtained and used to extrapolate to the zero-well-depth limit.

Quantum Monte Carlo with
N^2LO chiral EFT

Prediction for a Four-Neutron Resonance

A. M. Shirokov *et al.*, PRL 117, 182502 (2016)

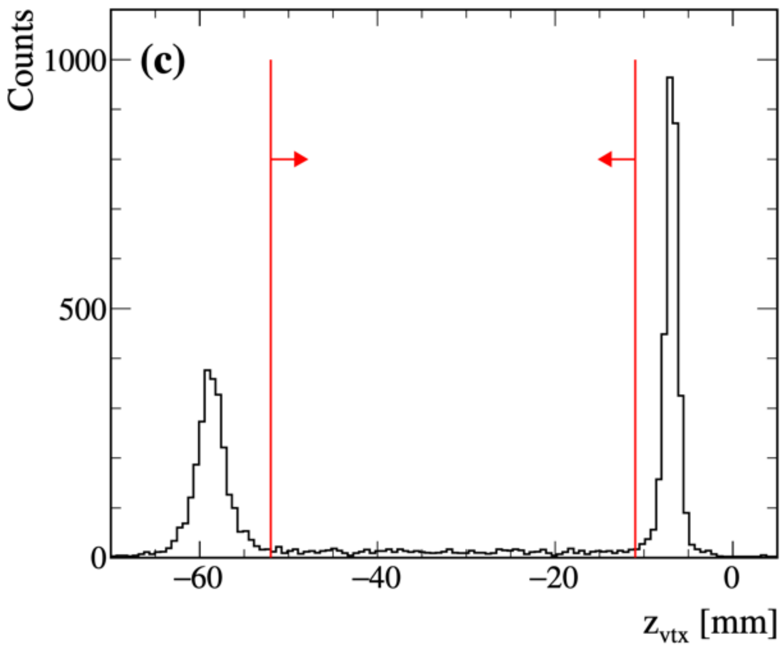
"The respective 4n resonance at E_r = 0.844 MeV and width Γ = 1.378 MeV appears consistent with what is expected from directly inspecting the 4n phase shifts and what is predicted to be seen experimentally."

NCSM + J-matrix with JISP16

Possibility of generating a 4-neutron resonance with a T = 3/2 isospin 3-neutron force

E. Hiyama *et al.*, PRC 93, 044004 (2016)

"In conclusion, we were not able to validate the recent observation of a 4n signal as related to the existence of resonant 4n states."


Counts
1000
500
0
(c)
−60
−40
−20
0
z_{vtx} [mm]

Very light nuclei

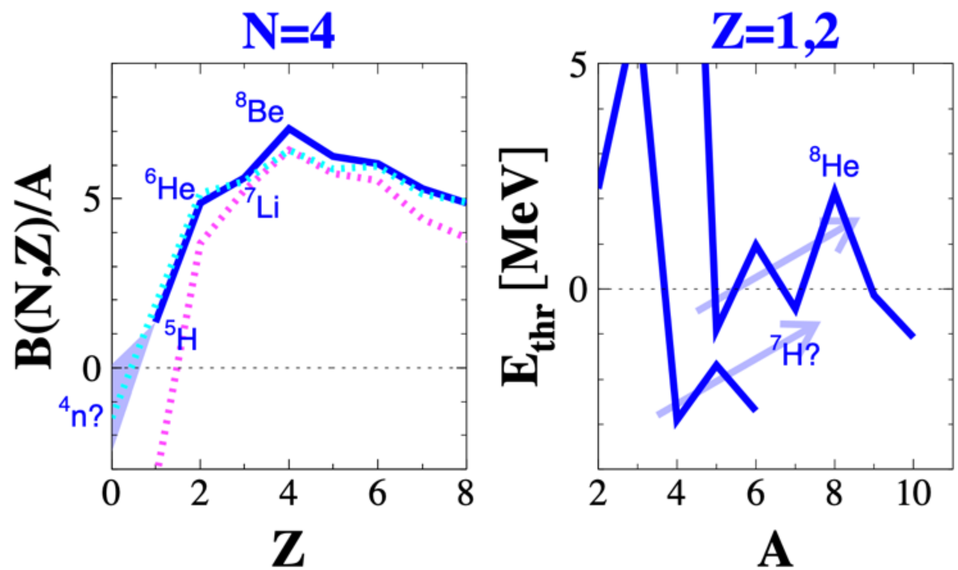
Systematics – SEMF

$$B(A,Z) = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{asym}\frac{(A-2Z)^2}{A} \pm \delta$$

