International Conference on Exotic Atoms and Related Topics

Stefan-Meyer-Institute for Subatomic Physics (Vienna, September 13–17, 2021)

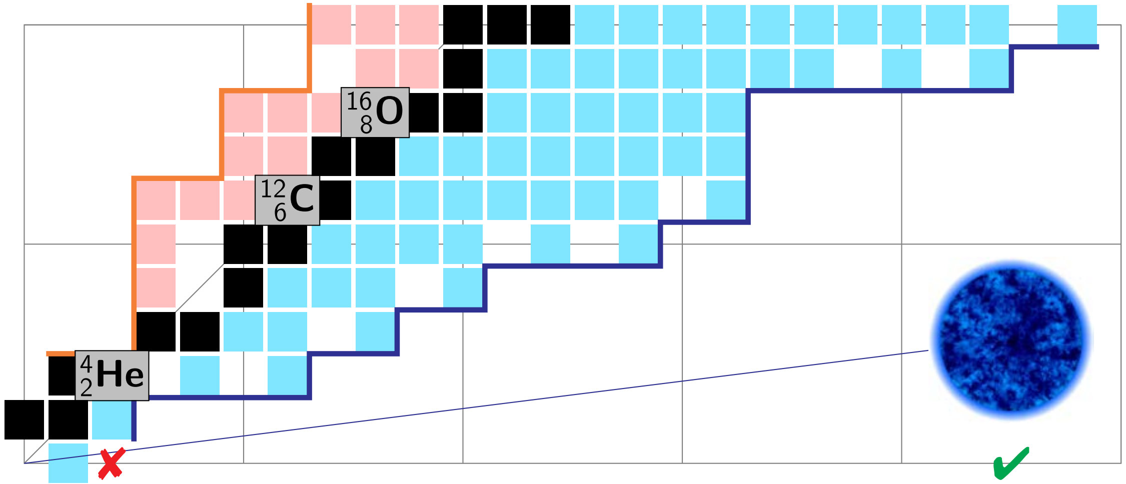
The neutron as a building block

F. Miguel Marqués

Laboratoire de physique corpusculaire

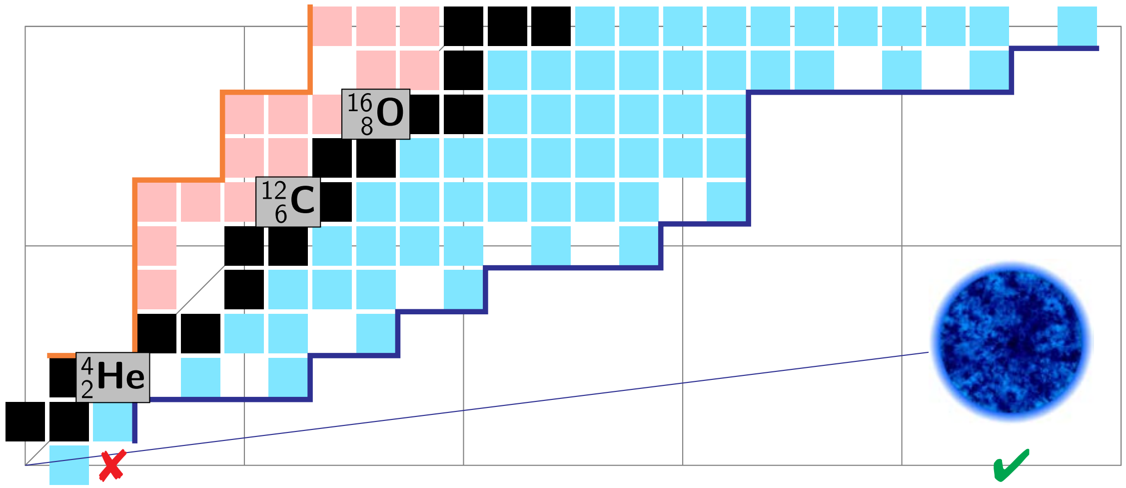
FMM & Carbonell, European Physical Journal A 57 (2021) 105

Multineutrons : Tetraneutrons ?

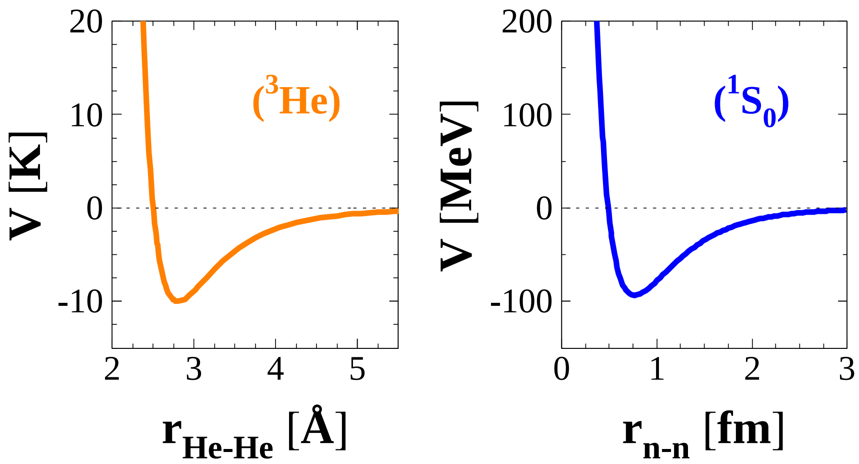


- Well-established facts :
  - N = 2 (✘) · · · 10^{57}(✔)

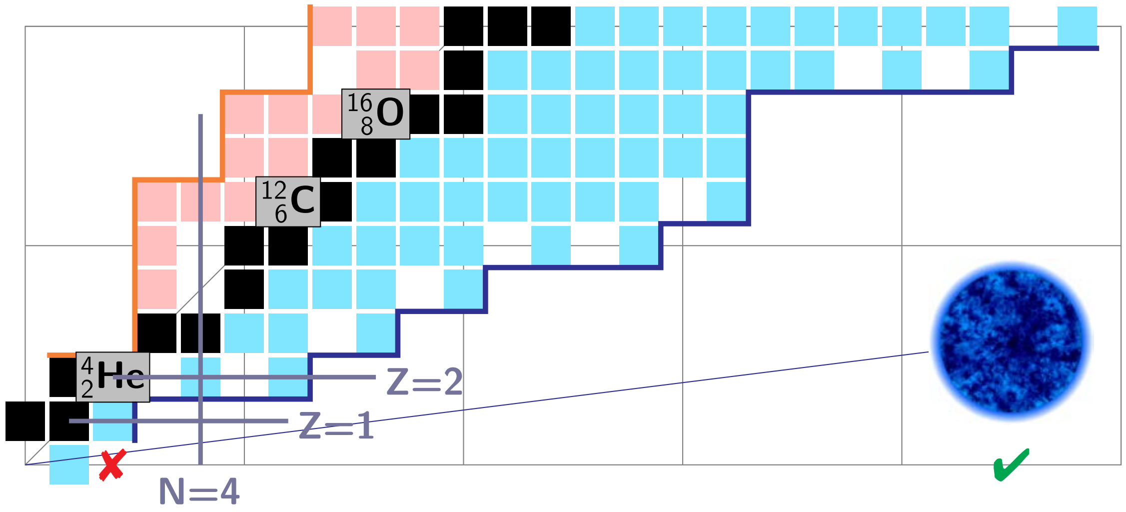
Multineutrons : Tetraneutrons ?



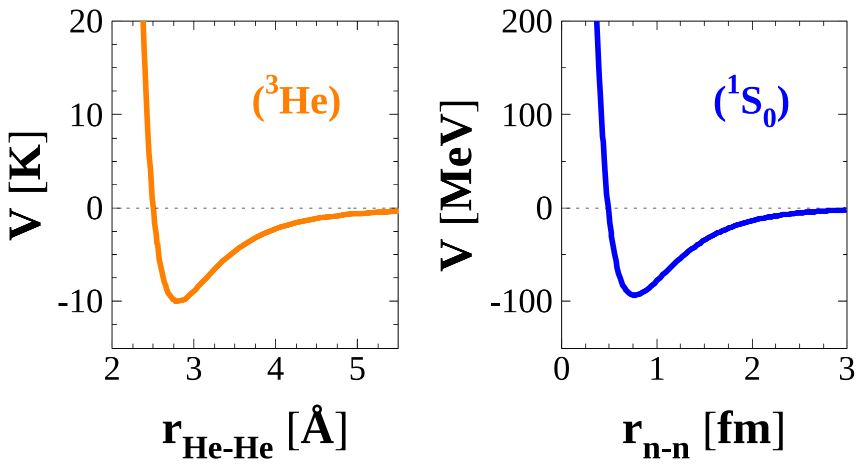
- Well-established facts :
  - $N = 2$ (✘) $\cdots$ 10^{57} (✔)
  - $(^3\mathrm{He})_2$ (✘) $\cdots$ $(^3\mathrm{He})_N$ (✔) : $N \sim 30$



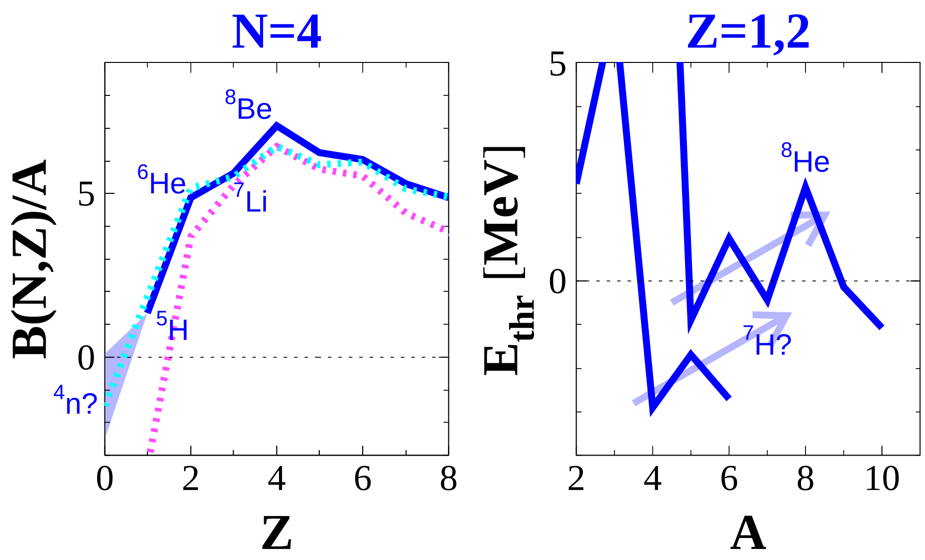
Multineutrons : Tetraneutrons ?



- Well-established facts :
  - $N = 2$ (✗) $\cdots$ 10^{57} (✔)
  - $(^3\mathrm{He})_2$ (✗) $\cdots$ $(^3\mathrm{He})_N$ (✔) : $N \sim 30$

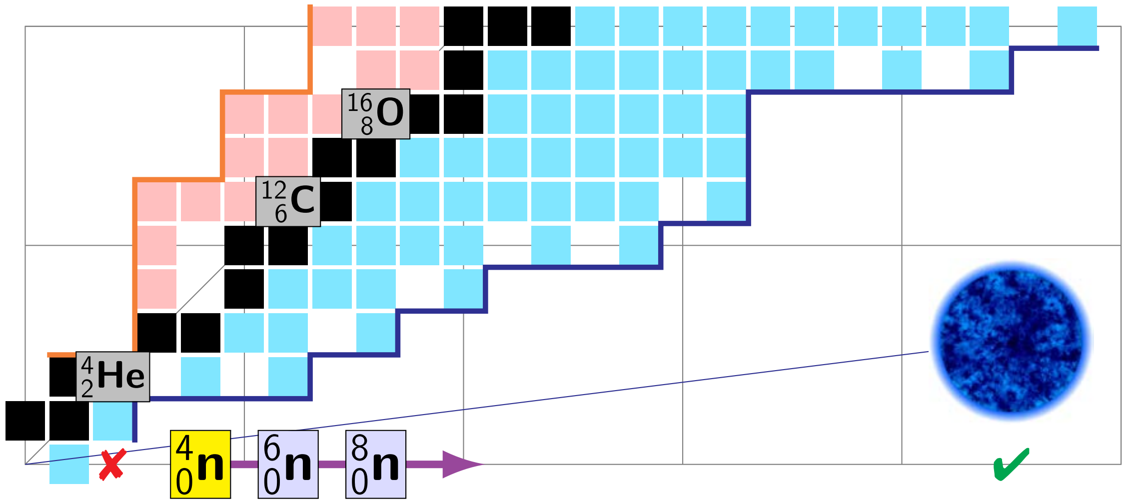


- Known masses :



- kink beyond ^{5}H ? "He(H) anomaly" ?

Multineutrons : Tetraneutrons ?



