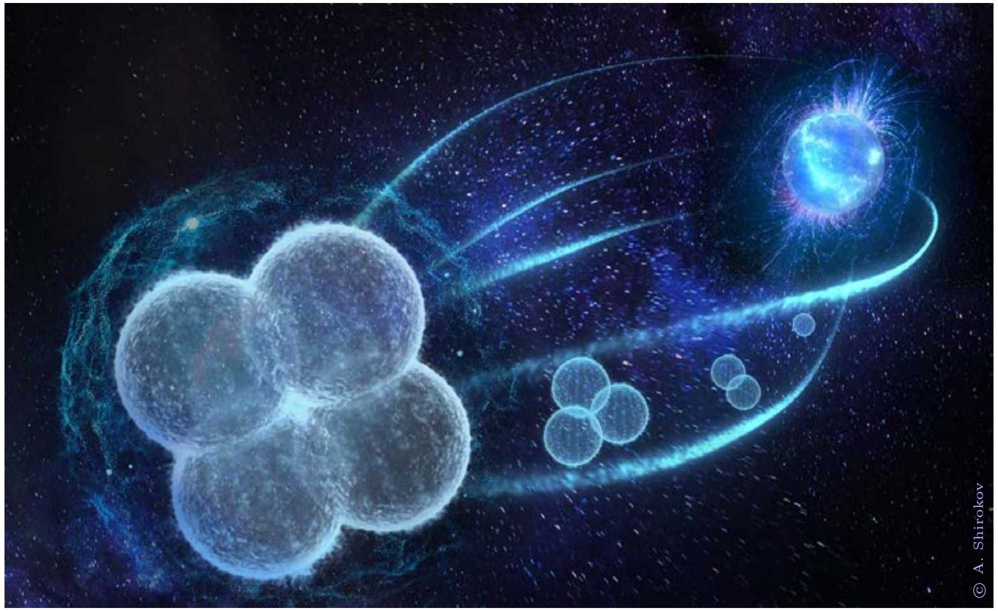
XX Colloque GANIL

October 15-20, 2017, Amboise (France)



The tetraneutron program at RIKEN

F. Miguel Marqués

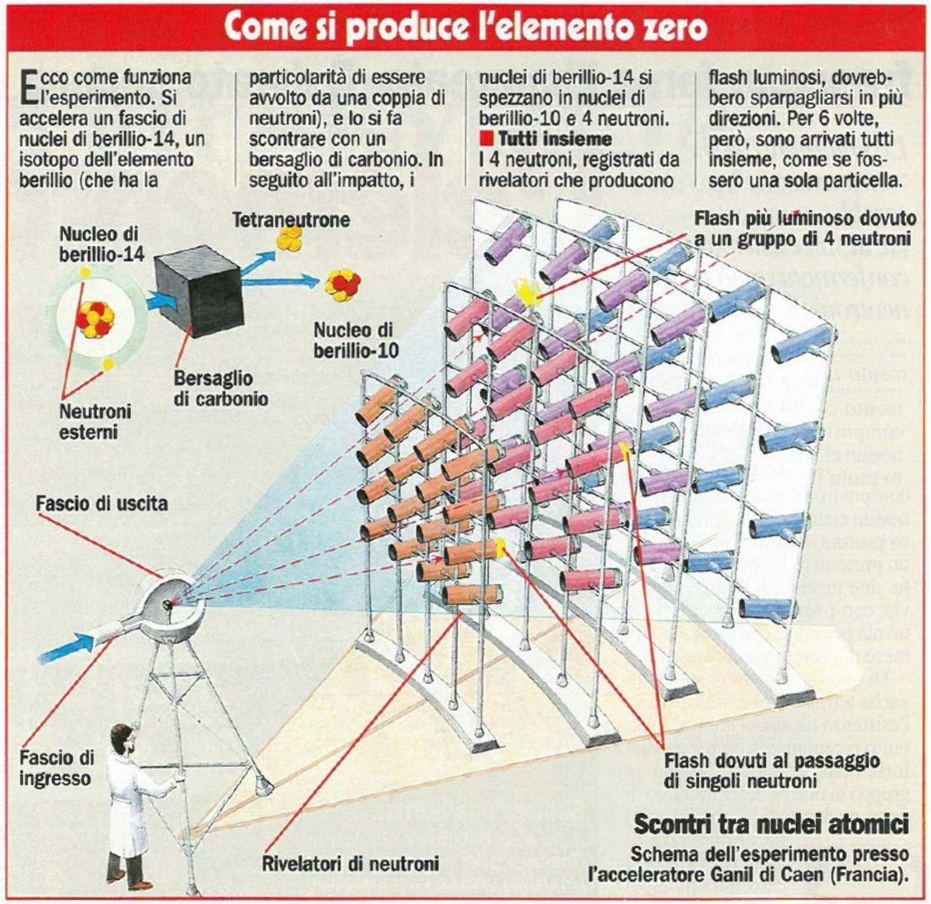
Laboratoire de physique corpusculaire

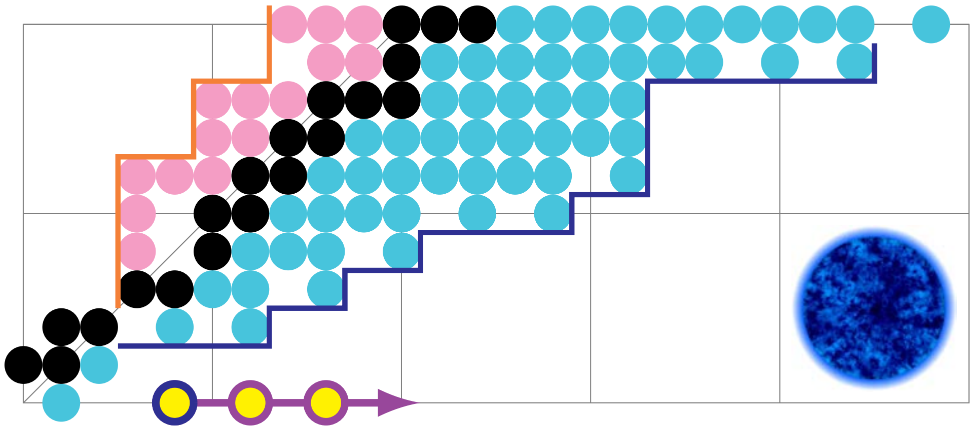
❶ The ^{A}n context :

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

❷ The RIKEN campaign :

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





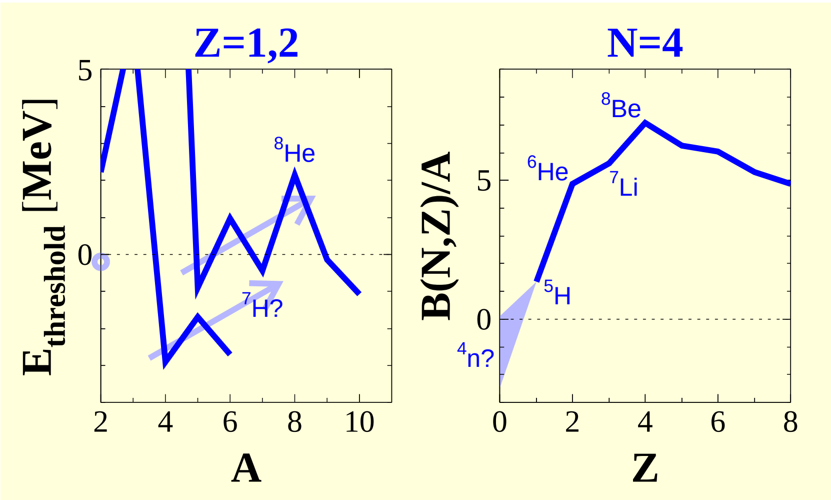
▶ Candidate systems ?

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

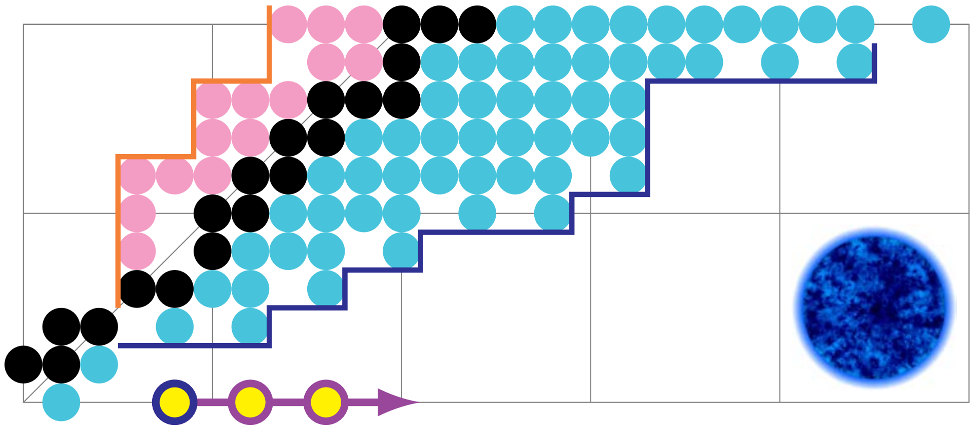
→ N = 4

▶ Well-established facts :

- N = 2 (✘) ··· 10^{57} (✔)
- the 'multi-neutron anomaly' :



Multi-neutrons : Tetraneutrons ?



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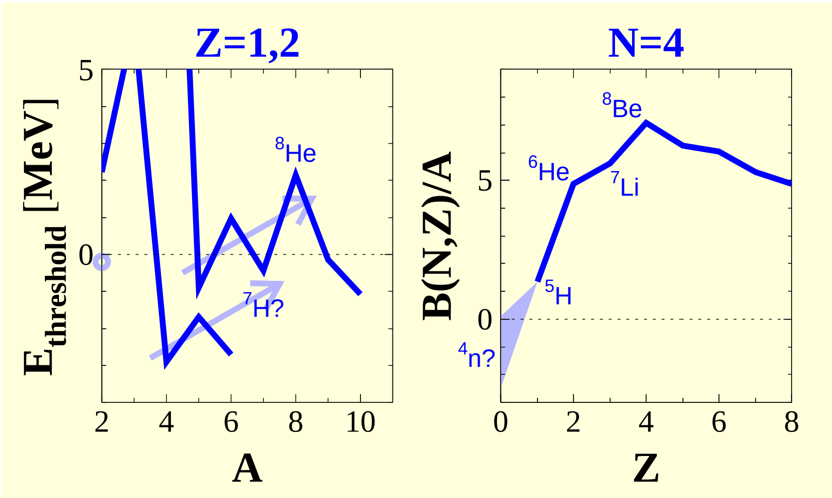

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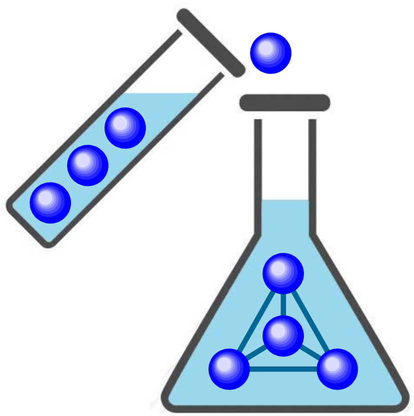
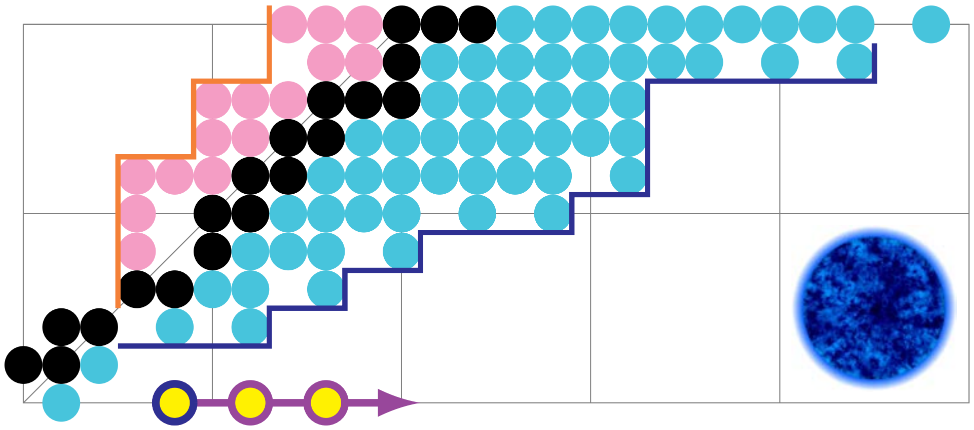
- production of a too n-rich system ...
- detection of a neutral object ...





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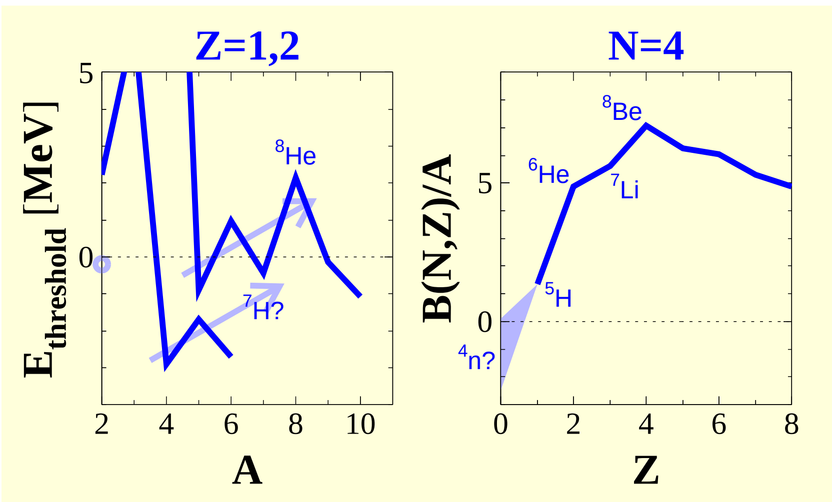

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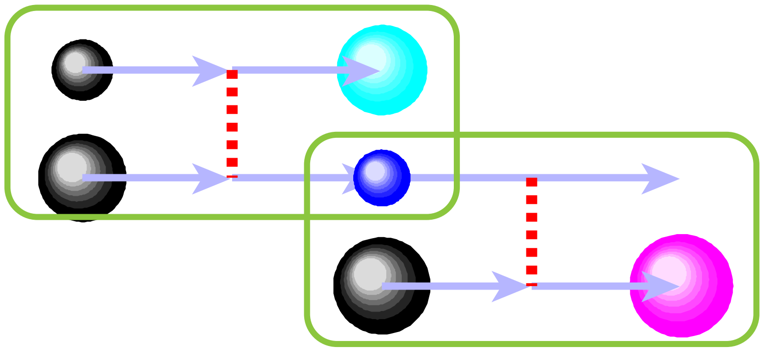
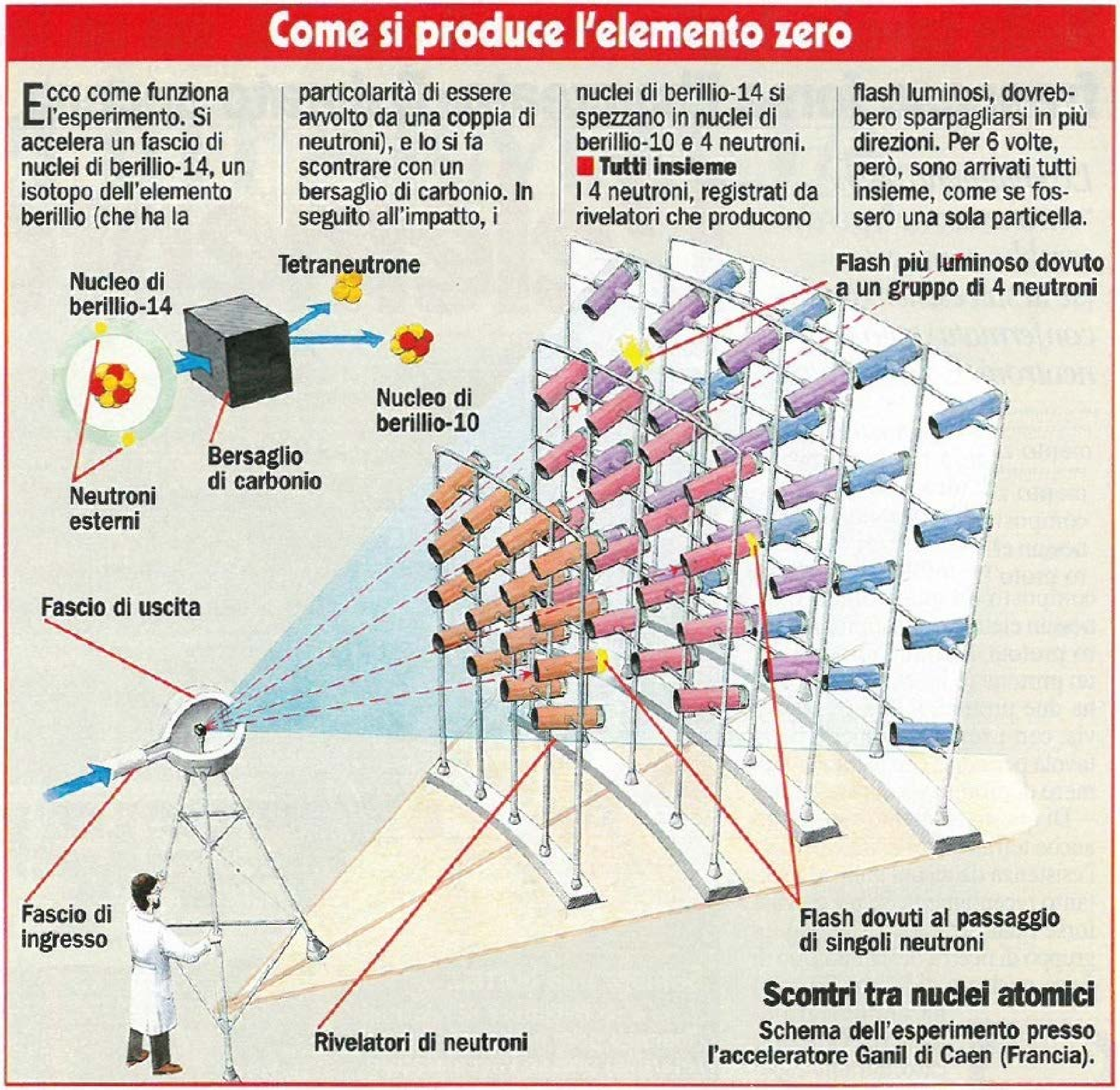


→ XX century : $\sigma(^{A}n)$ & backgrounds ...