If one naively uses best fitted parameters from the entire nuclear chart:

a_v =15.5MeV
a_S =16.8MeV
a_C =0.72MeV
a_{asym} =23.0MeV and
$\delta = \pm 11\ A^{-1/2}$ MeV or 0

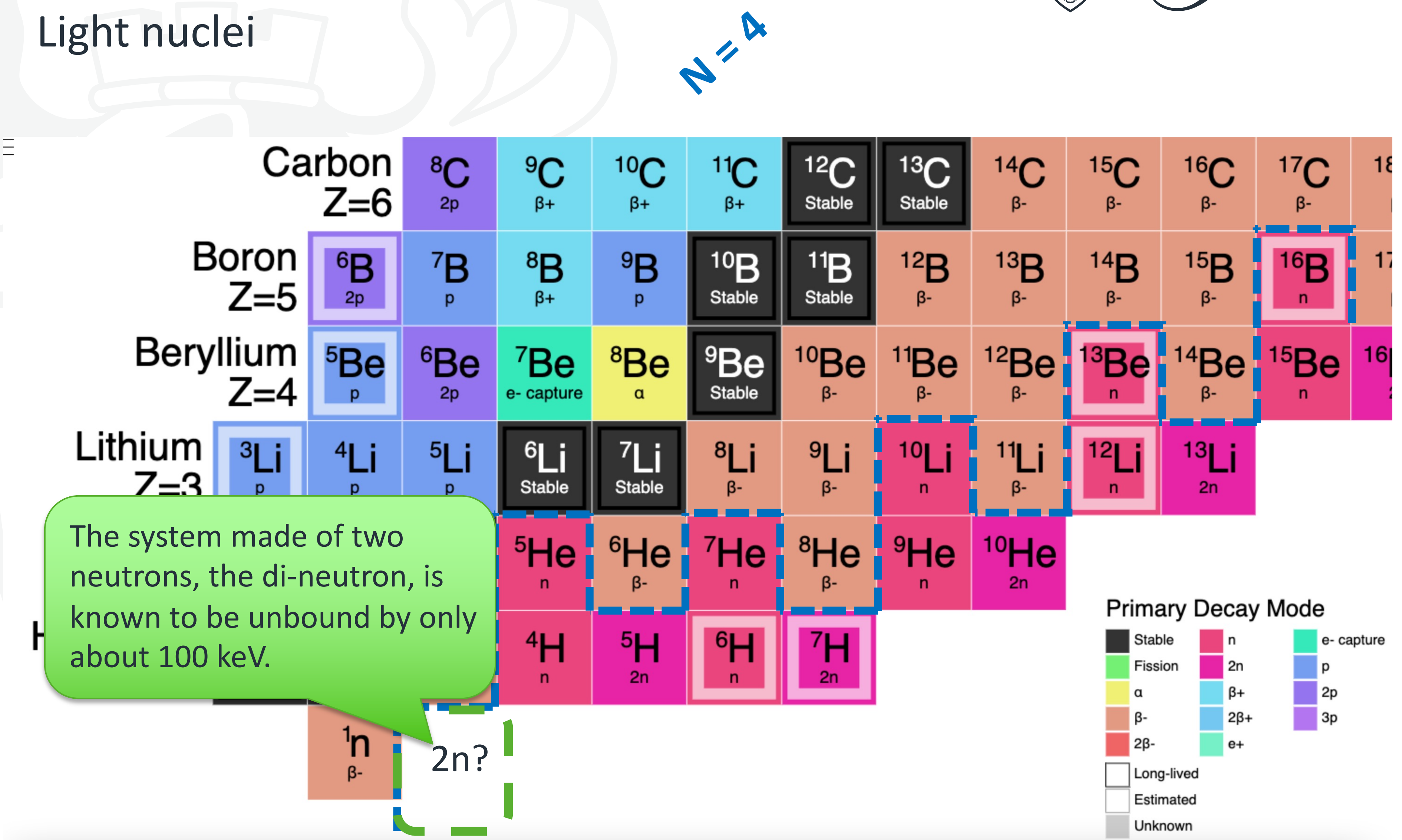
B/A = - 15 MeV



Figures by F.M. Marques

Nuclear landscape

Light nuclei



NN interaction
Delicate balance
Nature of the interactrion is such that deuteron is bound in T=0 channel and
Then resonance for the nn