▶ Well-established facts :

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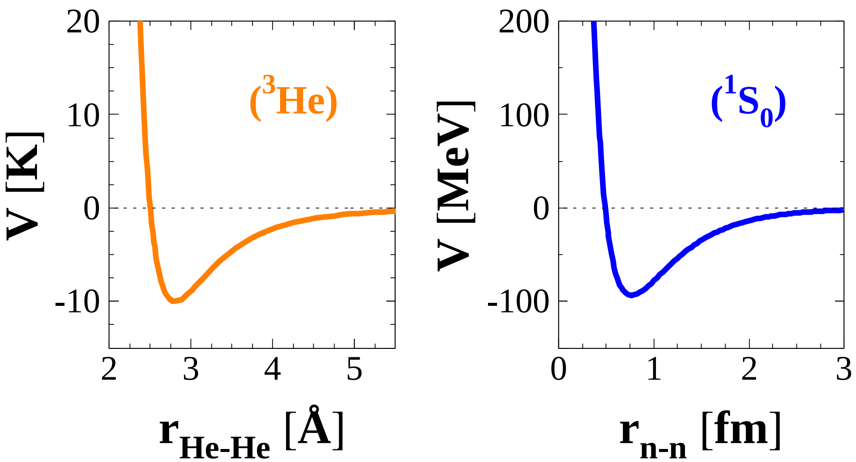
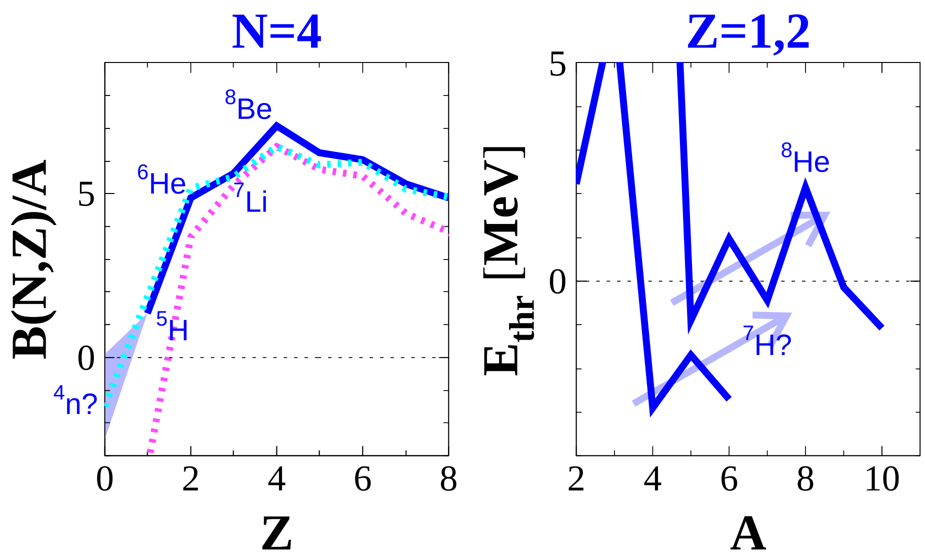
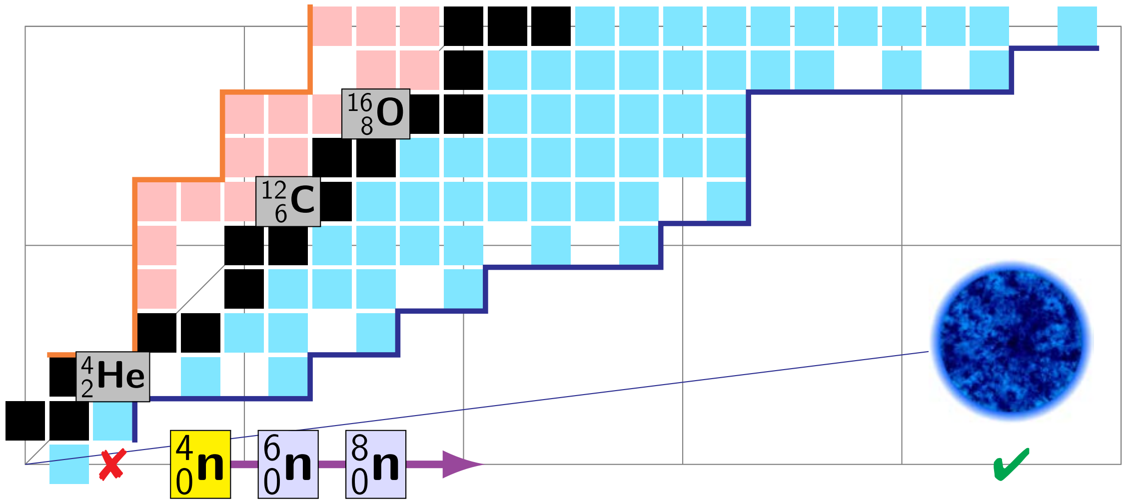


▶ Known masses :



- kink beyond ^{5}H ? "He(H) anomaly" ?
- even neutron numbers : $^{4}_{0}$n

Multineutrons : Tetraneutrons ?



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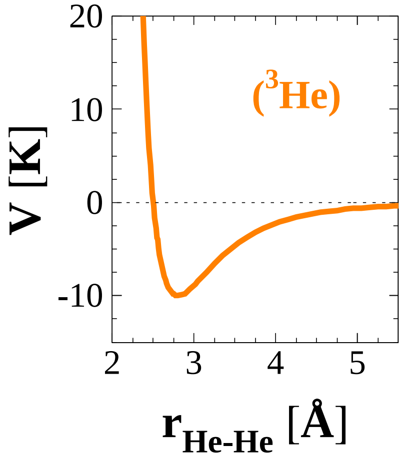

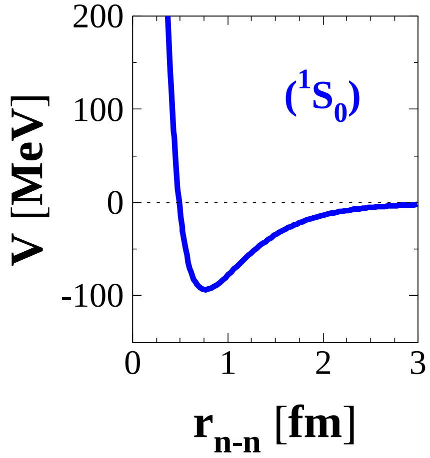

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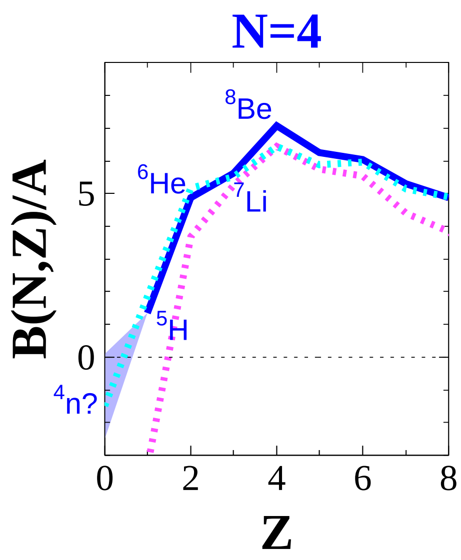

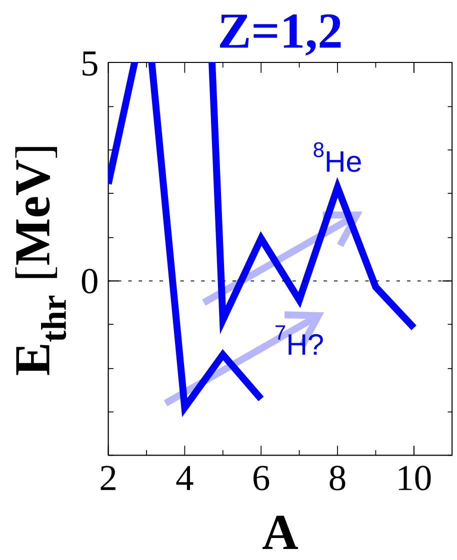

  - kink beyond ^{5}H ? "He(H) anomaly" ?
  - even neutron numbers : $^{4}_{0}$n

- Two challenges :
  - production (unstable)
  - detection (extremely low ε) :

    → $\varepsilon_{1n} = 10\,\%$ ⟹ $\varepsilon_{4n} < 0.1\,‰$!!!

Multineutron experiments & probes

two step

$$\begin{array}{ccc} ⓐ & \longrightarrow & ⓑ \\ & \Downarrow \\ & \Uparrow \\ ({}^{A}\mathsf{n}) & \longrightarrow & (X) \end{array}$$

missing mass

$$\begin{array}{ccc} ⓐ & \longrightarrow & ⓑ \\ & \Downarrow \\ & \Uparrow \\ ⓒ & \longrightarrow & ({}^{A}\mathsf{n}) \end{array}$$

neutron detection

$$\begin{array}{ccccc} ⓐ & \longrightarrow & X & & \\ & \Downarrow & & & \\ & \Uparrow & & & \\ ⓒ & \longrightarrow & ({}^{A}\mathsf{n}) & \longrightarrow & A\,ⓝ \end{array}$$

Multineutron experiments & probes

two step

$$
\begin{tikzcd}
ⓐ \arrow[r] \arrow[d, phantom, shift left=6ex, "\Downarrow\Uparrow"] & ⓑ \\
({}^{A}\mathsf{n}) \arrow[r] & (X)
\end{tikzcd}
$$

✔ charged-particle detection

✘ only bound states

✘ insensitive to energy

✘ infer lower limit of A

✘ contaminant $\neq$ ⓐ and/or uncontrolled 1st-step background

8 experiments

missing mass

$$
\begin{tikzcd}
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Multineutron experiments & probes

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$$\begin{tikzcd} ⓐ \arrow[r] \arrow[d, phantom, "\Downarrow\Uparrow"] & ⓑ \\ ⓒ \arrow[r] & ({}^{A}\mathsf{n}) \end{tikzcd}$$

- ✔ charged-particle detection
- ✔ bound & resonant states
- ✔ mass number well defined
- ✘ insensitive to internal structure
- ✘ cross-section of protons into ⓑ
- ✘ beam/target $\neq$ ⓐ/ⓒ


24 experiments

neutron detection

$$\begin{tikzcd} ⓐ \arrow[r] \arrow[d, phantom, "\Downarrow\Uparrow"] & X \\ ⓒ \arrow[r] & ({}^{A}\mathsf{n}) \arrow[r] & Aⓝ \end{tikzcd}$$

Multineutron experiments & probes

two step

$$\begin{array}{ccc} \textcircled{a} & \longrightarrow & \textcircled{b} \\ & \Downarrow\Uparrow & \\ ({}^{A}\mathrm{n}) & \longrightarrow & (X) \end{array}$$

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- ✘ only bound states
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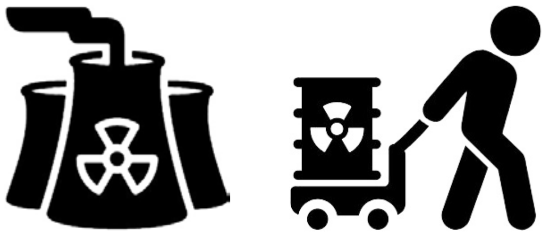

8 experiments

missing mass

$$\begin{array}{ccc} \textcircled{a} & \longrightarrow & \textcircled{b} \\ & \Downarrow\Uparrow & \\ \textcircled{c} & \longrightarrow & ({}^{A}\mathrm{n}) \end{array}$$

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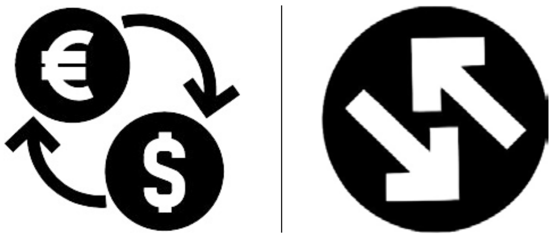

24 experiments

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$$\begin{array}{ccccc} \textcircled{a} & \longrightarrow & X & & \\ & \Downarrow\Uparrow & & & \\ \textcircled{c} & \longrightarrow & ({}^{A}\mathrm{n}) & \longrightarrow & A\textcircled{n} \end{array}$$

- ✔ unambiguous detection
- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency

4 experiments

Multineutron experiments & probes

two step

$$\begin{tikzcd} ⓐ \arrow[r] \arrow[d, phantom, "\Downarrow\Uparrow"] & ⓑ \\ ({}^A\mathrm{n}) \arrow[r] & (X) \end{tikzcd}$$

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- ✘ infer lower limit of A
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8 experiments

Détraz, PL 66B (1977) 333

✔ → ✘ (1980)

missing mass

$$\begin{tikzcd} ⓐ \arrow[r] \arrow[d, phantom, "\Downarrow\Uparrow"] & ⓑ \\ ⓒ \arrow[r] & ({}^A\mathrm{n}) \end{tikzcd}$$

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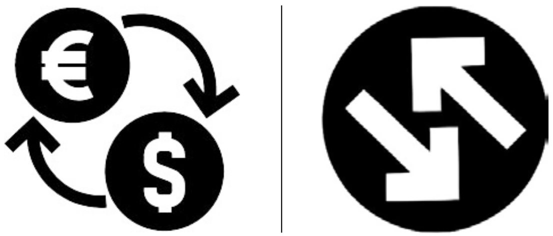

24 experiments

Kisamori, PRL 116 (2016) 052501

✔ (?)

neutron detection

$$\begin{tikzcd} ⓐ \arrow[r] \arrow[d, phantom, "\Downarrow\Uparrow"] & X & \\ ⓒ \arrow[r] & ({}^A\mathrm{n}) \arrow[r] & A ⓝ \end{tikzcd}$$

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- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency

4 experiments

FMM, PRC 65 (2002) 044006

✔ (?)

