Colloque GANIL 2023
Soustons, France

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

Observation of a correlated free four-neutron system

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

Mentions in news and blogs

Physicists may have finally spotted elusive clusters of four neutrons - TechNewsBoy.com

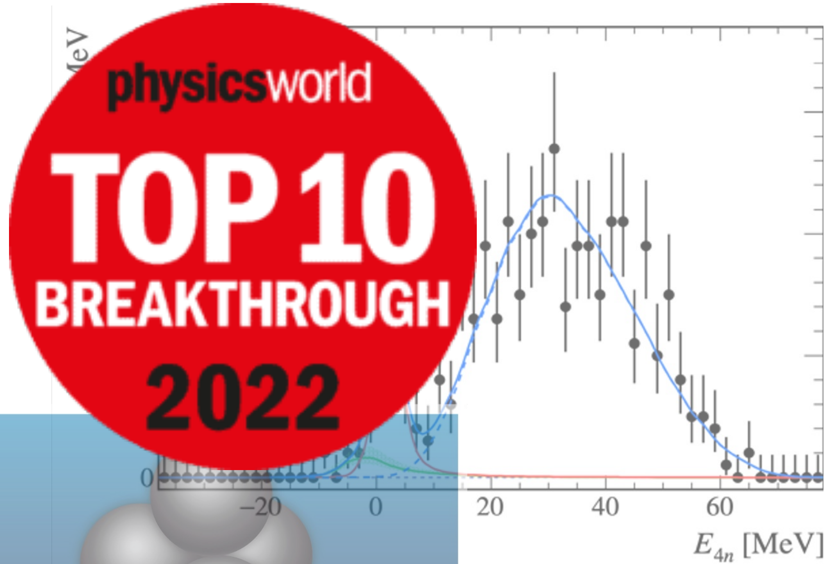
TechNewsBoy

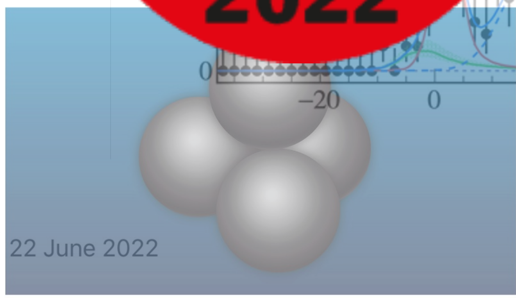
Long-sought particle of four neutrons discovered

Informationsdienst Wissenschaft

Long sought-after particle consisting of four neutrons discovered

Informationsdienst Wissenschaft





Access & Citations

56k	21	28
Article Accesses	Web of Science	CrossRef

NEWS AND VIEWS | 22 June 2022

Online attention

- 129 tweeters
- 44 news outlets
- 5 Wikipedia page
- 30 Mendeley
- 11 blogs
- 1 Redditors
- 3 Facebook pages
- 2 Video uploaders

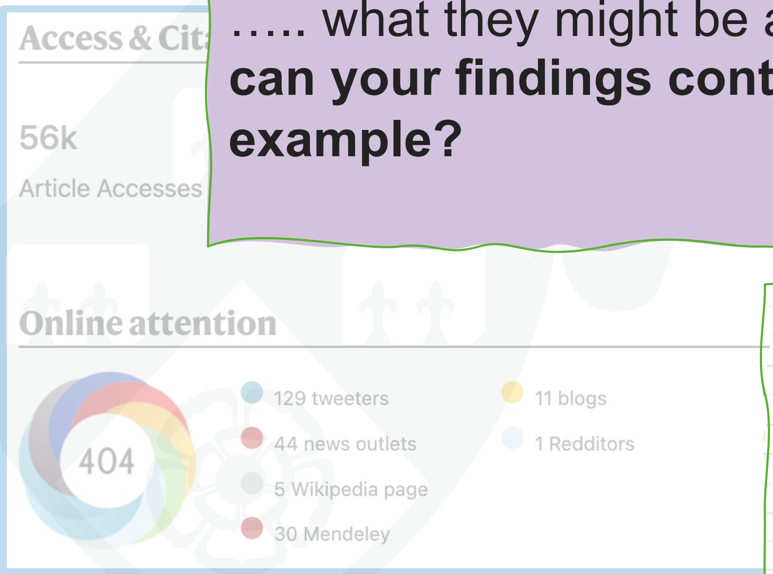
Collisions hint that four neutrons form a transient isolated entity

An experiment firing helium-8 nuclei at a proton target has generated evidence that four neutrons can exist transiently without any other matter. But doubts remain, because the existence of such systems is at odds with theory.

Lee G. Sobotka & Maria Piarulli

Observation of a correlated free four-neutron system

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



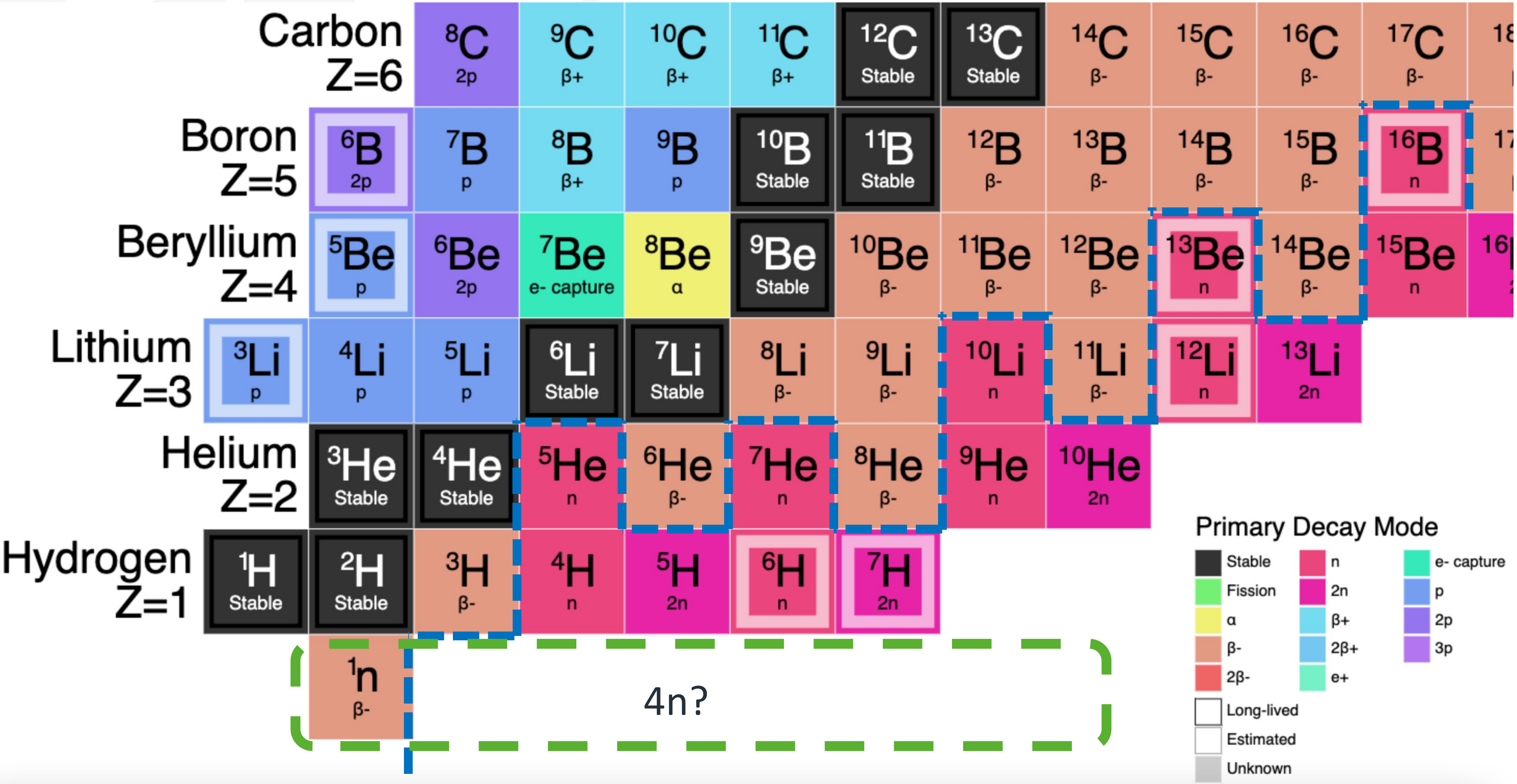
Head of Media Relations | The University of York

Thanks for the summary; it is quite a tricky one for a lay person to grasp…..

….. what they might be able to tell us **about the 'Big Bang', so can your findings contribute to that conversation for example?**

