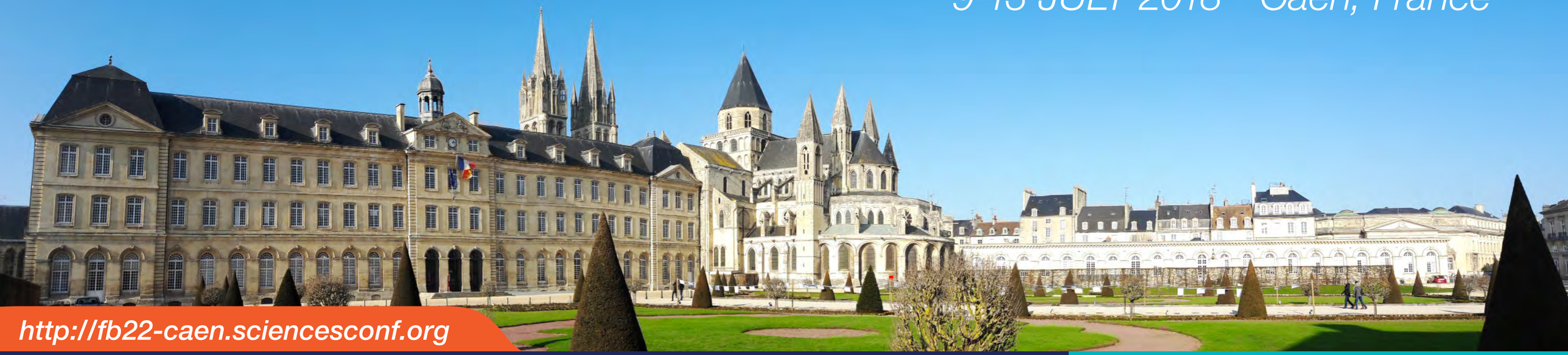
FB22 XXII INTERNATIONAL CONFERENCE ON FEW-BODY PROBLEMS IN PHYSICS

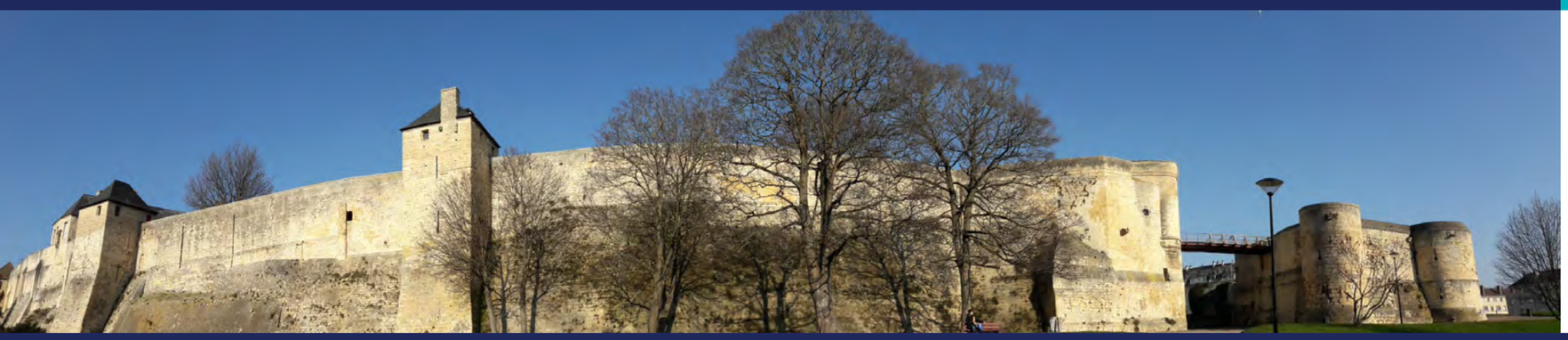
9-13 JULY 2018 - Caen, France



http://fb22-caen.sciencesconf.org

Topics

- Atomic and molecular physics
- Hadron physics and related high energy physics
- Strange and exotic matter, including hypernuclear physics
- Few-nucleon systems
- Few-body aspects of nuclear physics and nuclear astrophysics
- Interdisciplinary aspects of few-body physics and techniques



© L. Petizon - Com' IPN Orsay - CNRS

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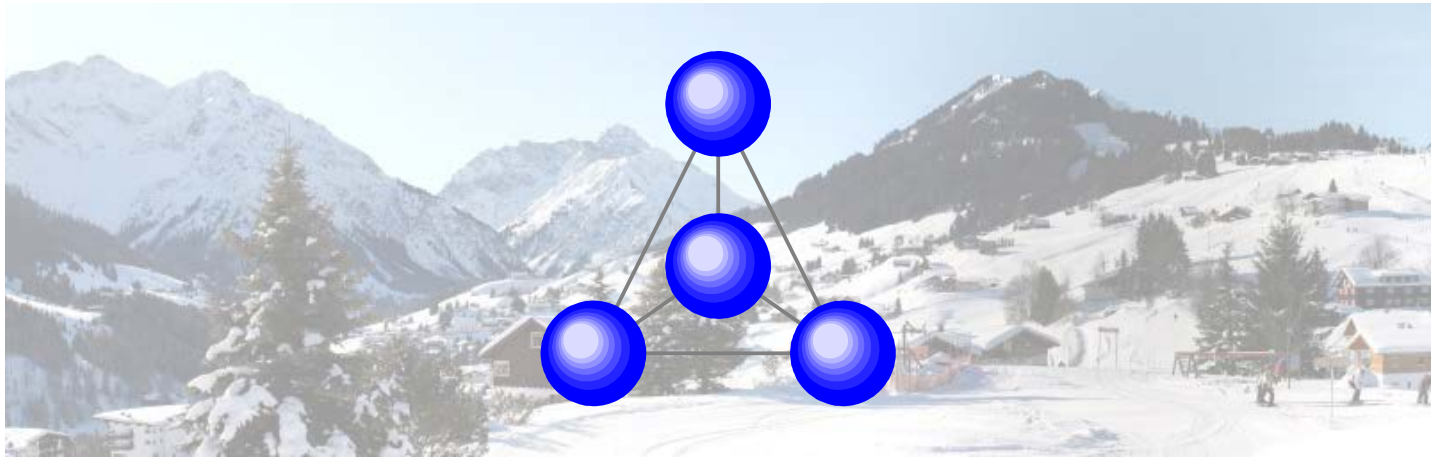
flashcode

Hirschegg 2018

Multiparticle resonances in hadrons, nuclei, and ultracold gases

International Workshop XLVI on Gross Properties of Nuclei and Nuclear Excitations

January 14-20, 2018, Hirschegg (Austria)



Tetraneutron : the experimental context

F. Miguel Marqués

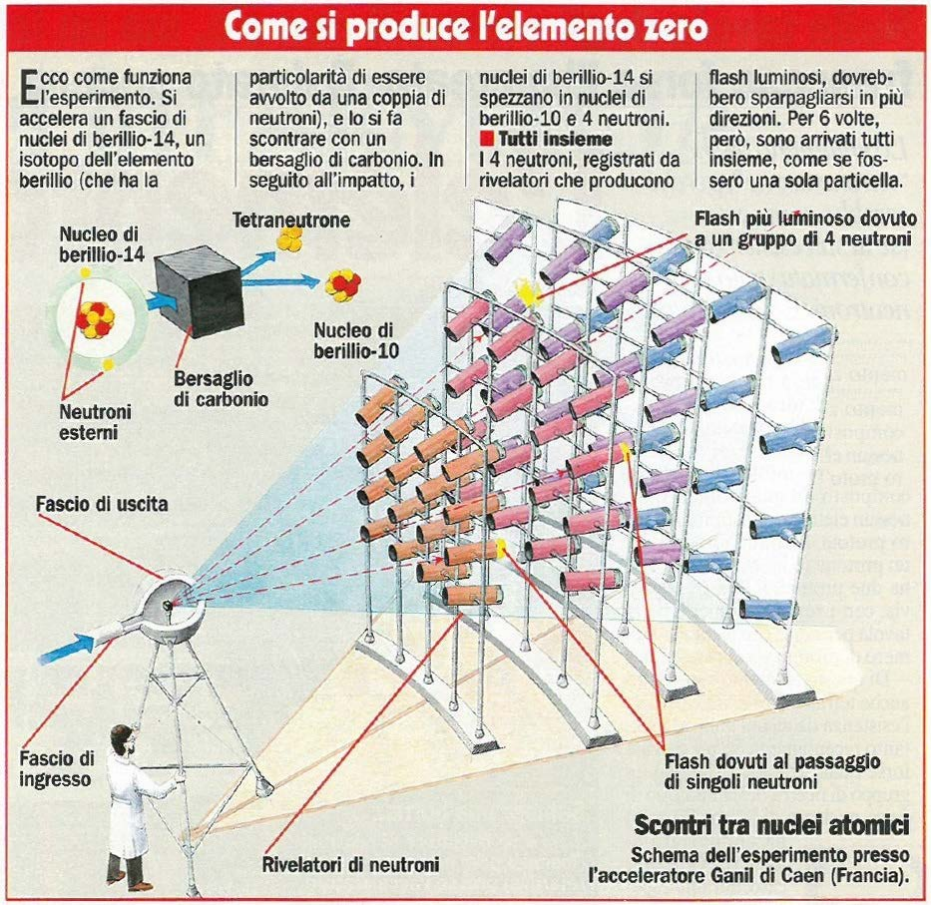
lpc caen

Laboratoire de physique corpusculaire

Outline

❶ The ^{A}n context :

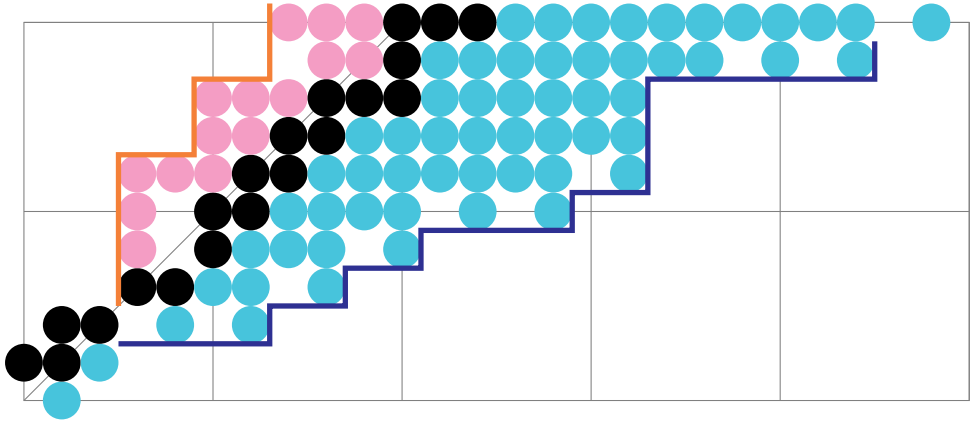
- XX century : $\sigma(^{A}\mathrm{n})$ & backgrounds ...
- XXI century : first signals !
  - → GANIL : theory & experiments
  - → RIKEN : more candidate events
- experimental constraints
- theoretical 'proofs' ?



❷ The RIKEN campaign :

- SHARAQ 2.0 : $^{4}\mathrm{He}\,(^{8}\mathrm{He},\alpha\alpha)\,^{4}\mathbf{n}$
- NEBULA+NeuLAND & MINOS :
  - → $^{8}\mathrm{He}\,(\mathrm{p},\mathrm{p}\alpha)\,^{4}\mathbf{n}$: 4n without FSI
  - → $^{8}\mathrm{He}\,(\mathrm{p},2\mathrm{p})\,\{^{3}\mathbf{H}+^{4}\mathbf{n}\}$: any $(\mathrm{E},\Gamma)_{\mathrm{R}}$

Multi-neutrons : Tetraneutrons ?



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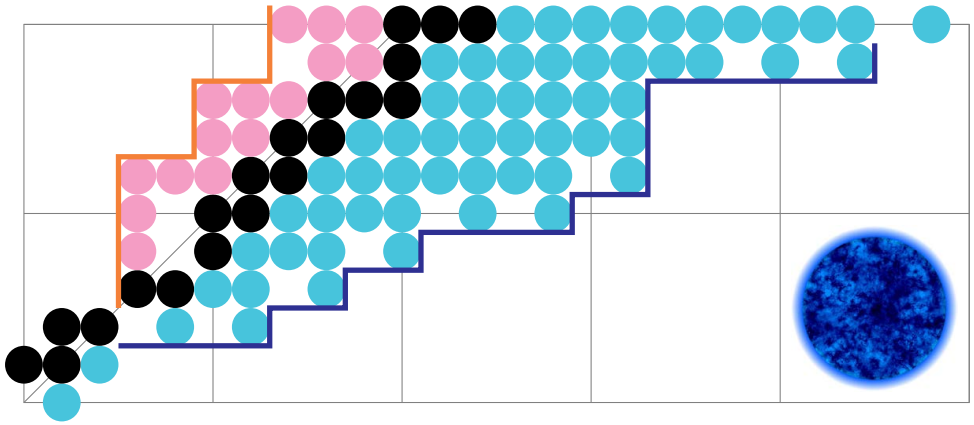
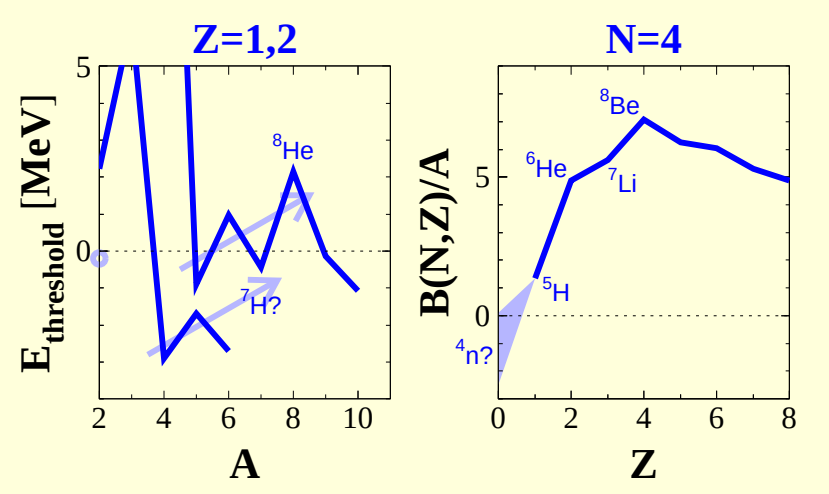


- Well-established facts :
  - N = 2 (✘) $\cdots$ 10^{57} (✔)
  - the 'multi-neutron anomaly' :



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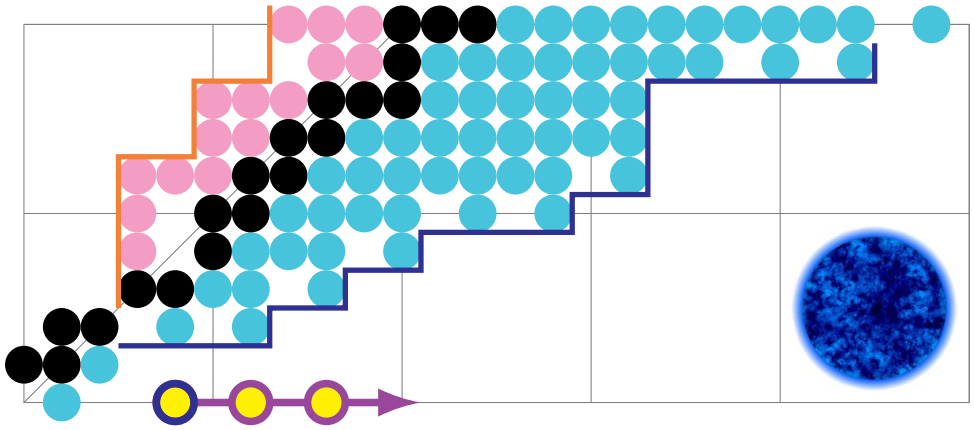

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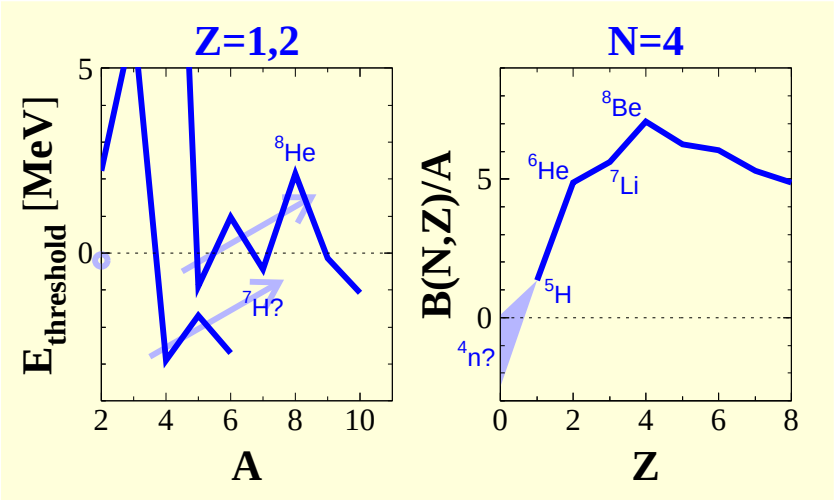

- Candidate systems ?
  - odd-even staggering : even N
  - hard to put many neutrons together !

  $\rightarrow$ N = 4

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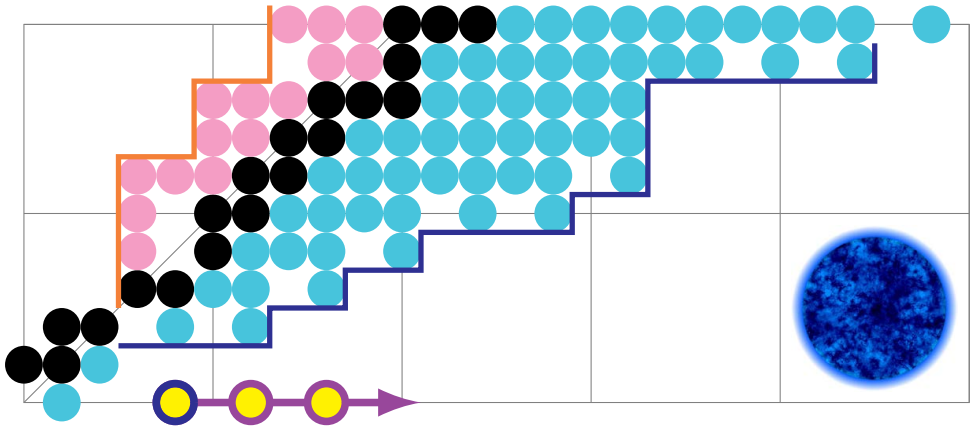

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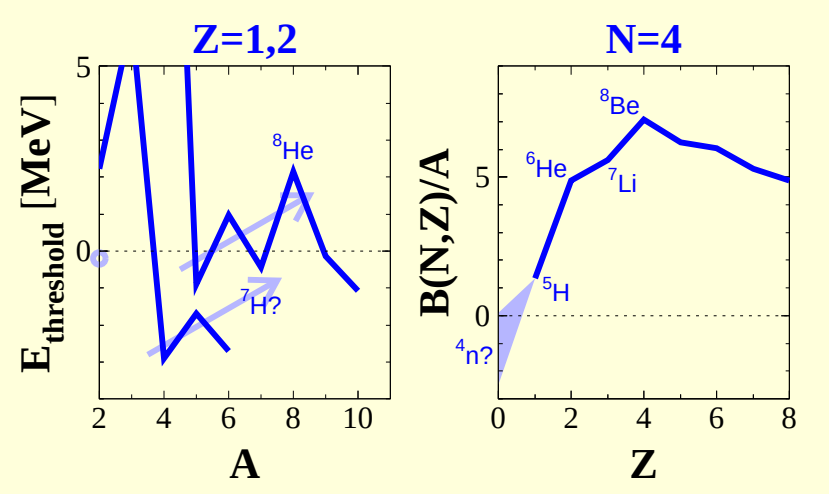

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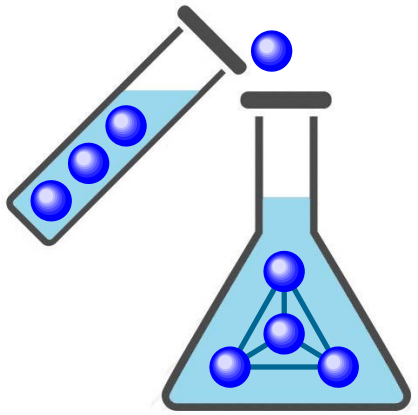
  - production of a too n-rich system ...
  - detection of a neutral object ...



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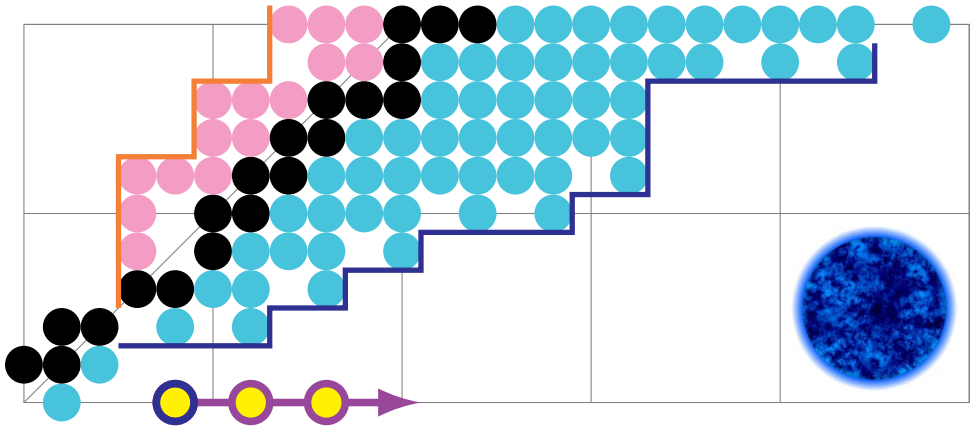

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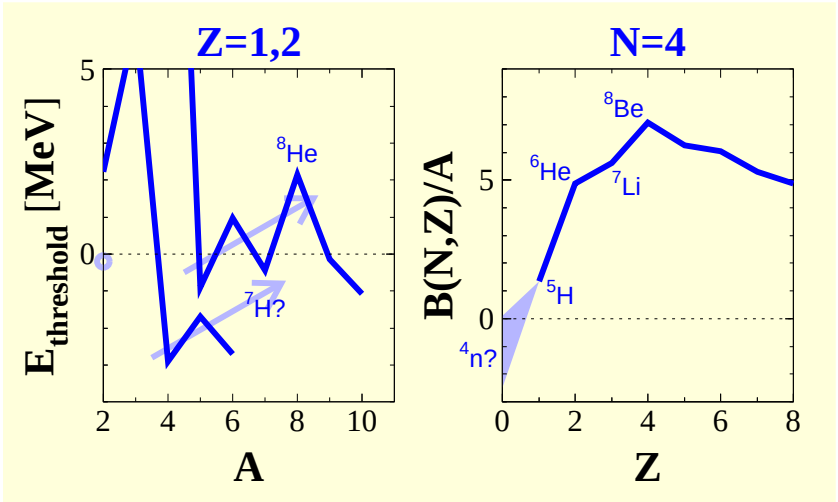

