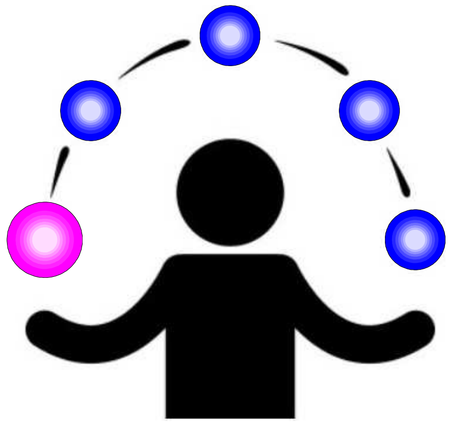
17th International Workshop on

Particle Correlations and Femtoscopy

November 4–8, 2024, Toulouse (France)

Inside the tetraneutron : correlations within the 4n system



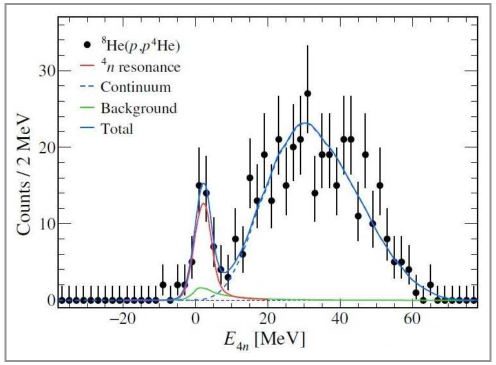
F. Miguel Marqués

SAMURAI

LPC CAEN

Outline

- **Fundamental** question :
  - few-neutron systems ?
  - tetraneutron "signal" !
  - resonance / initial correlations ?



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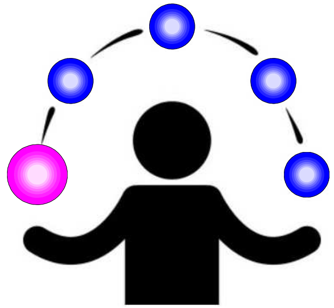
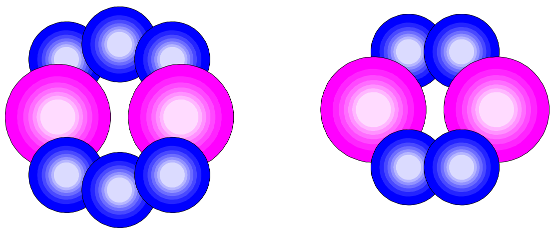
  - explore full kinematics …



- Back to the **future** ?
  - Beryllium 14 & 12
  - NP2412-SAMURAI81 …



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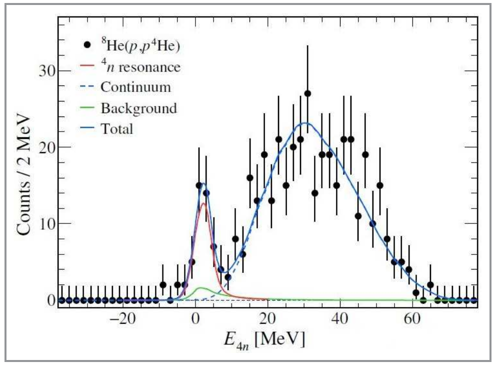

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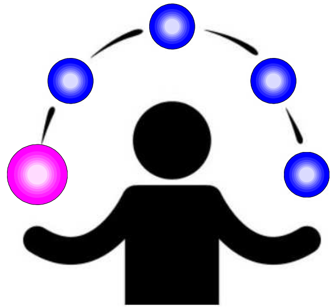

Audrey Anne, PhD

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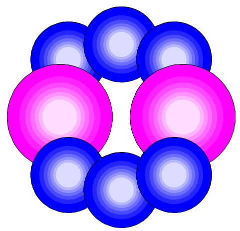
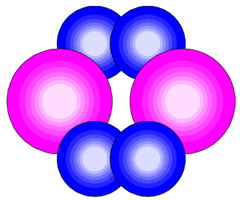
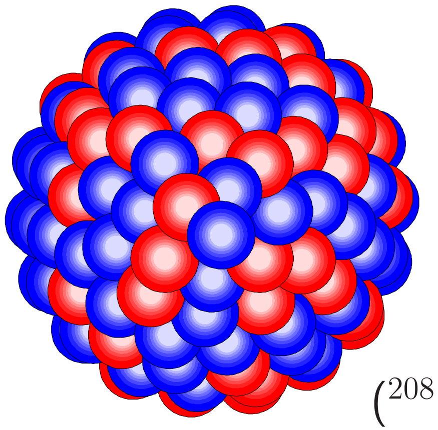




Fundamental question

- How do nucleons form nuclei ?



(^{208}Pb)

✘ collectivity, shells, model spaces ...

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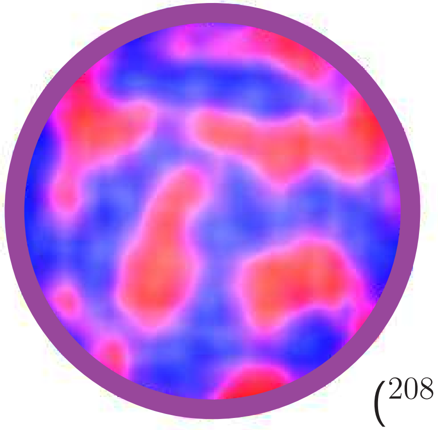

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- ✘ many $\neq$ models & approximations ...

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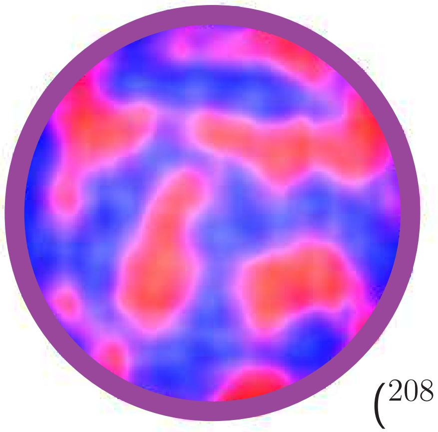

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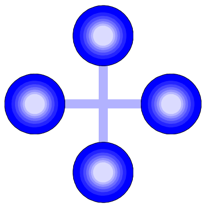

✔ only one constituent

✔ no Coulomb (only V_{nn})

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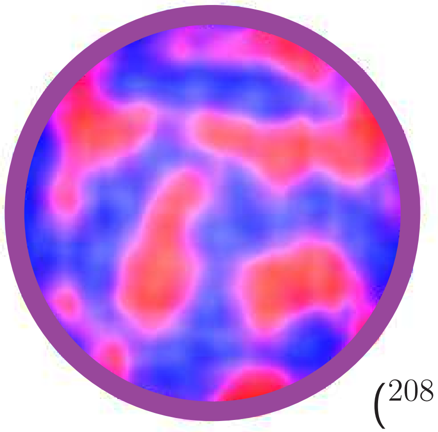

(^{208}Pb)

1960s :  ?

FMM & Carbonell, EPJA 57 (2021) 105

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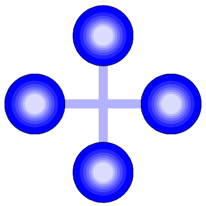

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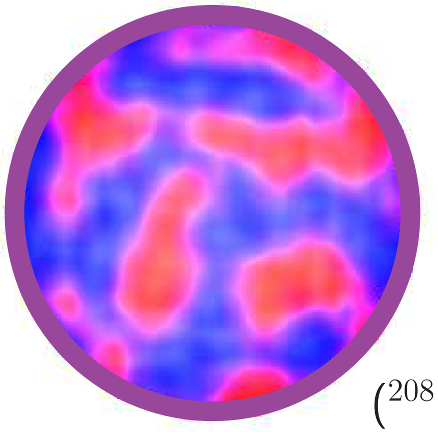

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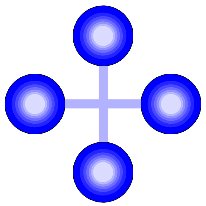

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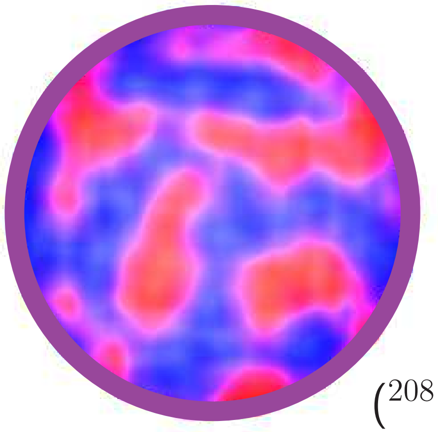

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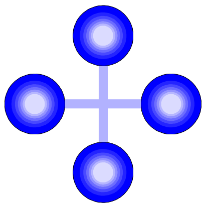

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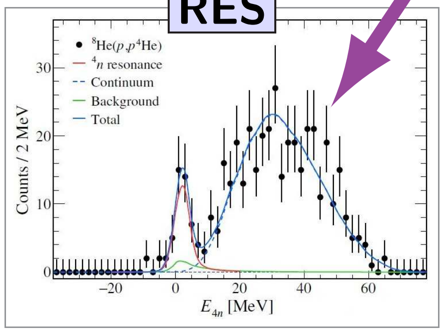
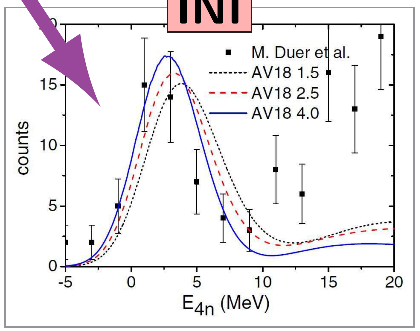
RES



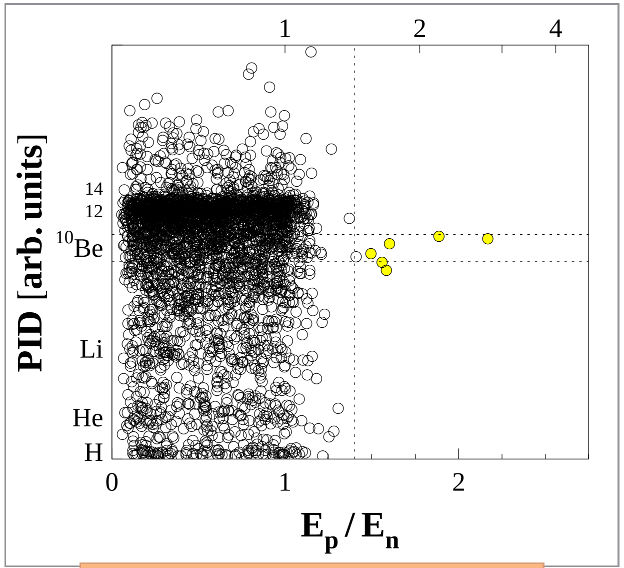
✘ / ✔ ???

INI



✔ ?

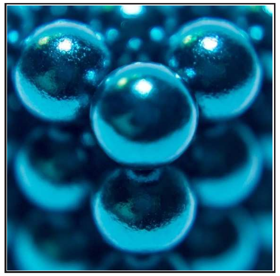
Confirmation of a 4n "signal"



FMM, PRC 65 (2002) 044006

FMM, arXiv:nucl-ex/0504009

$E(^4n) \sim [-1,+2]$ MeV (2.5σ)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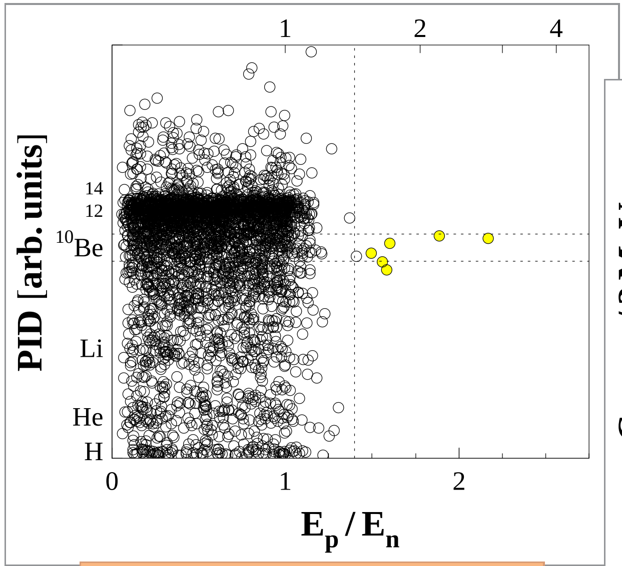

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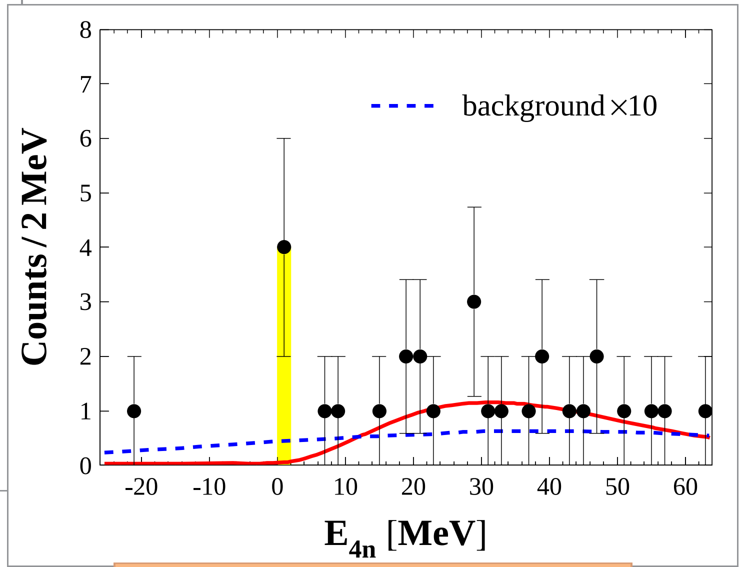

Kisamori, PRL 116 (2016) 052501

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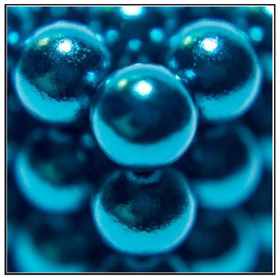

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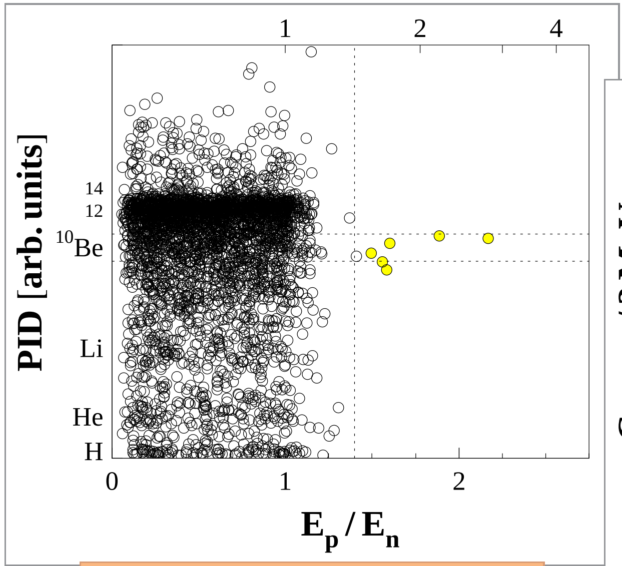

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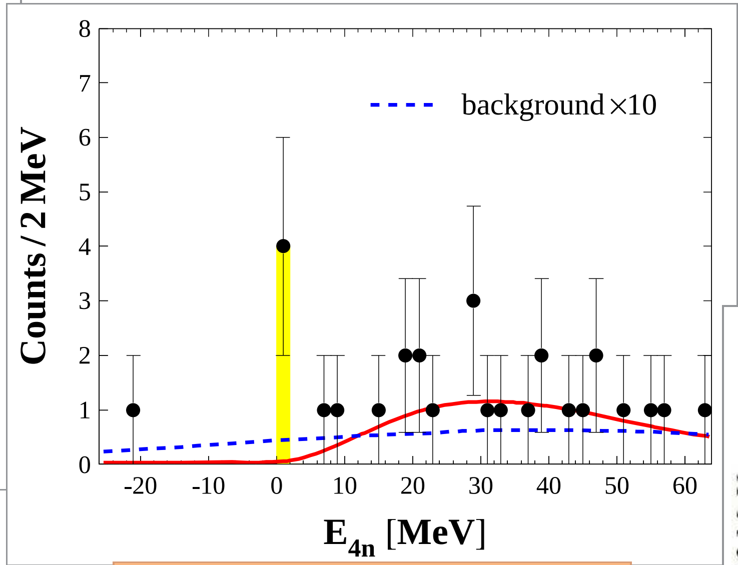

