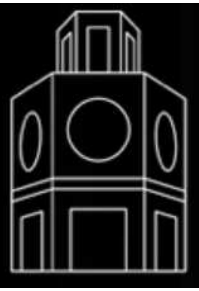
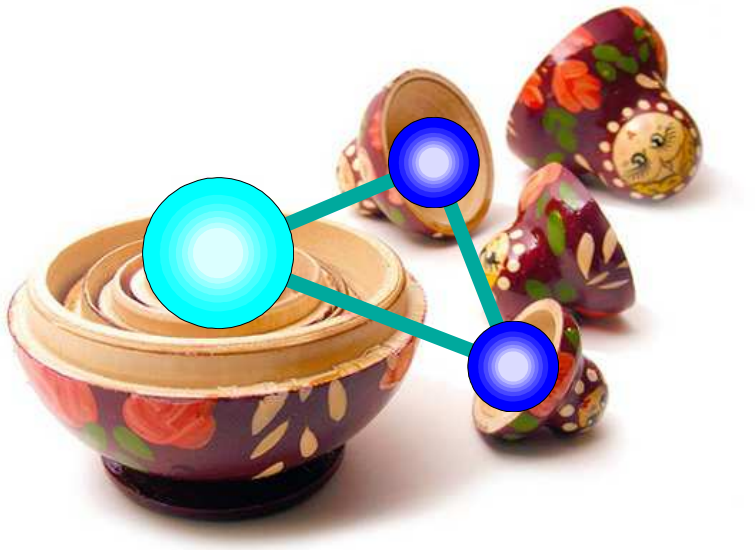


UC SANTA BARBARA
Kavli Institute for Theoretical Physics

Opportunities and Challenges in Few-Body Physics:
Unitarity and Beyond
May 23-26, 2022

# Neutron-rich three-body systems

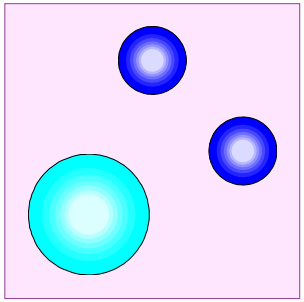



lpc caen
Laboratoire de physique corpusculaire

F. Miguel Marqués

samurai

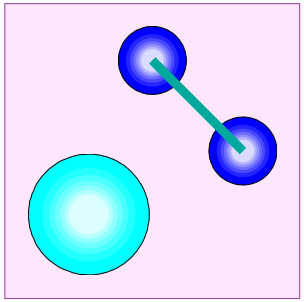
# Scattering lengths & three-body systems



$^{16}_{4}\mathbf{Be}$ : $^{14}$Be+n+n

Belén Monteagudo, PhD

# Scattering lengths & three-body systems



$^{16}_{4}$**Be** : $^{14}$Be+n+n  Belén Monteagudo, PhD

- $a_s$(nn) strong enough for "dineutron" ?
- experimental signature ?

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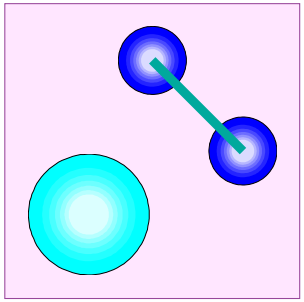

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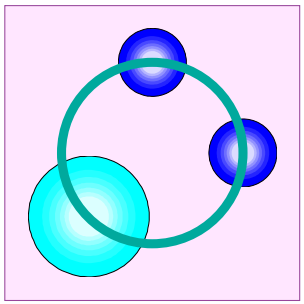
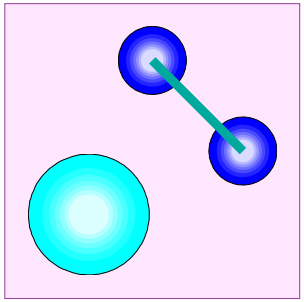


$^{19}_{5}$**B** : $^{17}$B+n+n  Hiyama, PRC 100 (2019) 011603R

# Scattering lengths & three-body systems



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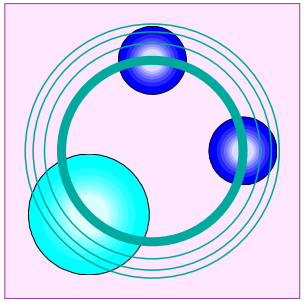

$^{19}_{5}$**B** : $^{17}$B+n+n  Hiyama, PRC 100 (2019) 011603R

- $a_s(^{18}\mathrm{B})$ strong enough for Efimov states ?
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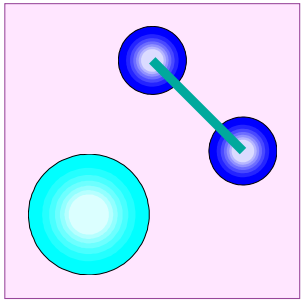
# Scattering lengths & three-body systems



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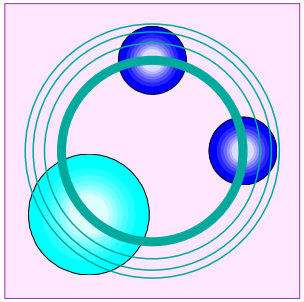

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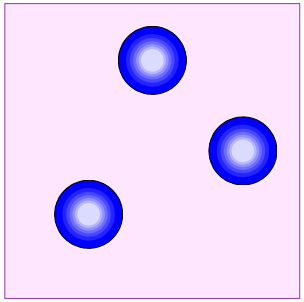
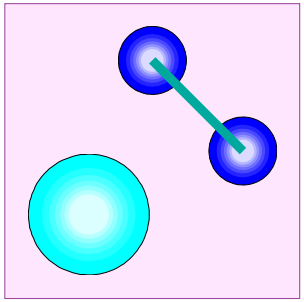


$^{3}_{0}$**n** : n+n+n — Cyril Lenain, PhD

# Scattering lengths & three-body systems



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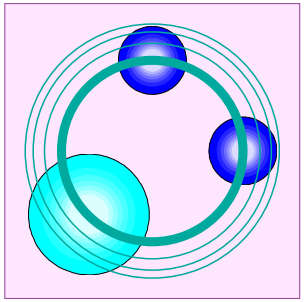

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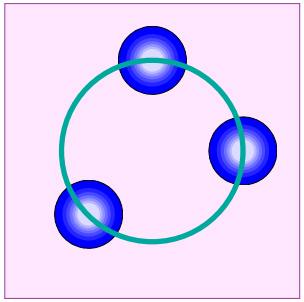
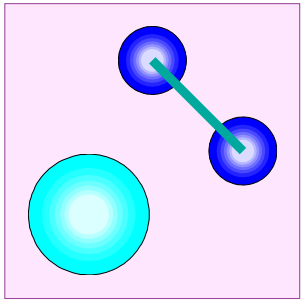


$^{3}_{0}$**n** : n+n+n — Cyril Lenain, PhD

- do multineutrons exist ?
- should multineutrons exist ?

# Scattering lengths & three-body systems



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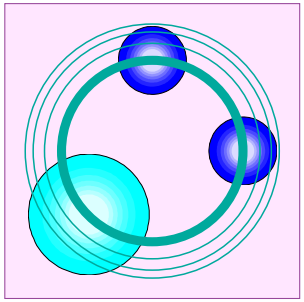

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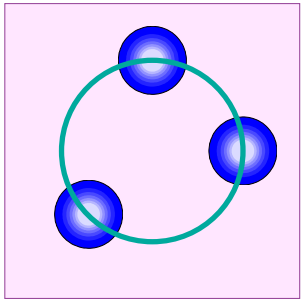

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- do multineutrons exist ?
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# Discovery of the "dineutron" ?

PHYSICAL REVIEW LETTERS

Featured in Physics | Editors' Suggestion

## First Observation of Ground State Dineutron Decay: $^{16}$Be

A. Spyrou, Z. Kohley, T. Baumann, D. Bazin, B. A. Brown, G. Christian, P. A. DeYoung, J. E. Finck, N. Frank, E. Lunderberg, S. Mosby, W. A. Peters, A. Schiller, J. K. Smith, J. Snyder, M. J. Strongman, M. Thoennessen, and A. Volya

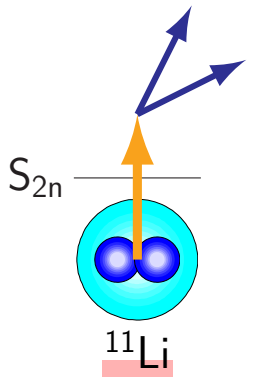
Phys. Rev. Lett. **108**, 102501 – Published 9 March 2012

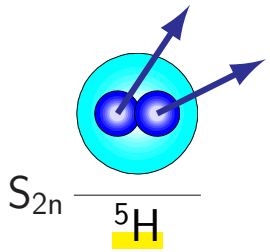
Physics See Focus story: Nuclei Emit Paired-up Neutrons

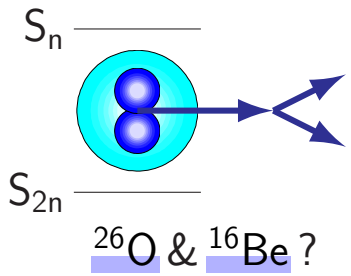
Article | References | Citing Articles (65) | PDF | HTML | Export Citation

ABSTRACT

We report on the first observation of dineutron emission in the decay of $^{16}$Be. A single-proton knockout reaction from a 53 MeV/u $^{17}$B beam was used to populate the ground state of $^{16}$Be. $^{16}$Be is bound with respect to the emission of one neutron and unbound to two-neutron emission. The dineutron character of the decay is evidenced by a small emission angle between the two neutrons. The two-neutron separation energy of $^{16}$Be was measured to be 1.35(10) MeV, in good agreement with shell model calculations, using standard interactions for this mass region.



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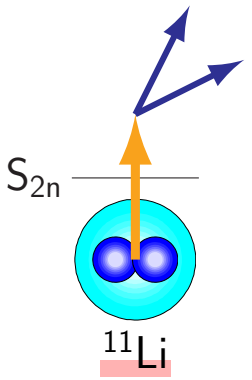


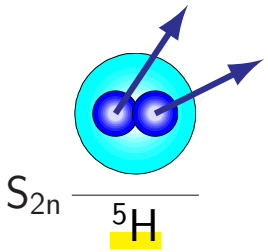


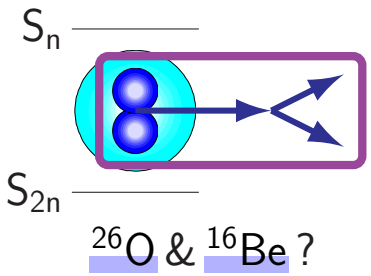

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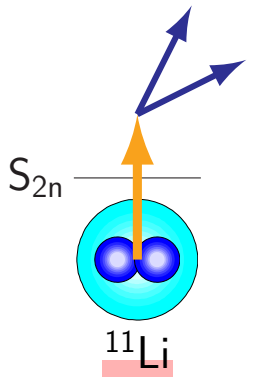
. . .

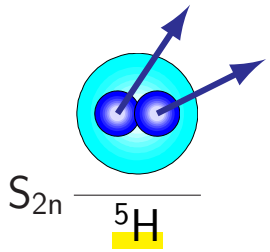
COMMENTS & REPLIES

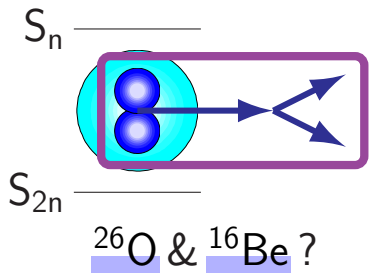
Comment on "First Observation of Ground State Dineutron Decay: $^{16}$Be"

F. M. Marqués, N. A. Orr, N. L. Achouri, F. Delaunay, and J. Gibelin

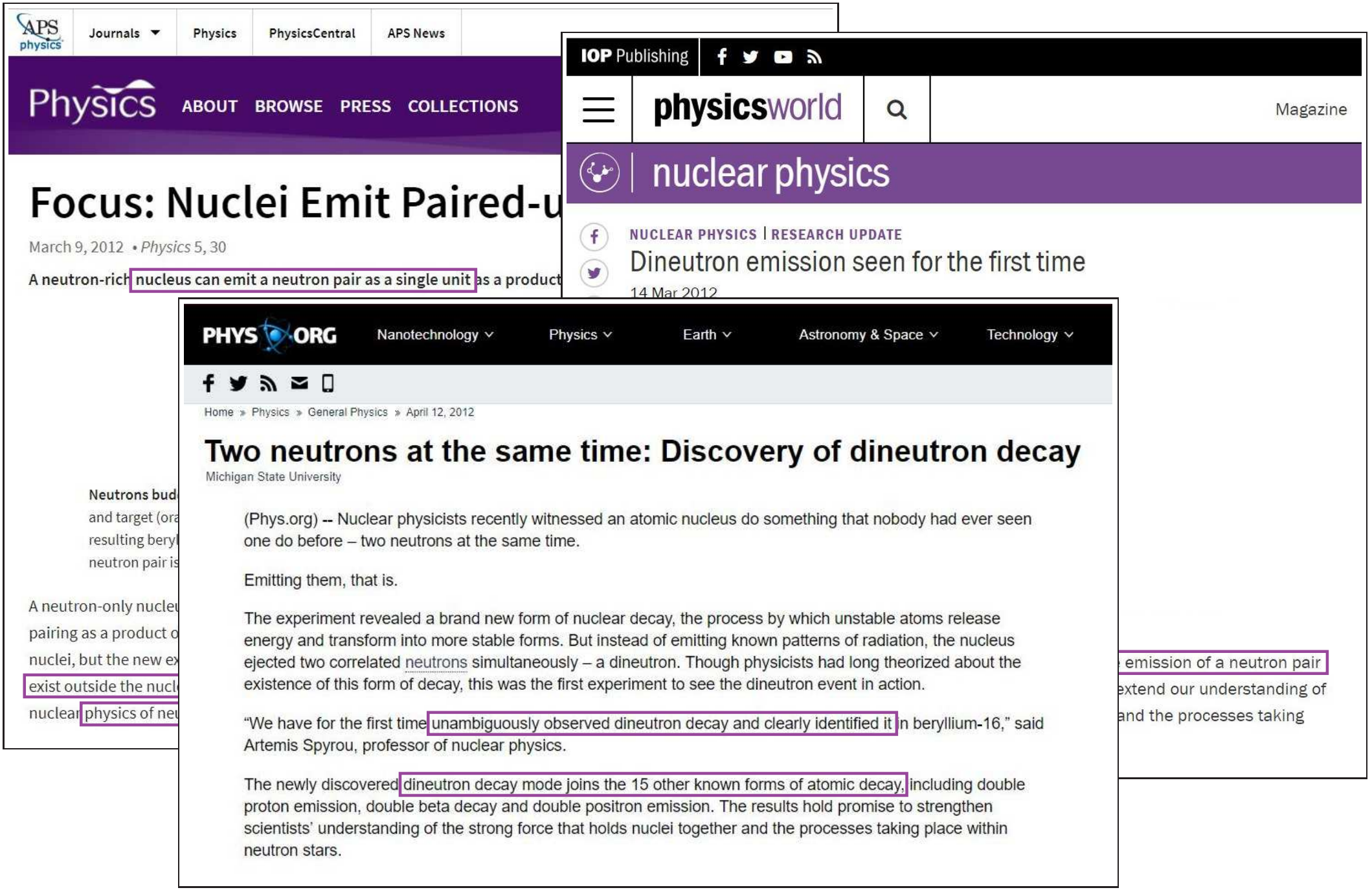
Phys. Rev. Lett. **109**, 239201 (2012)



# News spread ...


APS physics
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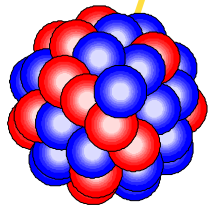
Focus: Nuclei Emit Paired-u
March 9, 2012 • Physics 5, 30
A neutron-rich nucleus can emit a neutron pair as a single unit as a product
IOP Publishing
physicsworld
Magazine
nuclear physics
NUCLEAR PHYSICS | RESEARCH UPDATE
Dineutron emission seen for the first time
14 Mar 2012
PHYS.ORG
Nanotechnology
Physics
Earth
Astronomy & Space
Technology
Home » Physics » General Physics » April 12, 2012
Two neutrons at the same time: Discovery of dineutron decay
Michigan State University
(Phys.org) -- Nuclear physicists recently witnessed an atomic nucleus do something that nobody had ever seen one do before – two neutrons at the same time.
Emitting them, that is.
The experiment revealed a brand new form of nuclear decay, the process by which unstable atoms release energy and transform into more stable forms. But instead of emitting known patterns of radiation, the nucleus ejected two correlated neutrons simultaneously – a dineutron. Though physicists had long theorized about the existence of this form of decay, this was the first experiment to see the dineutron event in action.
"We have for the first time unambiguously observed dineutron decay and clearly identified it in beryllium-16," said Artemis Spyrou, professor of nuclear physics.
The newly discovered dineutron decay mode joins the 15 other known forms of atomic decay, including double proton emission, double beta decay and double positron emission. The results hold promise to strengthen scientists' understanding of the strong force that holds nuclei together and the processes taking place within neutron stars.

# Sculpting Beryllium 16 [S18, Kubota/Corsi]

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

$\beta \sim 0.6\,c$

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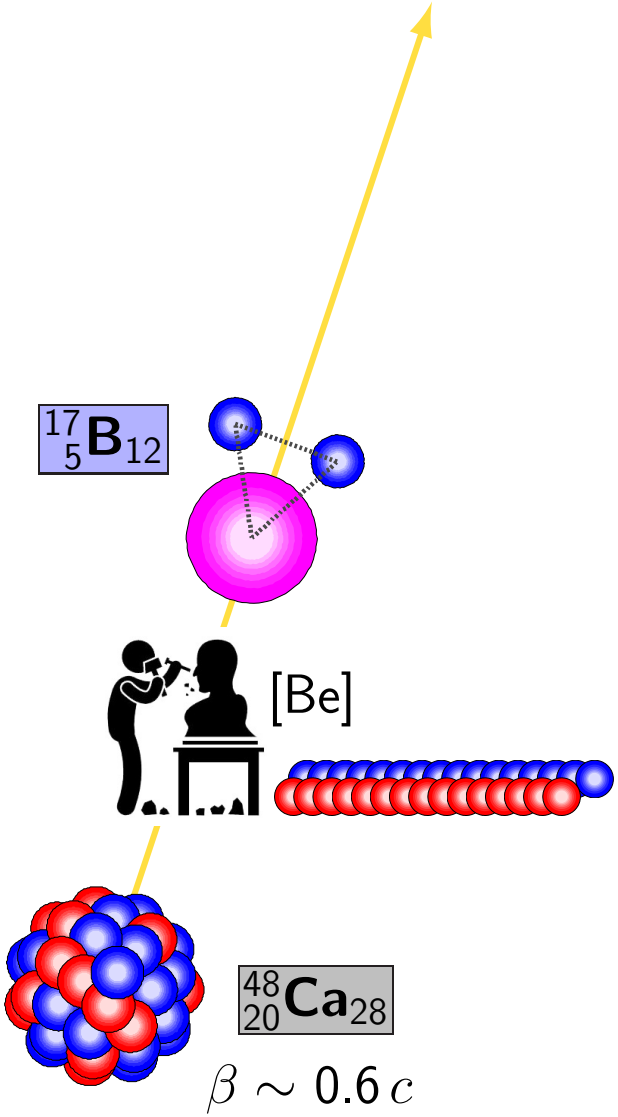

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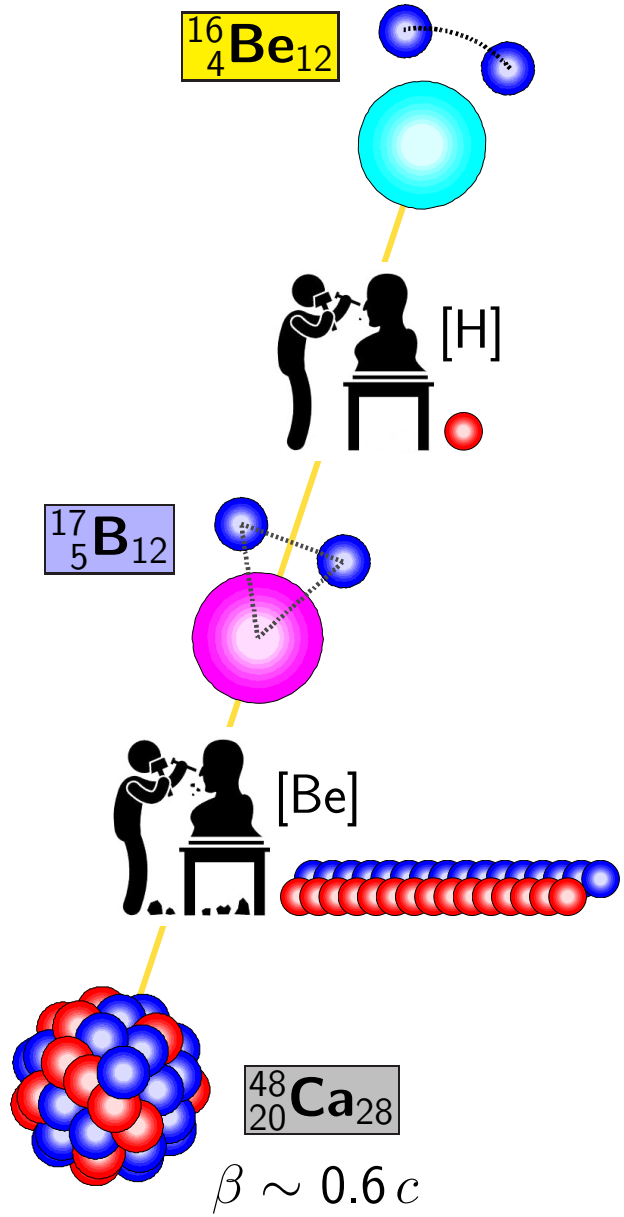
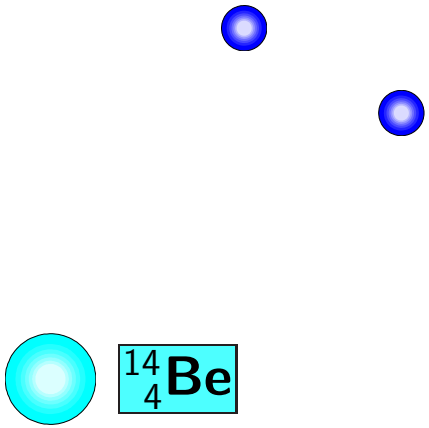


# Beryllium 16 goes to Hollywood



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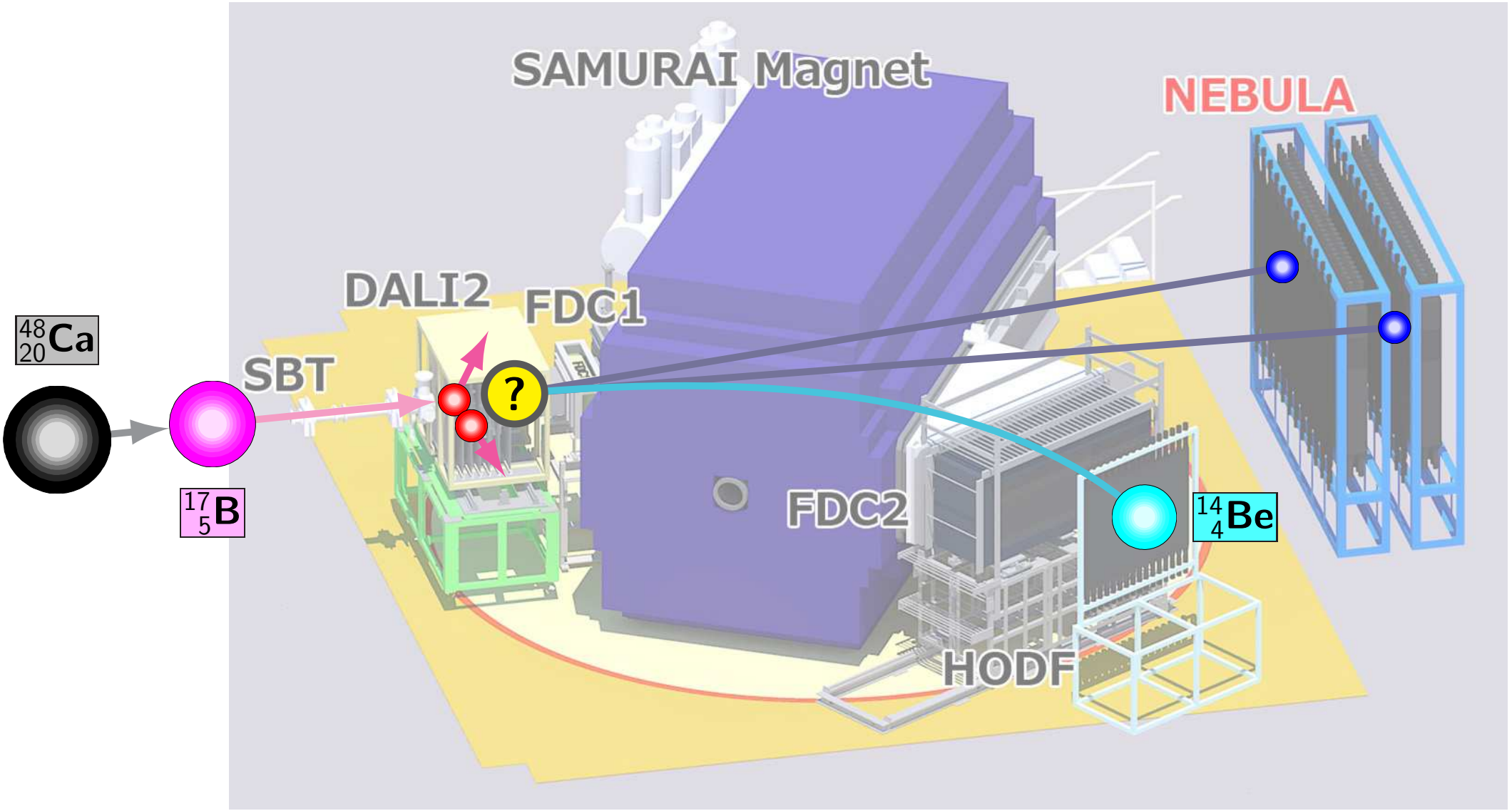