Could 3-body give rise to enhanced stability…

T=3/2

Paper by Ben Bayman

Then proceed with experimental history, some theory prediction

Cabonelli

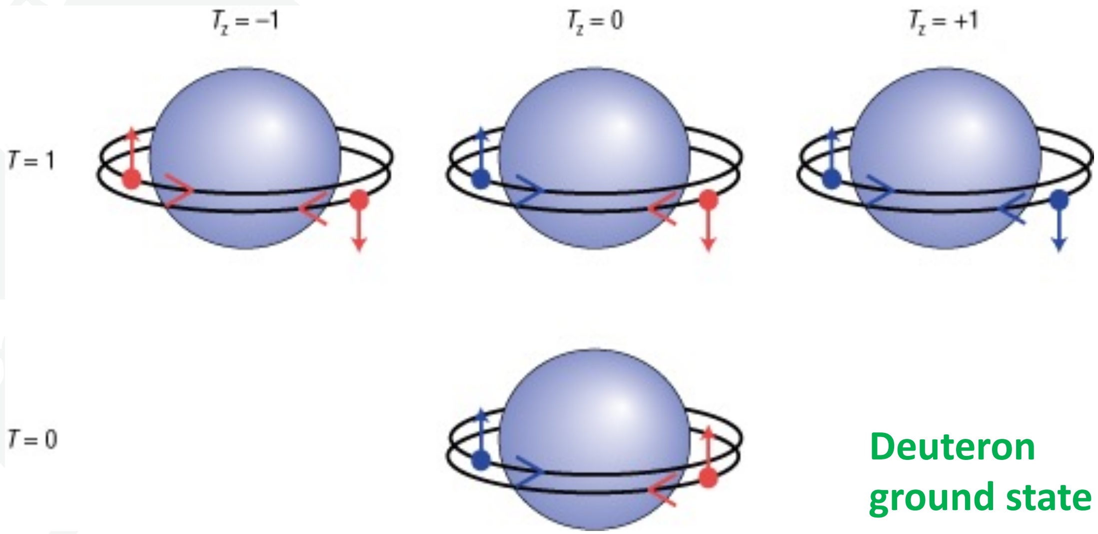
Nuclear Forces

Two-nucleon Systems

Di-proton

Deuteron excited resonant state

Di-neutron



Deuteron ground state

Spin/parity $=0^+$

Spin/parity $=1^+$

proton-proton

proton-neutron