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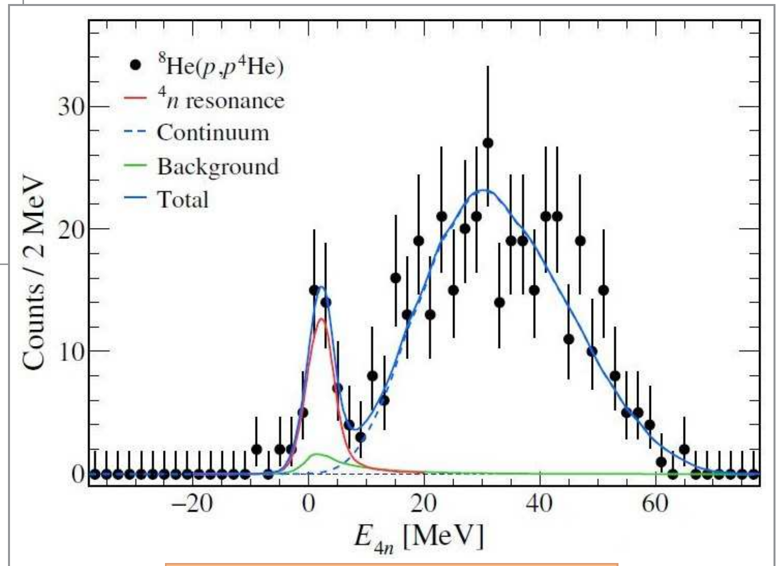

Duer, Nature 606 (2022) 678

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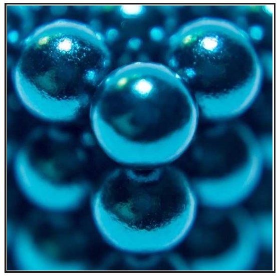

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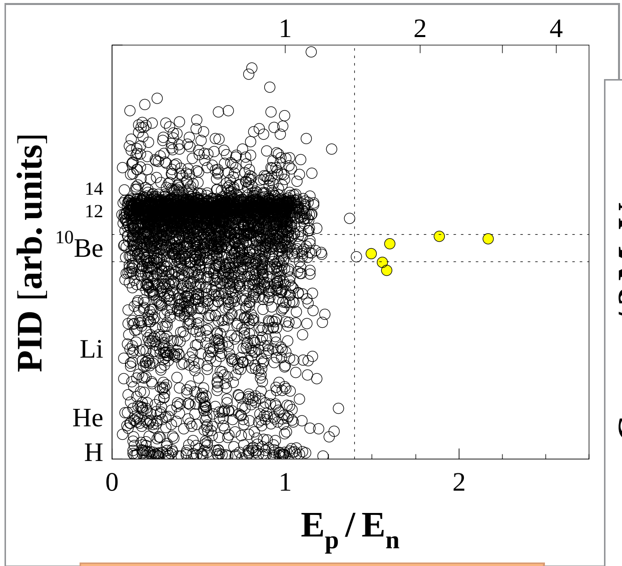

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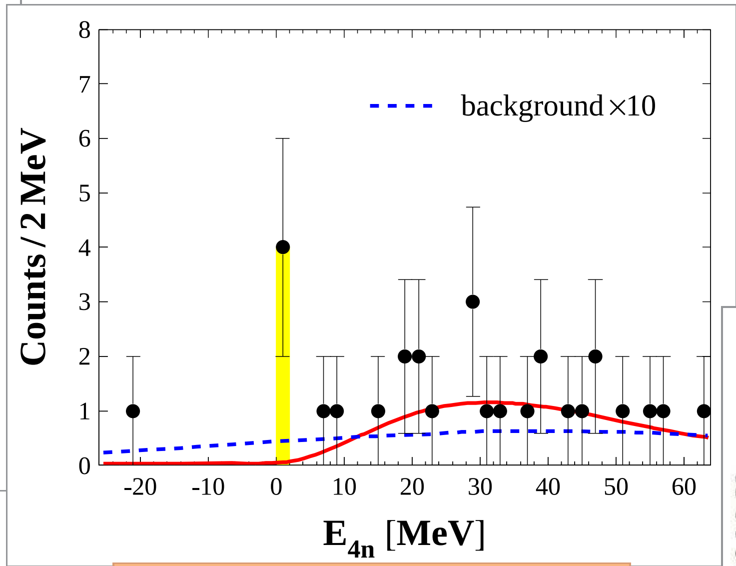

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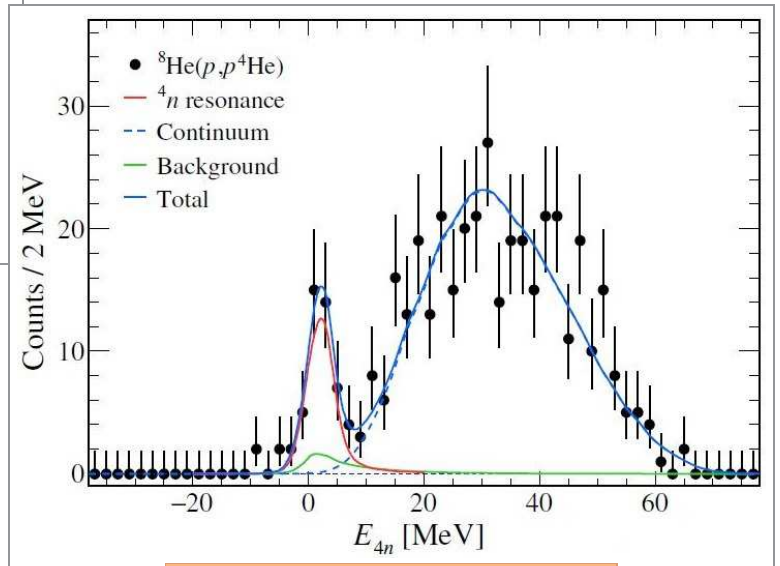

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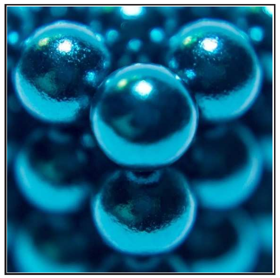

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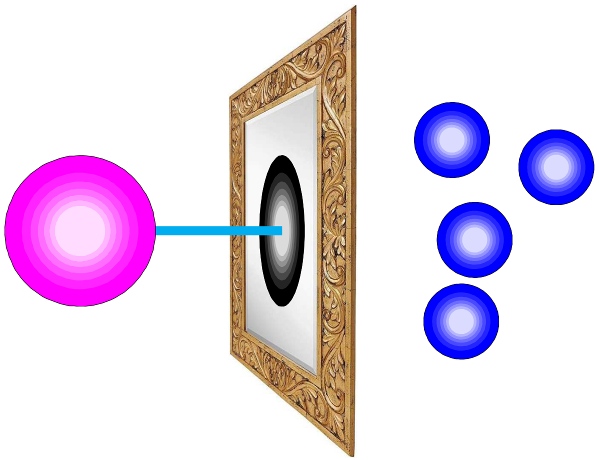

Lazauskas, PRL 130 (2023) 102501

(nn)-(nn) correlations in ^{8}He ?

(FMM, FBS 65 (2024) 37)

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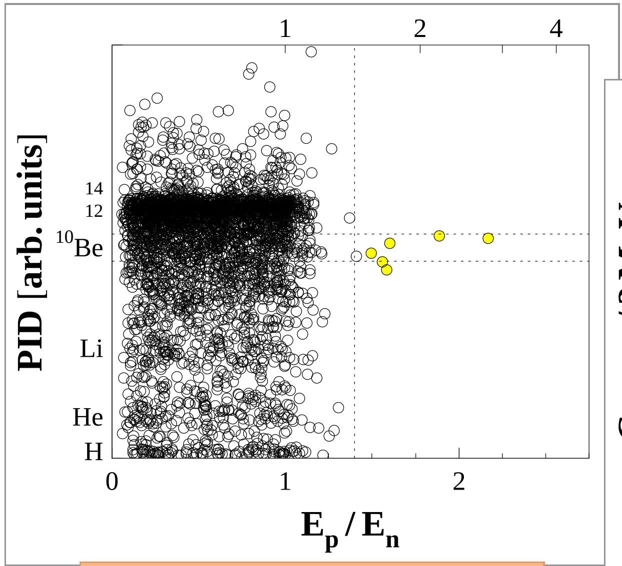

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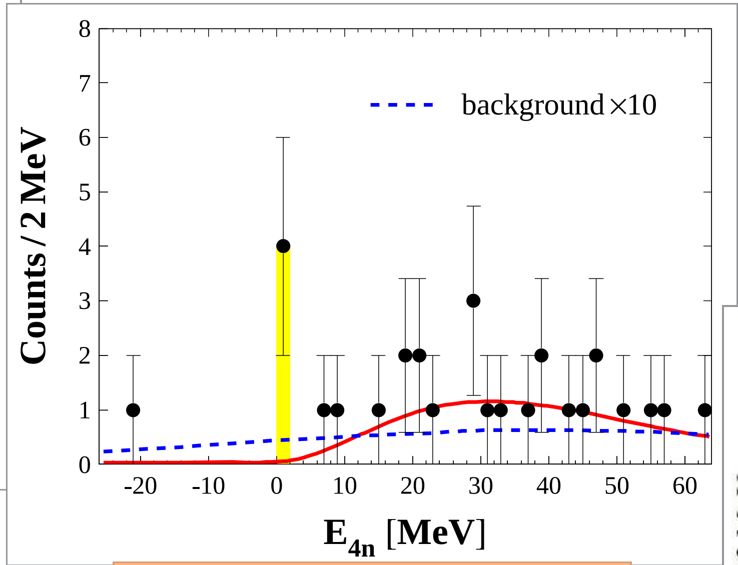

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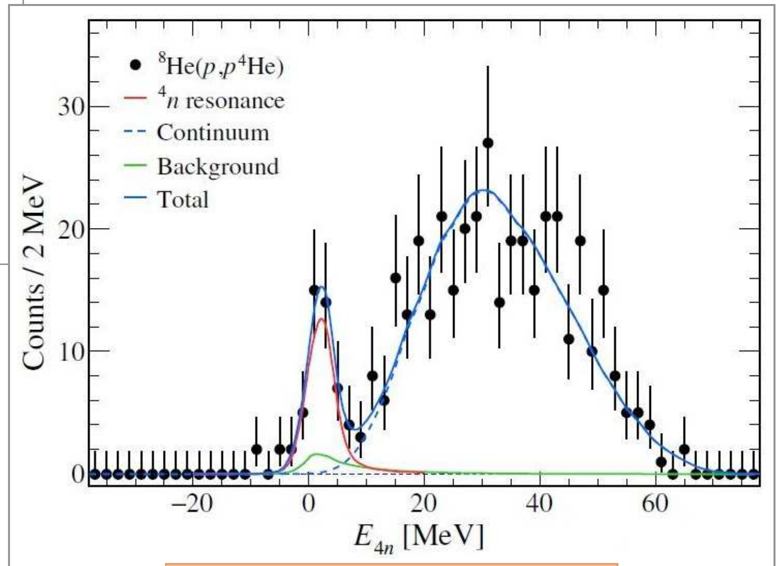

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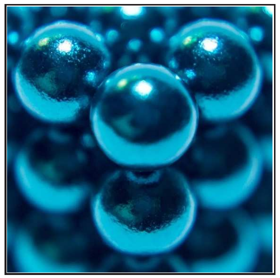

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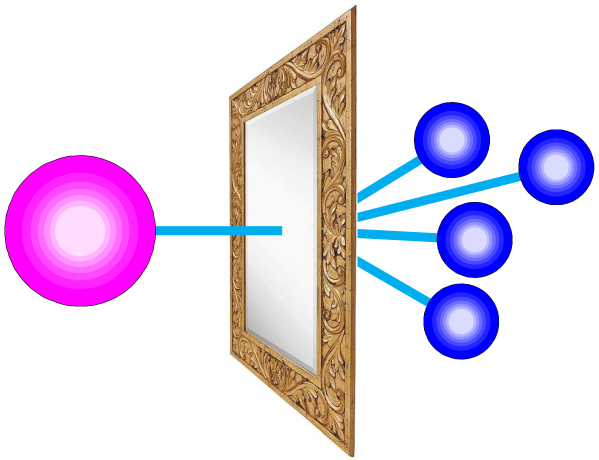

Lazauskas, PRL 130 (2023) 102501

(nn)-(nn) correlations in ^{8}He ?

(FMM, FBS 65 (2024) 37)

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

Lazauskas, PRL 130 (2023) 102501

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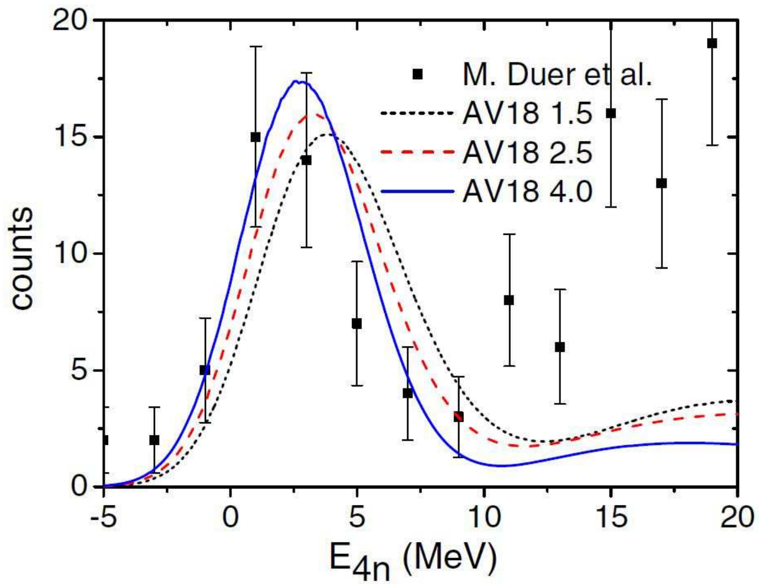

→ $\psi(^{8}$He$)$: core-(nn)-(nn)

→ fast core removal : without resonance !