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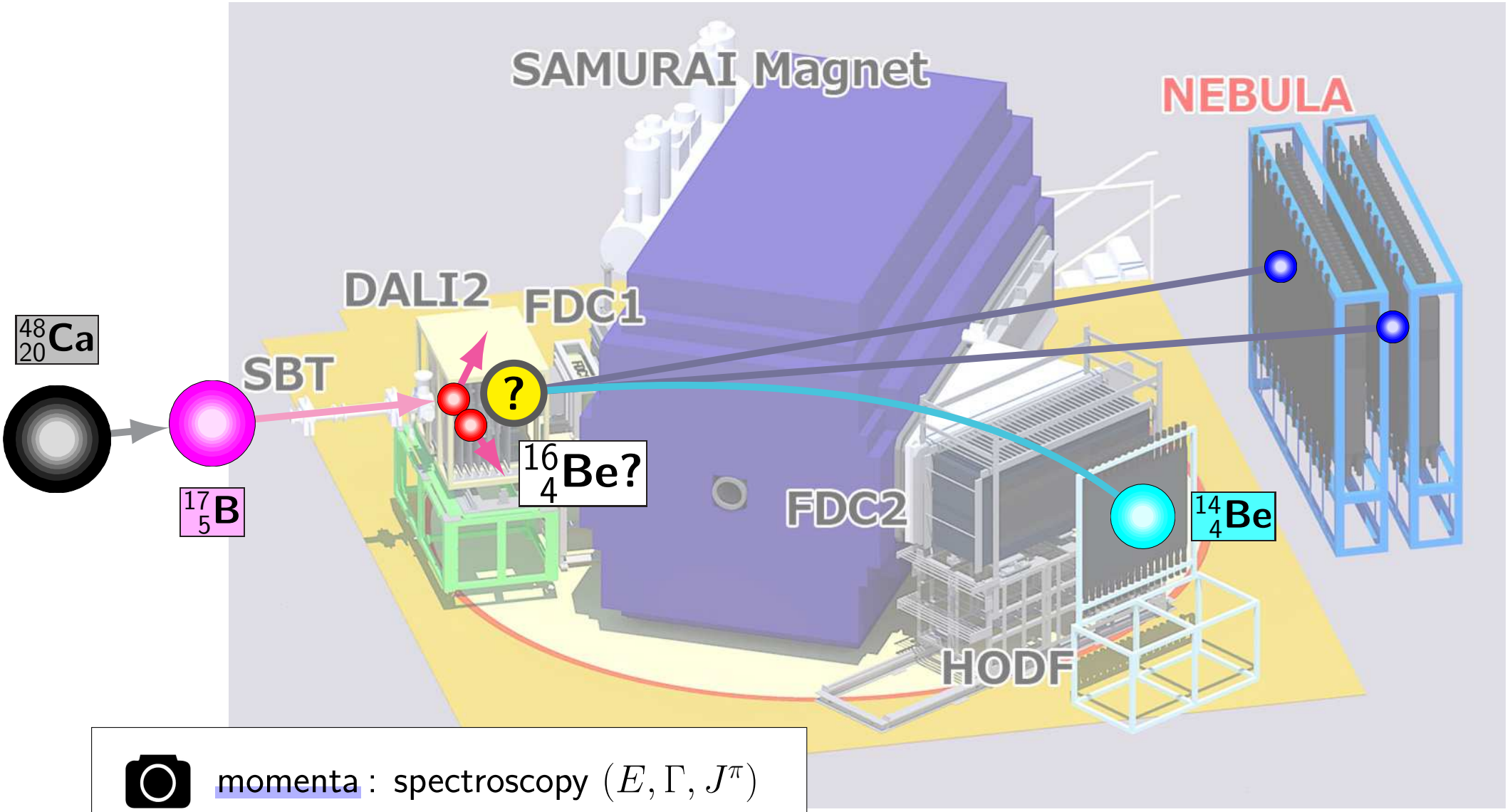



momenta : spectroscopy $(E, \Gamma, J^\pi)$

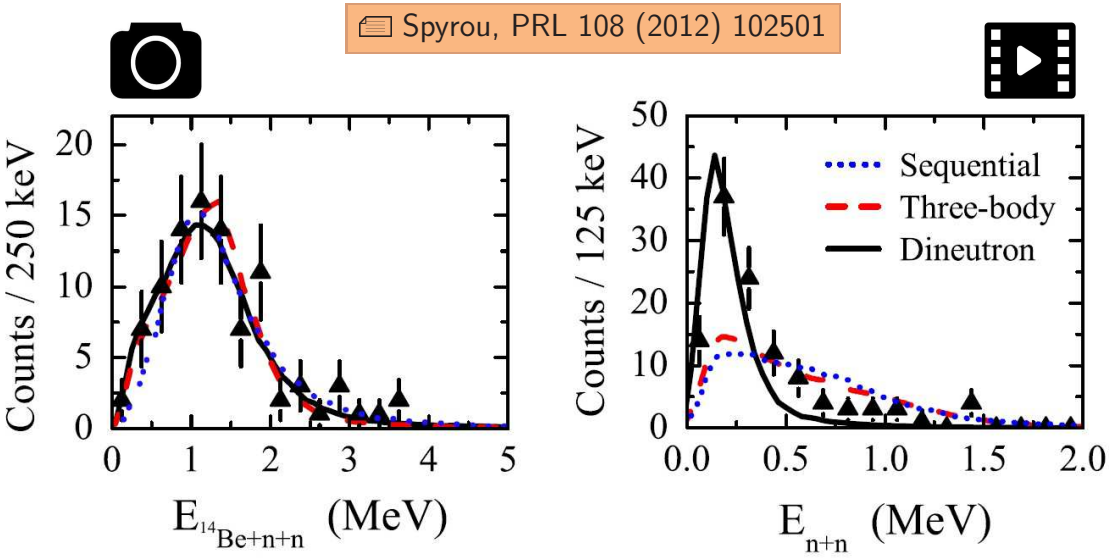
correlations : decay, sequentiality ...

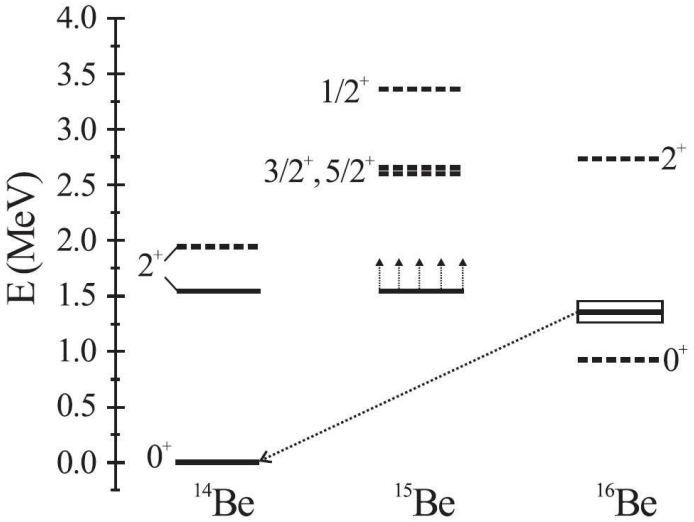
Corsi, PLB 797 (2019) 134843 : QFS into $^{13}$Be

Kubota, PRL 125 (2020) 252501 : 2n in $^{11}$Li

# The new Beryllium 16 [Monteagudo]

Spyrou, PRL 108 (2012) 102501



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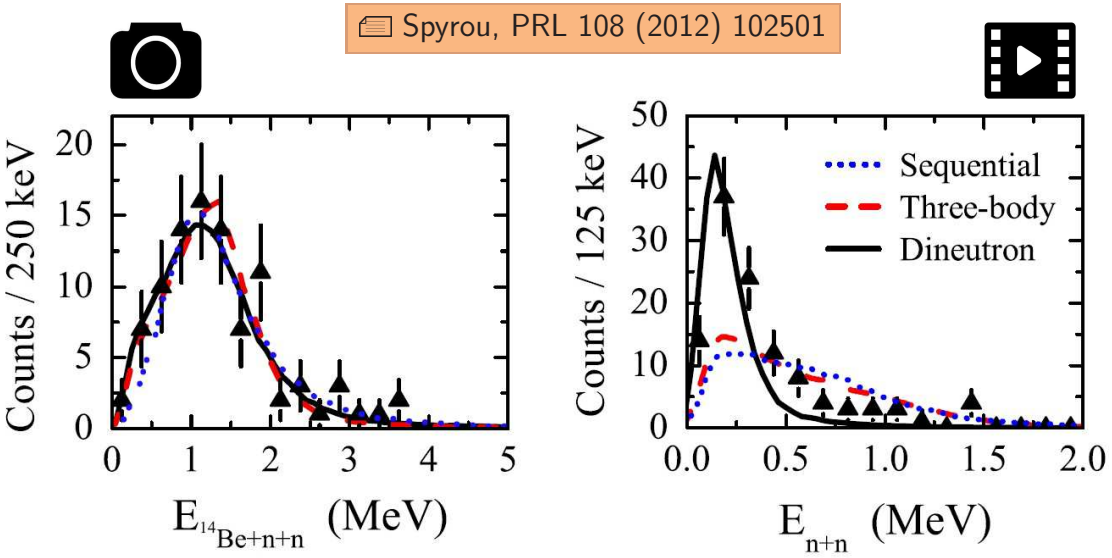


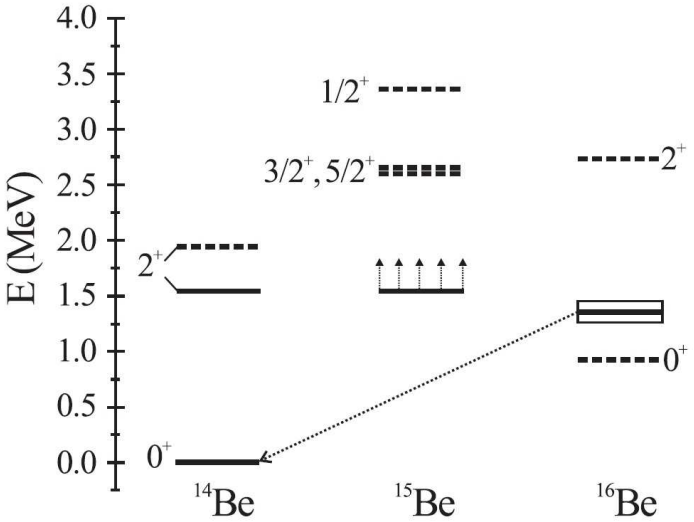


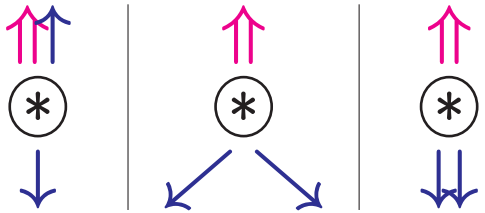

FMM, PRL 109 (2012) 239201

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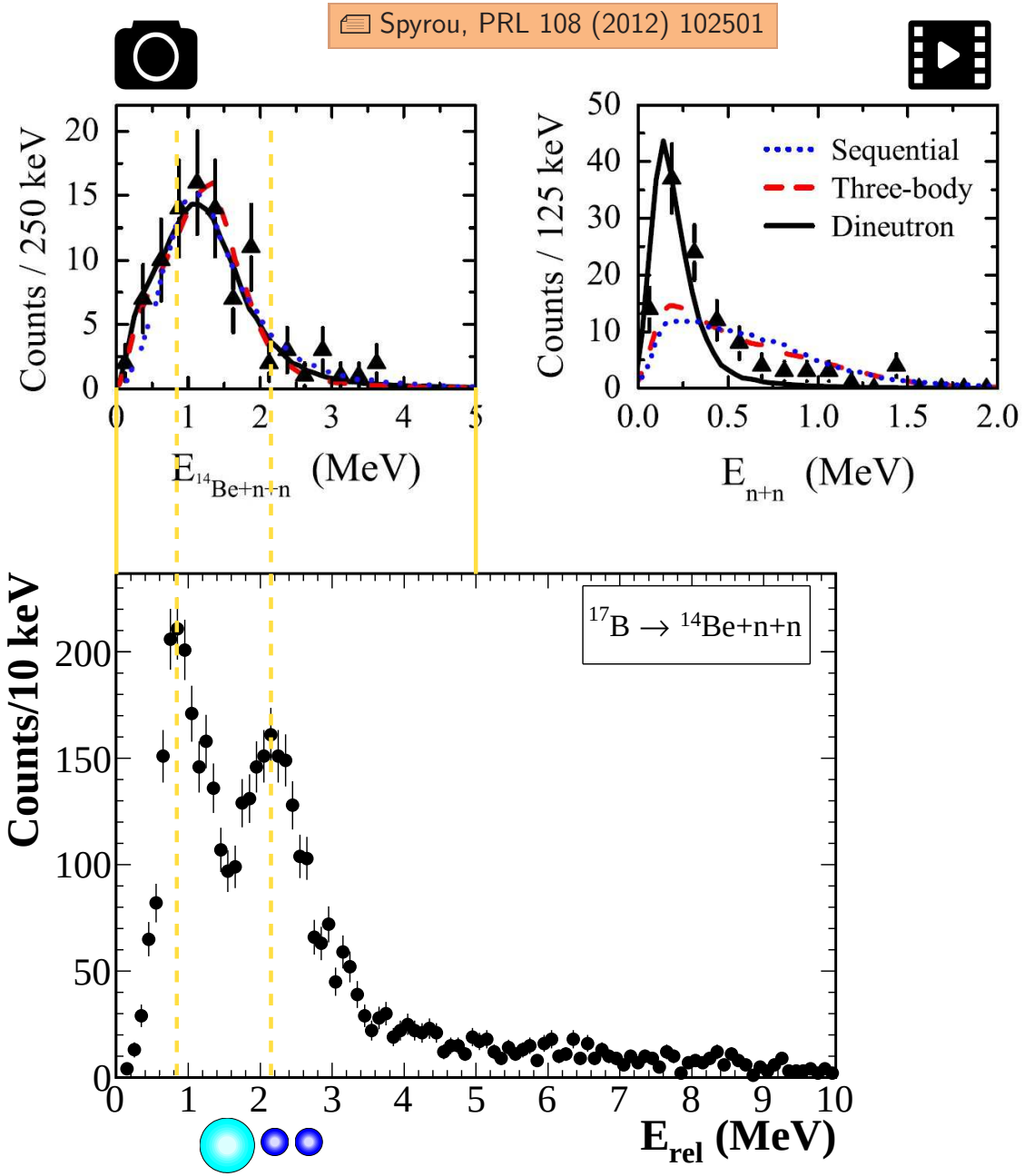
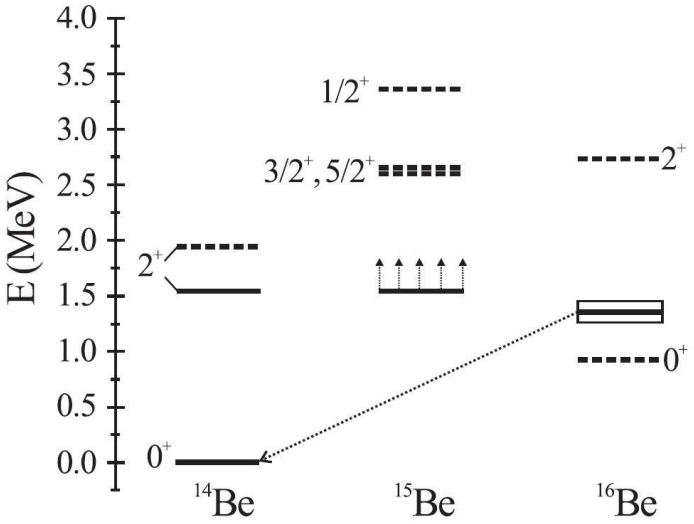
Spyrou, PRL 108 (2012) 102501



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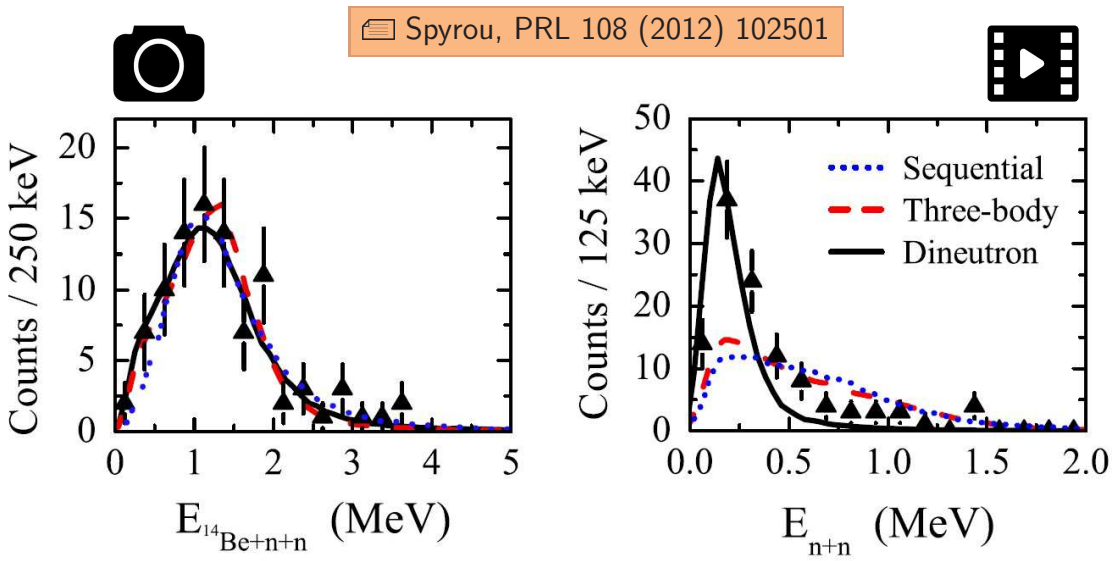
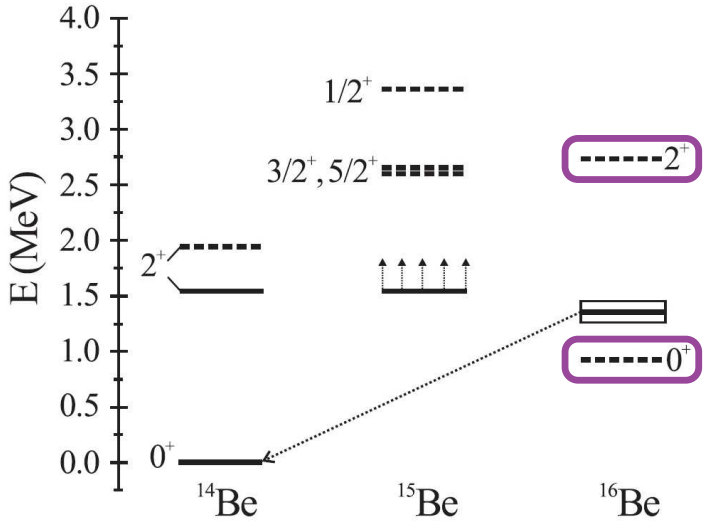
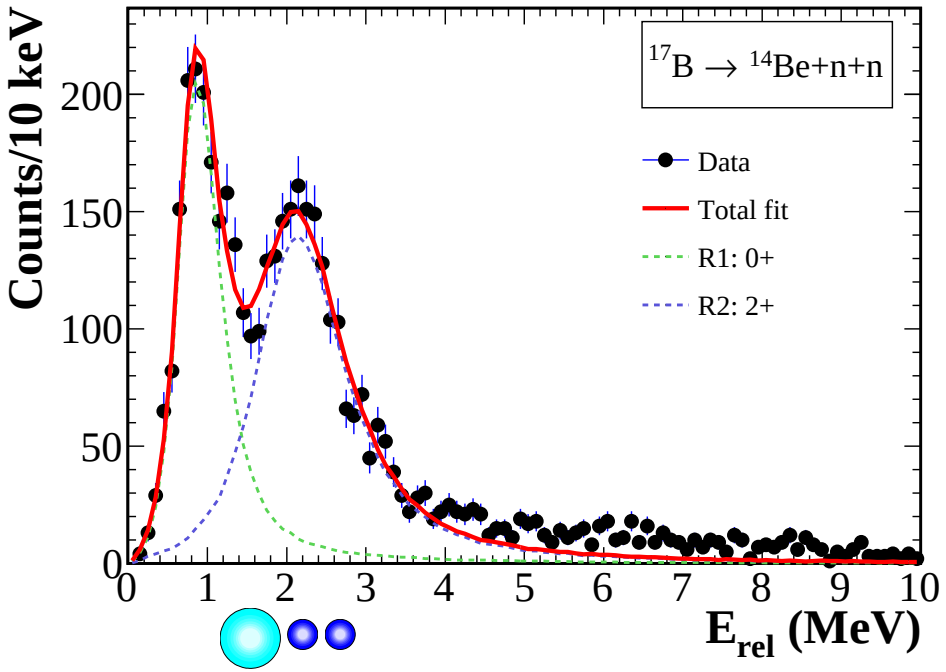
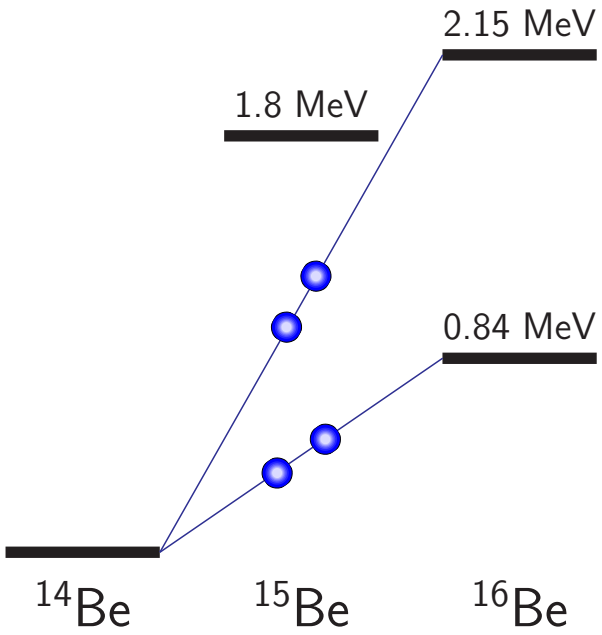
Spyrou, PRL 108 (2012) 102501



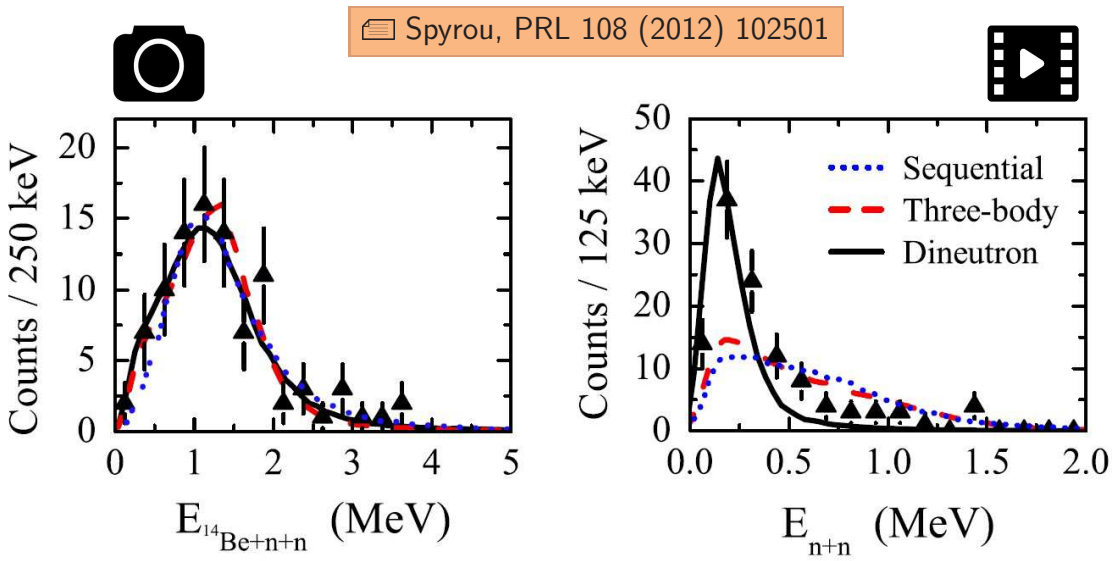



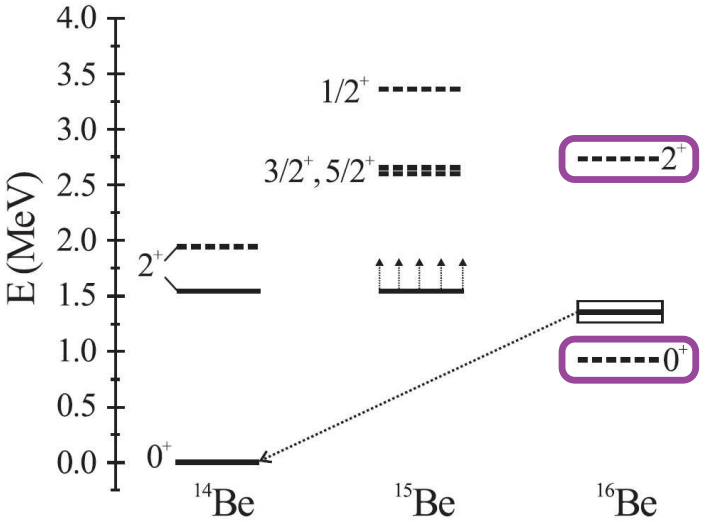



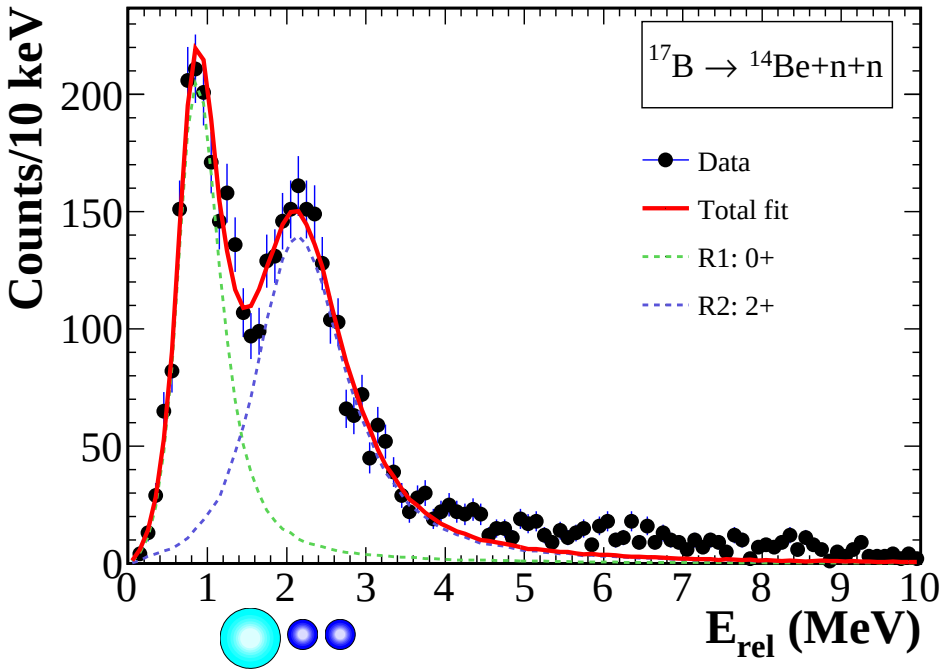



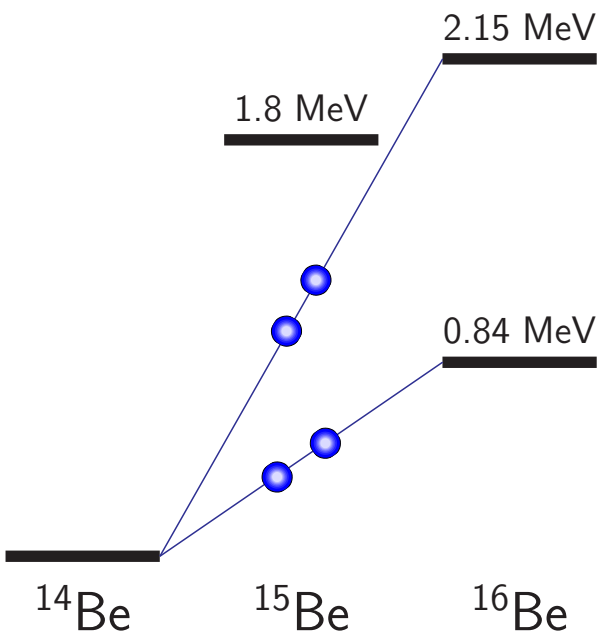
# The new Beryllium 16 [Monteagudo]