Missing-mass backgrounds

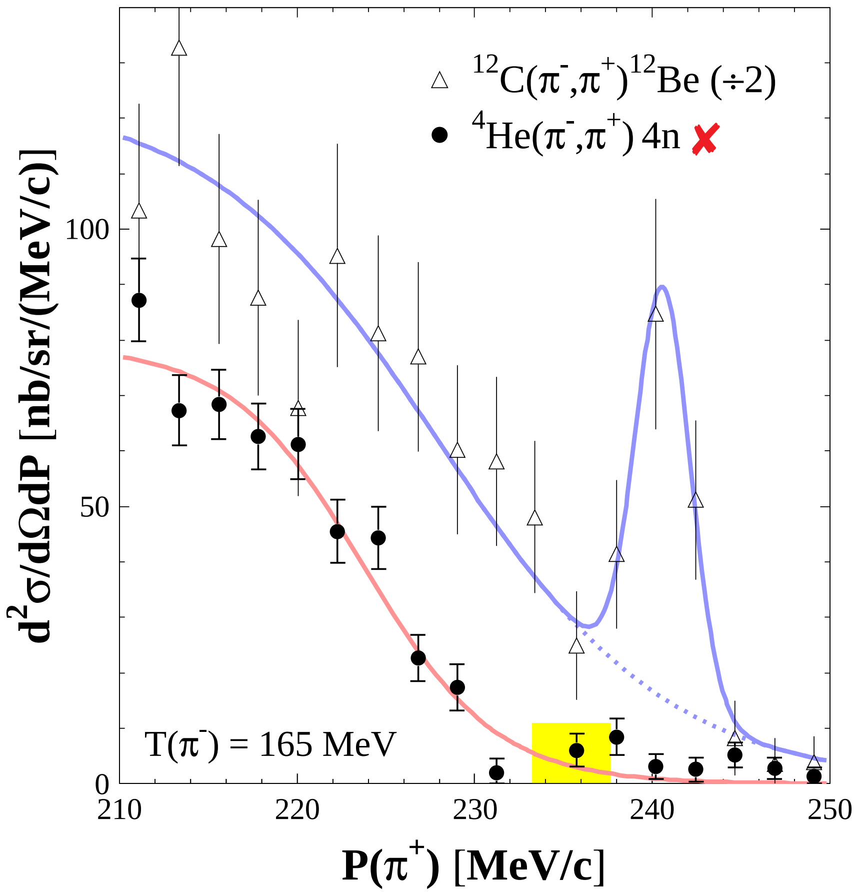
^{3,4}He (π^-, π^+) ^{3,4}n

(4n) Gilly, PL 19 (1965) 335 ✘

(3n) Sperinde, PL 32B (1970) 185 ✘

(3n) Sperinde, NP B78 (1974) 345 ✘

(4n) Ungar, PL 144B (1984) 333 :



(3n) Ajdačić, PRL 14 (1965) 444 : $^3\mathrm{H}(n,p)^3\mathrm{n}$ (✔) ✘

(3n) Thornton, PRL 17 (1966) 701 : $^3\mathrm{H}(n,p)^3\mathrm{n}$ ✘

(3n) Ohlsen, PR 176 (1968) 1163 : $^3\mathrm{H}(t,{}^3\mathrm{He})3\mathrm{n}$ (✔) ✘

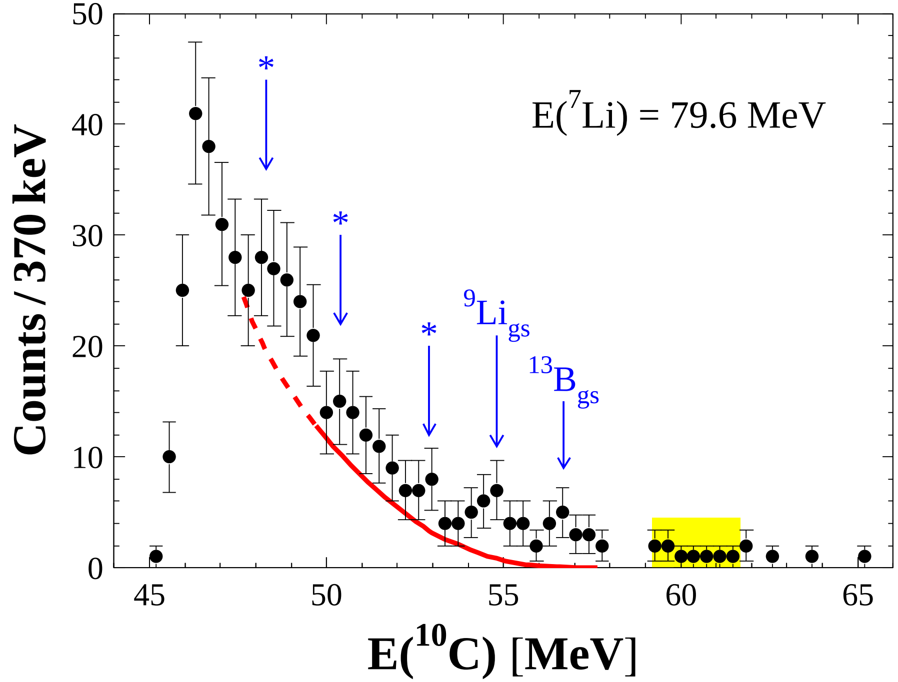
→ very poor data

→ some unclear "enhancements" ...

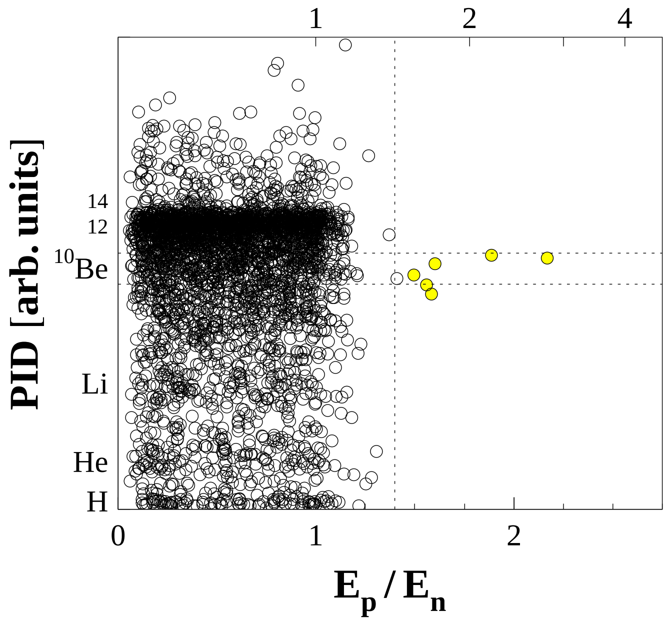
(3,4n) Cerny, PL 53B (1974) 247 :

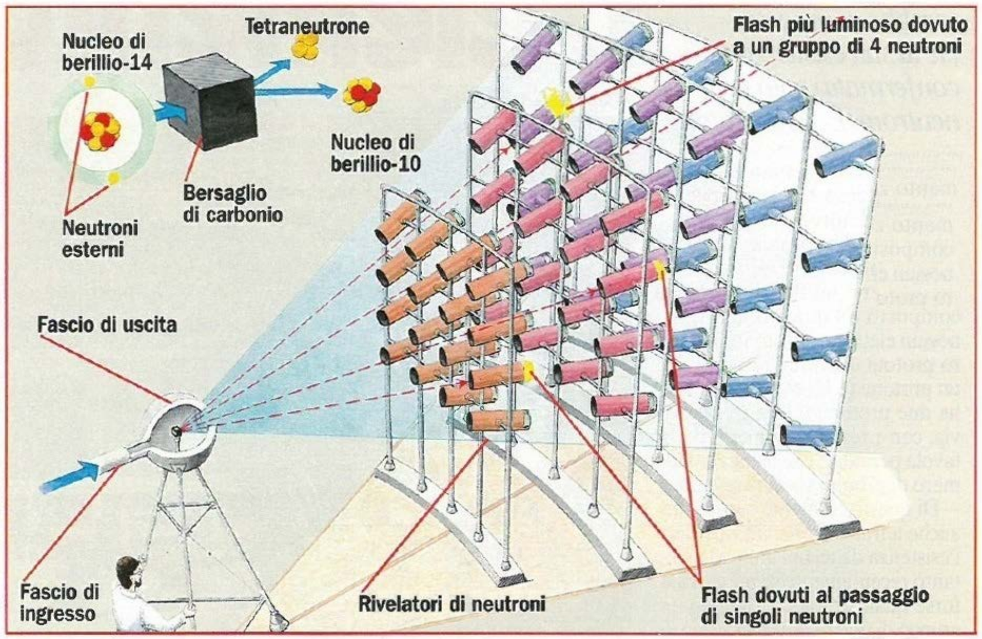
^{7}Li(^{7}Li,^{11}C)^{3}n ✘

^{7}Li(^{7}Li,^{10}C)^{4}n ✘

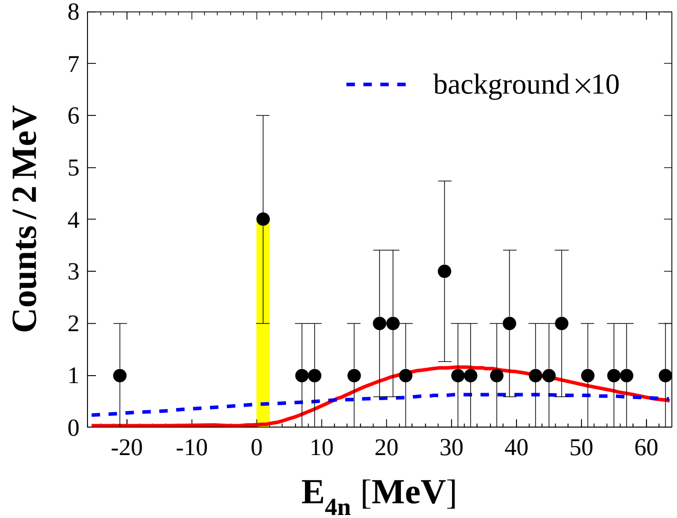


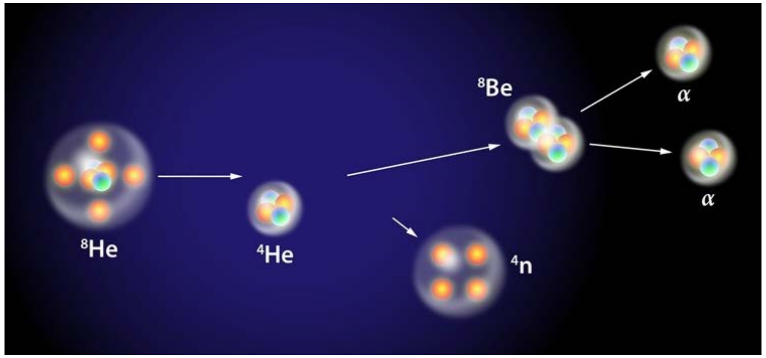
- $^{14}\mathrm{Be} \xrightarrow{(\mathrm{C})} {}^{10}\mathrm{Be} + \boxed{^{4}\mathbf{n}}$:





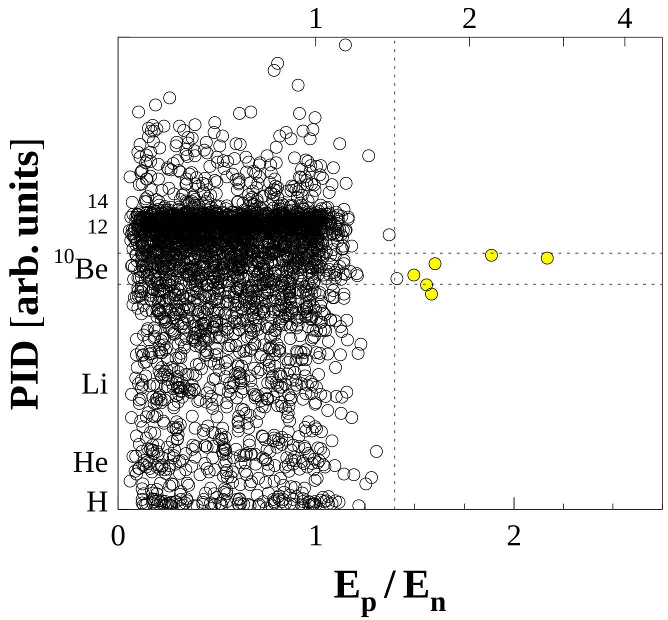
- $^{4}\mathrm{He}\,(^{8}\mathrm{He}, {}^{8}\mathrm{Be})\,\boxed{^{4}\mathbf{n}}$:

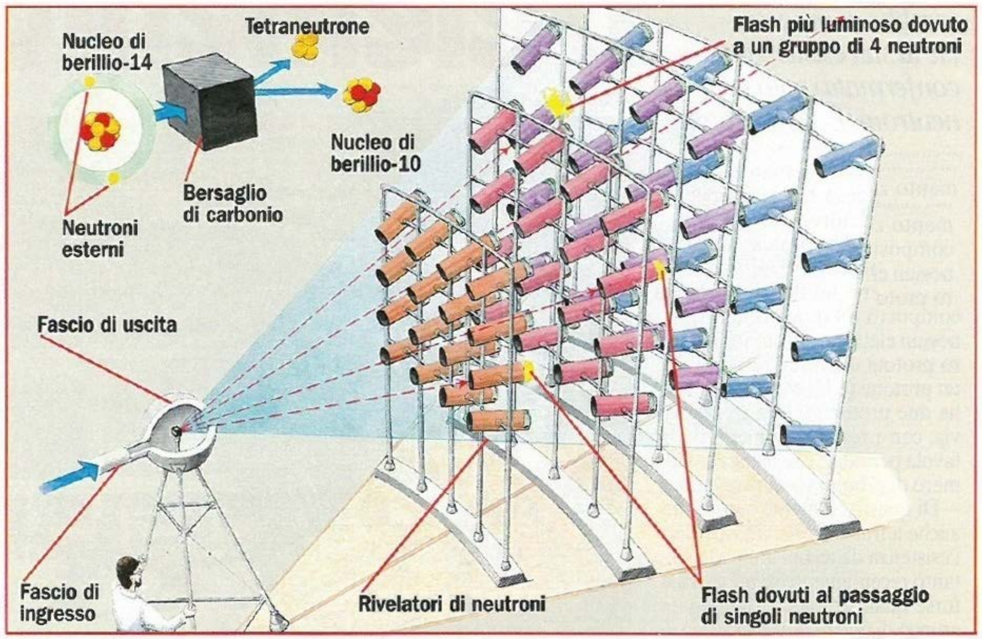




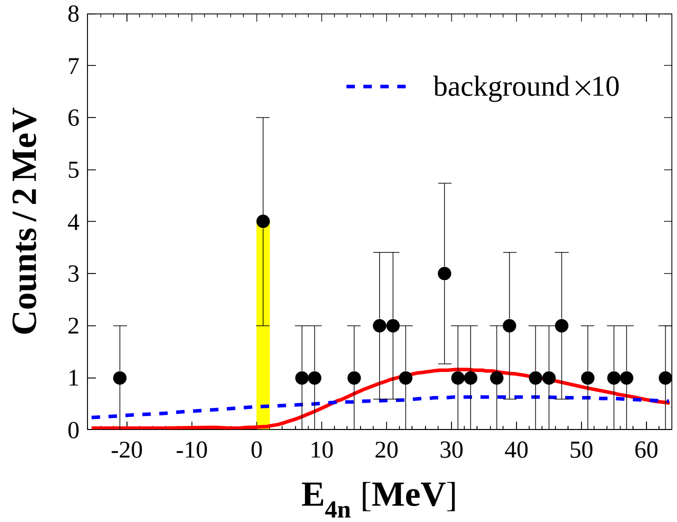
XXI century signals : GANIL & RIKEN

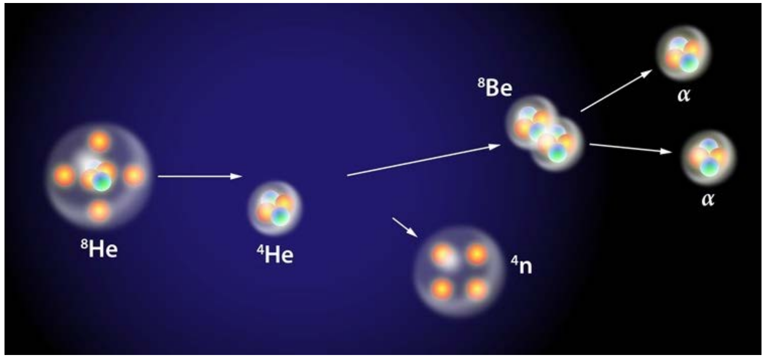
- $^{14}\text{Be} \xrightarrow{(\text{C})} {}^{10}\text{Be} + \boxed{{}^{4}\mathbf{n}}$:





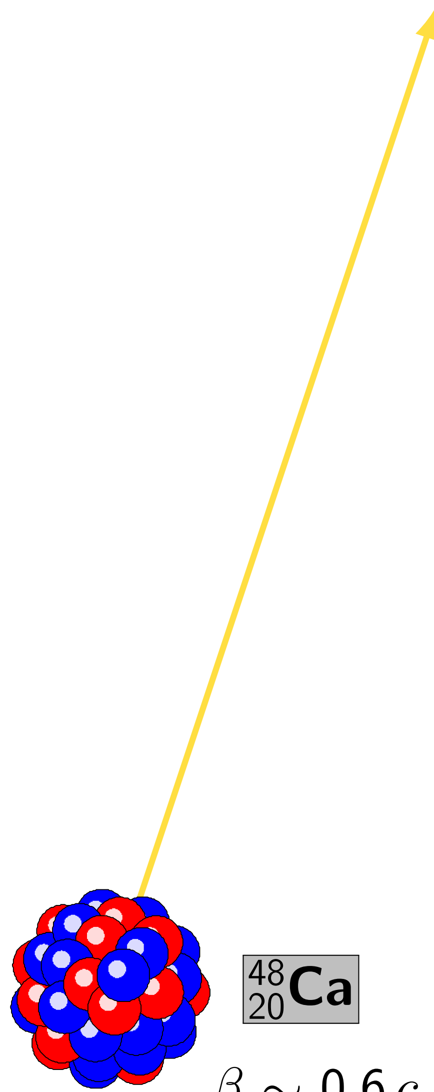
- $^{4}\text{He}\,(^{8}\text{He}, {}^{8}\text{Be})\,\boxed{{}^{4}\mathbf{n}}$:





Kisamori, PRL 116 (2016) 052501 → $E(4n) = 0.8 \pm 1.3$ MeV

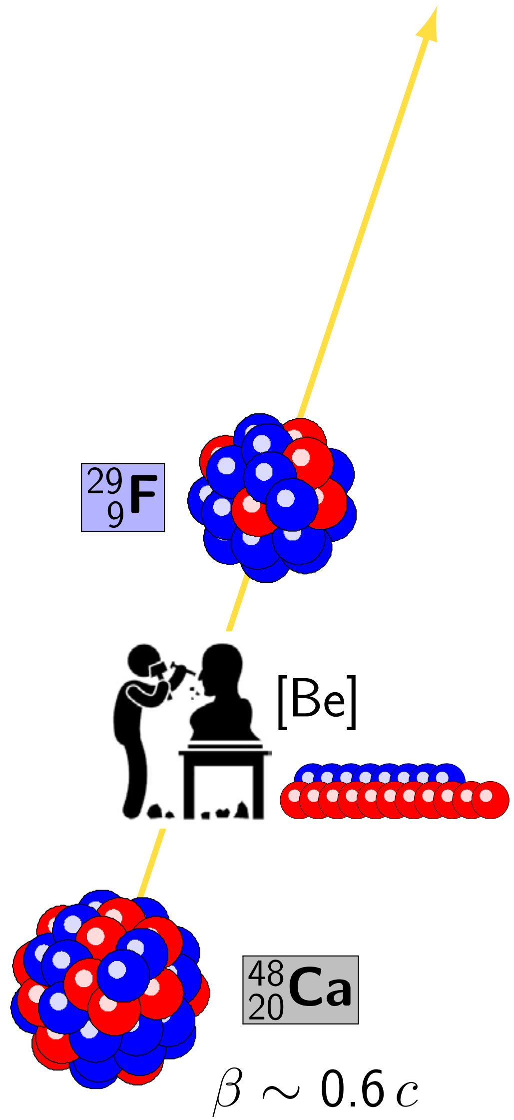
FMM, PRC 65 (2002) 044006
FMM, arXiv nucl-ex/0504009
} $E(4n) \in [-1.5, +2]$ MeV



$^{48}_{20}$Ca

$\beta \sim 0.6\,c$

Sculpting exotic nuclei @ RIKEN : Oxygen 28 [S21, Kondo]



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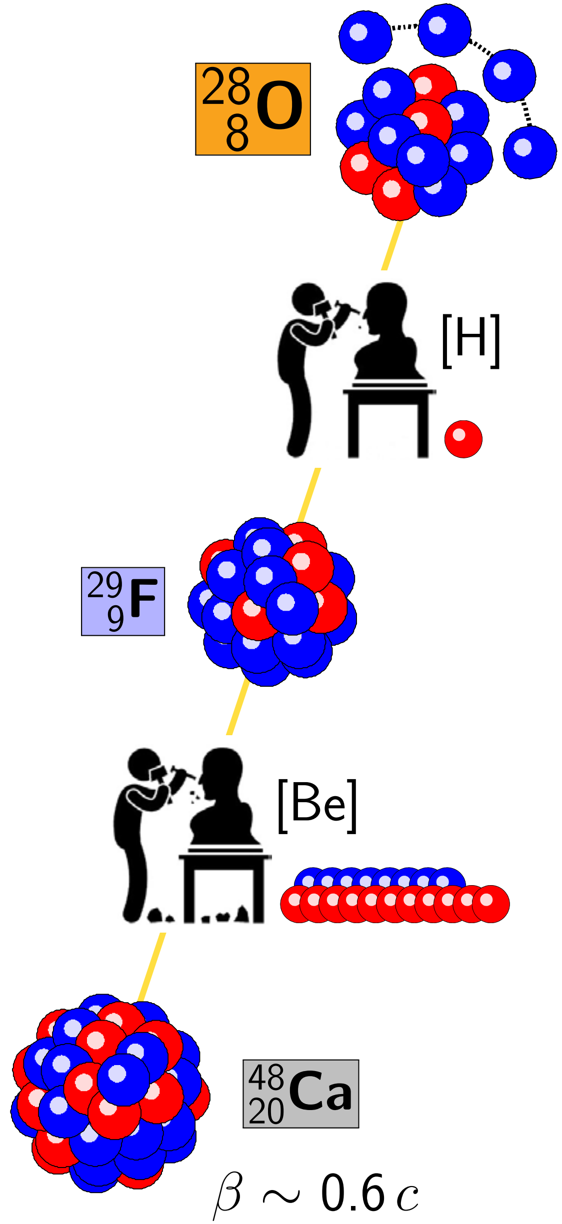
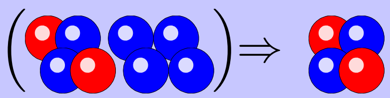
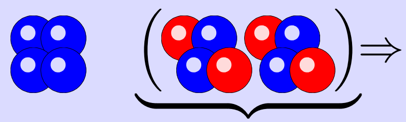
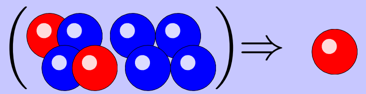
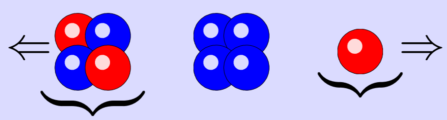
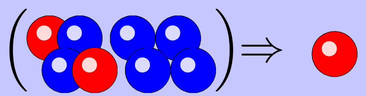
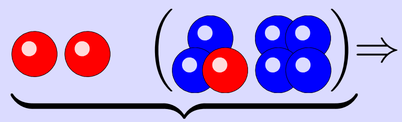
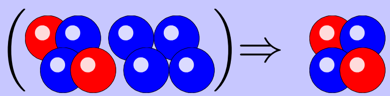
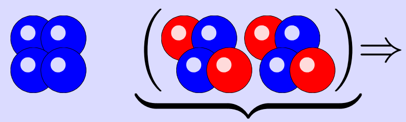
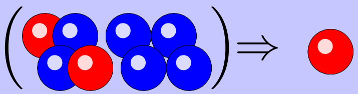
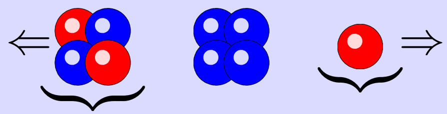
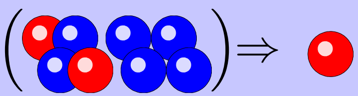
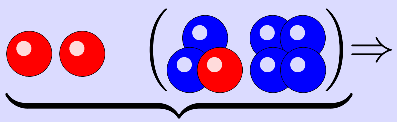


Tetraneutron context @ RIKEN

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

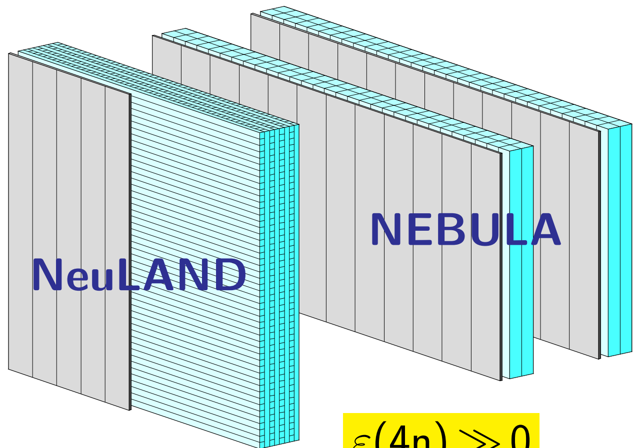
reaction	initial state	final state	σ	results
('16) $^4\mathrm{He}\,(^8\mathrm{He},\alpha\alpha)\,^4\mathbf{n}$ Shimoura, NP1512-SHARAQ10			nb	$\mathrm{N_{evt}} \sim 10\,\mathrm{s}$ $^4\mathrm{n}$: E, Γ
('17) $^8\mathrm{He}\,(\mathrm{p,p}\alpha)\,^4\mathbf{n}$ Paschalis, NP1406-SAMURAI19			μb	$\mathrm{N_{evt}} \sim 1000\,\mathrm{s}$ $^4\mathrm{n}$: E, Γ
('17) $^8\mathrm{He}\,(\mathrm{p,2p})\,\{^3\mathbf{H}+{}^4\mathbf{n}\}$ FMM/Yang, NP1512-SAMURAI34			**mb**	$\mathrm{N_{evt}} \sim \mathbf{10{,}000}\,\mathrm{s}$ $^4\mathrm{n}\,\&\,^7\mathrm{H}$: E, Γ, $\boldsymbol{\Omega}$

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

reaction	initial state	final state	σ	results
('16) ^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	N$_{evt}$ $\sim$ 10 s ^{4}n : E, Γ
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	N$_{evt}$ $\sim$ 1000 s ^{4}n : E, Γ
('17) ^{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

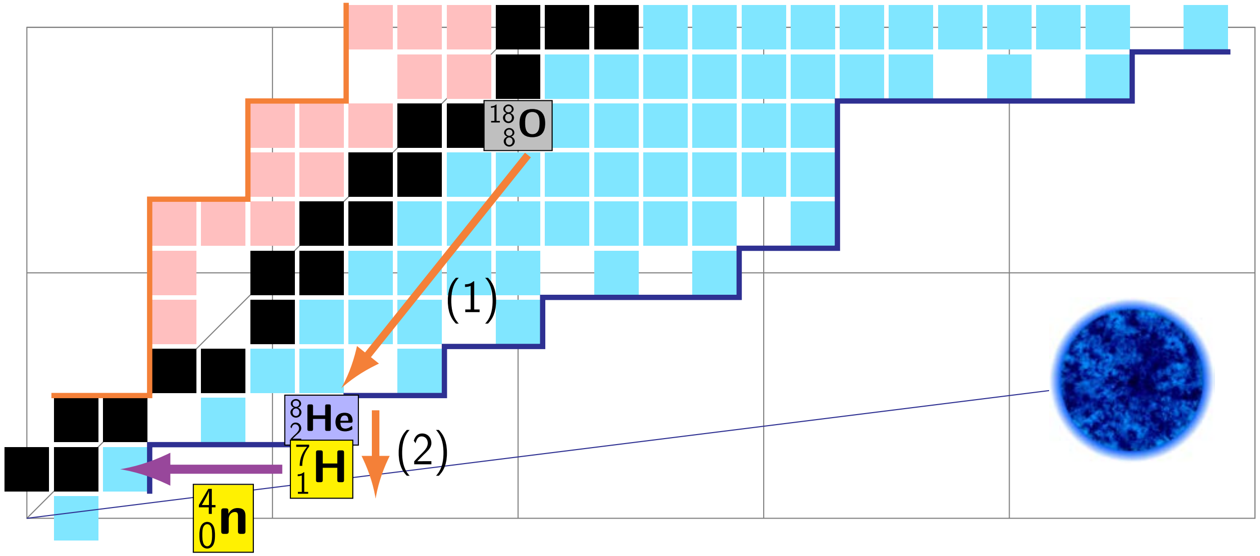
N$_{evt}$ $\propto$ $I \times \sigma \times \rho \times \varepsilon$

- beam **intensity**
- reaction **cross-section**
- number of **target** nuclei
- detection **efficiency**