“Nontrivial phenomenon”

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Lazauskas, PRL 130 (2023) 102501

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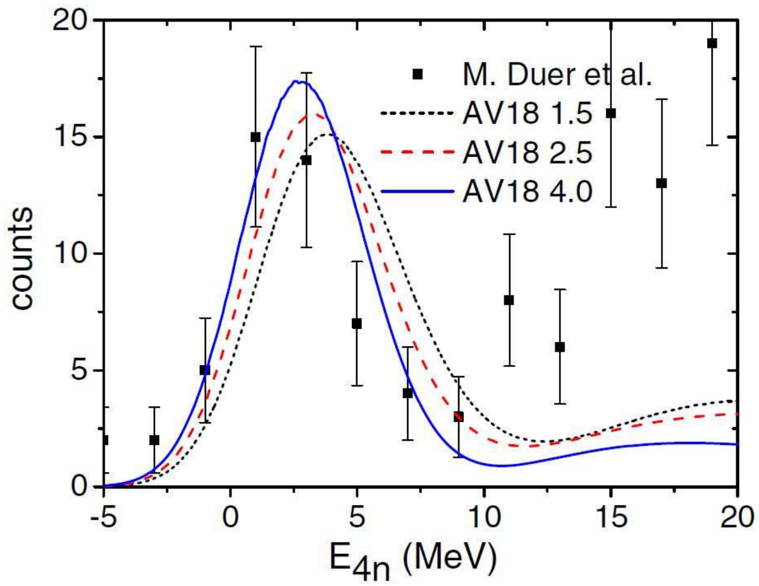

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$$\text{core}\begin{matrix}(nn)\\(nn)\end{matrix}\Big\} \Rightarrow \; \text{E}(4n)\sim 0 \; \Leftarrow \Big\{ \; ^{4}\text{n-core}$$

⟹ new observables (invariant mass)

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Lazauskas, PRL 130 (2023) 102501

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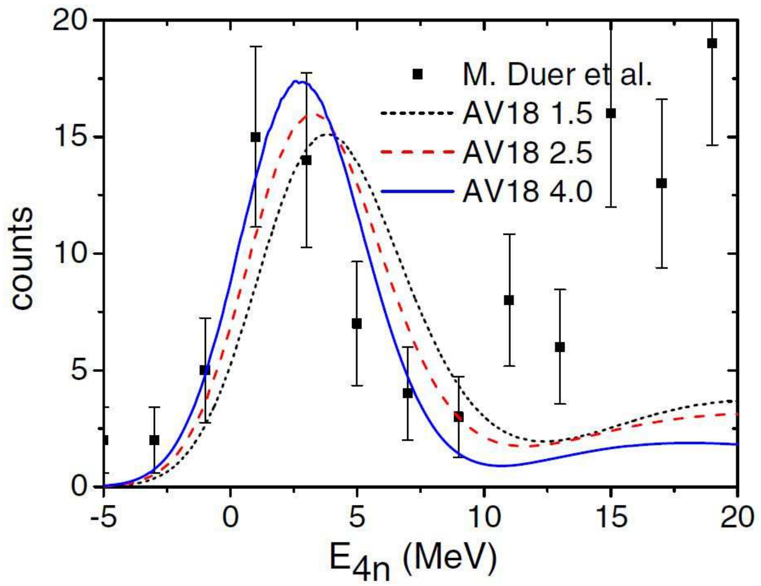

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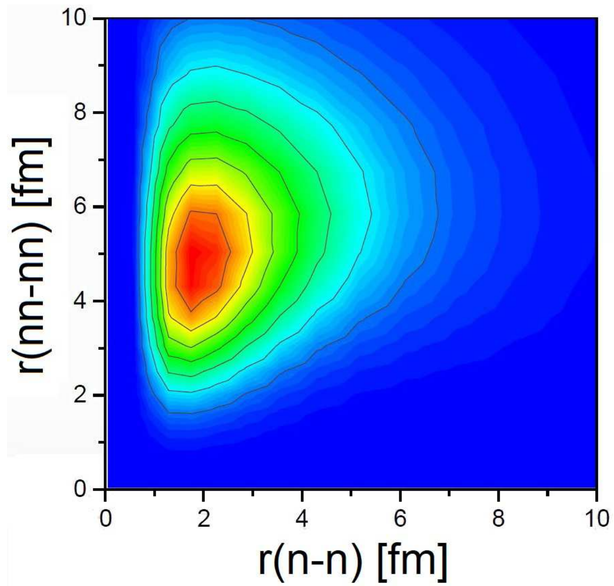
- Spatial (nn)-(nn) correlations :



⟹ link to (exp) momentum space ?

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  - tetraneutron "signal" !
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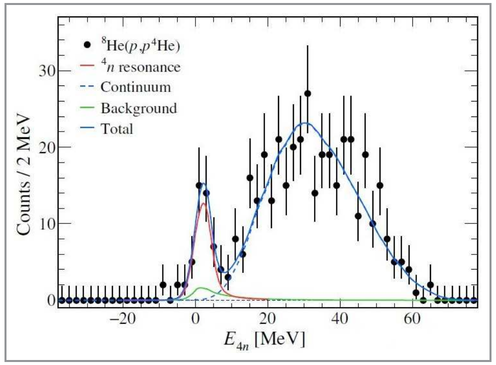

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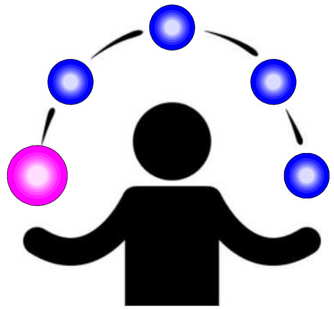

Audrey Anne, PhD

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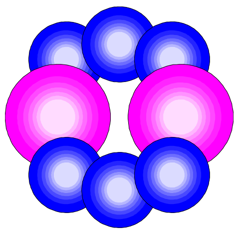
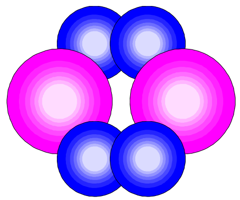




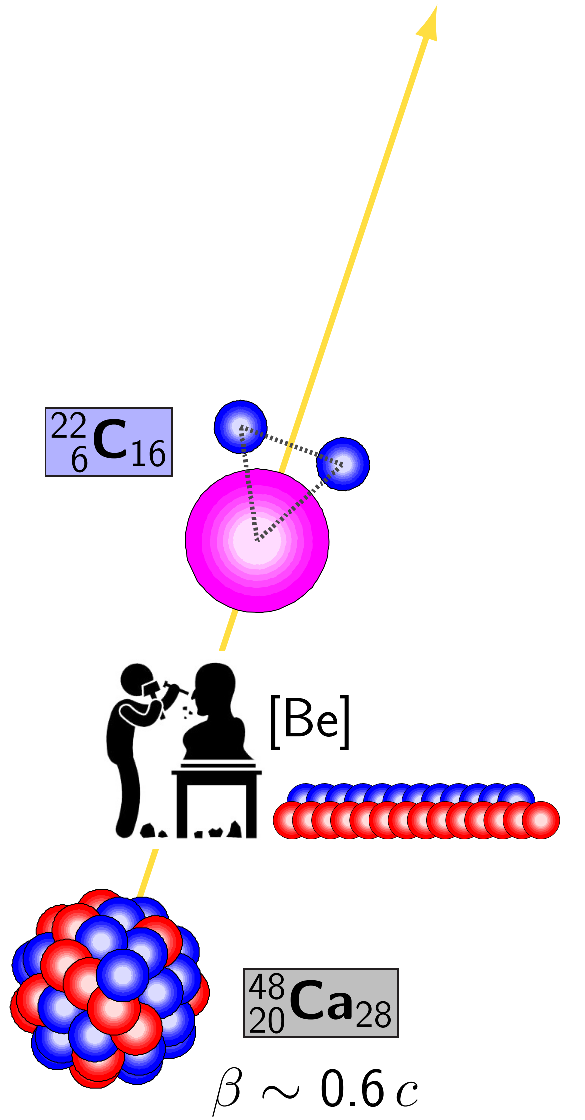
$^{48}_{20}\mathrm{Ca}_{28}$

$\beta \sim 0.6\,c$

Sculpting beams @ RIKEN : Boron 21

Leblond, PRL 121 (2018) 262502

"RIKEN RIBF youtube"



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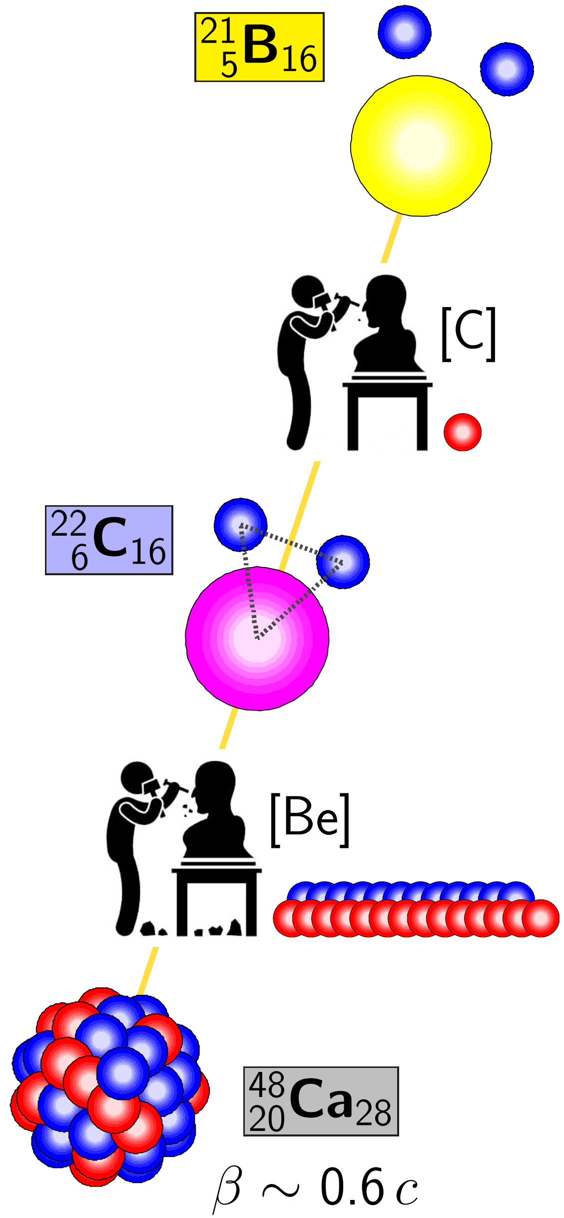
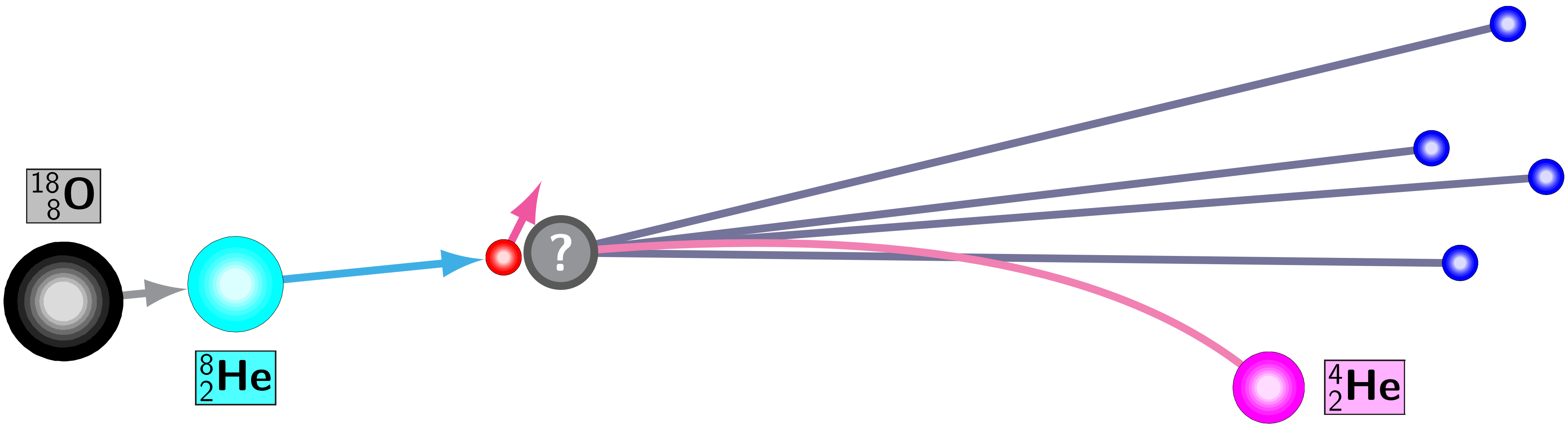
Leblond, PRL 121 (2018) 262502



Missing & Invariant mass : Helium 8



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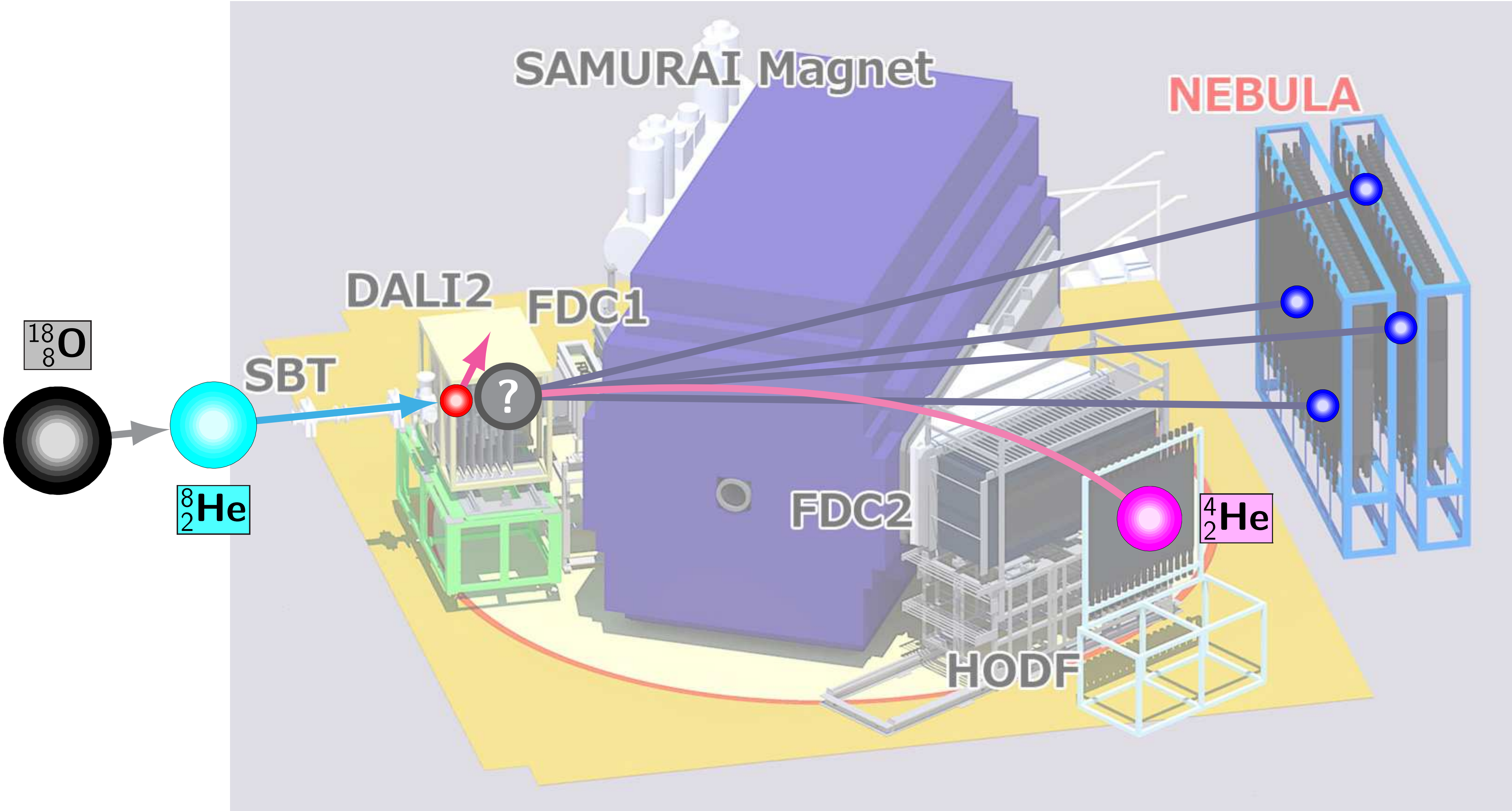
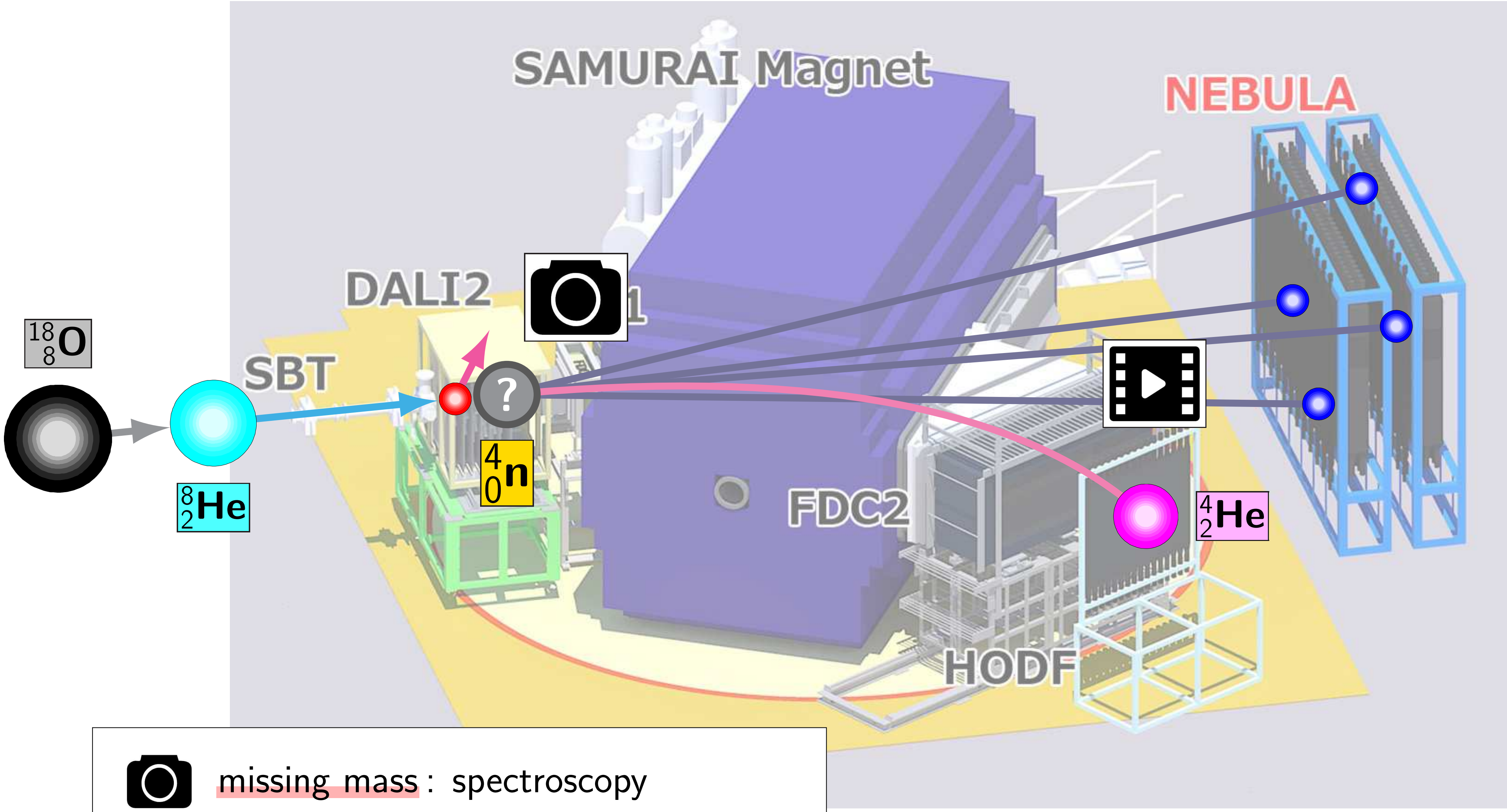