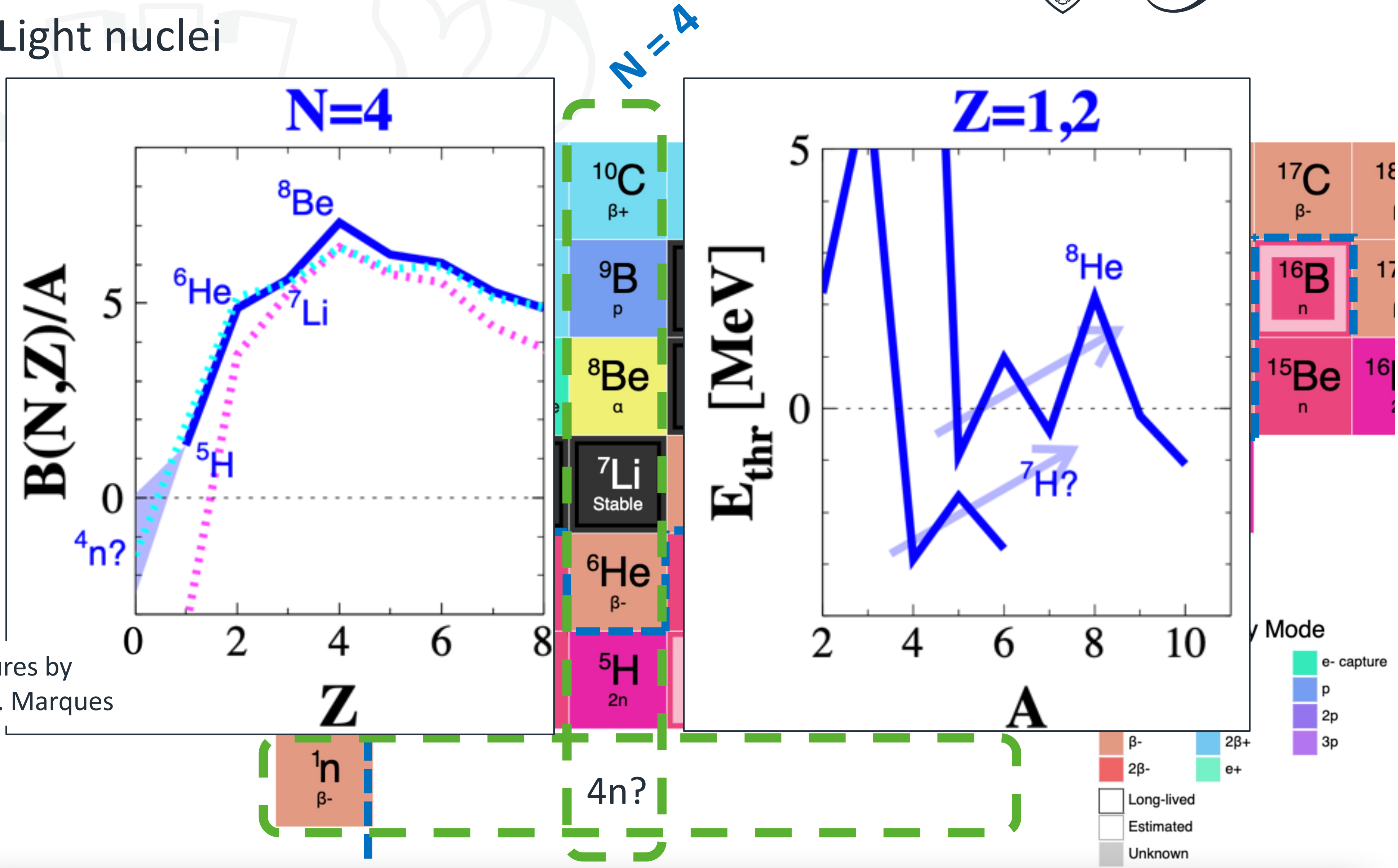
Nuclear landscape

Light nuclei



Nuclear landscape

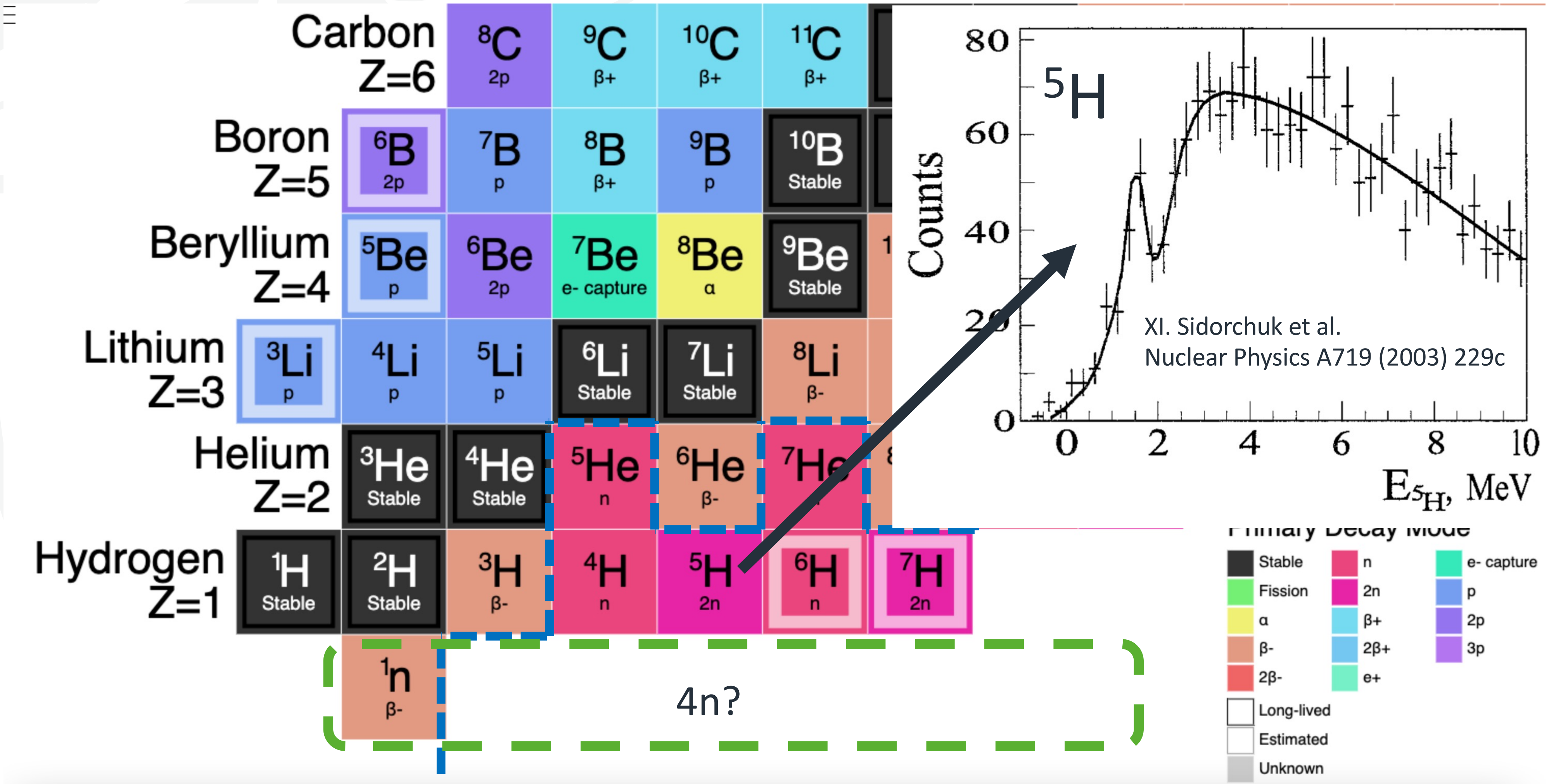
Light nuclei



Figures by
F.M. Marques

Nuclear landscape

Light nuclei



Nuclear Forces

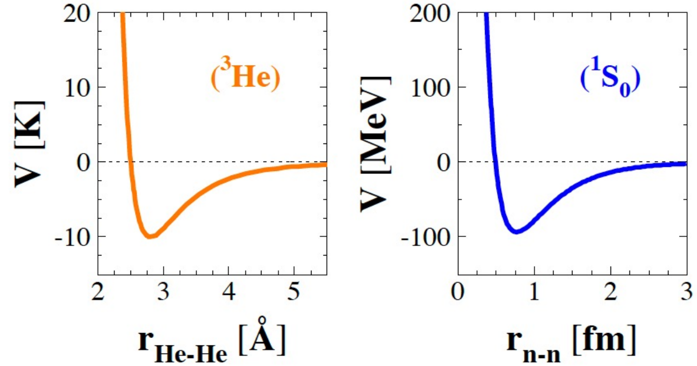
is known to be just unbound by only about 100 keV

Two-nucleon Systems:

	$T_z=-1$	$T_z=0$	$T_z=+1$	
T=1	Di-proton		Di-neutron	$\text{Spin}^{\pi}=0^{+}$
T=0		Deuteron ground state		$\text{Spin}^{\pi}=1^{+}$
	proton-proton	proton-neutron	neutron-neutron	

R. Guardiola, PRL 84, 1144 (2000)

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



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

A 60-year quest
of multi-neutron systems

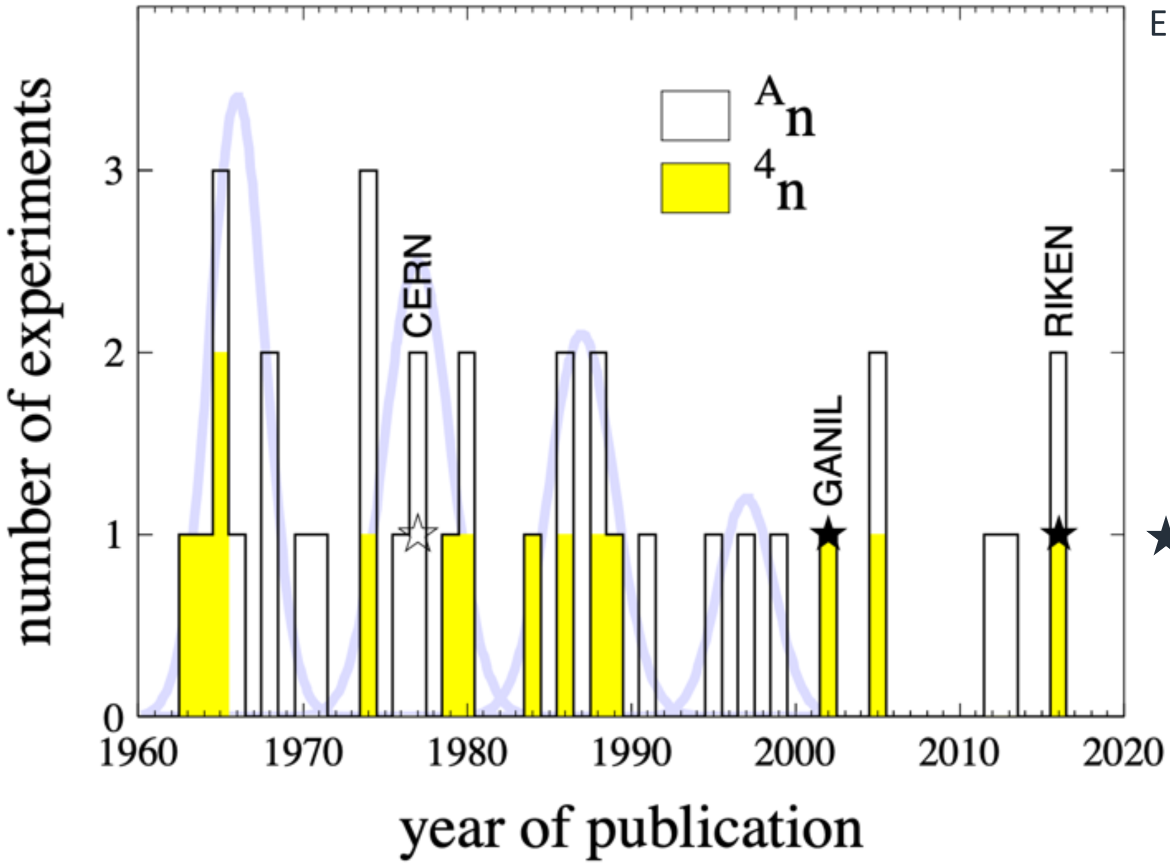
A 60-year quest

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)



★★

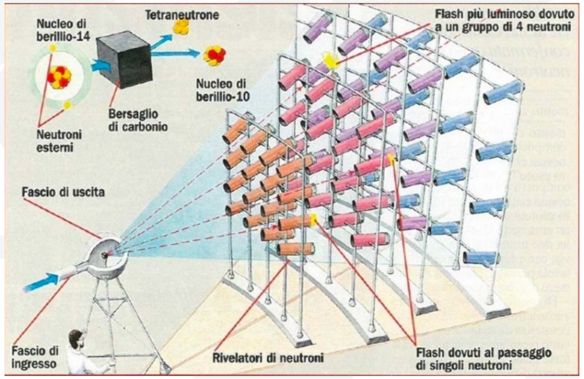
36+ experiments searching for multi-neutrons!!