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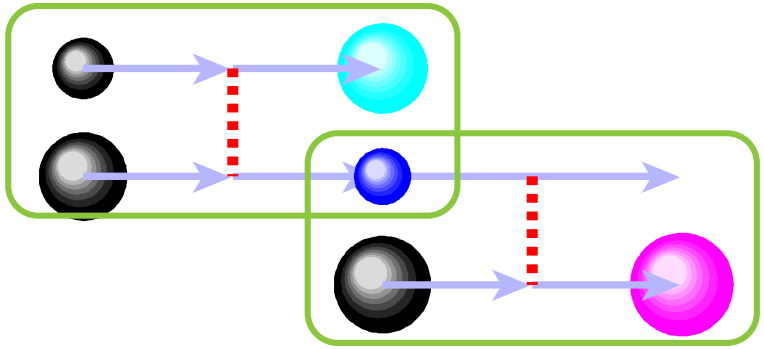
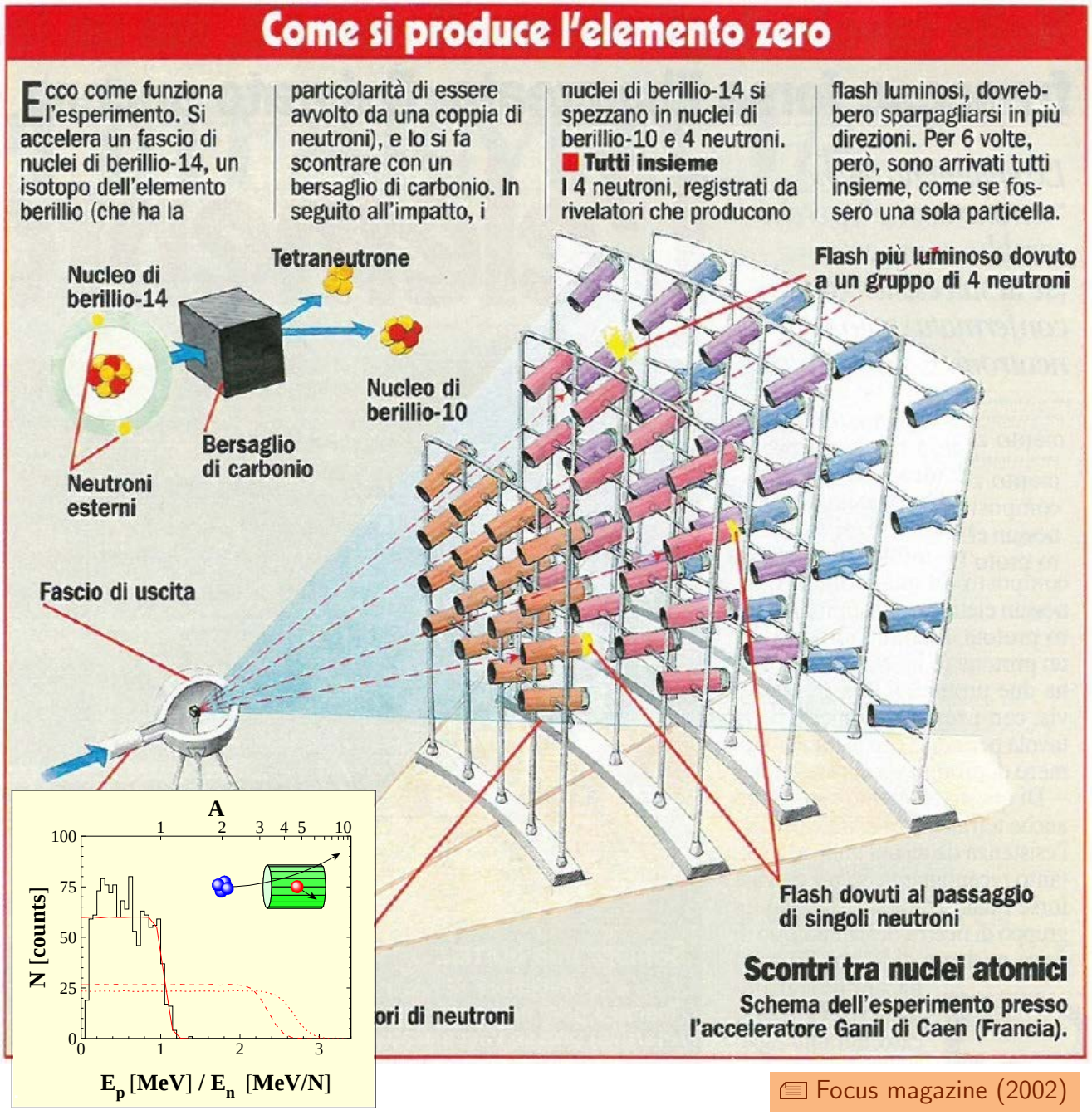
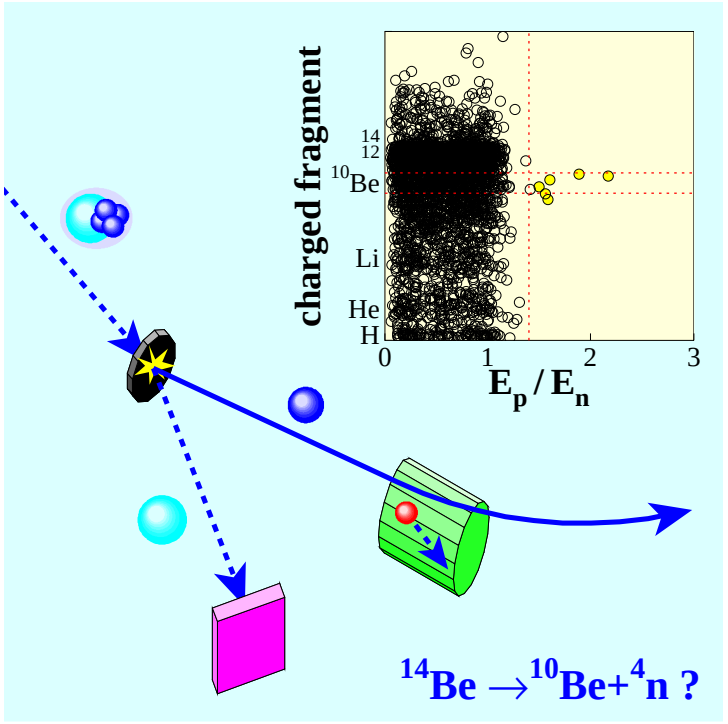


→ XX century : $\sigma(^{A}n)$ & backgrounds ...

The GANIL+DEMON experiment



Focus magazine (2002)



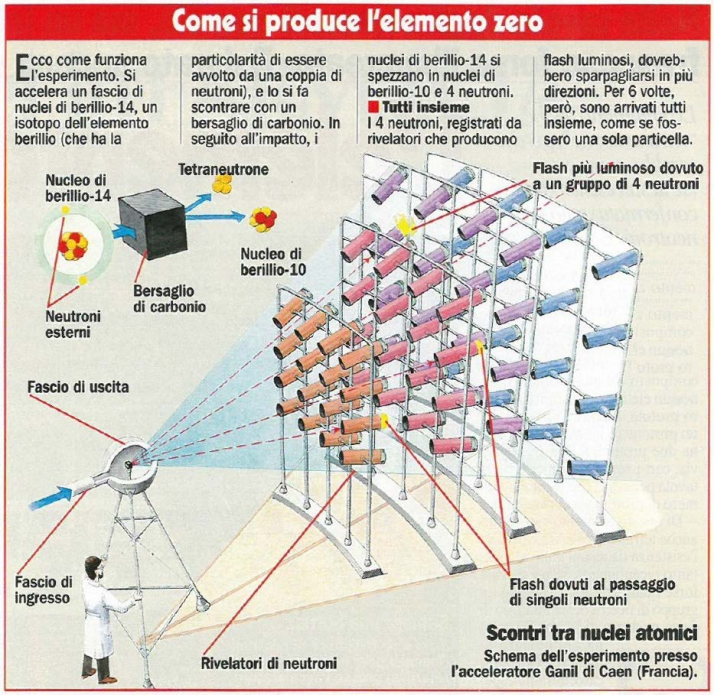
FMM, PRC 65 (2002) 044006

→ bound ^{4}n : ✔

→ $E_R \lesssim 2$ MeV ? ✔

FMM, arXiv:nucl-ex/0504009

- The DEMON campaigns :



$$^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n} \quad (\text{'01,'02})$$

$$^{8}\mathrm{He} \xrightarrow{(C)} {}^{4}\mathrm{He} + {}^{4}\mathrm{n} \quad (\text{'02})$$

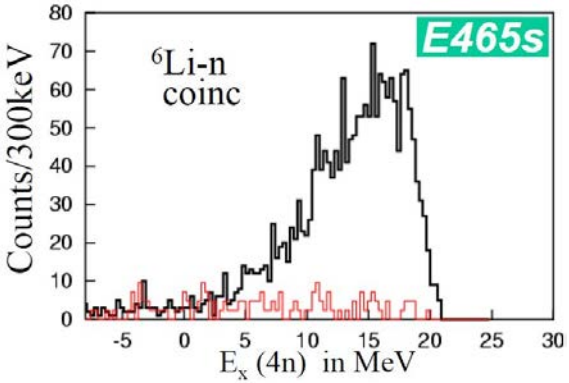
$$^{12/14}\mathrm{Be} \xrightarrow{(C)} \alpha\alpha + {}^{4/6}\mathrm{n} \quad (\text{'02})$$

$$^{15}\mathrm{B} \xrightarrow{(C)} {}^{14}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{n} \quad (\text{'05,'06})$$

⇨ experimental program stopped ...

- MUST collaboration :

$$^{8}\mathrm{He} \xrightarrow{(d)} {}^{6}\mathrm{Li}\ [+{}^{4}\mathrm{n}] \quad (\text{'02,'04})$$



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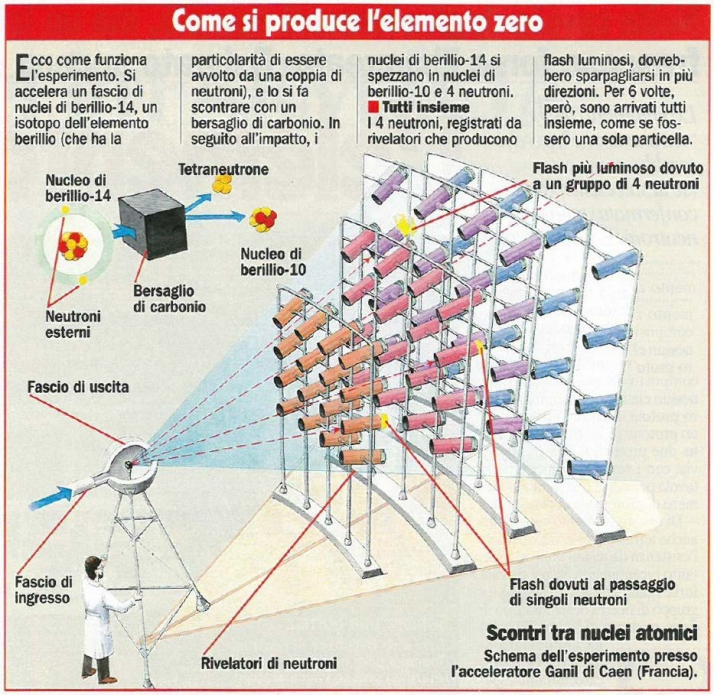
From GANIL ... to RIKEN

- The DEMON campaigns :



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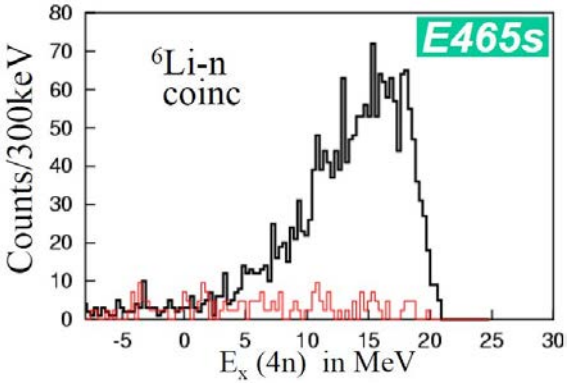
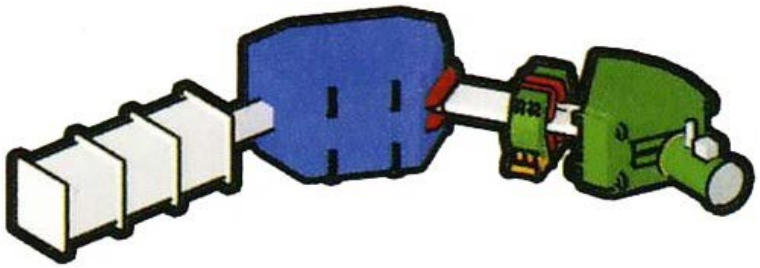


. . . . . .

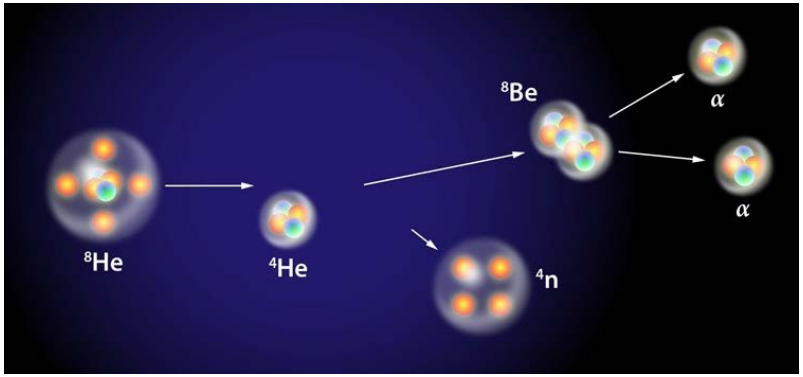
- Shimoura et al (SHARAQ) :



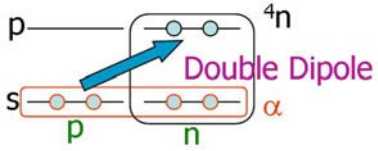
$$^{4}\mathrm{He}\,(^{8}\mathrm{He}, \alpha\alpha)\,{}^{4}\mathrm{n} \quad (\text{'12})$$

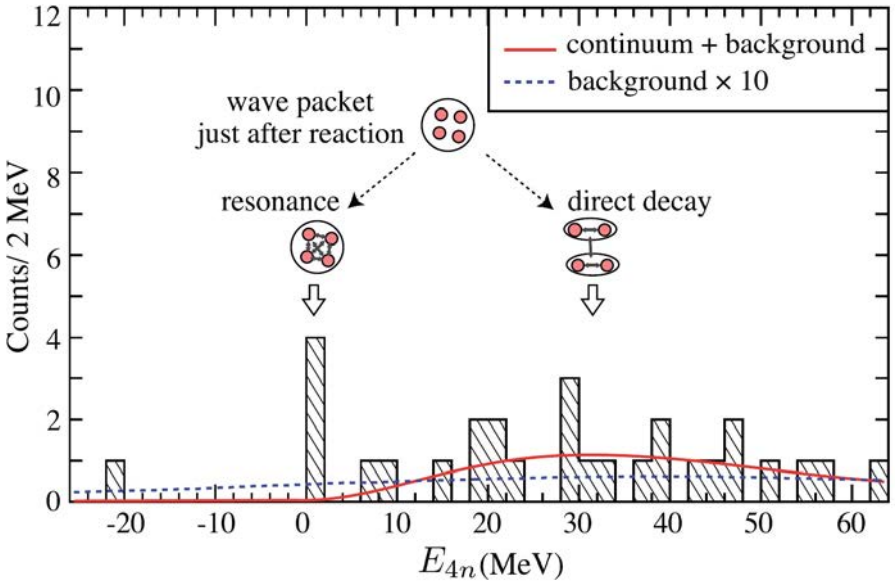
RIKEN : "Candidate Resonant Tetraneutron"

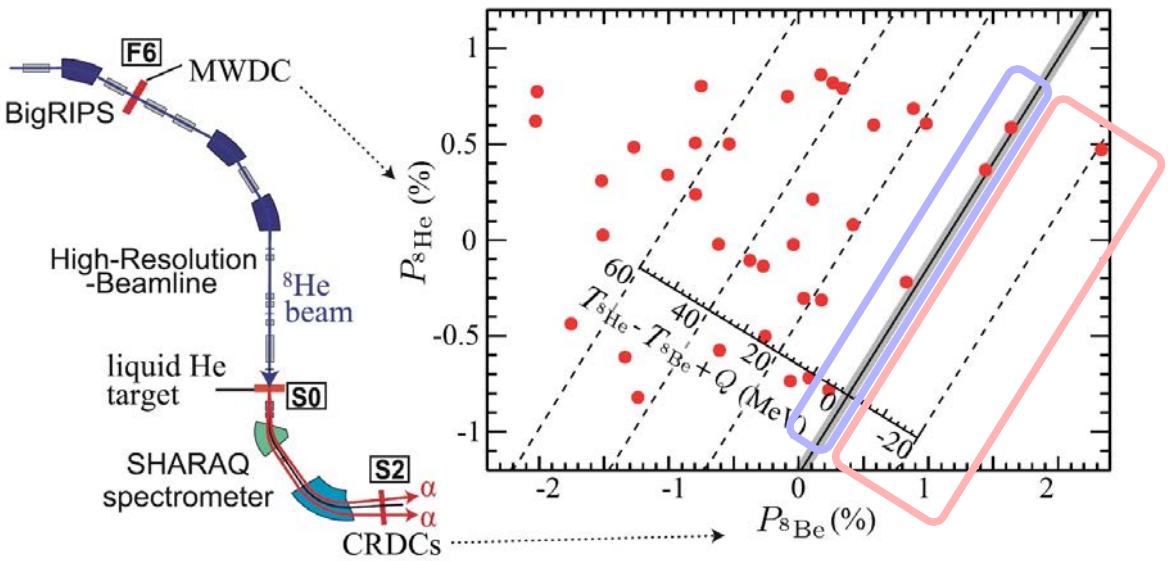
Kisamori, Shimoura, PRL 116 (2016) 052501



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







- only 1 event in unphysical region
- 4 events close to threshold !

$E(^{4}\mathrm{n}) = 0.8 \pm 1.3$ MeV

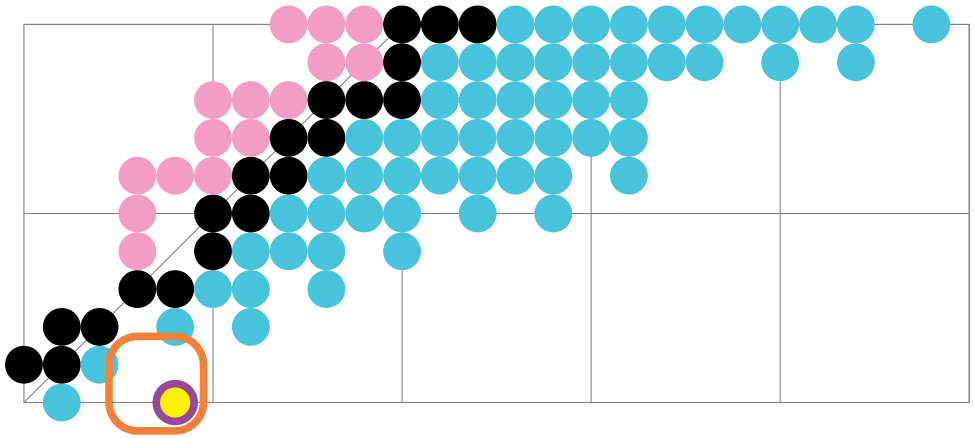
$\Gamma(^{4}\mathrm{n}) < 2.6$ MeV

$\sigma(^{4}\mathrm{n}) \sim 4$ nb

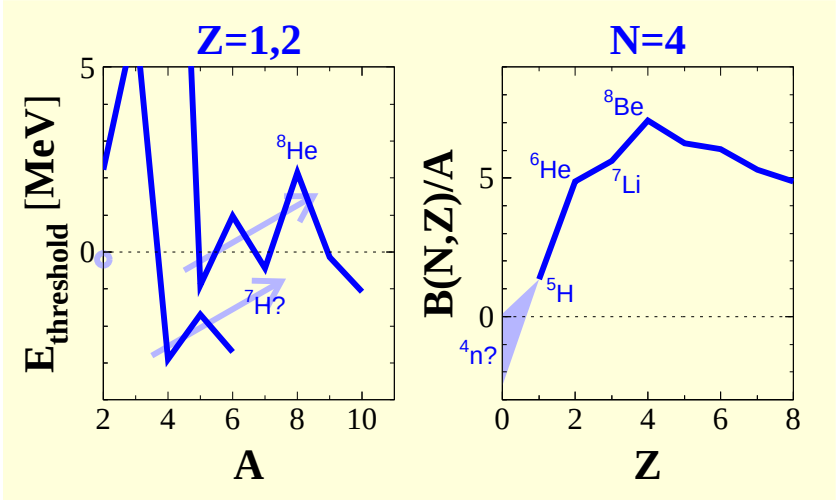
$\rightarrow$ resonance ? ✔

$\rightarrow$ bound ^{4}n ? ✔

Experimental constraints

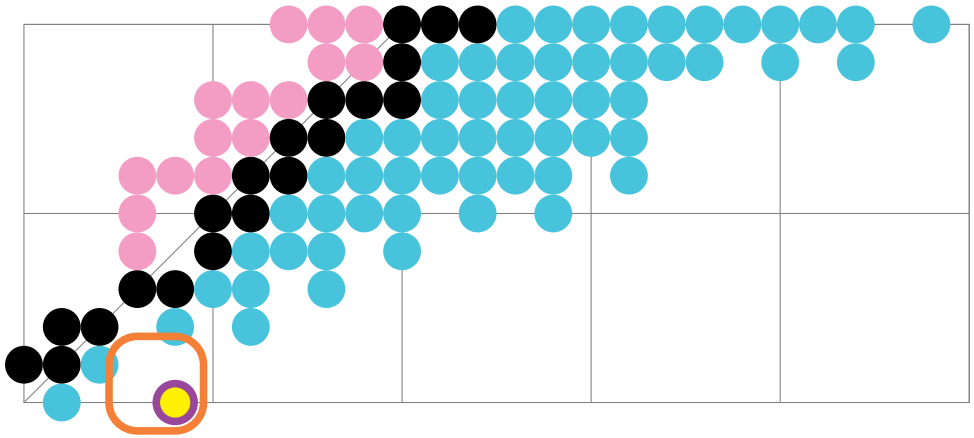


- H isotopes with 4N or 4n are unbound :



→ how could more n-rich systems be bound ?

Experimental constraints



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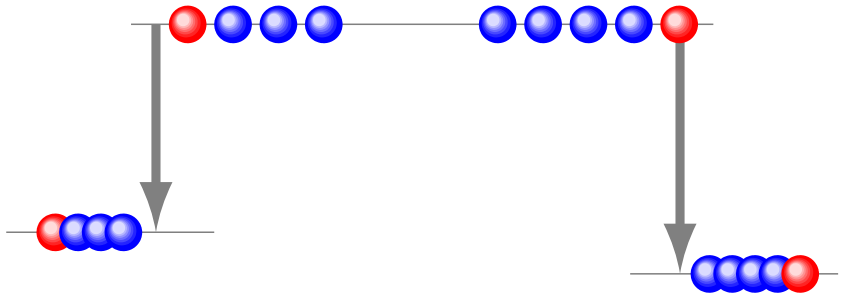

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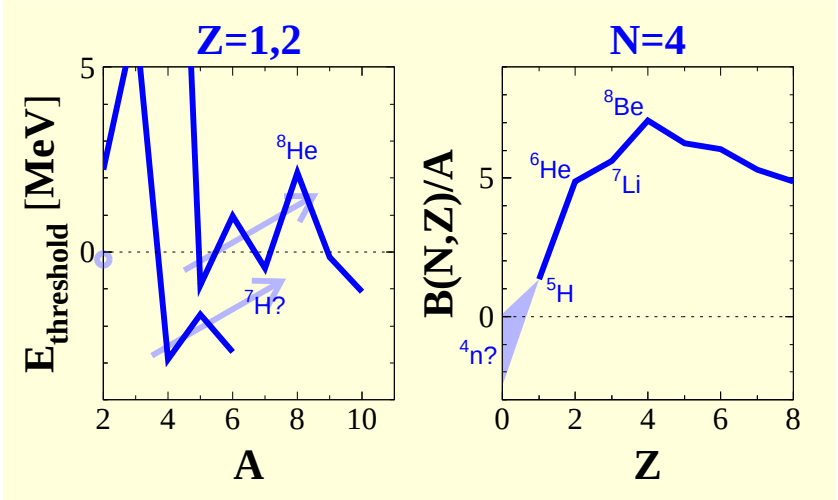

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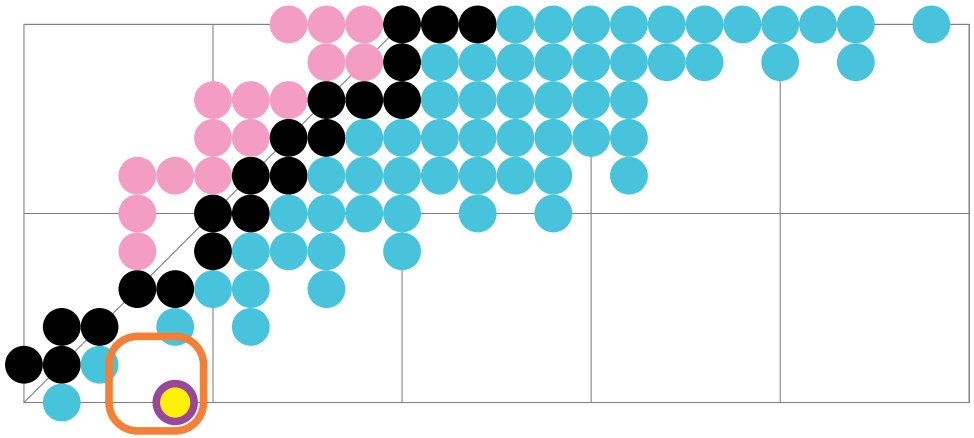

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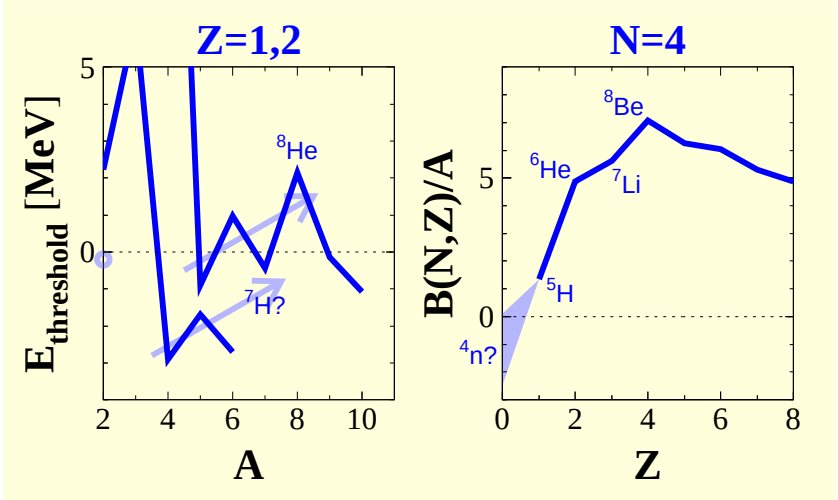