The GANIL+DEMON experiment



Come si produce l'elemento zero

Ecco come funziona l'esperimento. Si accelera un fascio di nuclei di berillio-14, un isotopo dell'elemento berillio (che ha la particolarità di essere avvolto da una coppia di neutroni), e lo si fa scontrare con un bersaglio di carbonio. In seguito all'impatto, i nuclei di berillio-14 si spezzano in nuclei di berillio-10 e 4 neutroni.

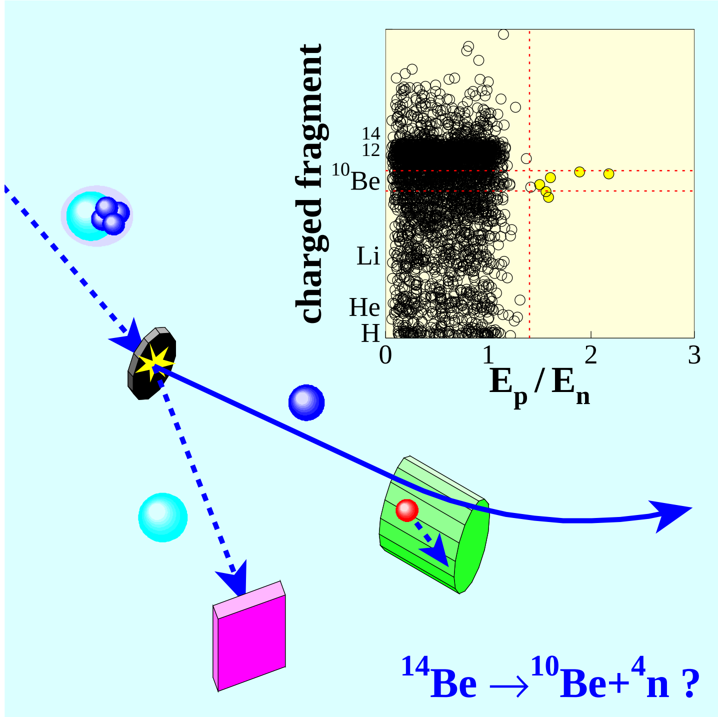
Tutti insieme

I 4 neutroni, registrati da rivelatori che producono flash luminosi, dovrebbero sparpagliarsi in più direzioni. Per 6 volte, però, sono arrivati tutti insieme, come se fossero una sola particella.

Scontri tra nuclei atomici

Schema dell'esperimento presso l'acceleratore Ganil di Caen (Francia).

Focus magazine (2002)



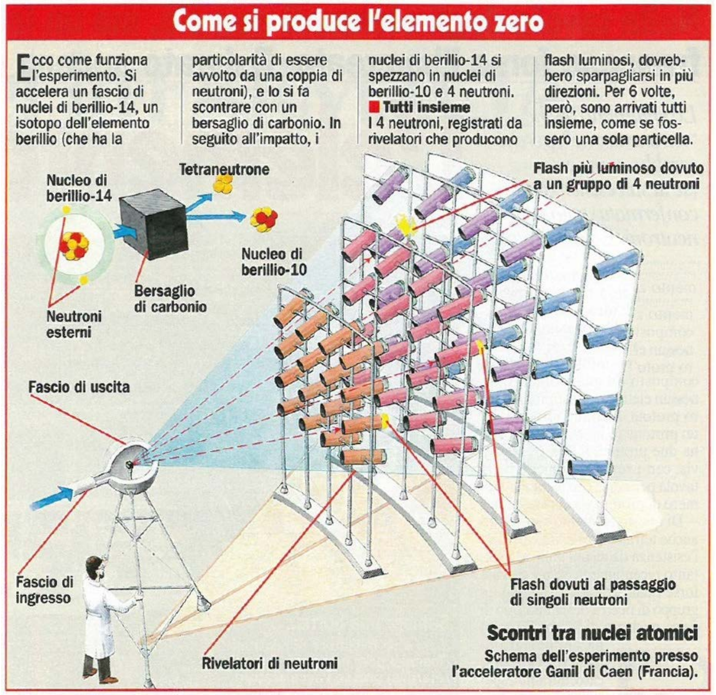
FMM, PRC 65 (2002) 044006

→ bound ^{4}n : ✔

→ $E_R \lesssim 2$ MeV ? ✔

FMM, arXiv:nucl-ex/0504009

- The DEMON campaigns :



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

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

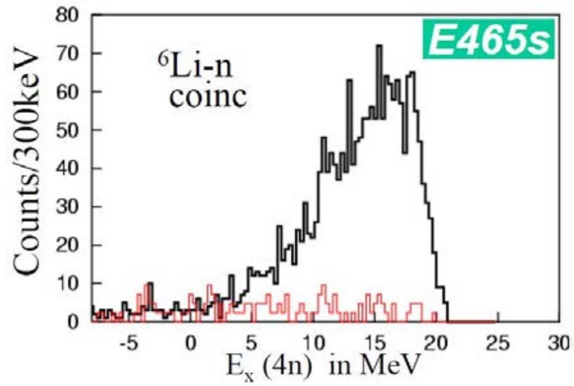
$$^{12/14}\text{Be} \xrightarrow{(\text{C})} \alpha\alpha + {}^{4/6}\text{n} \qquad ('02)$$

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

⇒ experimental program stopped ...

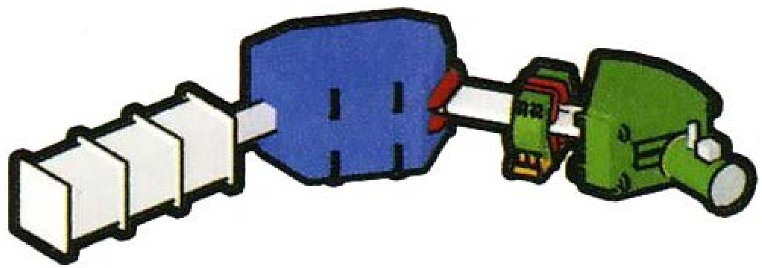
- MUST collaboration :

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



. . . .

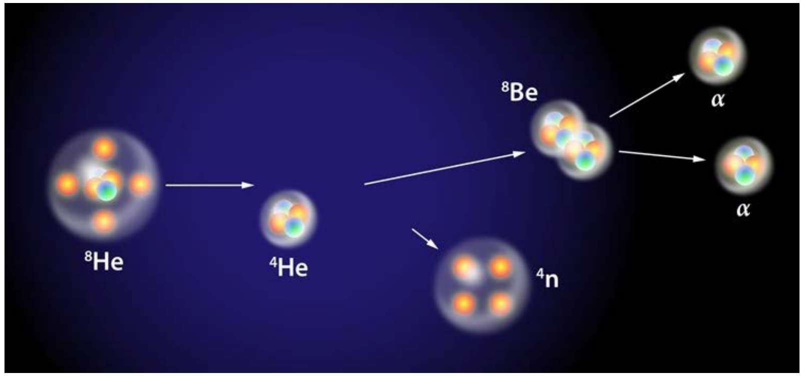
- Shimoura et al (SHARAQ) :



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

RIKEN : "Candidate Resonant Tetraneutron"

Kisamori, Shimoura, PRL 116 (2016) 052501



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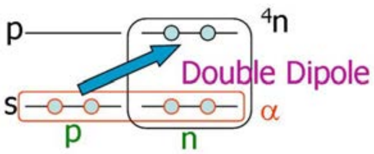

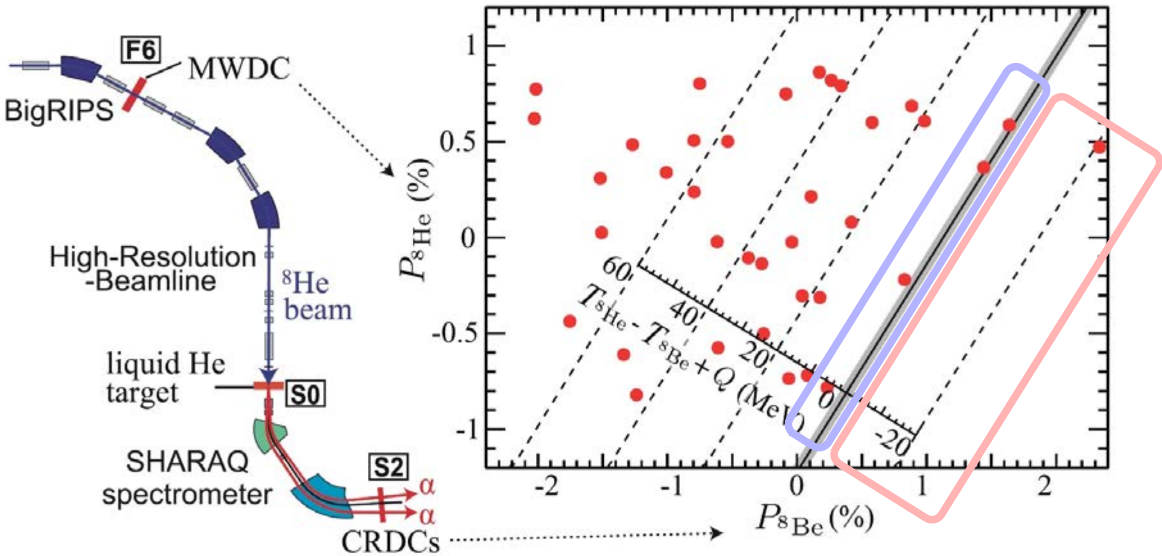

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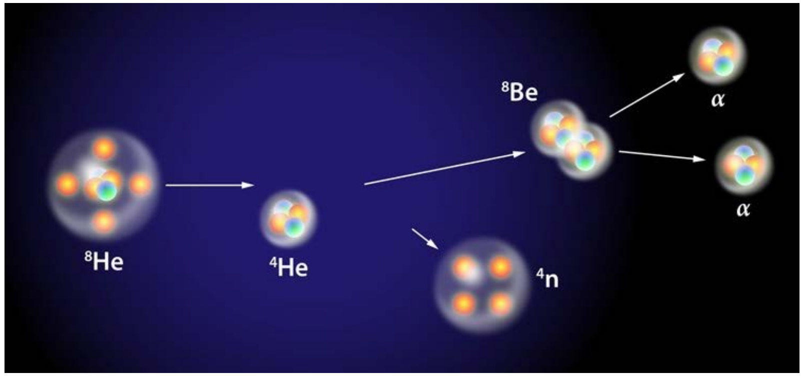
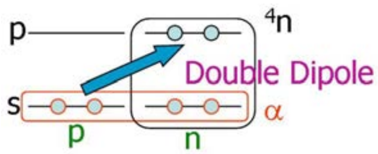
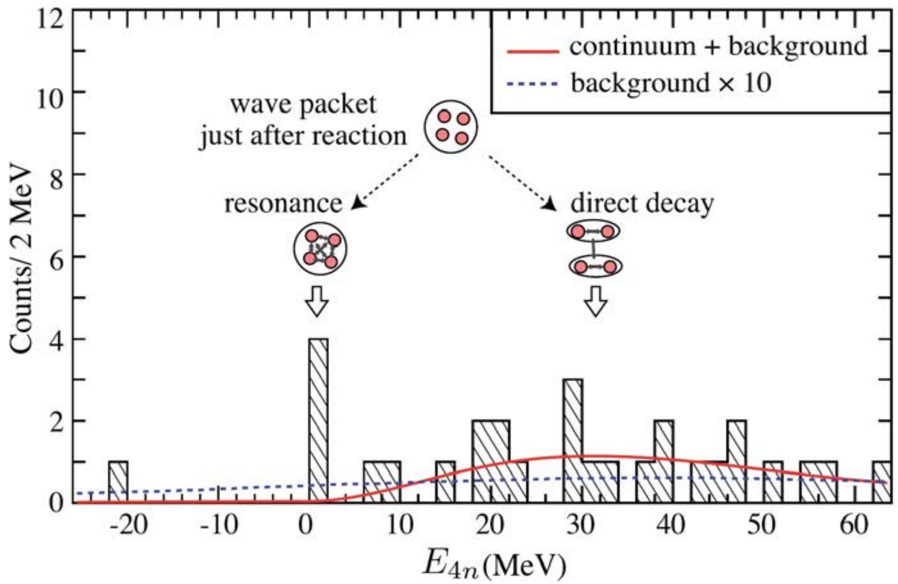
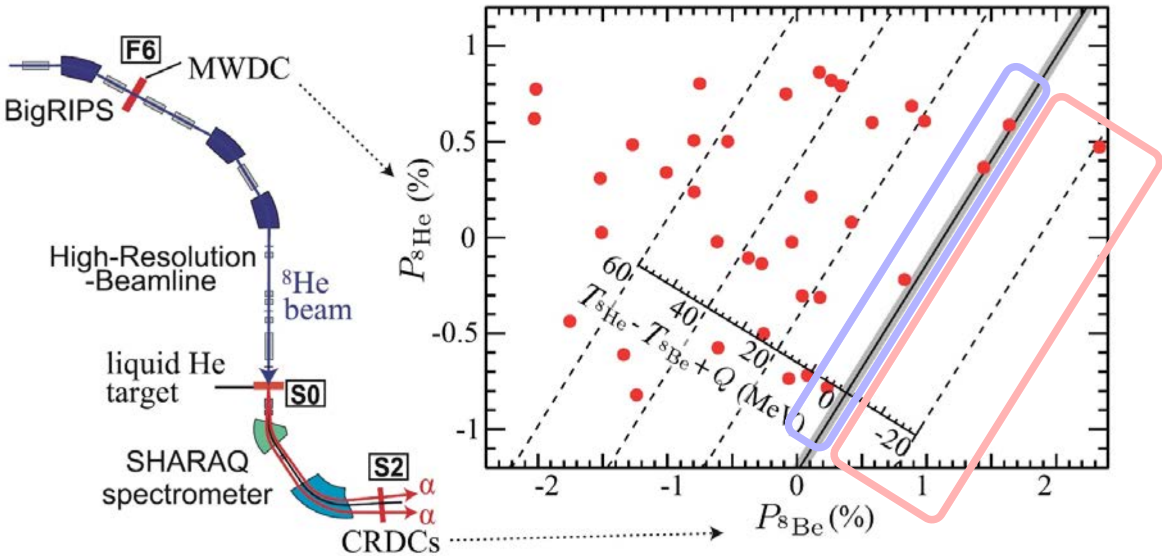


^{4}He (^{8}He, $\alpha\alpha$) ^{4}n







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

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

$\Gamma(^4n) < 2.6$ MeV

$\sigma(^4n) \sim 4$ nb

→ resonance ? ✔

→ bound ^{4}n ? ✔

- **ab initio** = "from first principles"

relies on basic and established laws of Nature
without additional assumptions or approximations

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

Theoretical 'proofs' ?

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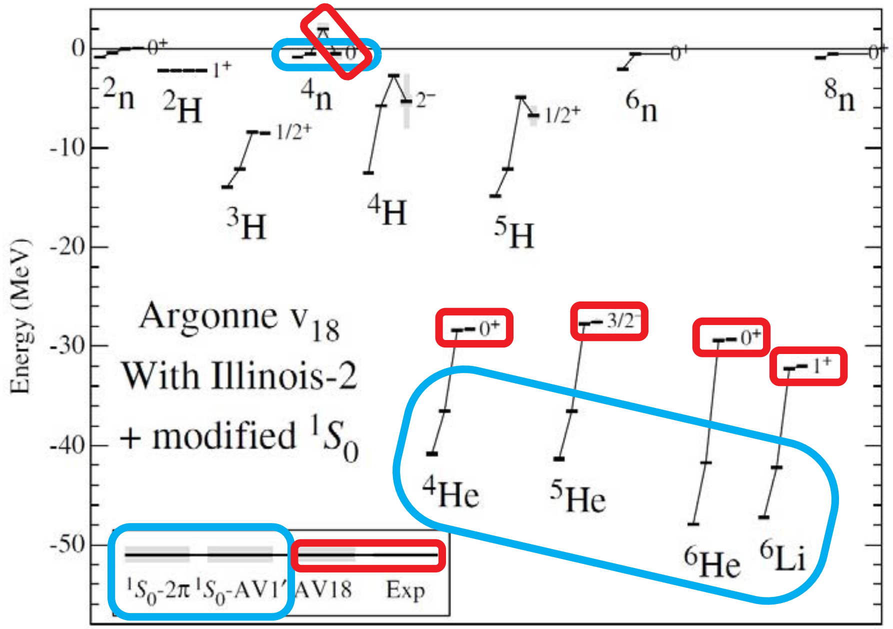
Pieper, PRL 90 (2003) 252501



⇨ proof that ^{4}n does not exist (?)