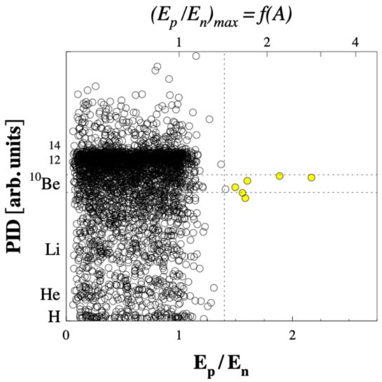
A 60-year quest

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)

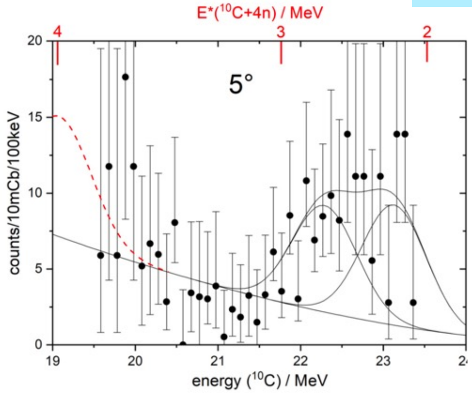
F.M. Marques et al., PRC 65, 044006 (2002) and arXiv:nucl-ex/0504009

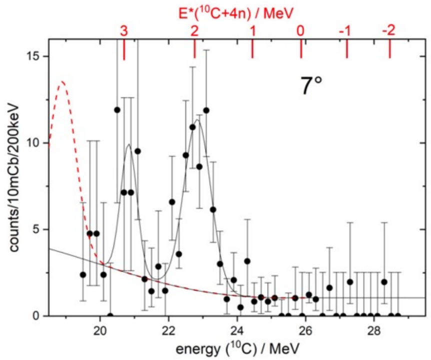
Thomas Faestermann et al., PLB 824 (2022) 136799

TUM – 2022

Multi-nucleon transfer

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





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

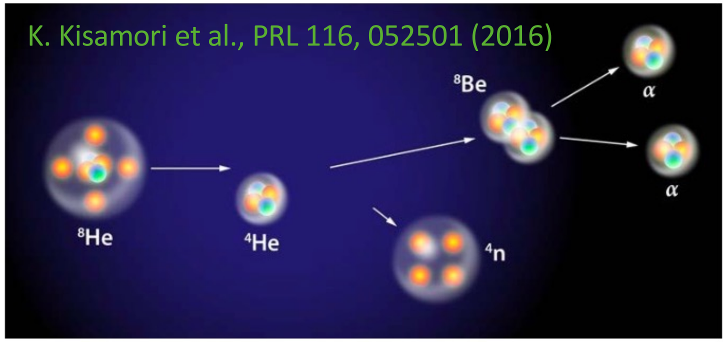
or

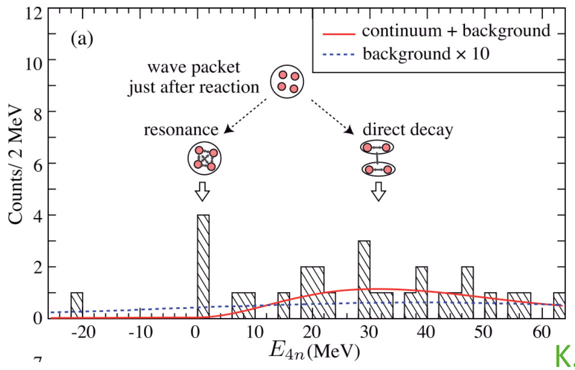
- 4n bound by 0.42(16) MeV & ^{10}C in 1st excited state

RIKEN – SHARAQ/RIBF – 2016

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

Double charge exchange reaction





- 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

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

Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?

Steven C. Pieper*

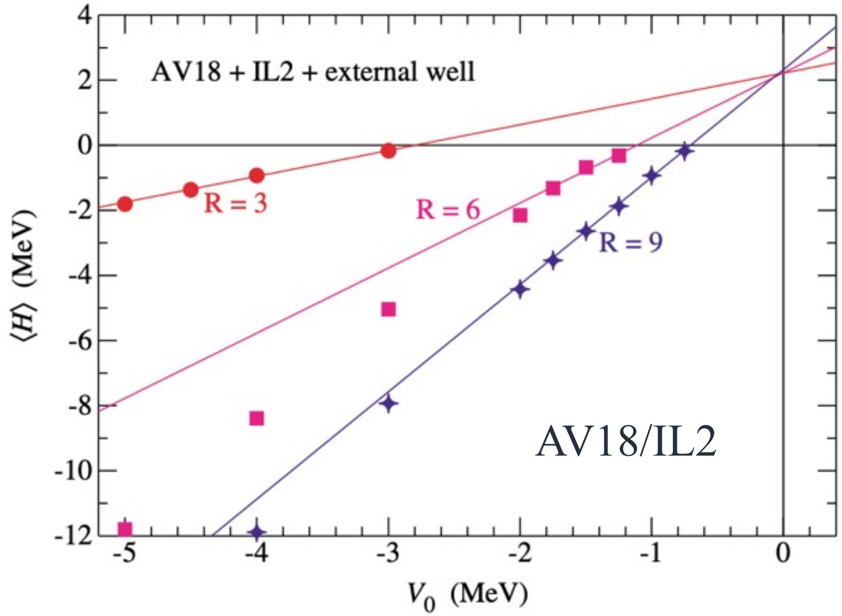


FIG. 1 (color online). Energies of ^4n in external wells versus the well-depth parameter V_0.

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

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)

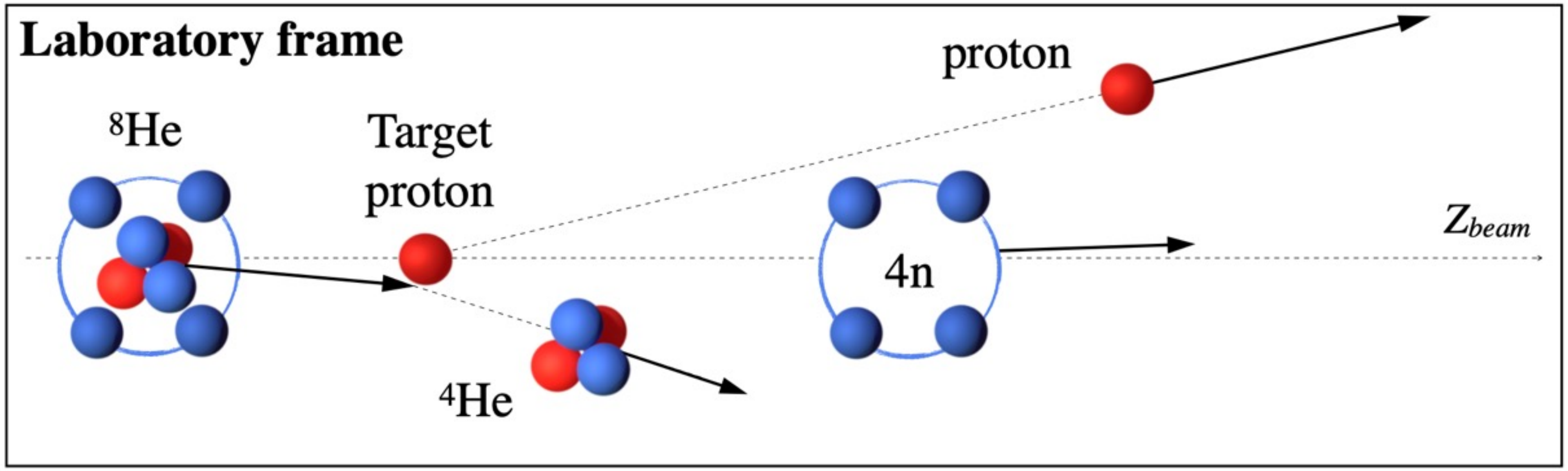
Method

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

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



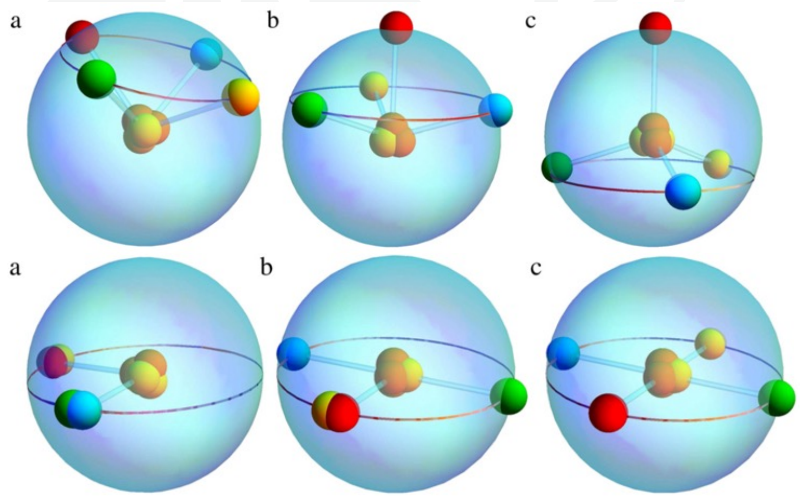
Method

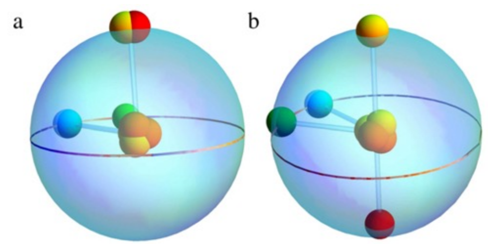
^{8}He(p,pα)^{4}n Quasi-Elastic knockout reaction at large momentum transfer

- ^{8}He a good starting point to populate a 4n system. Highest possible A/Z=4. Well-formed α cluster. Large overlap $\langle {}^{8}\mathrm{He} \mid \alpha \otimes 4n \rangle$

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

Tetrahedral configurations





Great circle configurations

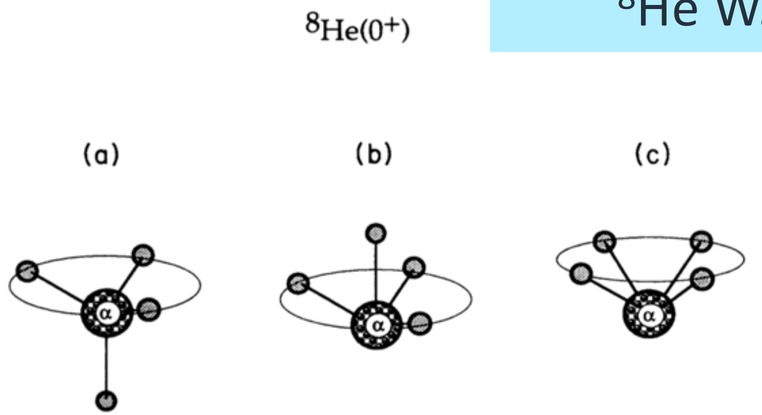
P. Mei, P. Van Isacker , Annals of Physics 327 (2012) 1182–1201

Method

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

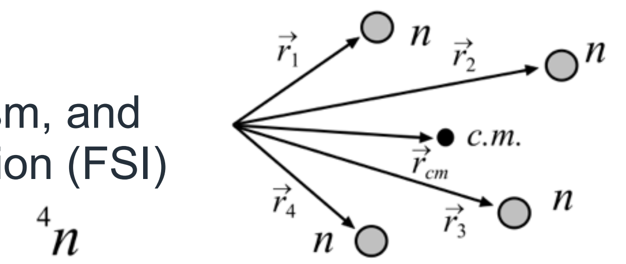
- ^{8}He a good starting point to populate a 4n system. Highest possible A/Z=4.