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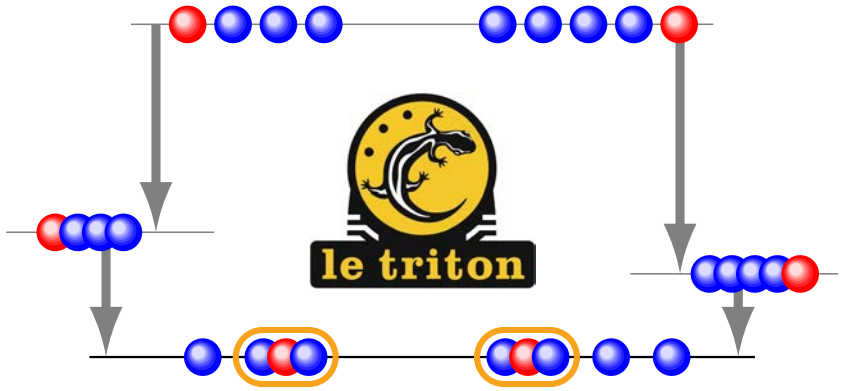
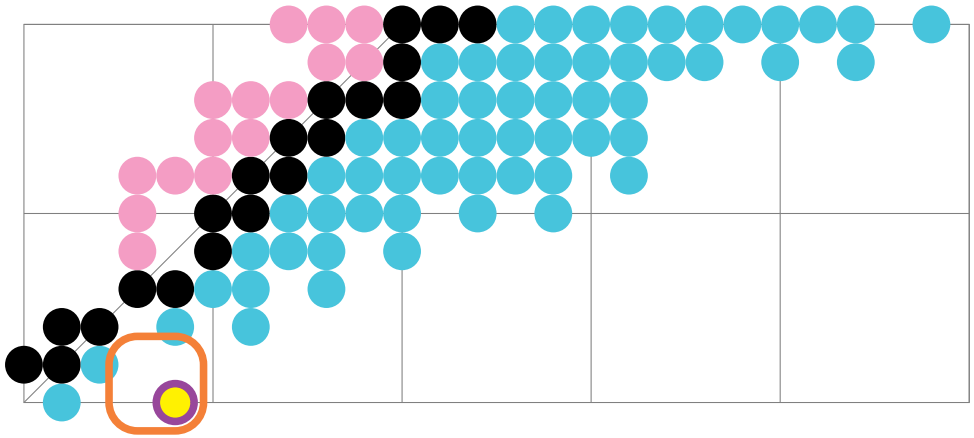


- only B(^{3}H) makes them unbound

Experimental constraints



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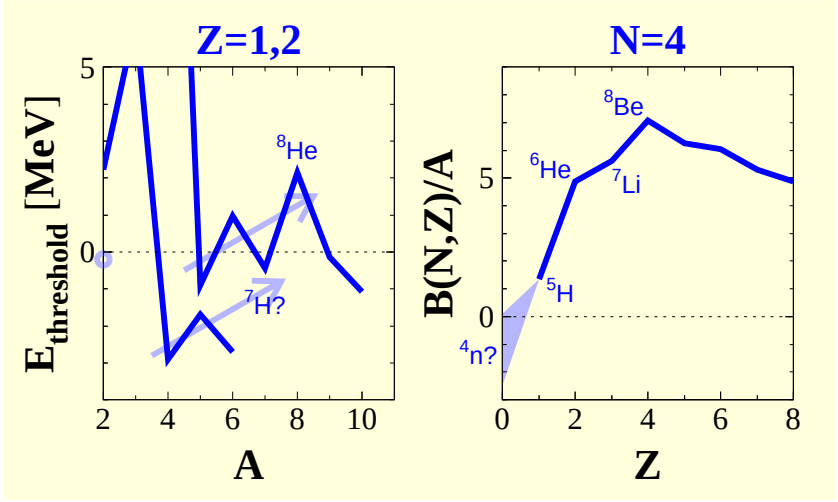

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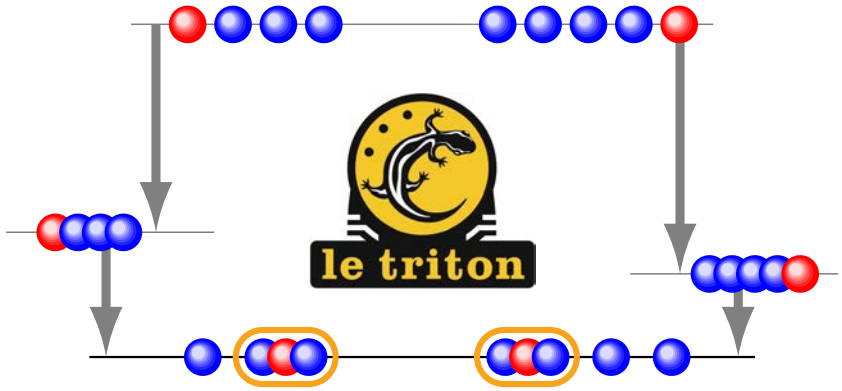

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- No 'triton' in 4n system :

- 1 eV binding would be enough !
- B(^{4}n) $<$ min$\{S_{4n}\}$

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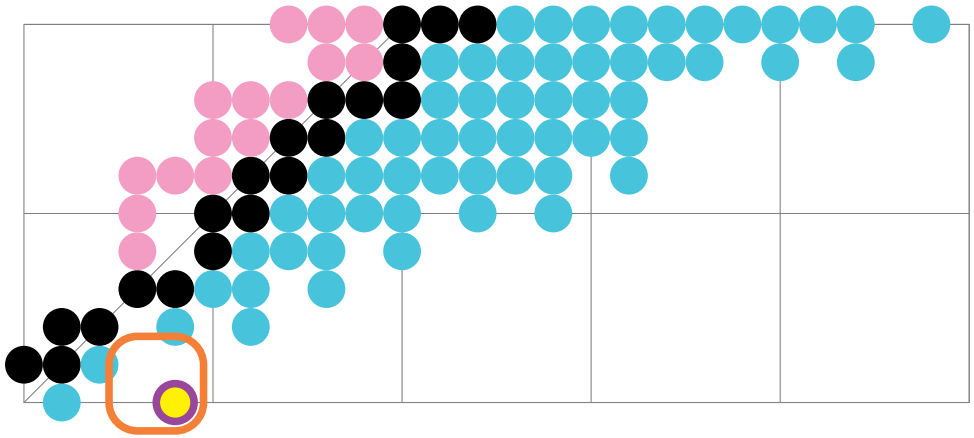

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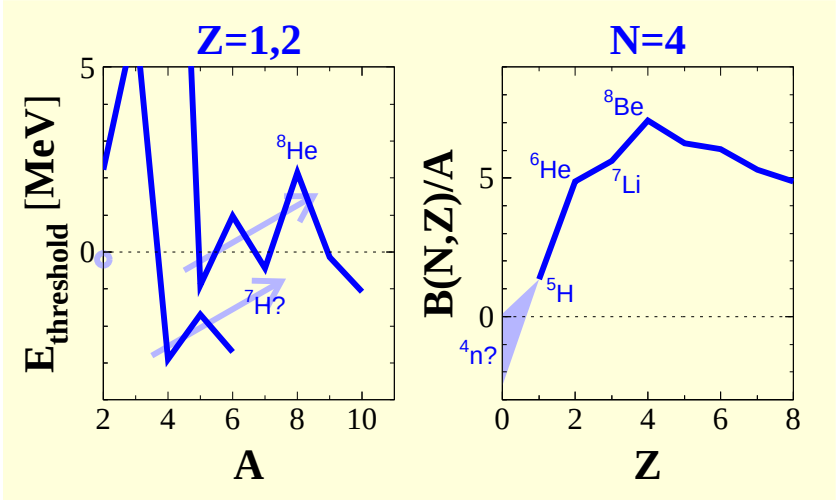

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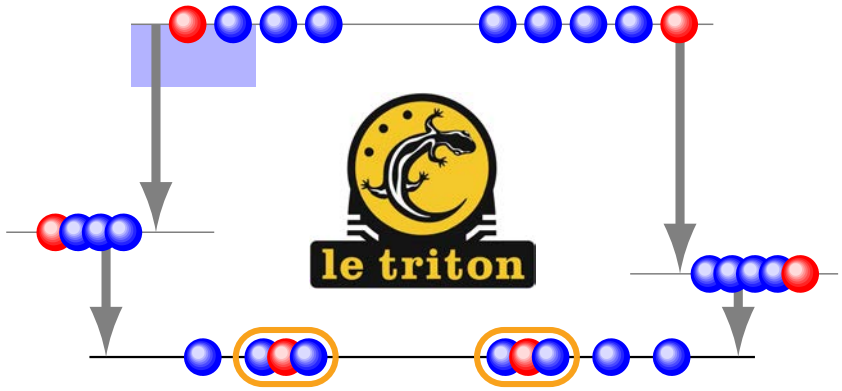

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- No 'triton' in 4n system :

- 1 eV binding would be enough !
- B(^{4}n) $<$ min$\{S_{4n}\} \sim$ 1.5 MeV (^{19}B)

  → ^{4}n would β-decay into ^{4}H

Theoretical 'proofs' ?

- **"ab initio"** = "*from first principles*"
  - realistic interactions
  - 'exact' calculations

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

Pieper, PRL 90 (2003) 252501

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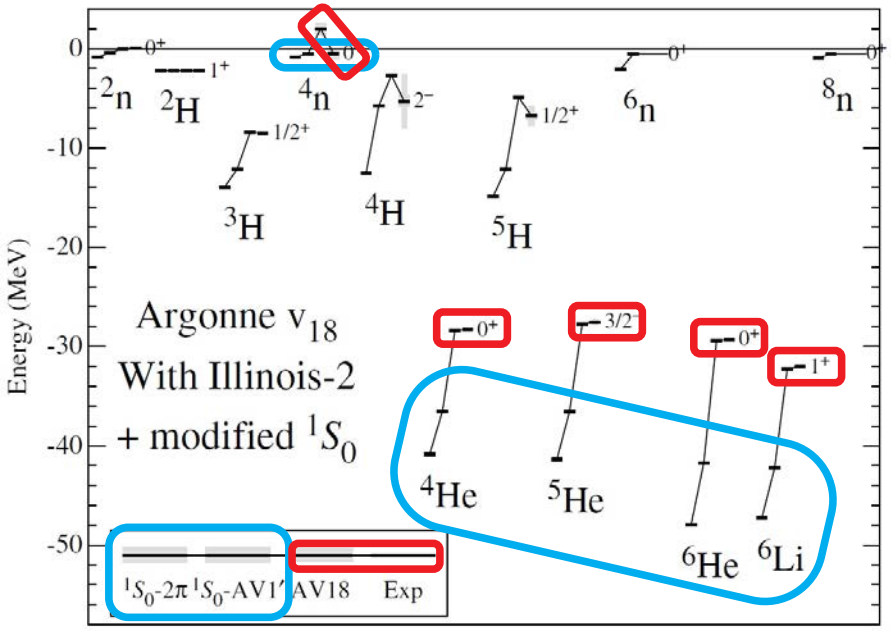
Pieper, PRL 90 (2003) 252501



⇨ proof that ^{4}n does not exist (?)

Theoretical 'proofs' ?

- **"ab initio"** = "*from first principles*"
  - realistic interactions
  - 'exact' calculations

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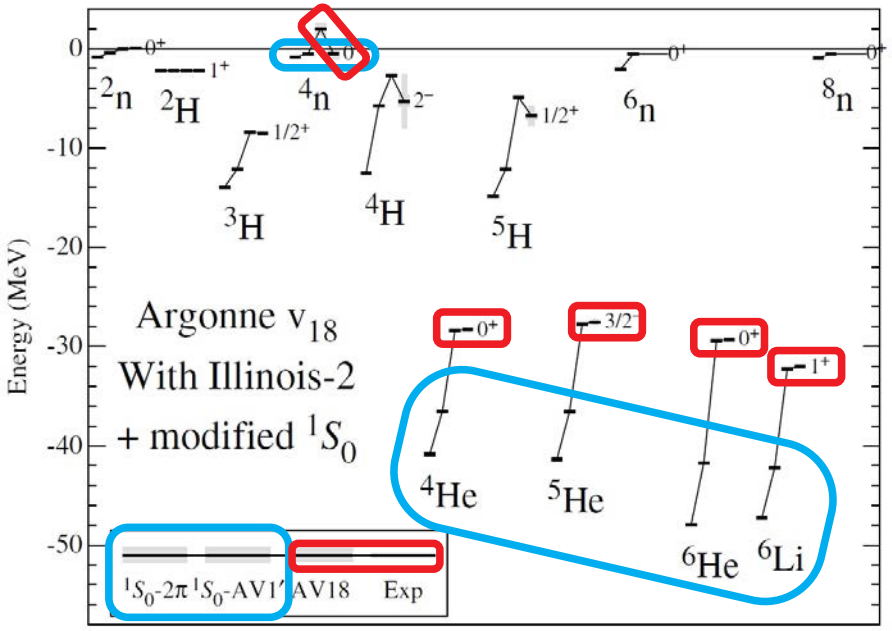
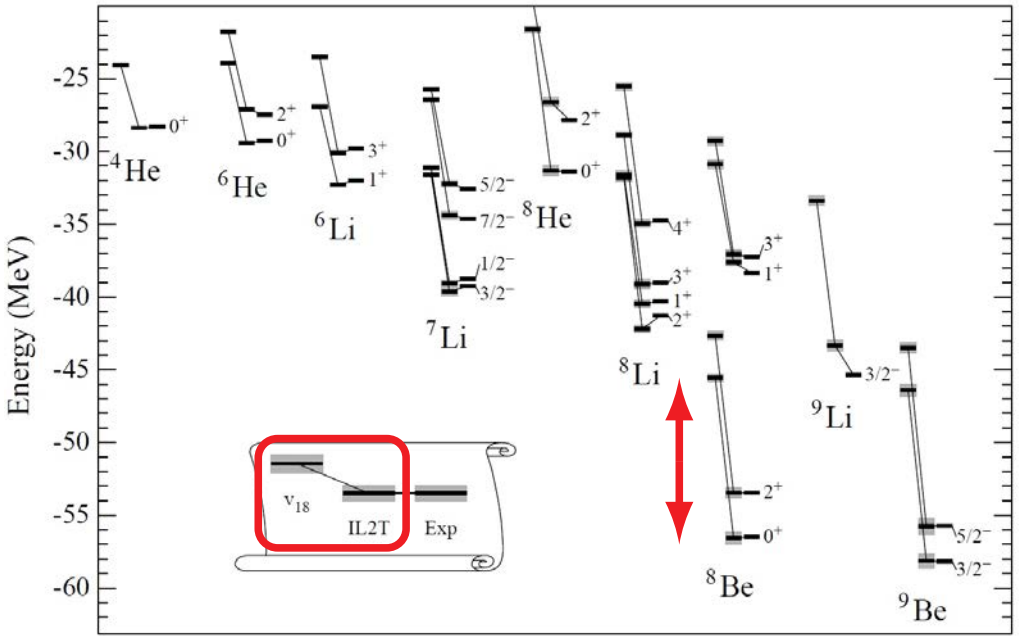


⇨ proof that ^{4}n does not exist (?)

- E(^{4}n) = −500 keV : 'strongly' bound !
- V_{ijk} not *ab initio* nor precise !
- exact to 1-2% ... of total E : ∼ MeV !



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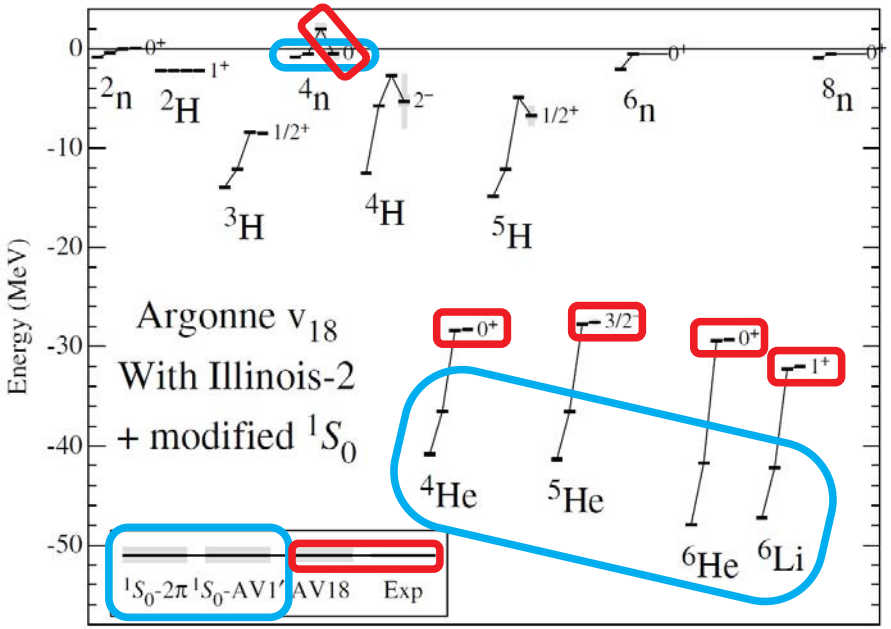
Pieper, PRL 90 (2003) 252501



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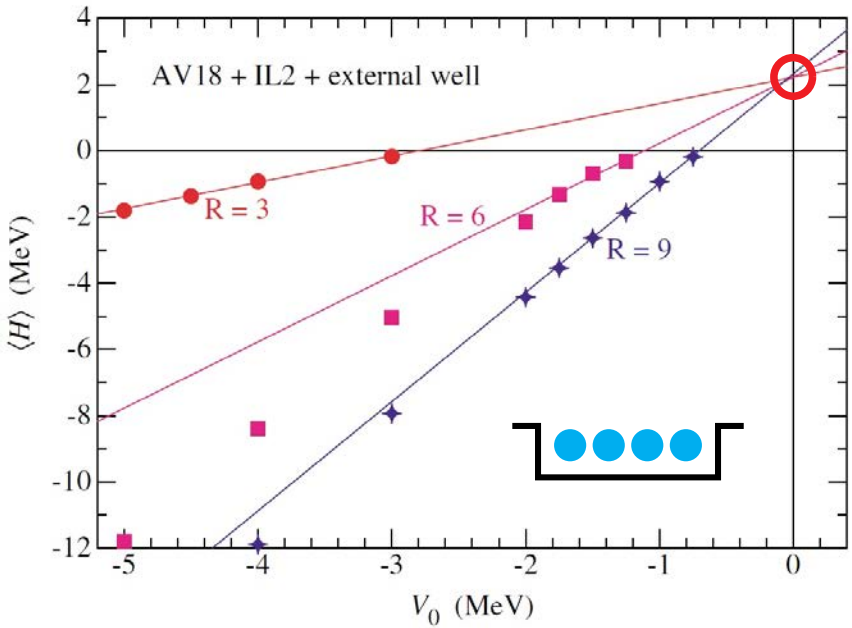

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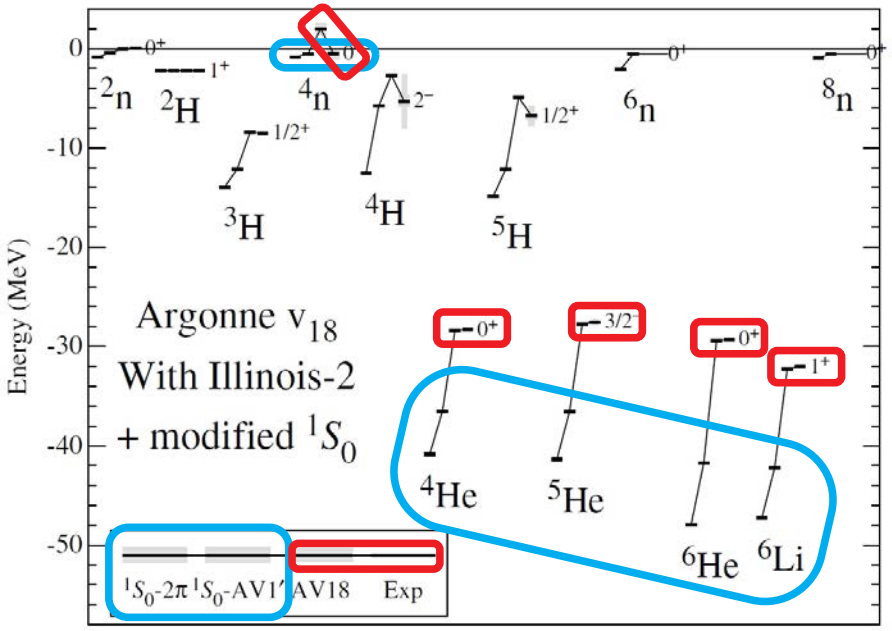
Pieper, PRL 90 (2003) 252501



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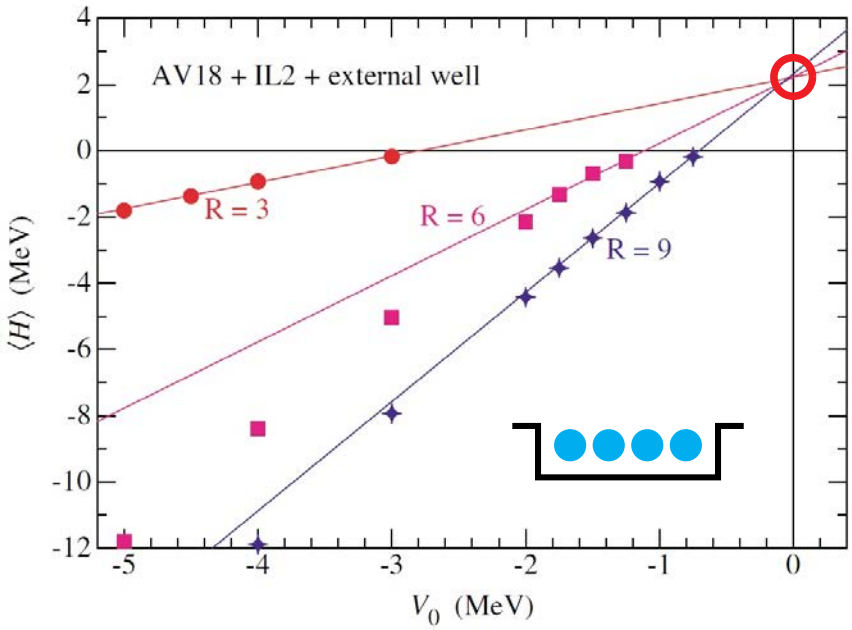
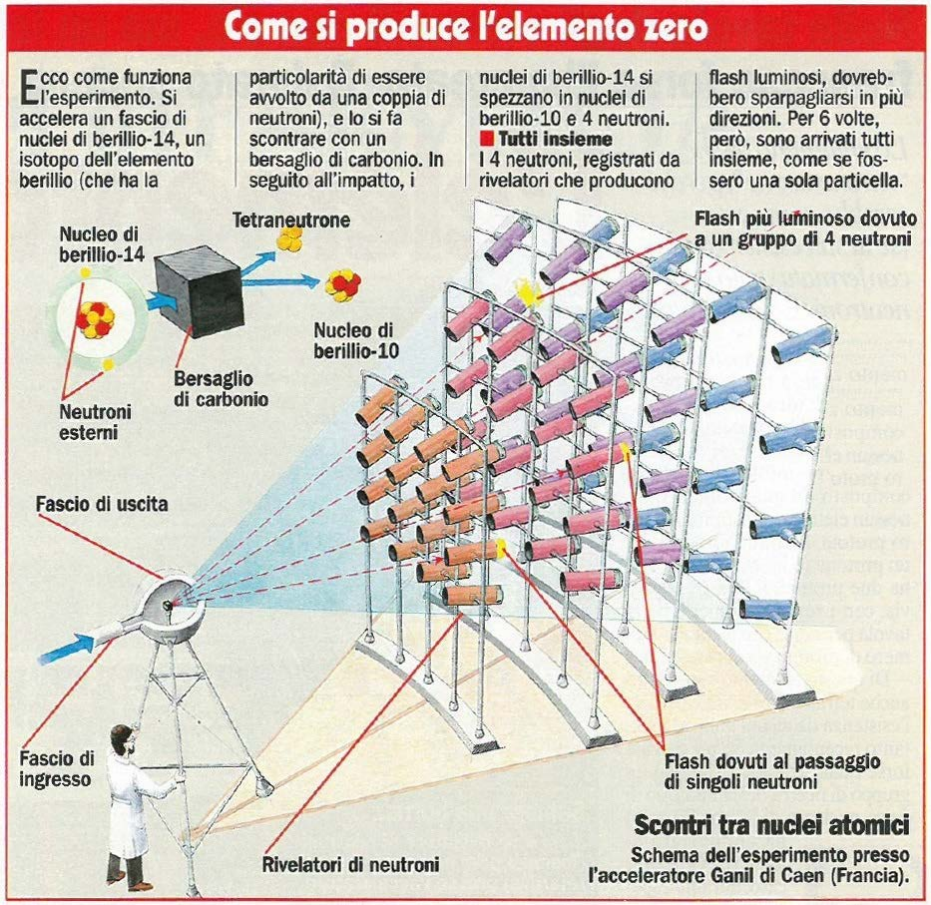


Lazauskas, PRC 71 (2005) 044004
Lazauskas, PRC 72 (2005) 034003
Hiyama, PRC 93 (2016) 044004
Shirokov, PRL 117 (2016) 182502
Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501

→ bound ^{4}n : ✘
→ resonance ? (✔)

❶ The ^{A}n context :

- XX century : $\sigma(^{A}\mathrm{n})$ & backgrounds ...
- XXI century : first signals !
  - → GANIL : theory & experiments
  - → RIKEN : more candidate events
- experimental constraints
- theoretical 'proofs' ?