Missing & Invariant mass : Helium 8



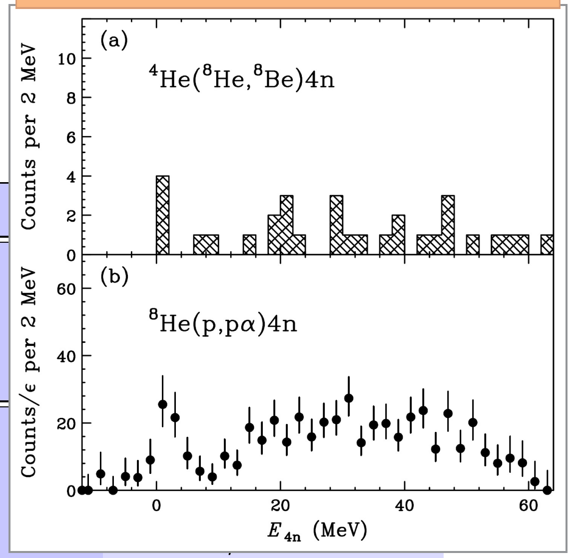
missing mass : spectroscopy

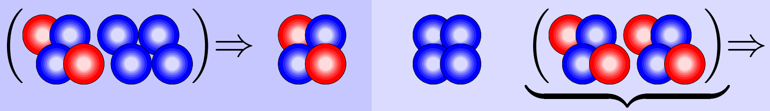
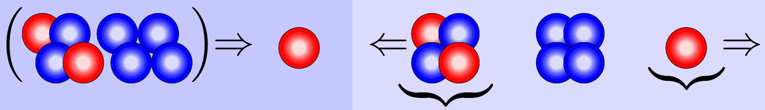
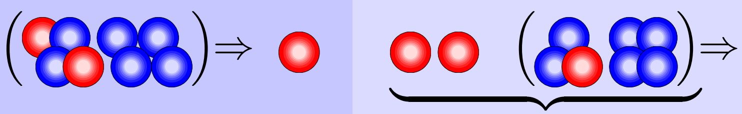
invariant mass : decay, correlations ...

Experimental acces to 4n correlations

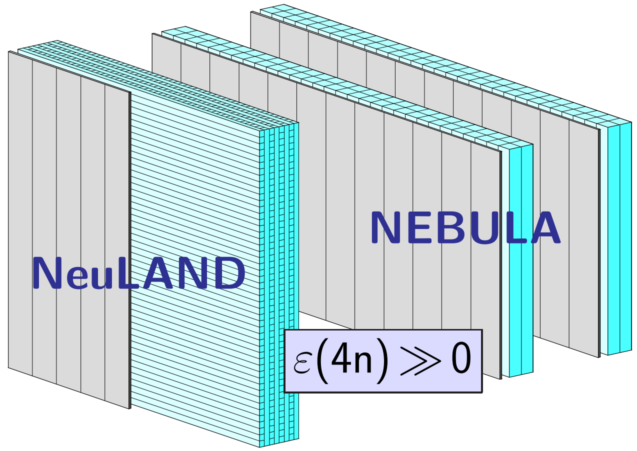
- 2016/17 "tetraneutron campaign" @ RIKEN :

  → first invariant-mass measurement of 4n decay !



reaction	initial state	final state		
('16) ^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10				
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19				
('17) ^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	N_{evt} ~ **10,000** s ^{4}n & ^{7}H : E, Γ, **Ω**

$$^8\text{He}\,(p,2p)\;{}^7\text{H} \longrightarrow {}^3\text{H} + {}^4\text{n}\;?$$



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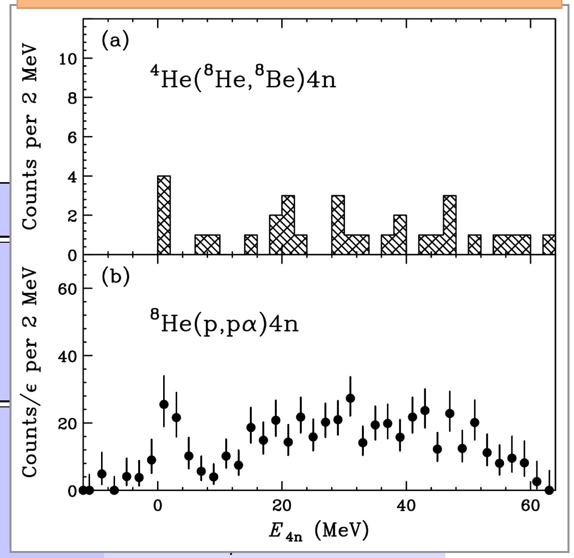

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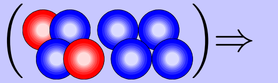
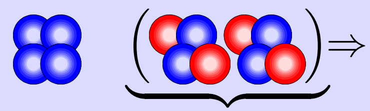
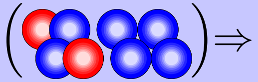
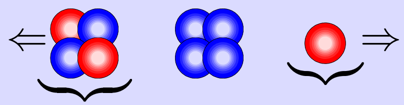
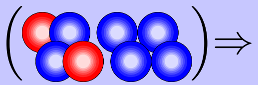
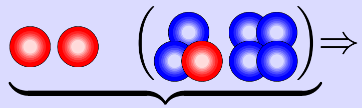
('16) ^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10				
('17) ^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19				
('17) ^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	N_{evt} ~ **10,000** s ^{4}n & ^{7}H : E, Γ, Ω

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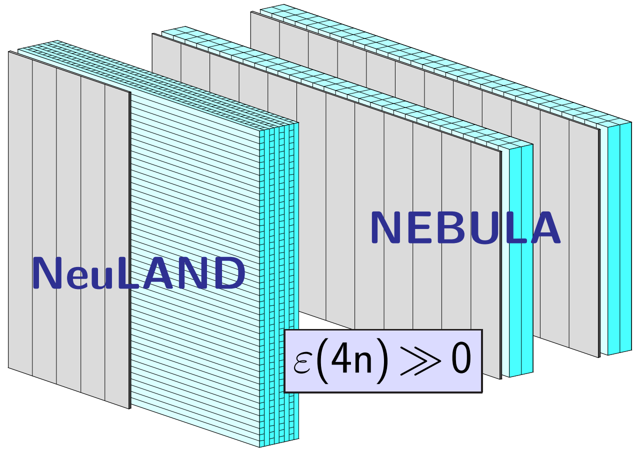
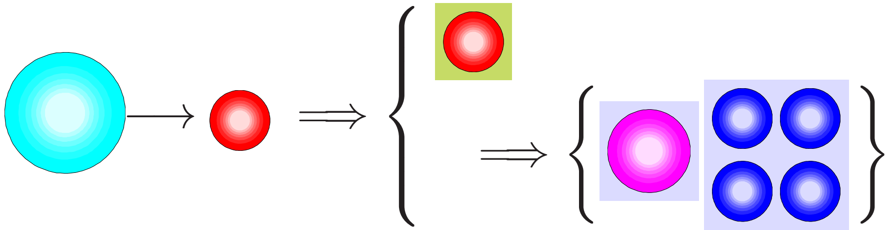


SAMURAI34 : VERY PRELIMINARY results !

^{8}He (p, p') ^{4}He+ 4n @ 150 MeV/N :



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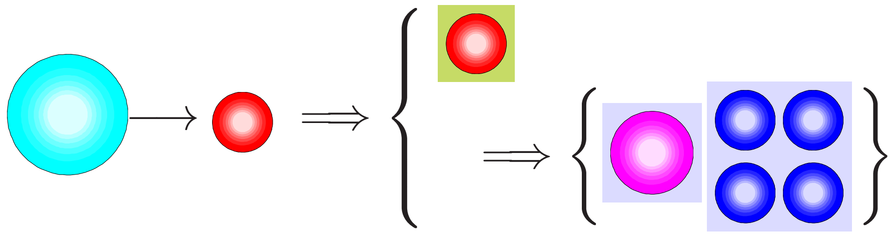
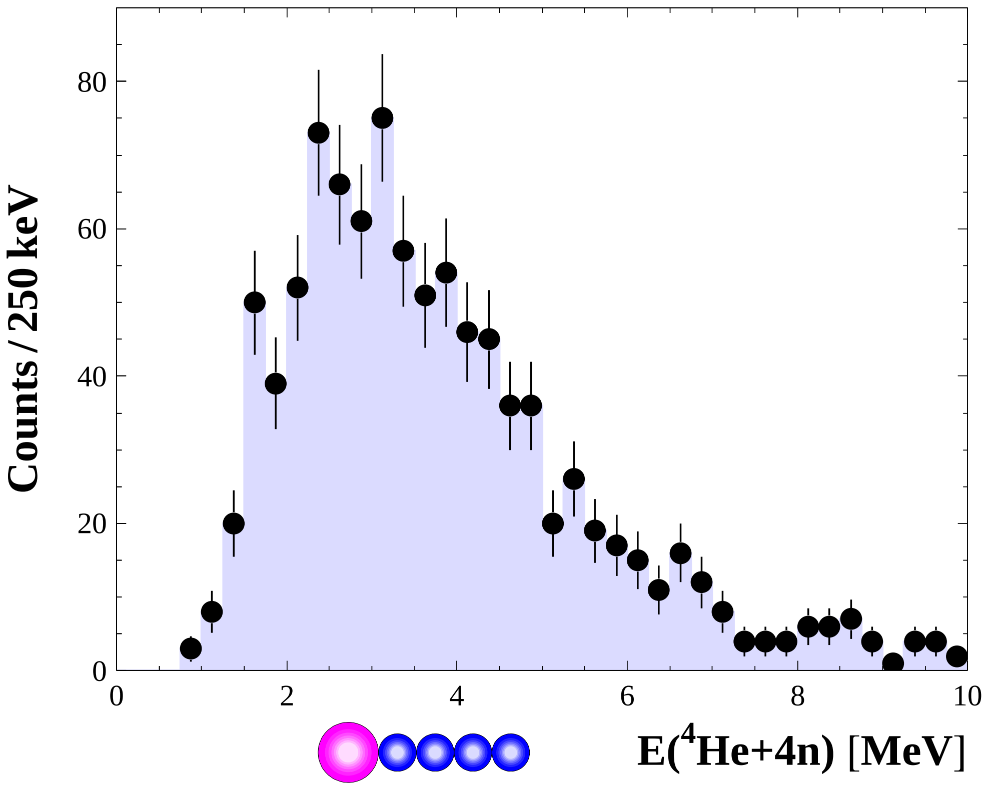


Audrey Anne, PhD



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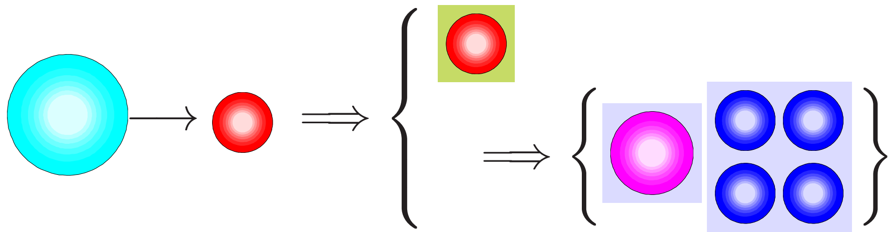

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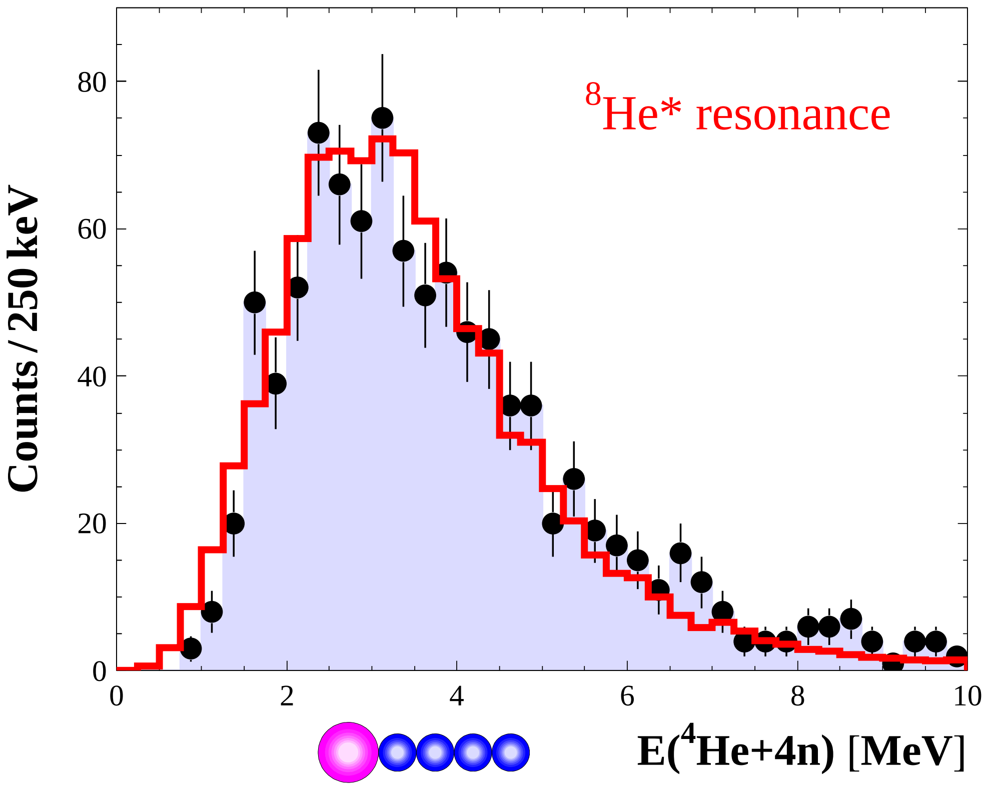

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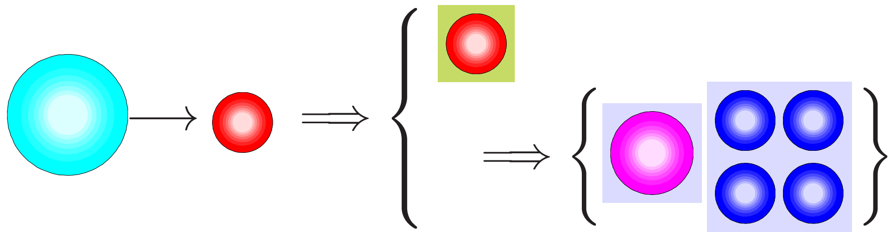