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



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

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



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.

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

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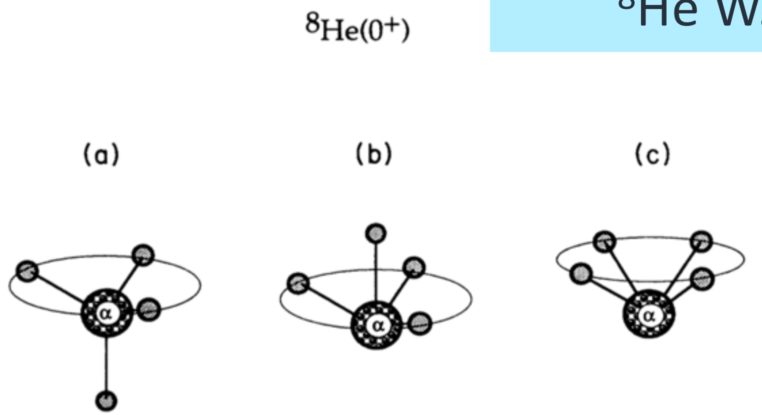

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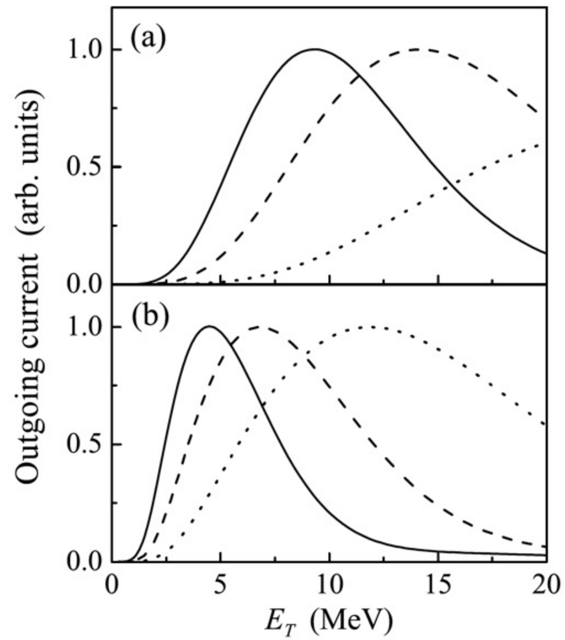
II. reaction mechanism,
III. final-state interaction



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M.V. Zhukov, PRC 50, R1 (1994)

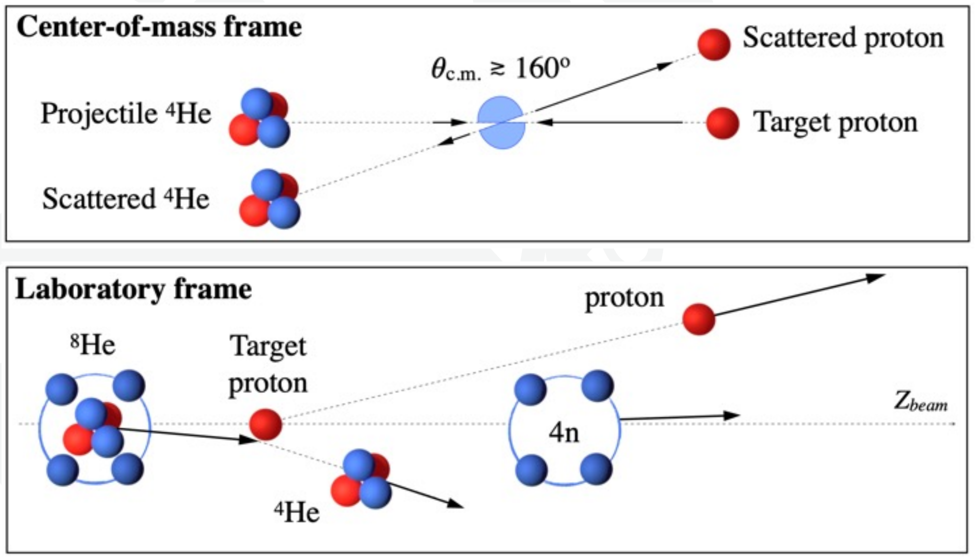
"Sudden remova
The exact case
the COSMA moc
L.V. Grigorenko e