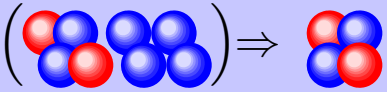
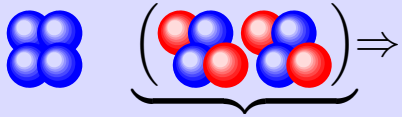
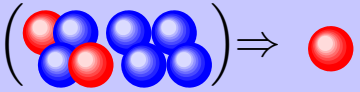
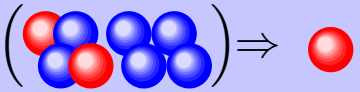
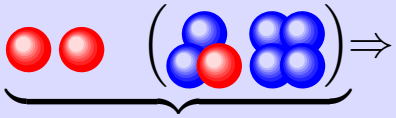


❷ The RIKEN campaign :

- SHARAQ 2.0 : $^{4}\mathrm{He}\,(^{8}\mathrm{He},\alpha\alpha)\,^{4}\mathbf{n}$
- NEBULA+NeuLAND & MINOS :
  - → $^{8}\mathrm{He}\,(\mathrm{p},\mathrm{p}\alpha)\,^{4}\mathbf{n}$: 4n without FSI
  - → $^{8}\mathrm{He}\,(\mathrm{p},2\mathrm{p})\,\{^{3}\mathbf{H}+^{4}\mathbf{n}\}$: any $(\mathrm{E},\Gamma)_{\mathrm{R}}$

Tetraneutron context @ RIKEN

- Three experiments : same beam (^{8}**He**) & energy (150–200 MeV/N) ?

reaction	initial state	final state	σ	results
^{4}He $(^{8}$He, $\alpha\alpha)$ ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
^{8}He (p,2p) $\{^{3}$**H**$+^{4}$**n**$\}$ FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω

Tetraneutron context @ RIKEN

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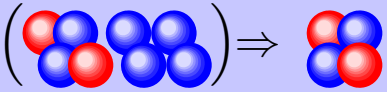
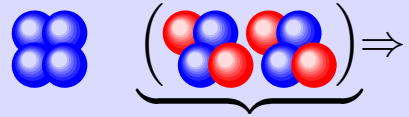
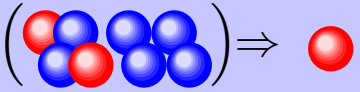
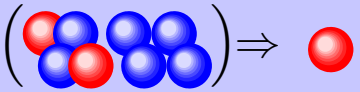
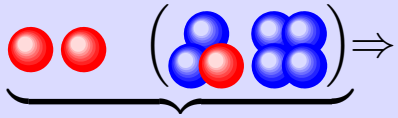
^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω

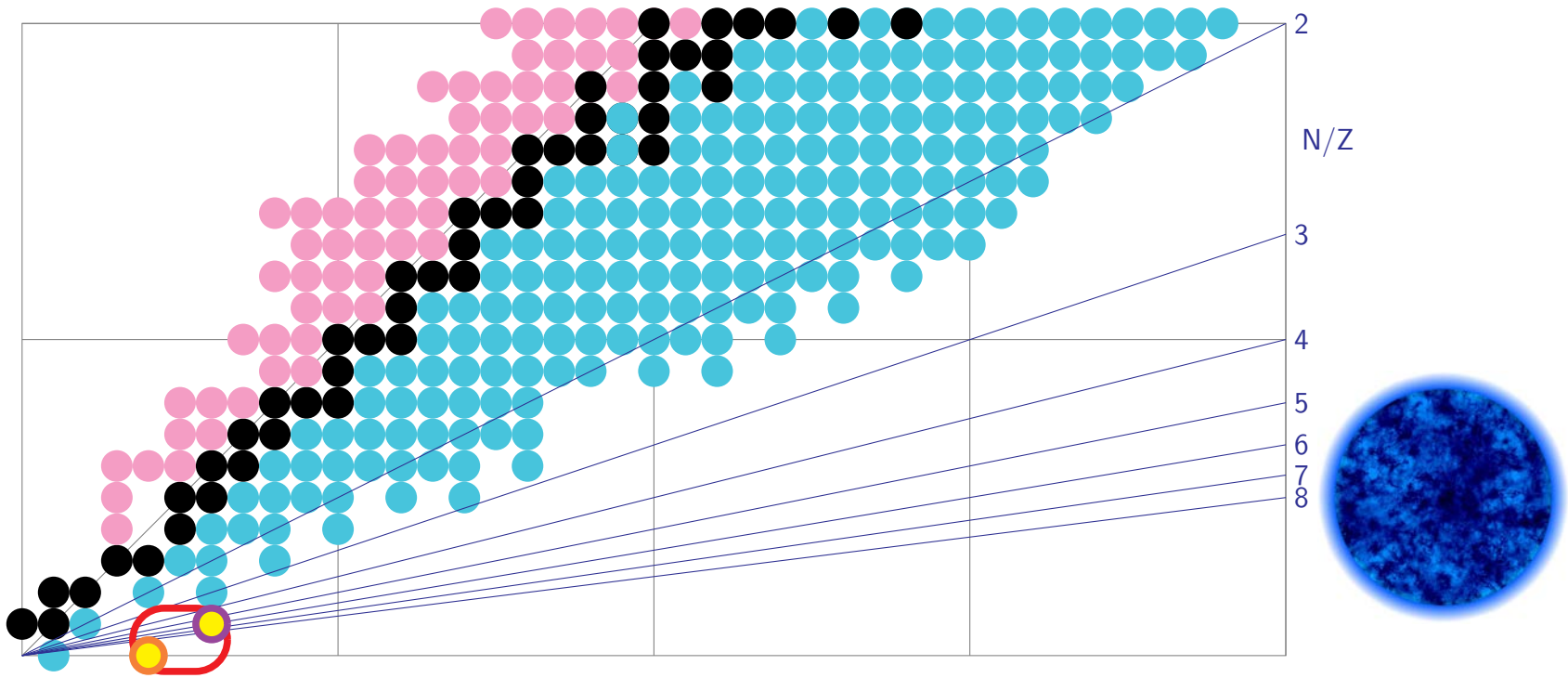
('16) SHARAQ 2.0 : {DAQ, tracking, calib.} $\Rightarrow$ stat. & res. $\times$5

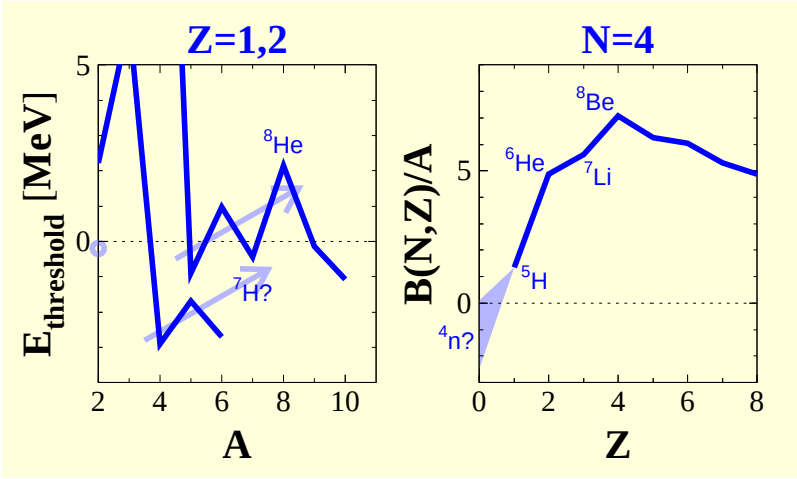
('17) QFS (p,pα) : $\theta_{cm} \lesssim 180°$ $\Rightarrow$ 4n without FSI

('17) 4n decay of ^{7}H $\Rightarrow$ high stat. & res. for any ^{7}H and ^{4}n state

$\Rightarrow$ definitive answer !

Hydrogen 7 : a tiny neutron star





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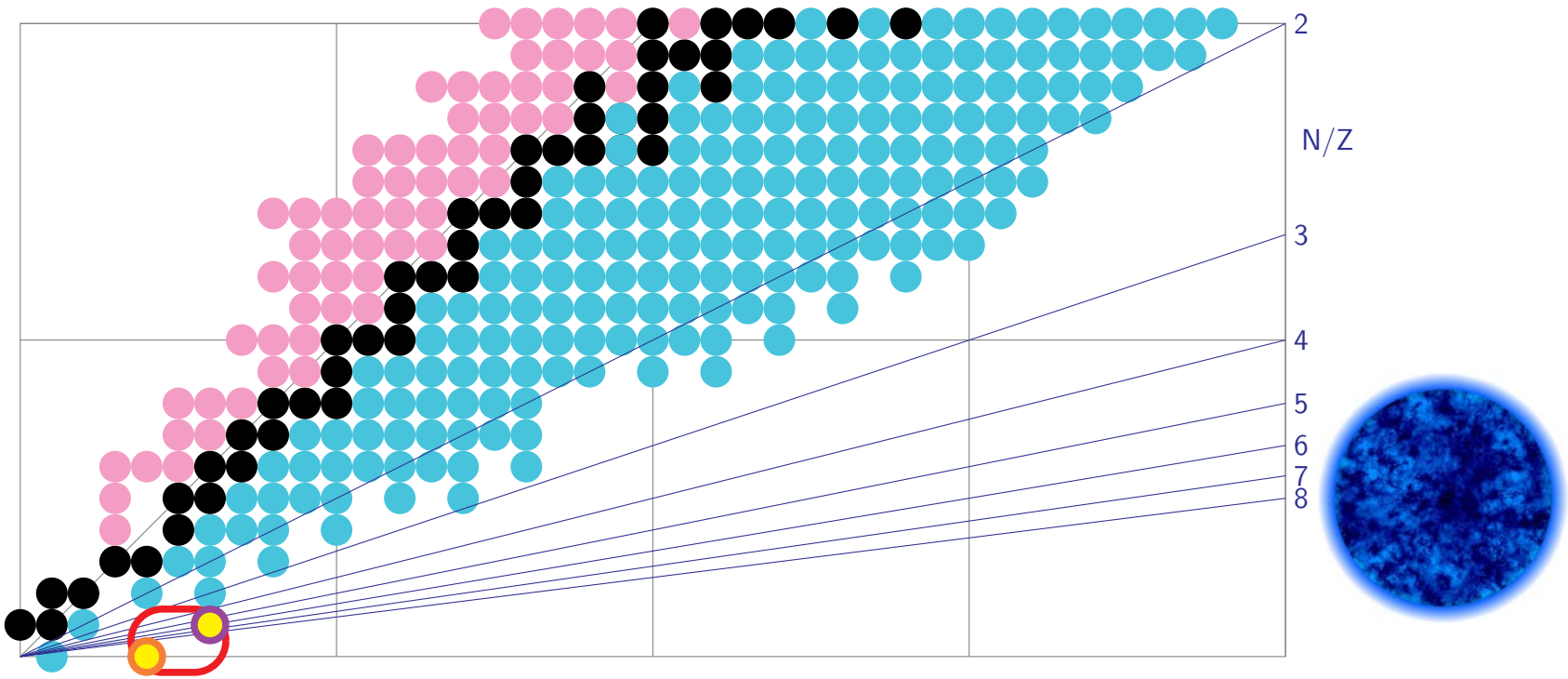
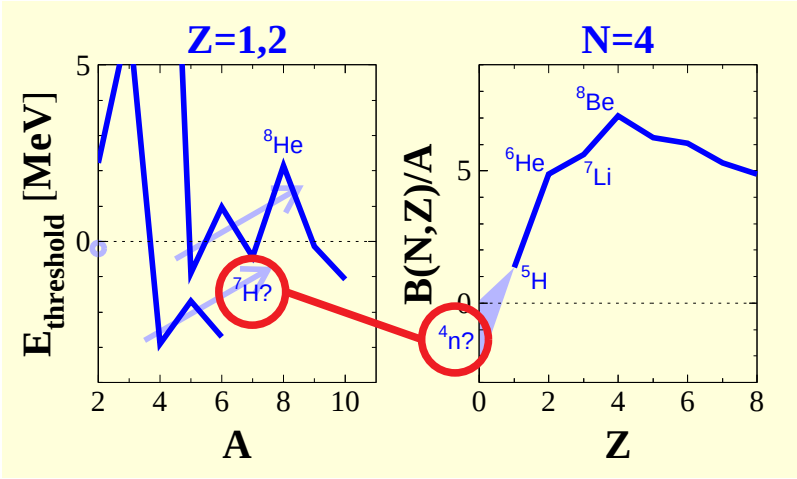
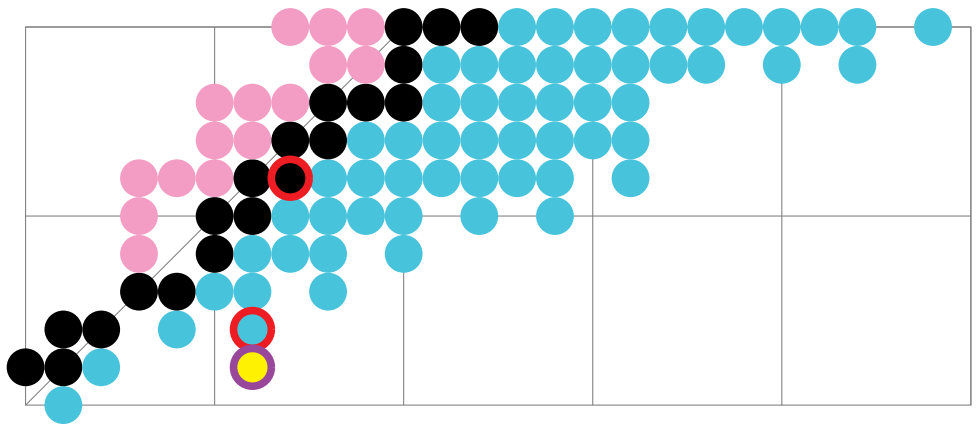


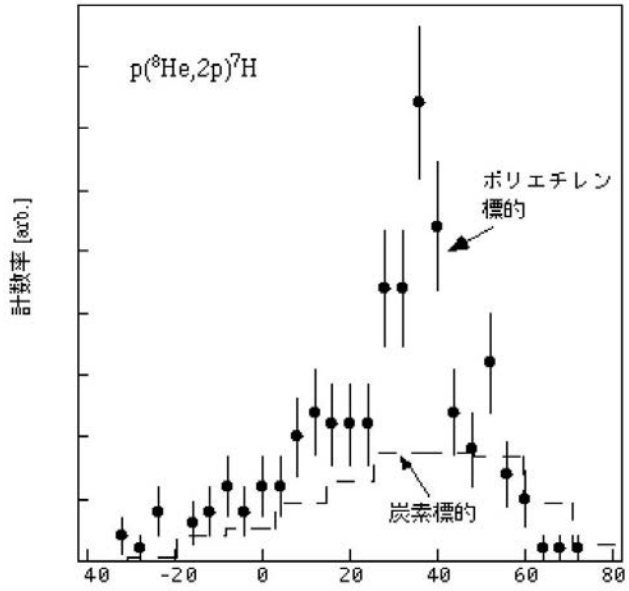


- Ambiguous and contradictory signals :
  - low statistics & resolutions
  - backgrounds (targets, binary channels)
  - missing mass : no neutron detection

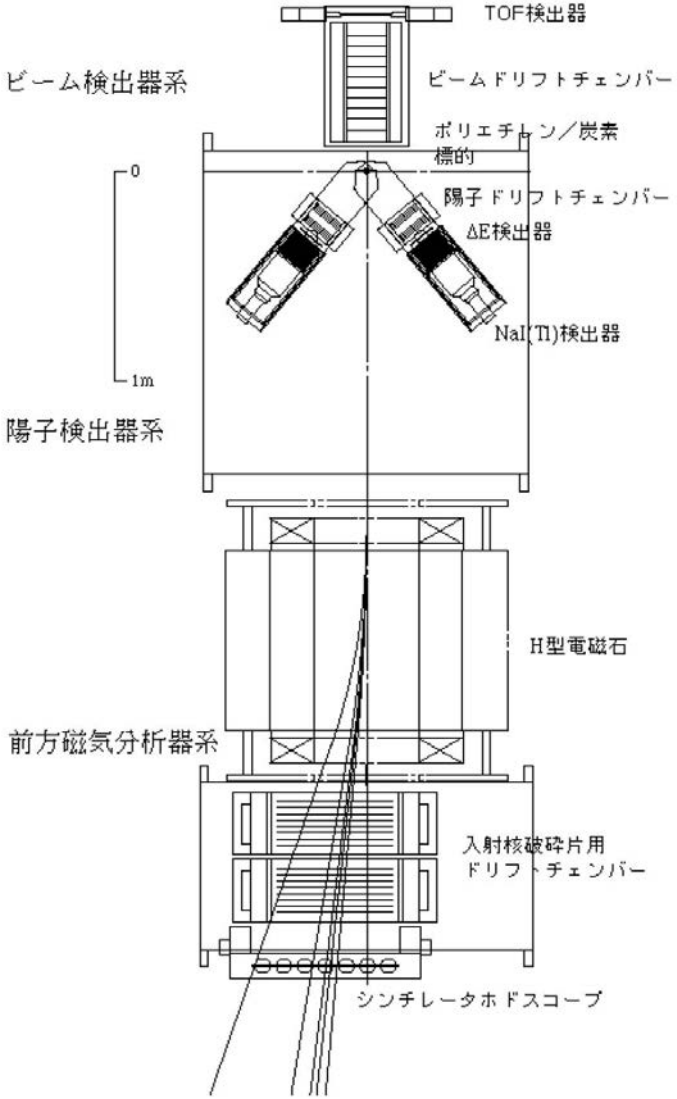
Japanese Hydrogen 7



- ^{8}He (p,2p) ^{7}H @ 190 MeV/N :



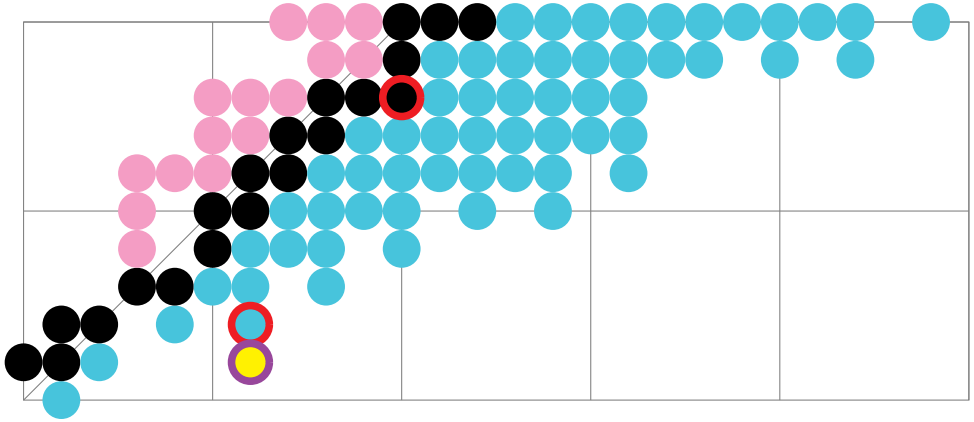
p(^{8}He,2p)^{7}H反応の陽子分離エネルギー分布

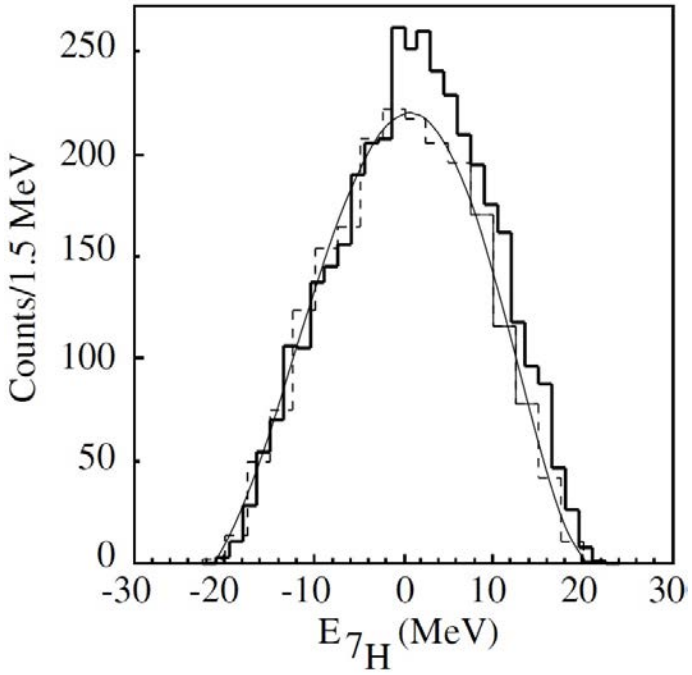


完成した前方磁気分析器と陽子検出器系

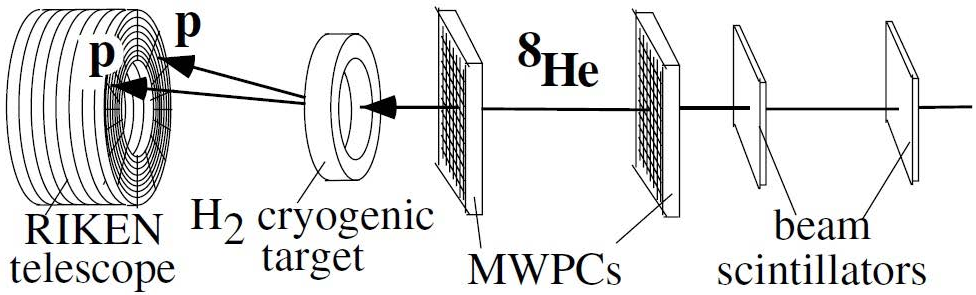
Kobayashi, HIMAC Report H12 (2000)

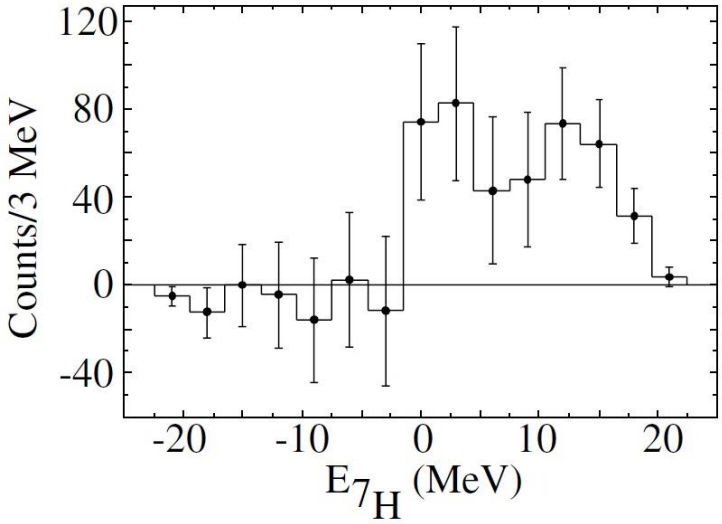
'Russian' Hydrogen 7



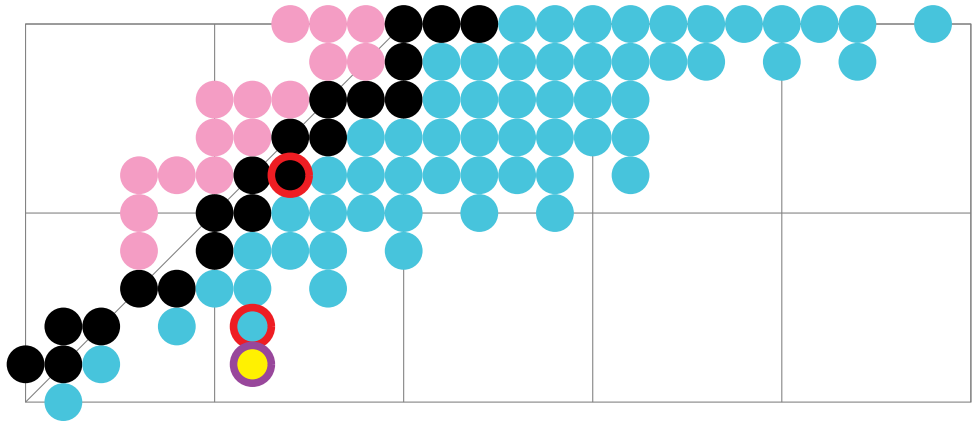


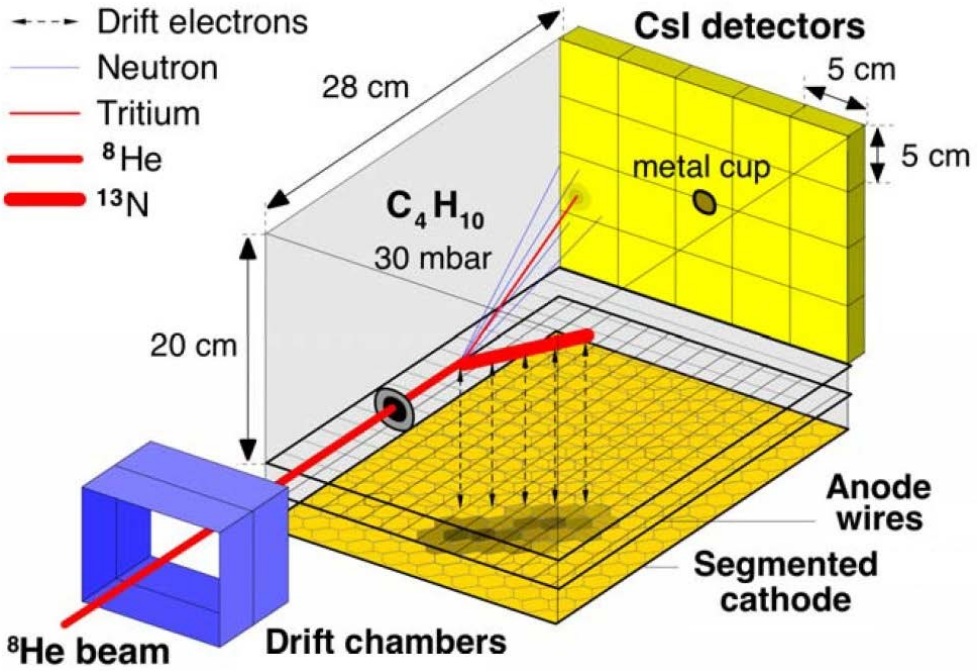
- ^{8}He (p,2p) ^{7}H @ 61 MeV/N :