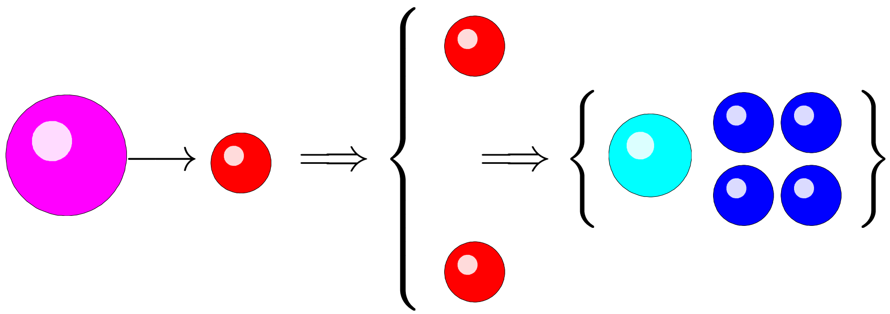


$\varepsilon(4n) \gg 0$

Hydrogen 7 & Tetraneutron 'emission' ? [S34, FMM/Yang]

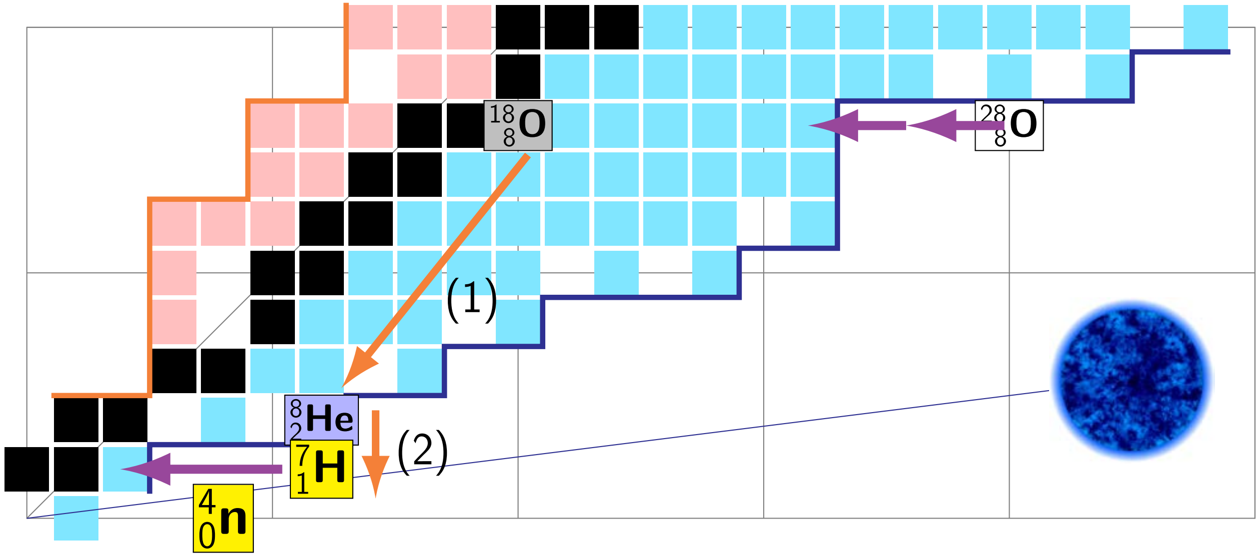


- ^{8}He (p,2p) ^{7}H @ 150 MeV/N :

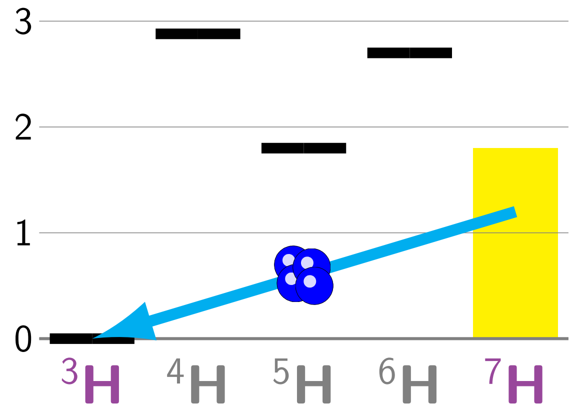


→ 7-body final state !

Hydrogen 7 & Tetraneutron ‘emission’ ? [S34, FMM/Yang]



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



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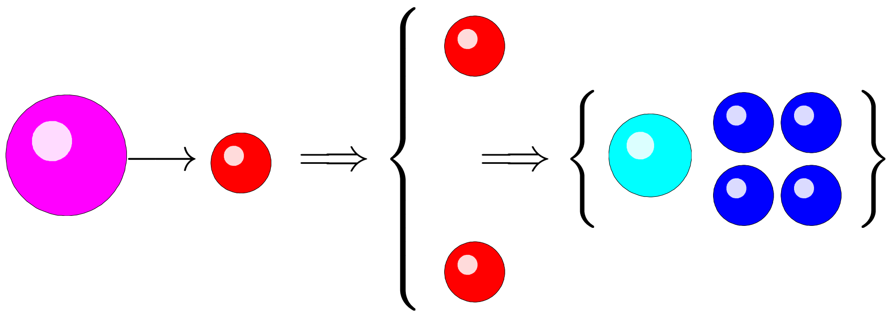

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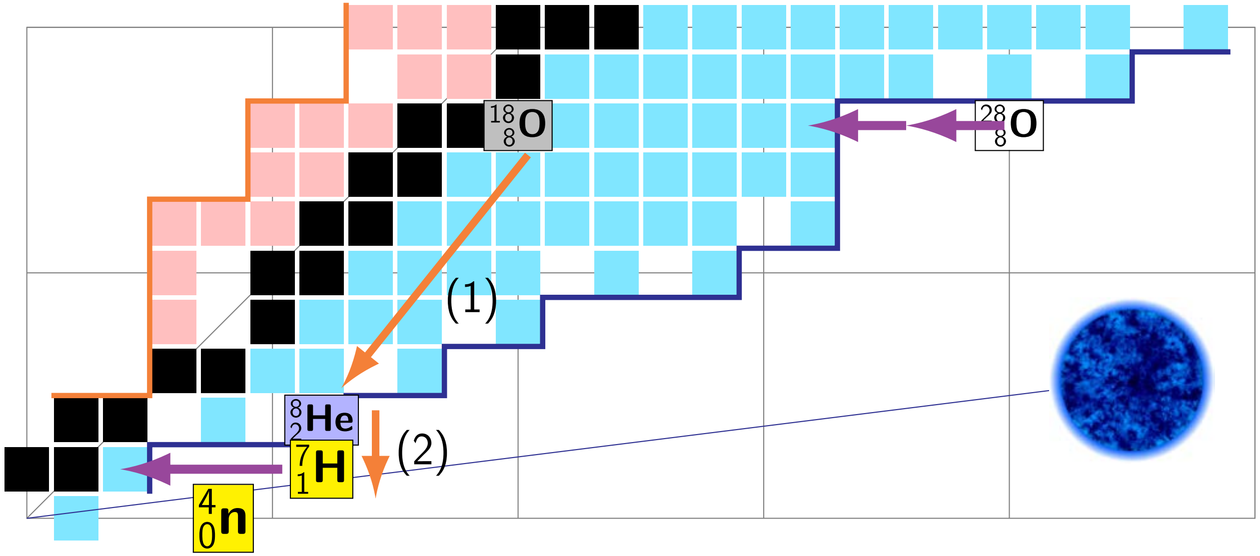

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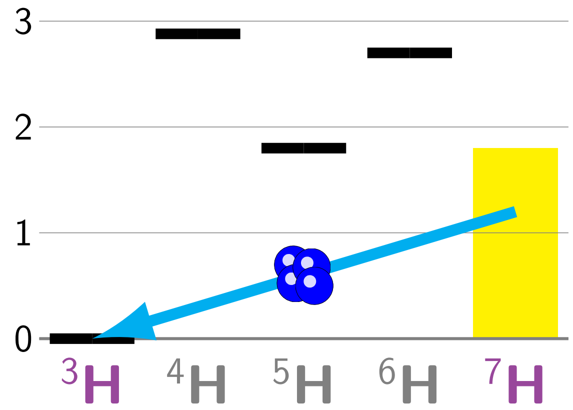

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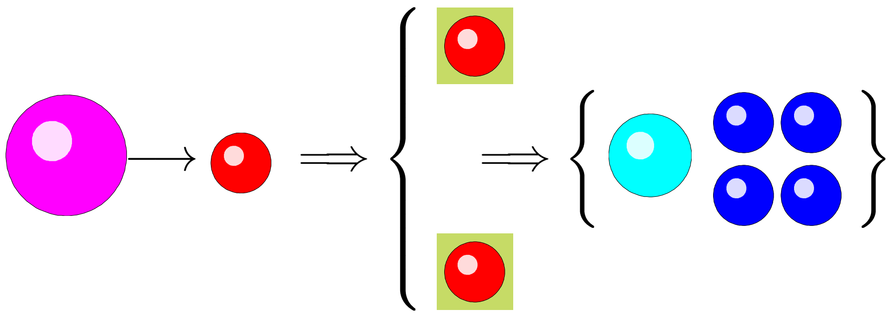
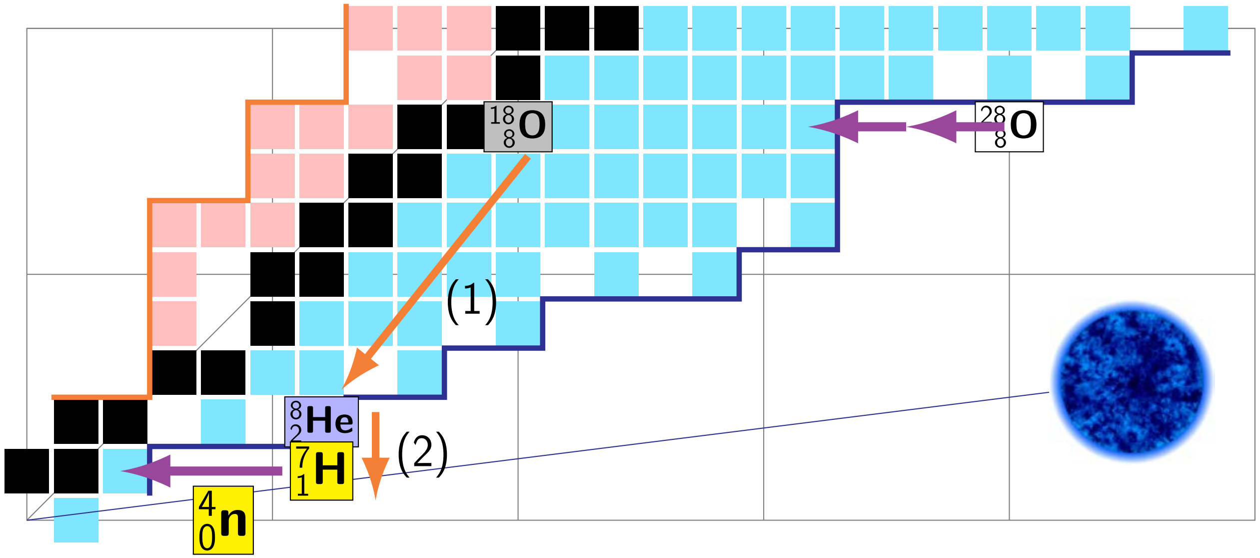


→ 7-body final state !

→ FWHM ∼ few MeV

- an array of arrays :
  - → **MINOS** liquid H target
  - → **DALI** NaI crystals

Hydrogen 7 & Tetraneutron 'emission'? [S34, FMM/Yang]



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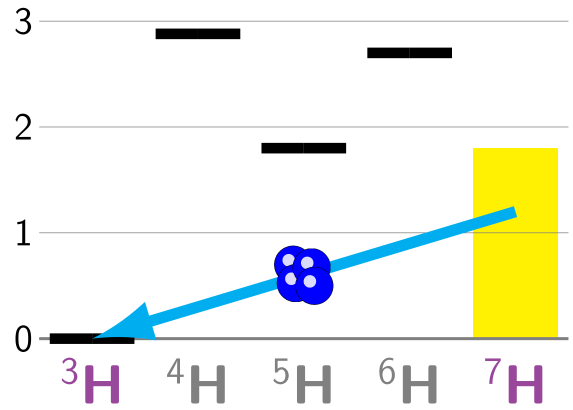

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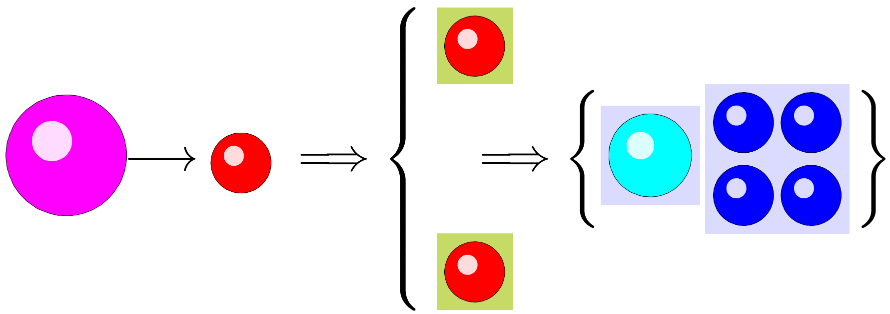
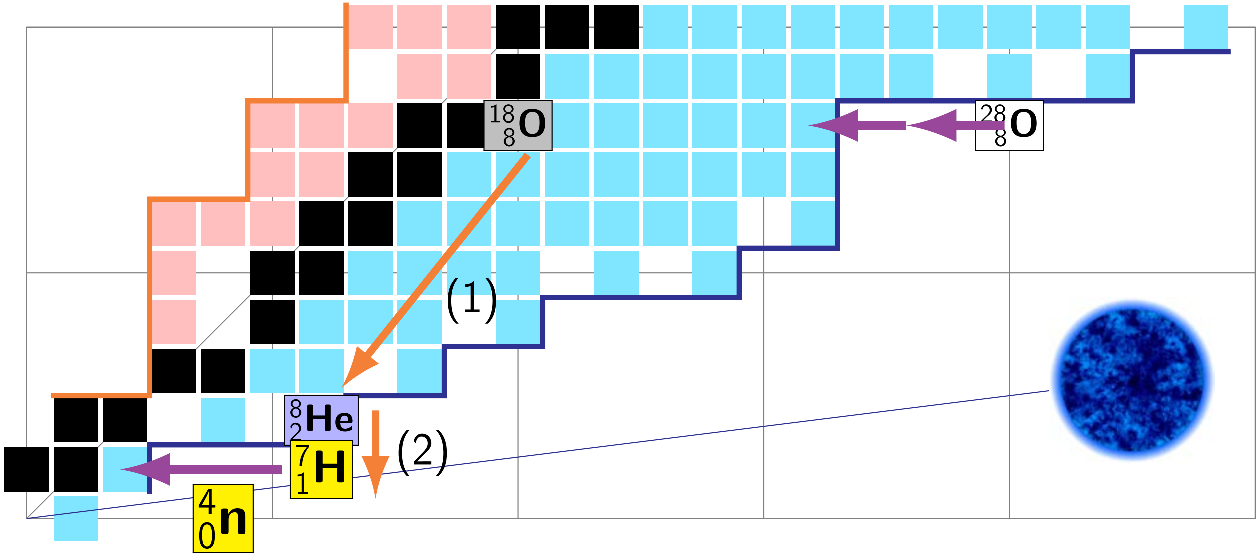


→ 7-body final state !