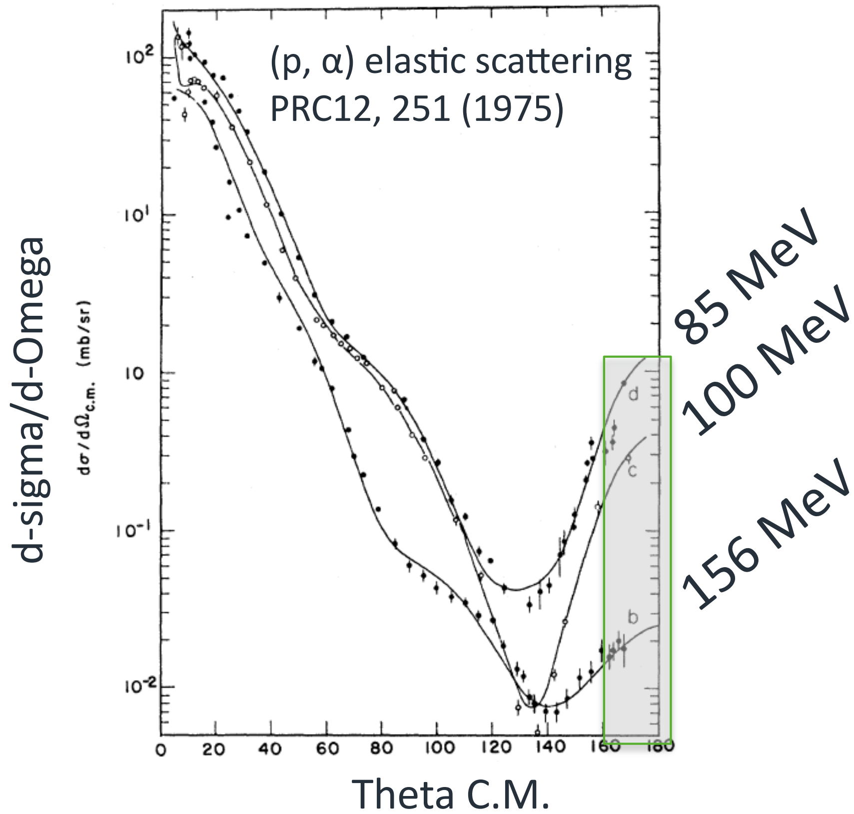
Method

^{8}He(p,pα)^{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

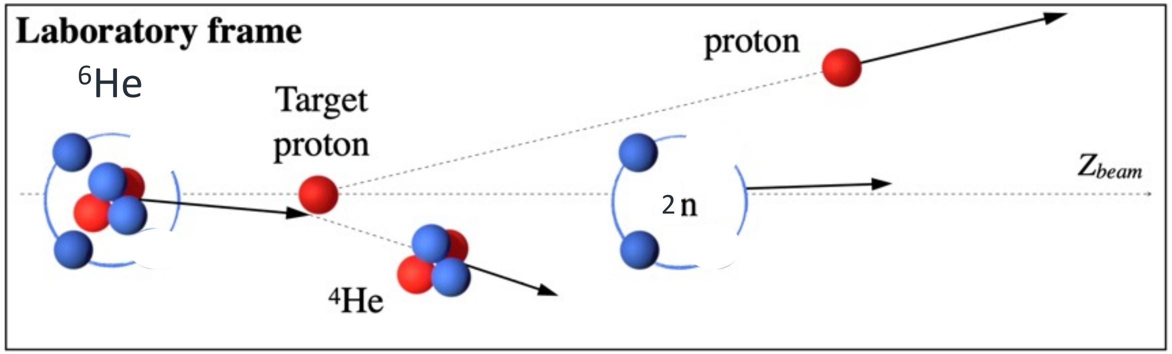


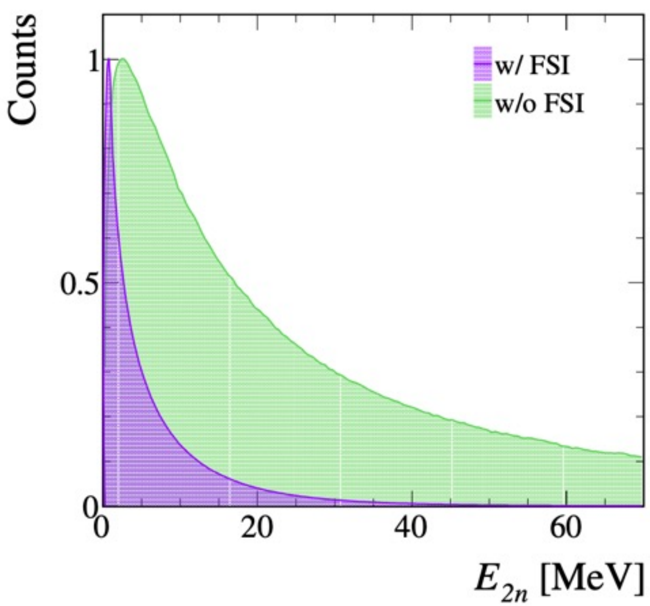


Method

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

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

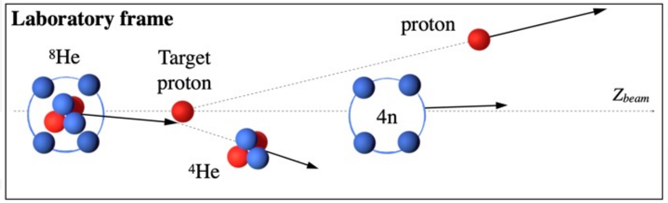


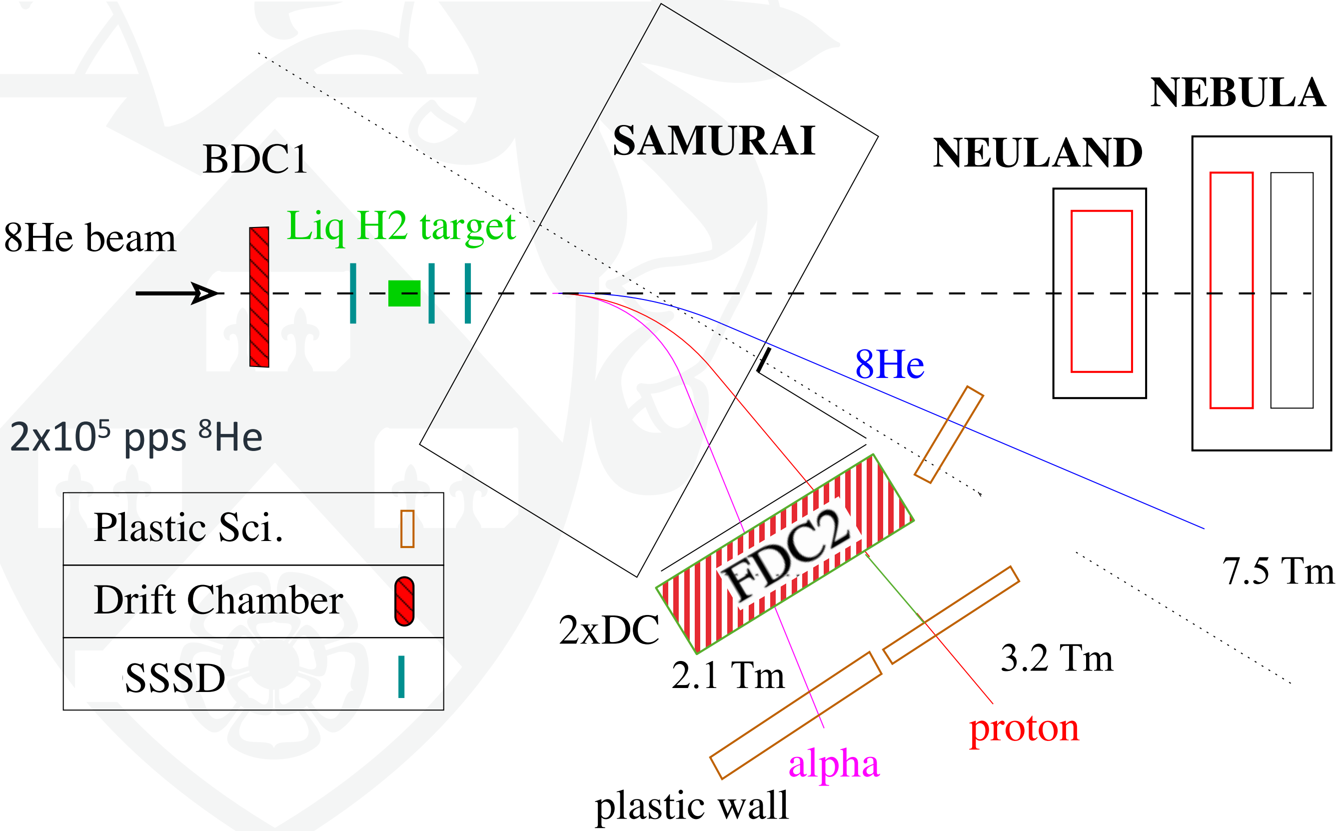


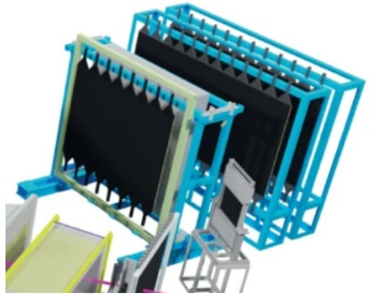
Theory:
Göbel, M. et al., “Neutron-neutron scattering length from the $^{6}He(p, p\alpha)nn$ reaction”
PRC 104, 024001 (2021).

Experimental setup

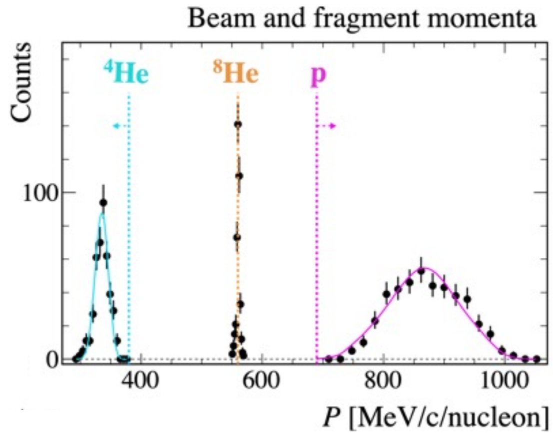
SAMURAI at RIBF/RIKEN







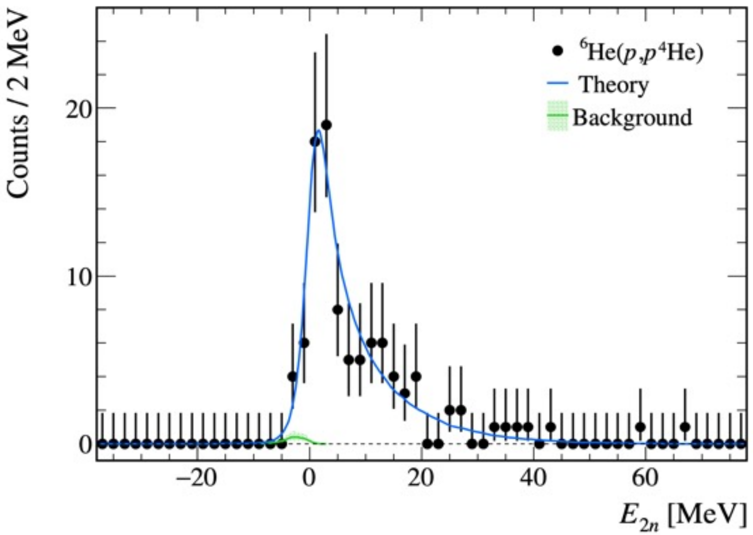
400 + 120 scintillator bars



Results:
Missing-mass spectra

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

two-neutron system



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Göbel, M. et al., “Neutron-neutron scattering length from the ^{6}He(p, pα)nn reaction”
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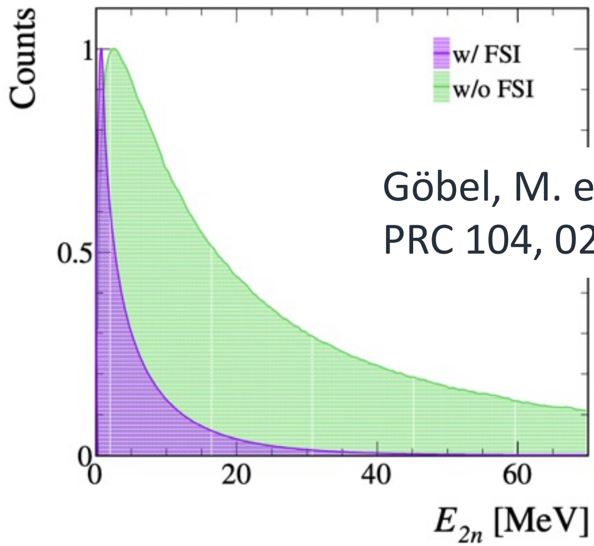


Göbel, M. et al.,
PRC 104, 024001 (2021)

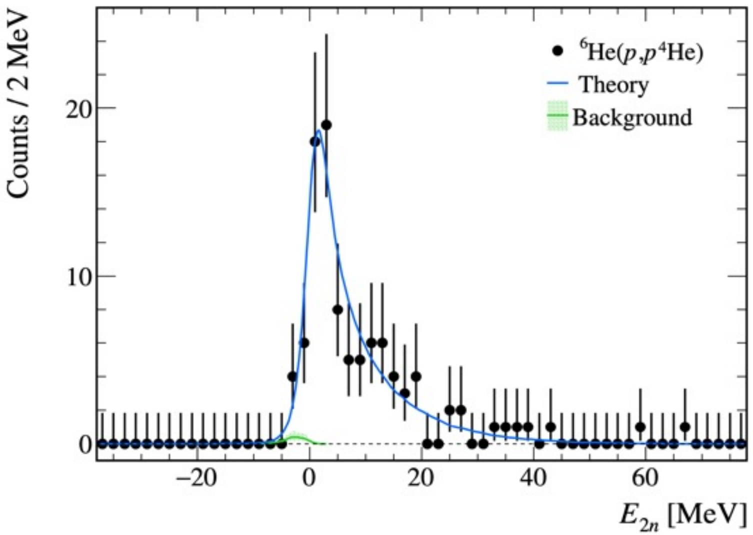
Confirming the expected low-energy structure for of di-neutron

“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**

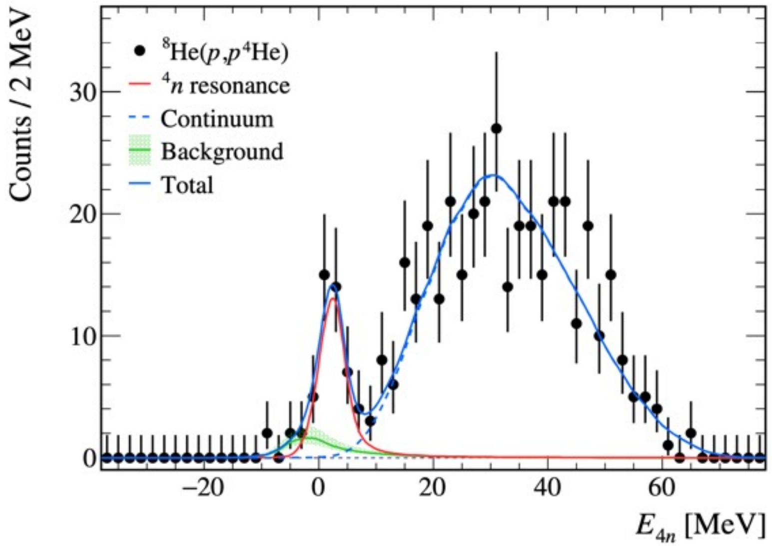
two-neutron system



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

^{8}He(p,pα)^{4}n

four-neutron system

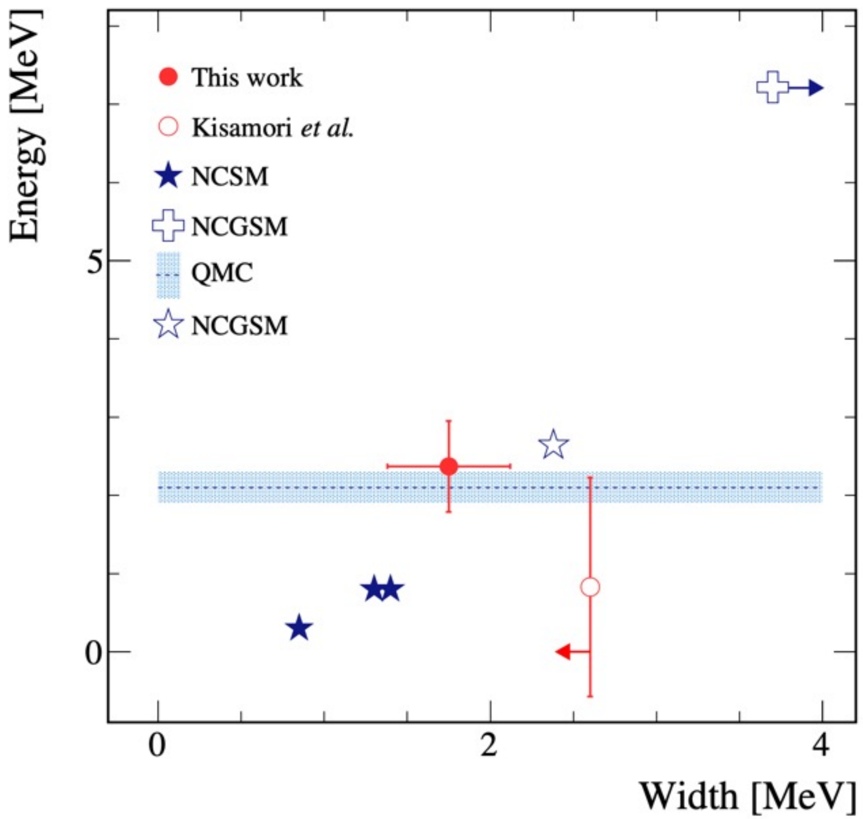


A near-threshold resonance-like structure:
E_r = 2.37 ± 0.38(stat.) ± 0.44(sys.) MeV