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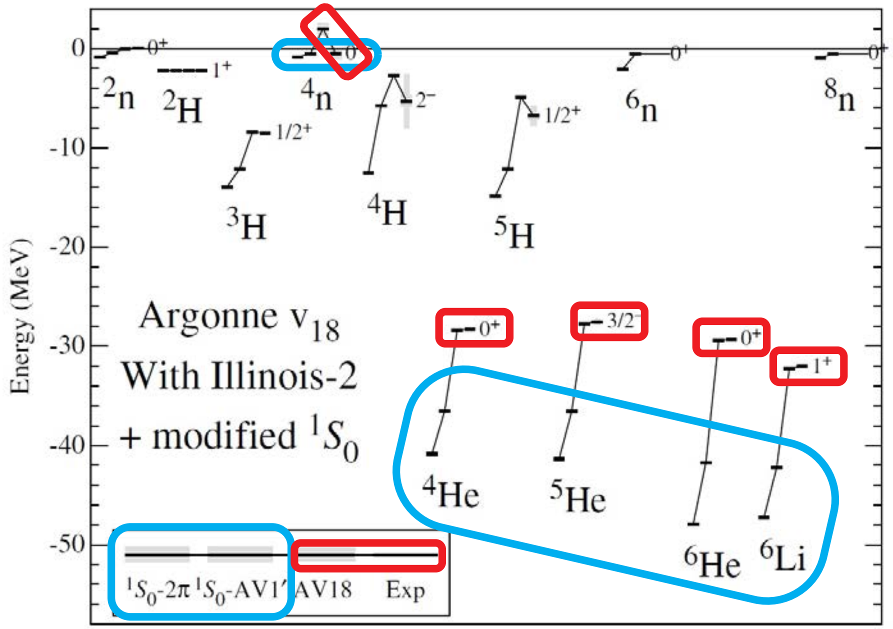
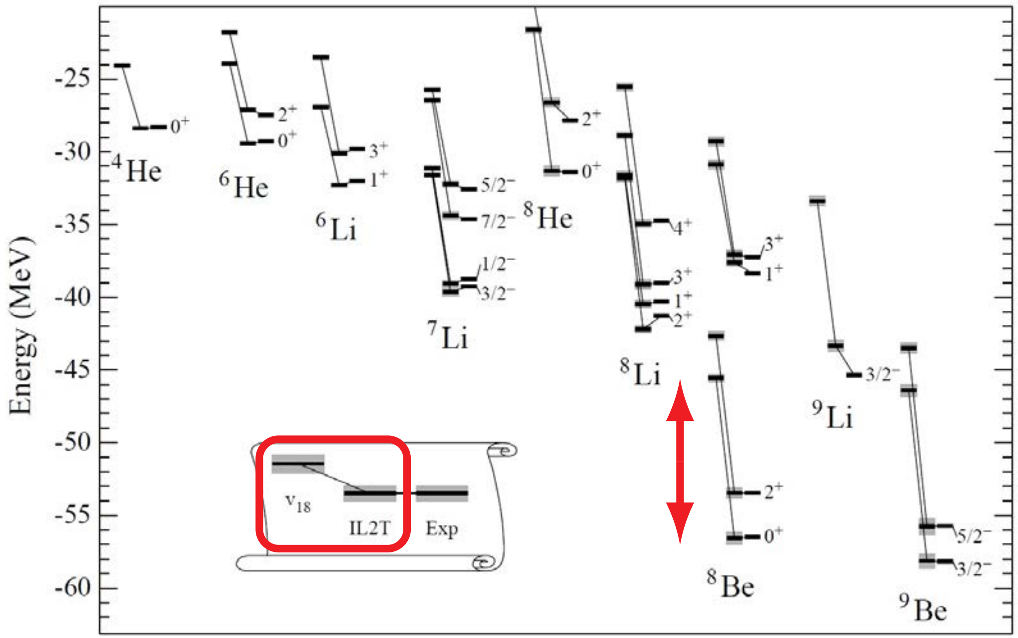


⟹ proof that ^{4}n does not exist (?)

- 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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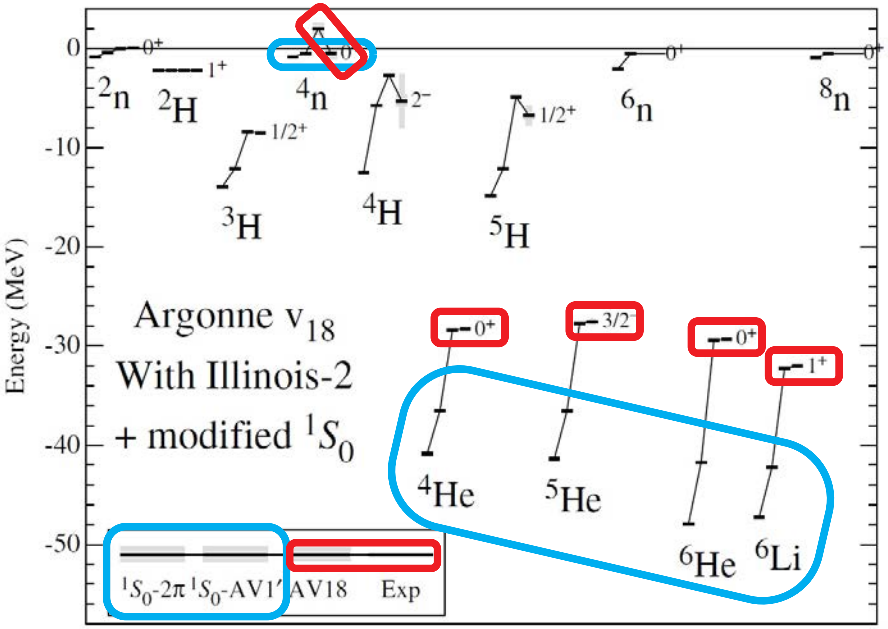

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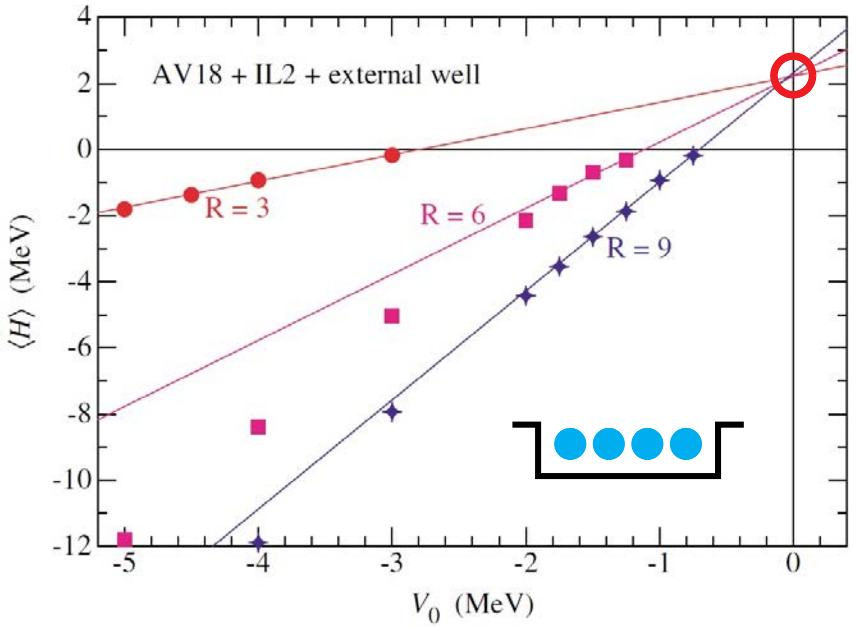

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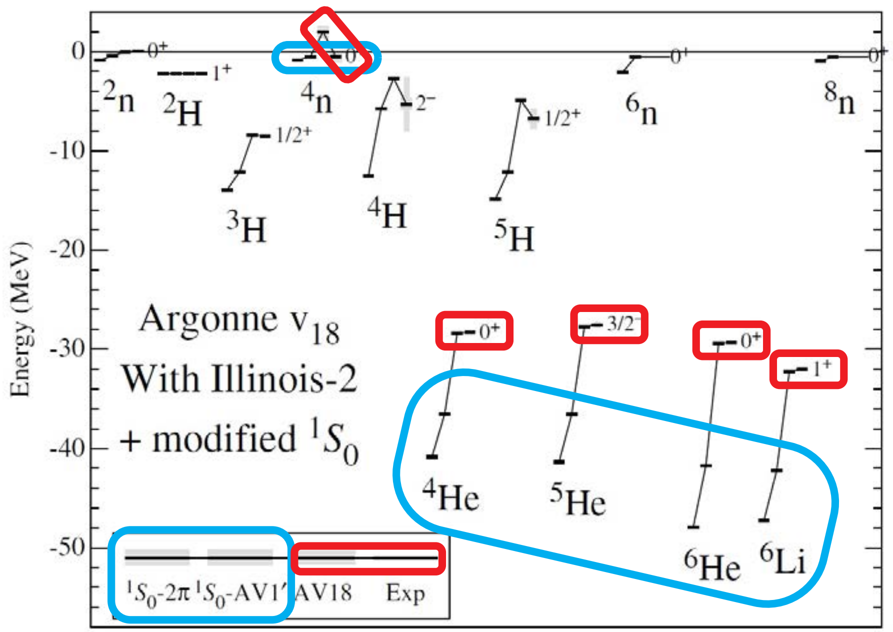

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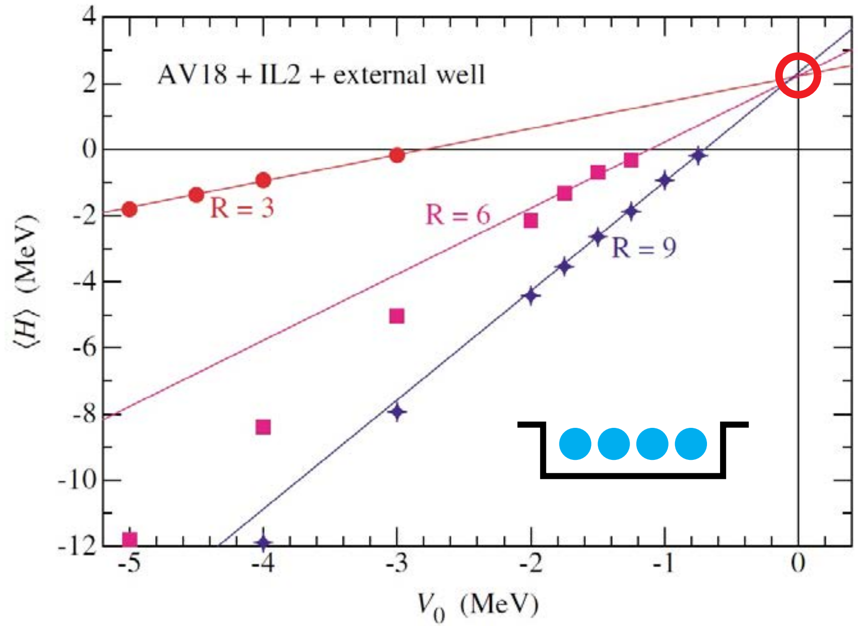
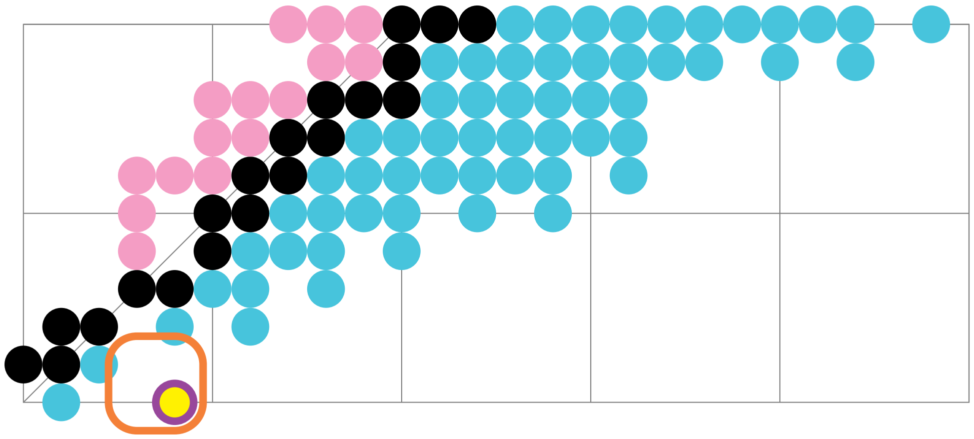
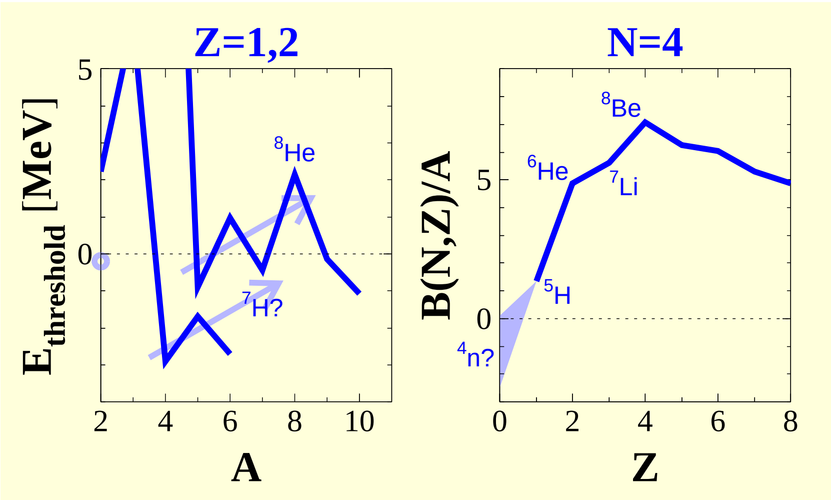


- Lazauskas, PRC 71 (2005) 044004
- Lazauskas, PRC 72 (2005) 034003
- Hiyama, PRC 93 (2016) 044004
- Shirokov, PRL 117 (2016) 182502
- Gandolfi, PRL 118 (2017) 232501
- Fossez, PRL 119 (2017) 032501

→ bound ^{4}n : ✘
→ (wide) res. ? ✔

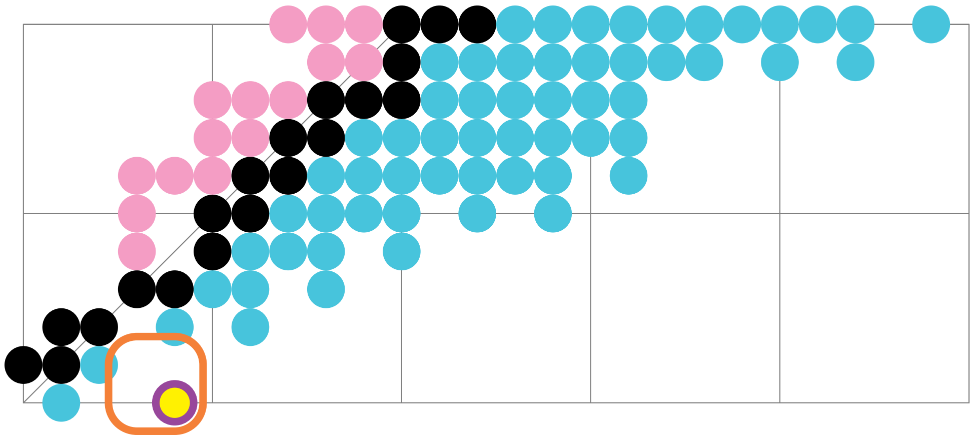


- H isotopes with 4N or 4n are unbound :

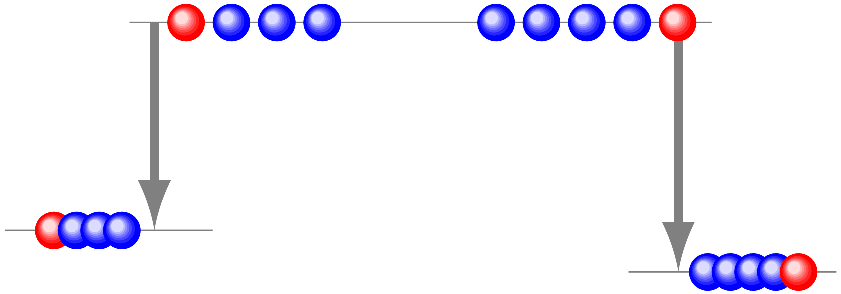


→ how could more n-rich systems be bound ?

Experimental constraints



▶ In fact ^{4,5}H are 'bound' !



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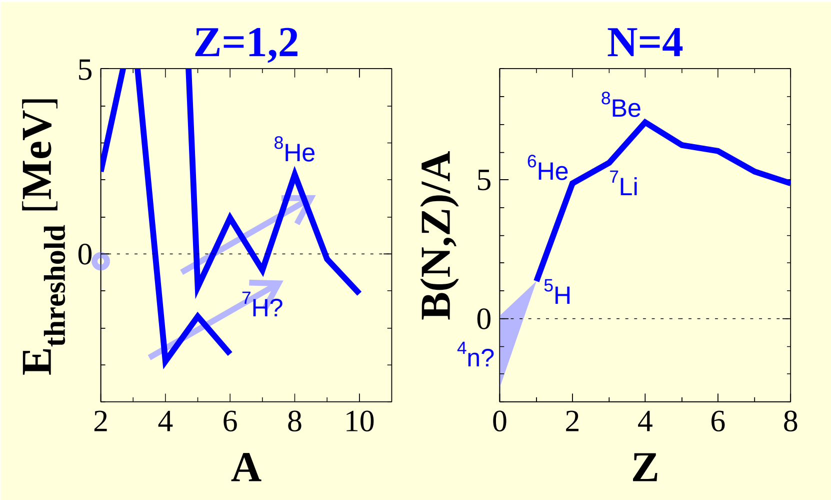

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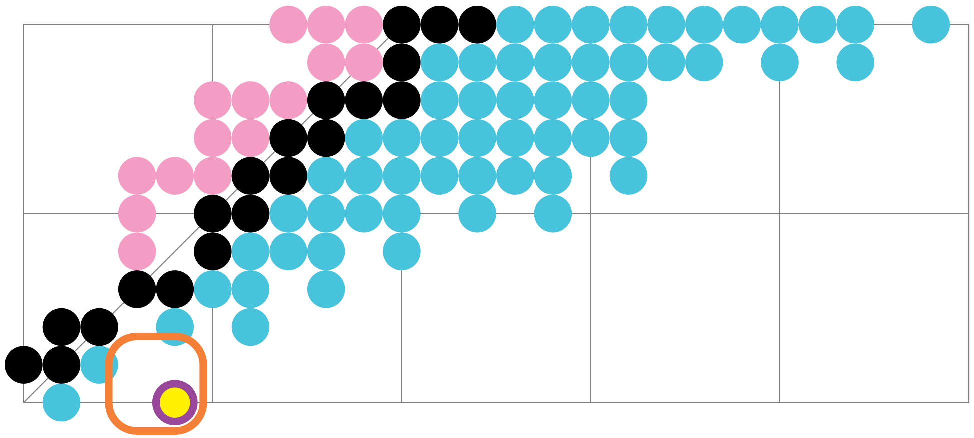

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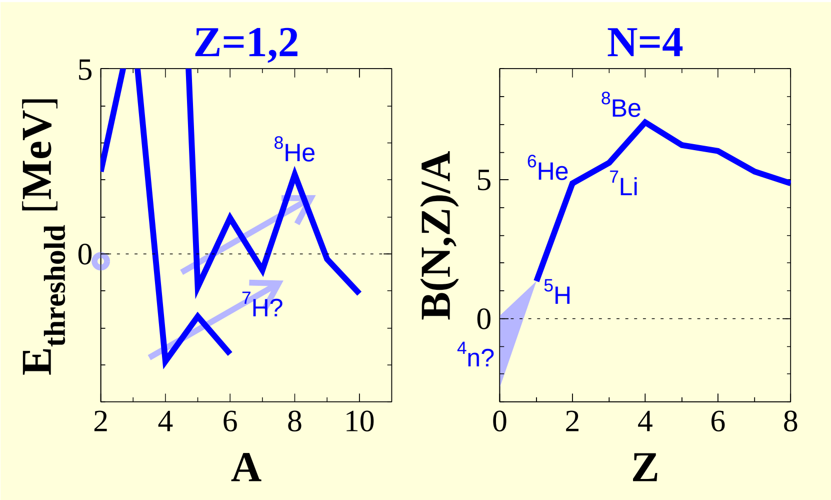