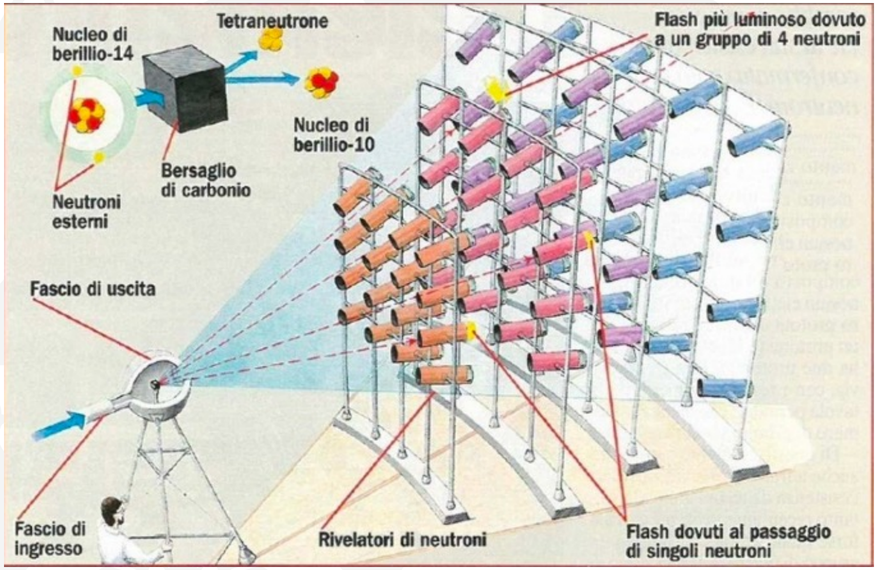
neutron-neutron

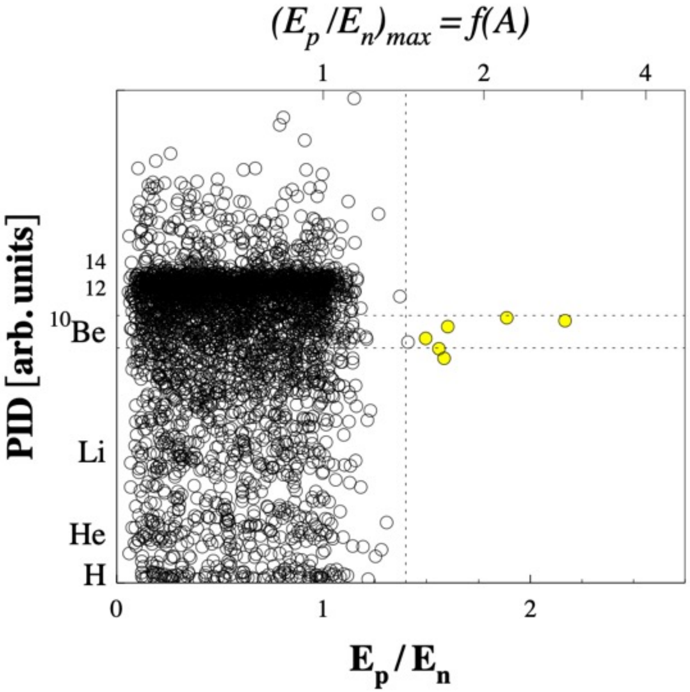
A 60-year quest

Experimental work – GANIL – 2002

C (^{14}Be, ^{10}Be) 4n

^{14}Be breakup on a carbon target





➢ The 6 events are consistent with bound ^{4}n or a low-energy resonance (E<2 MeV)

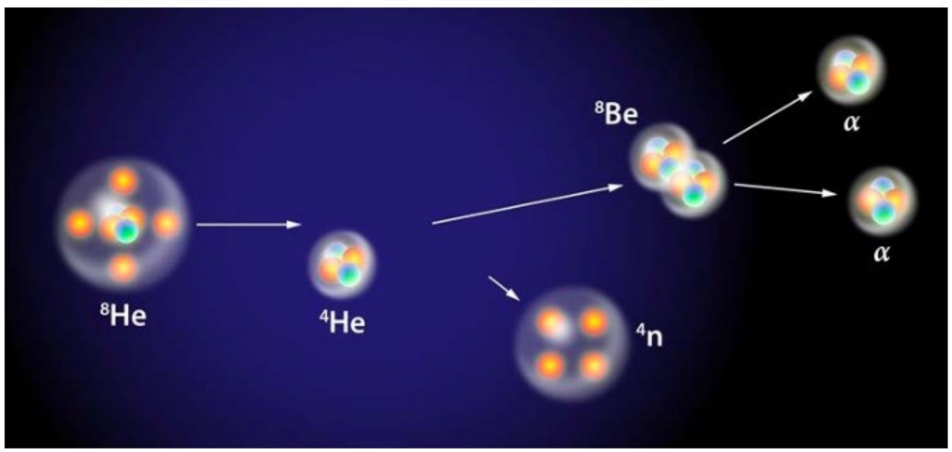
F.M. Marques et al., PRC 65, 044006 (2002) and arXiv:nucl-ex/0504009.