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

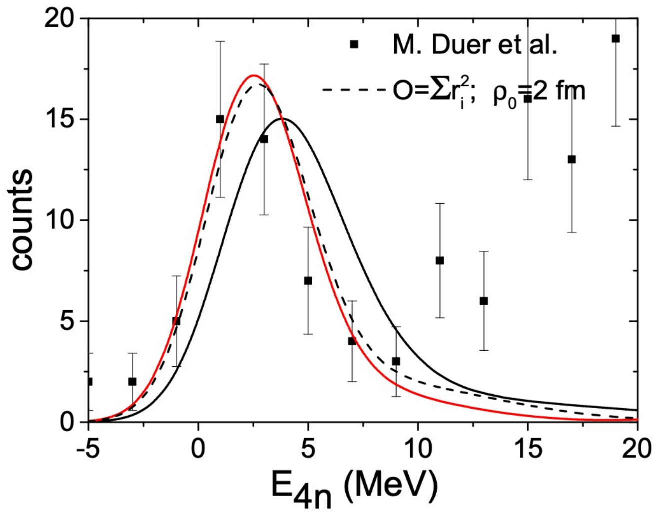
- No-Core Shell Model (**NCSM**)
  PRL 117, 182502 (2016)
- No-Core Gamow Shell Model (**NCGSM**)
  PRC 100, 054313 (2019)
  PRL 119, 032501 (2017)
  (where the blue arrow indicates that the width is predicted to be larger than 3.7 MeV)
- Quantum Monte Carlo (**QMC**)
  PRL 118, 232501 (2017)

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

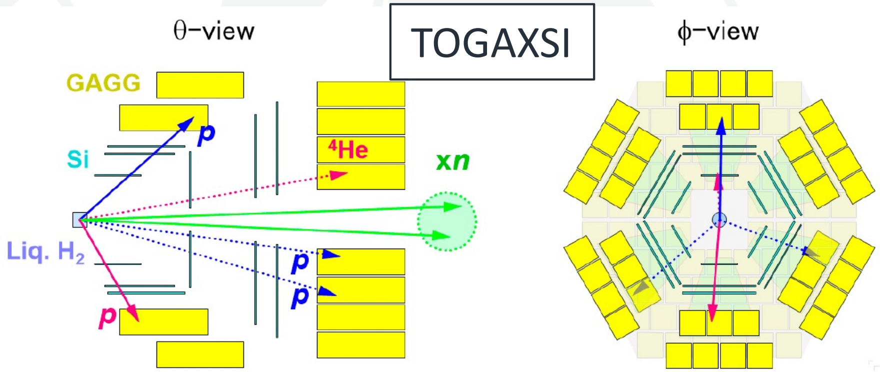
- Measuring the relative momentum amongst the neutrons should help resolve this

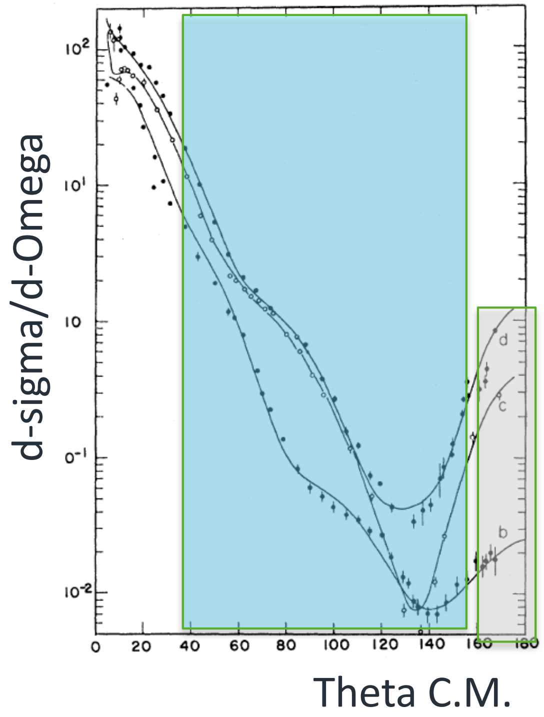
→ New experiment

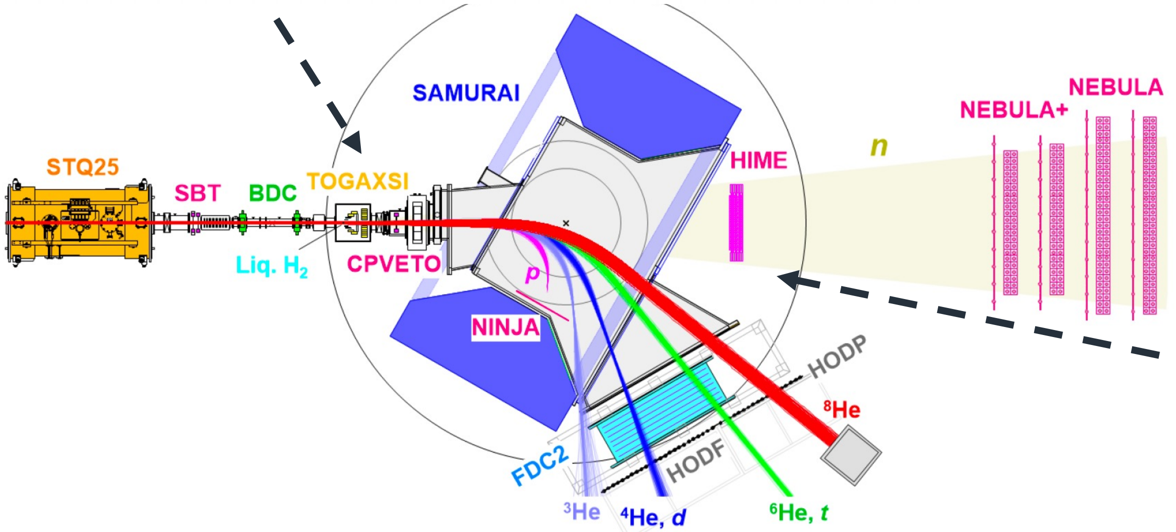
Accepted RIBF proposal SAMURAI74 (Kenjiro Miki & Meytal Duer)

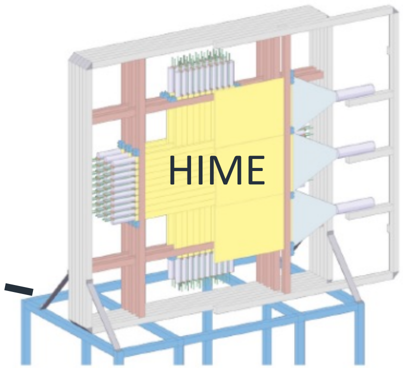
- ^{8}He(p, pα)4n
- ^{6}He(p, 3p)4n and ^{8}He(p, 3p)6n

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









HIME
NEBULA
NEBULA+

4n detection Eff. ~ 0.9%

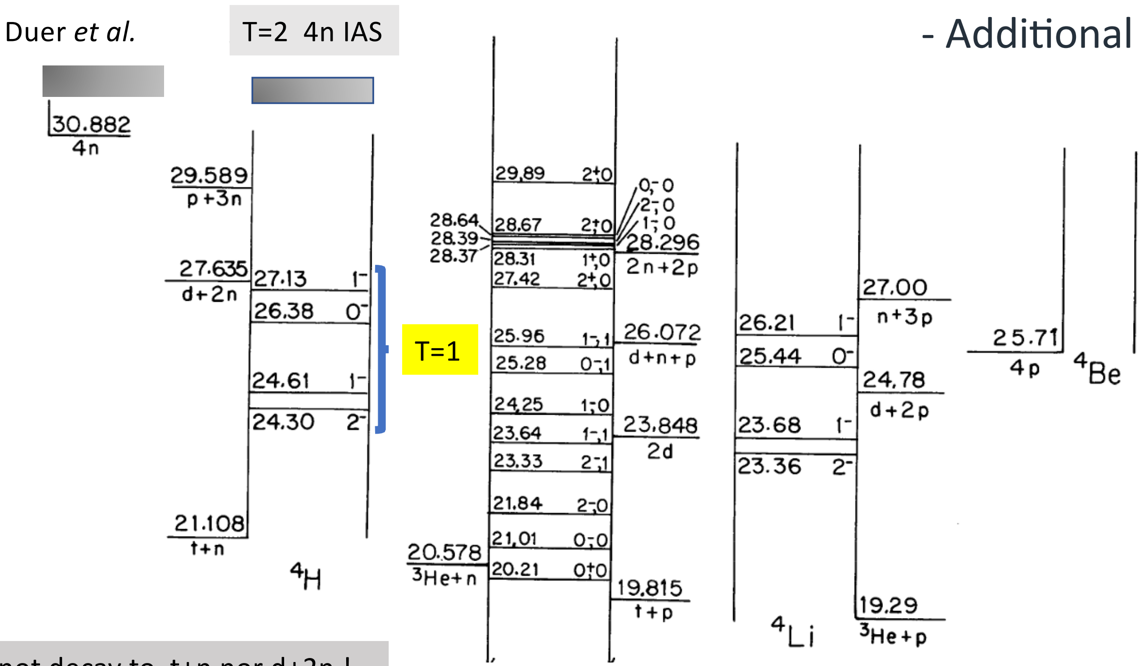
Accepted **GANIL** proposal

The tetra-neutron Isobaric Analog State in ^{4}H

(Augusto Macchiavelli & Marlène Assié)

- 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

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

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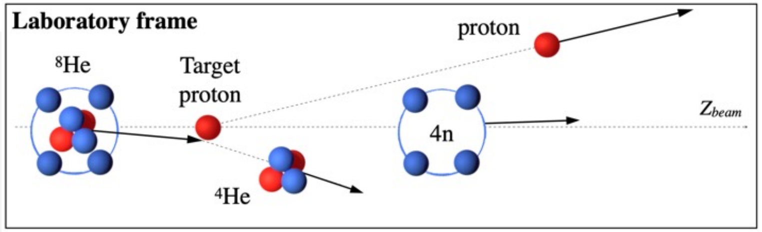
Thank you !!