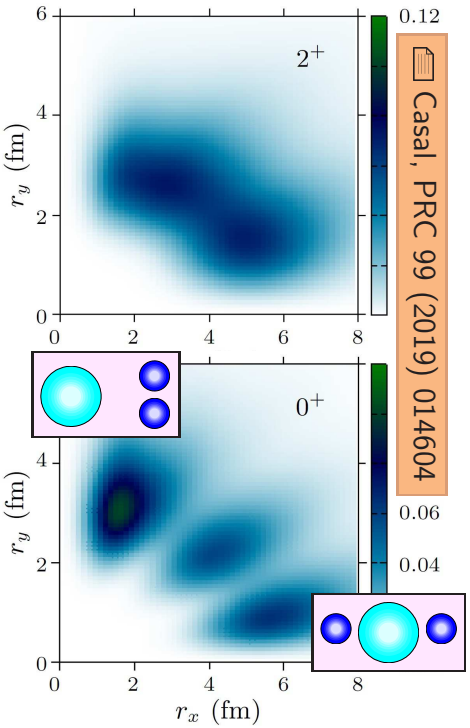
Spyrou, PRL 108 (2012) 102501



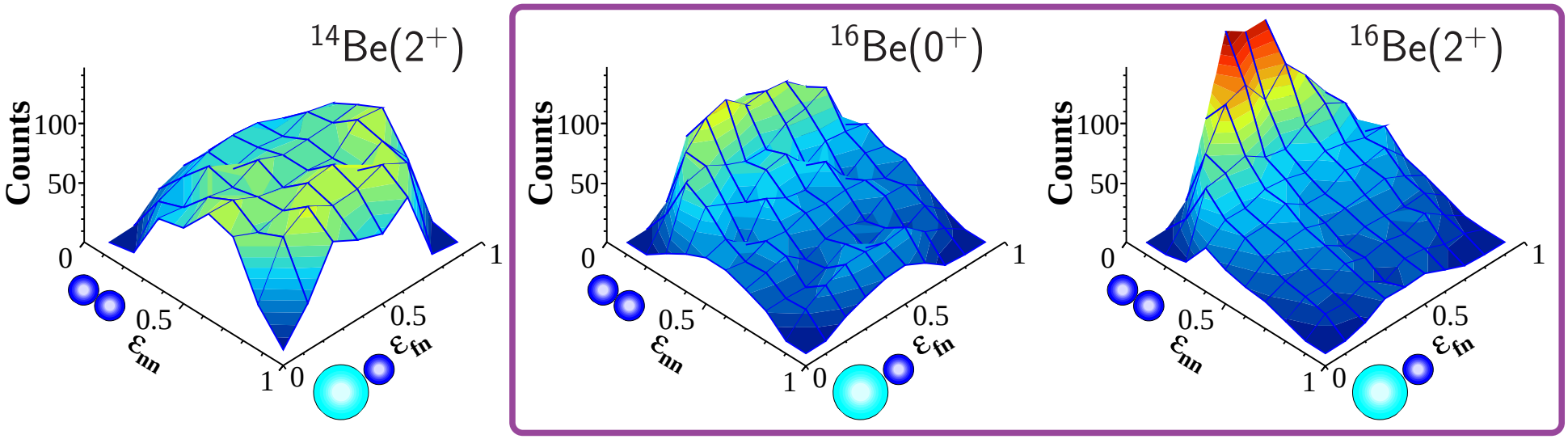




Casal, PRC 99 (2019) 014604

# Probing the 2n wave function [Monteagudo, Casal]

- Dalitz plot of 2n decay :



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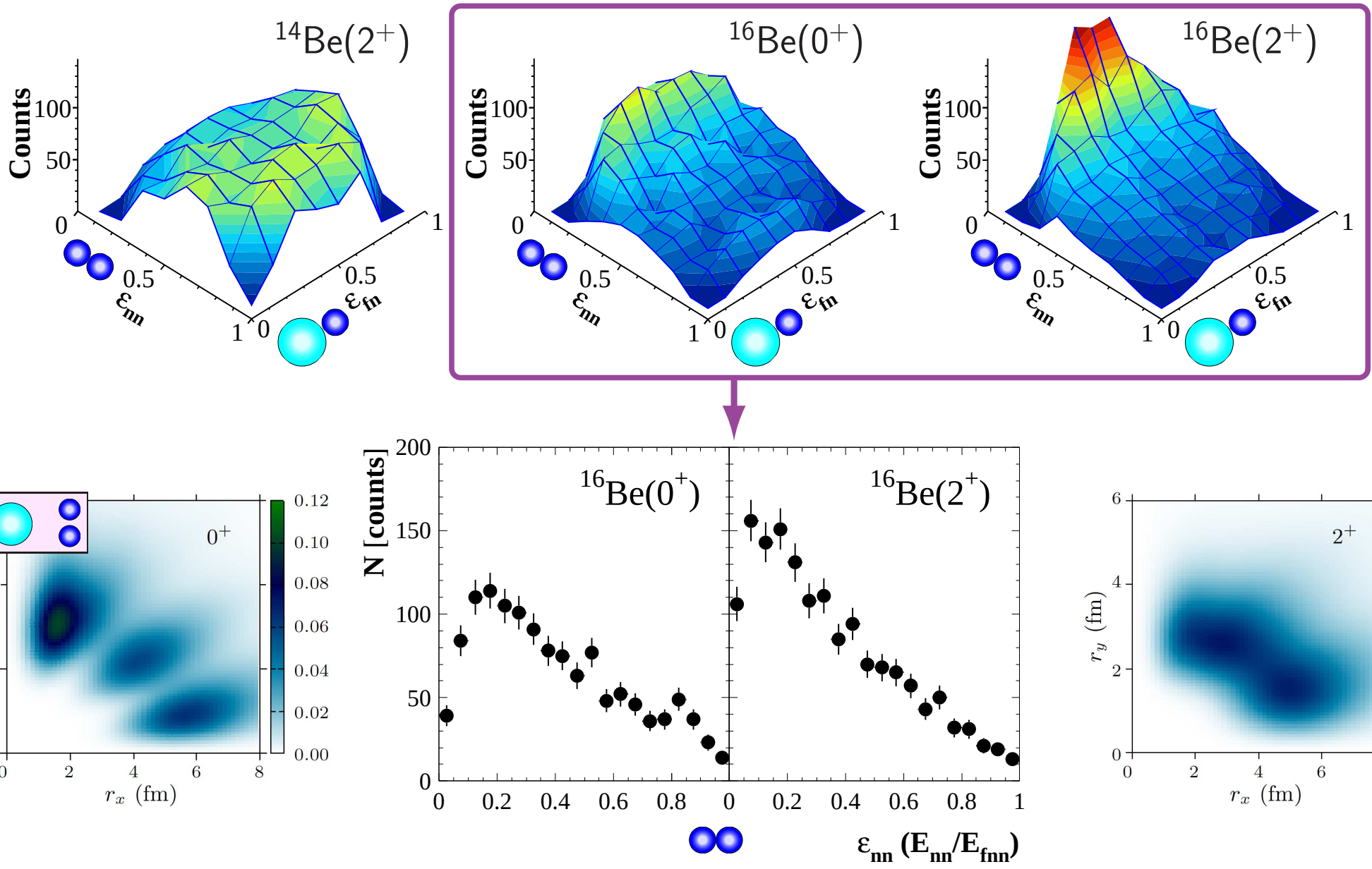

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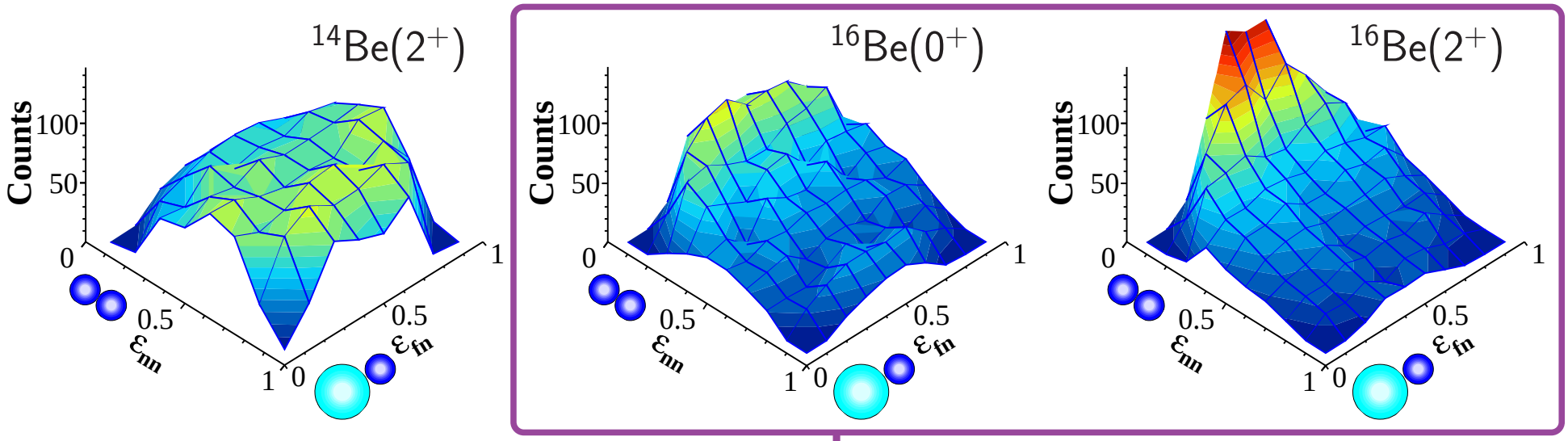
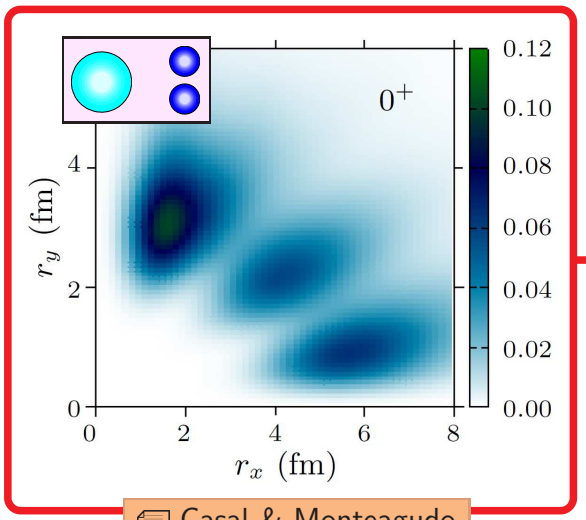
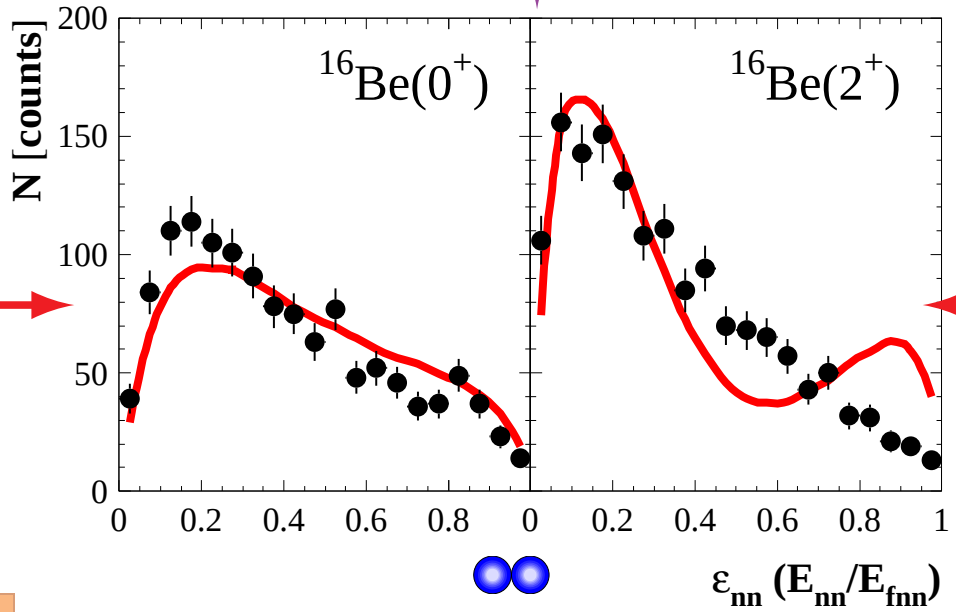
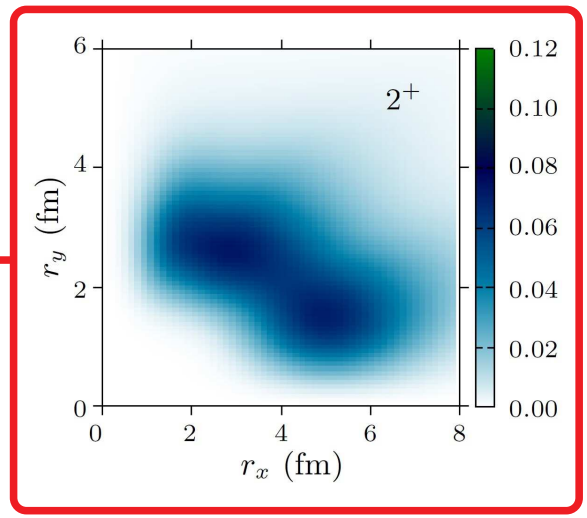


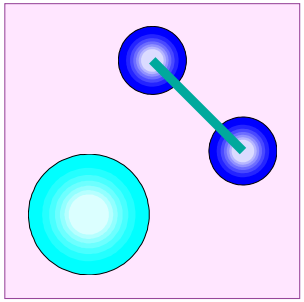




Casal & Monteagudo

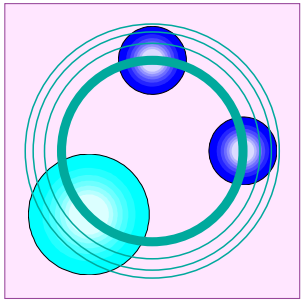
Wang, PRL 126 (2021) 142501

# Scattering lengths & three-body systems



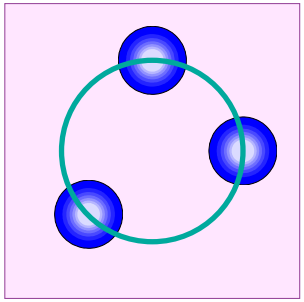
$^{16}_{4}$**Be** : $^{14}$Be+n+n — Belén Monteagudo, PhD

- $a_s$(nn) strong enough for "dineutron" ?
- experimental signature ?



$^{19}_{5}$**B** : $^{17}$B+n+n — Hiyama, PRC 100 (2019) 011603R

- $a_s(^{18}\mathrm{B})$ strong enough for Efimov states ?
- how big should it be ?



$^{3}_{0}$**n** : n+n+n — Cyril Lenain, PhD

- do multineutrons exist ?
- should multineutrons exist ?

# Should they exist ?

FMM & Carbonell, EPJA 57 (2021) 105

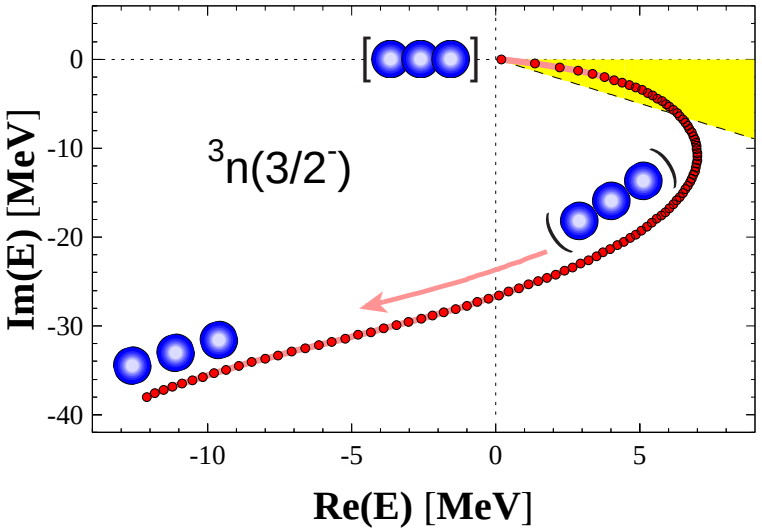
- 'Exact' calculations are categorical !

Glöckle, PRC 18 (1978) 564 : $V_{nn} \times 4.2$

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

Witała, PRC 60 (1999) 024002 : avoid $^2$n with $V_{nn}(^1S_0) \times 1$

Hemmdan, PRC 66 (2002) 054001 :




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

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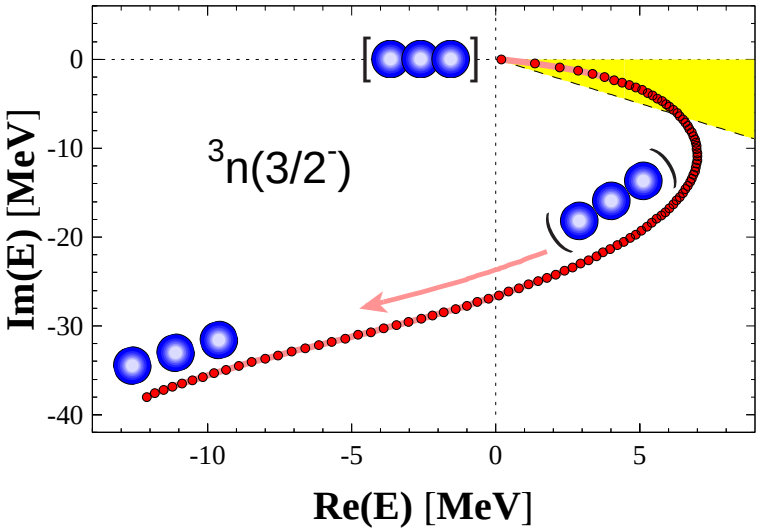


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(3n) Lazauskas, PRC 71 (2005) 044004 : 3NF ✘

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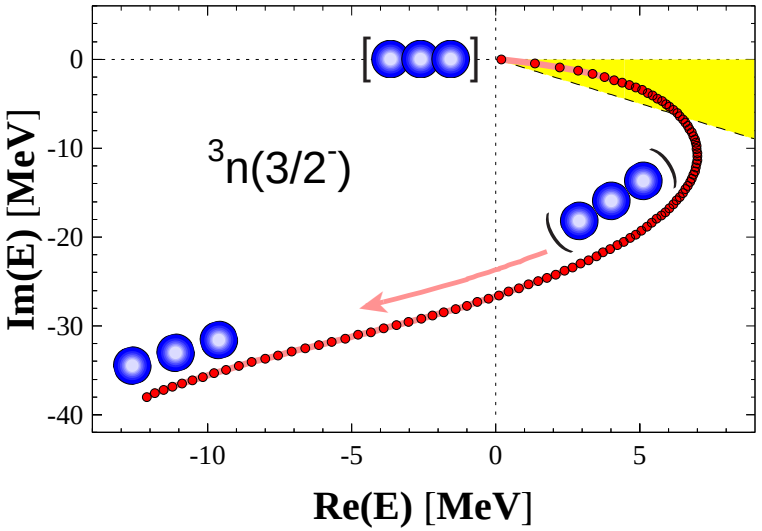


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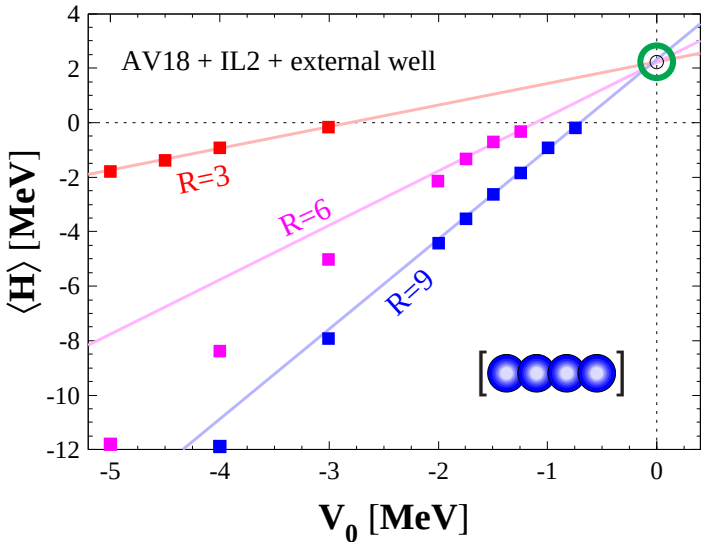
- Many-body approximations, not so much ...

Pieper, PRL 90 (2003), 252501 :




*"the resonance, if it exists at all, must be very broad"*

Shirokov, PRL 117 (2016) 182502

Gandolfi, PRL 118 (2017) 232501

Fossez, PRL 119 (2017) 032501

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} 3n/4n ✔ ?

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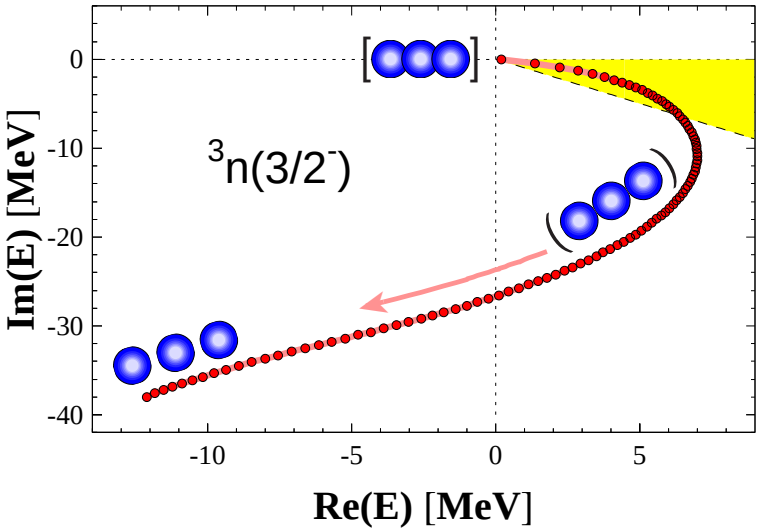


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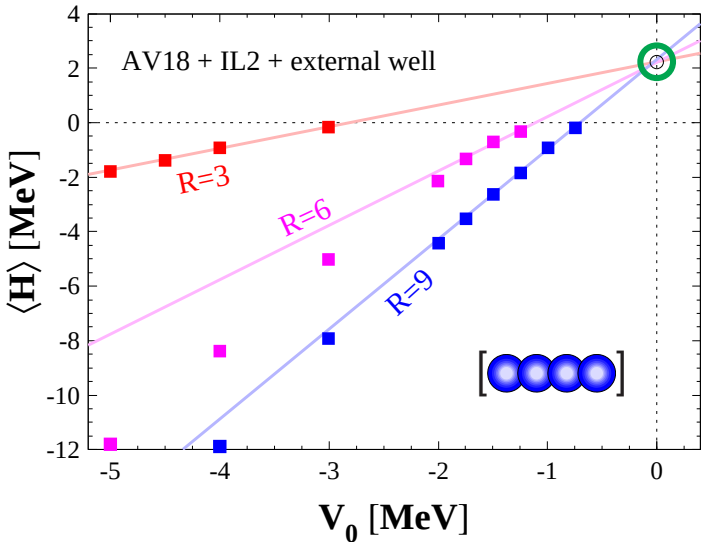


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} 3n/4n ✔ ?

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 ...