→ FWHM ~ few MeV → 100 keV !

- an array of arrays :
  - → **MINOS** liquid H target
  - → **DALI** NaI crystals
  - → **SAMURAI** spectrometer
  - → **NEBULA** + **NeuLAND**

Hydrogen 7 & Tetraneutron ‘emission’ ? [S34, FMM/Yang]



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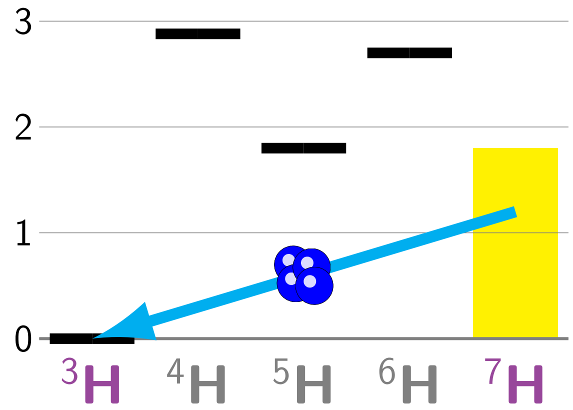

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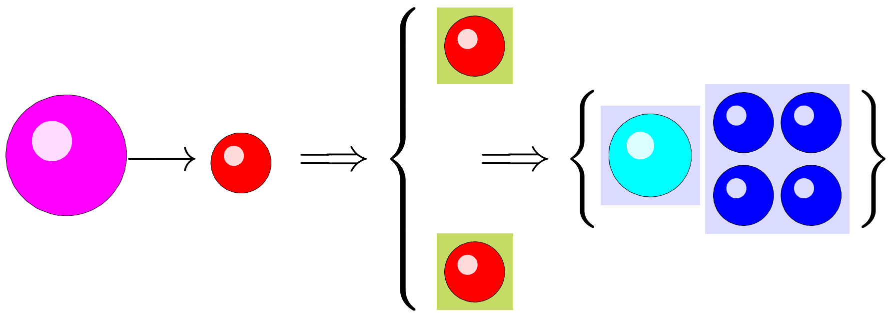

→ 7-body final state !

→ FWHM ∼ few MeV → 100 keV !

→ (2p+t+3n) ∼ 150 keV

- an array of arrays :
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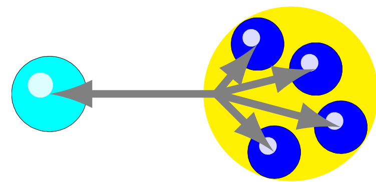
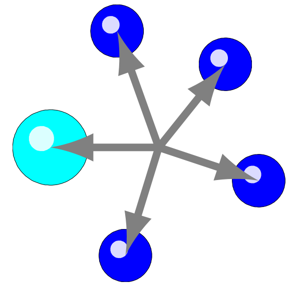
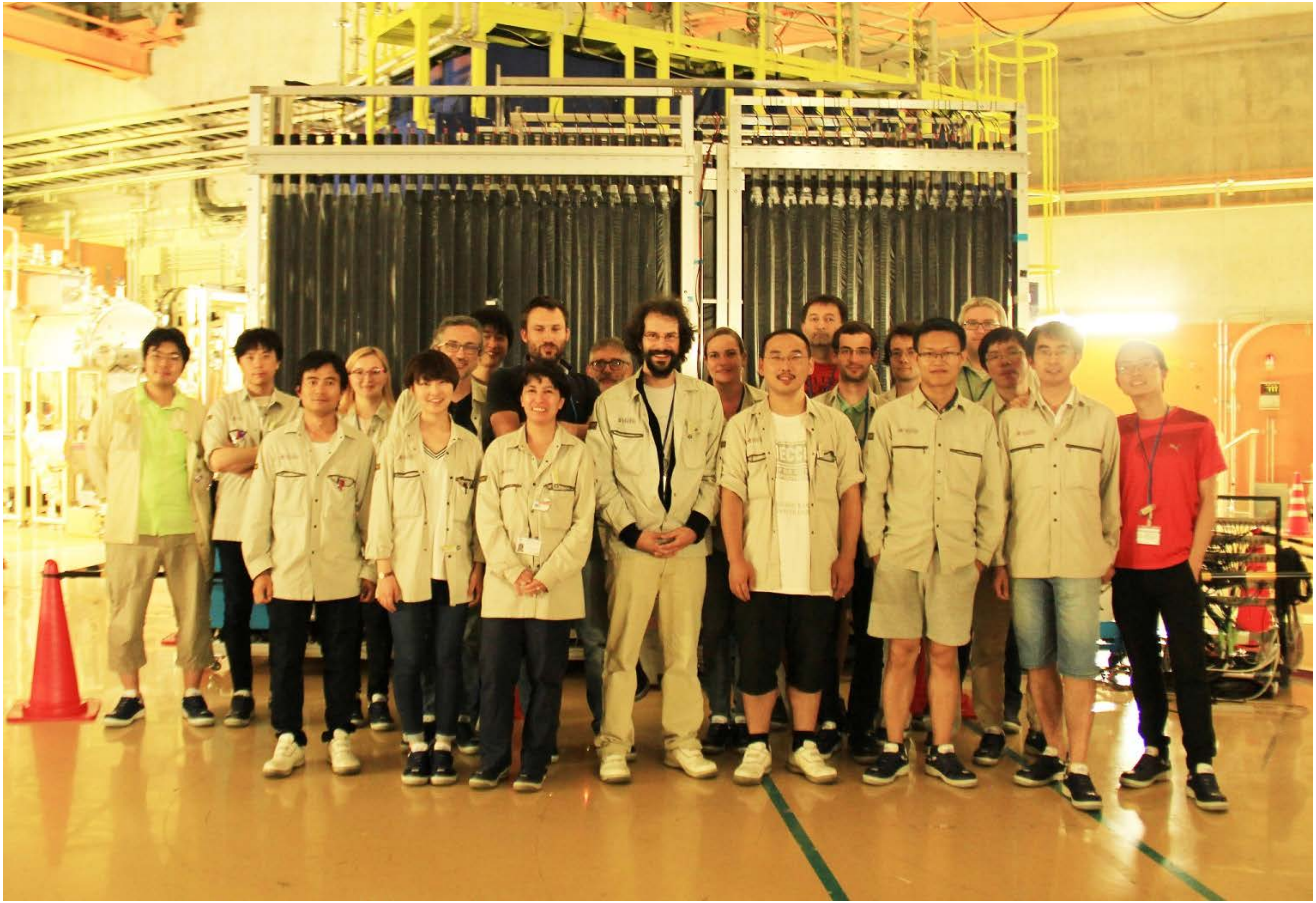
- angular correlations → E(4n) !



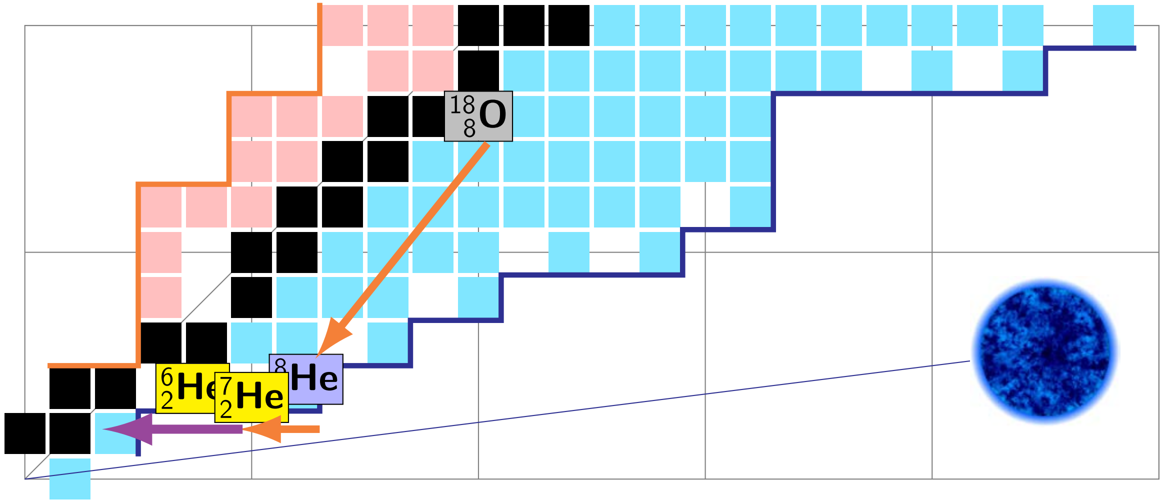


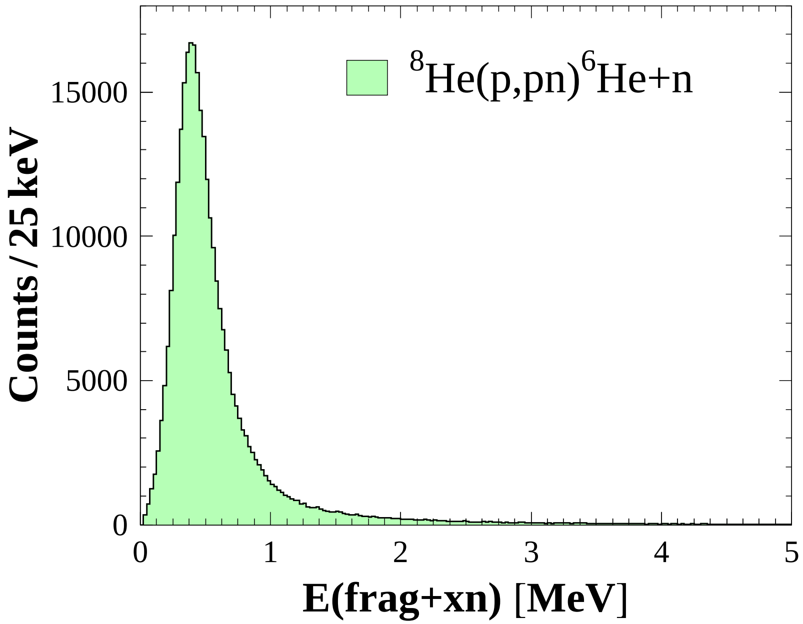
SAMURAI S34 collaboration (part)

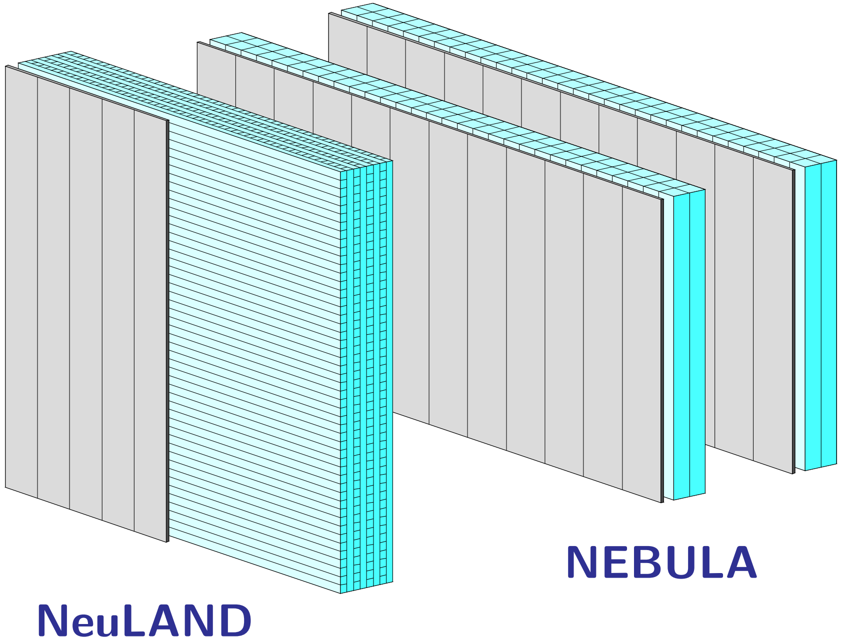


RIKEN : SAMURAI (& MINOS-DALI-NeuLAND/NEBULA)

VERY PRELIMINARY results [Lenain]