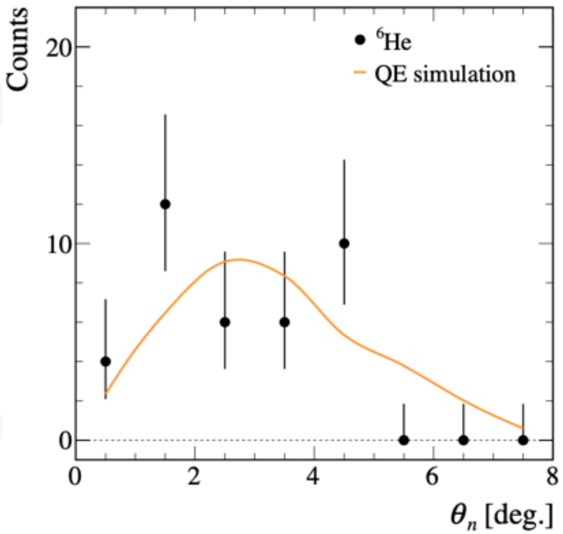
Backup slides

Neutron detection

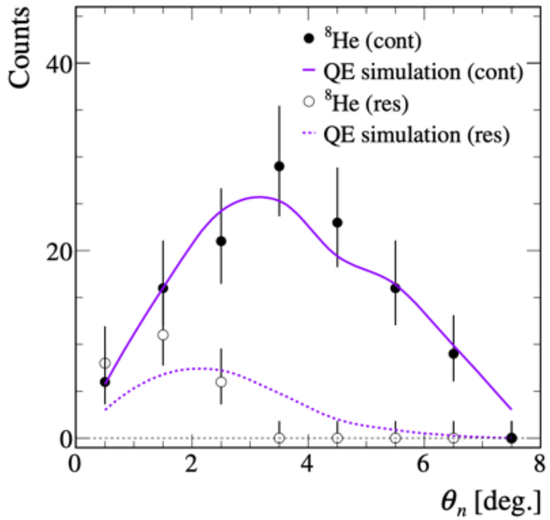
Events with **one neutron in coincidence** are consistent with expected distributions



^{6}He(p,pα)^{2}n



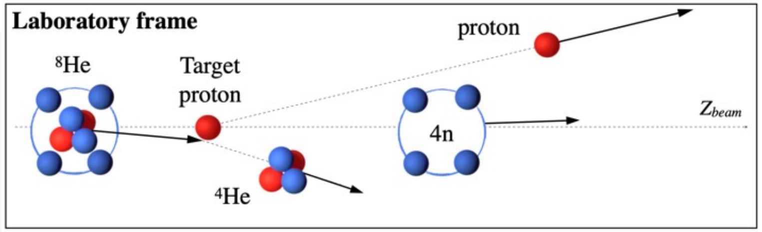
^{8}He(p,pα)^{4}n



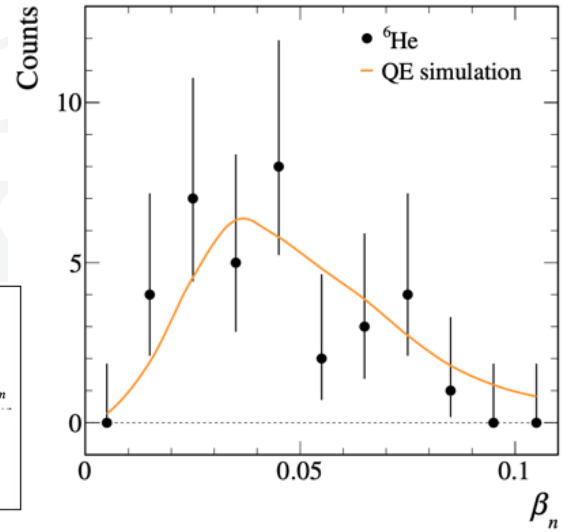
Duer, M., *et al.* *Nature* **606**, 678–682 (2022)