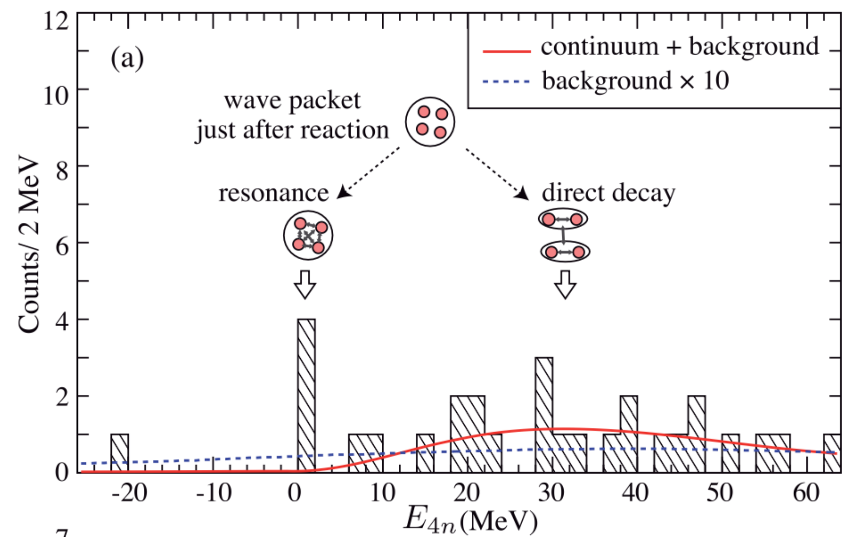
A 60-year quest

Experimental work – RIKEN – SHARAQ/RIBF – 2016

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

Double charge exchange reaction





➢ 4 events in the region 0 - 2MeV consistent with the formation of a tetraneutron resonance at E(4n) = 0.8 ± 1.3 MeV, Γ < 2.6 MeV

K. Kisamori et al., PRL 116, 052501 (2016)

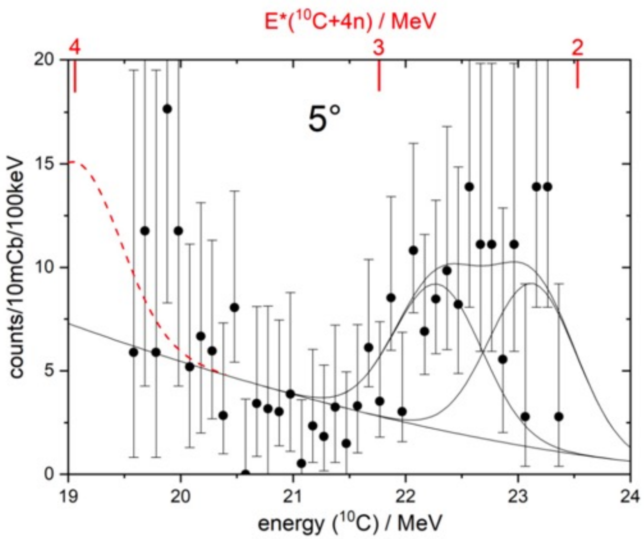
A 60-year quest

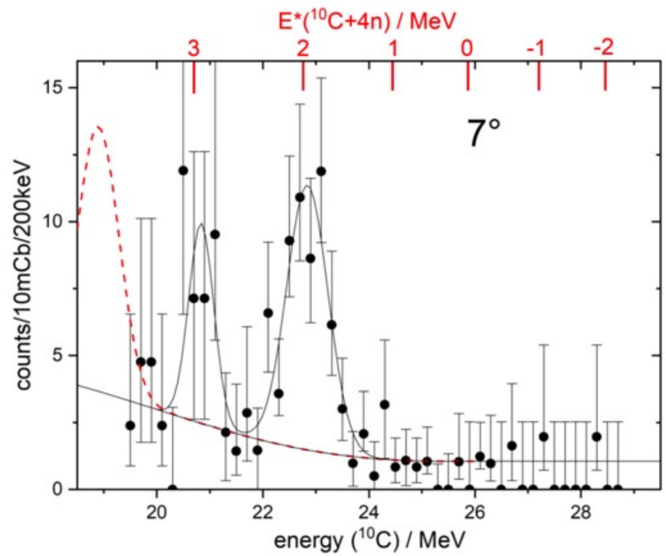
Experimental work – TUM – 2022

"Indications for a bound tetraneutron"