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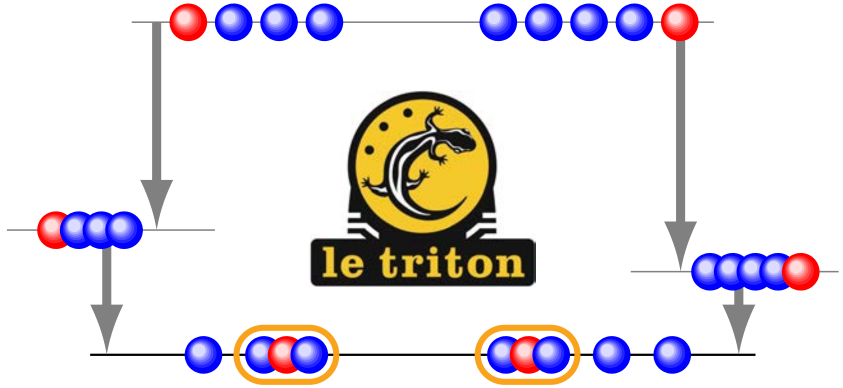

- only B(^{3}H) makes them unbound

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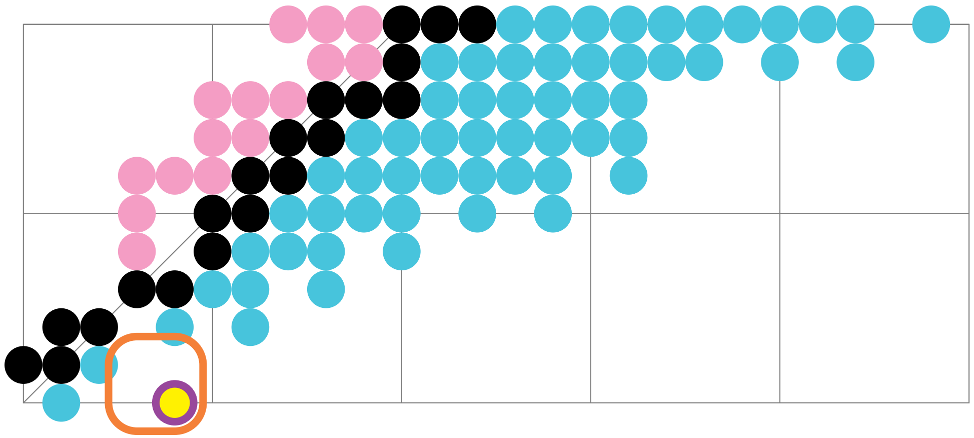

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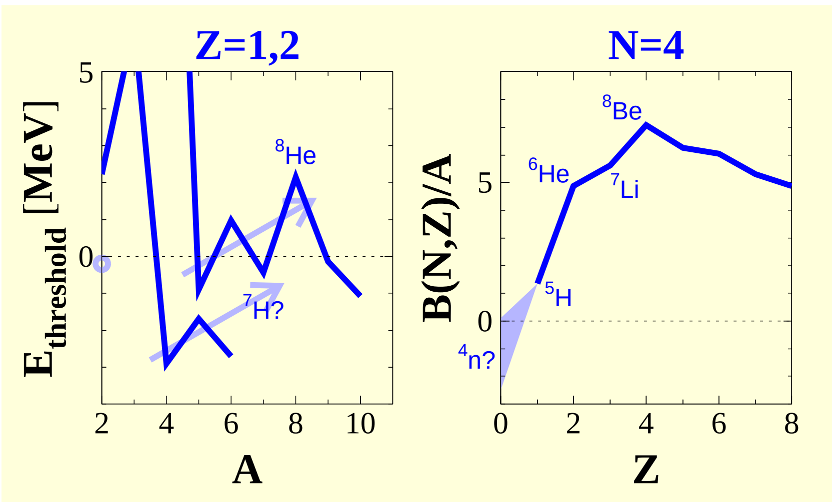

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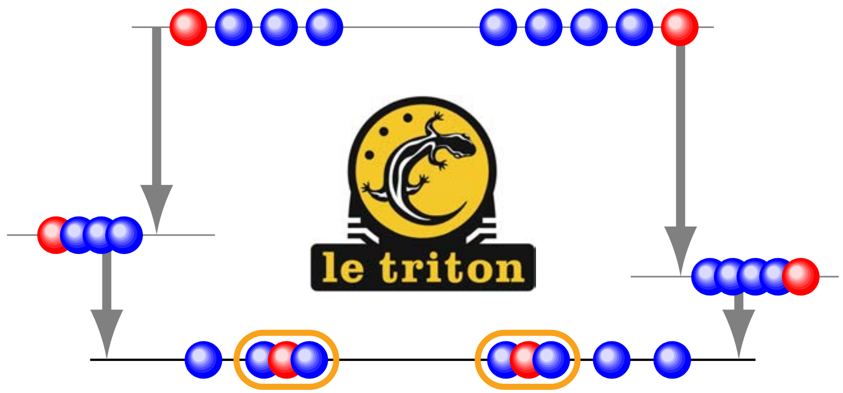

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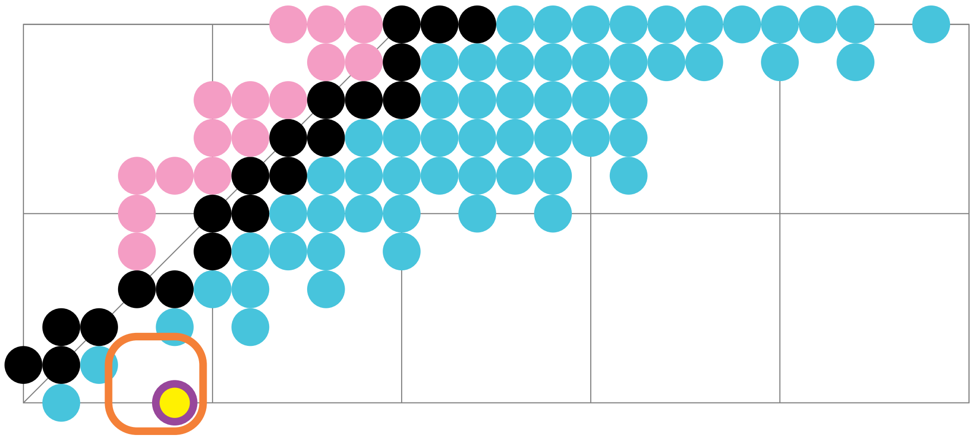
  - 1 eV binding would be enough !
  - B(^{4}n) $<$ min$\{S_{4n}\}$



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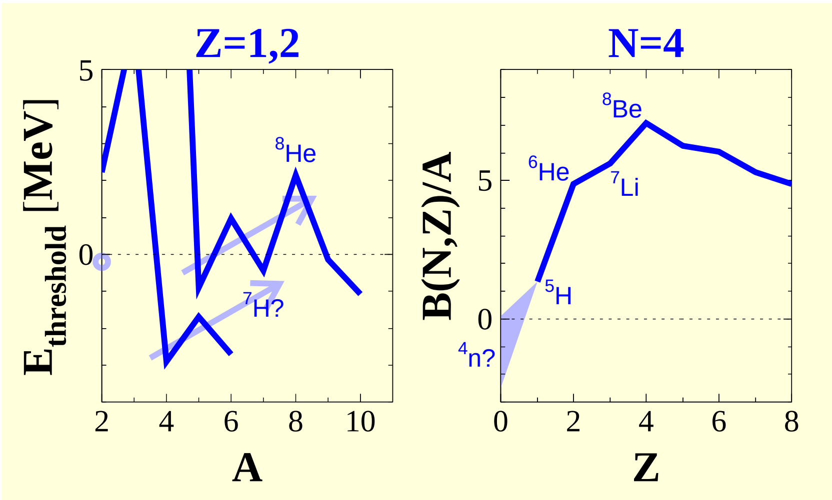

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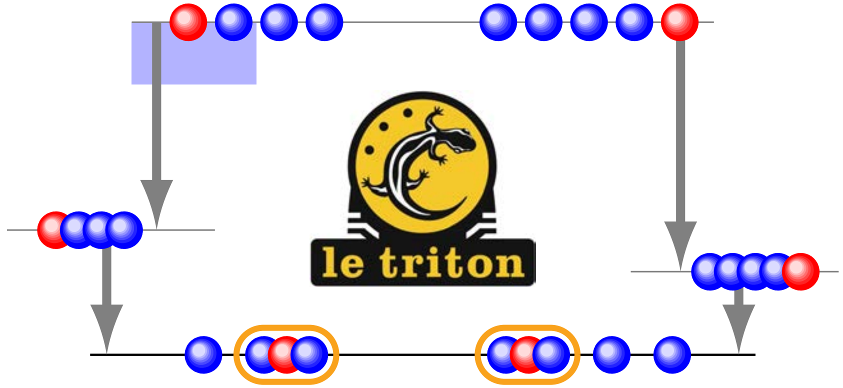

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  - B(^{4}n) $<$ min$\{S_{4n}\}$ $\sim$ 1.5 MeV (^{19}B)

  $\rightarrow$ ^{4}n would β-decay into ^{4}H

Outline

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- XXI century : first signals !
  - → GANIL : theory & experiments
  - → RIKEN : more candidate events
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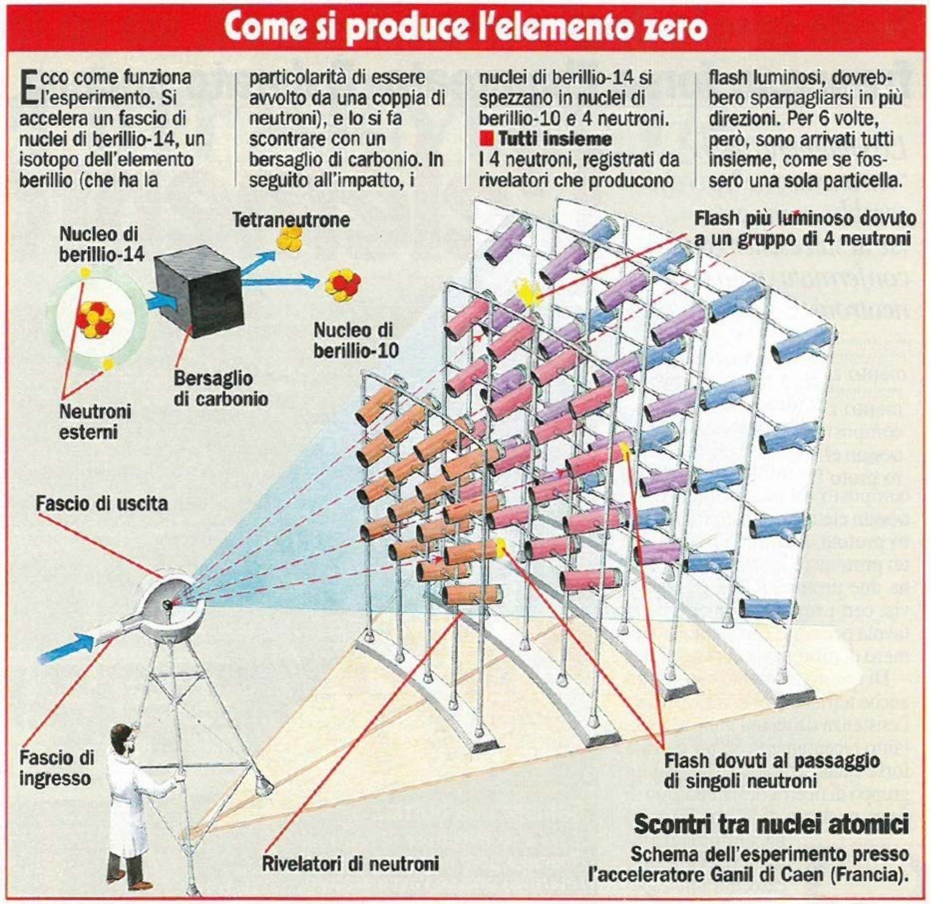
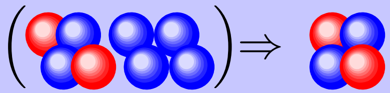
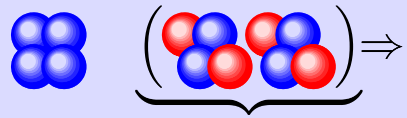
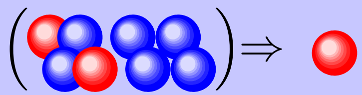
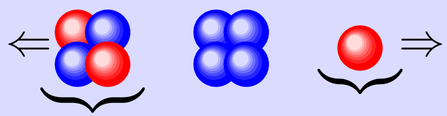
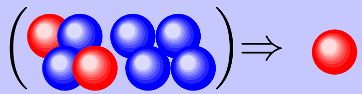
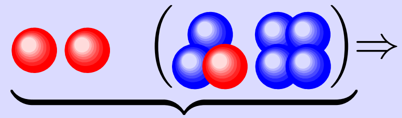
  - → $^{8}\mathrm{He}\,(\mathrm{p,2p})\,\{^{3}\mathbf{H}+^{4}\mathbf{n}\}$: any $(\mathrm{E},\Gamma)_{\mathrm{R}}$



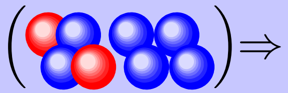
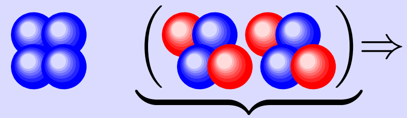
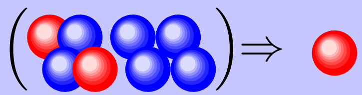
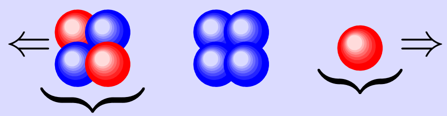
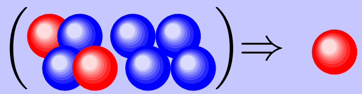
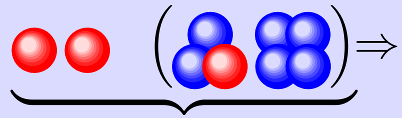
Tetraneutron context @ RIKEN

- Three experiments with same beam (^{8}**He**) at similar 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**} Yang/FMM, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω


RIビームファクトリー全体図
RIビームファクトリーではさまざまな実験装置を使って、原子核の構造と反応を研究しておるのじゃ。
加速する原理
RI BEAM FACTORY 01
RRC RIKEN RING CYCLOTRON
(理研リングサイクロトロン)
第1のリングサイクロトロン。RIビームファクトリーのサイクロトロンの中では一番の古株。
重さ 2,300t
直径 12.6m
RI BEAM FACTORY 02
fRC FIXED-FREQUENCY RING CYCLOTRON
(固定加速周波数型リングサイクロトロン)
第2のリングサイクロトロン。ウランを加速するために必要不可欠な装置。
重さ 1,500t
直径 10.8m
RI BEAM FACTORY 03
IRC INTERMEDIATE-STAGE RING CYCLOTRON
(中間段リングサイクロトロン)
第3のリングサイクロトロン。SRCにビームを送る他、実験装置へもビームを送る。
重さ 2,800t
直径 14.0m
RI BEAM FACTORY 04
SRC SUPERCONDUCTING RING CYCLOTRON
(超伝導リングサイクロトロン)
第4のリングサイクロトロンで最終加速。6基の超伝導電磁石を持つ史上最強のリングサイクロトロン。
重さ 8,300t
直径 18.5m
偏極RIビーム生成装置
回して調べる
AVFサイクロトロン
RILAC2
RIPS
GARIS
RILAC
ビーム発射
光速の4%
数値は地点通過時のビーム速度を表しています。
光速の16%
光速の32%
光速の47%
光速の70%
SAMURAI
反応を調べる
SCRIT
大きさをはかる
地下1階
地下2階
ゼロ度スペクトロメータ
形を調べる
稀少RIリング
重さをはかる
叩いて調べる
SHARAQ
SLOWRI
止まれ
止めて調べる
BigRIPS
原子核を壊す
ここには「ビームダンプ」という装置があって、重イオンビームからRIビームに変わるところなんだよ。

- Three experiments with same beam (^{8}**He**) at similar 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**} Yang/FMM, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, $\boldsymbol{\Omega}$

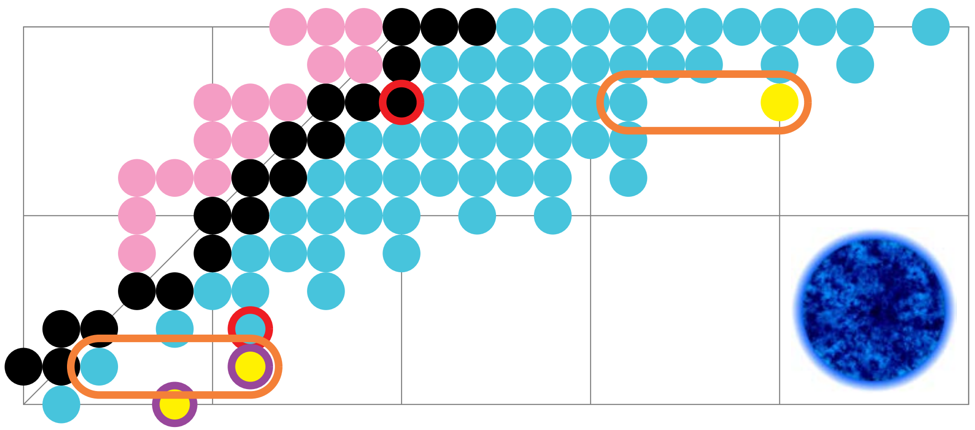
('16) SHARAQ 2.0 : {DAQ, tracking, calib.} ⇒ stat. & res. ×10

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

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

⇒ definitive answer !