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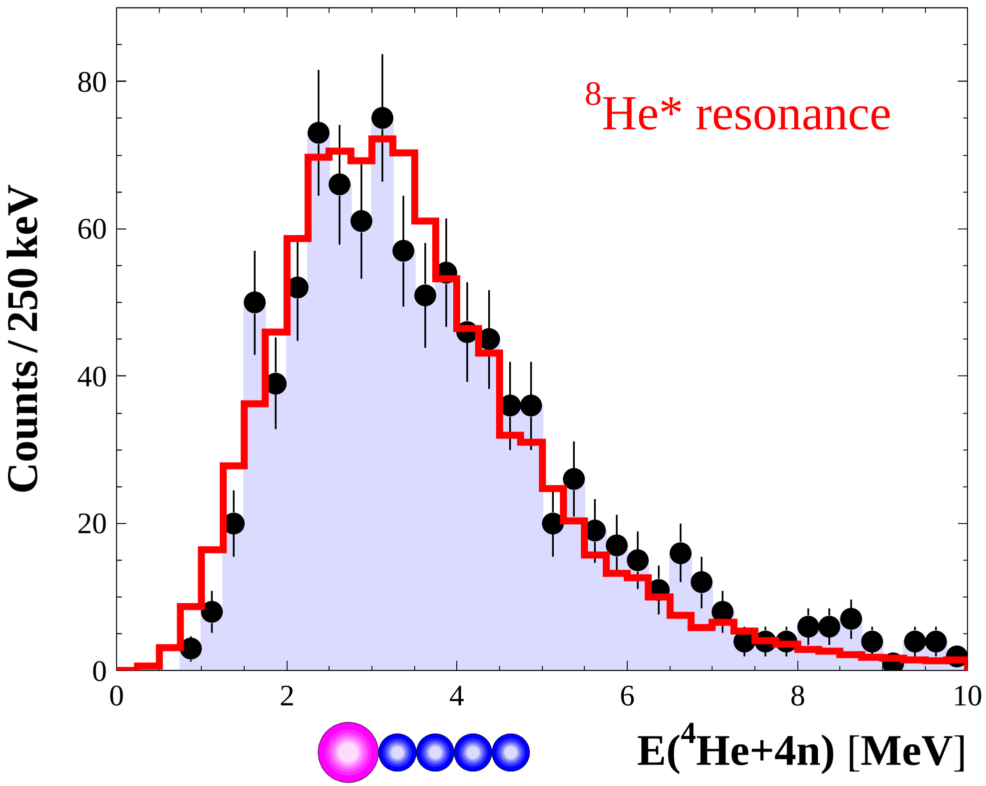

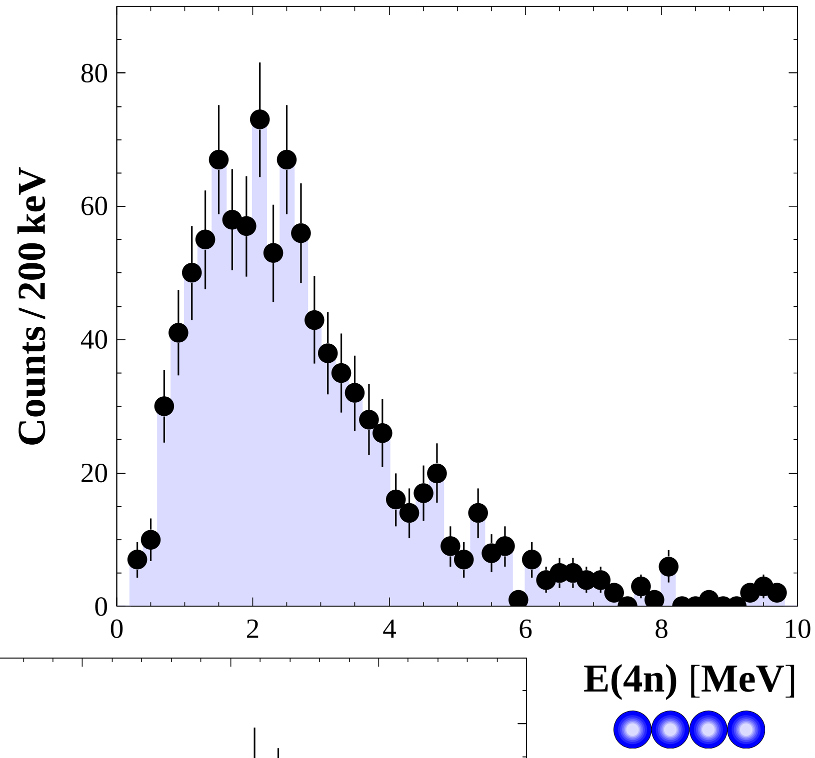

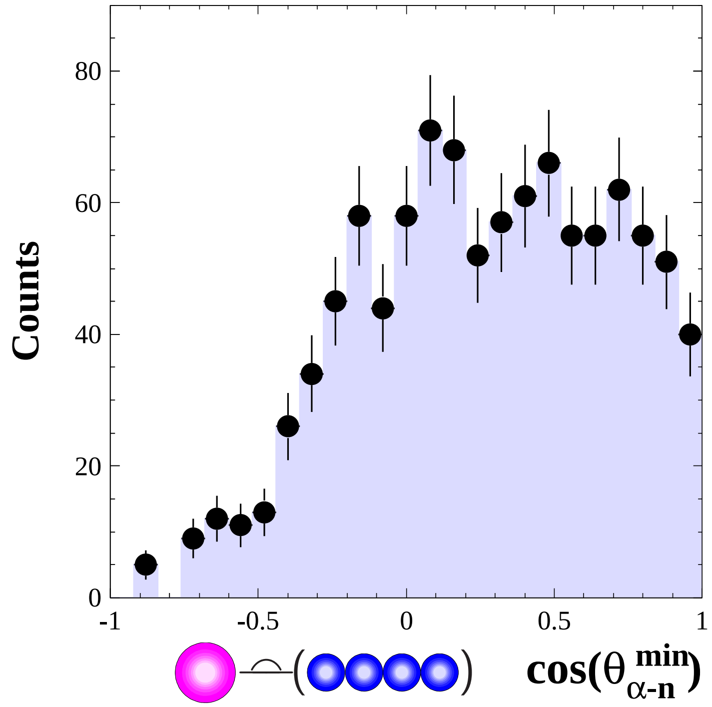

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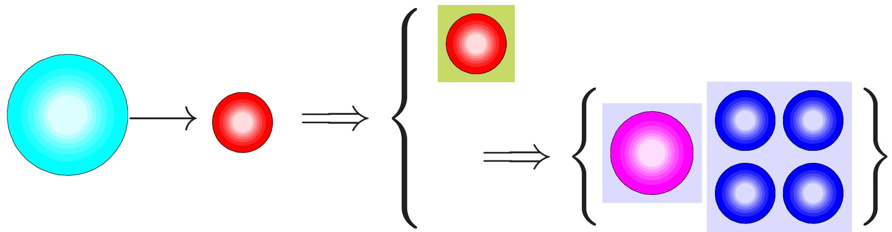

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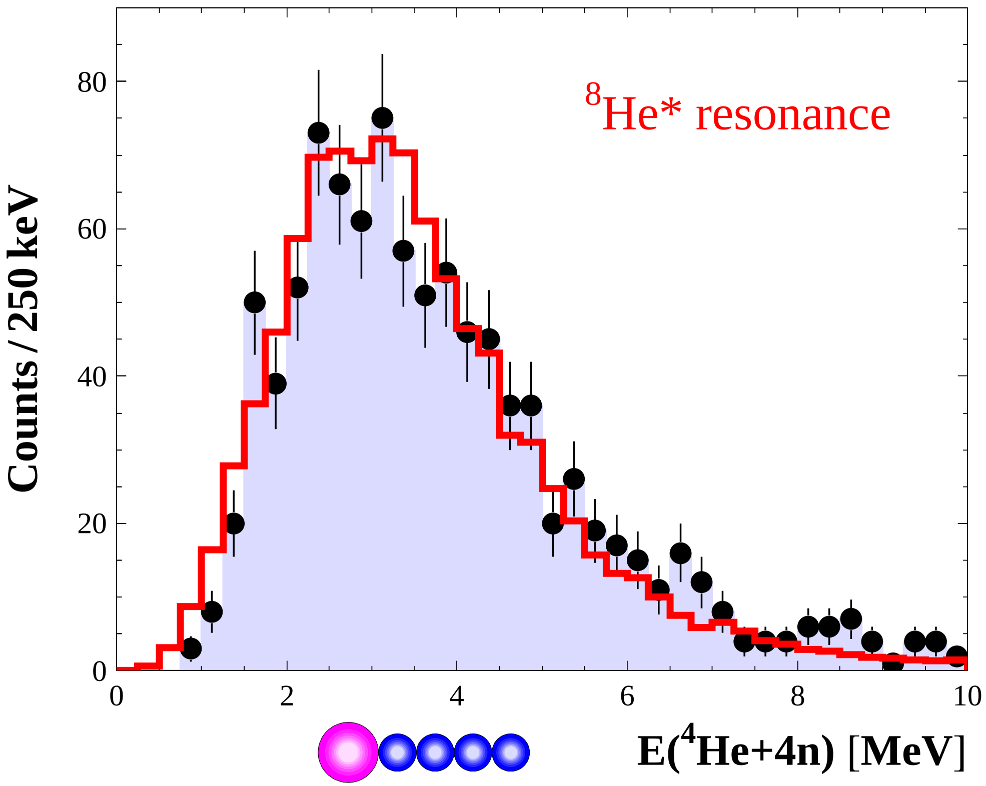
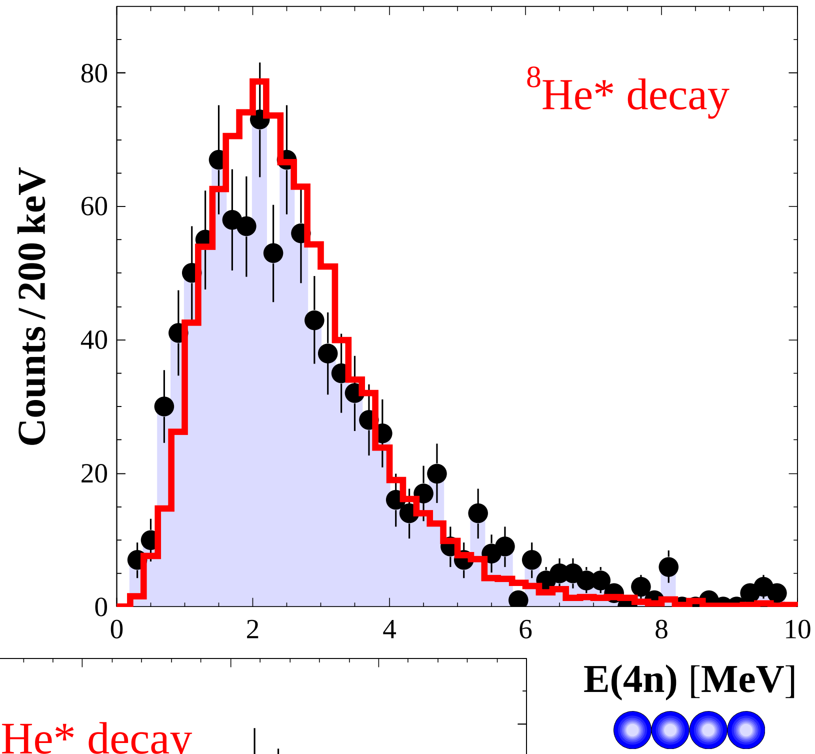
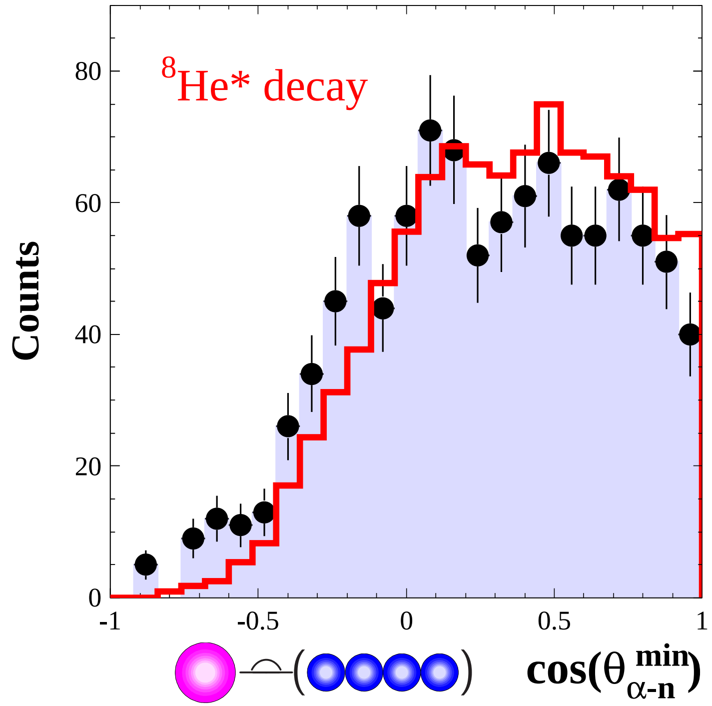
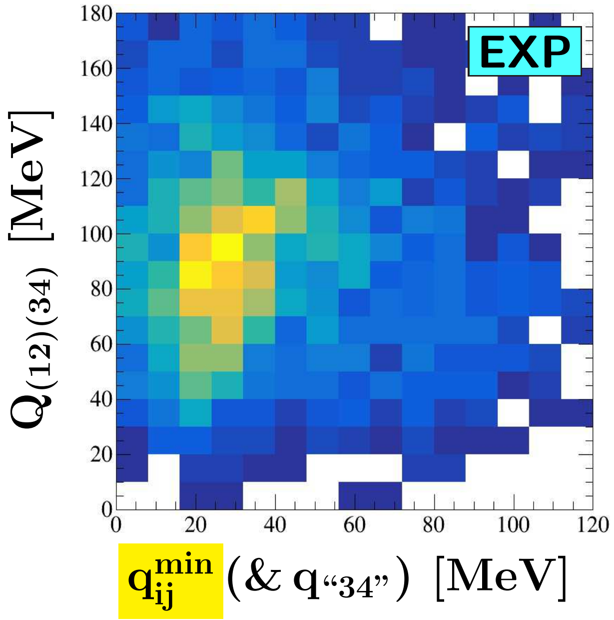
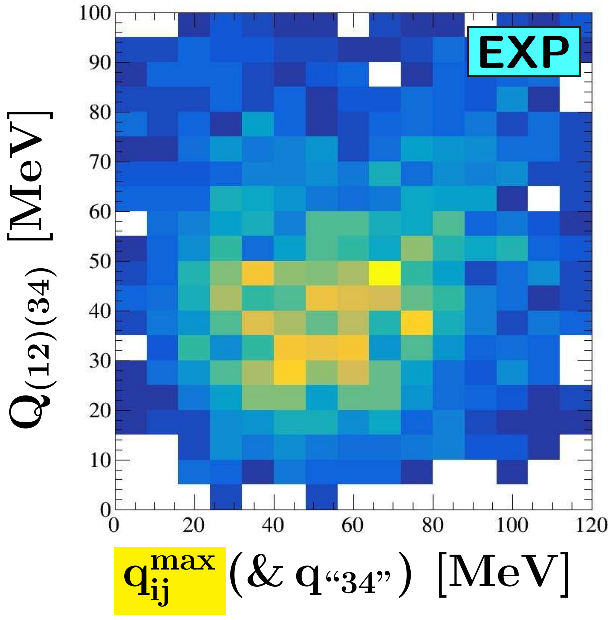