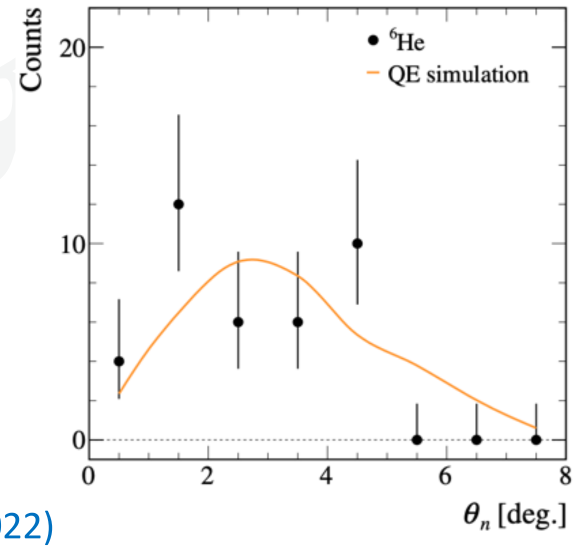
Neutron detection

Events with one detected neutron are consistent with expected distributions

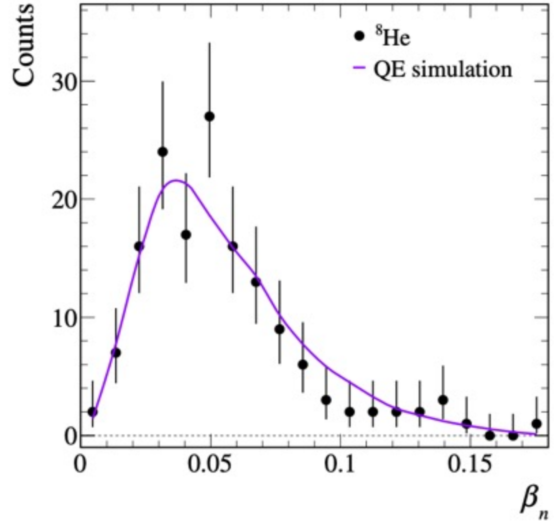


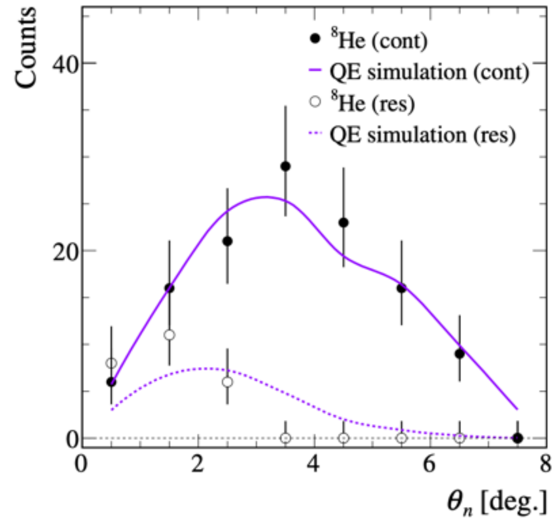
$^6He(p,p\alpha)^2n$





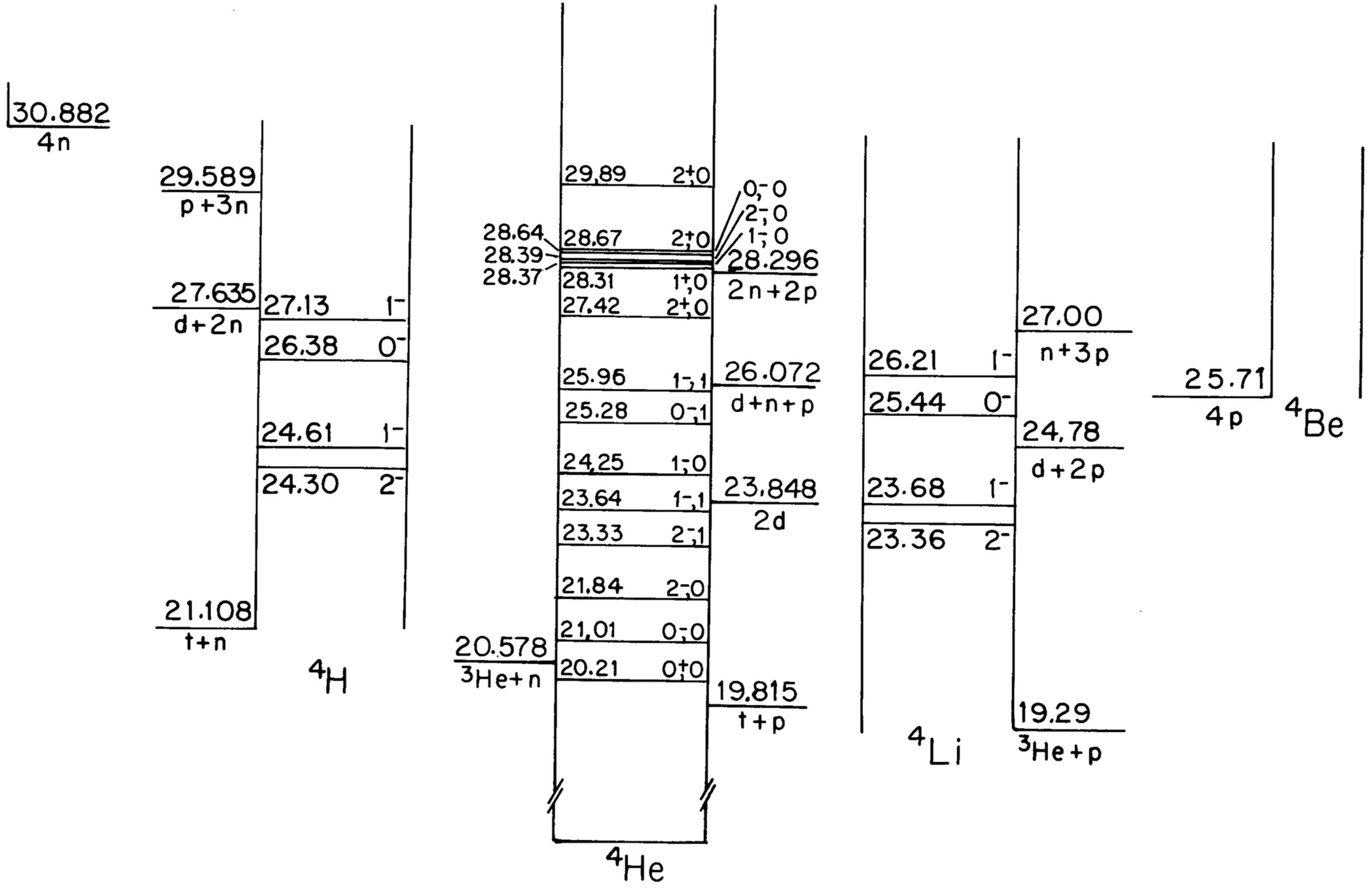
$^8He(p,p\alpha)^4n$





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

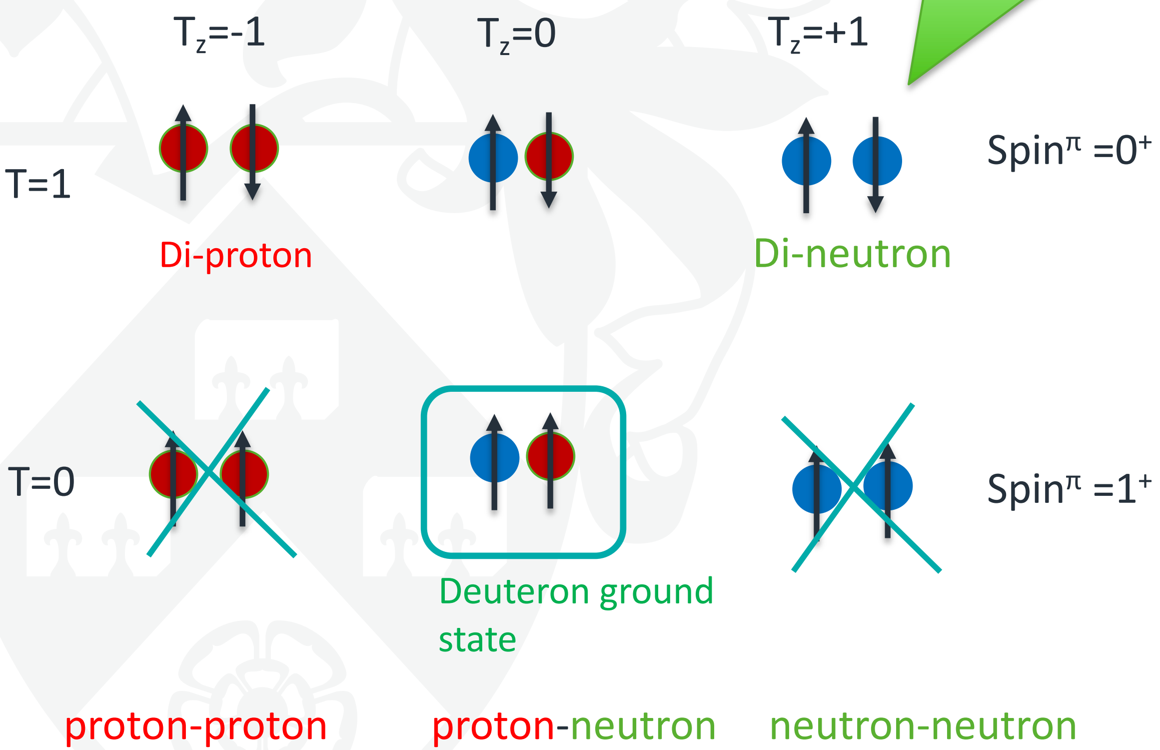
A=4 Isobaric Analog States - IAS



Nuclear Forces

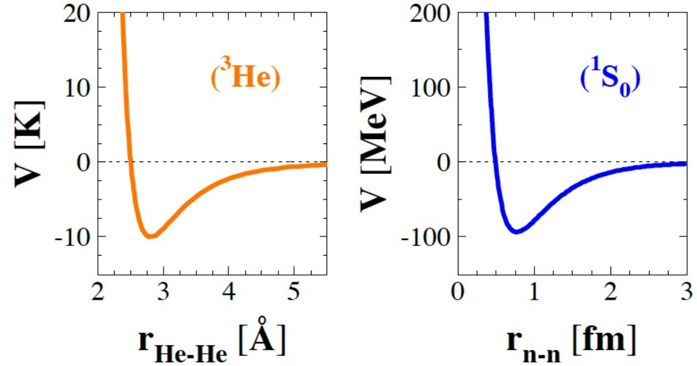
<u>Two-nucleon Systems:</u>

is known to be just unbound by only about 100 keV



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

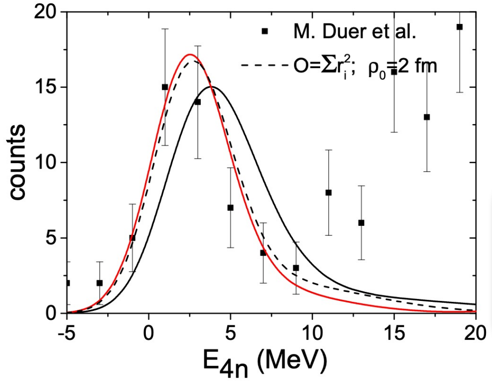
Lazauskas, PRL 130 (2022) 102501

“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

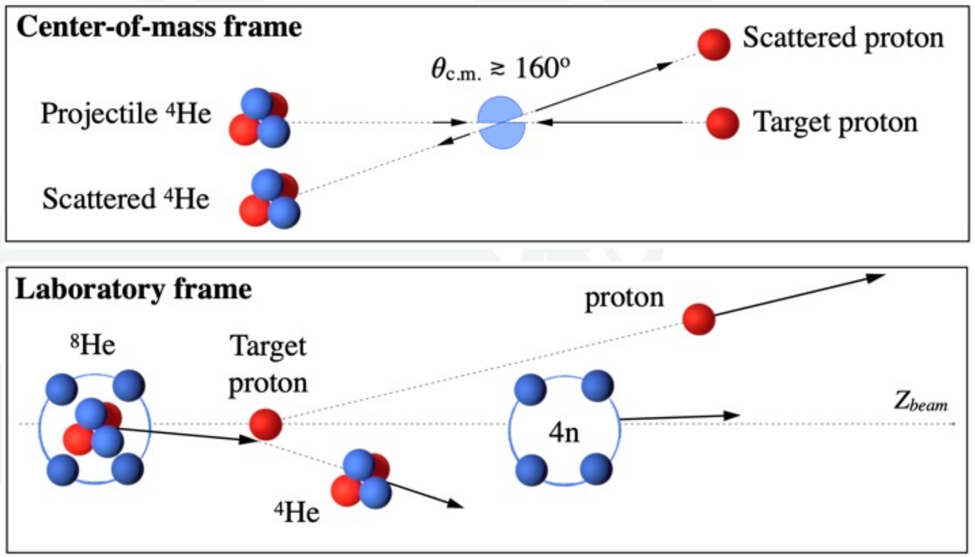
strong sensitivity of the response function to the neutrons’ initial distribution inside ^{8}He

Method

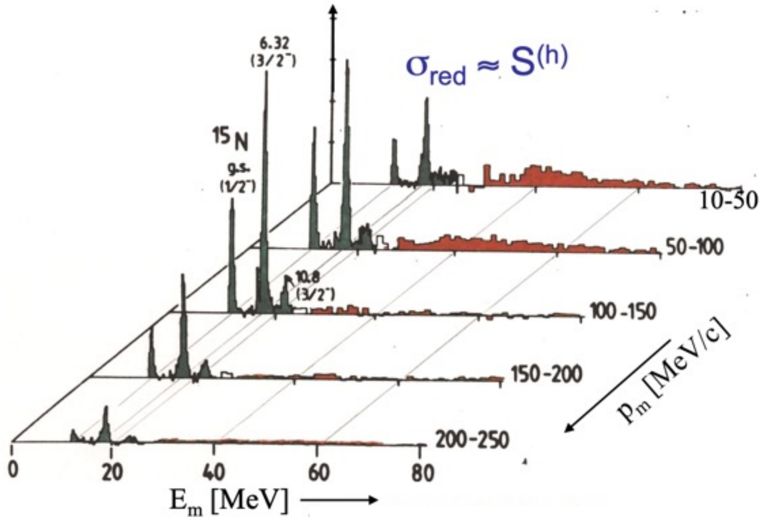
^{8}**He(p,pα)**^{4}**n** Quasi-Elastic knockout reaction at large momentum transfer

- 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.

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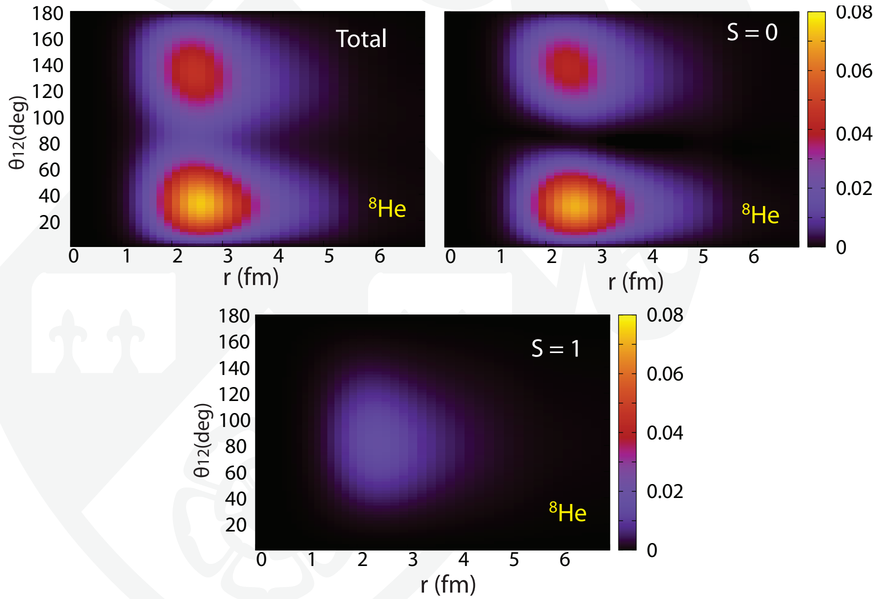
Structure of ^{8}He

COSM + Gamow

alpha + 4n, like with COSM, but using **Gamow** basis, continuum coupling etc..

Shows enhanced probability to find the four neutrons at the same side

Two-body neutron density plots



G. Papadimitriou, private communication

...(COSM + Gamow) is a pure structure method. It is not the decay of 4 neutrons from ^{8}He. We need appropriate many-body scattering boundary conditions for this. However, there is indeed a correlation, but we cannot say if there is a preformataion amplitude before decay. The calculations for this plot is from phenomenological COSM + Gamow basis model using a central interaction (Minnesota). Calculations for the 4n with Robert is from ab-initio using realistic interactions...

Relevant to G. Papadimitriou et al., PRC **84**, 051304(R) (2011), and his PhD Thesis