Hydrogen 7 & Tetraneutron



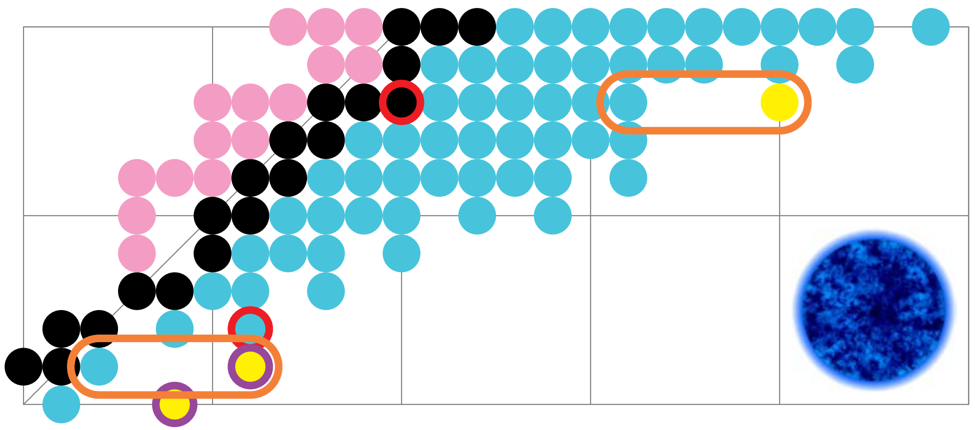
- ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

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

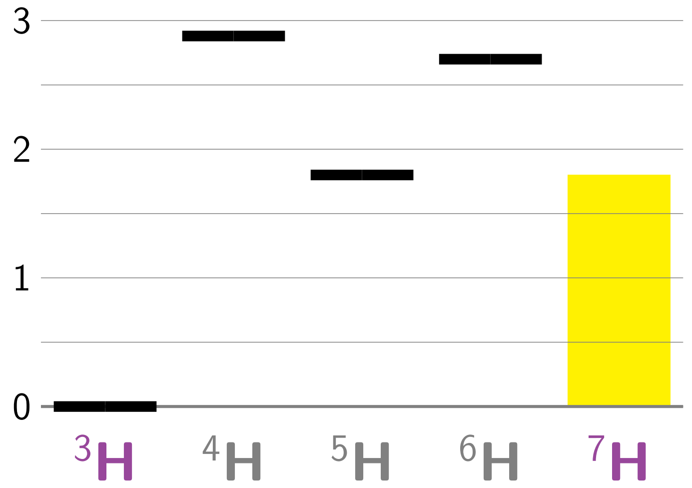
  Yang & FMM, RIBF NP1512-SAMURAI34

  - follow up of Orr, RIBF NP1306-LOI08

    → ^{28}O [Kondo] already done !



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



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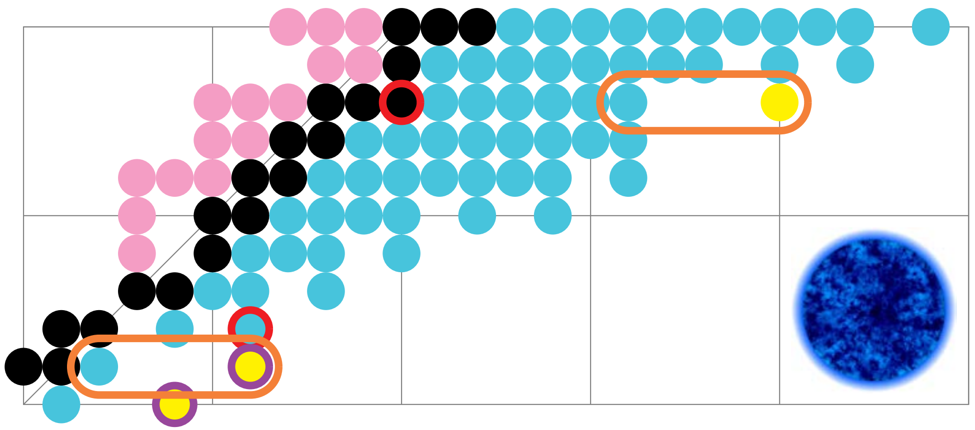

▶ ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

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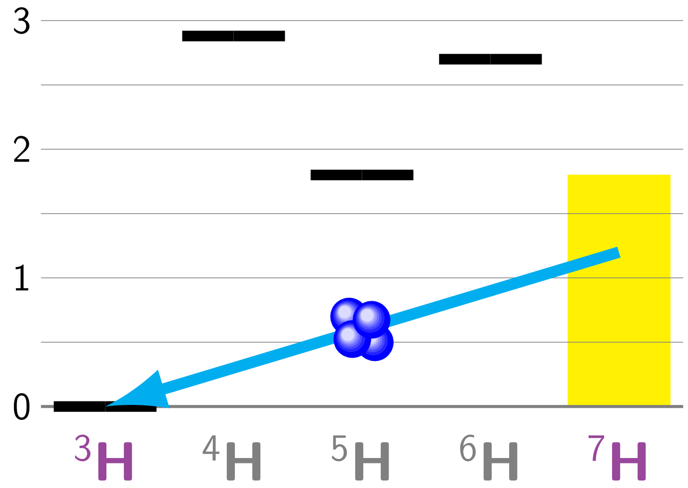
- $N = 6 \ (\nu p_{3/2})^4$ sub-shell closure ?



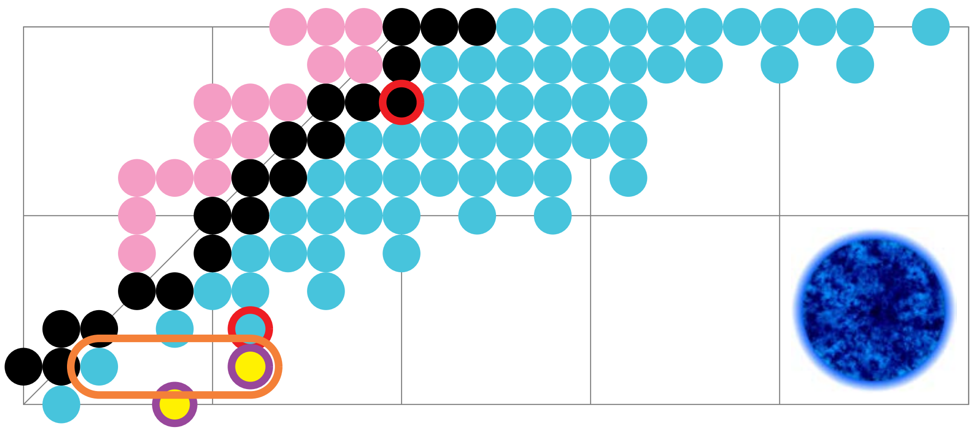
- direct 4n decay ?

  → ^{3}H + ^{4}n : 4n detection

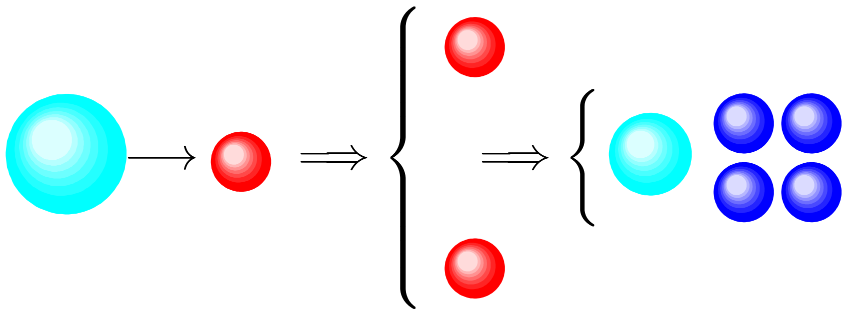
  → angular correlations : E_R !

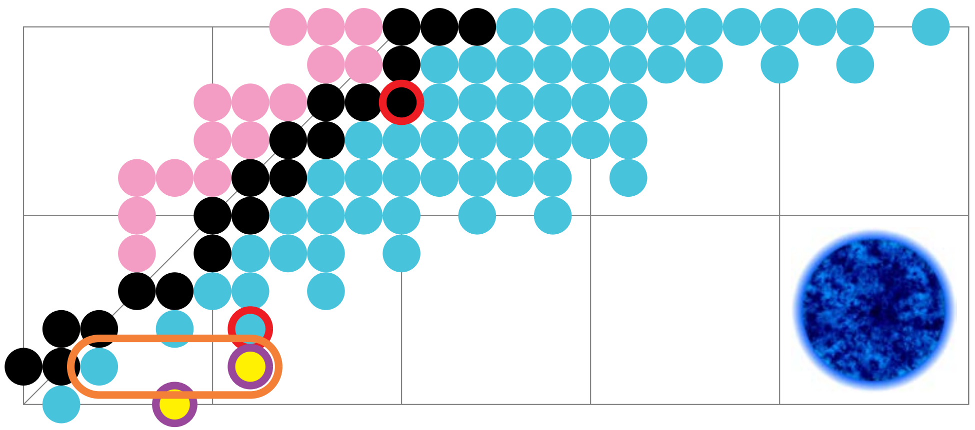
- low-lying ^{7}H / ^{4}n : bound $^{8}_{\Lambda}$H / $^{5}_{\Lambda}$n ?

  Hiyama, PRC 89 (2014) 061302(R)

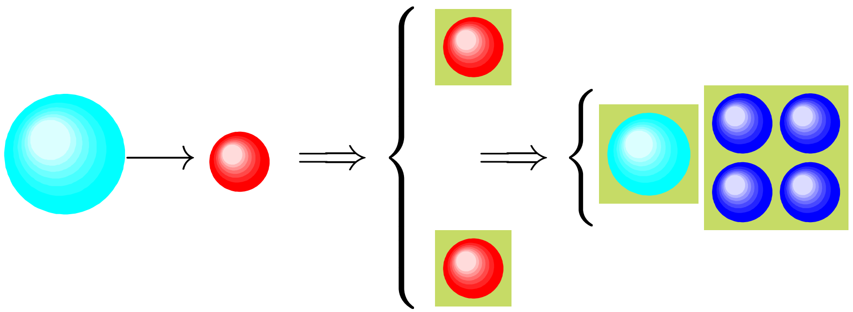


^{8}He (p,2p) ^{7}H @ 150 MeV/N :





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

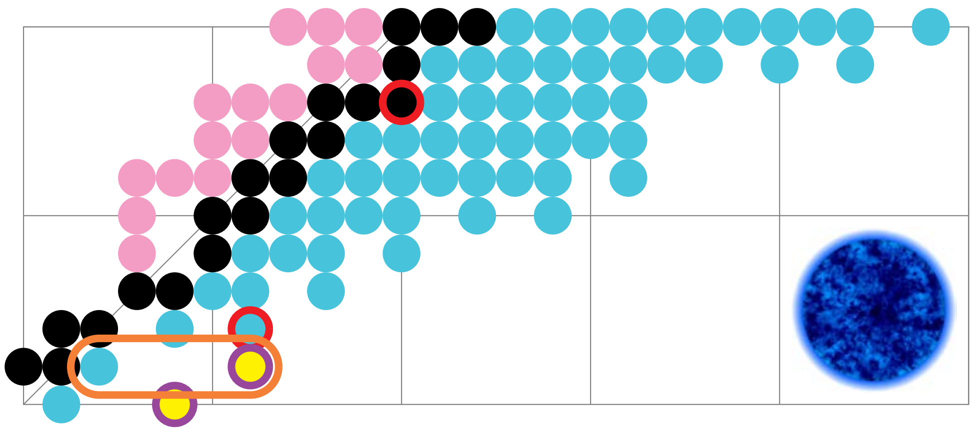


→ detection of the 7-body final state !

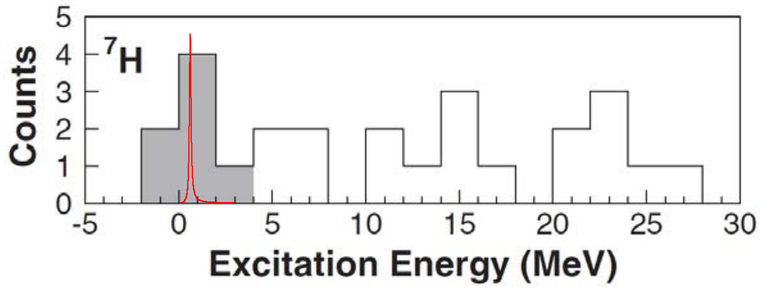
- **MINOS** liquid H target :
  - → high luminosity (*statistics*)
  - → proton angles (*resolution*)
- **DALI** NaI crystals :
  - → proton energies (*efficiency*)
- **SAMURAI** :
  - → triton momentum (*resolution & correlations*)
- **NEBULA** + **NeuLAND** :
  - → 3/4 neutron momenta (*efficiency,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

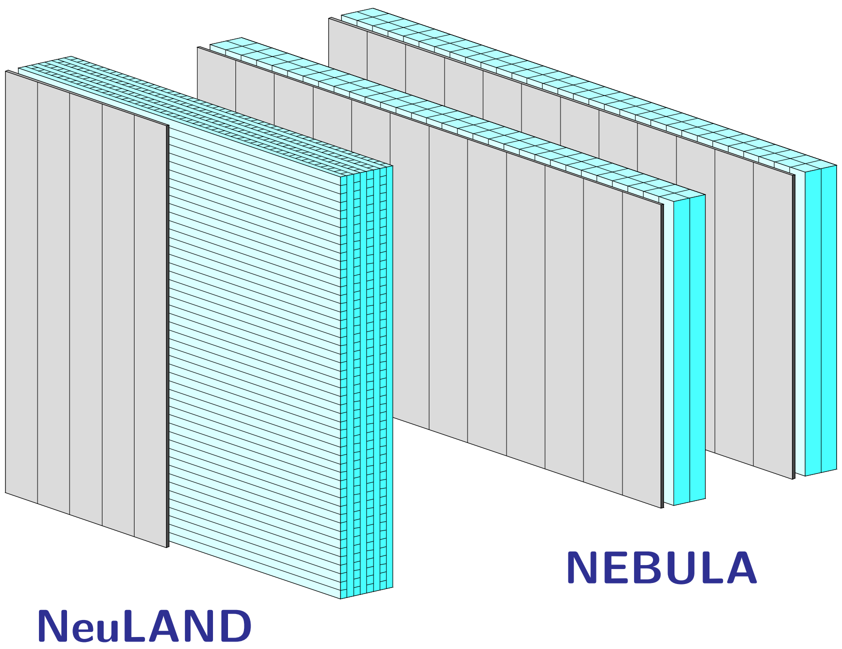
$$\text{FWHM} \sim \begin{cases} 5 \text{ MeV} & (2p) \\ 150 \text{ keV} & (2p+t+3n) \\ 100 \text{ keV} & (t+4n) \;!!! \end{cases}$$