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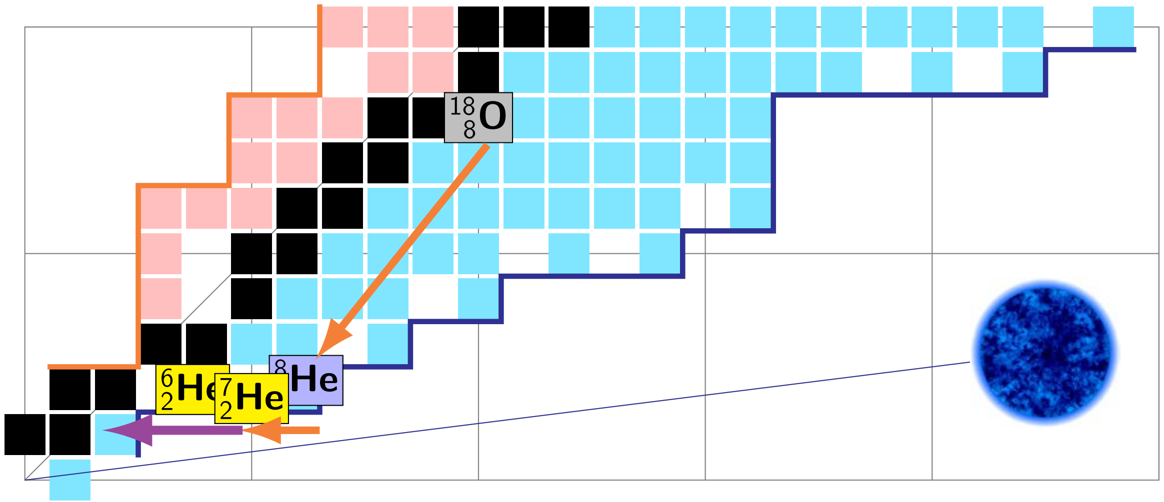
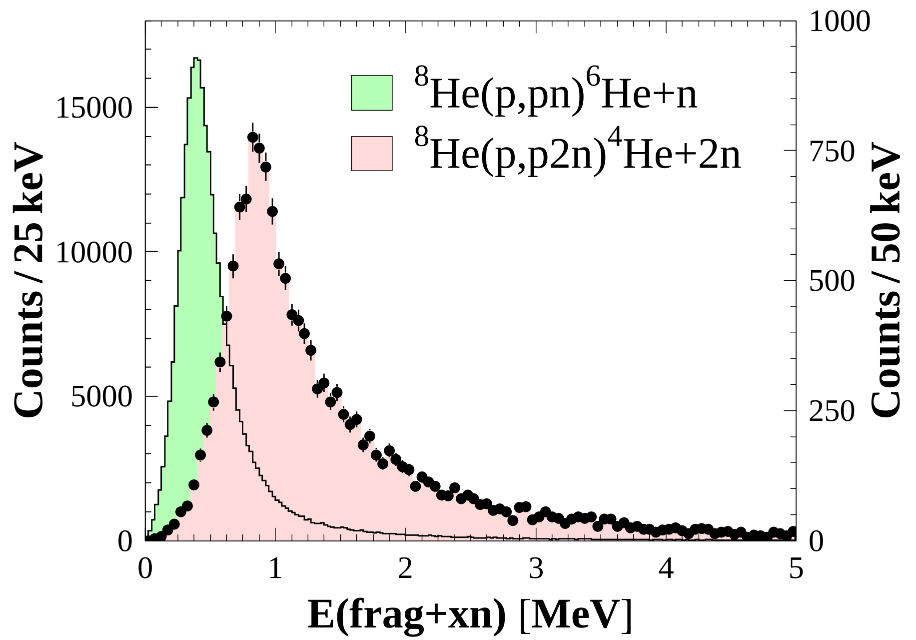
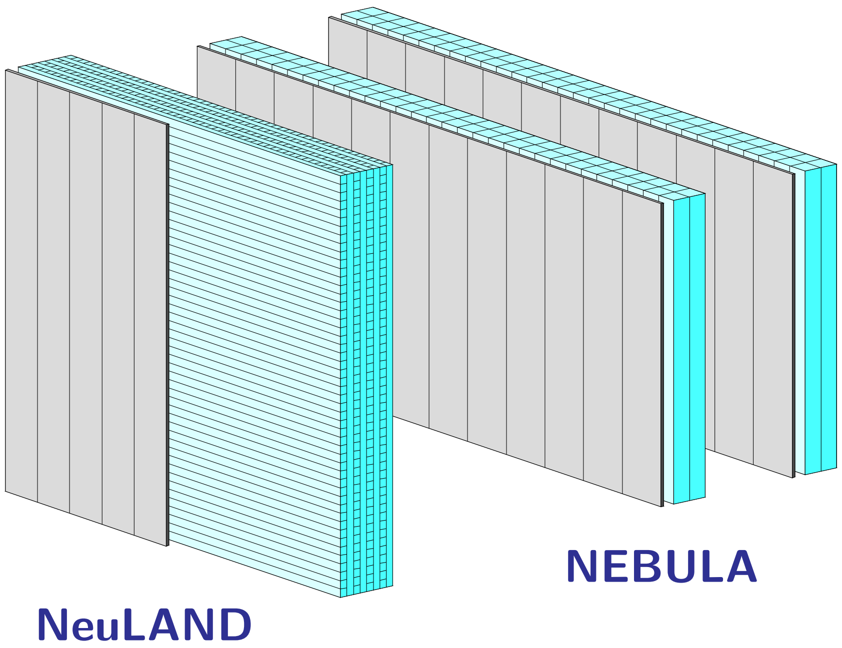
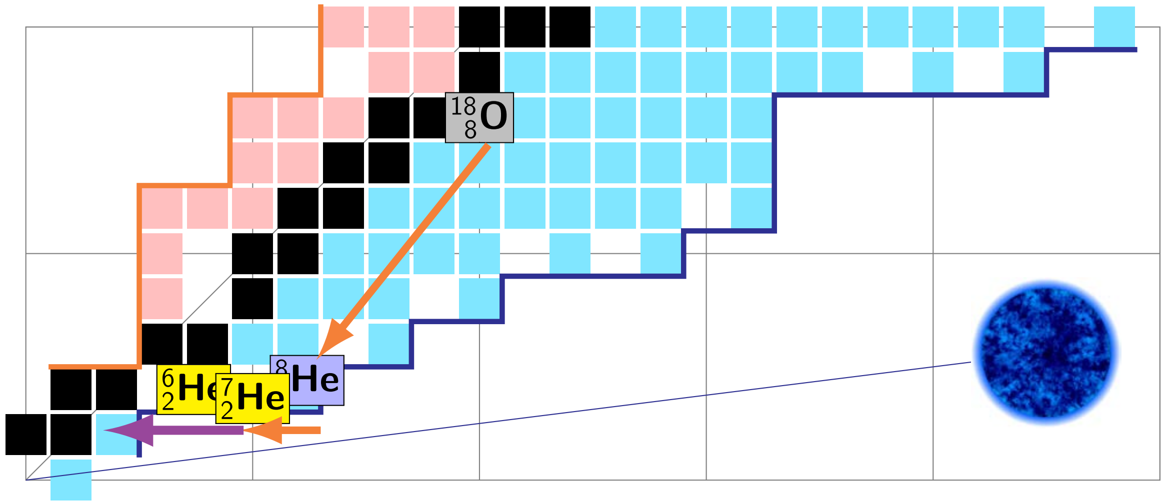
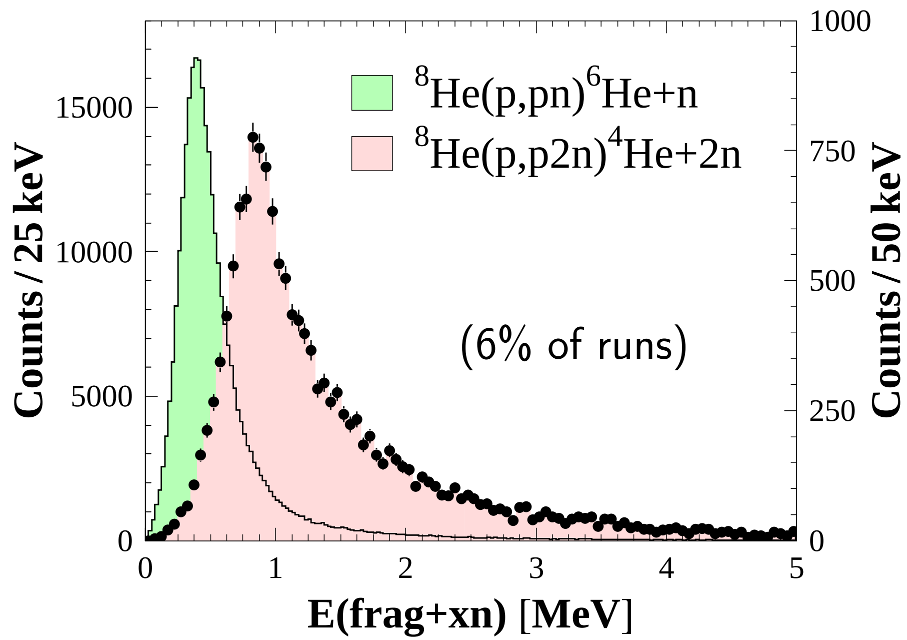




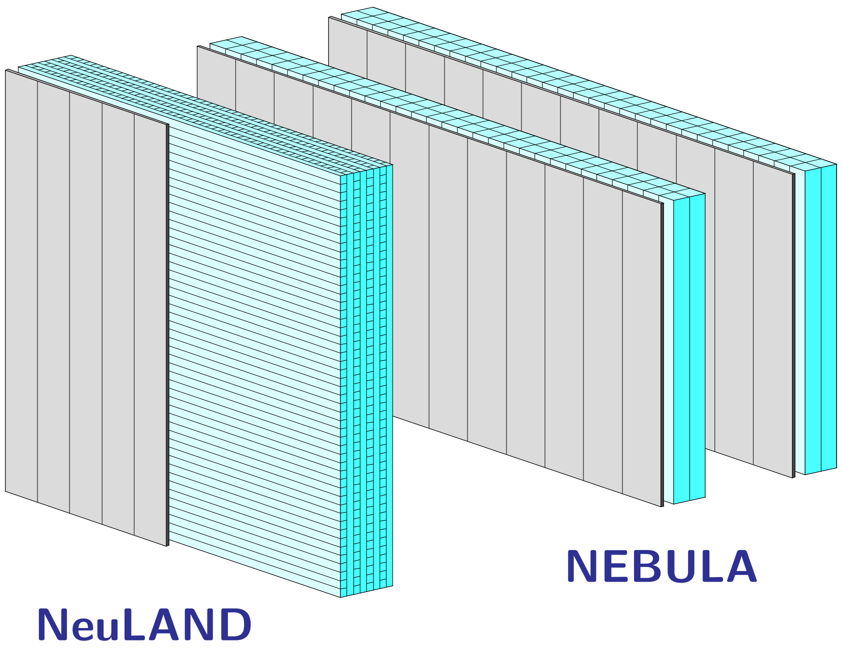




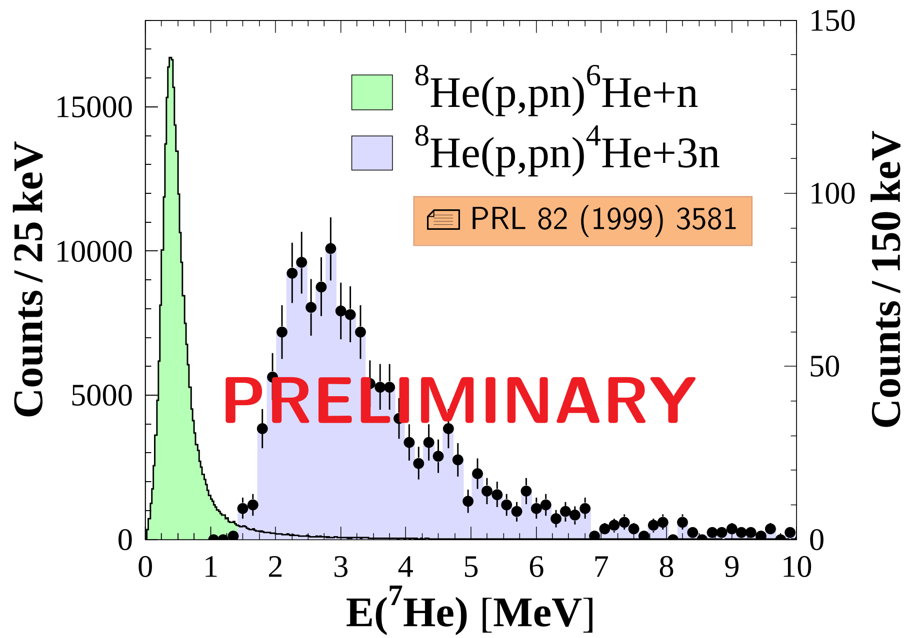
$^{18}_{8}$O
$^{6}_{2}$He
$^{7}_{2}$He
^{8}He



Counts / 25 keV
Counts / 50 keV
^{8}He(p,pn)^{6}He+n
^{8}He(p,p2n)^{4}He+2n
(6% of runs)
E(frag+xn) [MeV]



NEBULA
NeuLAND



Counts / 25 keV
Counts / 150 keV
^{8}He(p,pn)^{6}He+n
^{8}He(p,pn)^{4}He+3n
PRL 82 (1999) 3581
PRELIMINARY
E(^{7}He) [MeV]

Summary & Perspectives

"As in most experiments of this sort, however,
a negative result cannot be regarded as conclusive"

Schiffer, PL 5 (1963) 292

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"As in most experiments of this sort, however,
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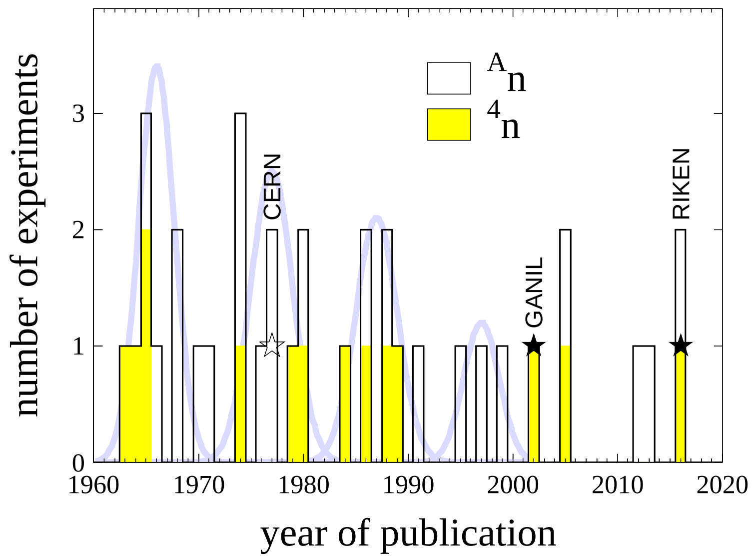
Schiffer, PL 5 (1963) 292

- A very long quest !
  - fascinating experiments
  - some precise 3n results
  - few weak 4n signals :

    $\rightarrow$ refute / states / "enhancements" ?