# Searching for 3n into the light

Miller, NPA 343 (1980) 347 :

$^3$H ($\pi^-$, $\gamma$) 3n

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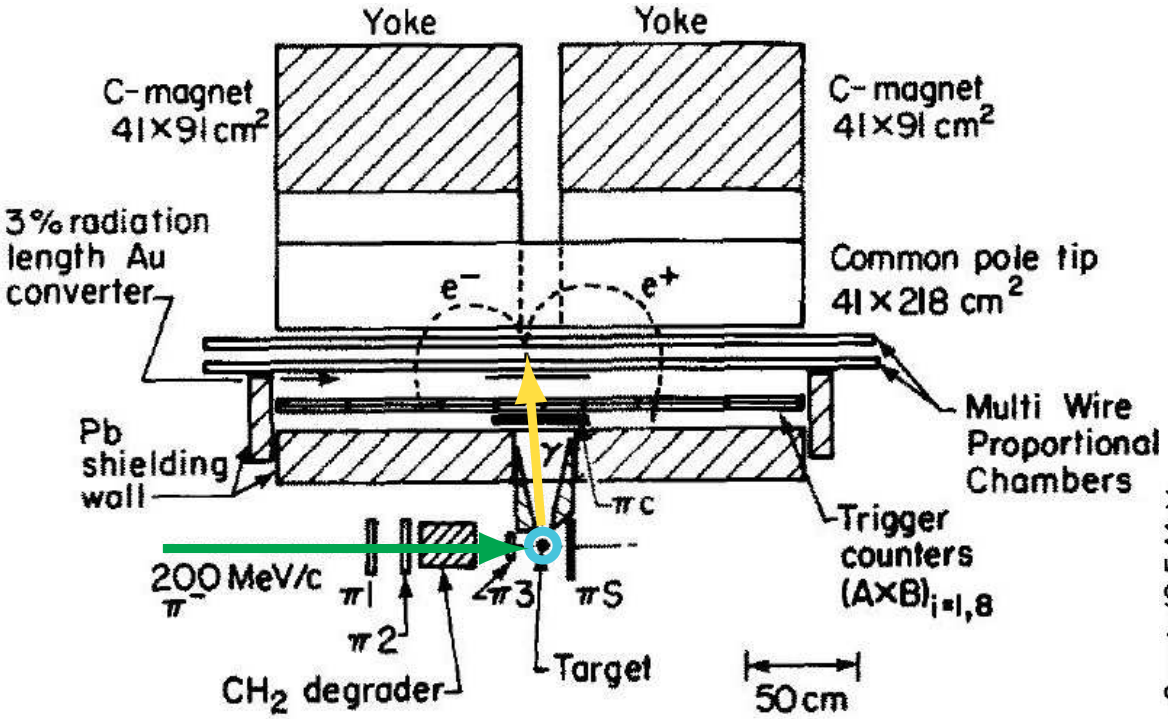


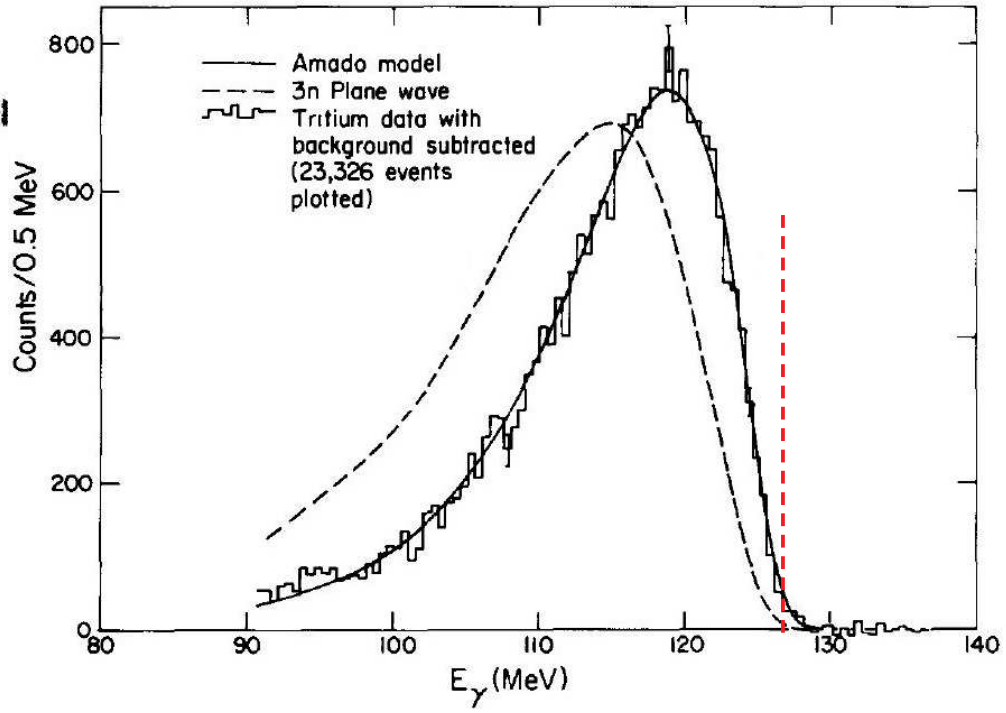

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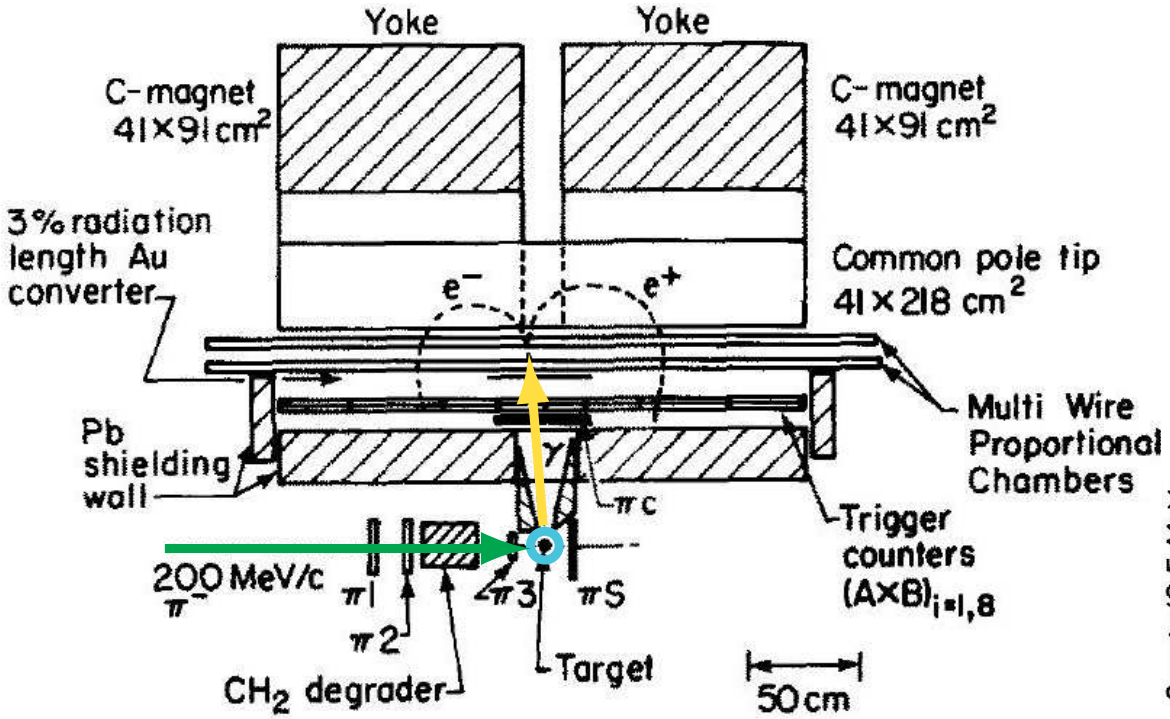


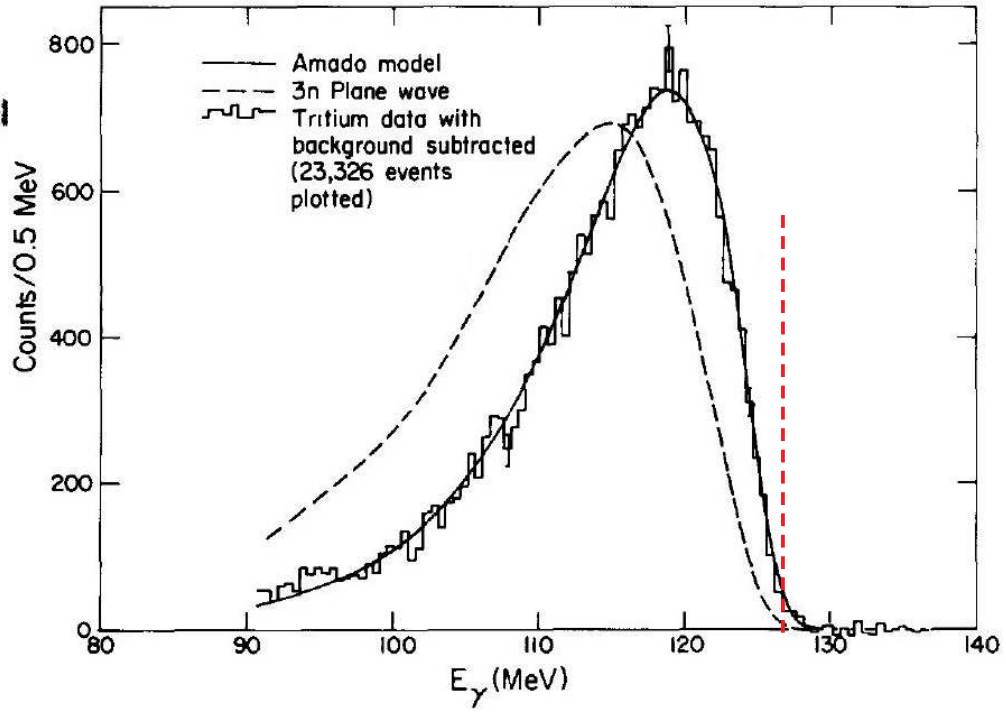


*"We have performed an experiment highly sensitive to 3n structure near threshold and see no evidence for it. A shift to low 3n energy can be explained in terms of the simple s-wave pairwise interaction between neutrons"*

# Don't waste your money !

Offermann & Glöckle, NPA 318 (1979) 138 :

*"The [changes] are not so small that one likes to push forward a very expensive experiment to measure a three-neutron resonance"*

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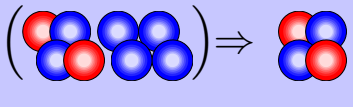
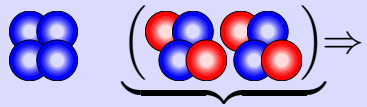
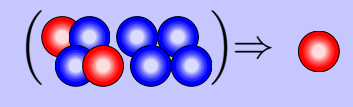
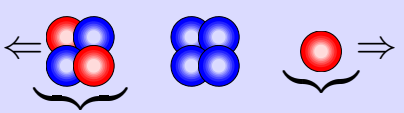
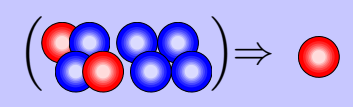
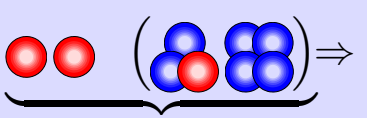
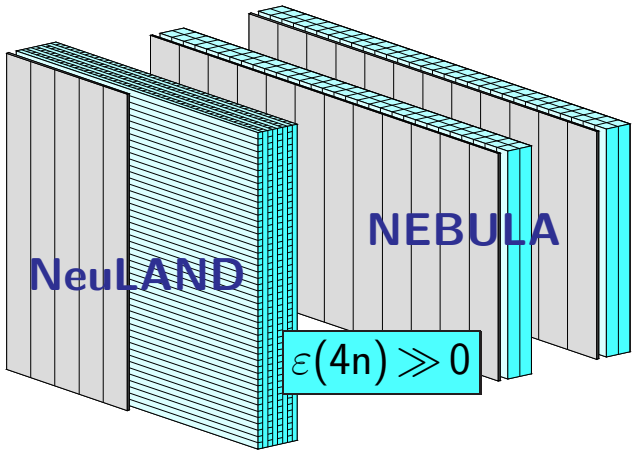
| reaction | initial state | final state | $\sigma$ | results |
|---|---|---|---|---|
| ('16) $^{4}$He $(^{8}$He, $\alpha\alpha)$ $^{4}$**n**<br>Shimoura, NP1512-SHARAQ10 |  |  | nb | $N_{evt} \sim 10$ s<br>$^{4}$n : E, $\Gamma$ |
| ('17) $^{8}$He (p,p$\alpha$) $^{4}$**n**<br>Paschalis, NP1406-SAMURAI19 |  |  | $\mu$b | $N_{evt} \sim 1000$ s<br>$^{4}$n : E, $\Gamma$ |
| ('17) $^{8}$He (p,2p) $\{^{3}$**H**$+^{4}$**n**$\}$<br>FMM/Yang, NP1512-SAMURAI34 |  |  | **mb** | $N_{evt} \sim$ **10,000** s<br>$^{4}$n & $^{7}$H : E, $\Gamma$, $\Omega$ |

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



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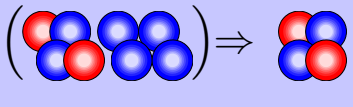
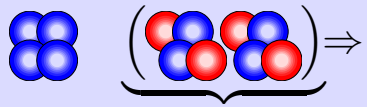
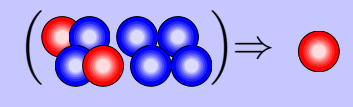
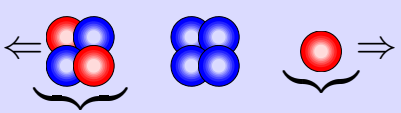
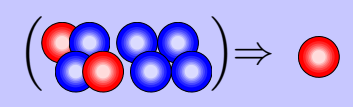
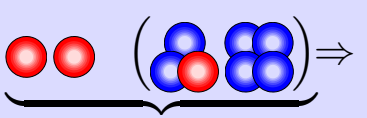
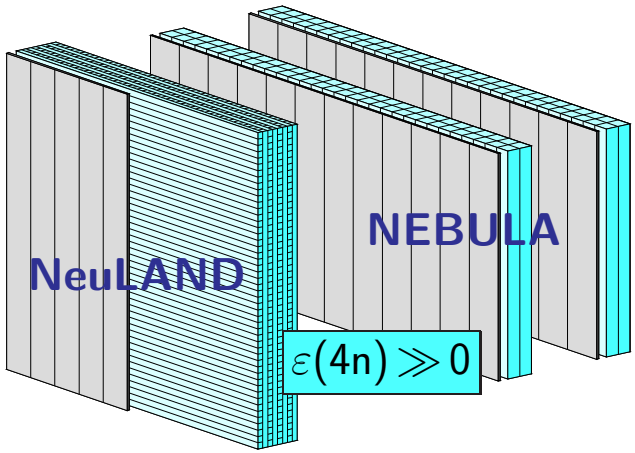
| ('16) $^{4}$He $(^{8}$He, $\alpha\alpha)$ $^{4}$**n**<br>Shimoura, NP1512-SHARAQ10 |  |  | nb | $N_{evt} \sim 10$ s<br>$^{4}$n : E, $\Gamma$ |
| ('17) $^{8}$He (p,p$\alpha$) $^{4}$**n**<br>Paschalis, NP1406-SAMURAI19 |  |  | $\mu$b | $N_{evt} \sim 1000$ s<br>$^{4}$n : E, $\Gamma$ |
| ('17) $^{8}$He (p,2p) $\{^{3}$**H**$+^{4}$**n**$\}$<br>FMM/Yang, NP1512-SAMURAI34 |  |  | **mb** | $N_{evt} \sim$ **10,000** s<br>$^{4}$n & $^{7}$H : E, $\Gamma$, $\Omega$ |

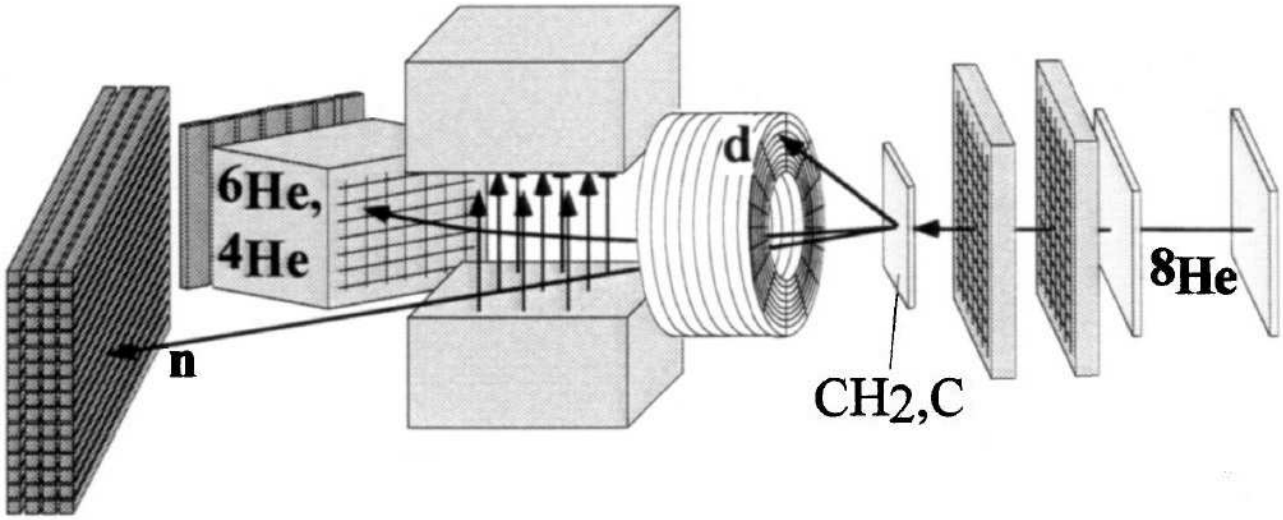
$^{8}$He (p,2p) $^{7}$H $\longrightarrow$ $^{3}$H + $^{4}$n ?

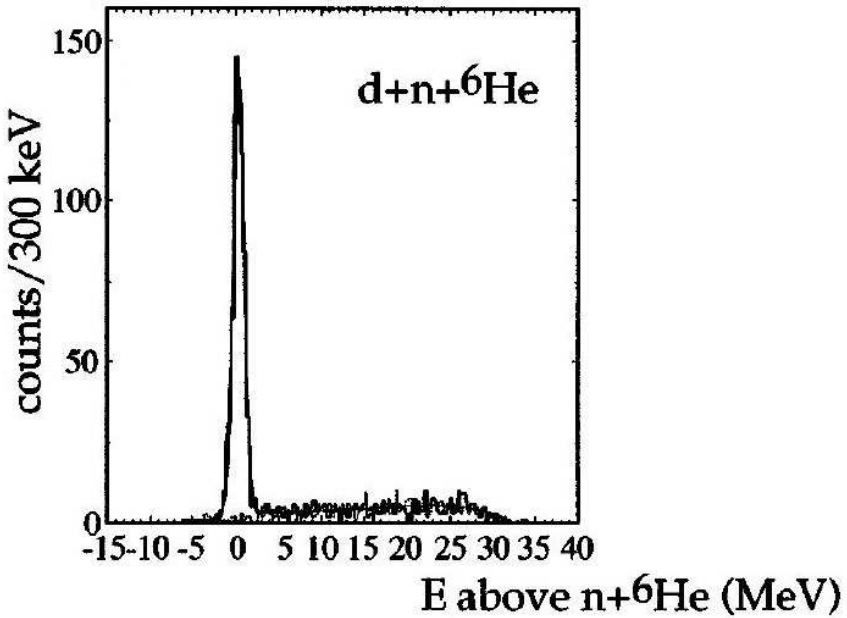
$^{8}$He (p,pn) $^{7}$He* $\longrightarrow$ $^{4}$He + $^{3}$n ???



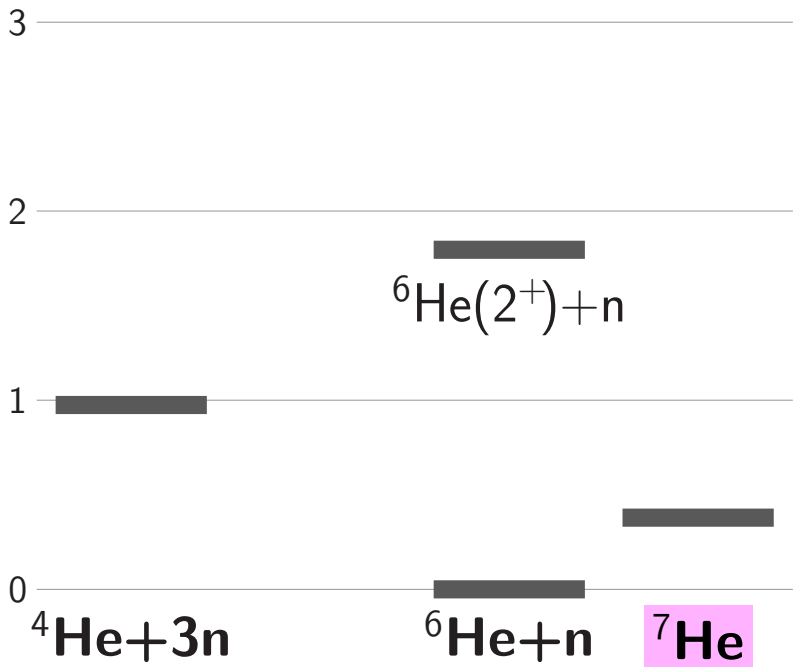
# “Excited state with unusual structure”

Korsheninnikov, PRL 82 (1999) 3581 :



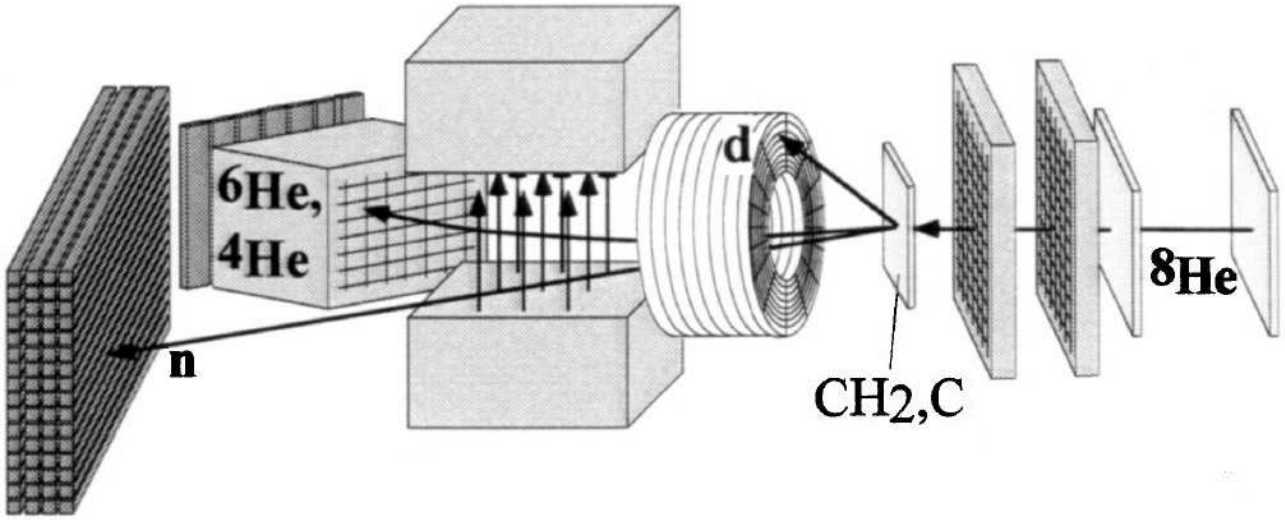



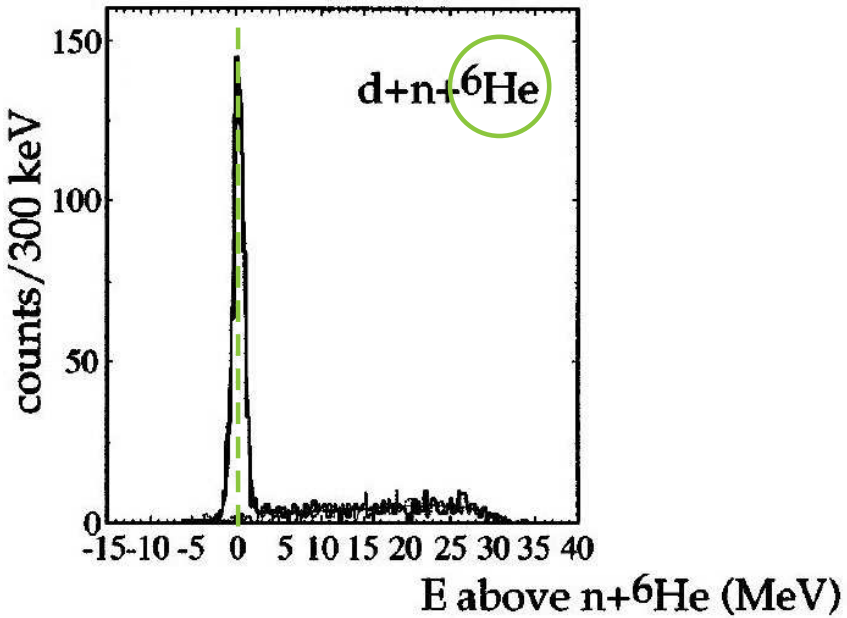

$^{8}\mathrm{He}\,(\mathrm{p},\mathrm{d})\,^{7}\mathrm{He}$



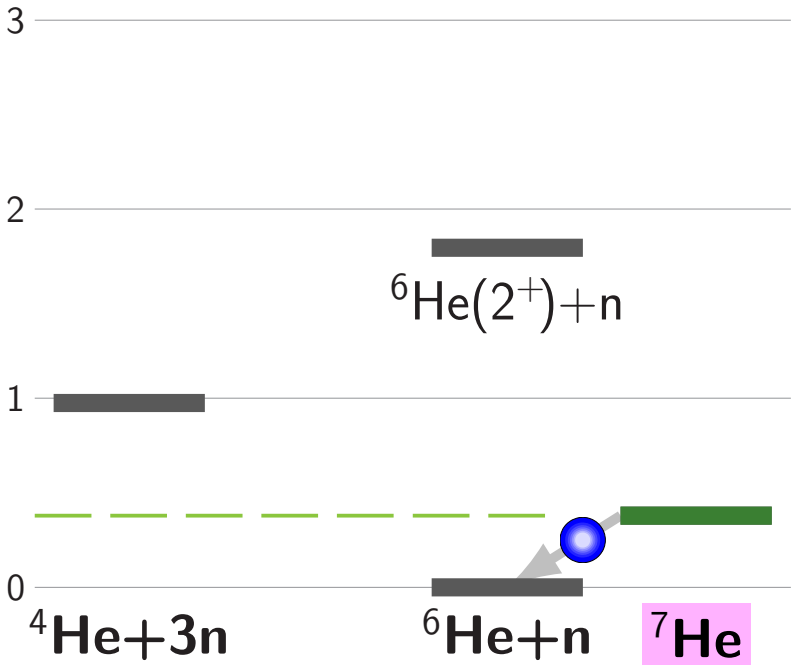
# “Excited state with unusual structure”