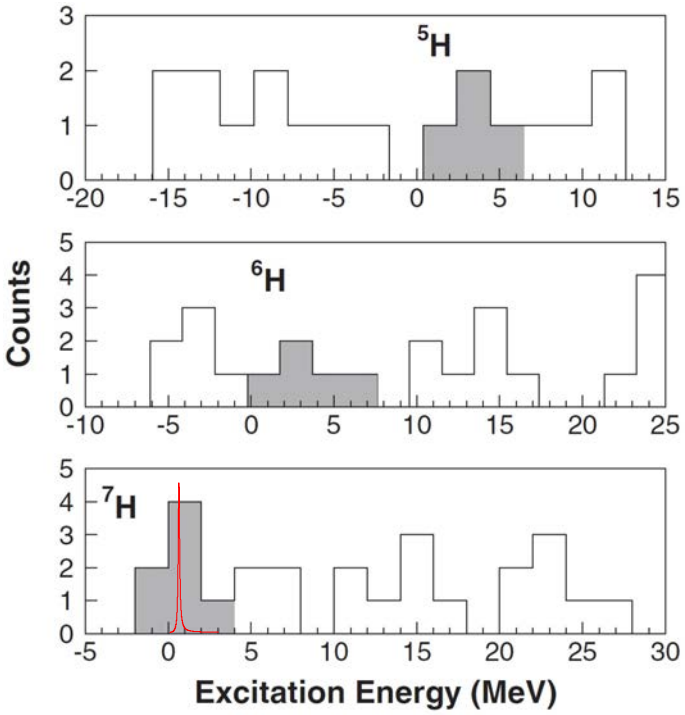
Korsheninnikov, PRL 90 (2003) 082501





Caamaño, PRL 99 (2007) 062502

- ^{8}He (^{12}C,^{13}N) ^{7}H @ 15 MeV/N :

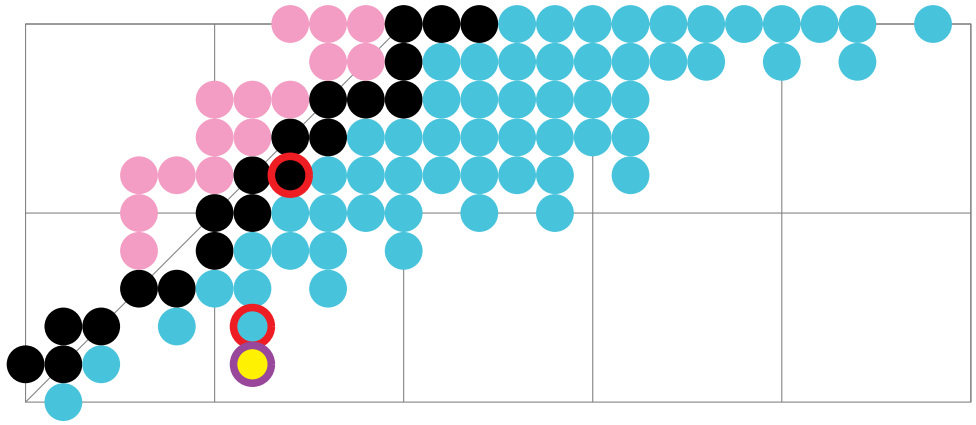


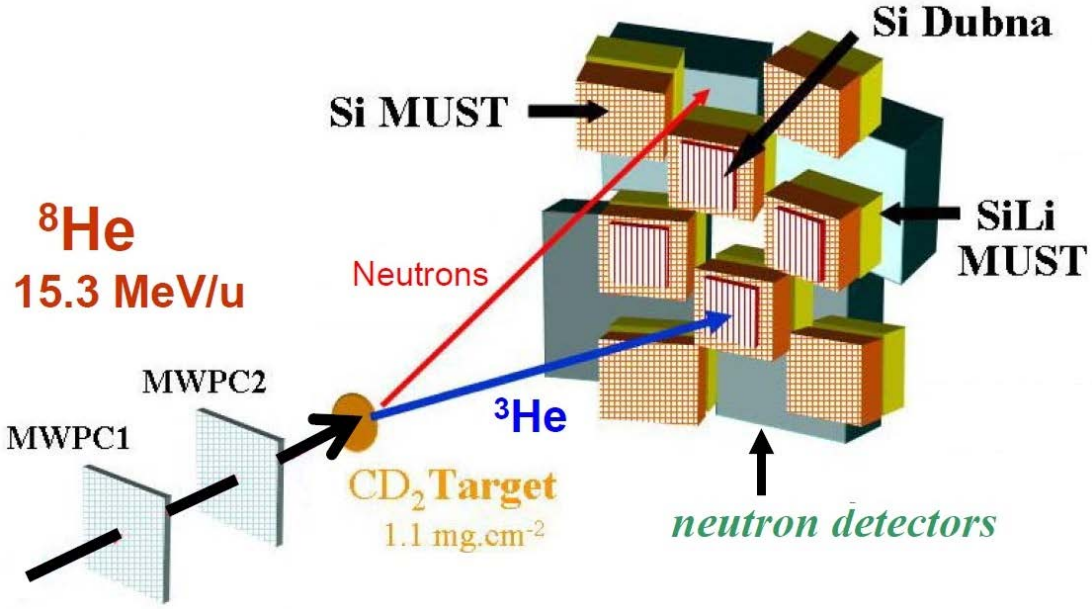
"represents an unambiguous proof"

- $E_{gs}(^{7}H) = 0.6 \pm 0.3$ MeV $(\Gamma \sim 0.1)$

⇨
- low resolution & statistics
- no mass identification for ^{A}N
- only part of triton branch ...

Another French Hydrogen 7 ?

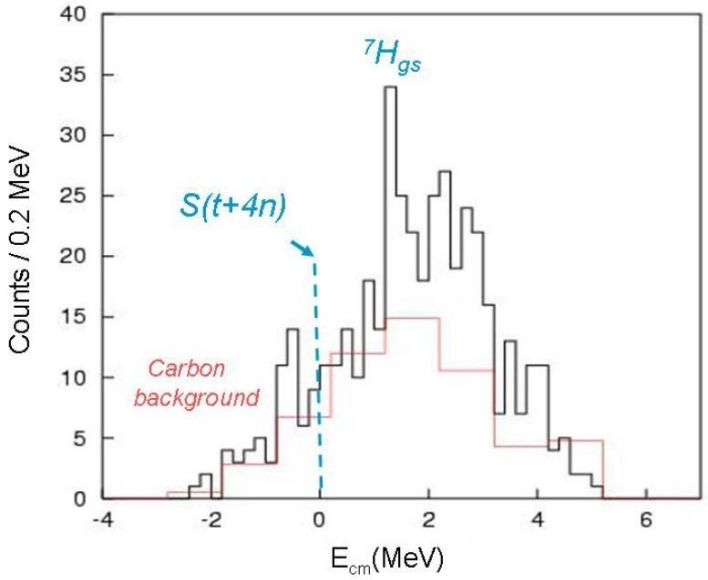


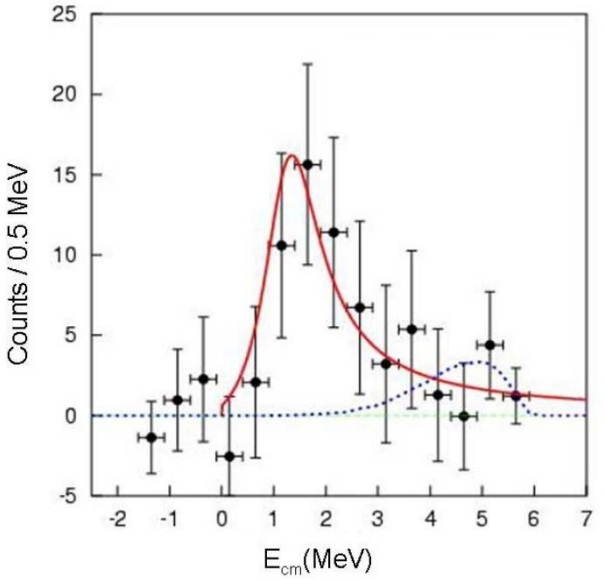


Beaumel, PISA Workshop (2008)

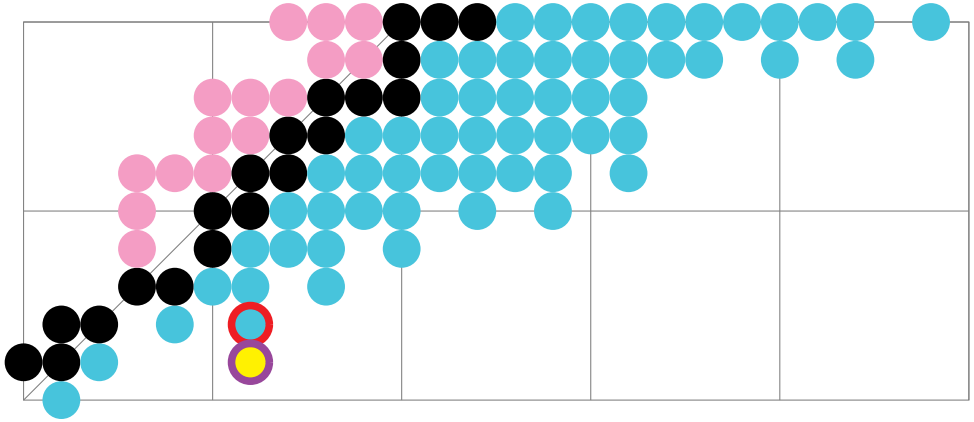
Fortier, EXON Symposium (2006)

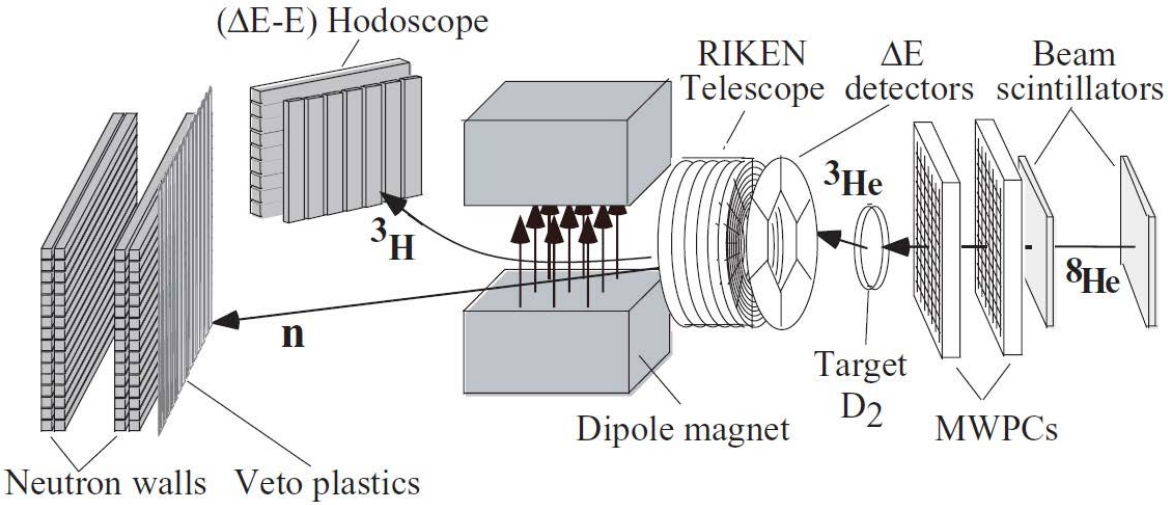
▶ ^{8}He (d,^{3}He) ^{7}H @ 15 MeV/N :





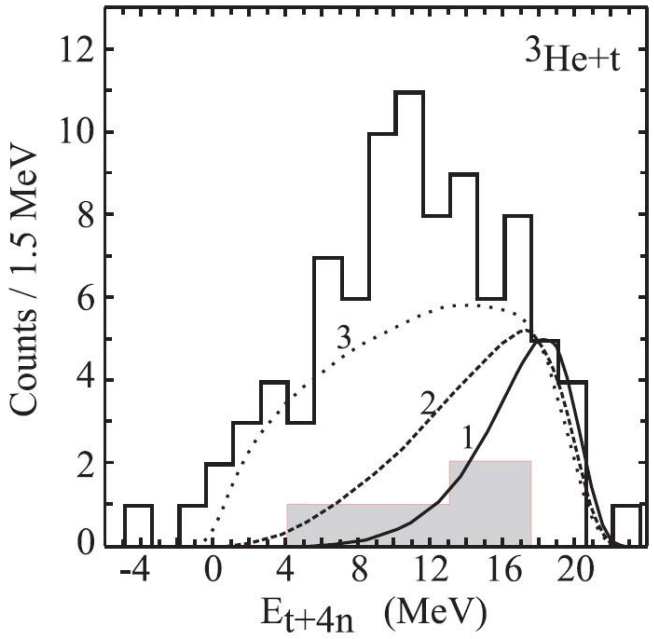
Another 'Russian' Hydrogen 7 (and a 4n) ?





Nikolskii, PRC 81 (2010) 064606

▶ ^{8}He(d,^{3}He)^{7}H @ 42 MeV/N :

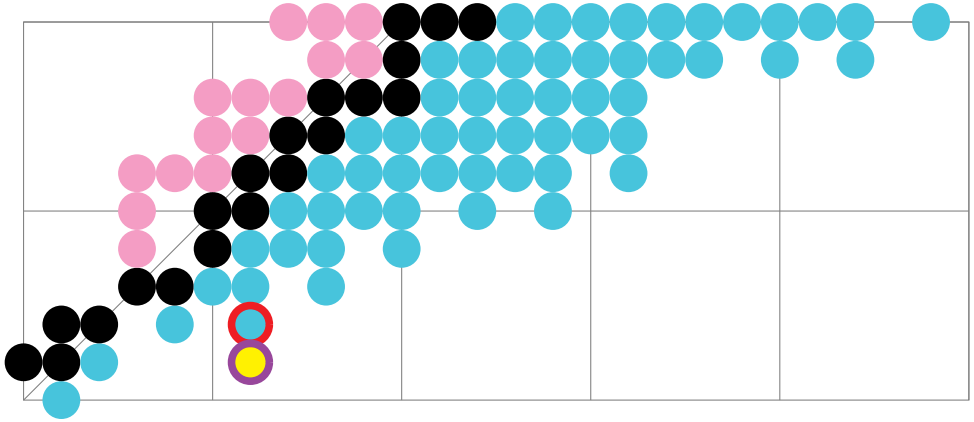


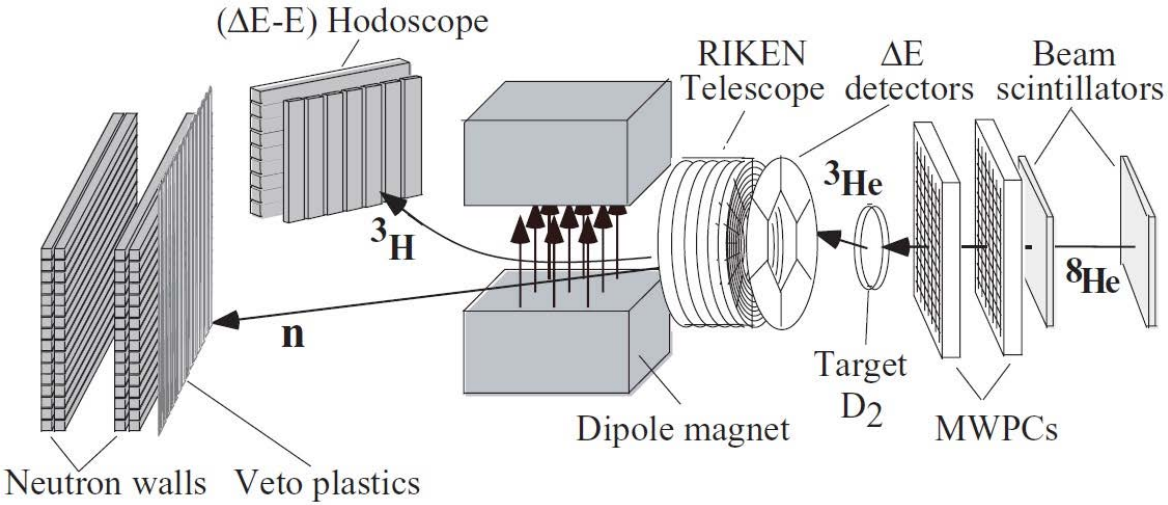
"a peculiarity at ∼ 2 MeV" ?

1) 5-body (t+n+n+n+n) PS

2) 3-body (t+2n+2n) PS

Another 'Russian' Hydrogen 7 (and a 4n) ?





Nikolskii, PRC 81 (2010) 064606

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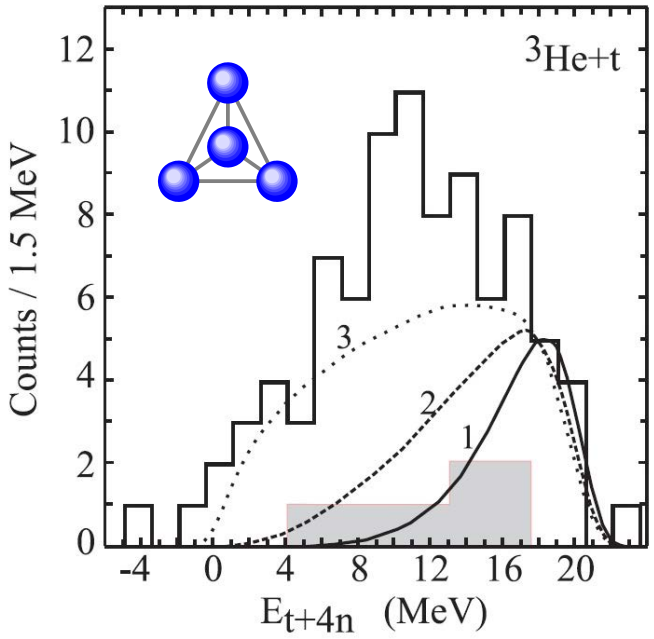


"a peculiarity at ∼ 2 MeV" ?

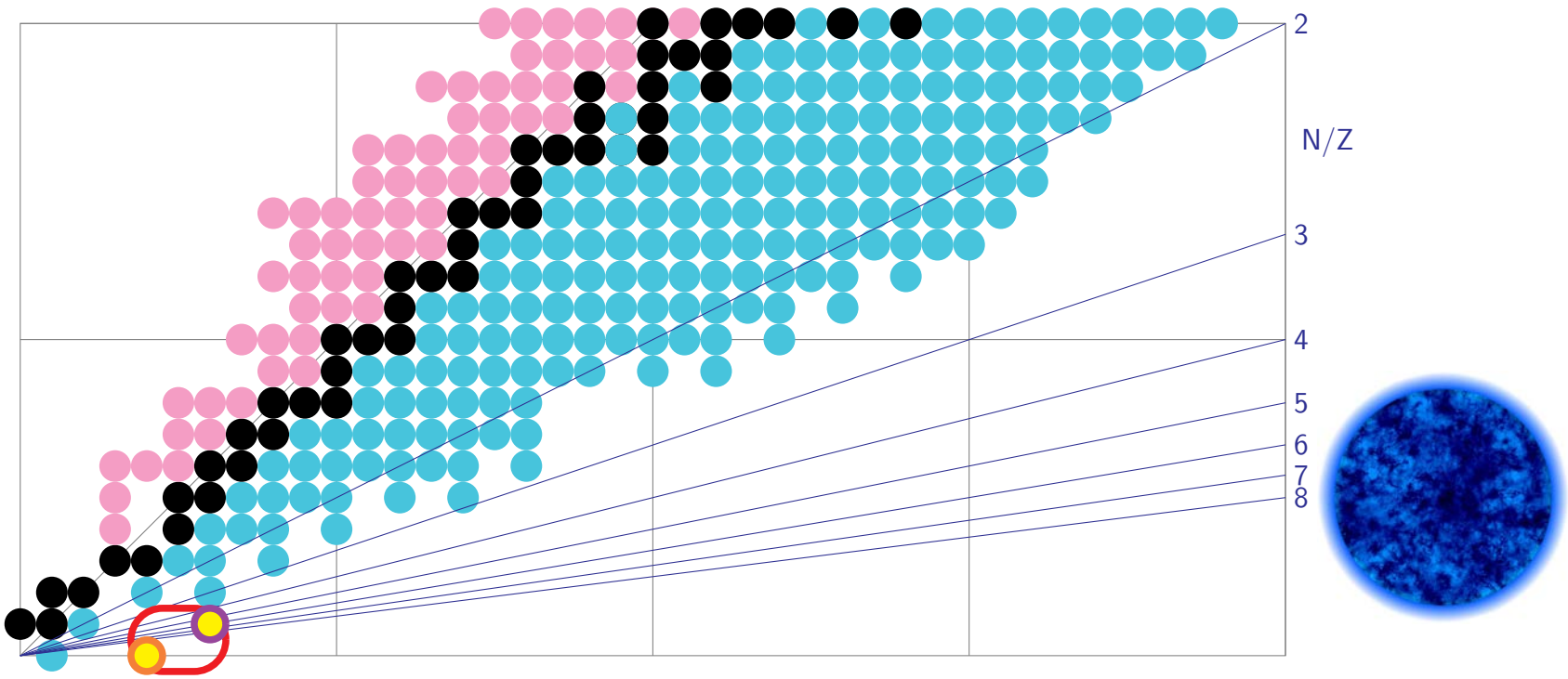
1) 5-body (t+n+n+n+n) PS

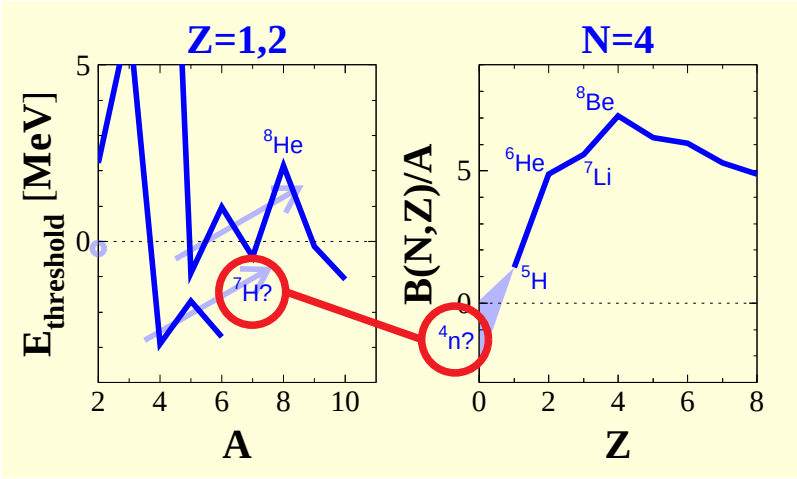
2) 3-body (t+2n+2n) PS

3) 2-body (t+4n) PS !

⇨ *"extreme, unrealistic case"* !!!

Hydrogen 7 : a tiny neutron star



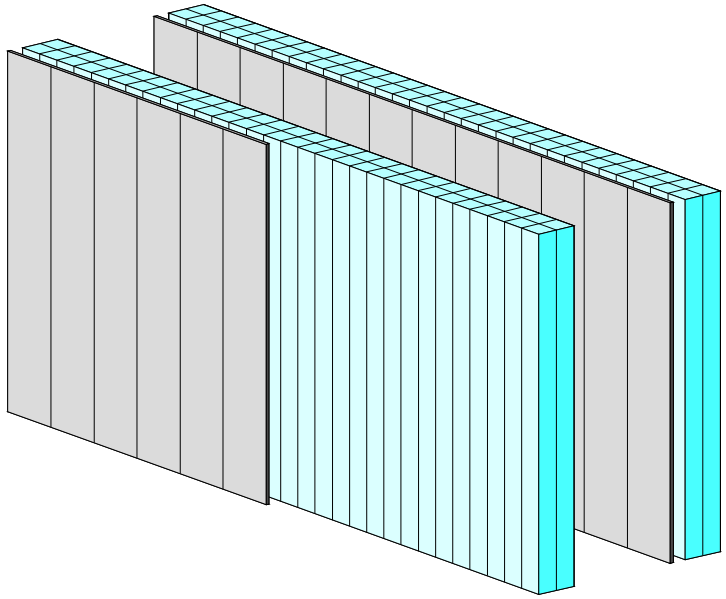


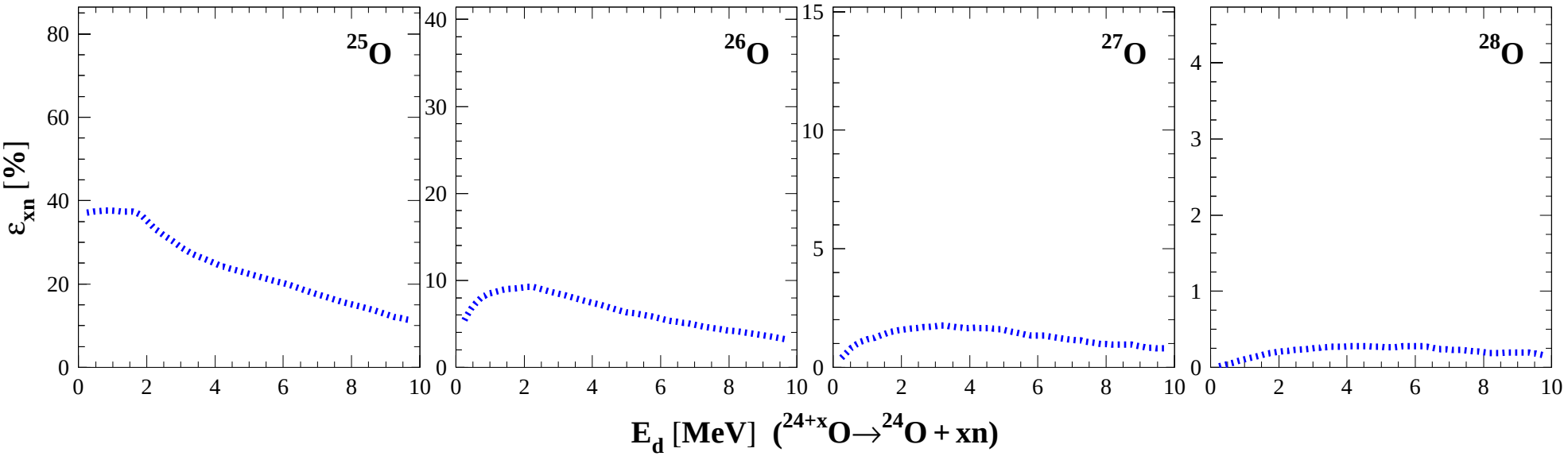
- Ambiguous and contradictory signals :
  - low statistics & resolutions
  - backgrounds (targets, binary channels)
  - missing mass : no neutron detection

  ⇨ ^{7}H & ^{4}n proposal with $\varepsilon(4n) \gg 0$!