FMM & Carbonell, EPJA 57 (2021) 105

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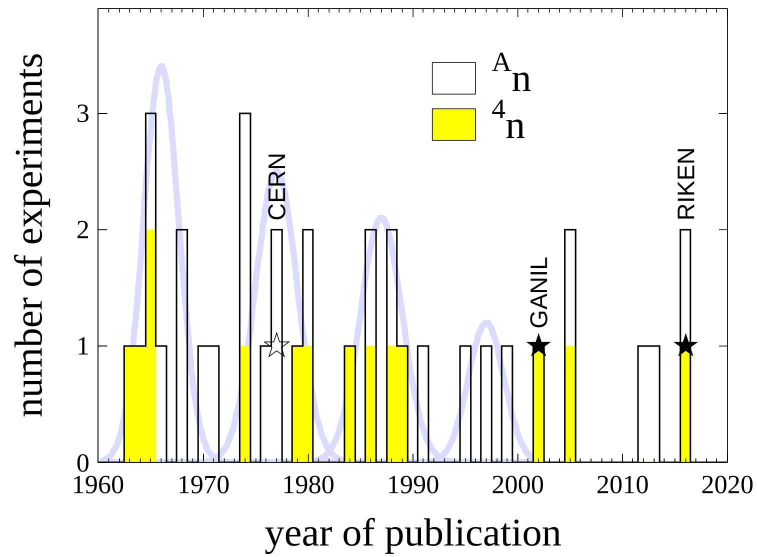

FMM & Carbonell, EPJA 57 (2021) 105

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- Promising 2020s perspectives !

reaction	initial state	final state	σ	results
('16) ^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
('17) ^{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

→ high statistics & resolution

→ 6n experiments (^{10}He decay) ...

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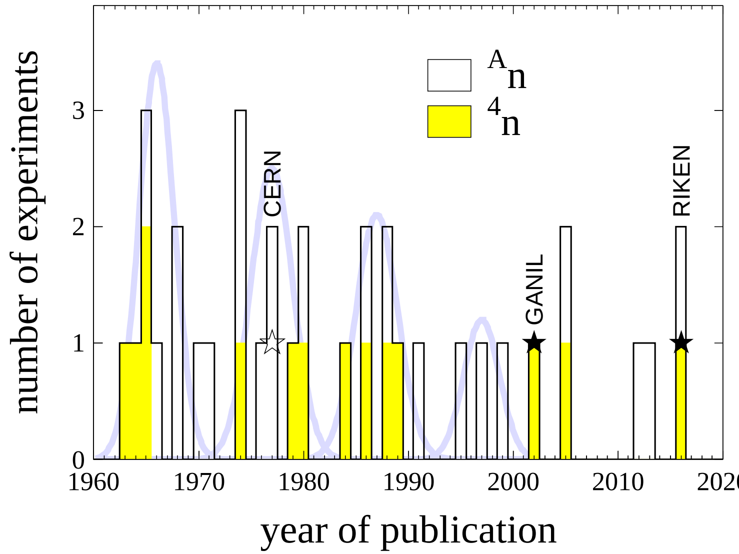

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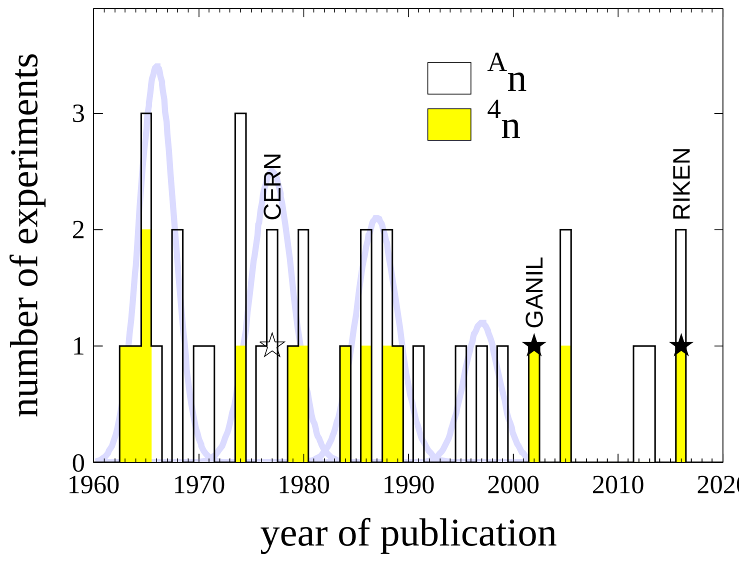

FMM & Carbonell, EPJA 57 (2021) 105

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  - robust 4n results : new physics ?
  - heavier masses trend : 6,8,10n ?

International Conference on Exotic Atoms and Related Topics

Stefan-Meyer-Institute for Subatomic Physics (Vienna, September 13–17, 2021)

The neutron as a building block

F. Miguel Marqués

laboratoire de physique corpusculaire caen

FMM & Carbonell, European Physical Journal A 57 (2021) 105

Theory : another hard & interesting quest

- 'Exact' calculations are categorical !

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Offermann, NPA 318 (1979) 138 : $V_{nn}\times 3.7$ (+P-waves)

Witała, PRC 60 (1999) 024002 : avoid ^{2}n with $V_{nn}(^1\mathrm{S}_0)\times 1$

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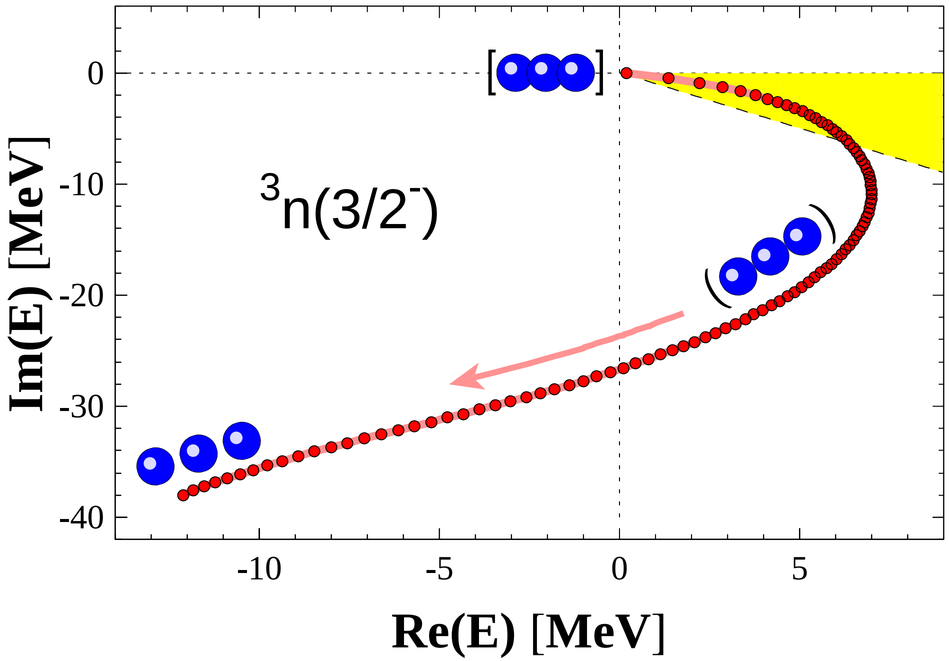

"3n resonances close to the physical region will not exist"

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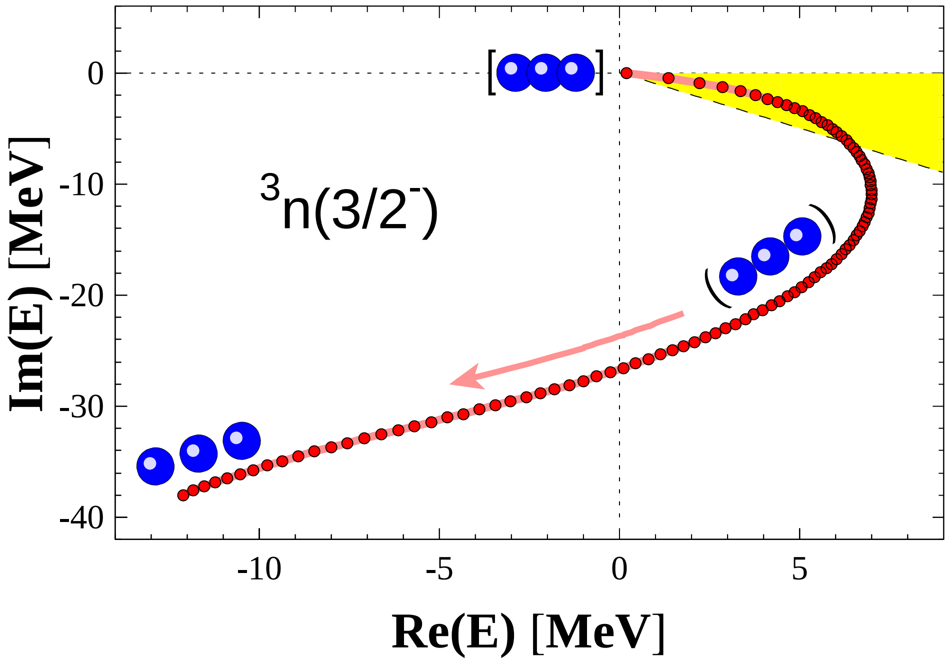

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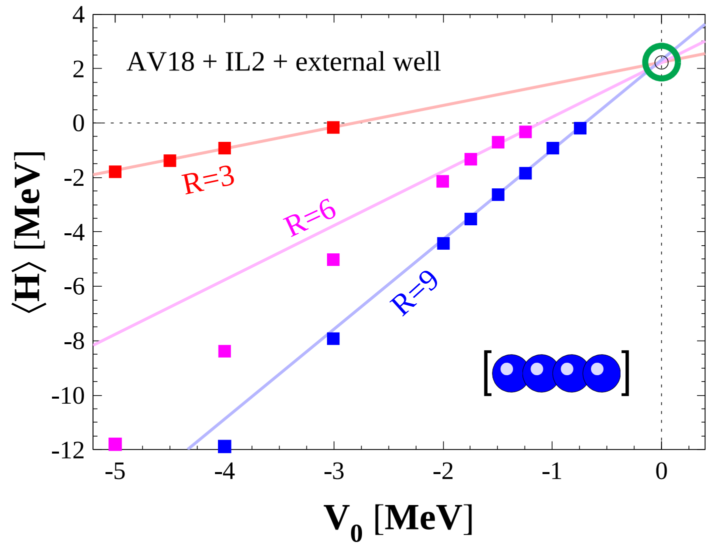

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Gandolfi, PRL 118 (2017) 232501
Fossez, PRL 119 (2017) 032501
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} 3n/4n ✔ ?

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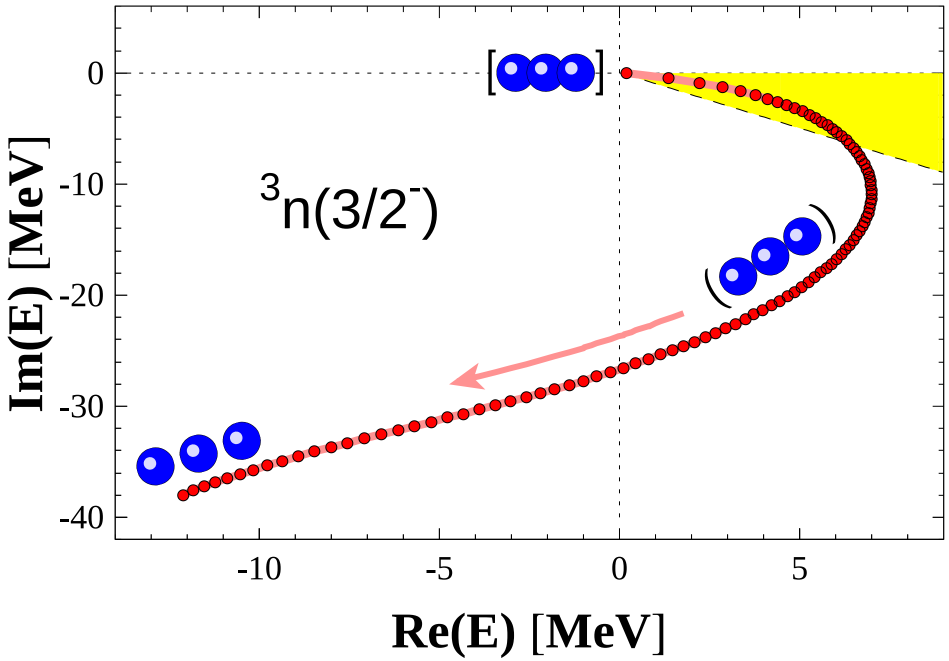

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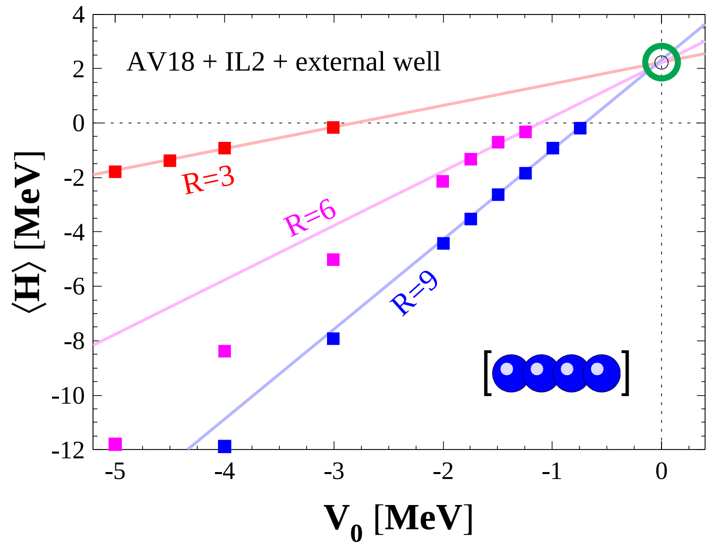

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Deltuva, PRL 123 (2019) 069201
Deltuva, PRC 100 (2019) 044002
Ishikawa, PRC 102 (2020) 034002
} 3n/4n ✘ !!! (trap/evolution/scaling)

Deltuva, PLB 782 (2018) 238
Higgins, PRL 125 (2020) 052501
} QM enhancements …

- Expand NEBULA multineutron capabilities :
  - France : LPC, IRFU, IPNO
  - Japan : TITech, RIKEN
  - +90 bars : Commissioning & Day-1 in 2022 (?)