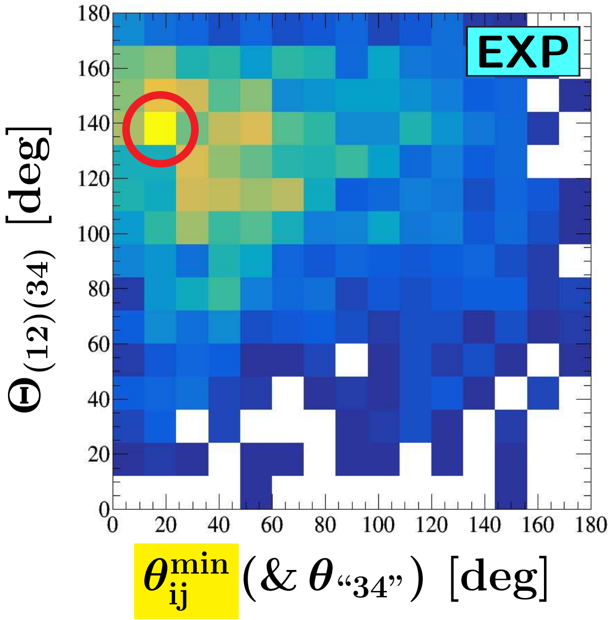




Preliminary 4n correlation observables







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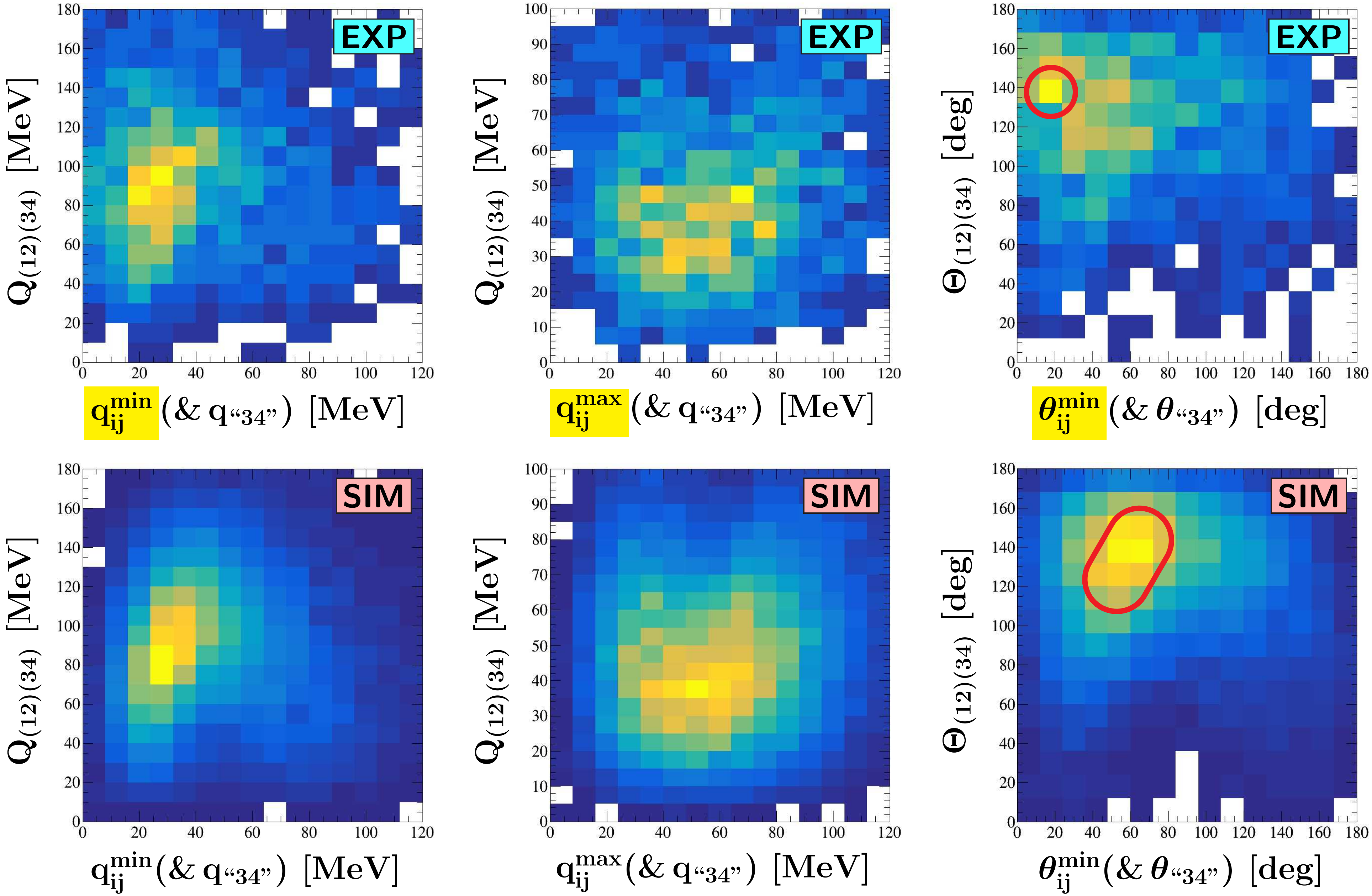
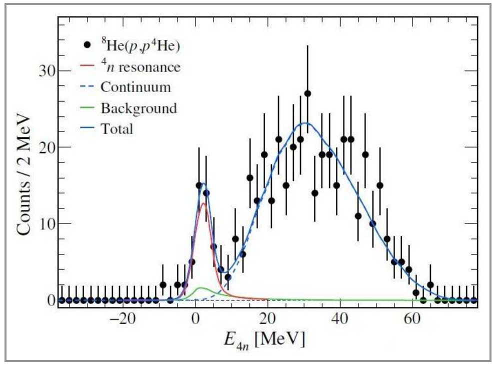
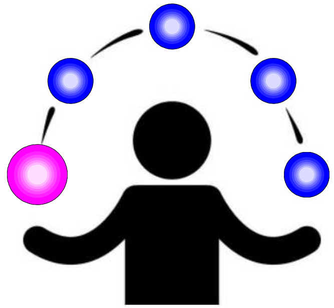


Outline

- **Fundamental** question :
  - few-neutron systems ?
  - tetraneutron "signal" !
  - resonance / initial correlations ?

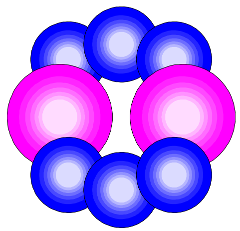


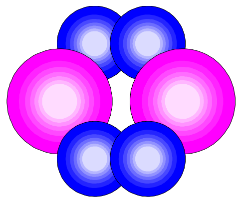
- **Inside** the tetraneutron :
  - 4n invariant mass !
  - low-energy structures
  - explore full kinematics ...



Audrey Anne, PhD

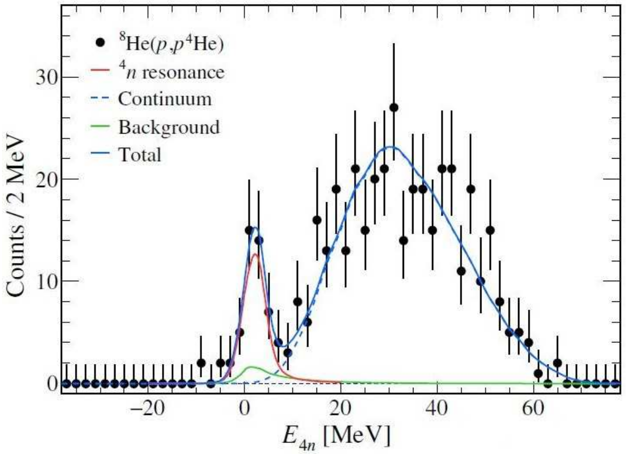
- Back to the **future** ?
  - Beryllium 14 & 12
  - NP2412-SAMURAI81 ...





Back to the future

- How to probe resonant character?



$(E, \Gamma) = (2.4, 1.8)$ MeV?

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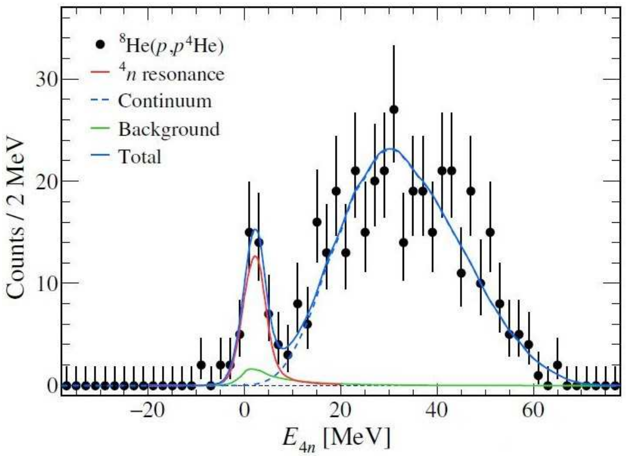

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❶ Alternative ‘mounts’ !

beam	S_{xn} [MeV] $4n$	$6n$	I [pps]	source
^{8}He	3.1	31.4	10^5	^{18}O
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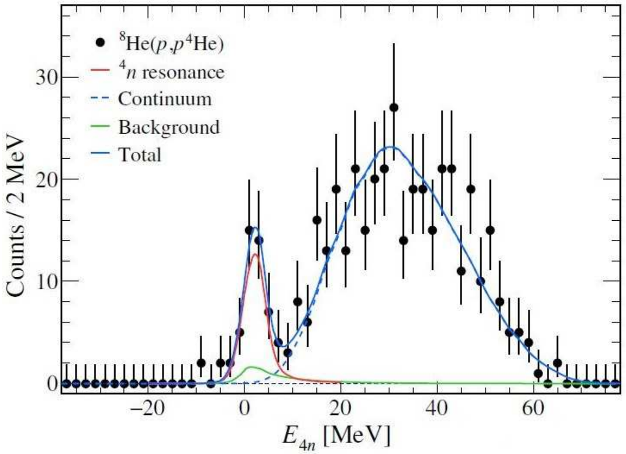

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→ best compromise: Beryllium!

Back to the future

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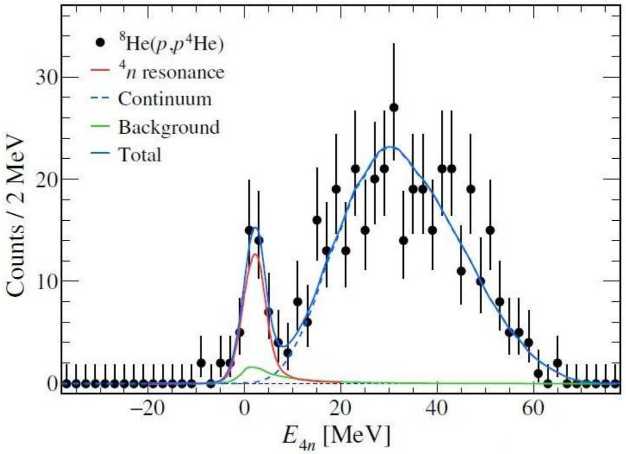

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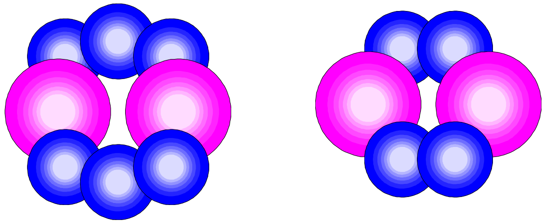

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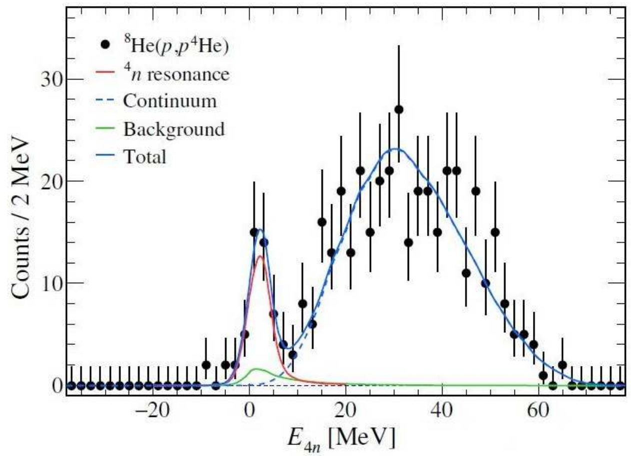

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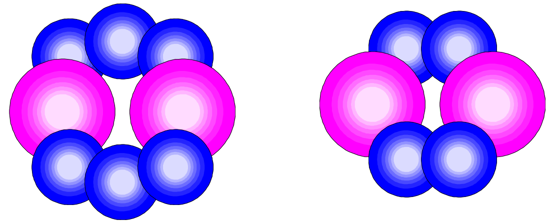

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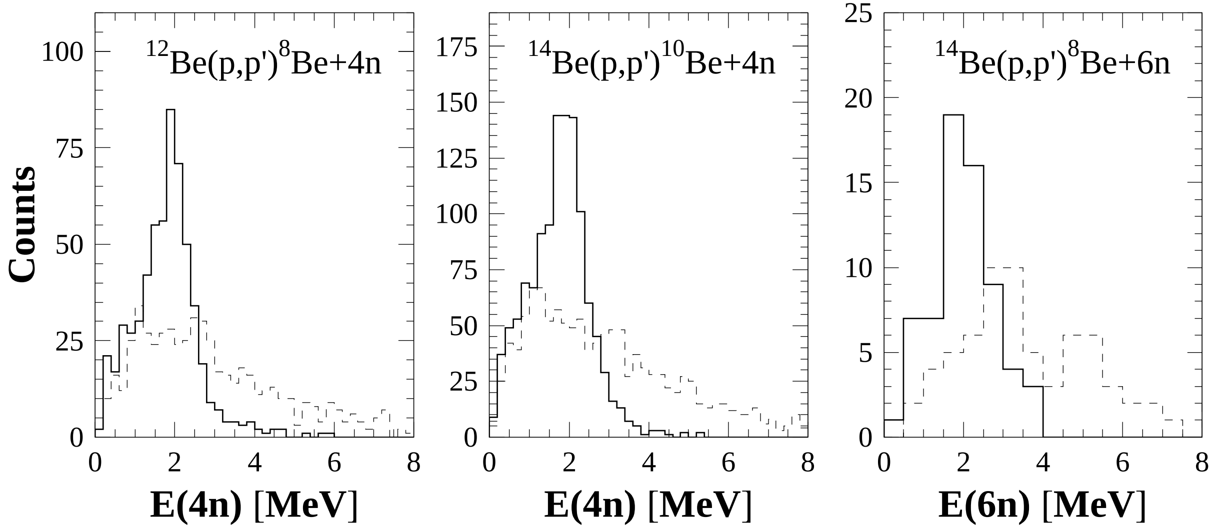
2 Invariant mass ? $(E,\Gamma) = (2,1)$ MeV :



- NEBULA/HIME+ : $\varepsilon(4n) \approx 1\%$ & $\varepsilon(6n) \approx 0.05\%$

Multineutron proposal

❸ Resonance veto :

$$^{12}\text{Be}^* \rightarrow \begin{cases} ^8\text{Be}^{(*)} + 4n \rightarrow 2\alpha + {}^4\text{n} \\ ^9\text{Be}^* + 3n \rightarrow 2\alpha + 4n \end{cases}$$

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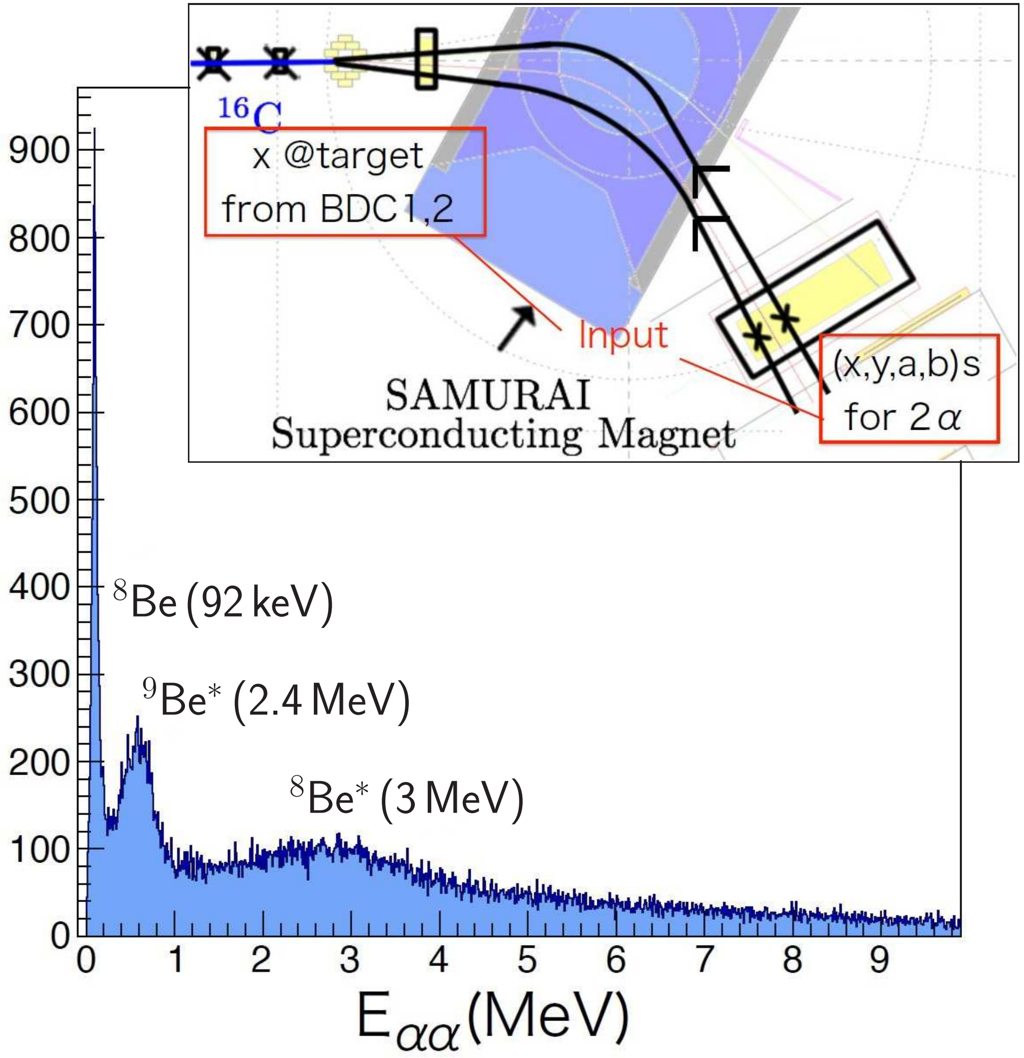