Expected statistics & resolution

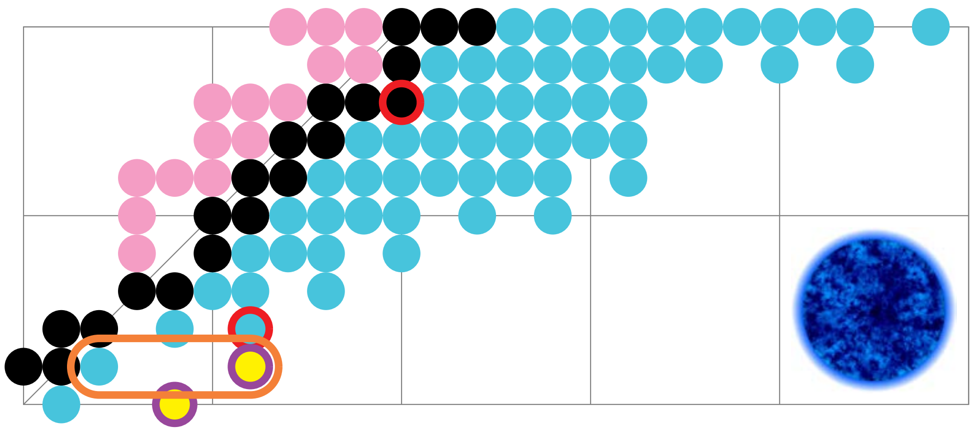


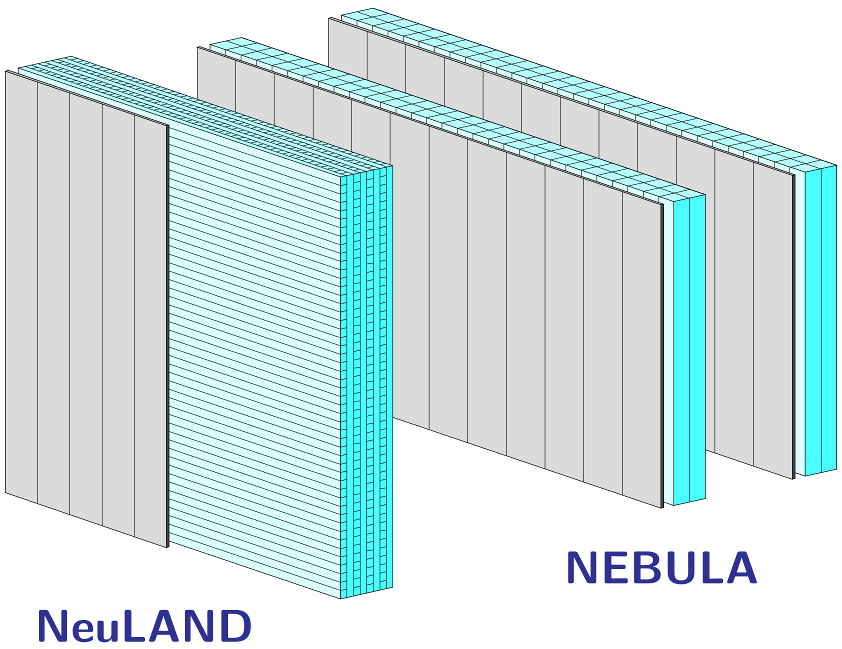
Caamaño, PRL 99 (2007) 062502

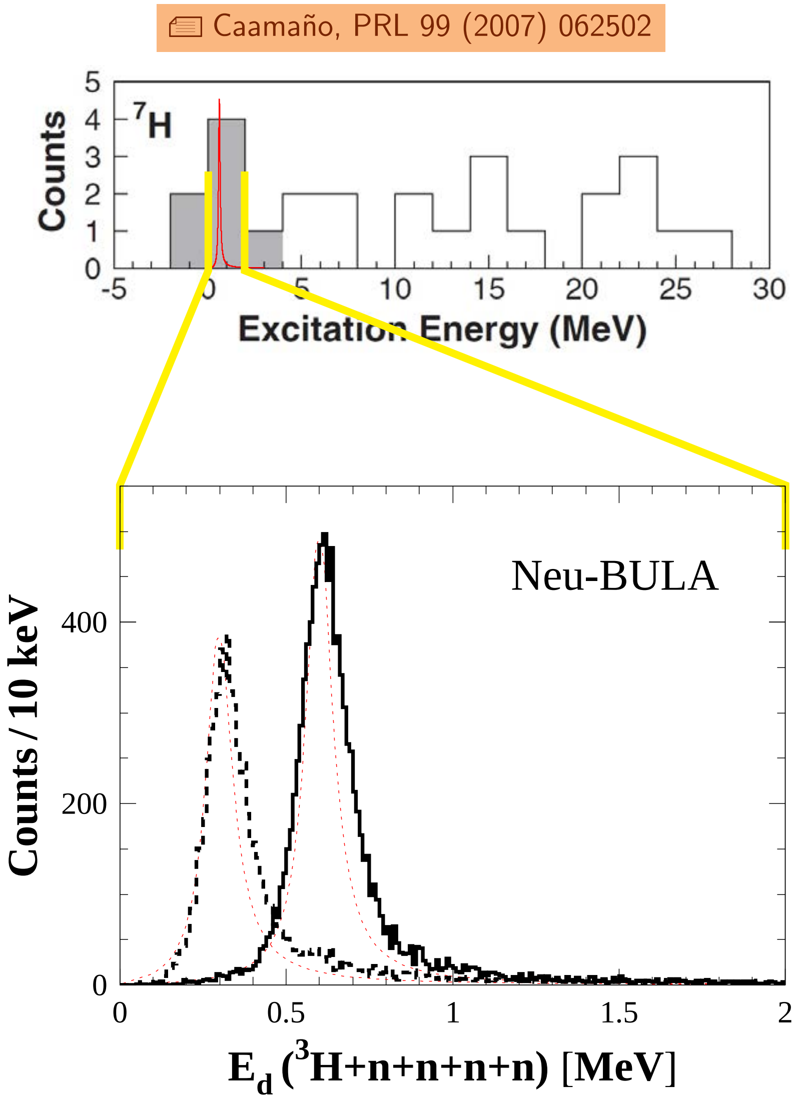




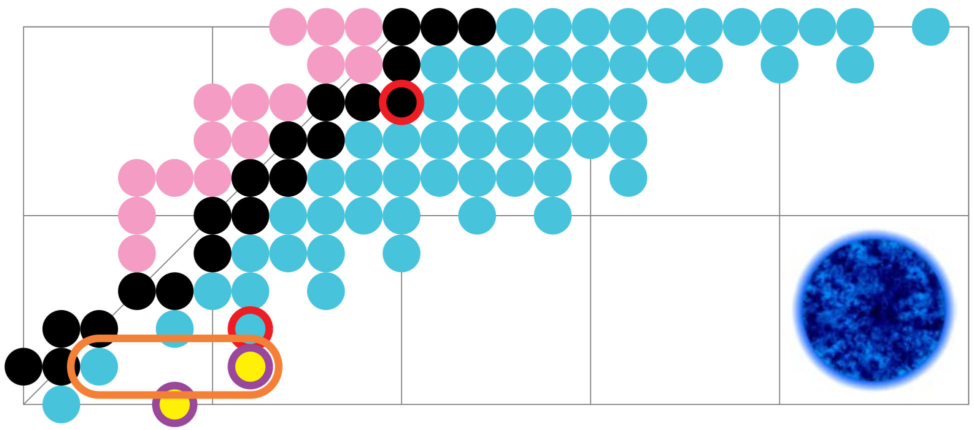
Expected statistics & resolution

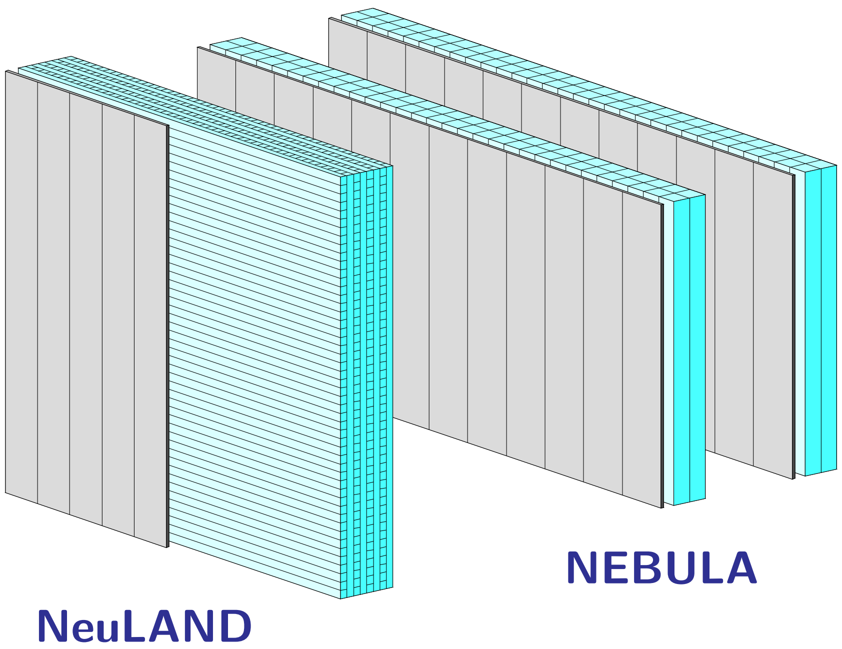




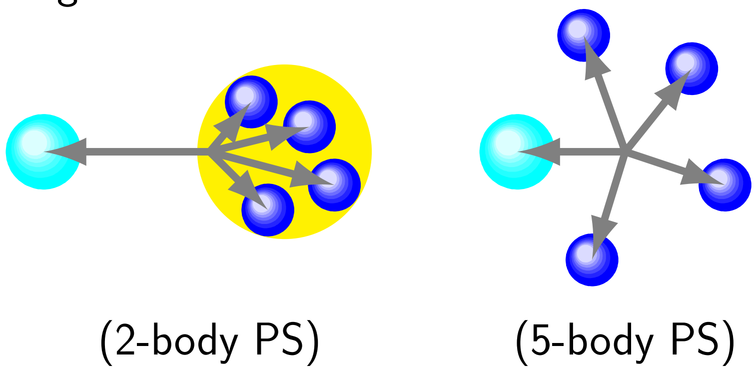


Direct 4n-decay : sensitivity



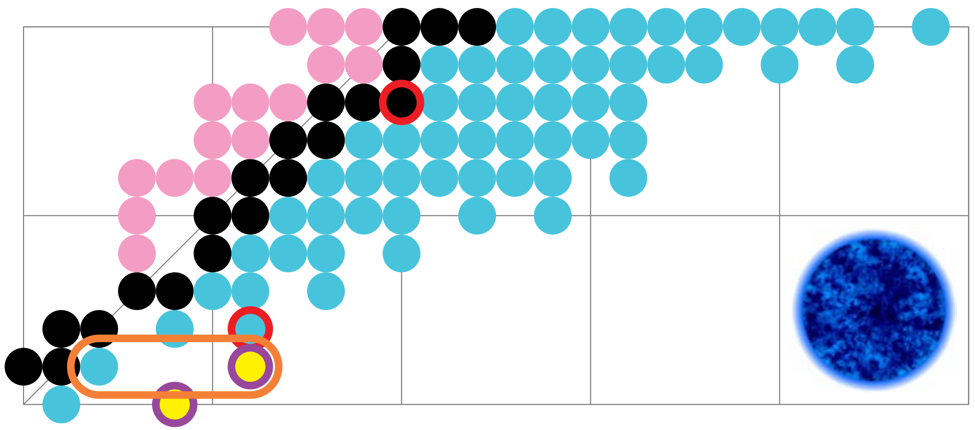


- Angular correlations :

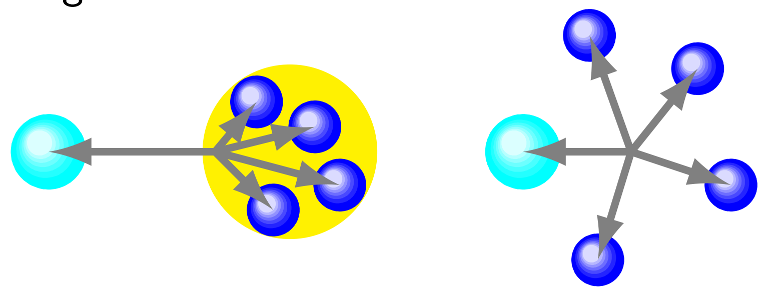


→ sensitive to $E_R(^4n)$ for any Γ !

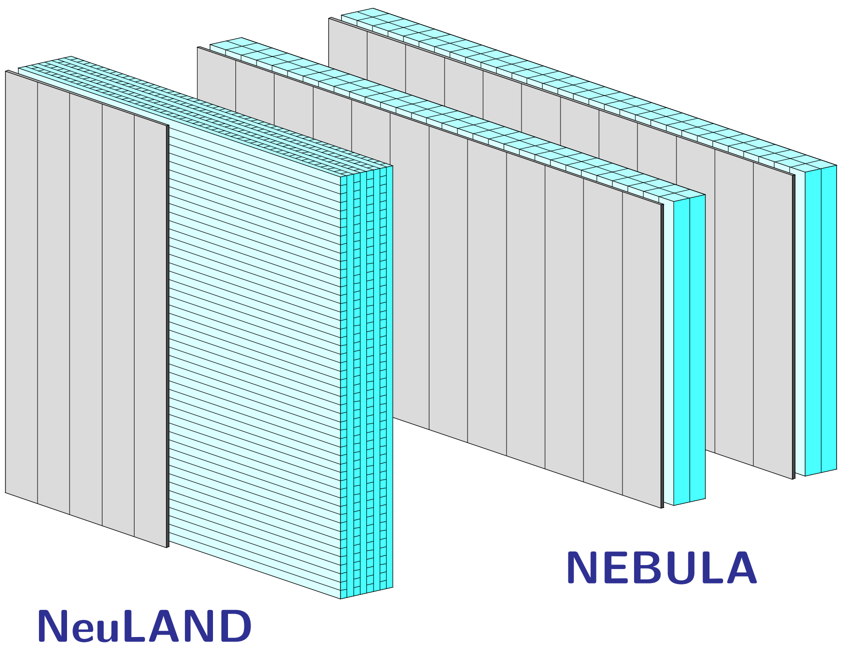
Direct 4n-decay : sensitivity



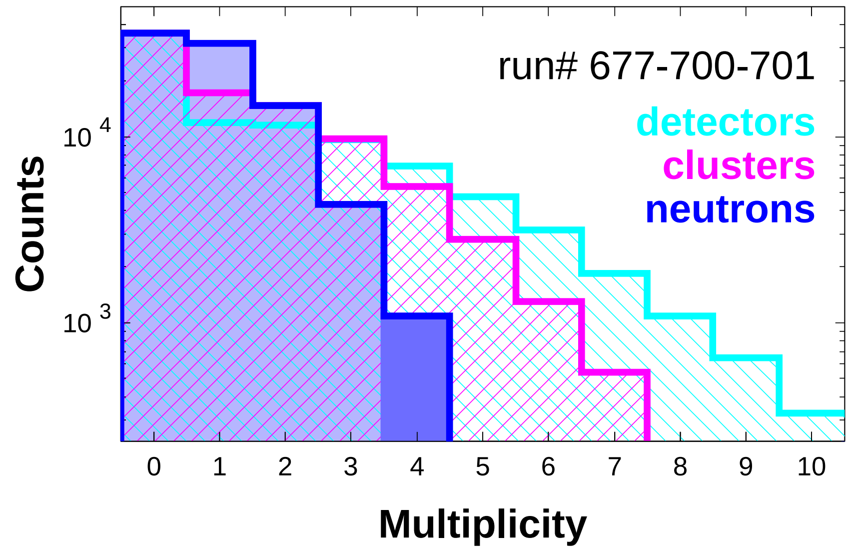
- Angular correlations :



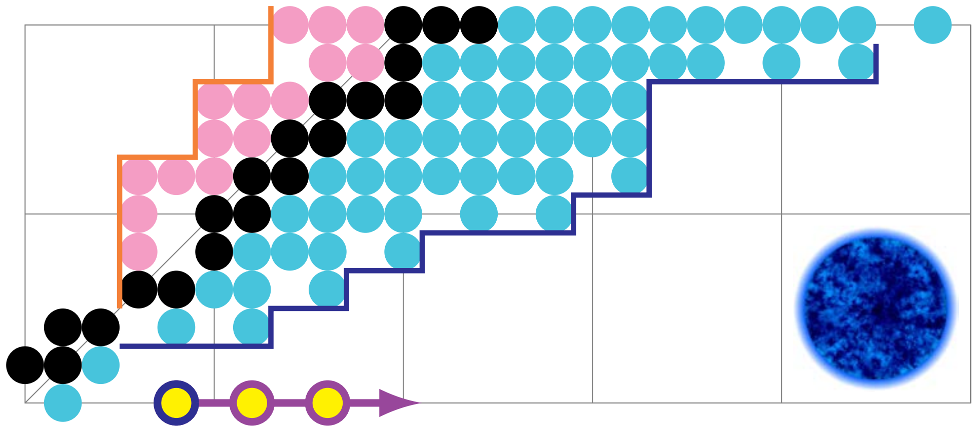
→ sensitive to $E_R(^4n)$ for any Γ !



- On-line [Revel] : $^8He(p,2p)^3H$



→ complete events : 1k/90 min ≈ 10^5 !!!



❶ **The ^{A}n context** :

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

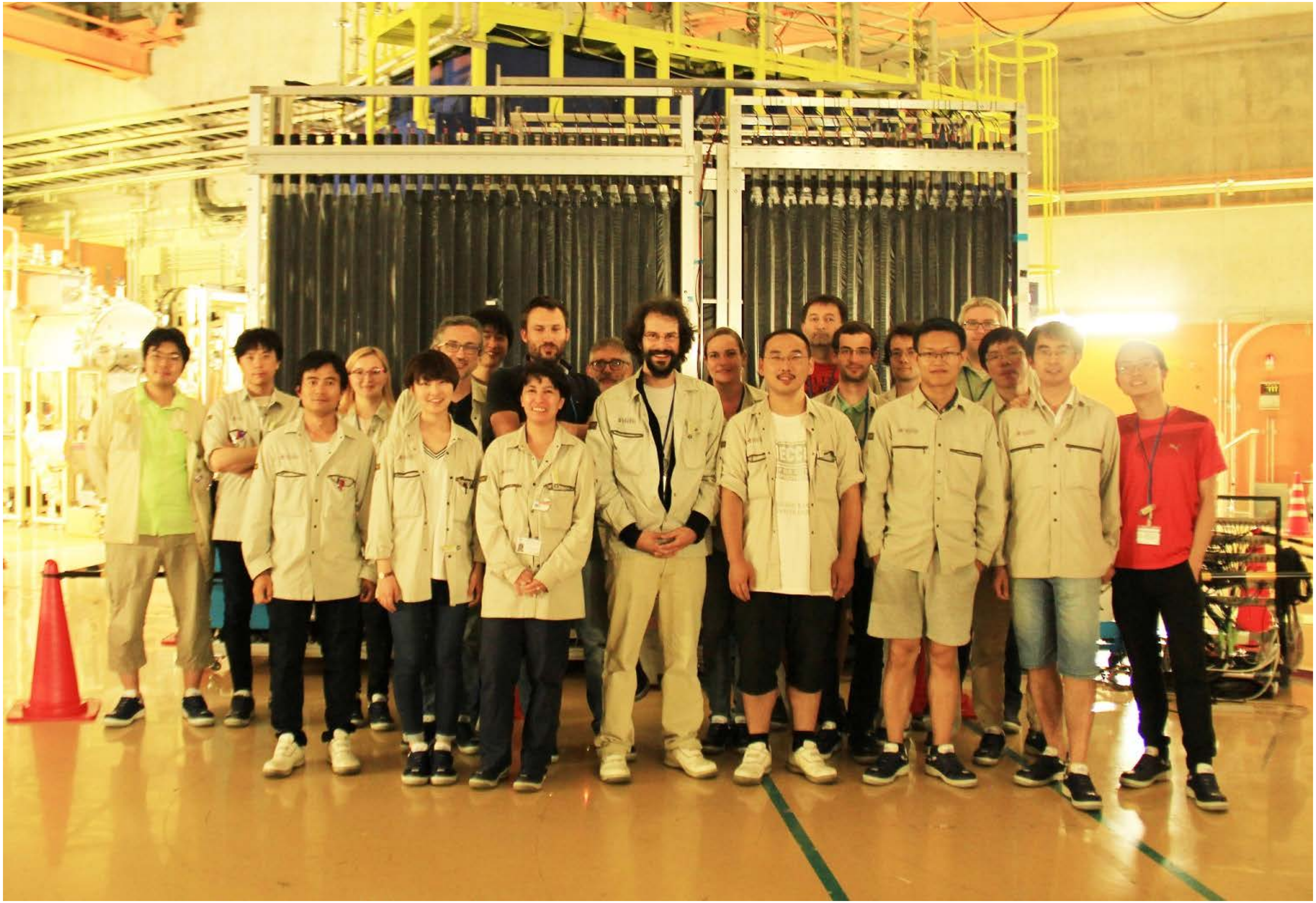
❷ **The RIKEN campaign** :

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

❸ **Short/Mid-term future** :

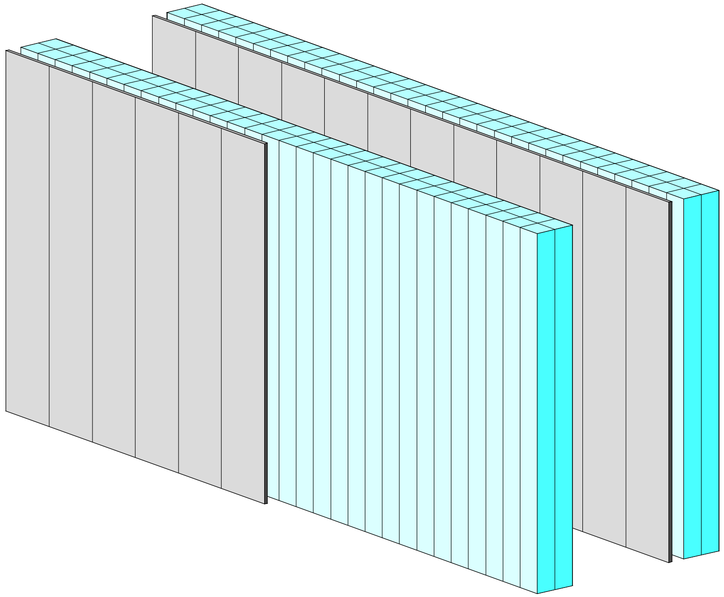
- confirm (refute) ^{4}n signals !
- $^{12,14}\text{Be}\,(\text{p,p}2\alpha)\,^{4,6}\mathbf{n}$ ('18)
  Beaumel, NP1206-SAMURAI12
- what next ?
  - → theory : reliable ^{4}n and beyond ...
  - → hexaneutron ? $^{8}\text{He}\,(\text{p,2p})^{1}\text{H}$ ...
  - → ^{A}n emission ? $\text{Q}_{\beta 6\text{n}}(^{19}\text{B}) \sim 8$ MeV ...