Korsheninnikov, PRL 82 (1999) 3581 :




$^{8}$He (p, d) $^{7}$He



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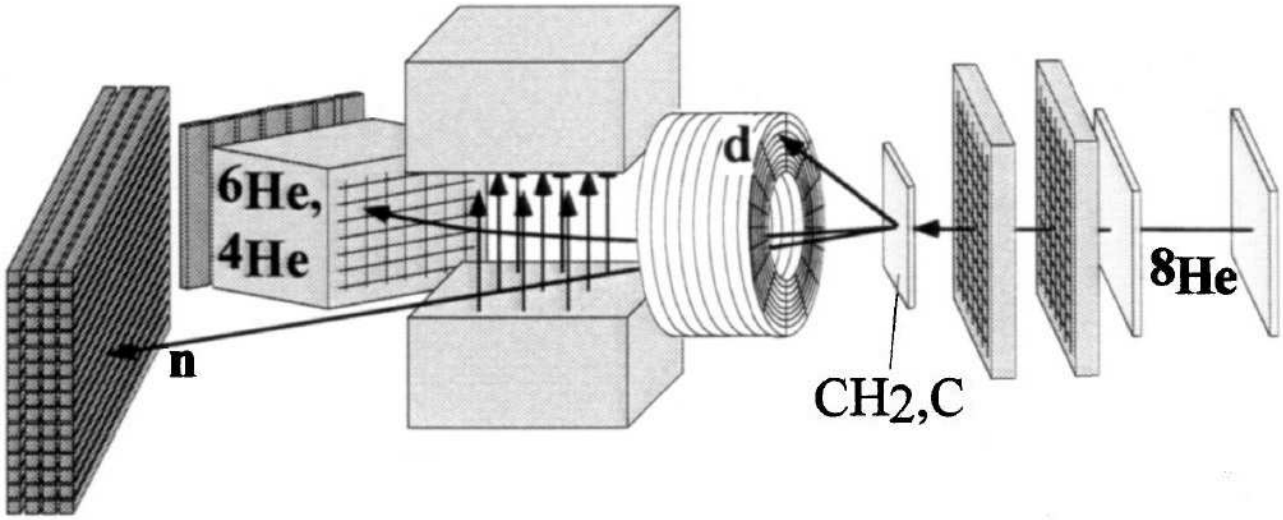
Korsheninnikov, PRL 82 (1999) 3581 :

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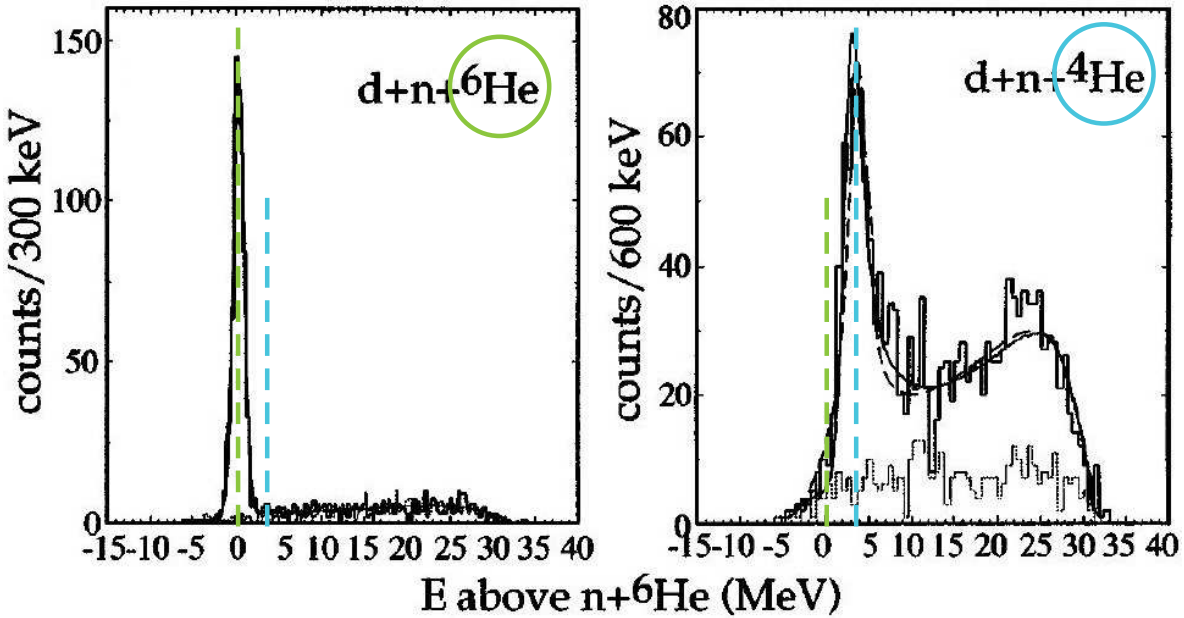


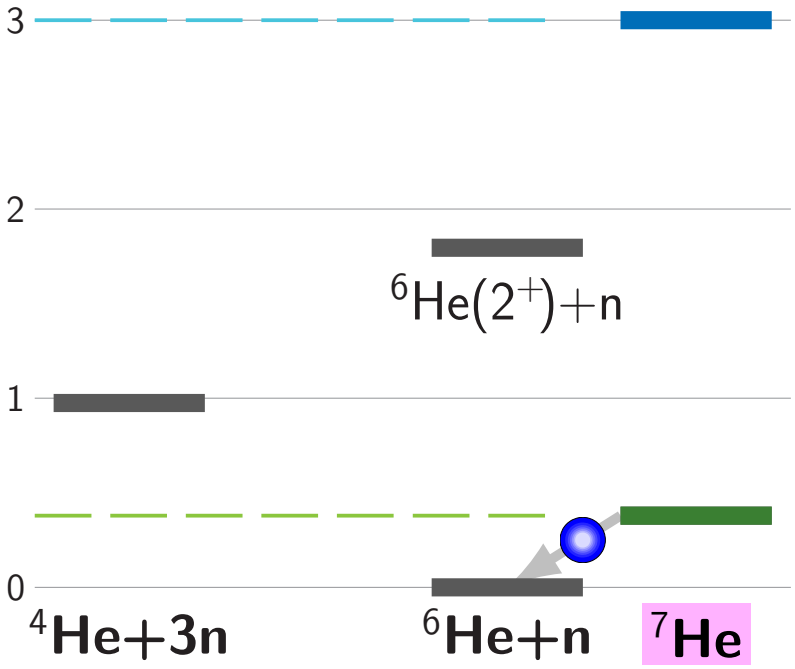

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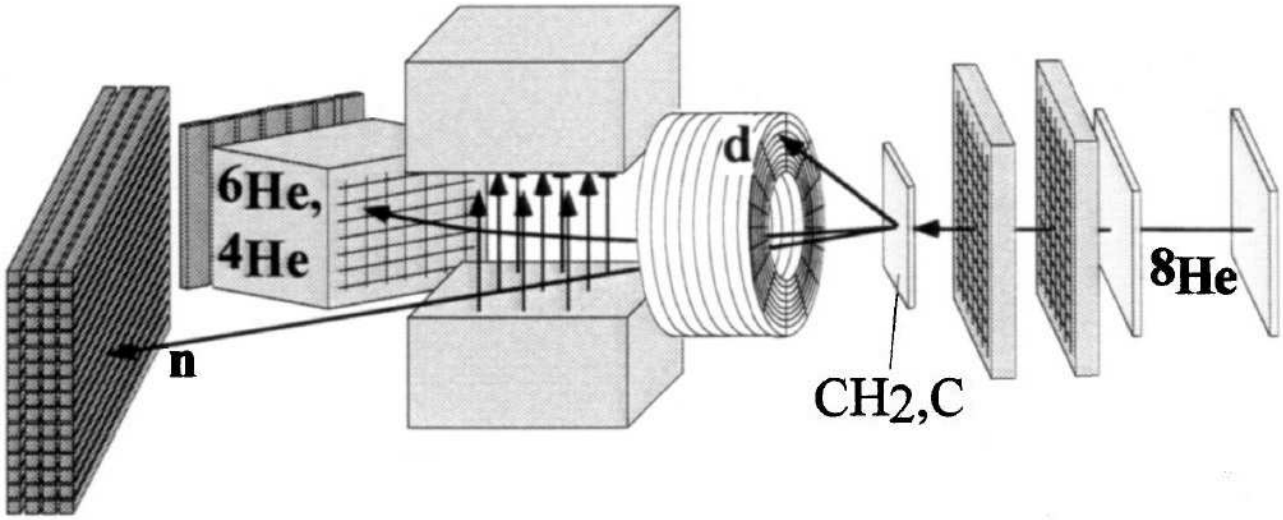
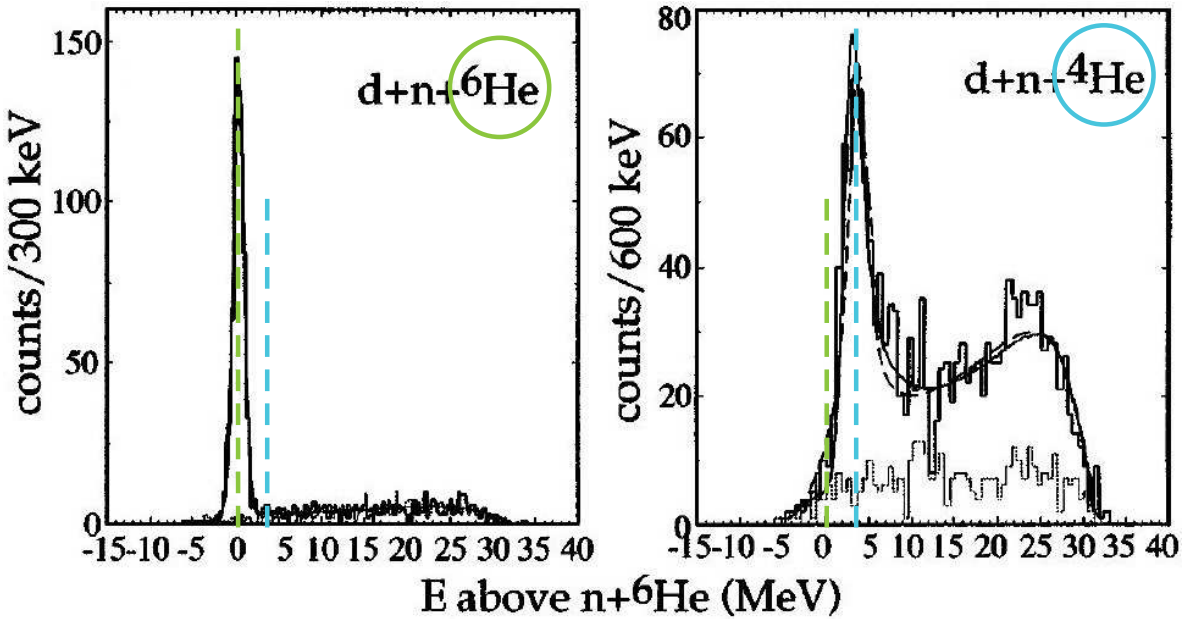
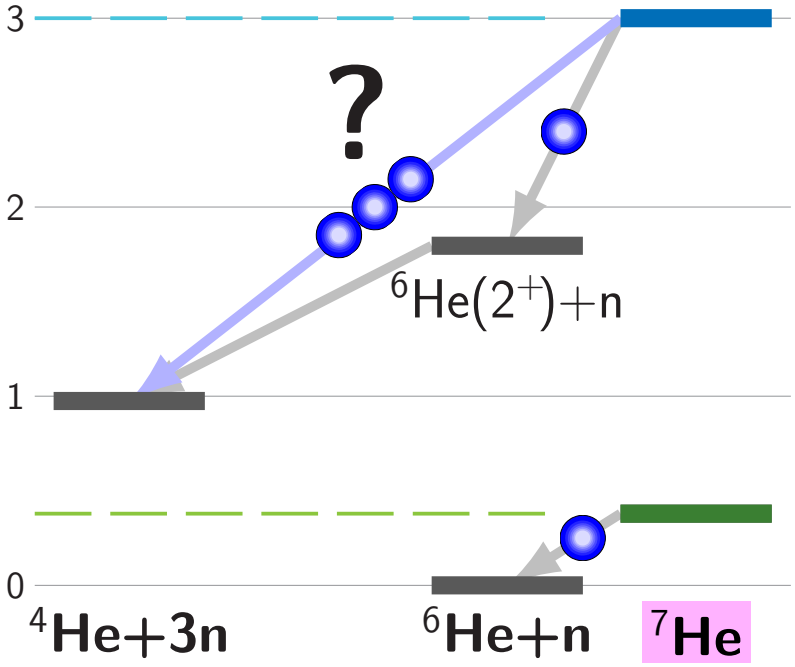



$^{8}$He (p, d) $^{7}$He



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

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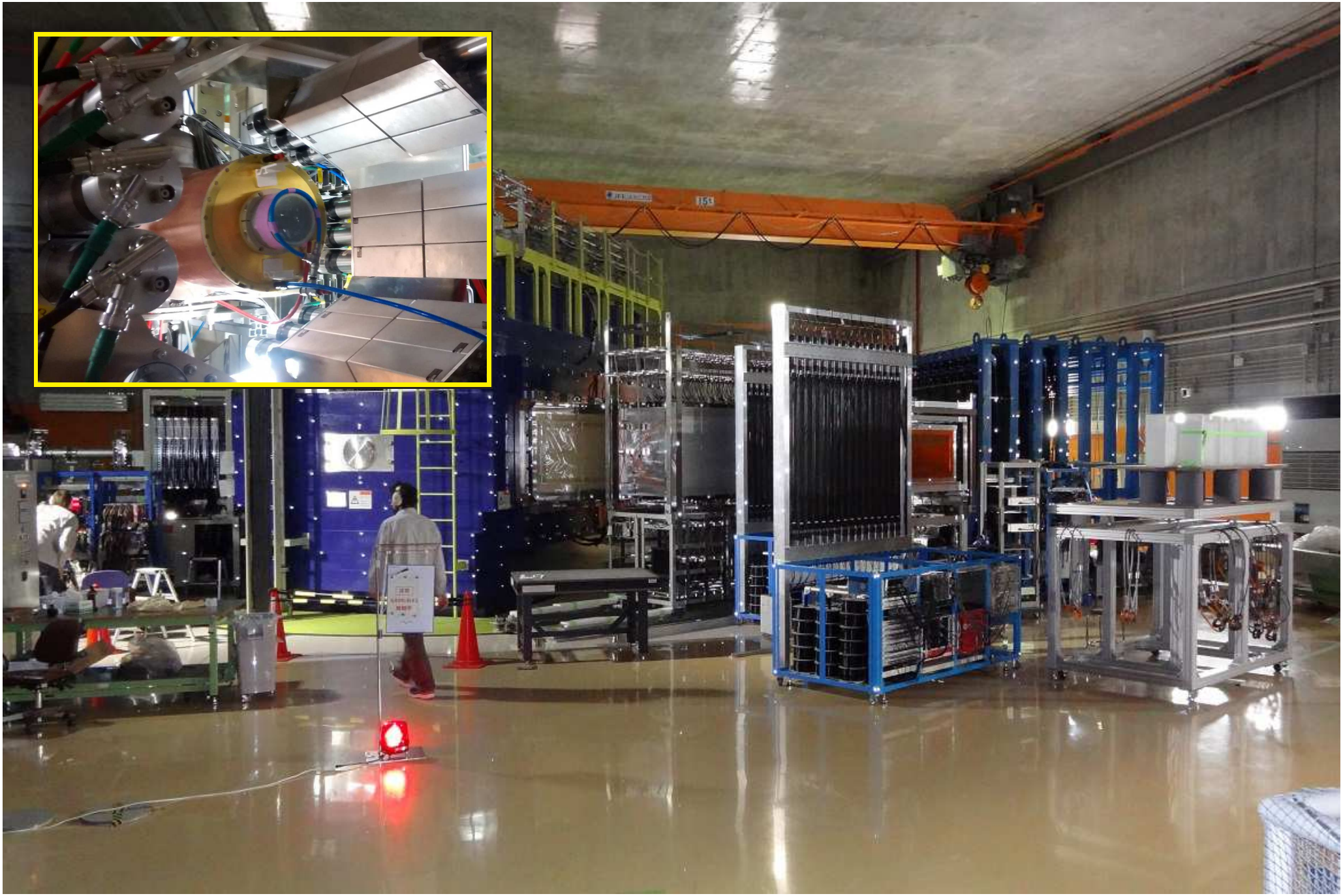
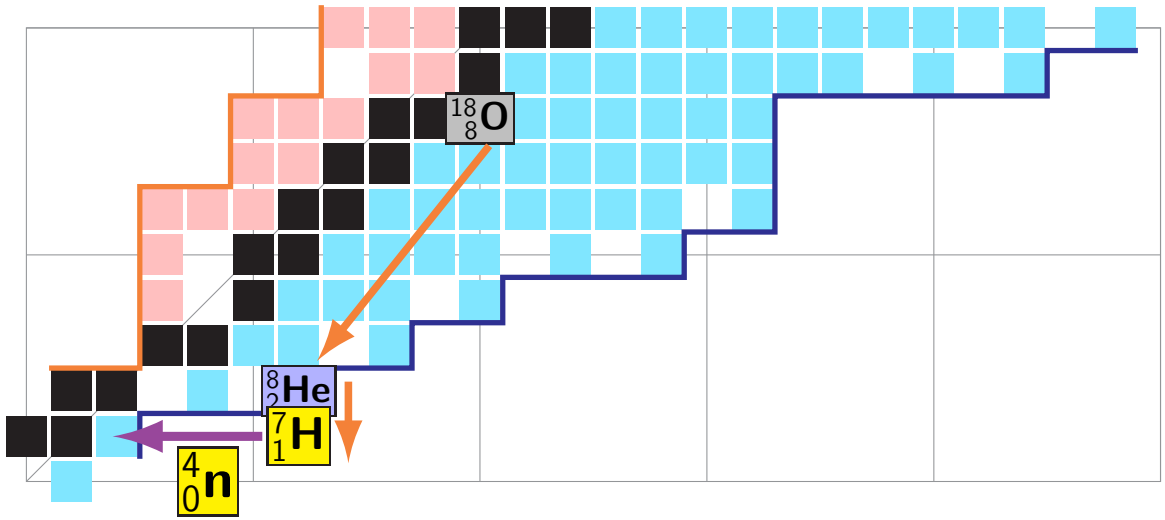
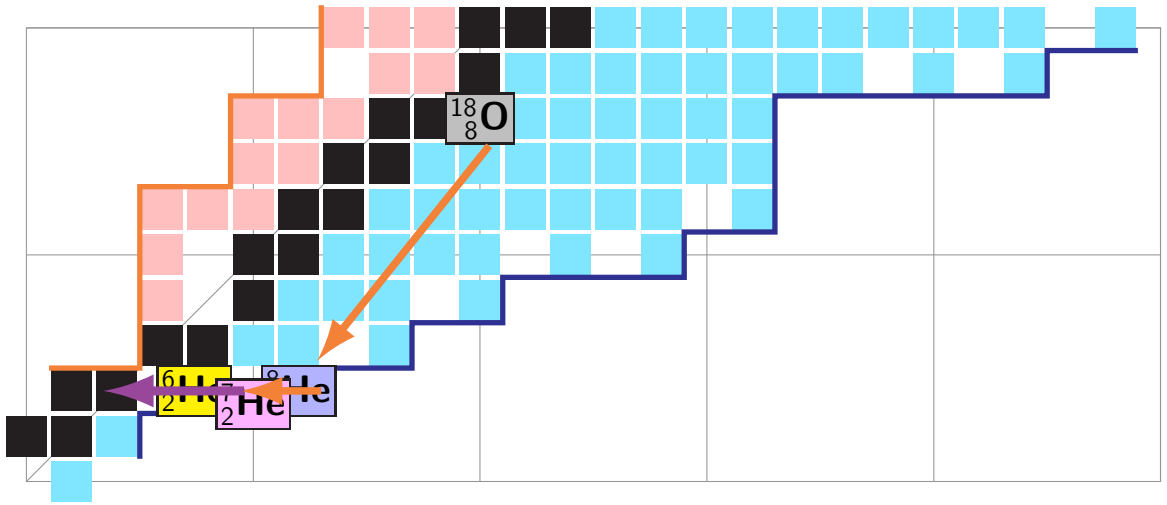


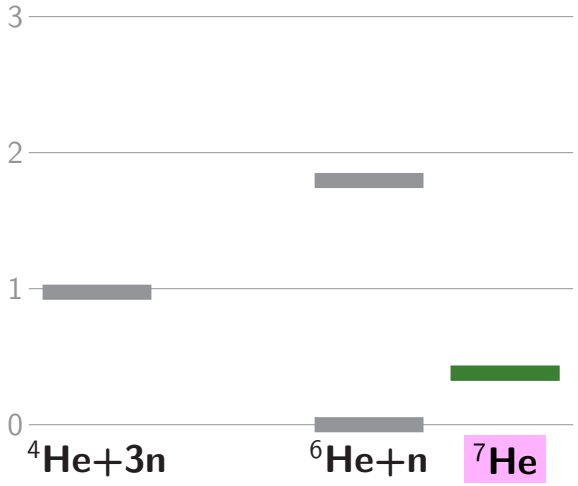
# SAMURAI S34 collaboration (part)

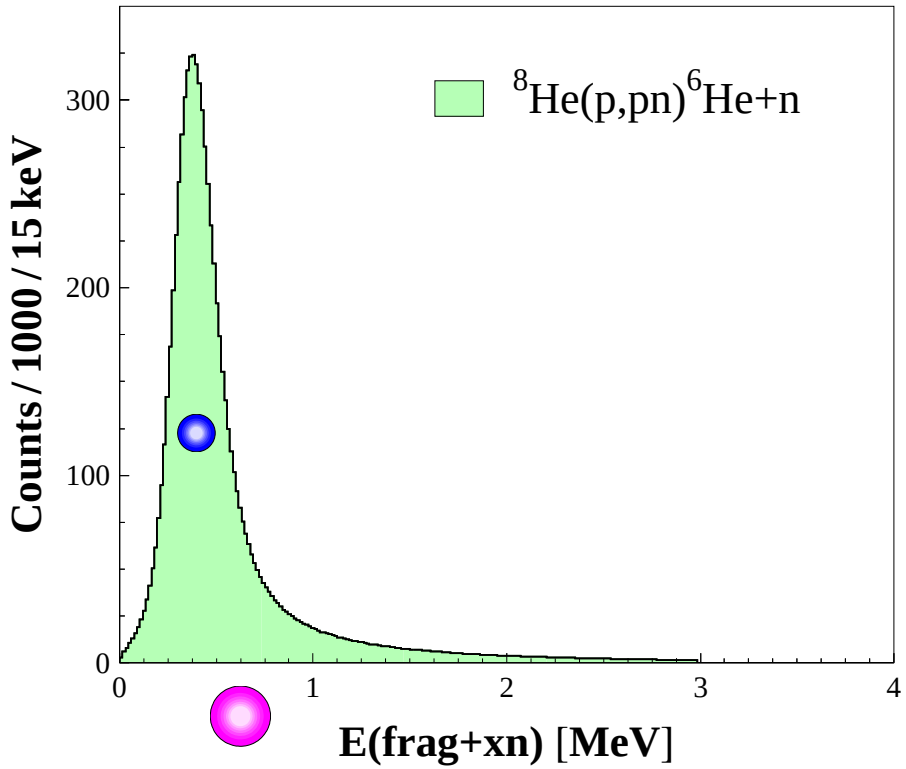
# PRELIMINARY results ! [Lenain]



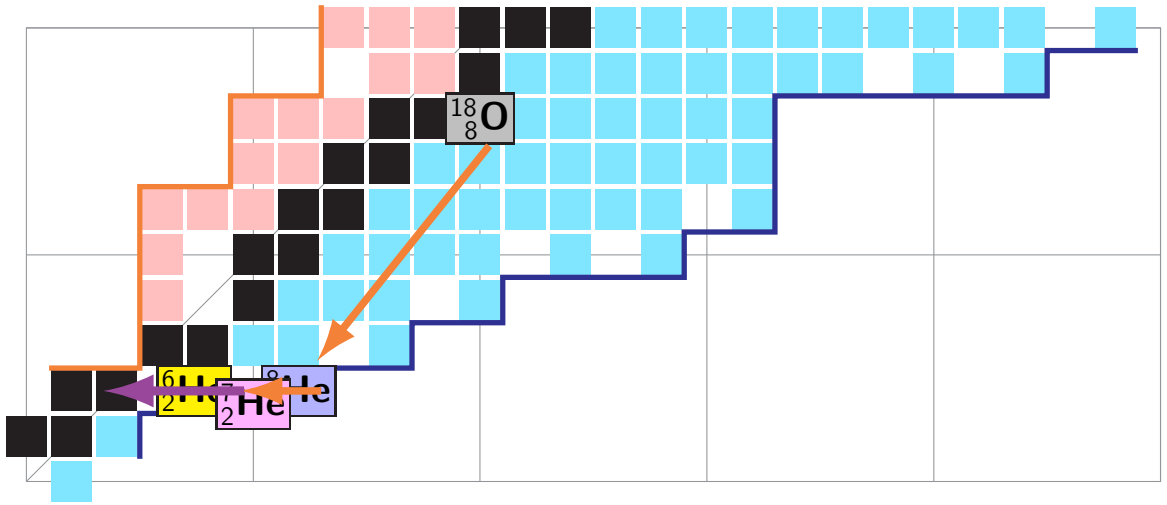
# PRELIMINARY results ! [Lenain]