Shumpei Koyama, SAMURAI08

Multineutron proposal

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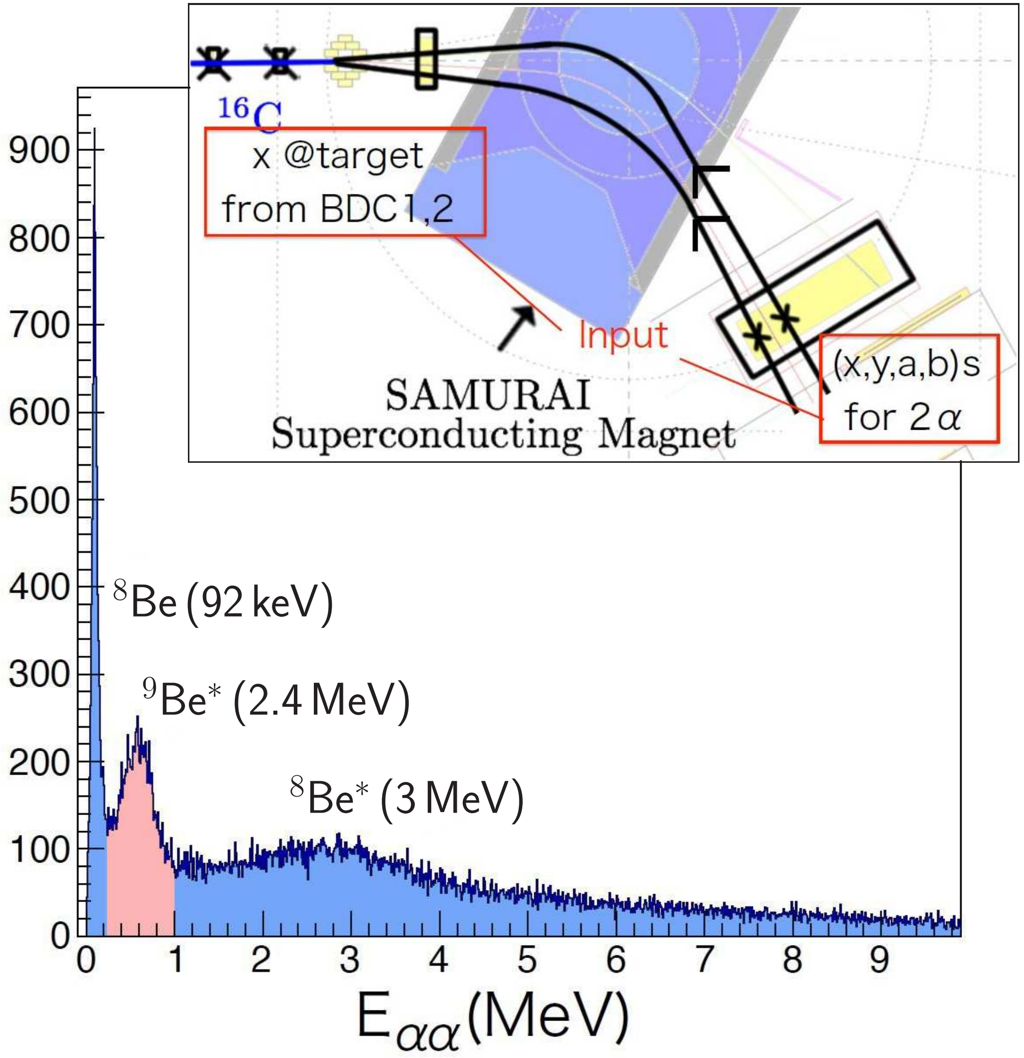

Shumpei Koyama, SAMURAI08

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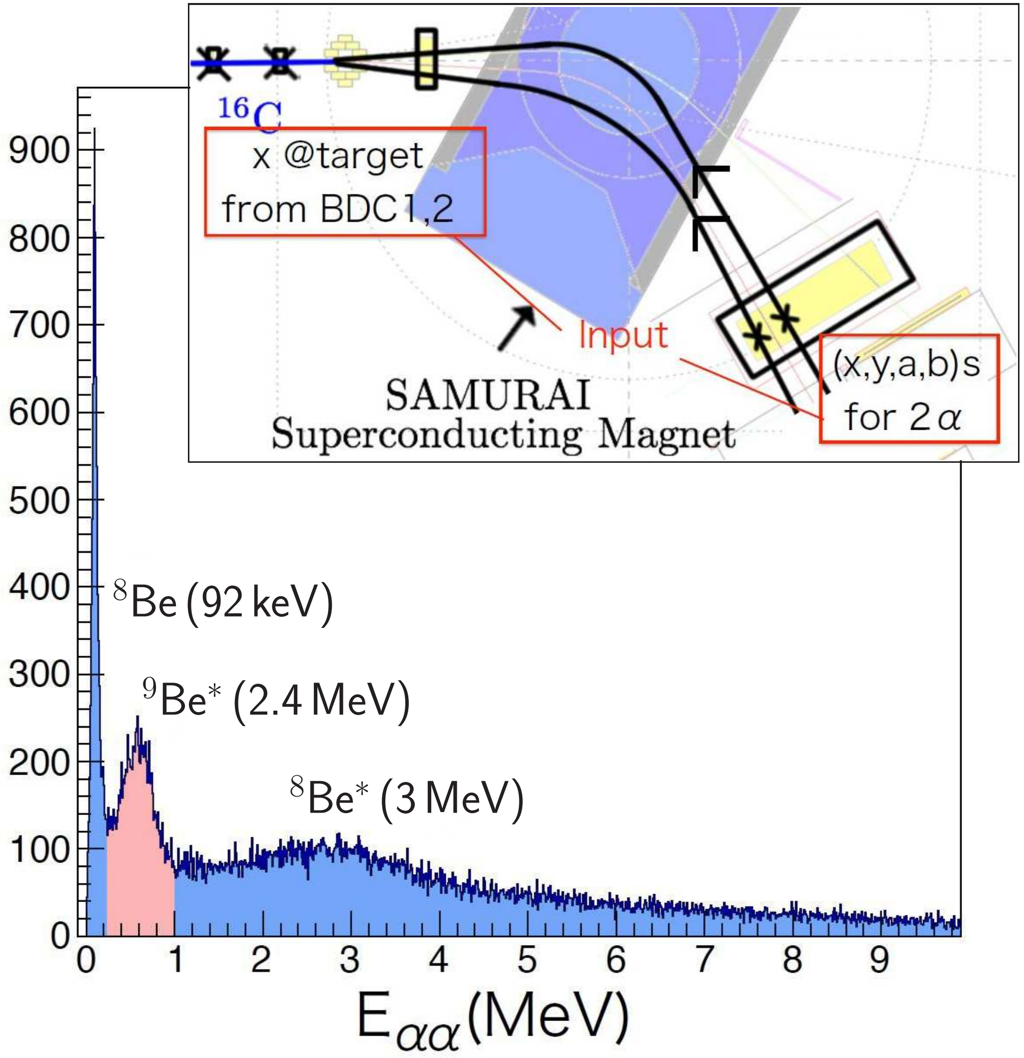
→ signal + ^{9}Be* : initial correlations

→ signal + ^{8}Be$^{(*)}$: tetra/hexaneutron !



Shumpei Koyama, SAMURAI08

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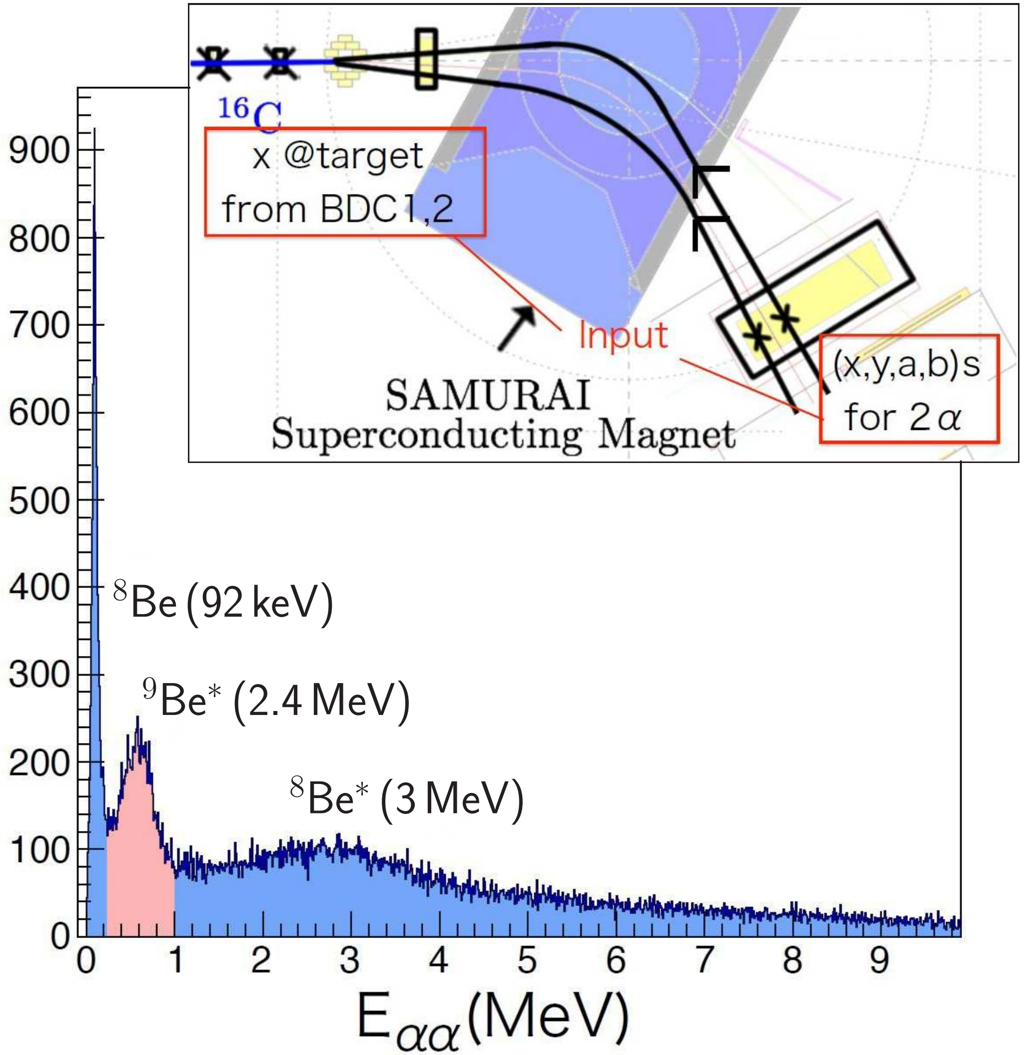


Shumpei Koyama, SAMURAI08

- **NP2412-SAMURAI81** :
  - nature of 4(6)n signals ?

❶ (E, Γ) : resonance(s)

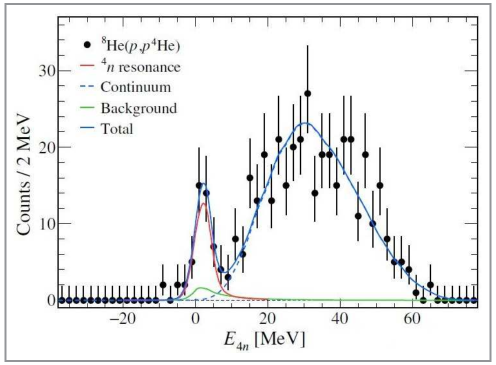
❷ invariant mass : correlations

❸ resonance veto : confirmation

$\rightarrow$ $^{12,14}\text{Be}(p, p')$ on LH_2 target (1+2 days) ...

Summary

- ▶ Fundamental question :
  - few-neutron systems ?
  - tetraneutron "signal" !
  - resonance / initial correlations ?



- ▶ Inside the tetraneutron :
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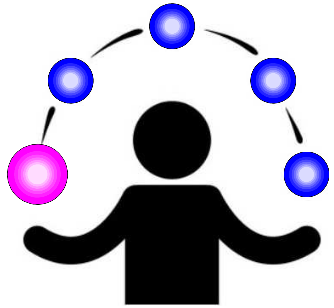
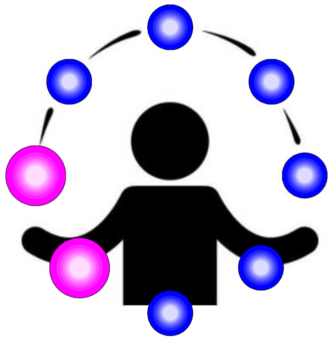


- ▶ Back to the future ?
  - Beryllium 14 & 12
  - NP2412-SAMURAI81 ...