$^{7}Li(^{7}Li,^{10}C)\ ^{4}n$

Multi-nucleon transfer



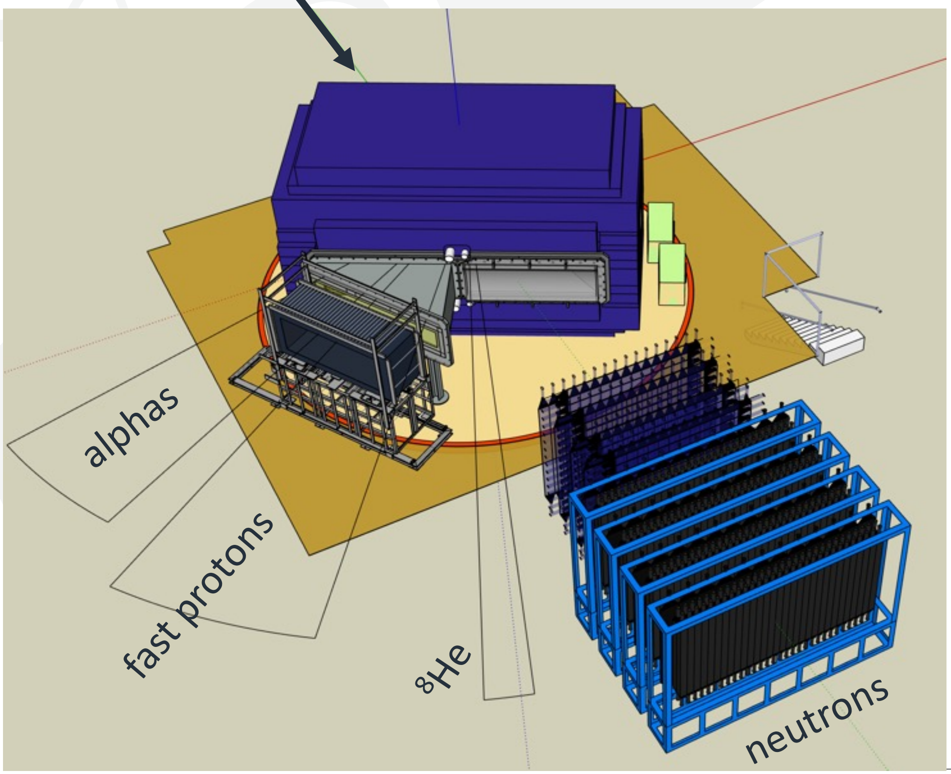


- Two possible explanations:
  1. a ^{4}n state unbound by 2.93 MeV and an extraordinarily small width ($\Gamma < 0.24$ MeV)
  2. the ^{10}C is in the first excited state and the 4n has a bound state with a binding energy of BE=+0.42(16) MeV