EXPAND : French ANR funding

- Expand NEBULA multi-n capabilities :
  - France : LPC, IRFU, IPNO
  - Japan : TITech, RIKEN



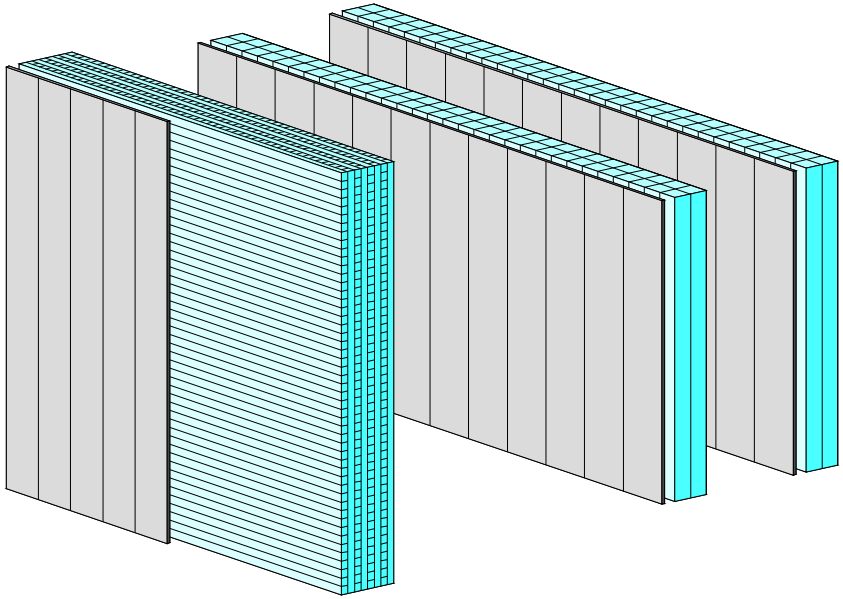


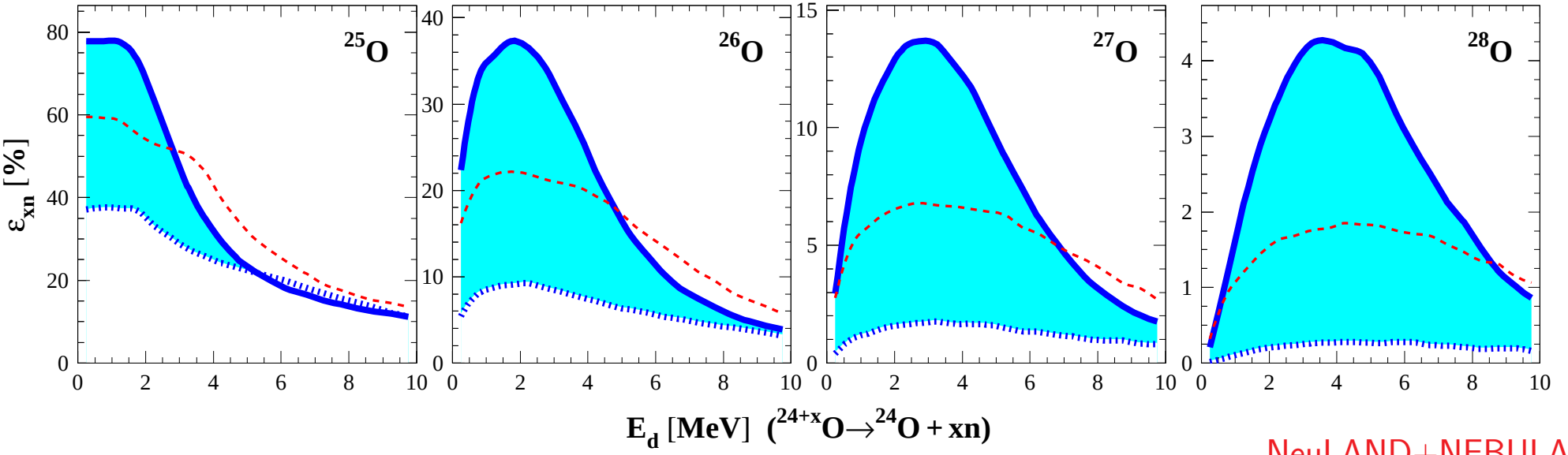
($\varepsilon_{xn} < \varepsilon_n^x$ due to neutron cross-talk) FMM, NIM A 450 (2000) 109

EXPAND : French ANR funding

- Expand NEBULA multi-n capabilities :
  - France : LPC, IRFU, IPNO
  - Japan : TITech, RIKEN
  - +90 bars : Comm. & Day-1 in 2019
  - suggested configuration :

    ⇨ ε(4n) enhanced $\sim \times 16$!





--- NeuLAND+NEBULA

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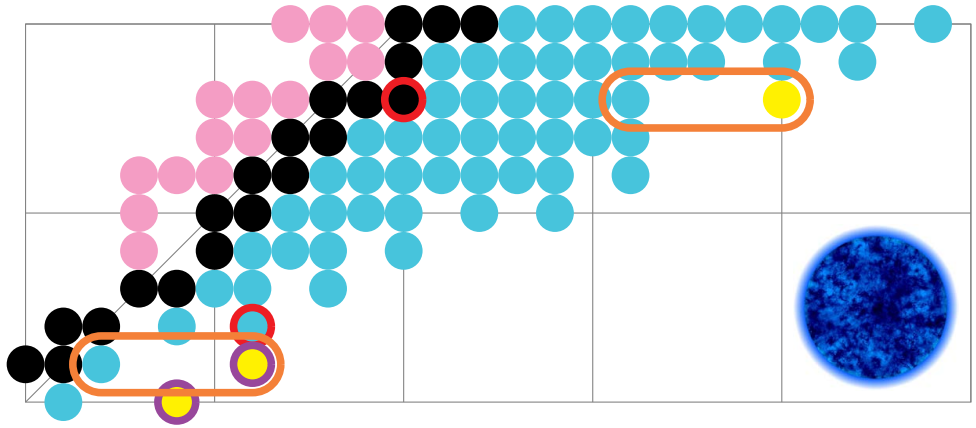
Hydrogen 7 & Tetraneutron



- ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

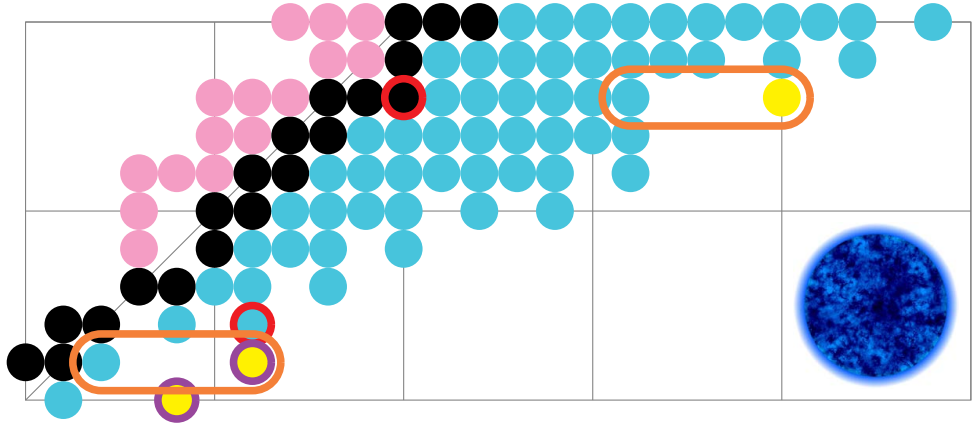
"Many-neutron systems:
search for superheavy Hydrogen 7
and its Tetraneutron decay"

Yang & FMM, RIBF NP1512-SAMURAI34

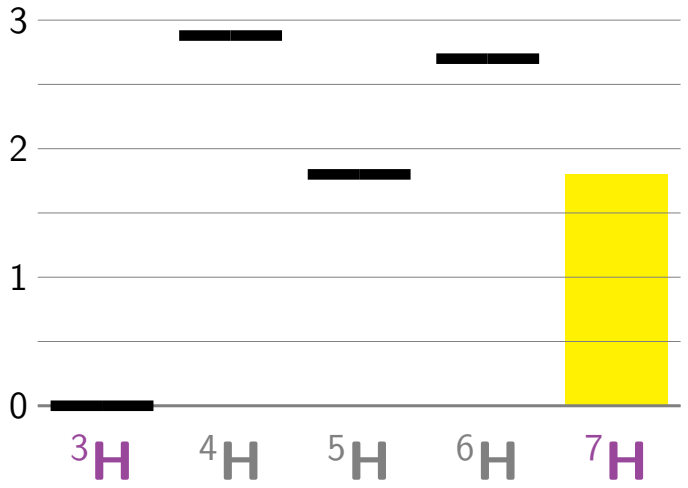
- follow up of Orr, RIBF NP1306-LOI08

  → ^{28}O [Kondo] already done !

Hydrogen 7 & Tetraneutron



- $N = 6$ $(\nu p_{3/2})^4$ sub-shell closure ?



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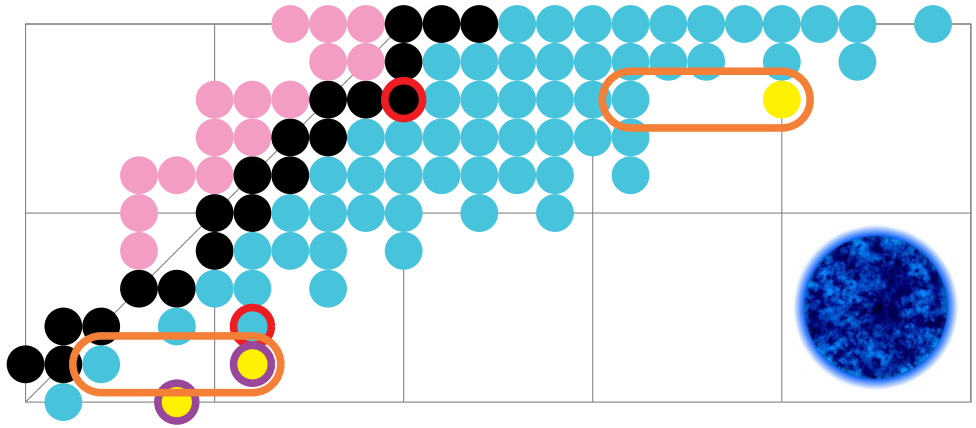

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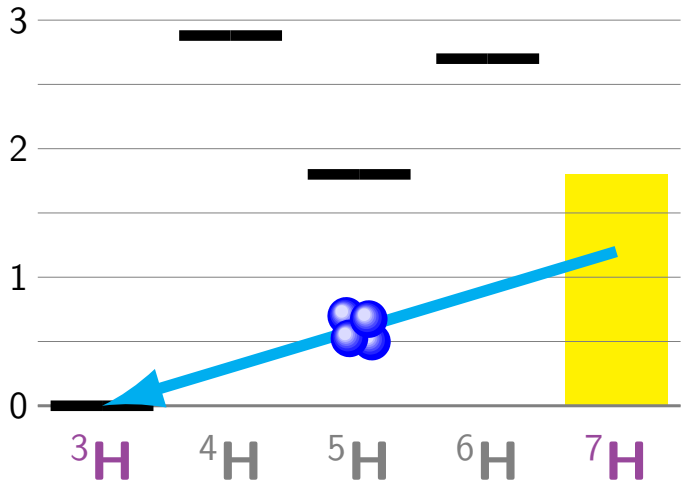

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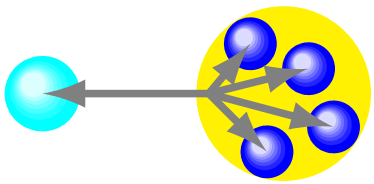
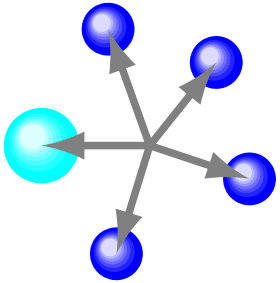
  → ^{28}O [Kondo] already done !

- direct ^{4}n decay ? $E_R(4n)$!

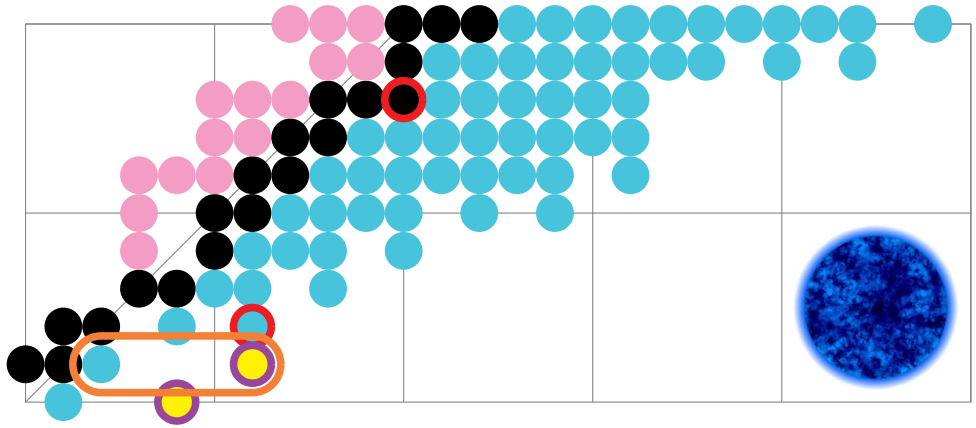


(2-body PS)

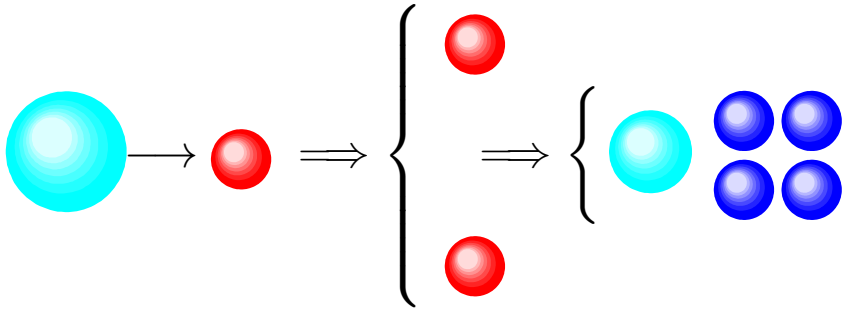


(5-body PS)

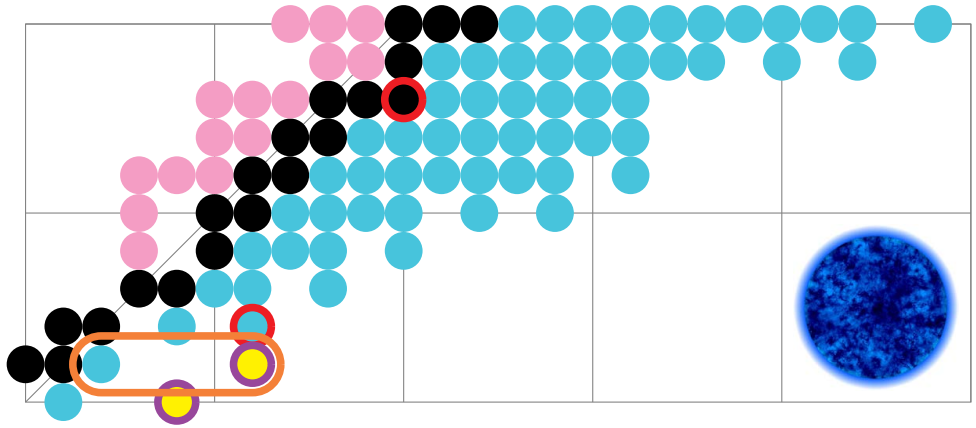
Hydrogen 7 & Tetraneutron : complete kinematics



^{8}He (p,2p) ^{7}H @ 150 MeV/N :



Hydrogen 7 & Tetraneutron : complete kinematics



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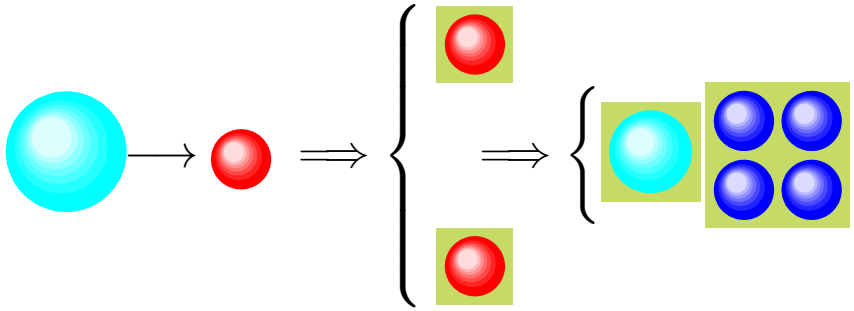


→ detection of the 7-body final state !

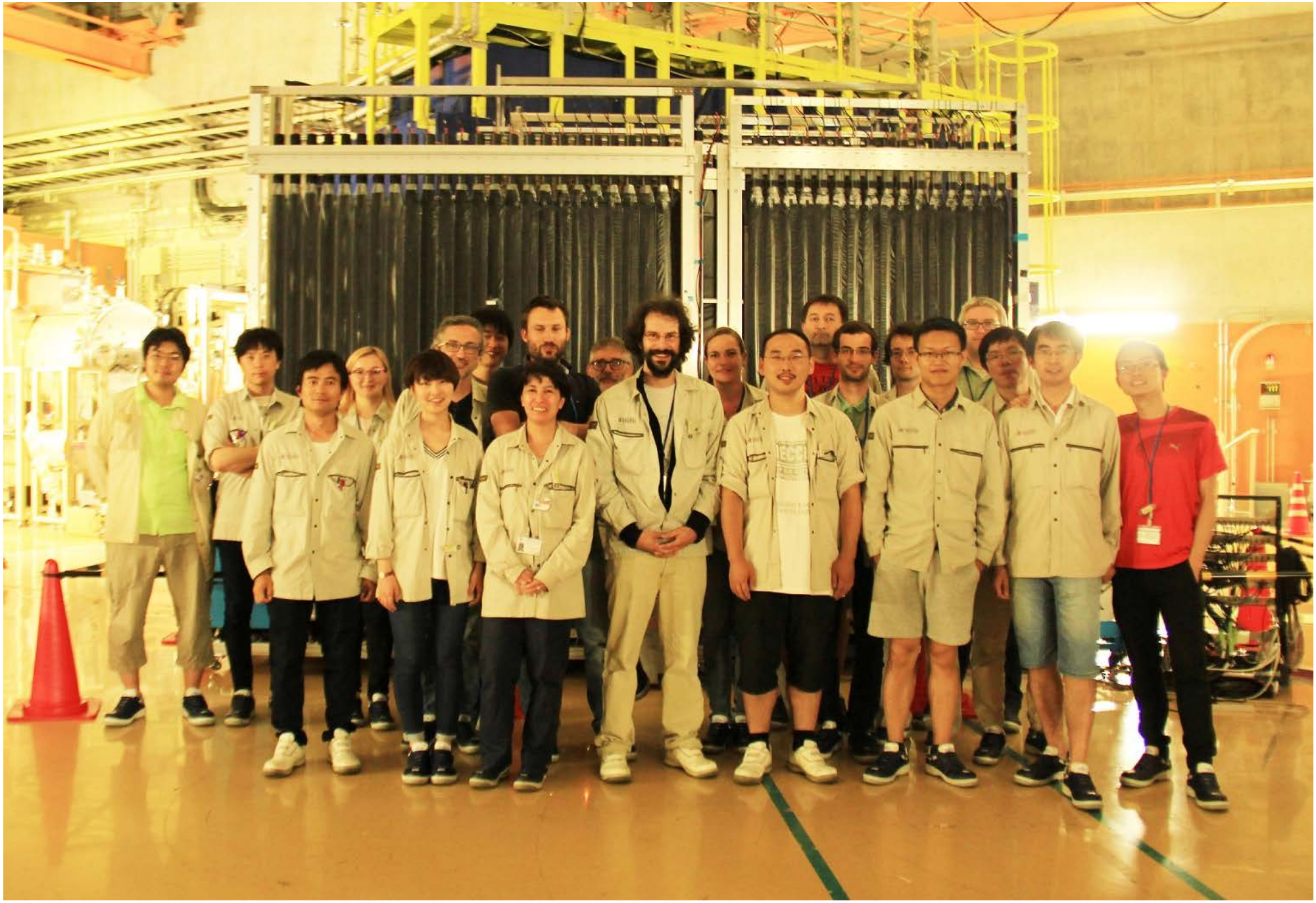
- **MINOS** liquid H target :
  - → high luminosity (*statistics*)
  - → proton angles (*resolution*)
- **DALI** NaI crystals :
  - → proton energies (*efficiency*)
- **SAMURAI** :
  - → triton momentum (*resolution & correlations*)
- **NEBULA** + **NeuLAND** :
  - → 3/4 neutron momenta (*efficiency, resolution & correlations*)

$$\text{FWHM} \sim \begin{cases} 5 & \text{MeV} & (2p) \\ 150 & \text{keV} & (2p{+}t{+}3n) \\ 100 & \text{keV} & (t{+}4n)\ !!! \end{cases}$$

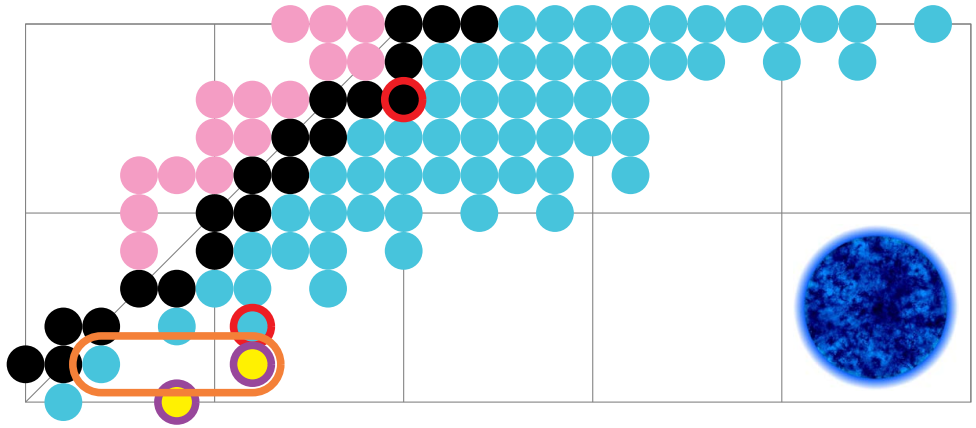
RIKEN : SAMURAI

RIKEN : SAMURAI

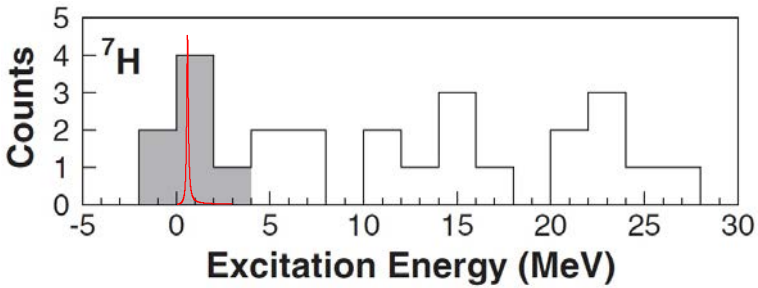
SAMURAI S34 collaboration (part)

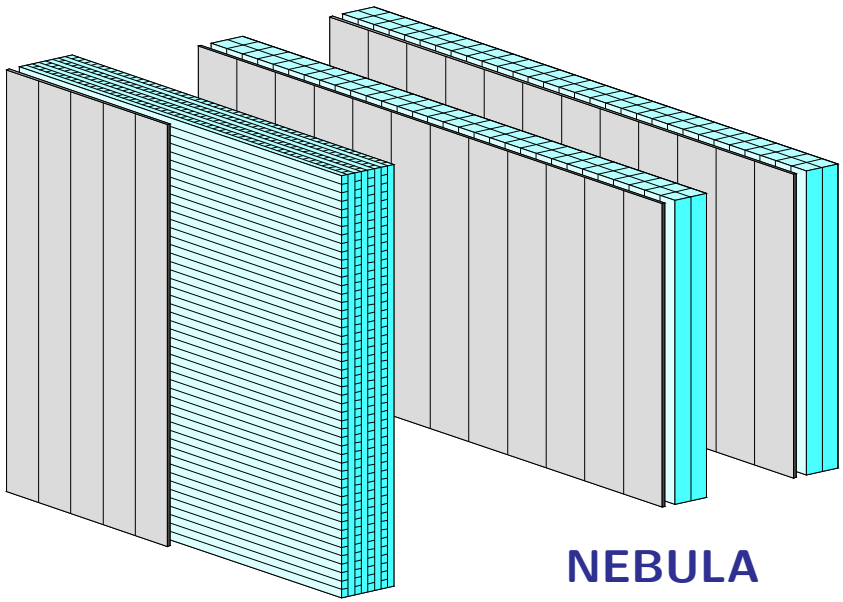


Expected statistics & resolution (MC simulation)