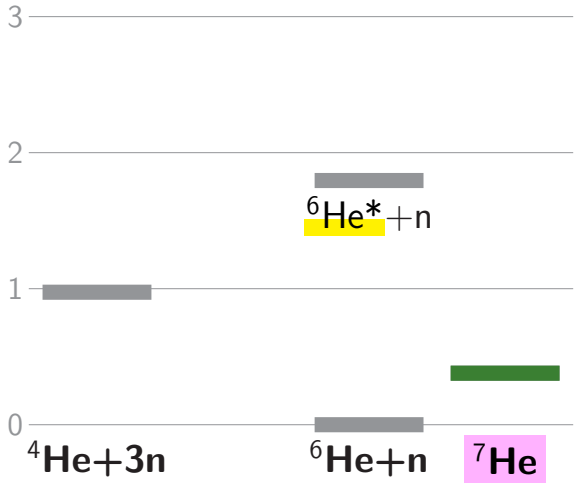


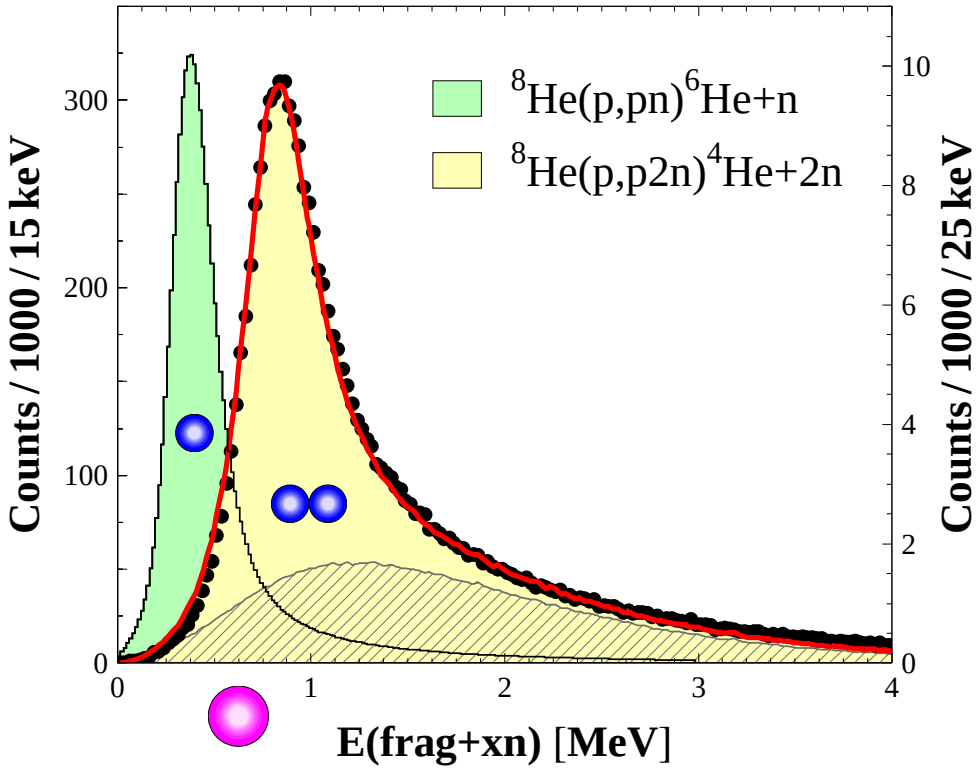



# PRELIMINARY results ! [Lenain]



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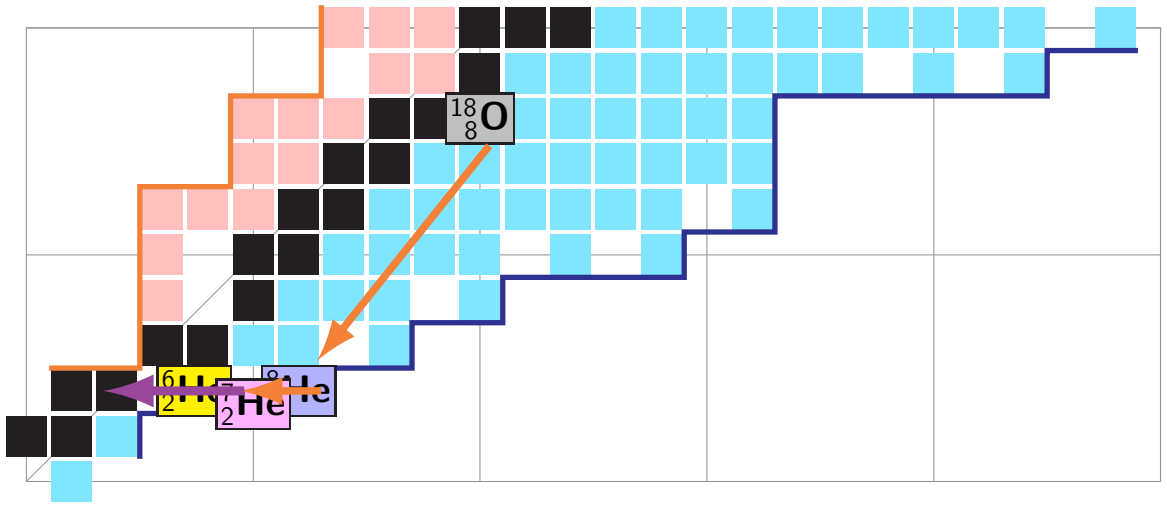
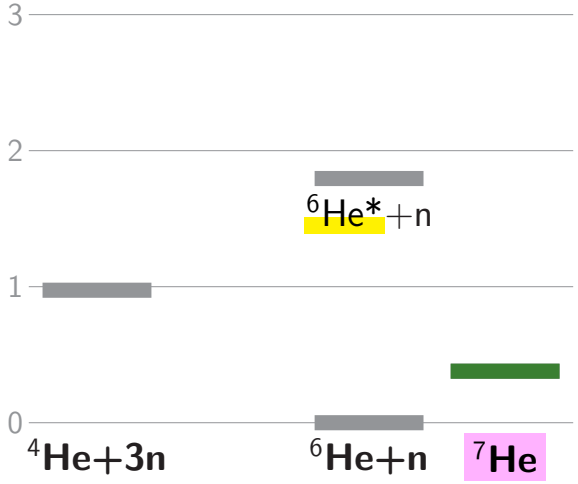
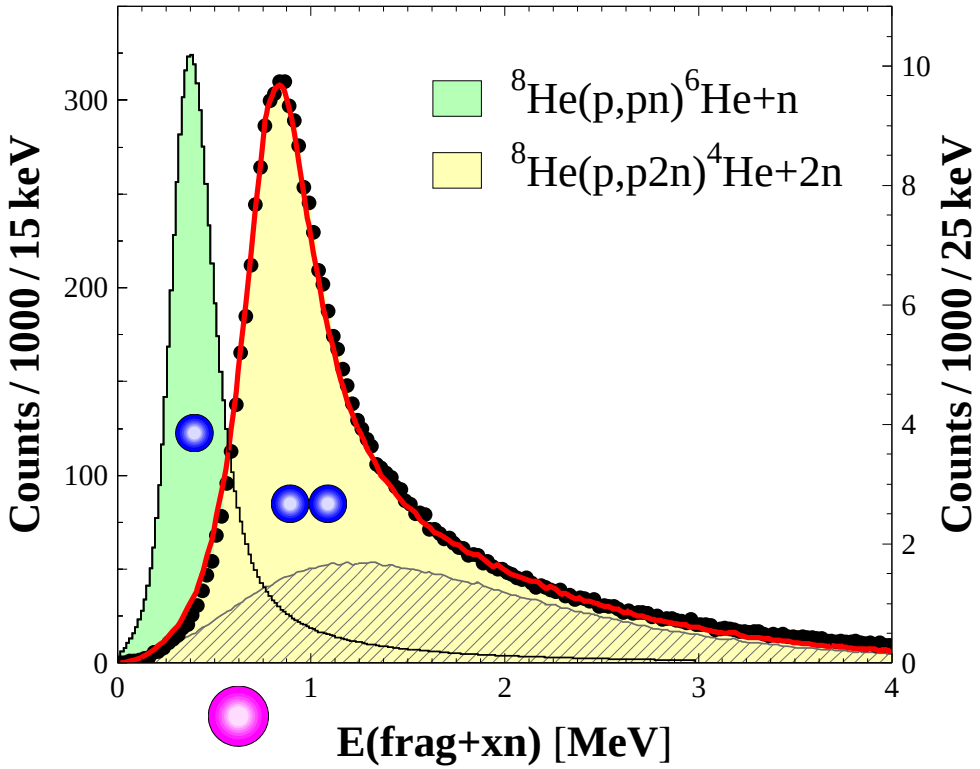
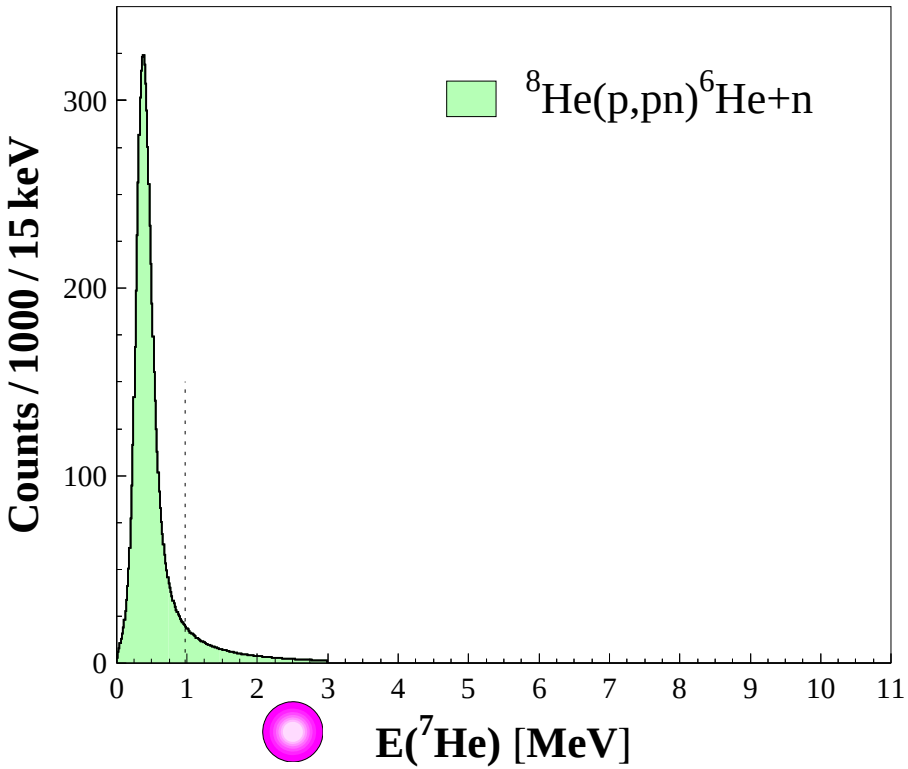
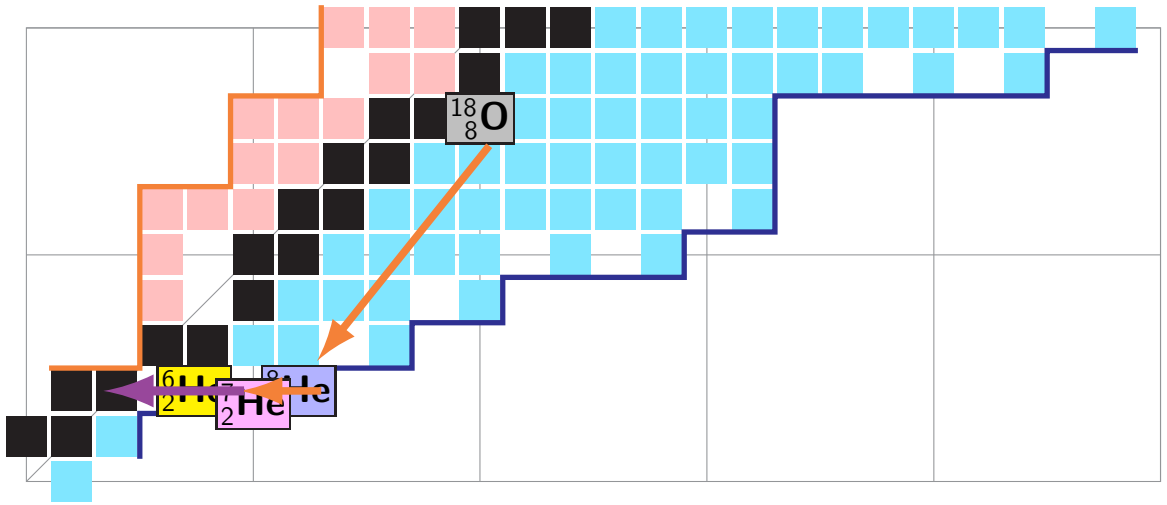


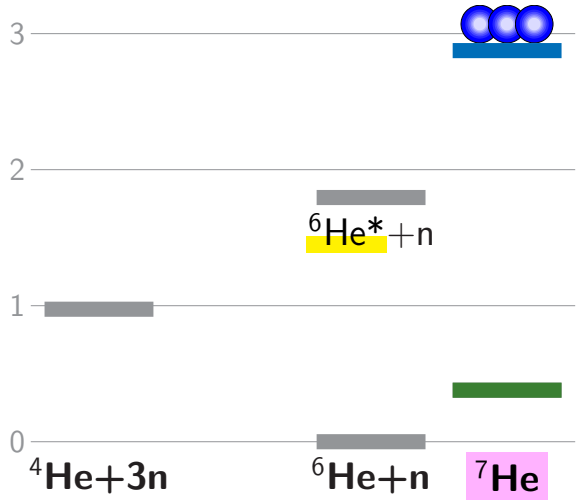



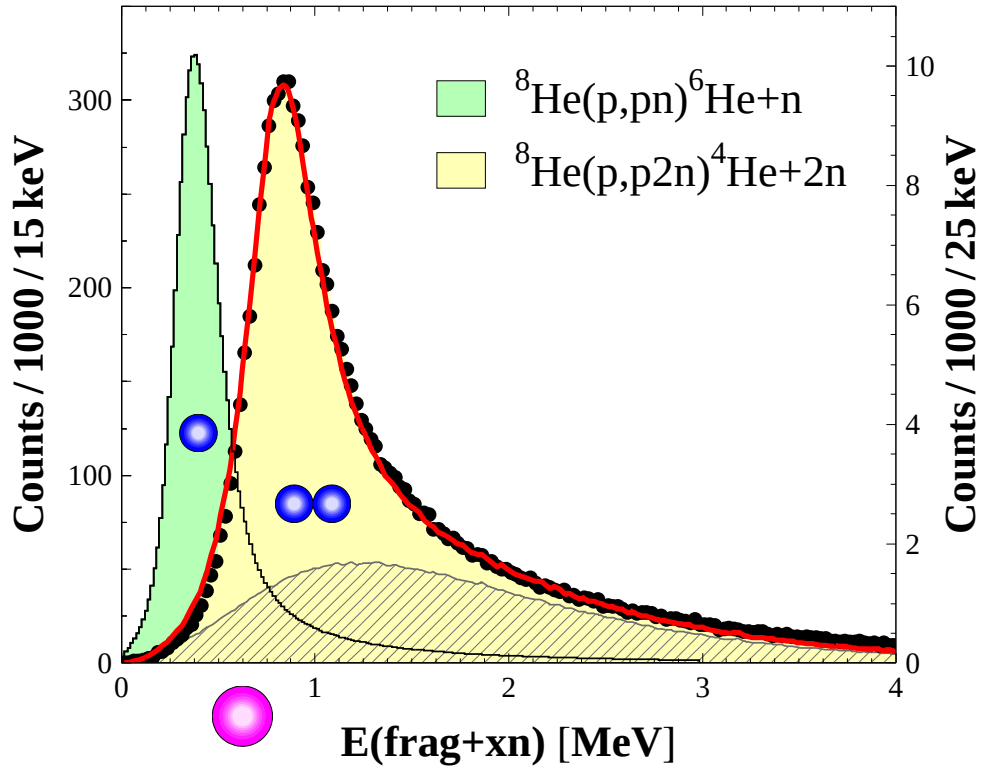



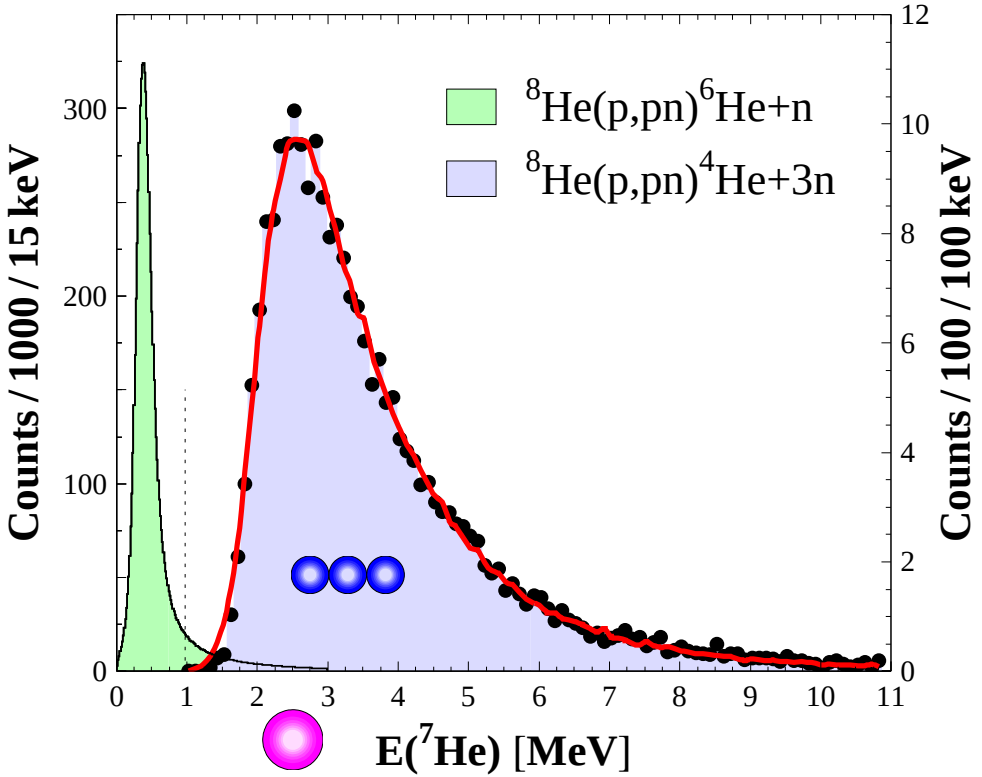



# PRELIMINARY results ! [Lenain]



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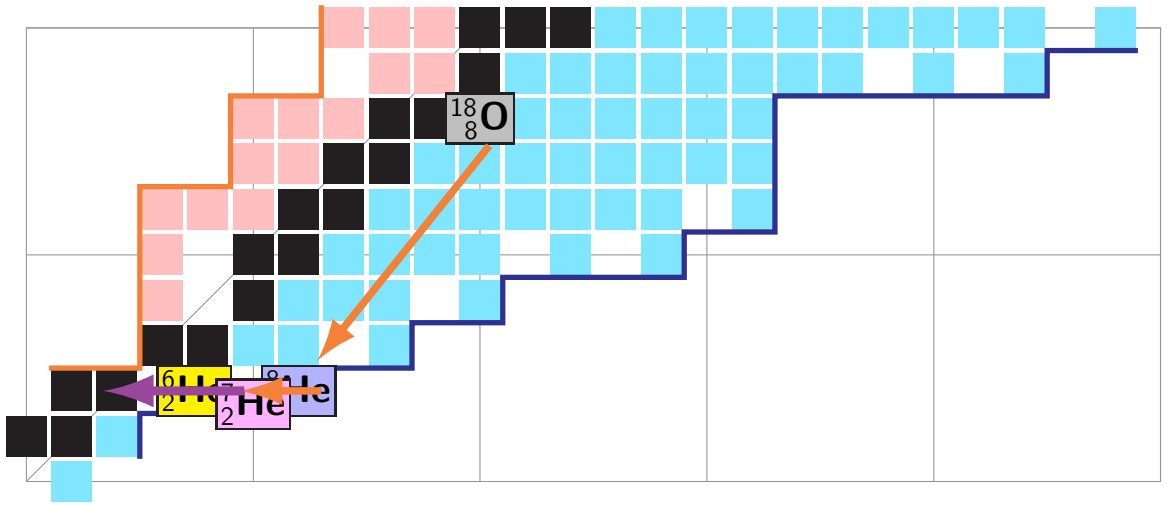
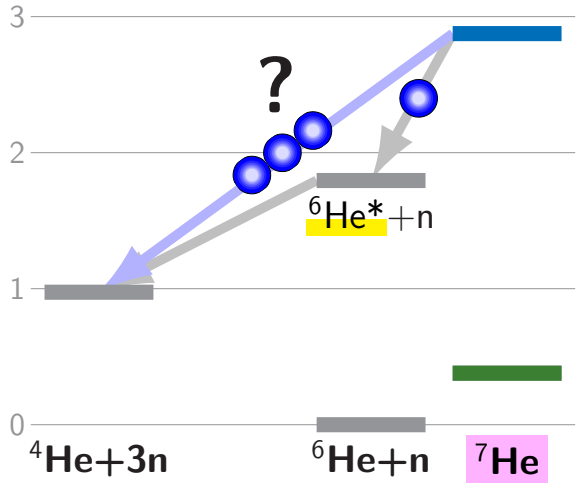
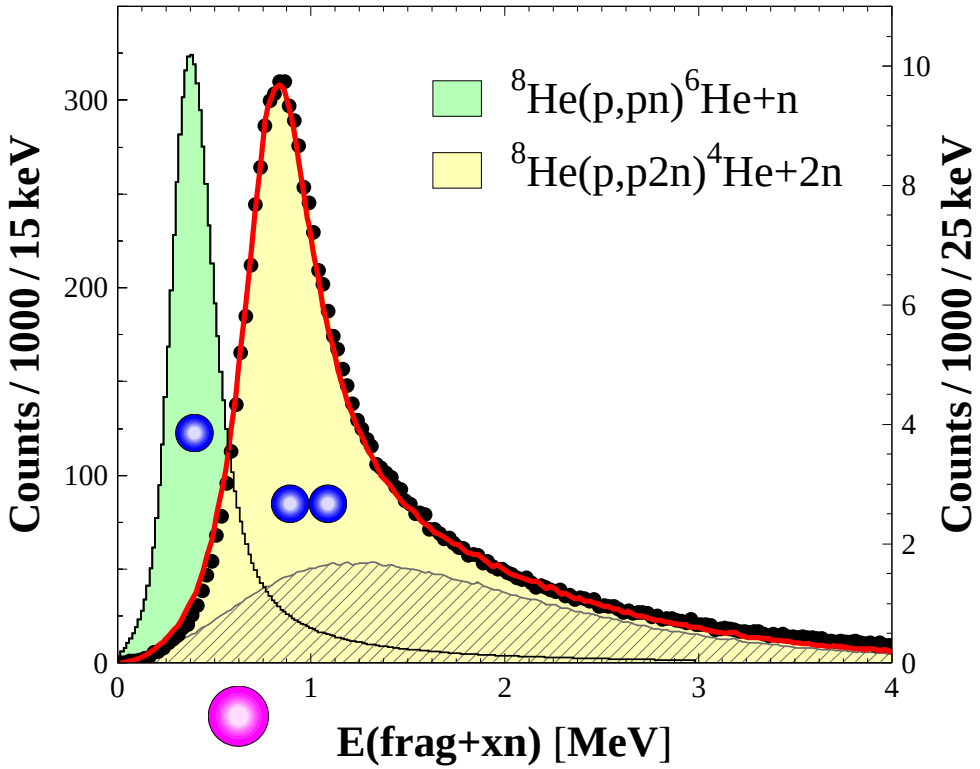
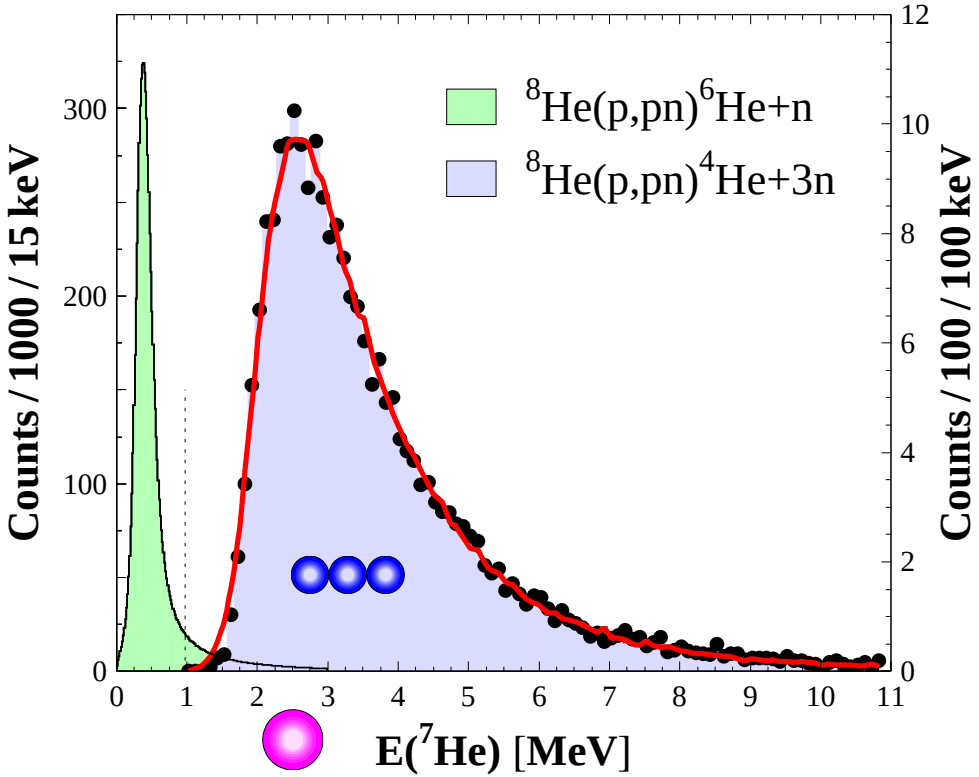
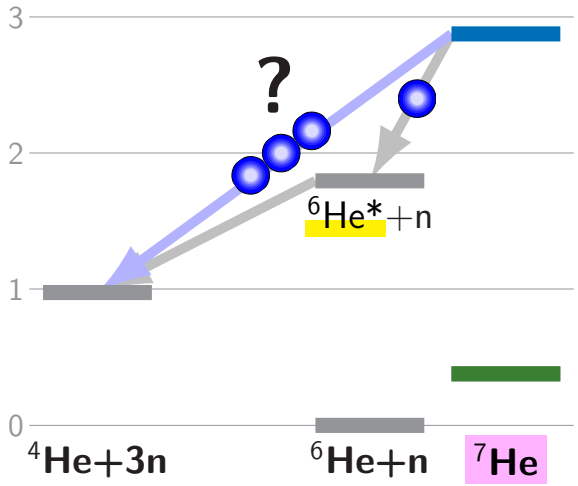