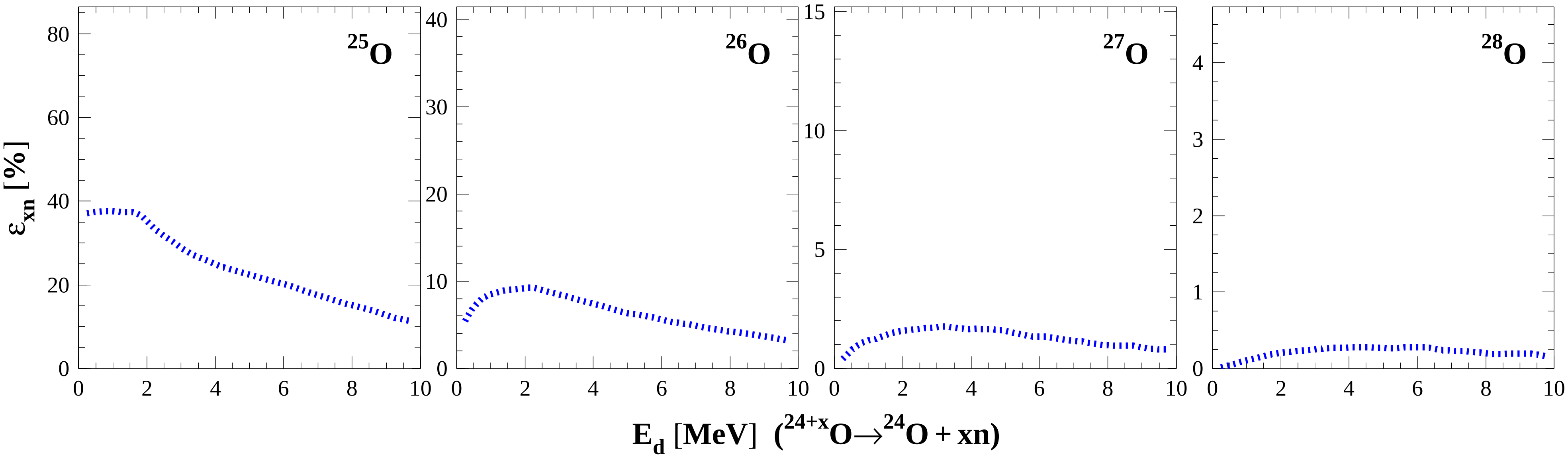
SAMURAI S34 collaboration (part)




TOSHIBA

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



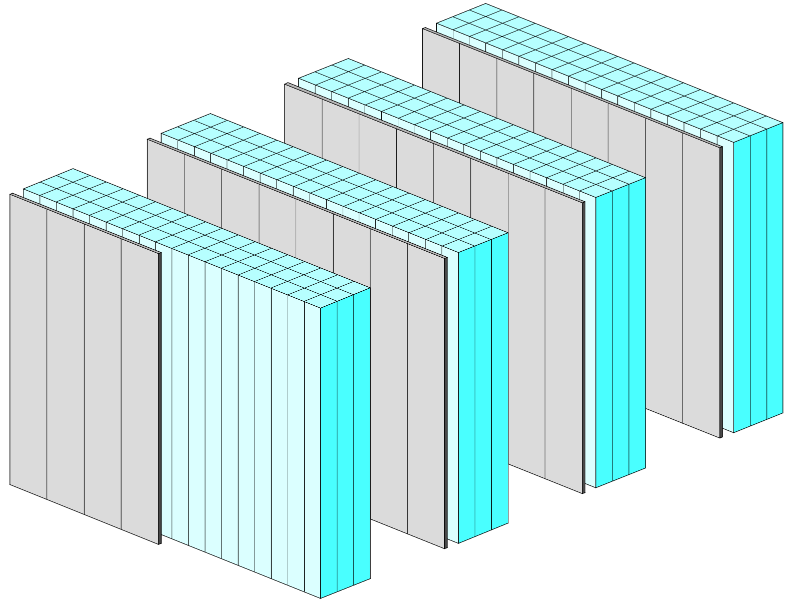


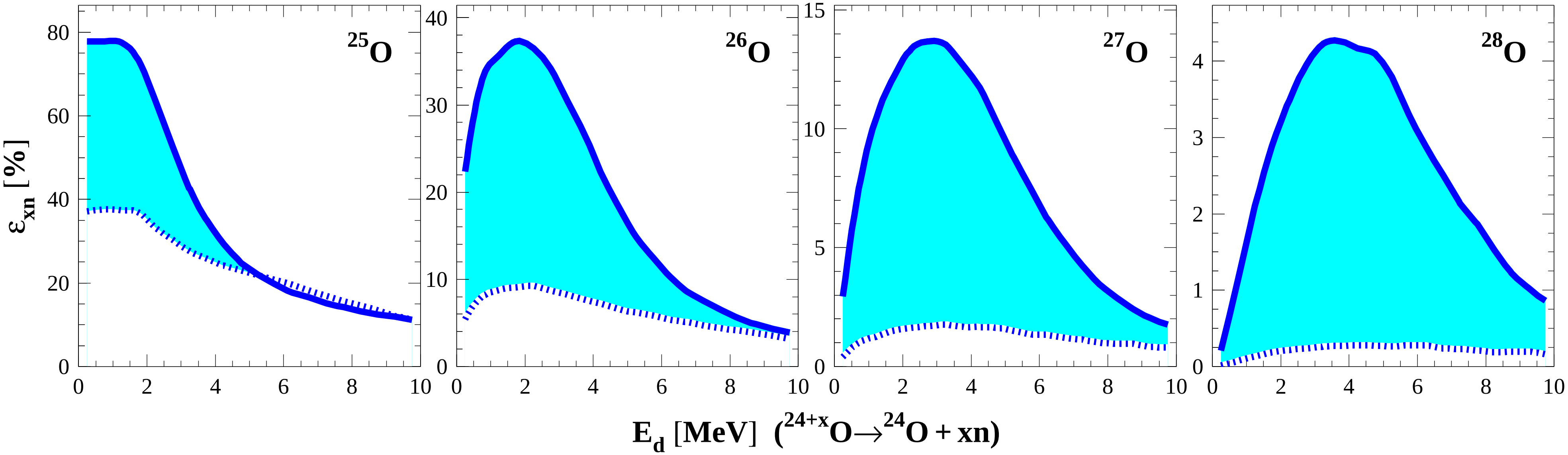
($\varepsilon_{xn} < \varepsilon_n^x$ due to neutron cross-talk) FMM, NIM A 450 (2000) 109

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 $\sim \times 16$!





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

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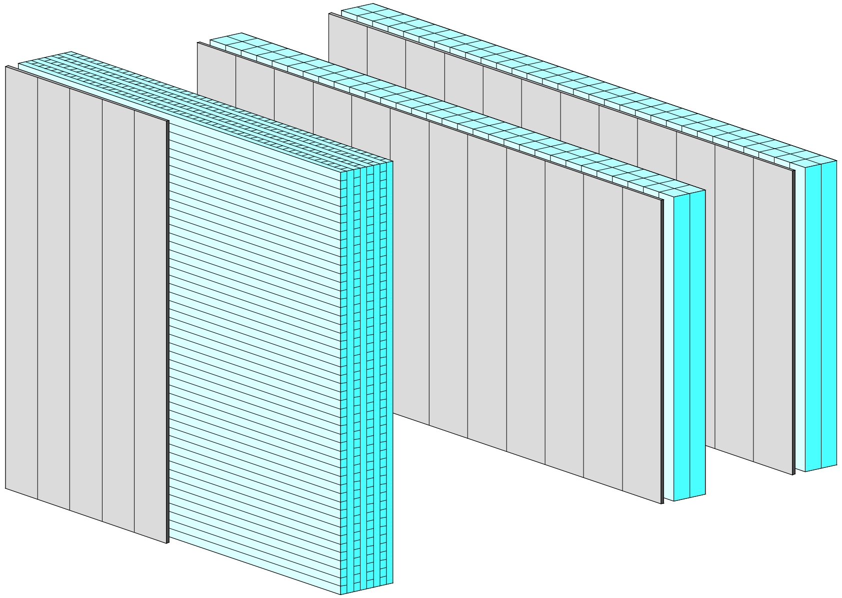
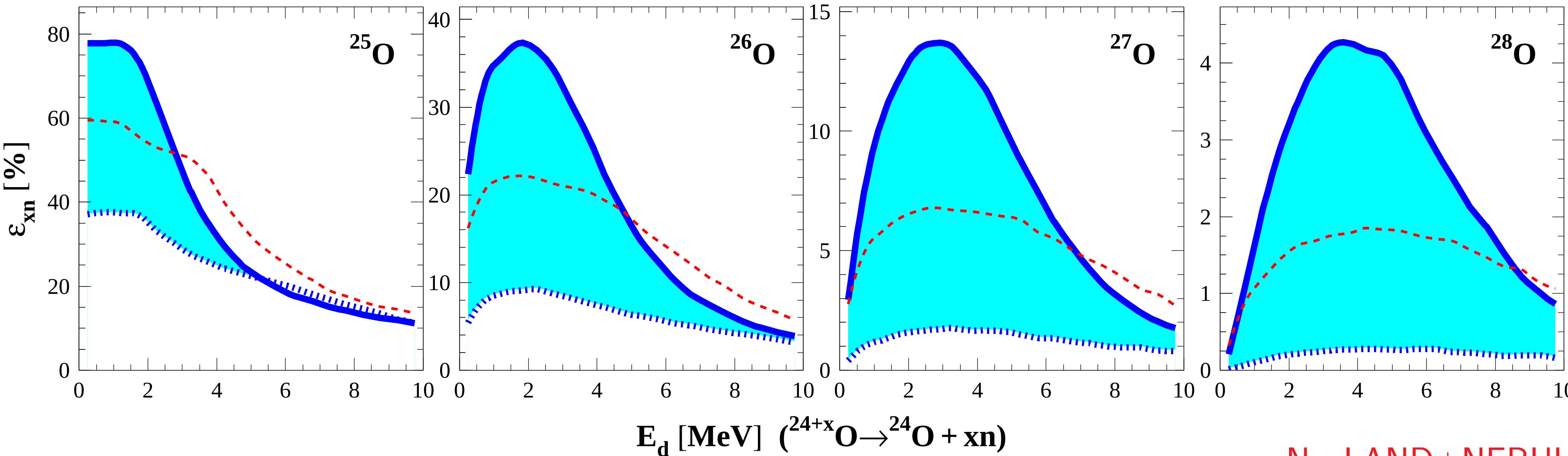
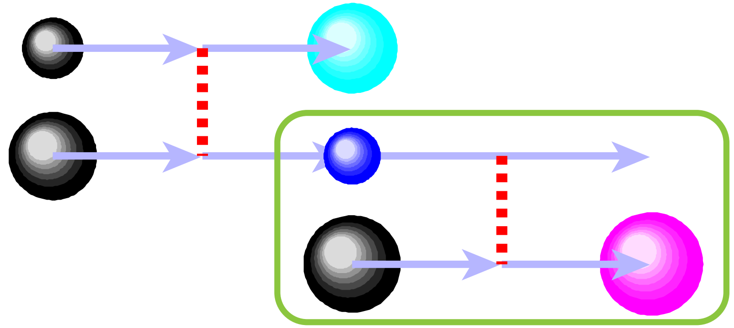


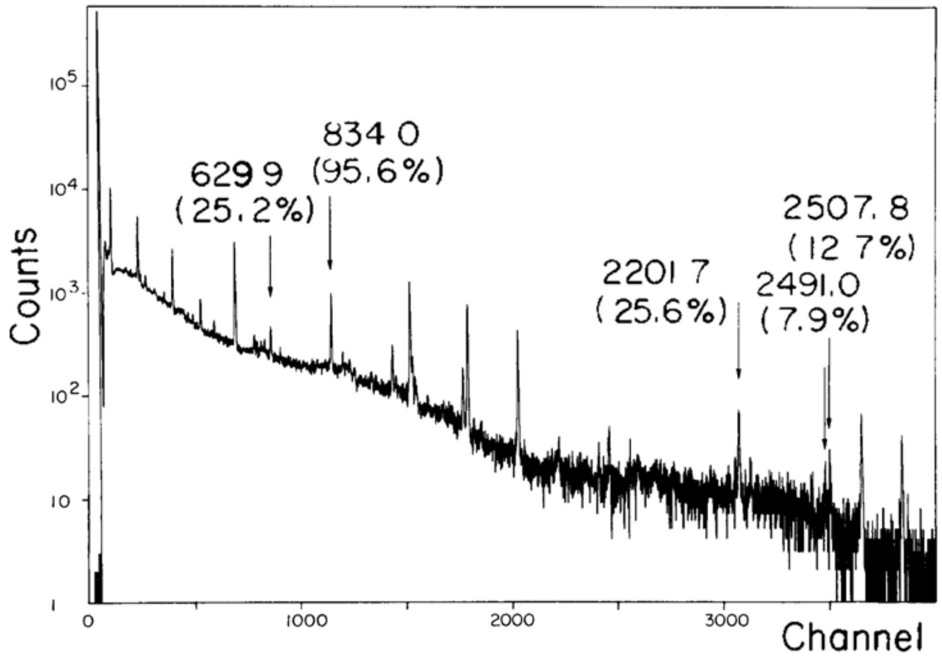


($\varepsilon_{xn} < \varepsilon_n^x$ due to neutron cross-talk) FMM, NIM A 450 (2000) 109

- Two-step reactions :
  - p + W —▮→ ^{A}n + ^{70}Zn → ^{72}Zn (→^{72}Ga) !!!

    Detraz, PLB 66 (1977) 33 ☜



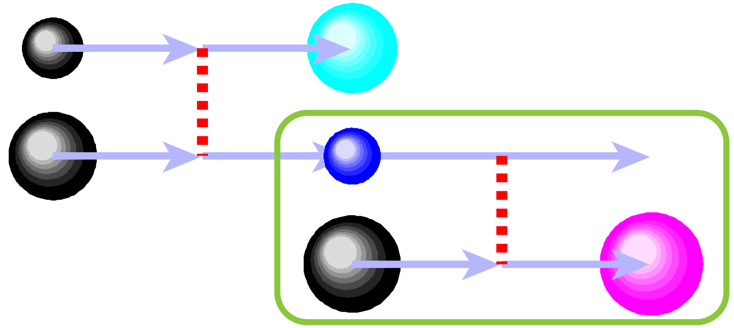


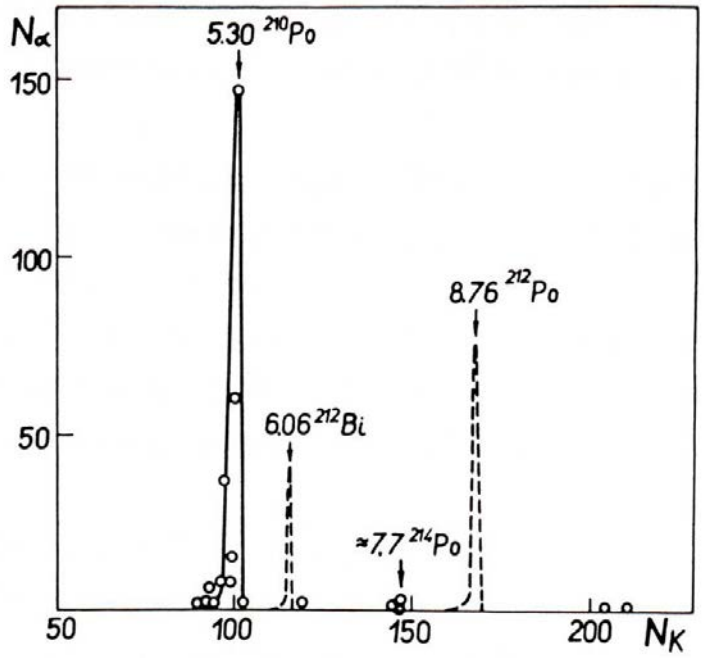
✗ ^{70}Zn (t,p) ^{72}Zn through Aluminium ...