Caamaño, PRL 99 (2007) 062502





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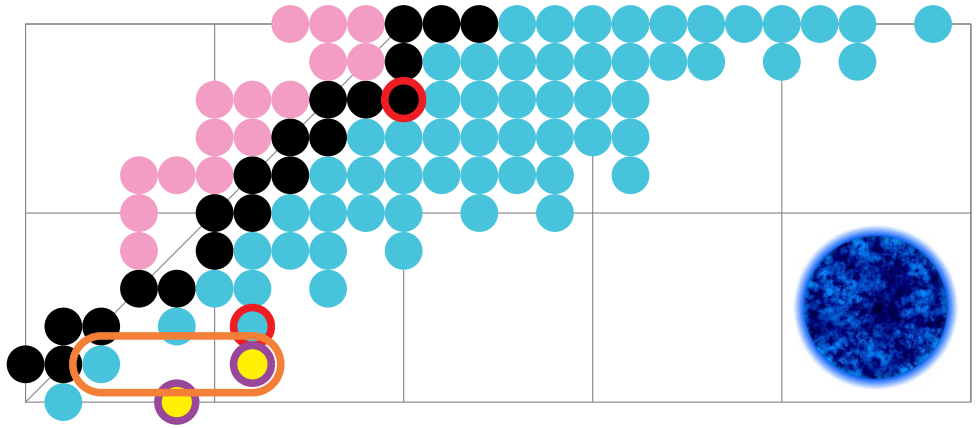

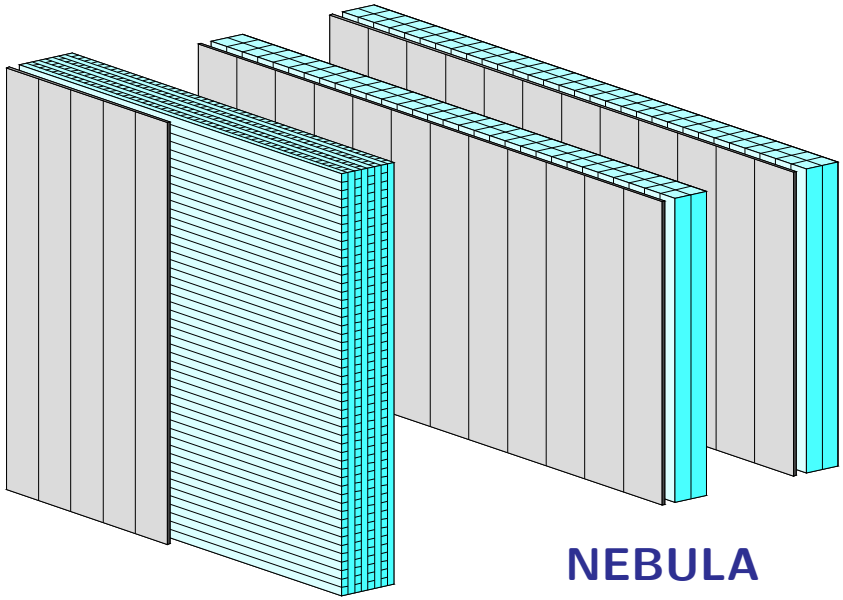

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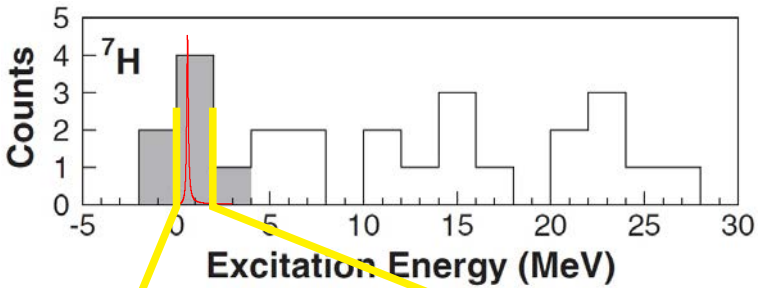
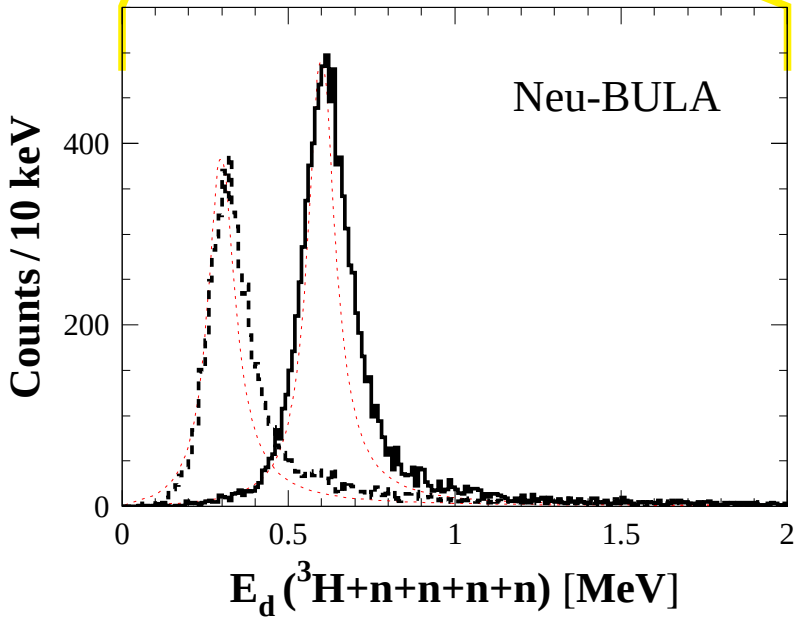
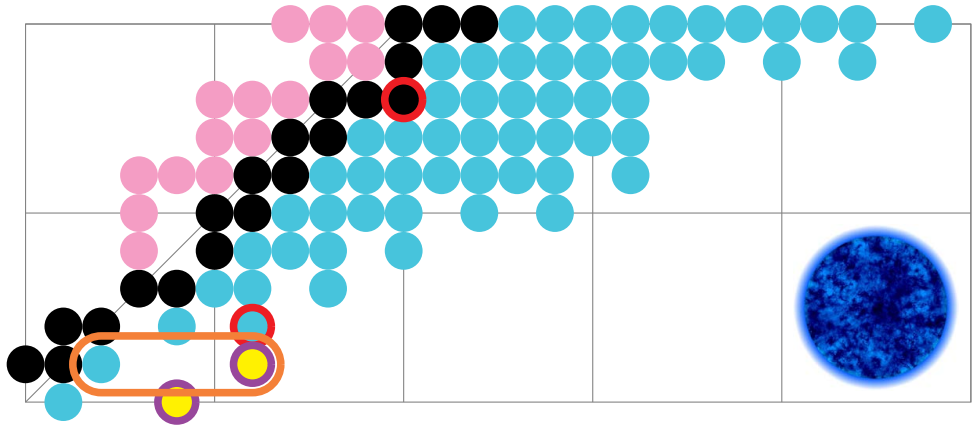


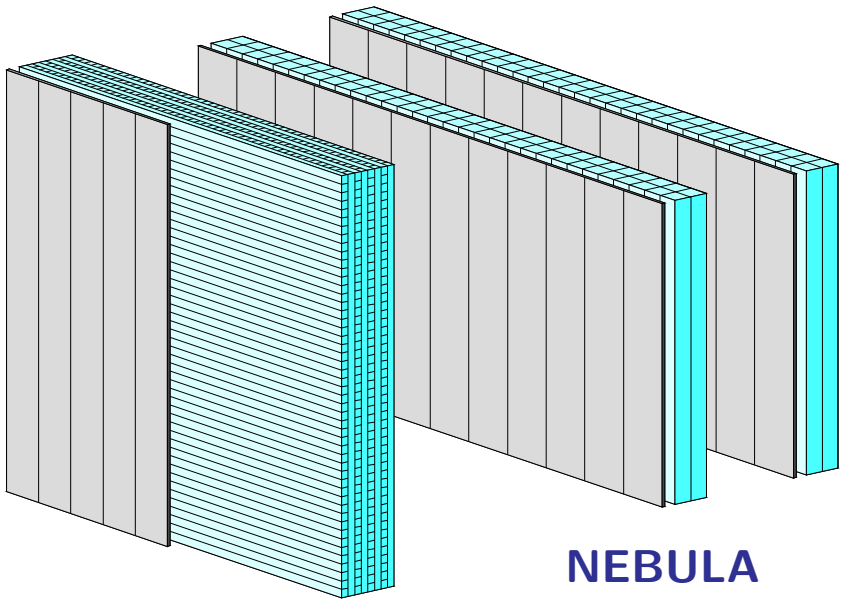


First online 'results' ...



- Online analysis : ^{8}He (p,2p) ^{3}H+^{4}**n**
  - ✔ ^{8}He on target
  - ✔ 2p detected
  - ✔ ^{3}H detected

  → $\geqslant$ 4 bars ?



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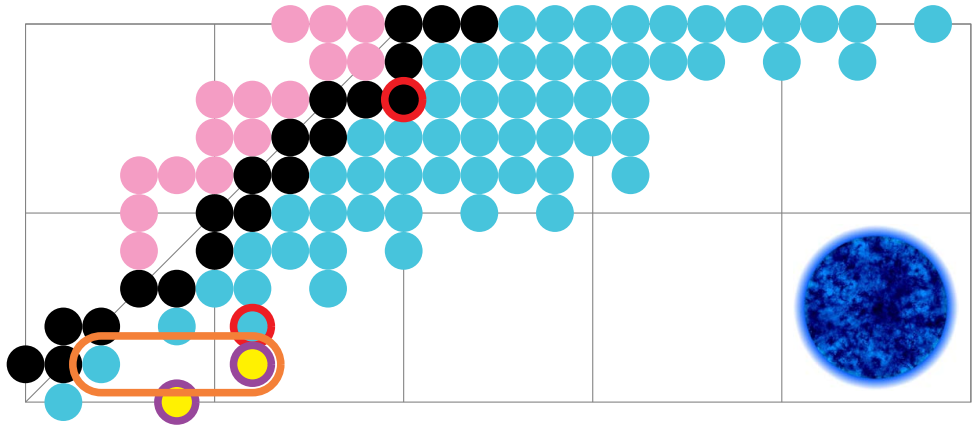

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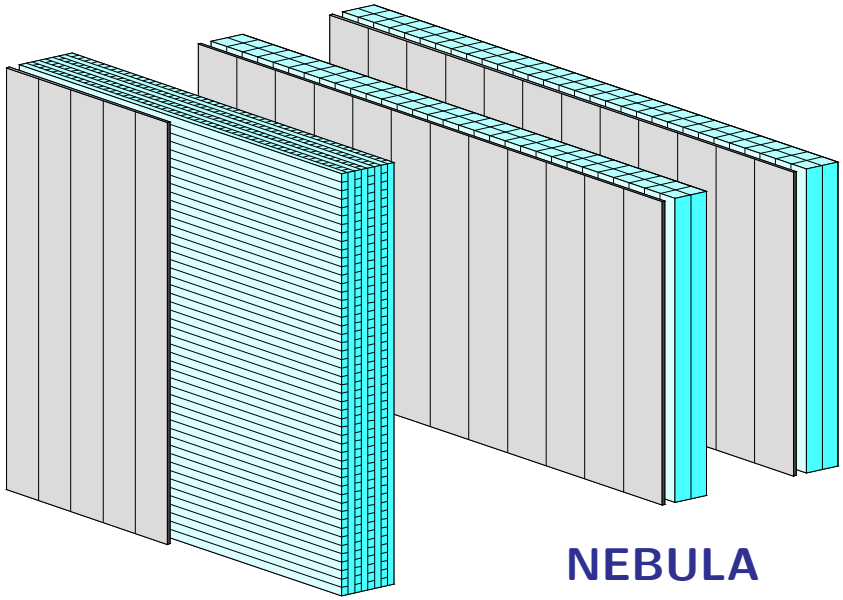
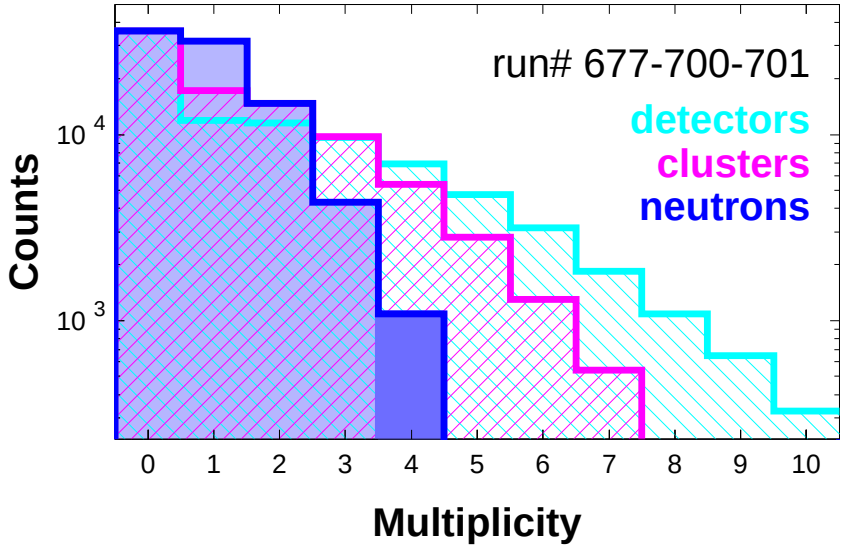




- → complete events : $\approx$ 8×10^{4} !!!
- → promising results in 1-2 years ...

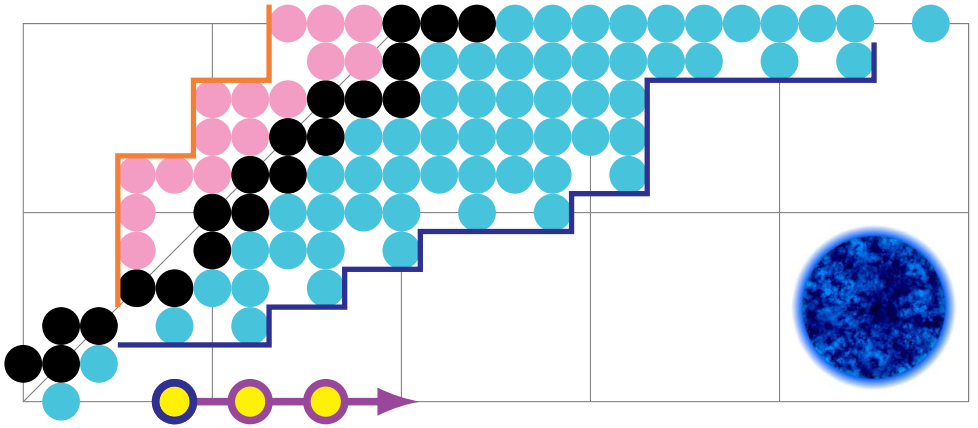
Summary & Outlook

❶ The ^{A}n context :

- XX century : $\sigma(^{A}\mathrm{n})$ & backgrounds ...
- XXI century : first signals !
  - → GANIL : theory & experiments
  - → RIKEN : more candidate events
- experimental constraints
- theoretical 'proofs' ?

❷ The RIKEN campaign :

- SHARAQ 2.0 : $^{4}\mathrm{He}\,(^{8}\mathrm{He},\alpha\alpha)\,^{4}\mathbf{n}$
- NEBULA+NeuLAND & MINOS :
  - → $^{8}\mathrm{He}\,(\mathrm{p},\mathrm{p}\alpha)\,^{4}\mathbf{n}$: 4n without FSI
  - → $^{8}\mathrm{He}\,(\mathrm{p},2\mathrm{p})\,\{^{3}\mathbf{H}+^{4}\mathbf{n}\}$: any $(\mathrm{E},\Gamma)_{\mathrm{R}}$



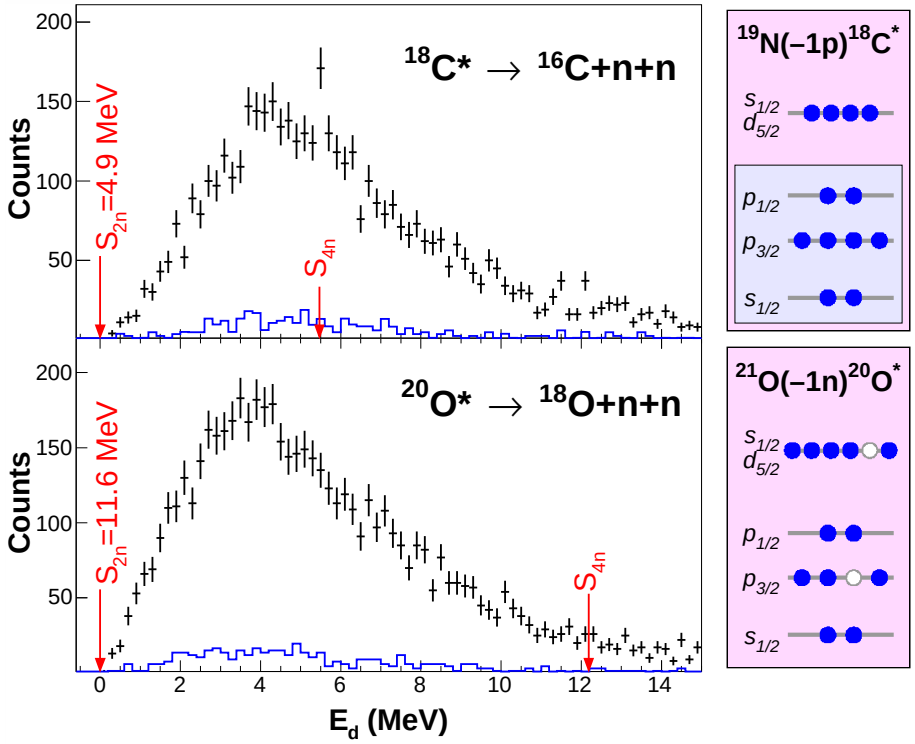
❸ Short/Mid-term future :

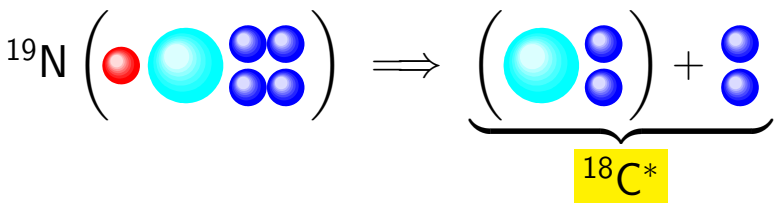
- confirm (refute) ^{4}n signals !
- $^{12,14}\mathrm{Be}\,(\mathrm{p},\mathrm{p}2\alpha)\,^{4,6}\mathbf{n}$ ('18)

  Beaumel, NP1206-SAMURAI12
  - → theory : reliable ^{4}n and beyond ...
  - → hexaneutron ? $^{8}\mathrm{He}\,(\mathrm{p},2\mathrm{p})^{1}\mathrm{H}$ ...
  - → ^{A}n emission ? $\mathrm{Q}_{\beta 6\mathrm{n}}(^{19}\mathrm{B}) \sim 8$ MeV ...
  - → core+$\boldsymbol{x}$**n** systems/thresholds ?

- **R3B** collaboration (LAND @ GSI) :
  - N = 12 isotones (^{18}C & ^{20}O) above S_{2n}

Revel, submitted to PRL (2018)





"Strong neutron pairing in core+4n nuclei" [A. Revel]

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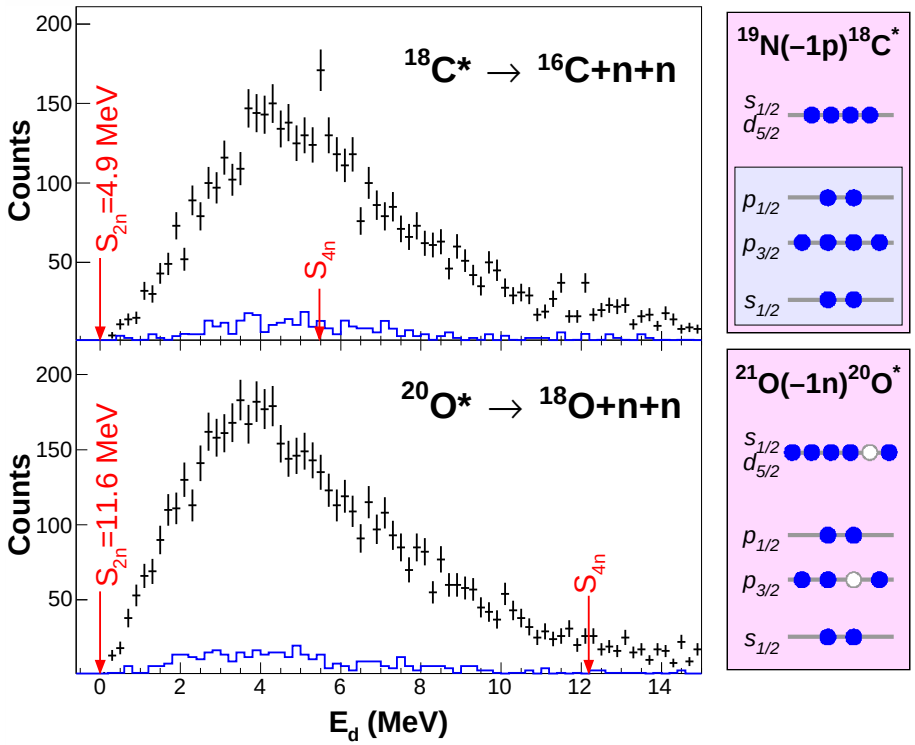