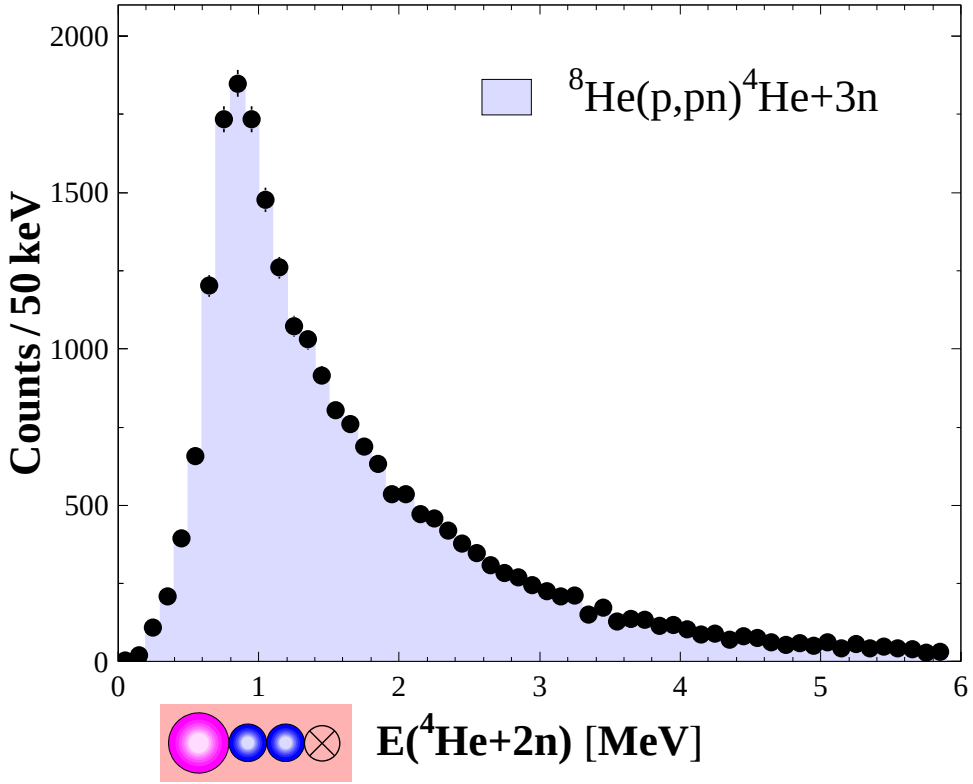



# VERY PRELIMINARY results ! [Lenain]



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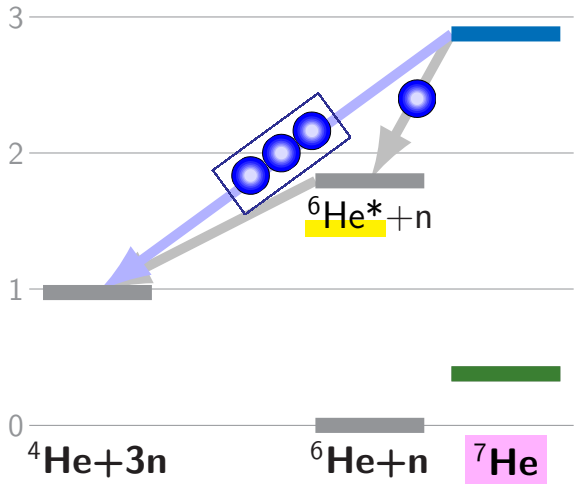
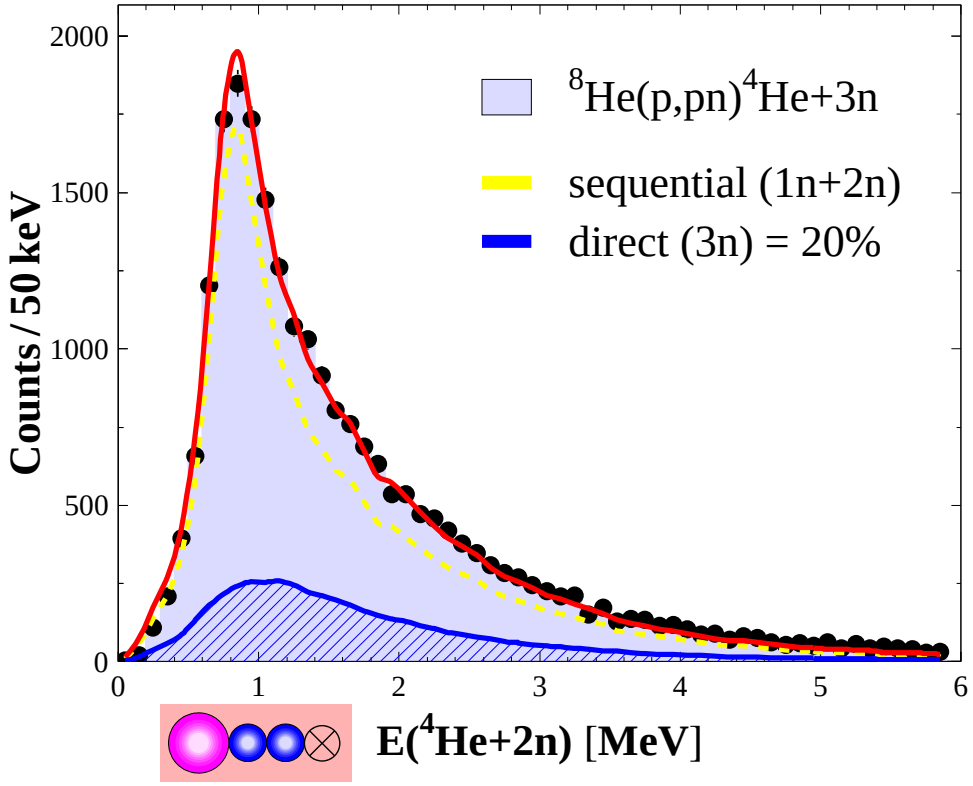
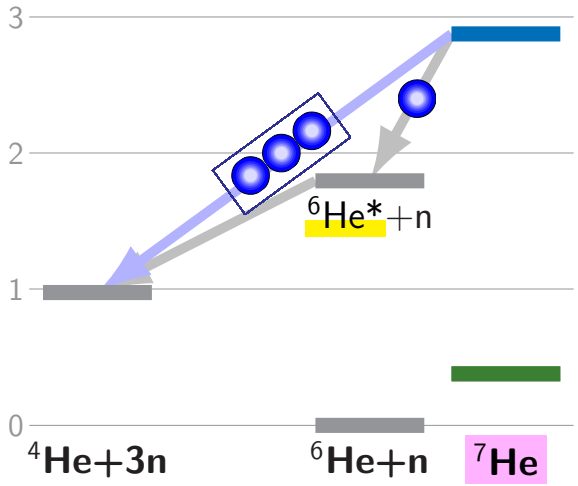
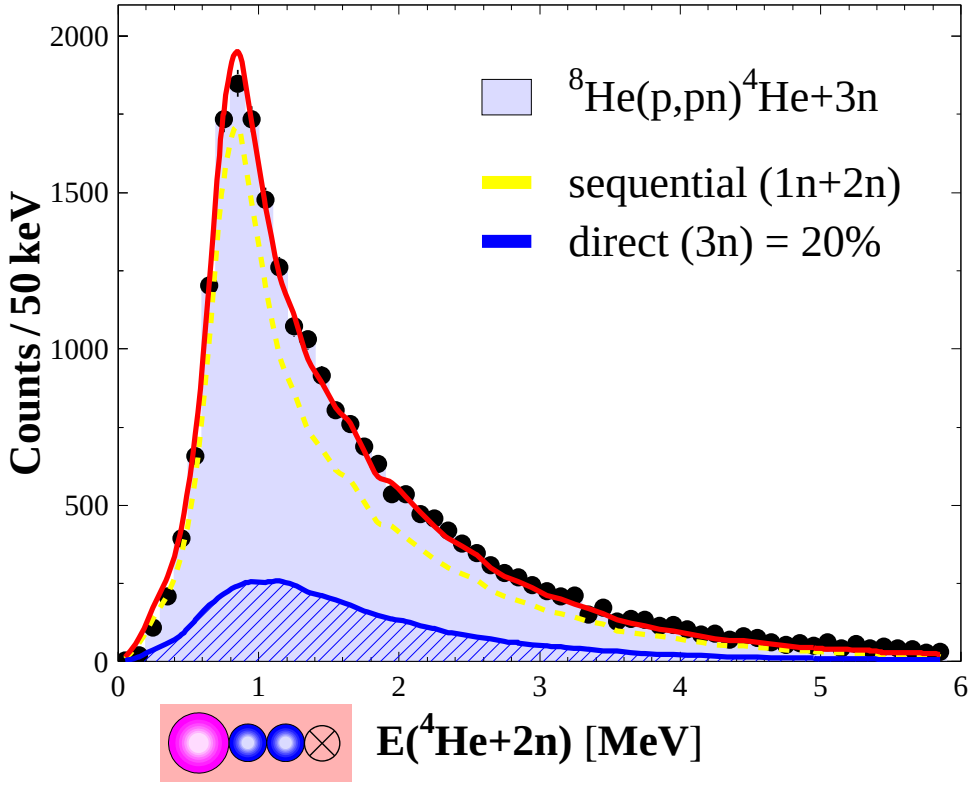
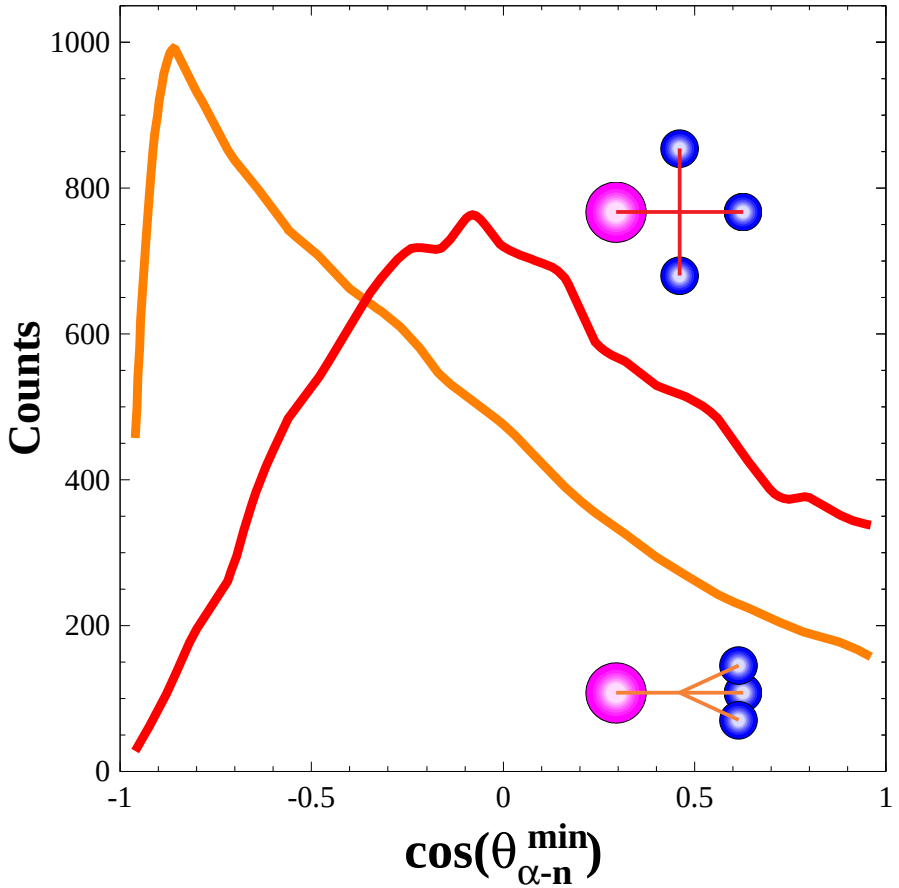


# VERY PRELIMINARY results ! [Lenain]



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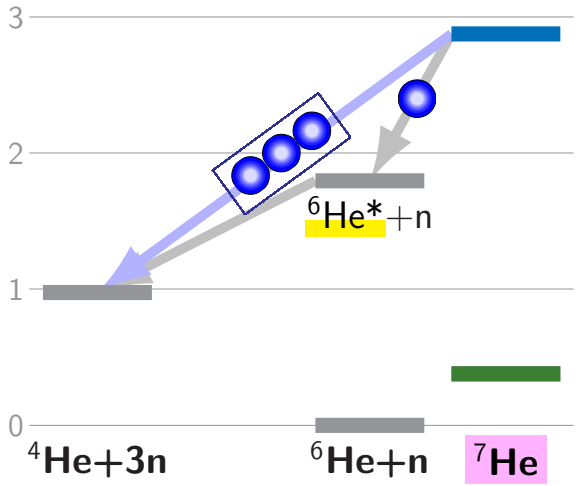


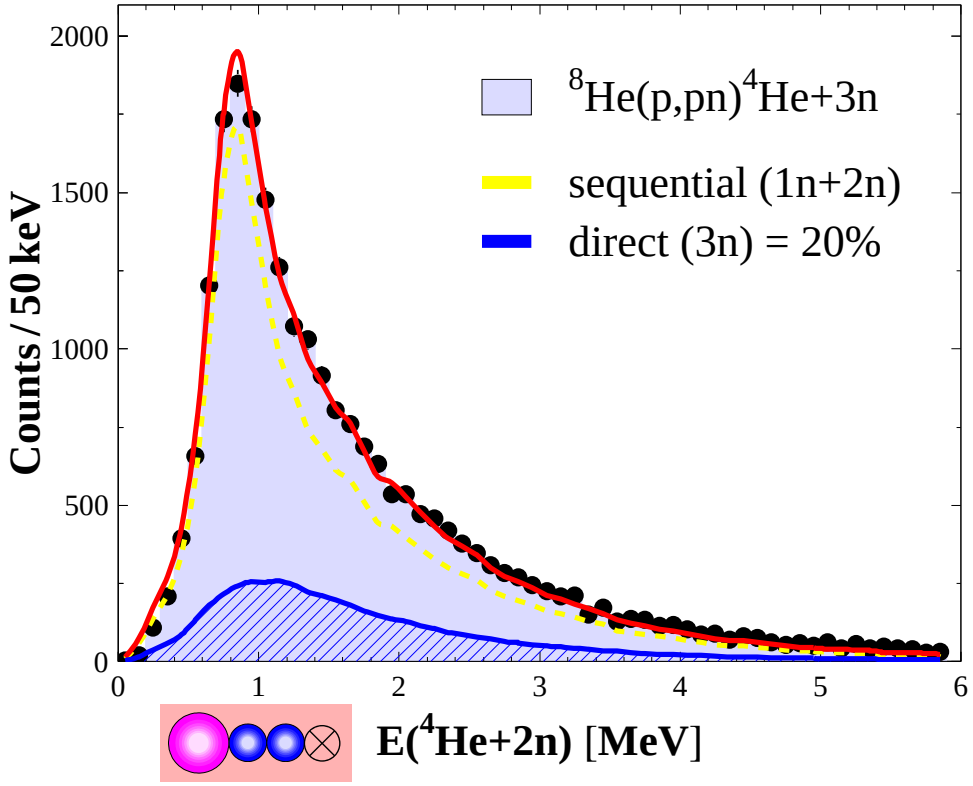


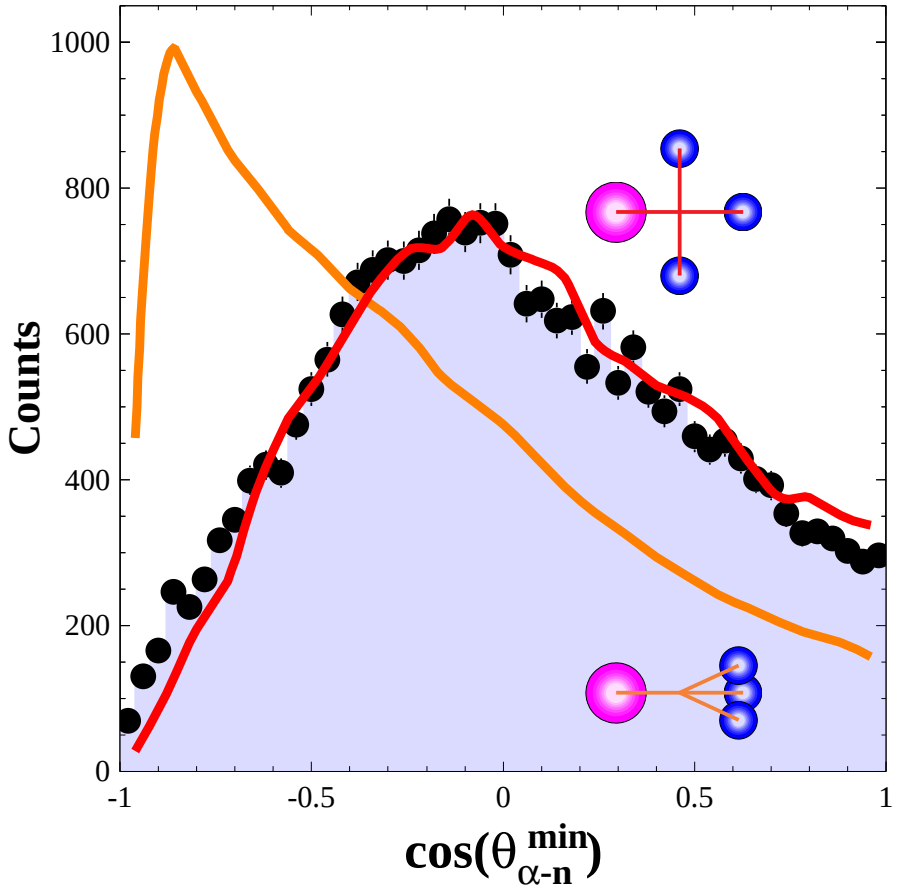

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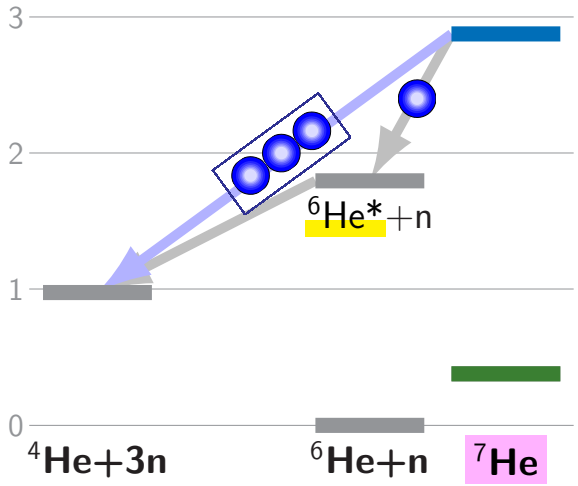
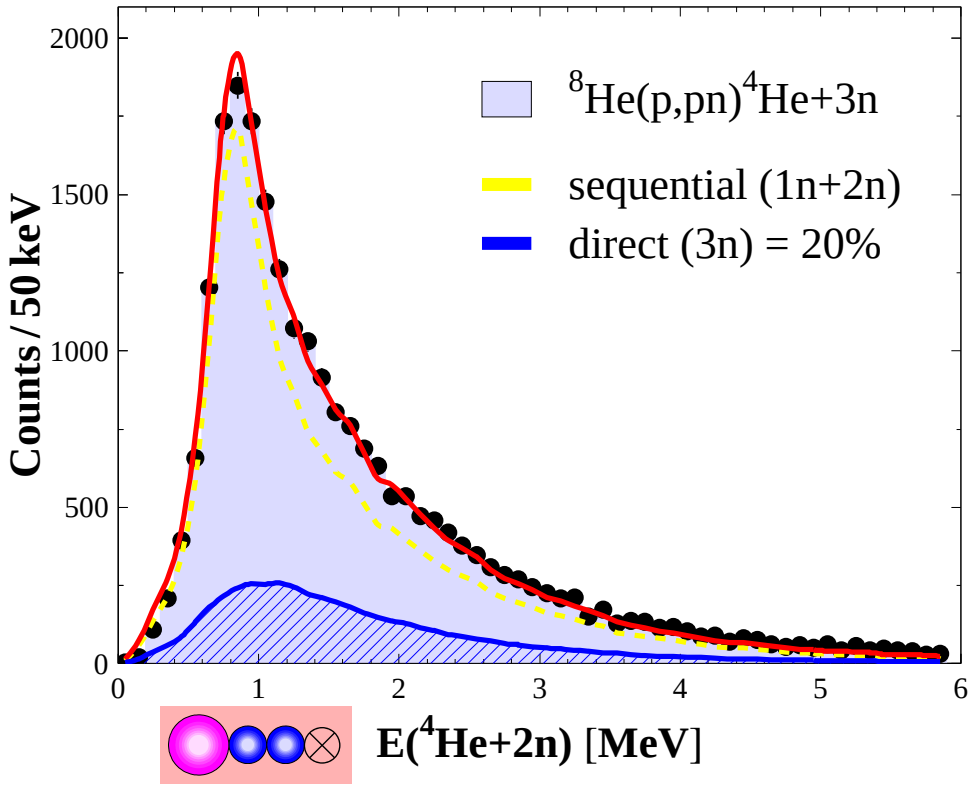
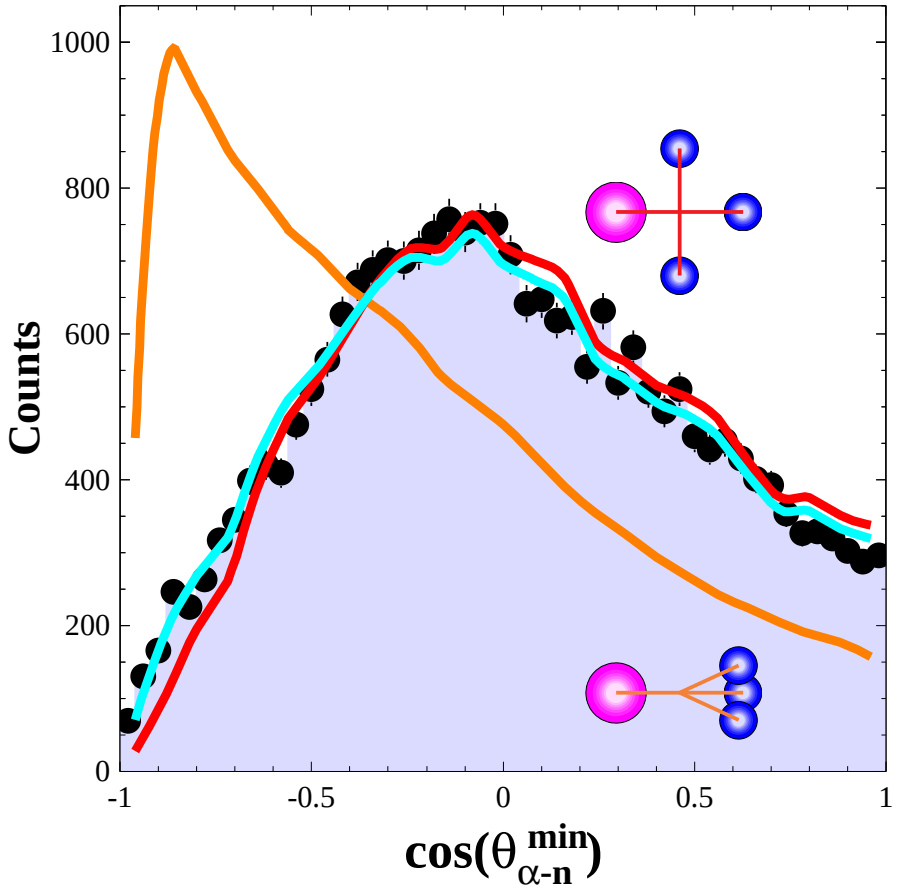


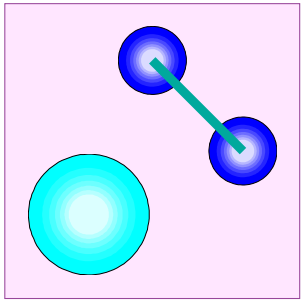




→ first evidence of 3n emission !

→ no significant $^3_0$n signal ?

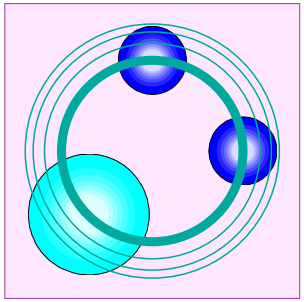
→ PS4 exploration in progress ...

# Scattering lengths & three-body systems



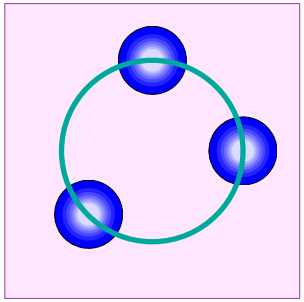
$^{16}_{4}$**Be** : $^{14}$Be+n+n  Belén Monteagudo, PhD

- $a_s$(nn) strong enough for "dineutron" ?
- experimental signature ?