- Two-step reactions :
  - p + W —▮→ ^{A}n + ^{70}Zn → ^{72}Zn (→^{72}Ga)

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

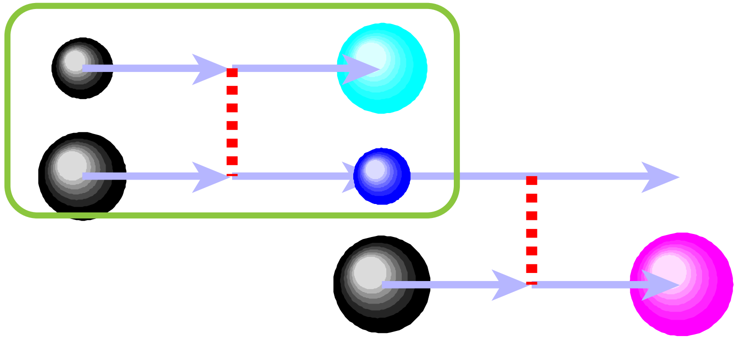
    Chultem, NPA 316(1979) 290 ☜



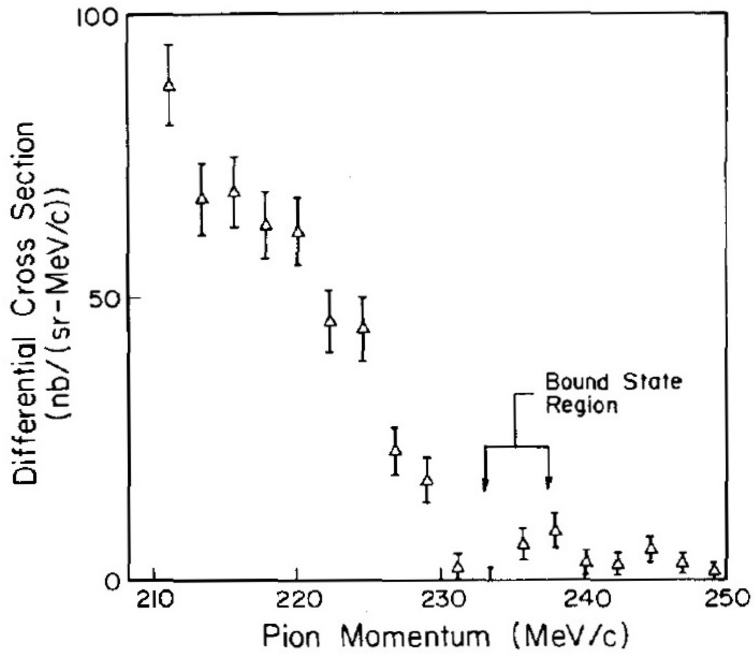


1960s : a long quest begins

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



- Pion charge-exchange :
  - ${}^{3}H\,(\pi^-, \gamma)\,3n$
    Miller, NPA 343 (1980) 347
  - ${}^{4}He\,(\pi^-, \pi^+)\,4n$
    Ungar, PLB 144 (1984) 333 ☜



1960s : a long quest begins

- Two-step reactions :
  - p + W —▮→ ^{A}n + ^{70}Zn → ^{72}Zn (→ ^{72}Ga)
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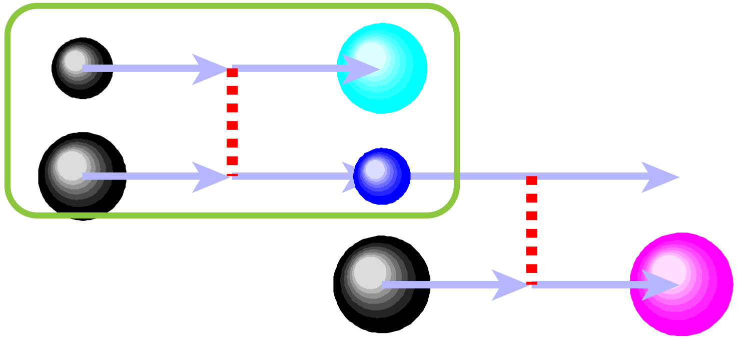
  - ^{208}Pb (π^-, π^+) ^{4}n $\xrightarrow{(\mathrm{Pb})}$ ^{212}Pb (→ ^{212}Bi → ^{212}Po)
    Chultem, NPA 316(1979) 290



- Pion charge-exchange :
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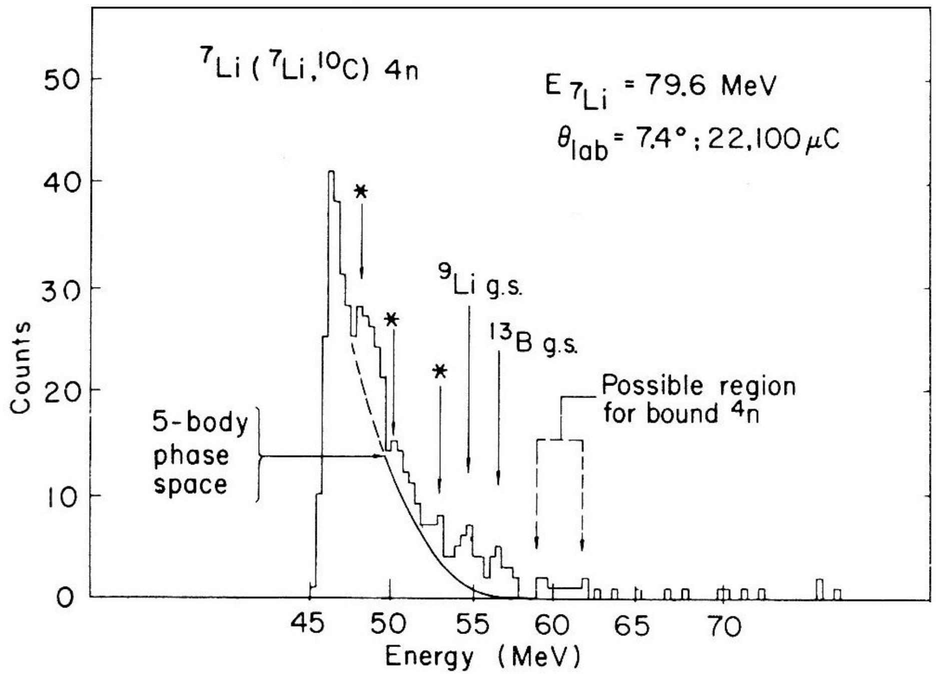
    Miller, NPA 343 (1980) 347
  - ^{4}He (π^-, π^+) 4n
    Ungar, PLB 144 (1984) 333
- Multinucleon transfer :
  - ^{7}Li + ^{11}B → ^{14}O + 4n
    Belozyorov, NPA 477 (1988) 131
  - ^{7}Li + ^{7}Li → $^{10(11)}$C + 4(3)n
    Cerny, PLB 53 (1974) 247



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

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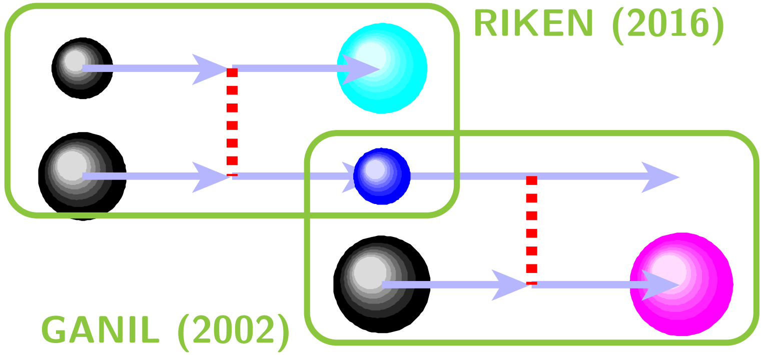

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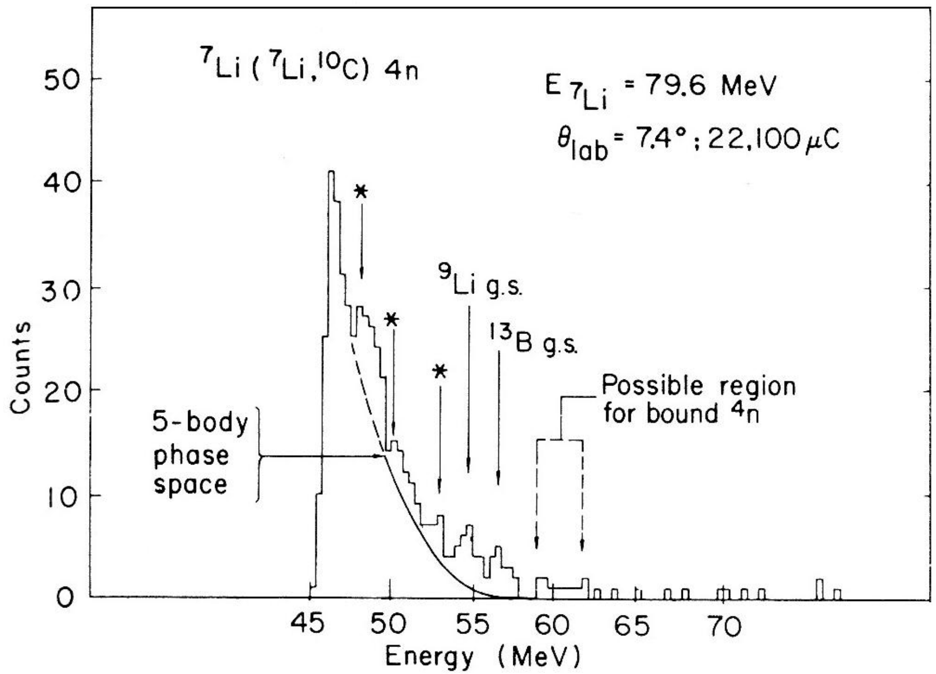

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Blind/shy experimentalists ?

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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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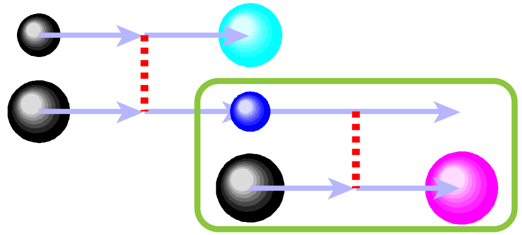
Light nuclear-stable multineutrons among products of the fission of ^{238}U nuclei that is induced by 62-MeV alpha particles have been searched by the activation method with a ^{27}Al sample. These multineutrons have been detected by characteristic gamma rays emitted by the nuclei from the beta-decay chain ^{28}Mg ⟶ ^{28}Al ⟶ ^{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 $x \geq 6$.



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

⇨ 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.

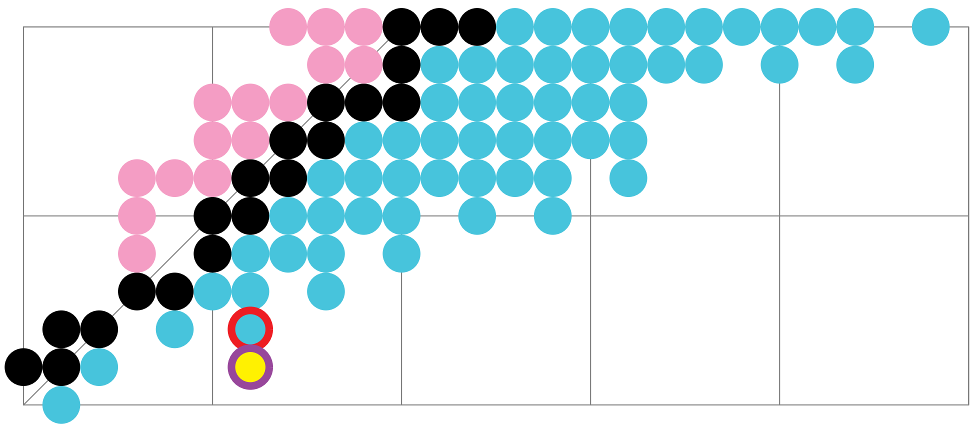
4. CONCLUSIONS

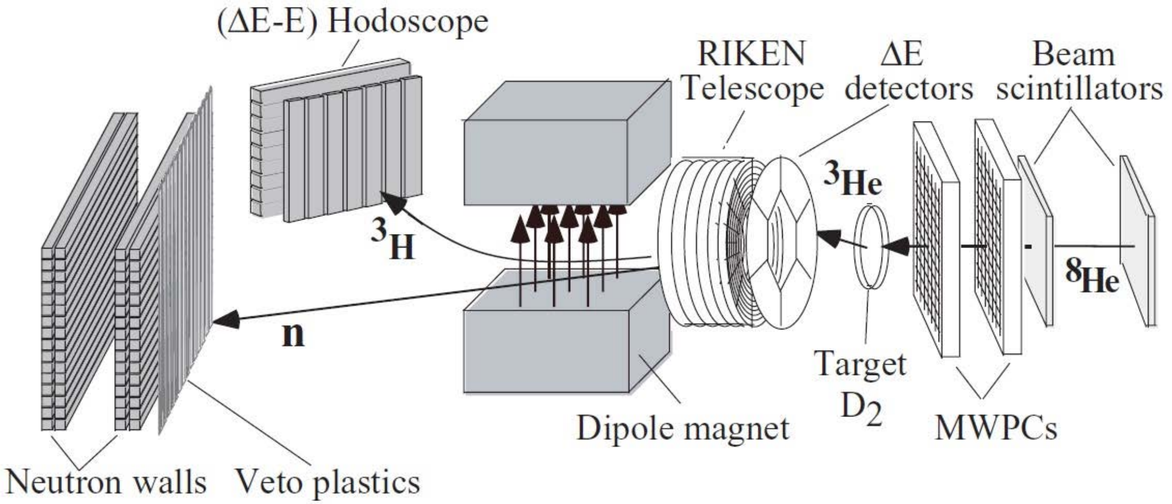
To conclude, nuclear-stable multineutrons among products of the ternary fission of ^{238}U nuclei that is induced by 62-MeV alpha particles have been sought by the activation method.

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 $^{88}Sr + {}^{x}n \rightarrow (x-4)n + {}^{92}Sr \rightarrow {}^{92}Y$ 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.

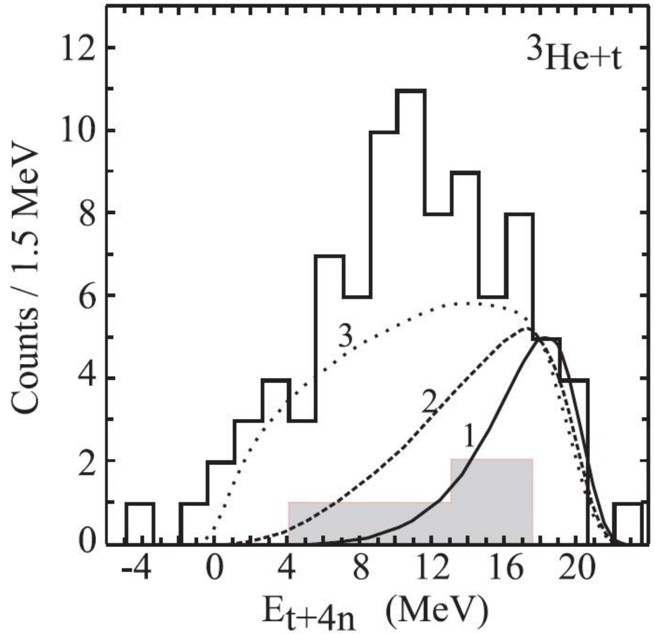
Blind/shy experimentalists ?





Nikolskii, PRC 81 (2010) 064606

► ^{8}He (d,^{3}He) ^{7}H @ 42 MeV/N :



"a peculiarity at $\sim$ *2 MeV"* ?

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

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

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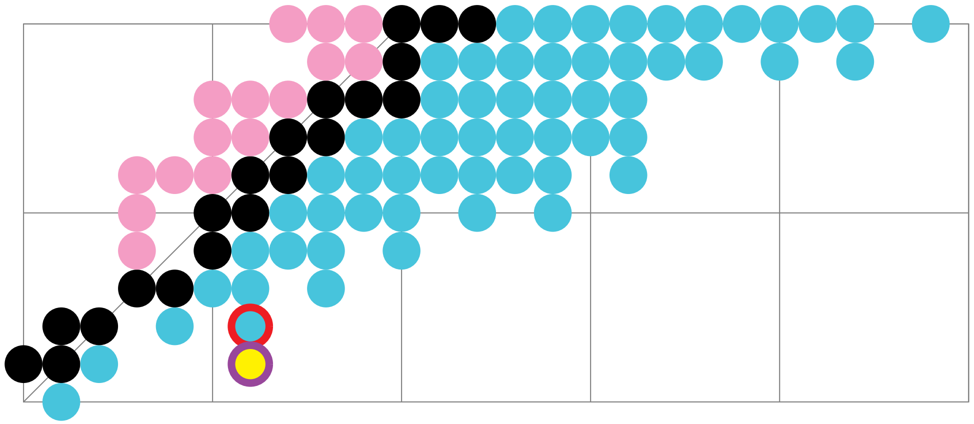

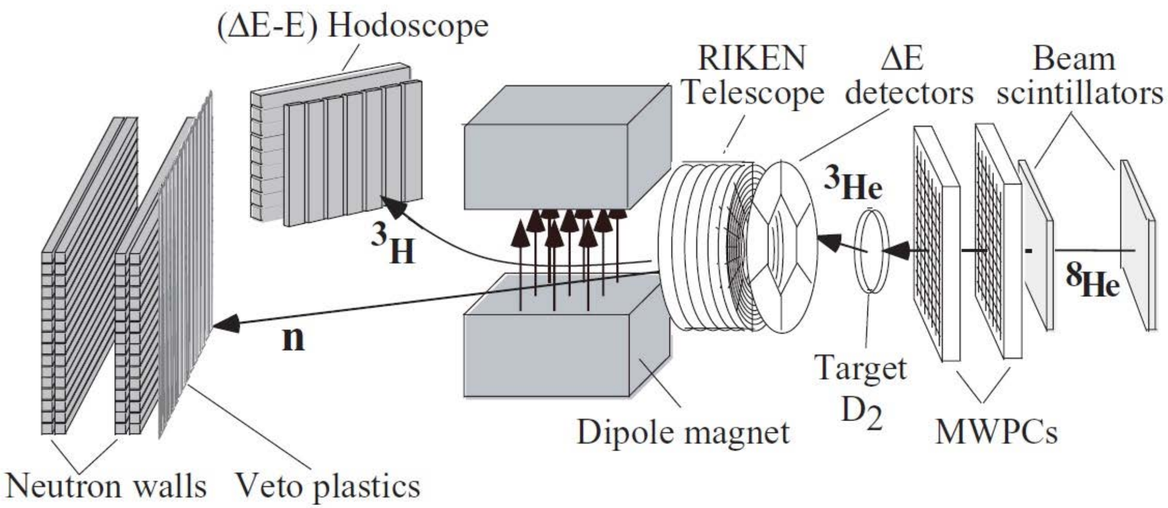

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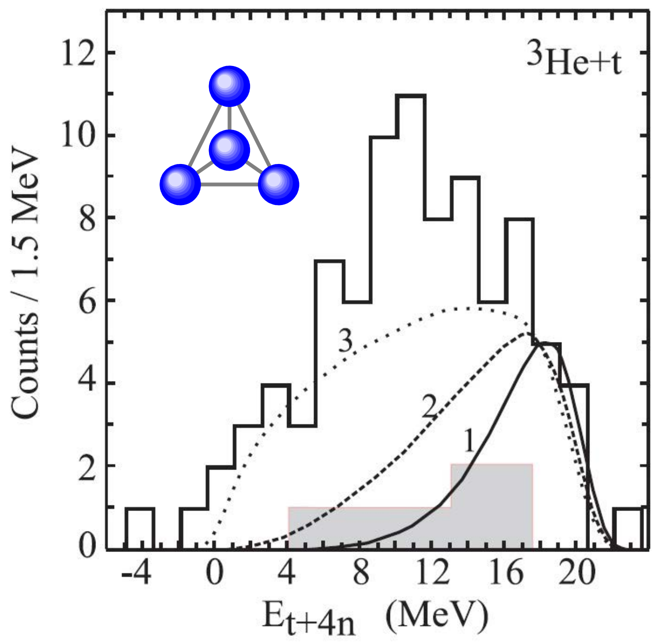

"a peculiarity at ∼ 2 MeV" ?

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"* !!!