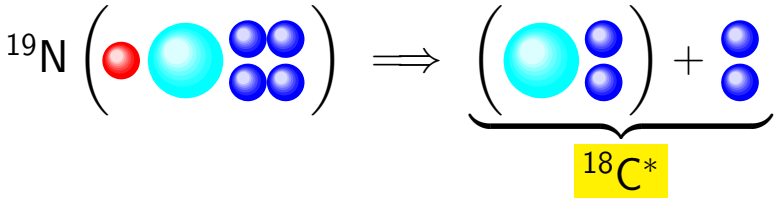

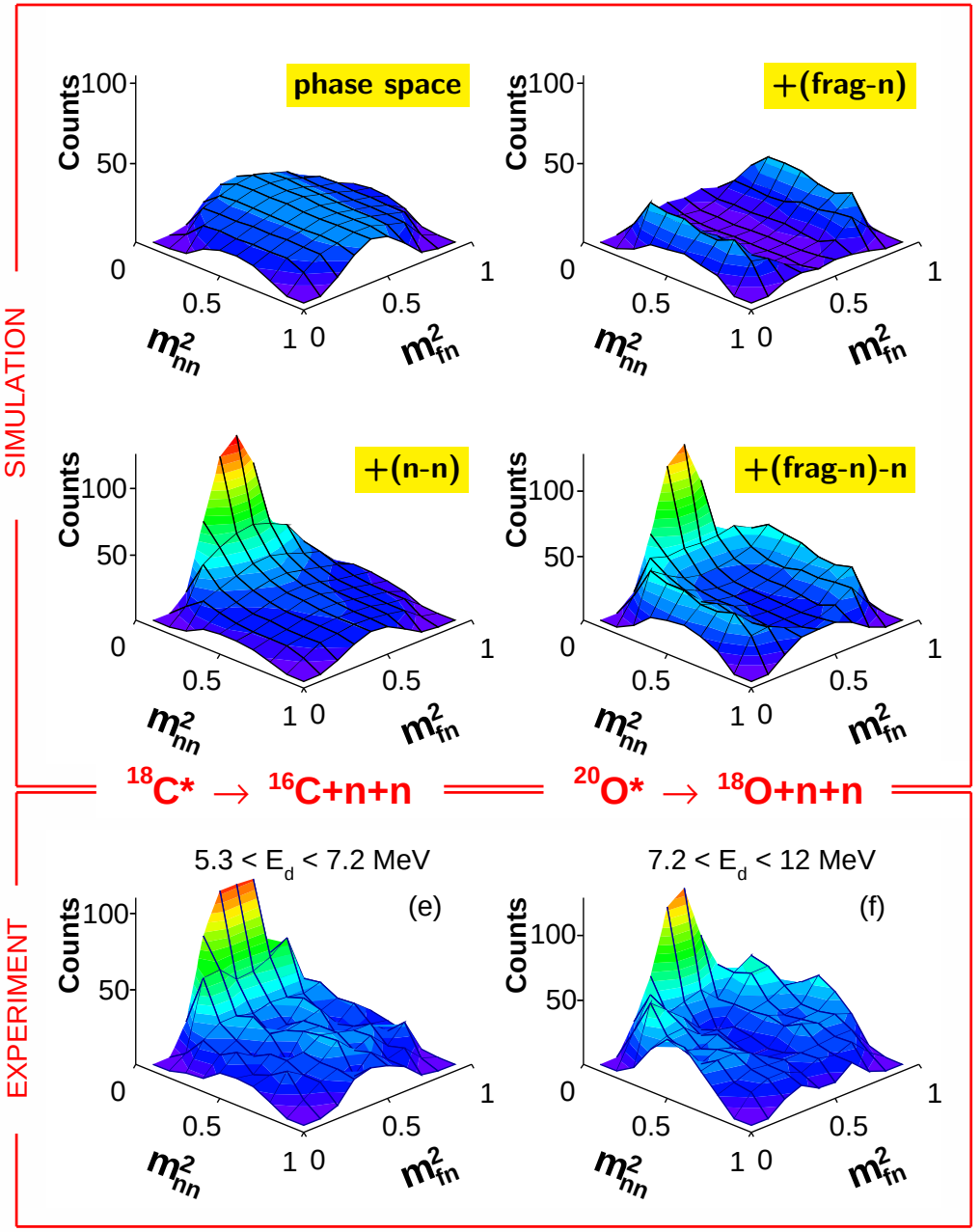

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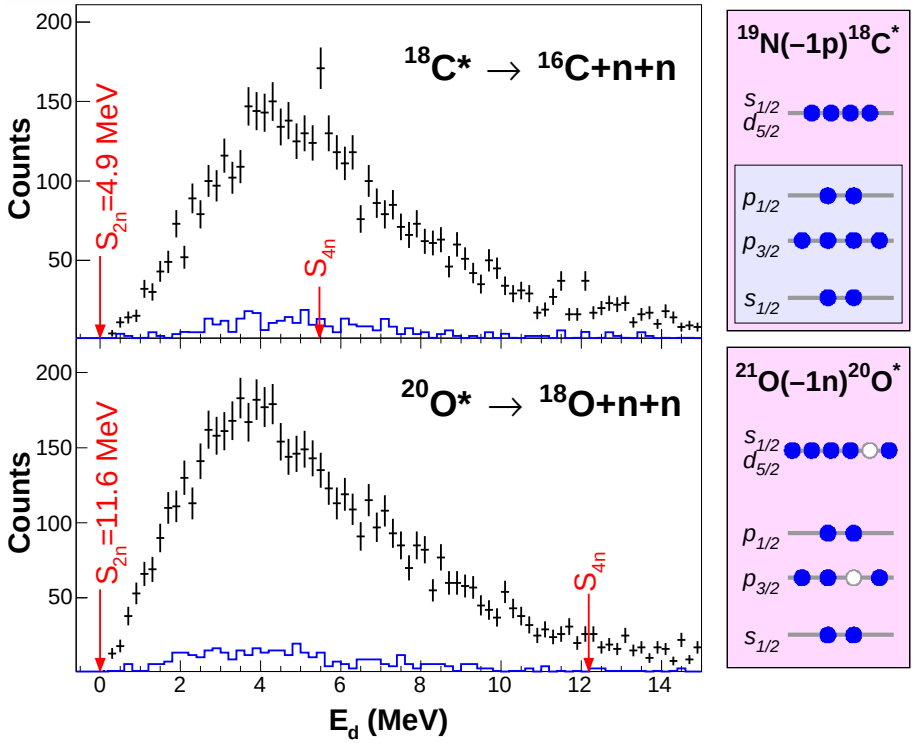
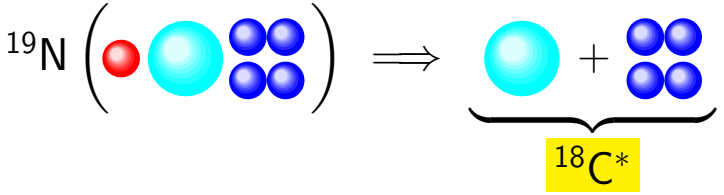
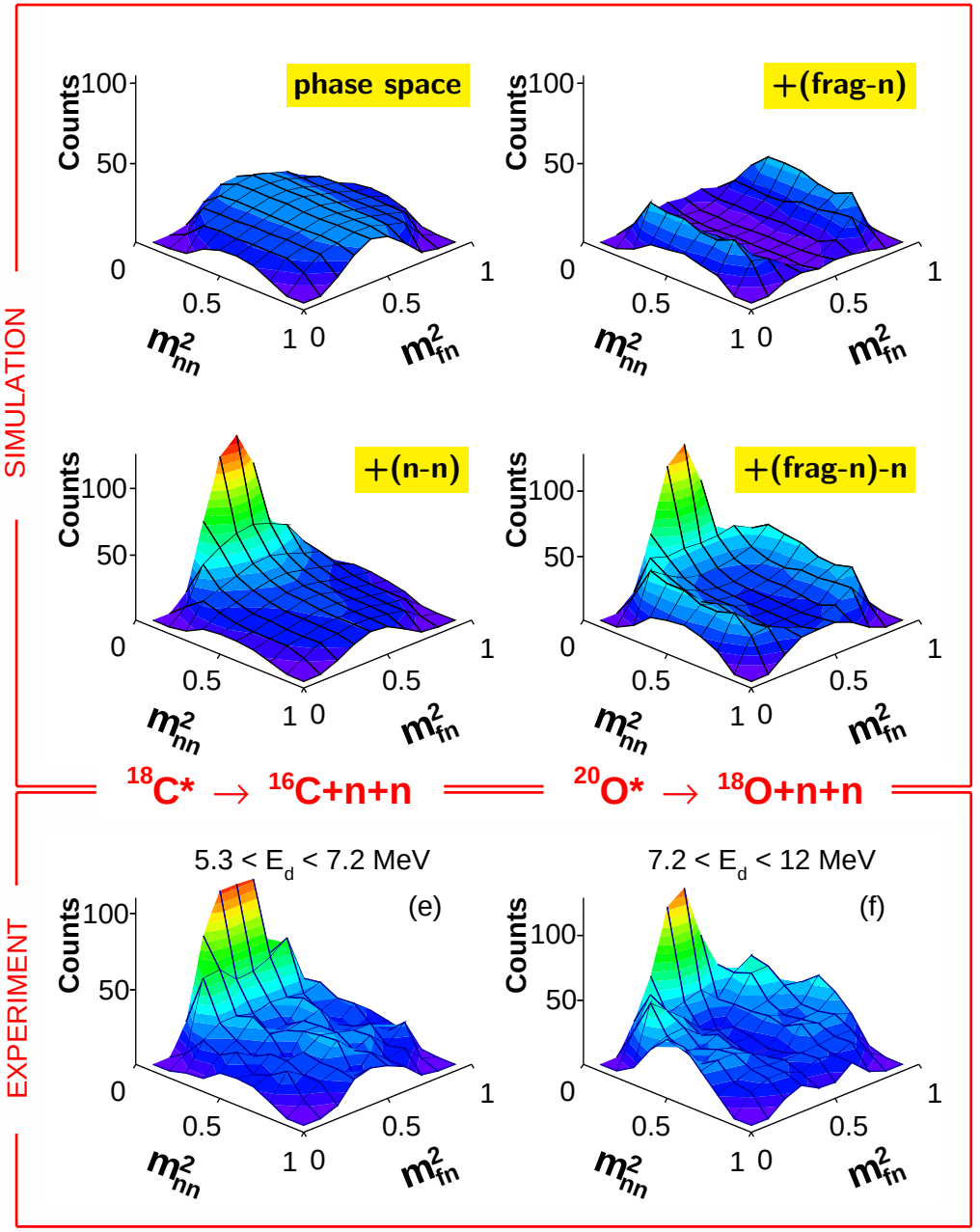


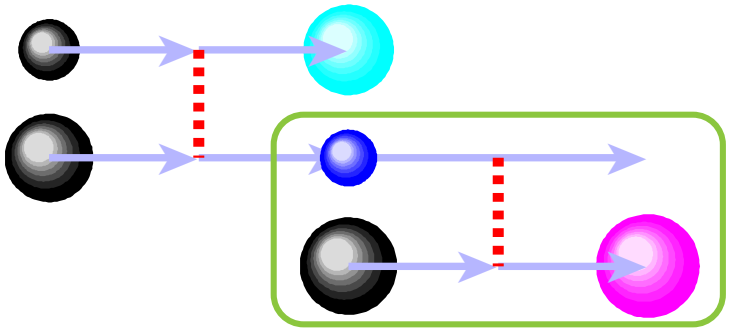


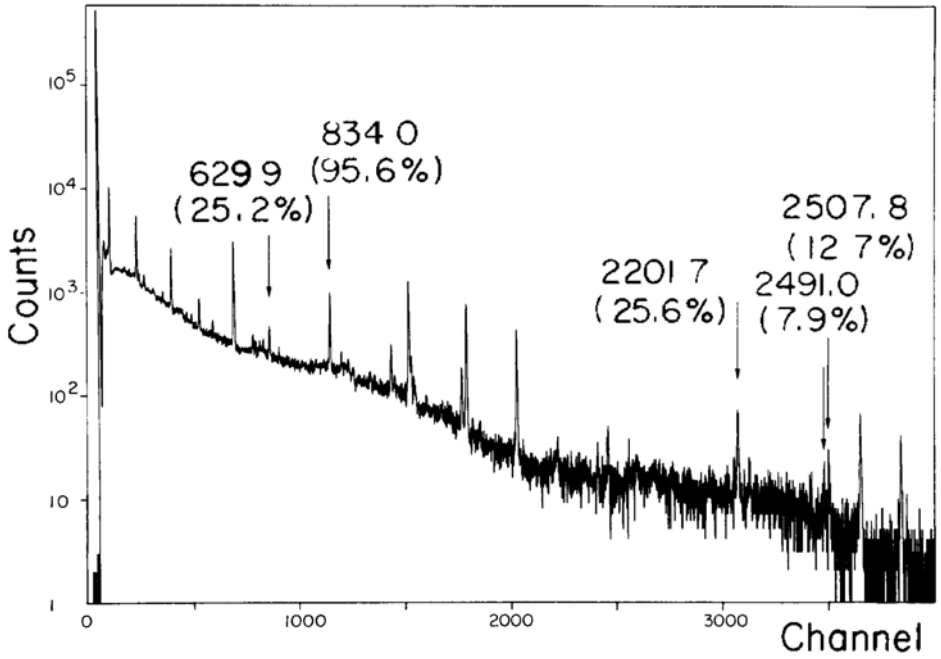


1960s : a long quest begins

- Two-step reactions :
  - $p + W \dashrightarrow {}^{A}n + {}^{70}Zn \rightarrow {}^{72}Zn$ $(\rightarrow {}^{72}Ga)$!!!

    Detraz, PLB 66 (1977) 33 ☜





✗ ^{70}Zn (t,p) ^{72}Zn through Aluminium ...

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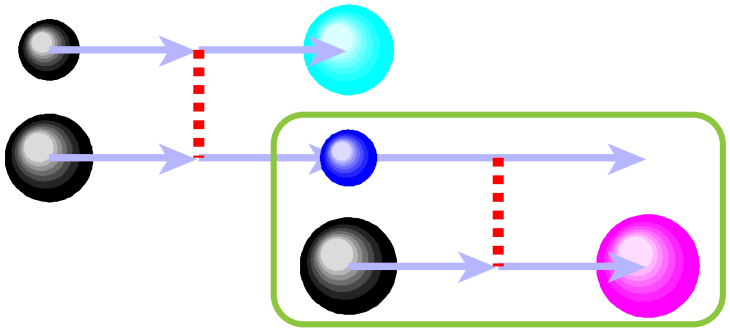
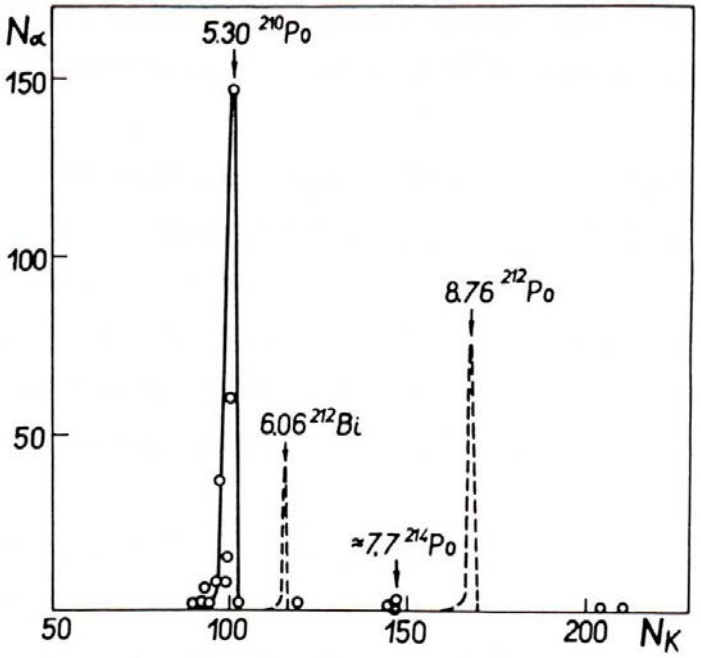
    Detraz, PLB 66 (1977) 33
  - ${}^{208}Pb\,(\pi^-, \pi^+)\,{}^{4}n \xrightarrow{(Pb)} {}^{212}Pb$ $(\rightarrow {}^{212}Bi \rightarrow {}^{212}Po)$

    Chultem, NPA 316(1979) 290 ☜





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  - $p + W \rightarrow {}^{A}n + {}^{70}Zn \rightarrow {}^{72}Zn$ $(\rightarrow {}^{72}Ga)$

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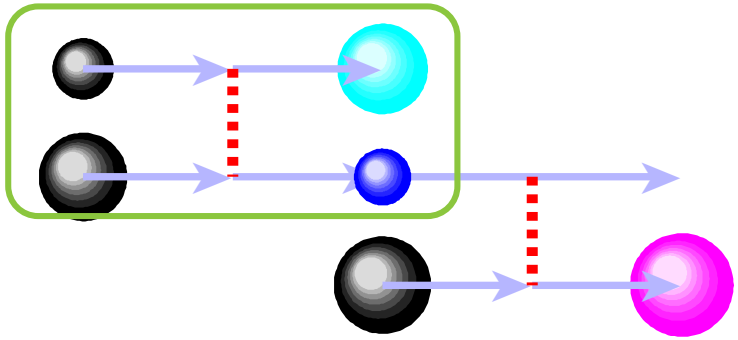
    Chultem, NPA 316(1979) 290



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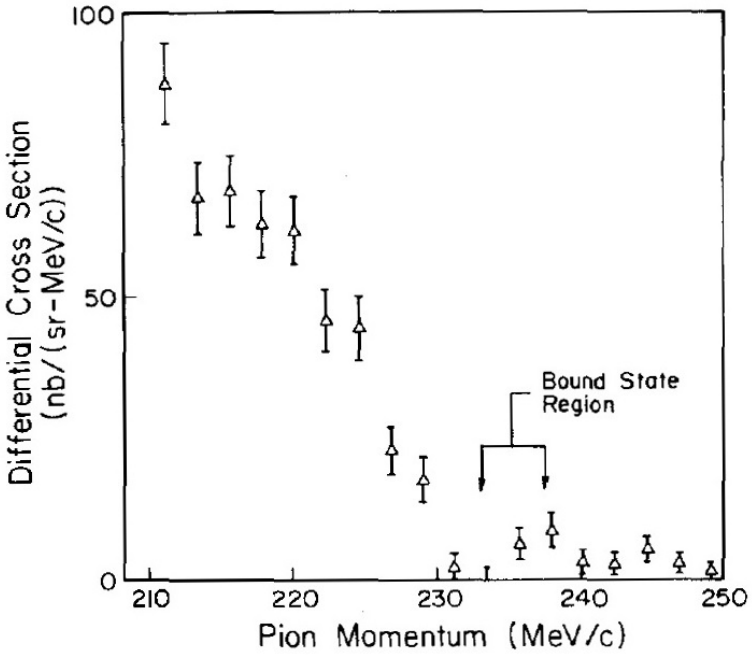

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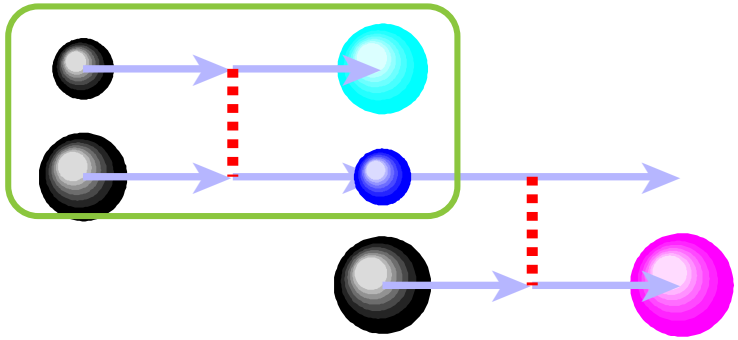

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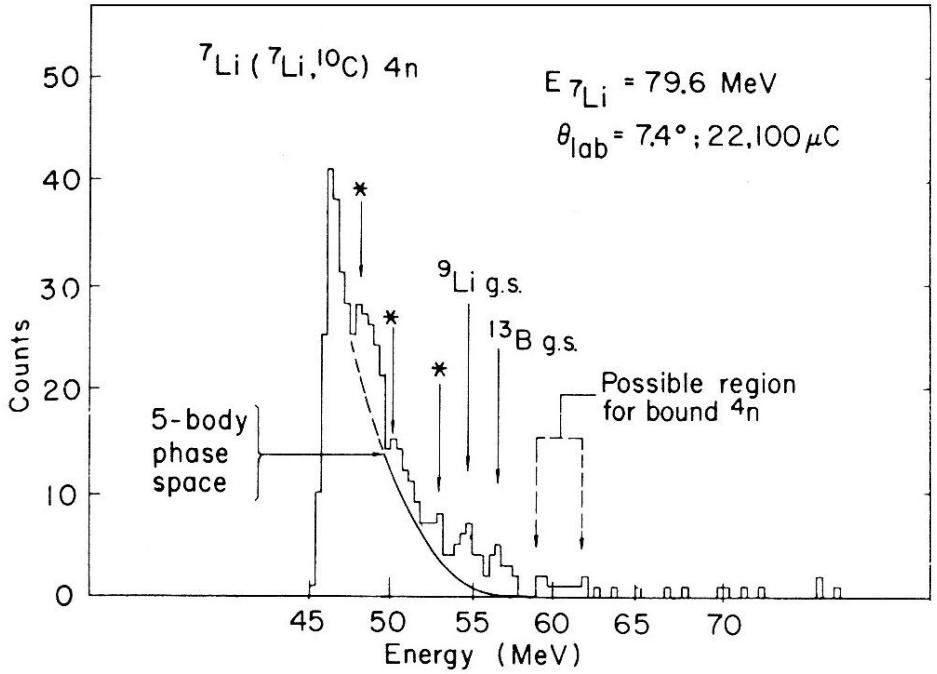
    Cerny, PLB 53 (1974) 247



⇨ XX century : cross-sections & backgrounds ...

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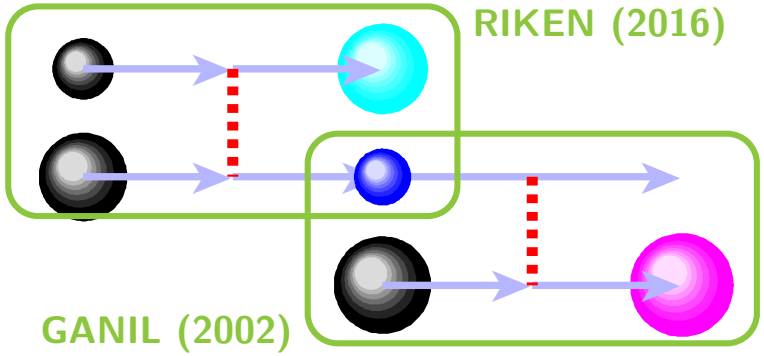

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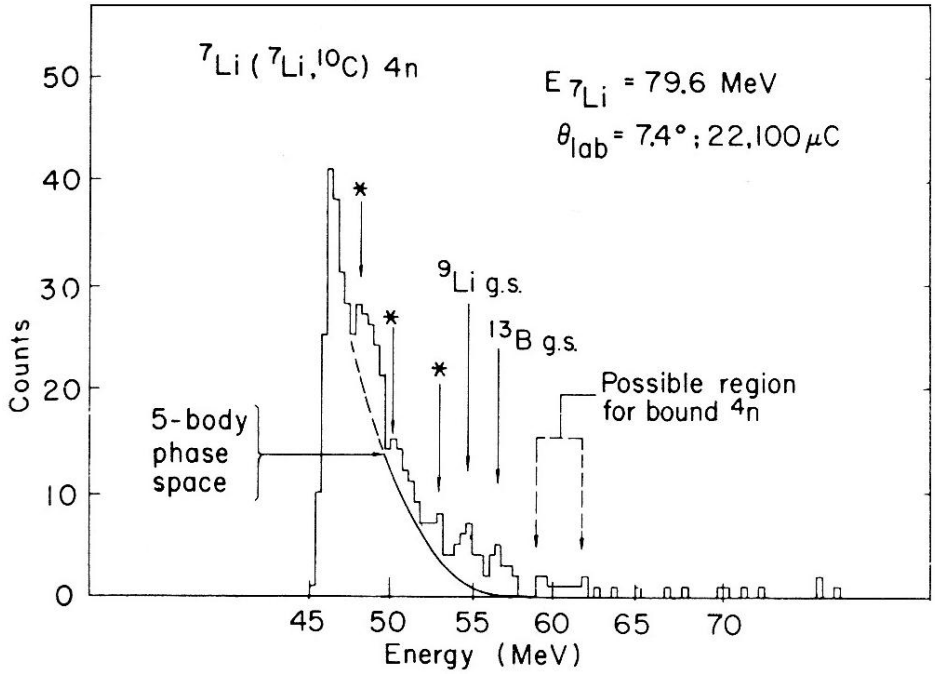

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‘Superheavy’ multineutrons (or most likely nothing) ?

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Detection of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U by the Activation Method with ^{27}Al

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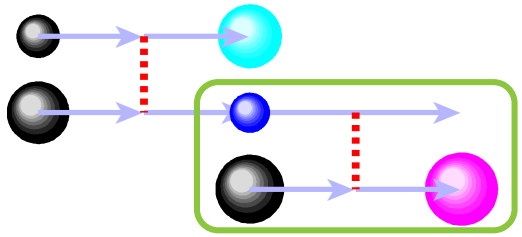
Light nuclear-stable multineutrons among products of the fission of ^{238}U nuclei that is induced by 62-MeV alpha particles have been searched by the activation method with a ^{27}Al sample. These multineutrons have been detected by characteristic gamma rays emitted by the nuclei from the beta-decay chain ^{28}Mg $\longrightarrow$ ^{28}Al $\longrightarrow$ ^{28}Si. The ^{28}Mg parent nucleus can be formed in the ^{27}Al + $^{x}n \longrightarrow$ ^{28}Mg + $p(x-2)n$ process. The gamma-ray spectra of the irradiated sample exhibit lines of 1342- and 1779-keV photons accompanying the beta decay of the ^{28}Mg and ^{28}Al nuclei, respectively. The decrease in the activity corresponds within the measurement accuracy with the half-life $T_{1/2} \sim 21$ h of ^{28}Mg, which certainly indicates the detection of nuclear-stable multineutrons ^{x}n with $x \geq 6$.



$$\alpha + {}^{238}\mathrm{U} \longrightarrow {}^{A}\mathrm{n} + {}^{27}\mathrm{Al} \rightarrow {}^{28}\mathrm{Mg}$$

$\Rightarrow$ A >1 : but only 6/8n can exist !

1. INTRODUCTION

The problem of stability of nuclei consisting of neutrons only has long been actively studied both experimentally and theoretically. Interest in this problem is quite understandable, since the discovery of neutron nuclei would be revolutionarily important for nuclear physics and would radically change our representations on the nucleon–nucleon interaction with far-reaching consequences not only for nuclear physics but also for other fields of science, in particular, astrophysics. This discovery would be applied with the appearance of the possibility of the accumulation of neutron matter.

It is well known that two neutrons do not form a bound nuclear system. The overwhelming majority of experimental investigations indicate that the systems of three and four neutrons are also unstable.

Thus, the negative result of numerous searches for ^{2}n–^{4}n nuclei [5–9] does not exclude the existence of heavier neutron clusters.

2. DESCRIPTION OF THE EXPERIMENT

The primary target (a ^{238}U foil 160 μm thick) placed at the center of a scattering chamber was bombarded with a beam of 62-MeV alpha particles accelerated at the cyclotron of the Kurchatov Institute.

An aluminum sample with a mass of 2.8 g was placed in a hermetically sealed container installed in a vacuum scattering chamber at an angle of 20° with respect to an incident alpha-particle beam. An additional beryllium filter 1 mm thick was placed upstream of the aluminum sample in order to suppress the background of scattered alpha particles, tritons from the ^{238}U(α,t) reaction, and other charged particles. In view of a high activity in the room, the irradiated samples were transported and processed half an hour after irradiation.

In this case, the intense 1368- and 2754-keV gamma lines of the ^{24}Na isotope from the ^{27}Al (n, α) ^{24}Na (Q =3.13 MeV) reaction and the corresponding Compton background are the only factors hindering the reliable identification of gamma rays from the chain of nuclei ^{28}Mg → ^{28}Al → ^{28}Si.

4. CONCLUSIONS

To conclude, nuclear-stable multineutrons among products of the ternary fission of ^{238}U nuclei that is induced by 62-MeV alpha particles have been sought by the activation method.

The reported measurements confirm the results of our previous work [10], where the possible emission of multineutrons from the ternary fission of ^{238}U was established by characteristic 1384-keV gamma rays from the ^{88}Sr + $^{x}n \rightarrow (x-4)n$ + ^{92}Sr → ^{92}Y process in the activated strontium sample. Comparison showed that the yield of ^{28}Mg in the case of the interaction of multineutrons with ^{27}Al is an order of magnitude higher than the yield of ^{92}Sr.

The results of two independent experiments indicate that nuclear-stable multineutrons (most likely, ^{6}n) are emitted from the alpha-particle-induced ternary fission of ^{238}U. In the future, we are going to improve the statistics of the measurements by increasing the intensity of the beam and irradiation time of sample.