SAMURAI34 collaboration (part)

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

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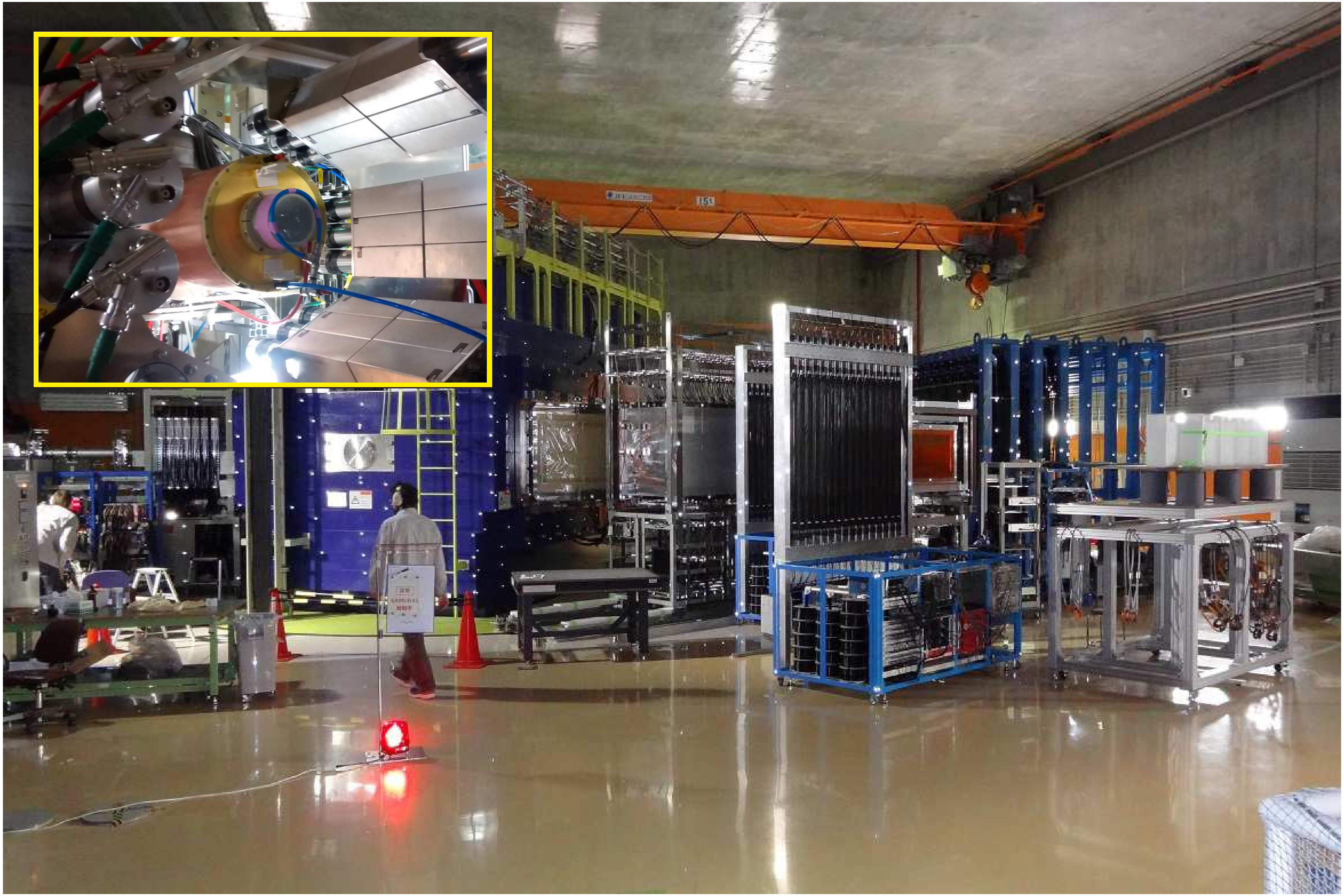
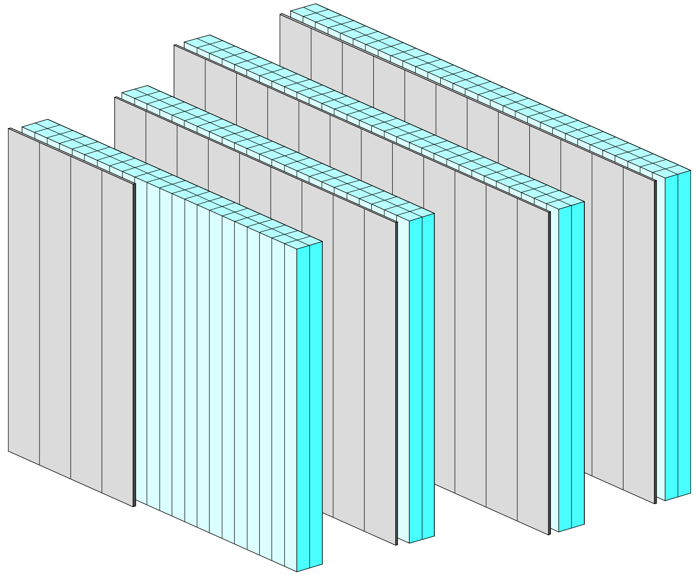
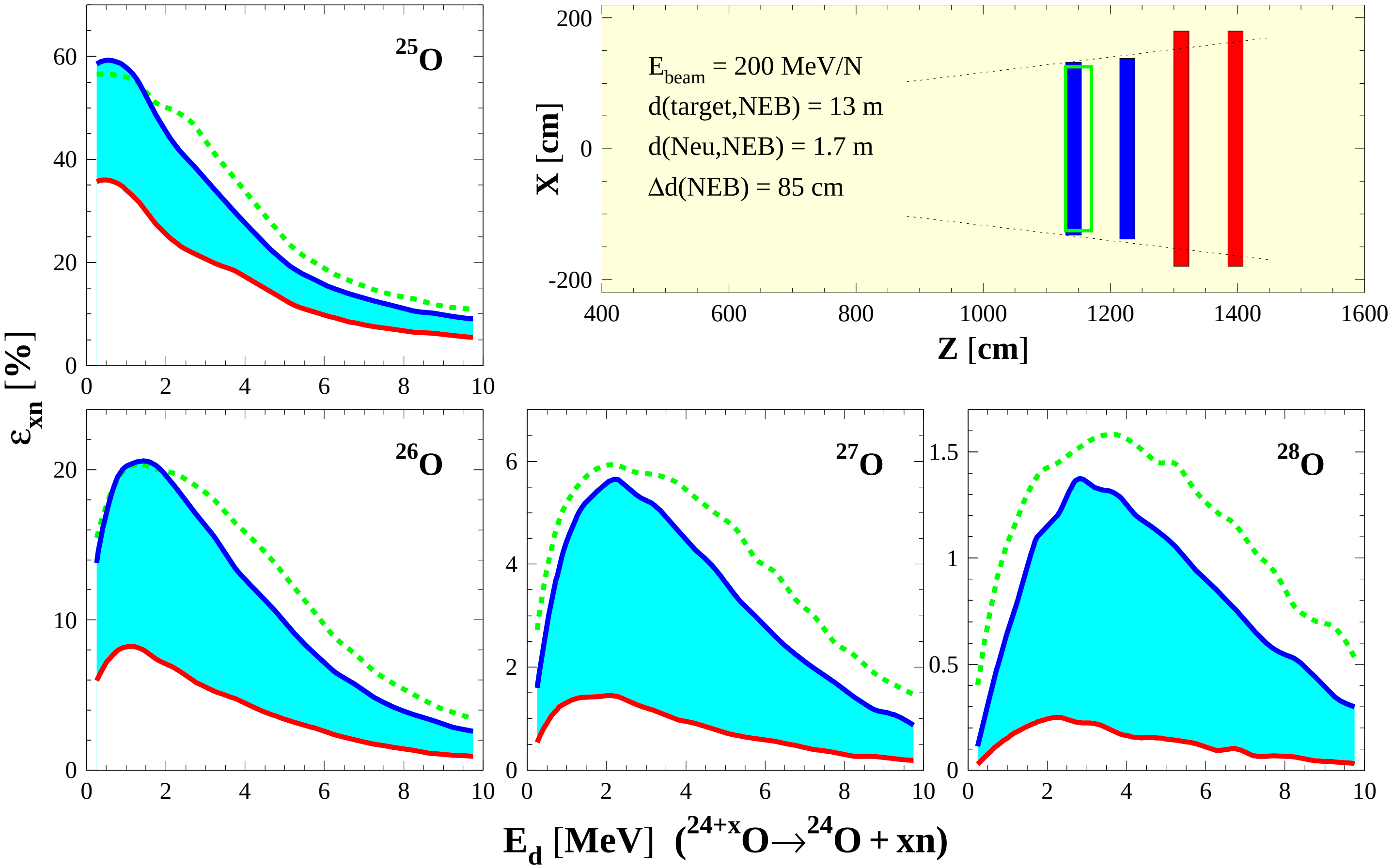
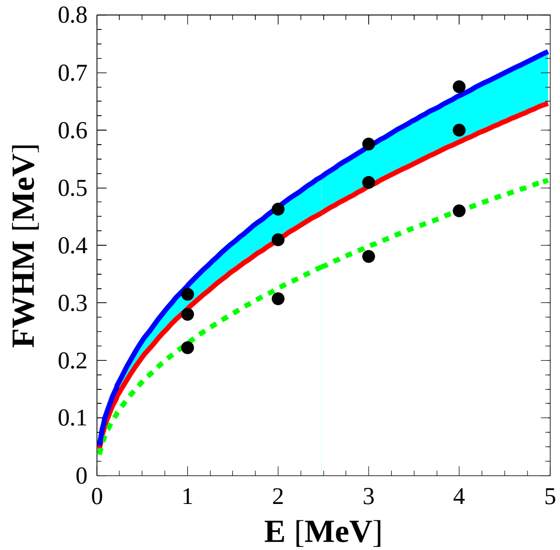


EXPAND project (French ANR)

- Expand NEBULA multineutron capabilities :
  - France : LPC, IRFU, IPNO
  - Japan : TITech, RIKEN
  - +90 bars : Commissioning & Day-1 in 2024 !







Pauli-principle driven correlations in four-neutron nuclear decays

"The valence neutrons are pushed to the symmetry-allowed configurations in the 4n-precursor structure ... It should be noted that much more correlation information characterizing core+4n decay in principle exist. However ... at the moment we find too premature to discuss such complicated things"

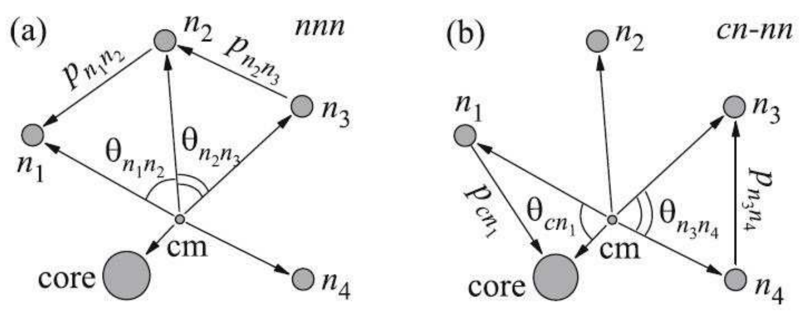


Fig. 3. Schemes of kinematical variables describing 5-body decays, which are used in constructing correlated two-dimensional energy $\{\varepsilon_{ik}, \varepsilon_{nm}\}$ and angular $\{\theta_{ik}, \theta_{nm}\}$ distributions of fragments. Examples (a) of "connected" nnn and (b) of "disconnected" cn-nn topologies. The related energy distribution parameters are defined as $\varepsilon_{ik} = p^2_{ik}/(2\mu_{ik}E_T)$

$$^7\mathrm{H}: [p^4_{3/2}]_0 \rightarrow C_{2323}[p^4_{3/2}]_0 + C_{0123}[s^2_{1/2}p^2_{3/2}]_0, \quad (12)$$

$$^{28}\mathrm{O}: [d^4_{3/2}]_0 \rightarrow C_{4343}[d^4_{3/2}]_0 + C_{0143}[s^2_{1/2}d^2_{3/2}]_0 + C_{0123}[s^2_{1/2}p^2_{3/2}]_0. \quad (13)$$

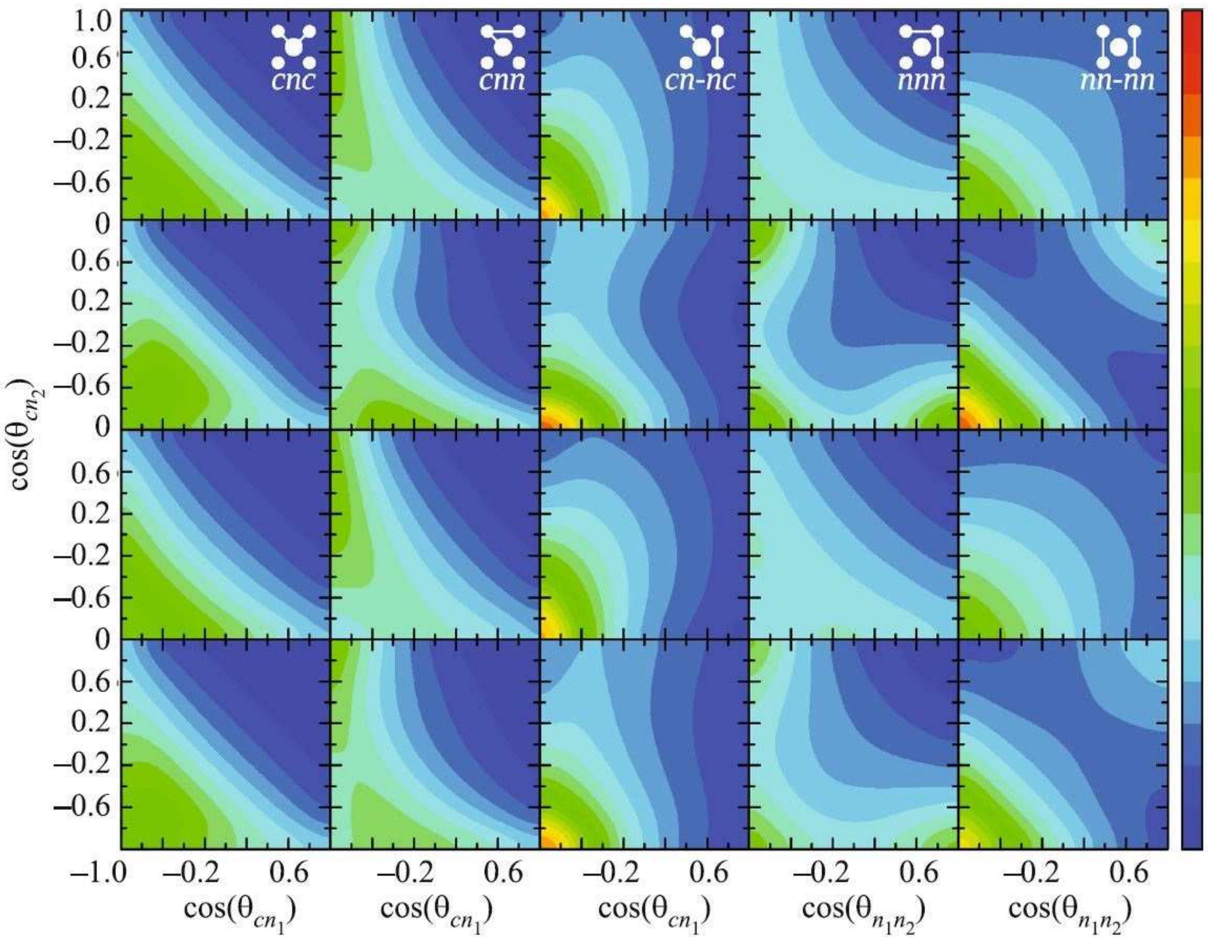
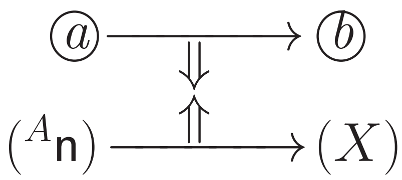


Fig. 9. Correlated distributions for core+$4n$ decays in $C_{0123}[s^2_{1/2}p^2_{3/2}]_0 + C_{0121}[s^2_{1/2}p^2_{1/2}]_0$ configuration mixing. The following cases are illustrated: $C_{0121} = 1, 0.48, -0.48$, and 0.

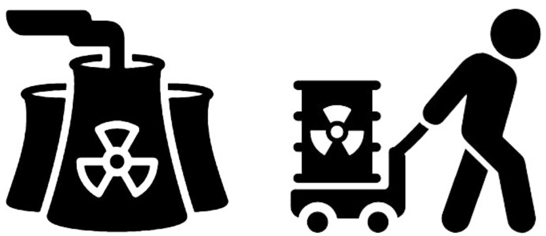
Multineutron probes ?

FMM & Carbonell, EPJA 57 (2021) 105

two step



- ✔ charged-particle detection
- ✘ only bound states
- ✘ insensitive to energy
- ✘ infer lower limit of A
- ✘ contaminant ≠ ⓐ and/or uncontrolled 1st-step background

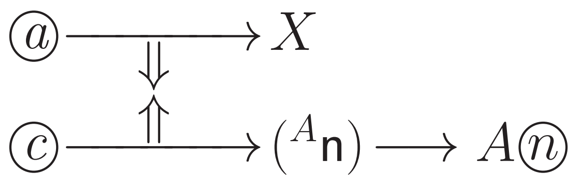


8 experiments

Détraz, PL 66B (1977) 333

✔ → ✘ (1980)

neutron detection



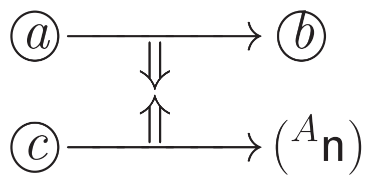
- ✔ unambiguous detection
- ✔ breakup or resonant decay
- ✔ neutron correlations
- ✘ extremely low efficiency

4 experiments

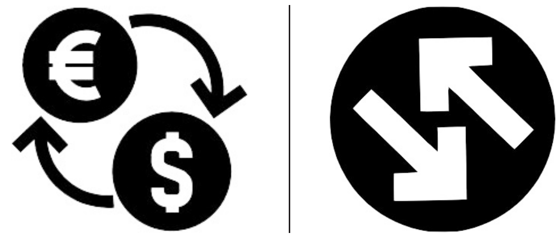
FMM, PRC 65 (2002) 044006

✔ (?)

missing mass



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



25 experiments

Kisamori, PRL 116 (2016) 052501 ✔ (?)

Duer, Nature 606 (2022) 678 ✔