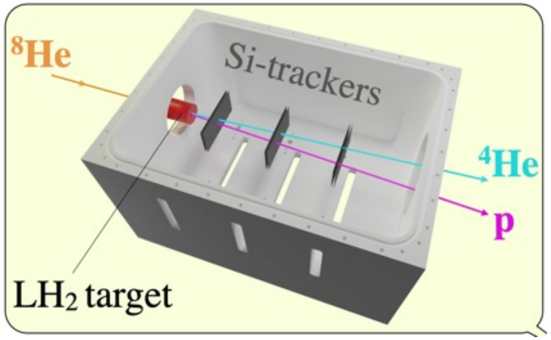
Experimental setup

SAMURAI at RIBF/RIKEN

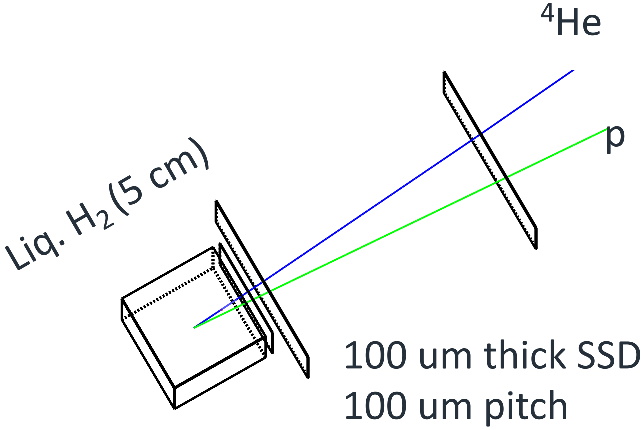
incoming ^{8}He beam from BigRIPS



Precise vertex reconstruction



Si tracker: TU Munich & SAMURAI

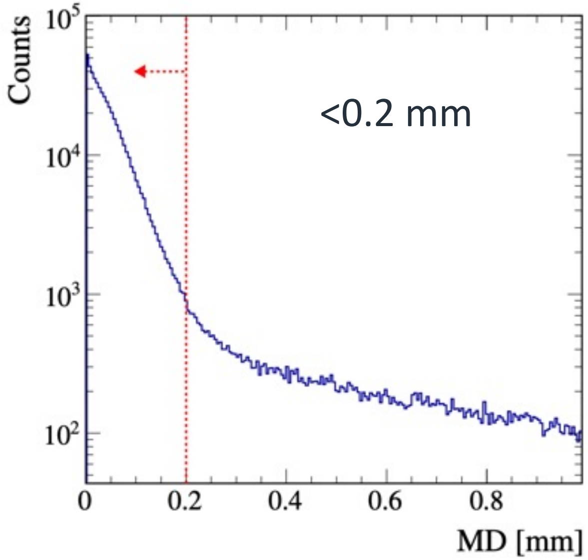


100 um thick SSDs
100 um pitch
Readout by the APV ASIC

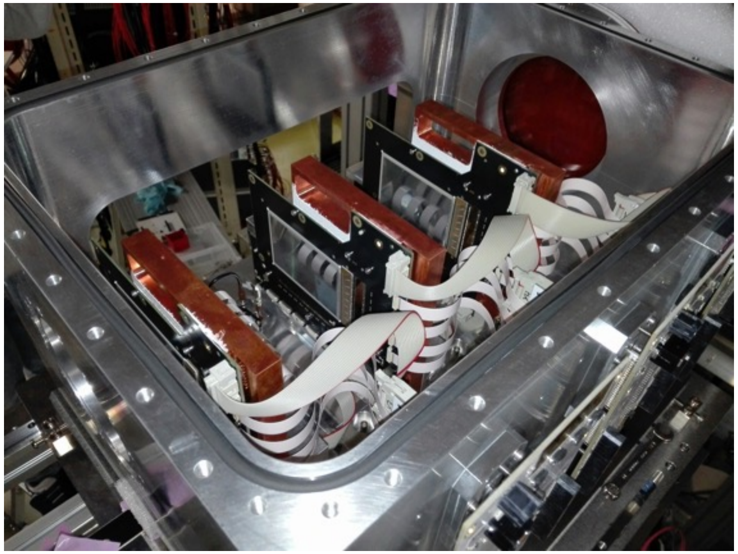
Experimental setup

SAMURAI at RIBF/RIKEN

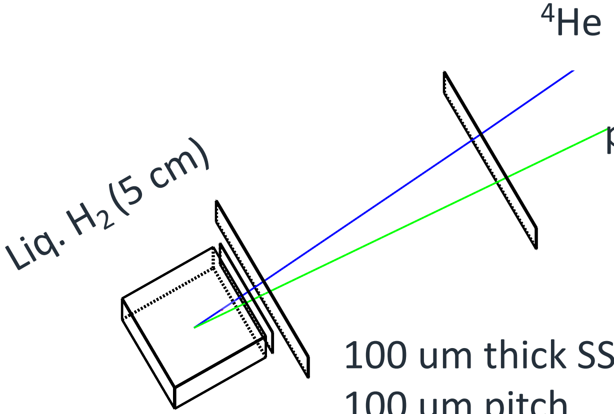
Reaction vertex reconstruction



MINOS LH_2 target



Si tracker: TU Munich & SAMURAI



100 um thick SSDs
100 um pitch
Readout by the APV ASIC