$^{19}_{5}$**B** : $^{17}$B+n+n  Hiyama, PRC 100 (2019) 011603R

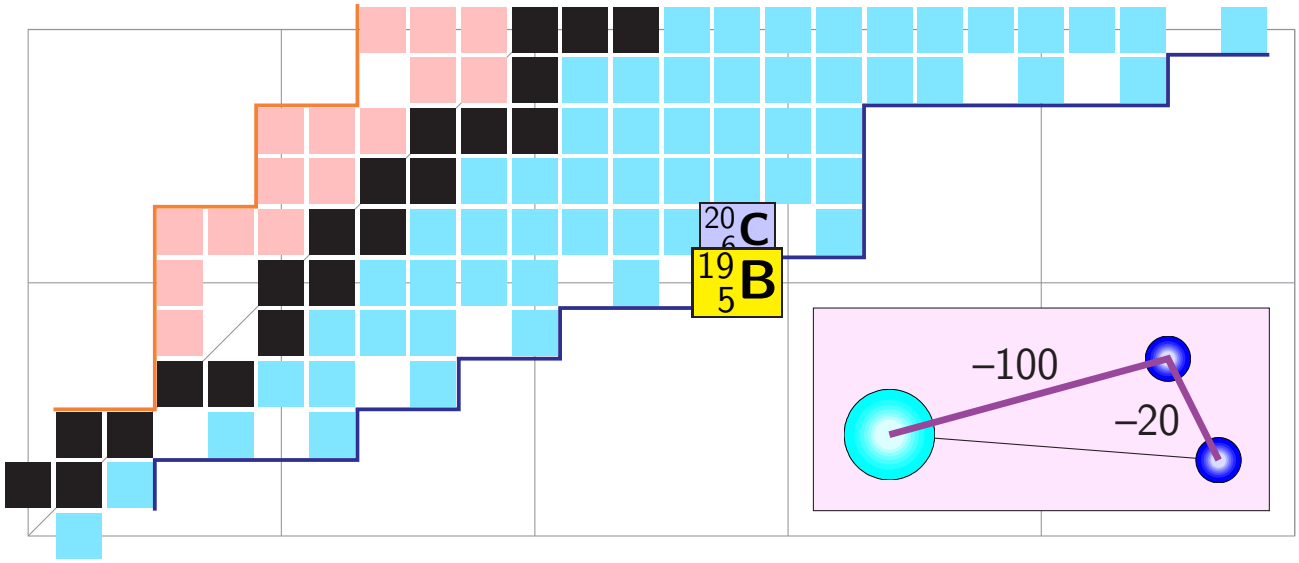
- $a_s(^{18}\mathrm{B})$ strong enough for Efimov states ?
- how big should it be ?

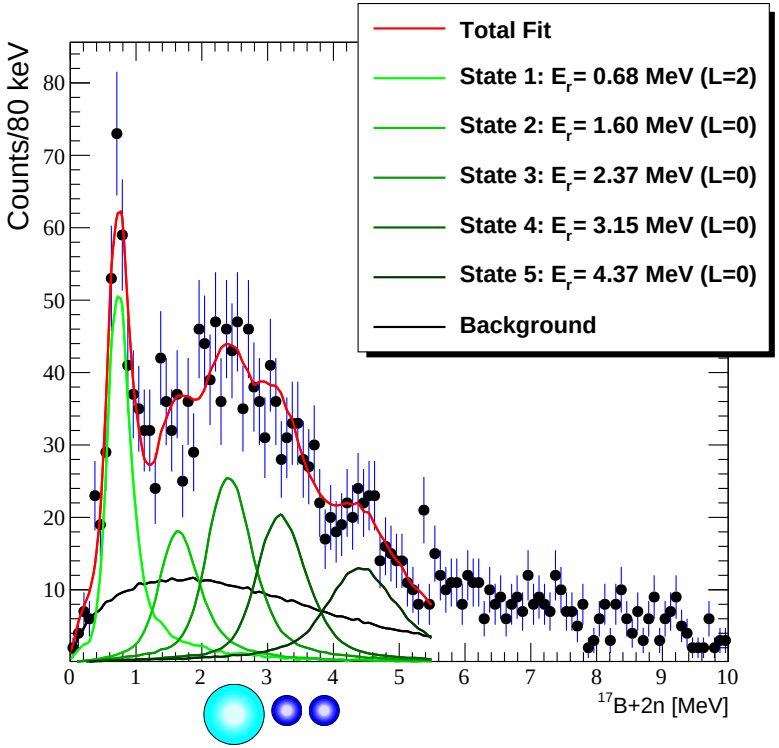


$^{3}_{0}$**n** : n+n+n  Cyril Lenain, PhD

- do multineutrons exist ?
- should multineutrons exist ?

# Boron 19 : two large $a_s$ ! [Gibelin]



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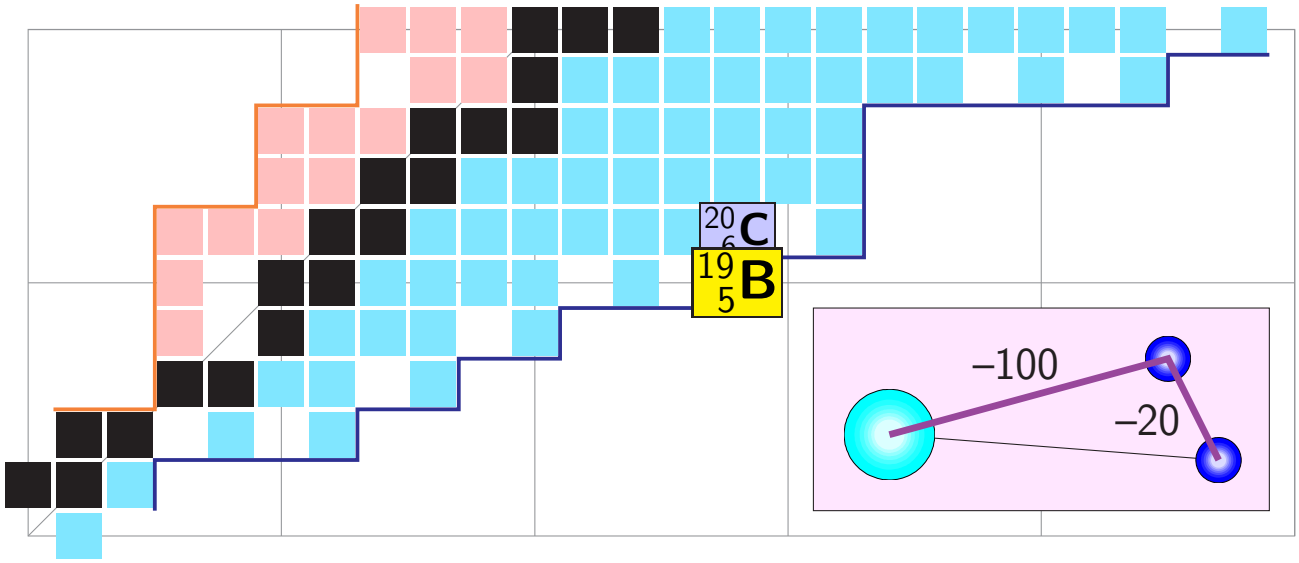


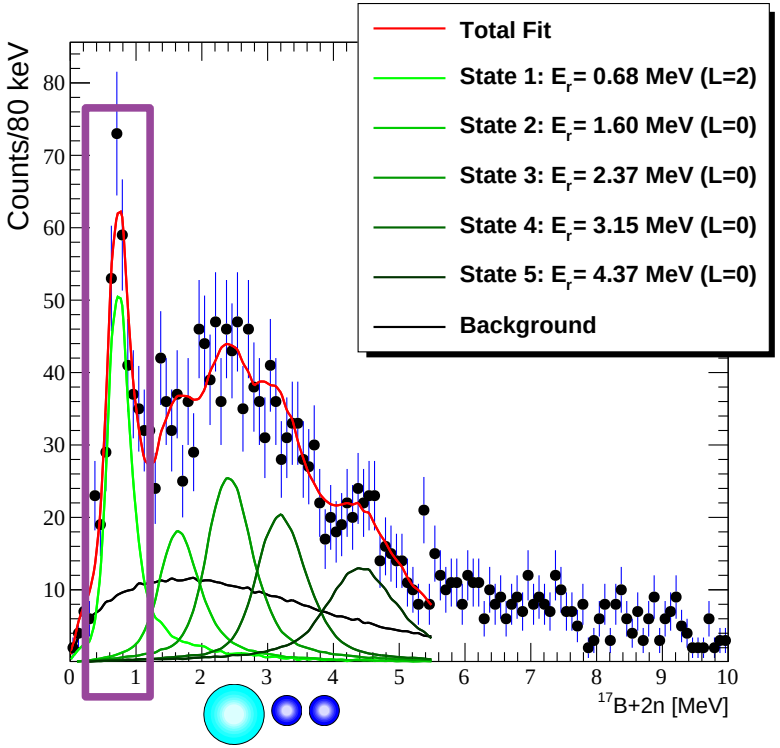


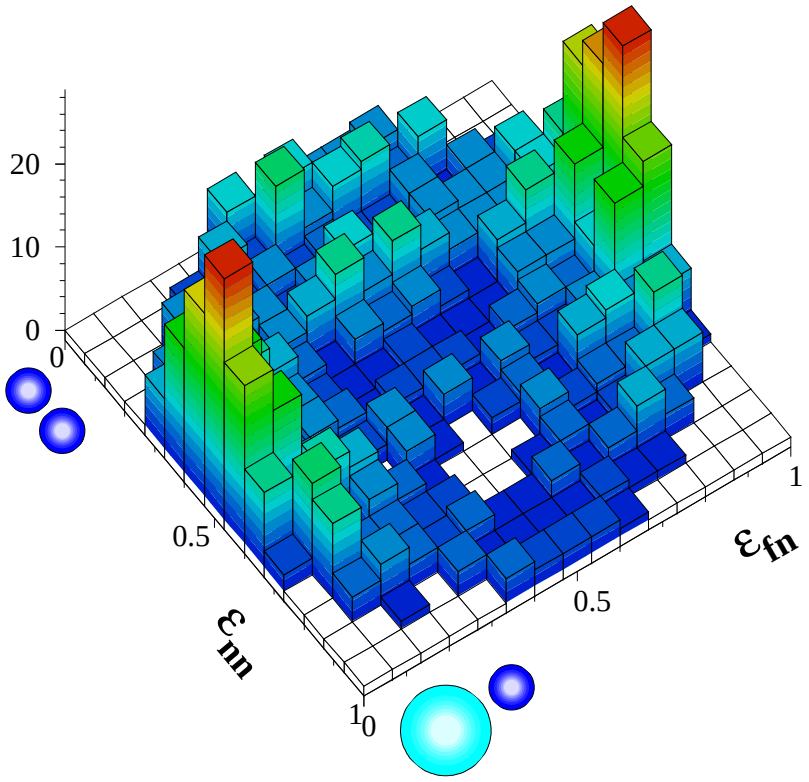

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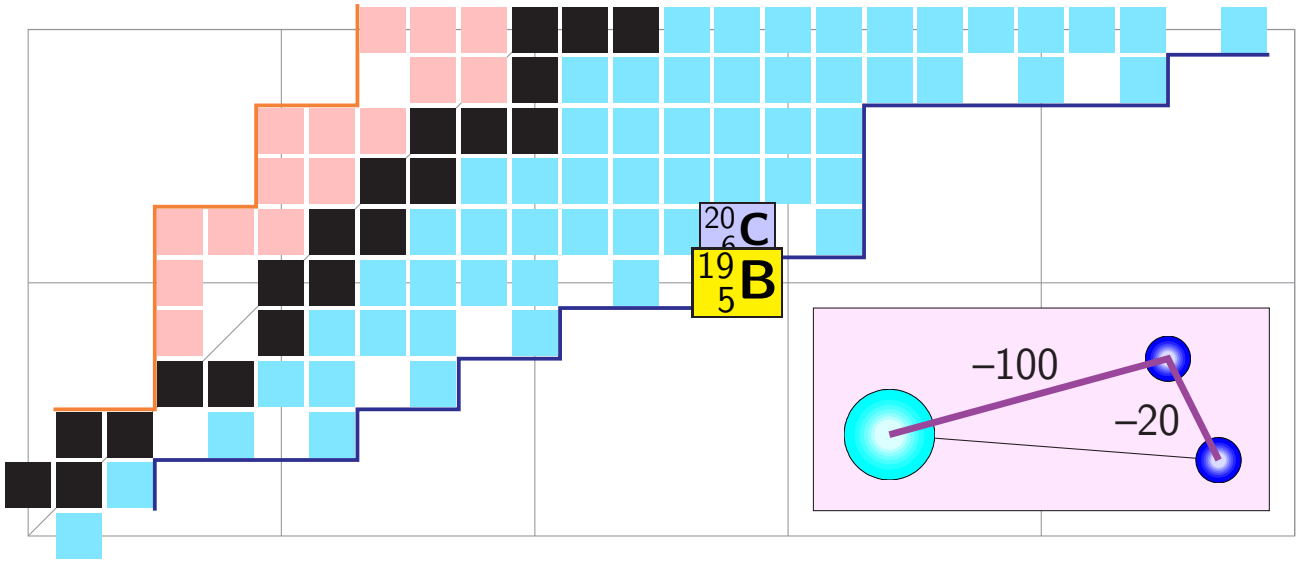


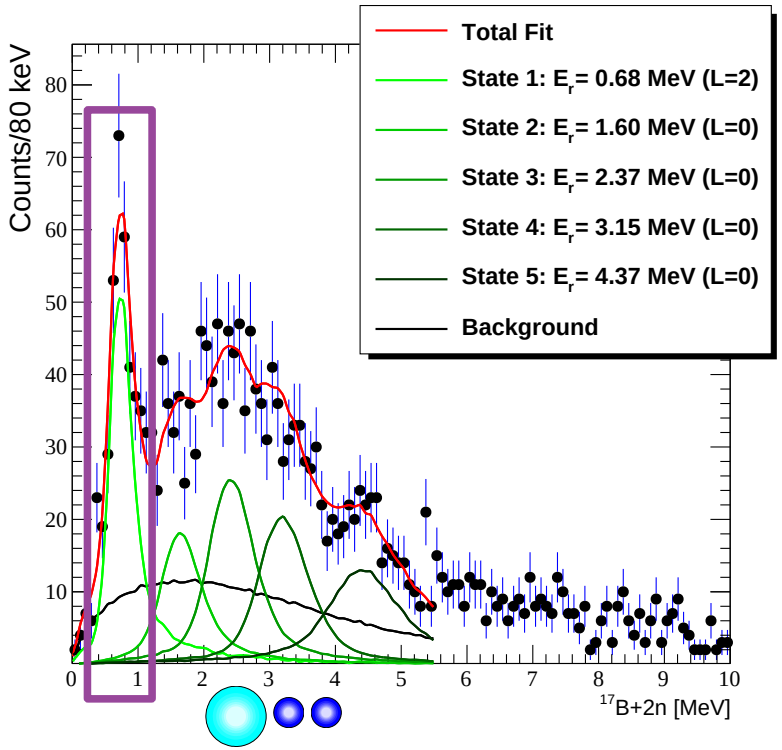


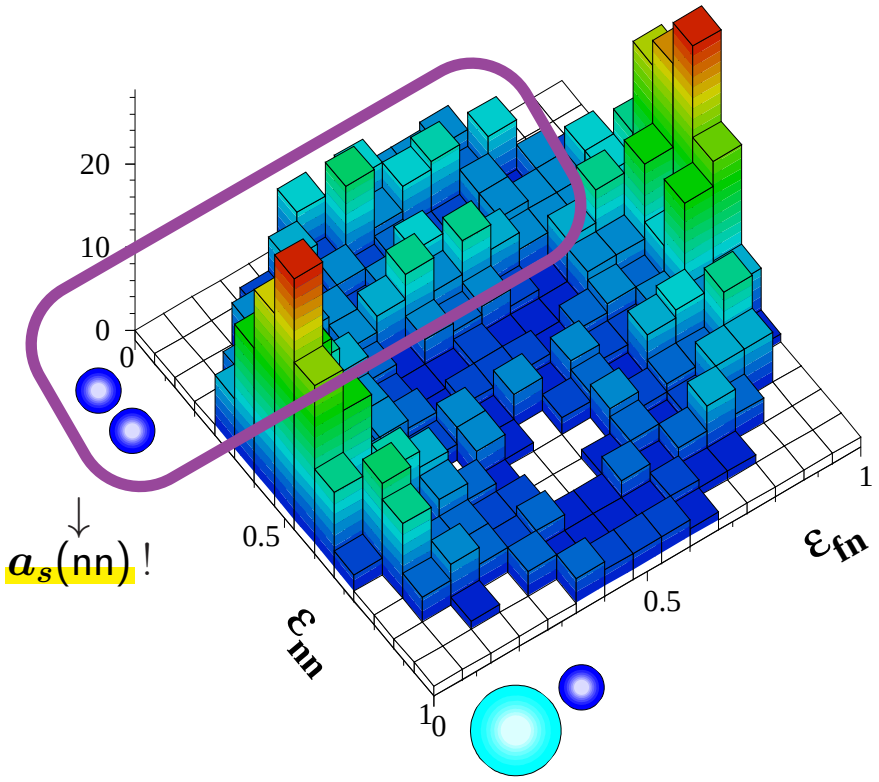

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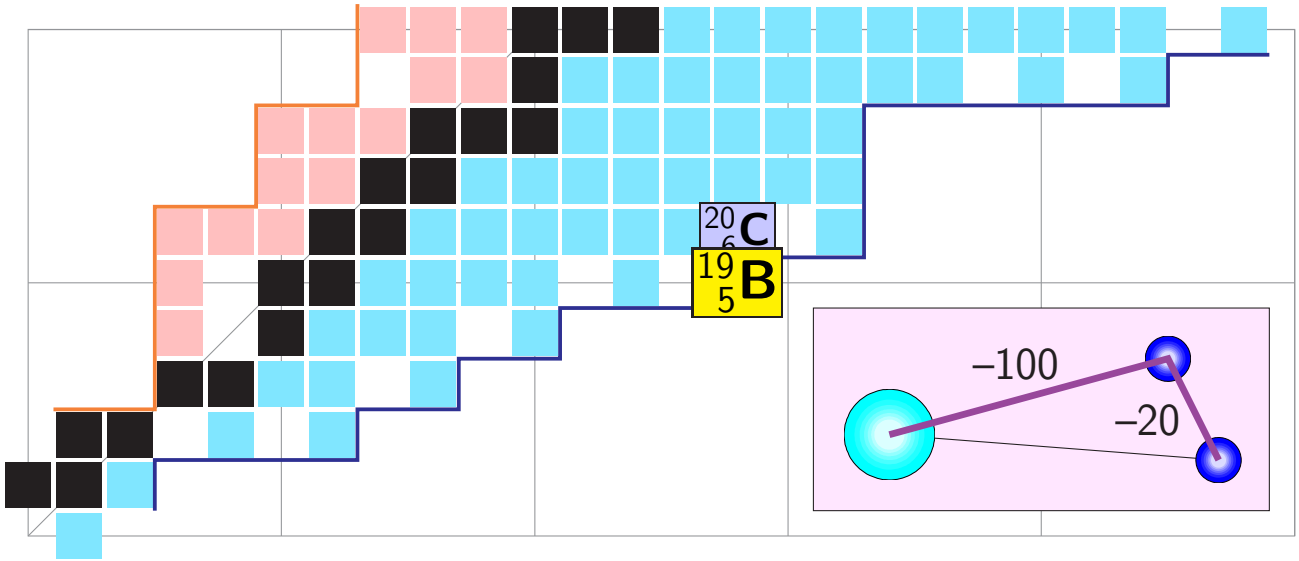
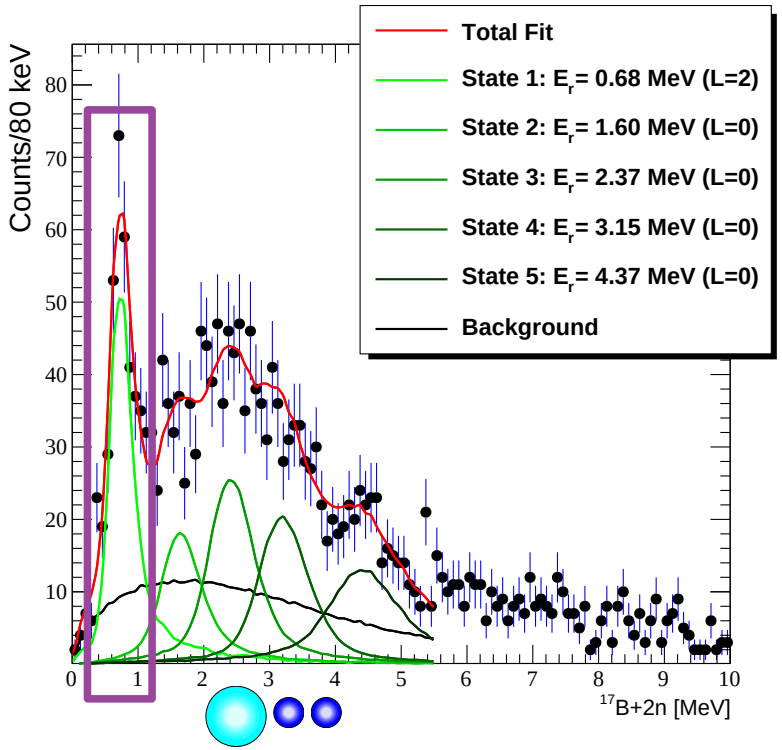
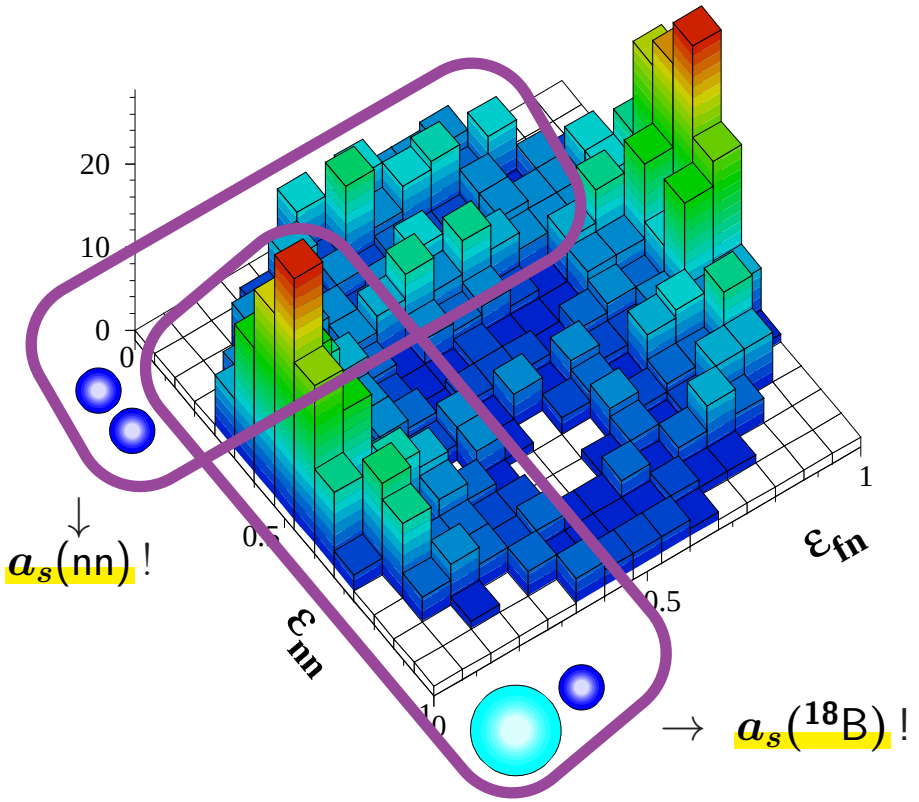
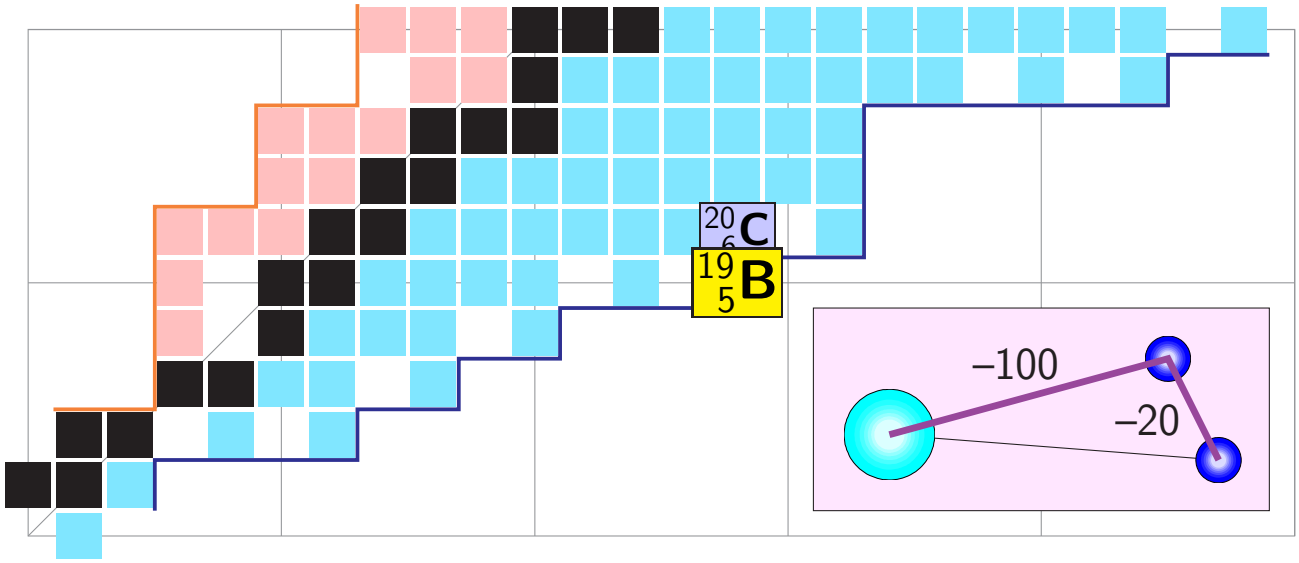
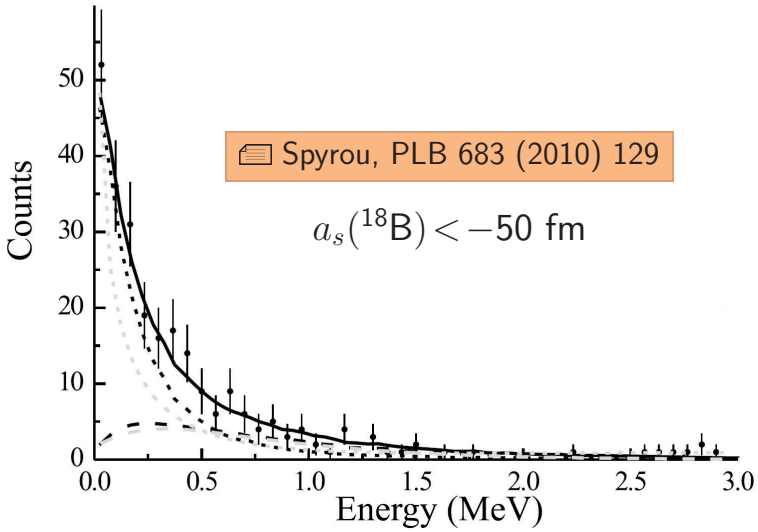


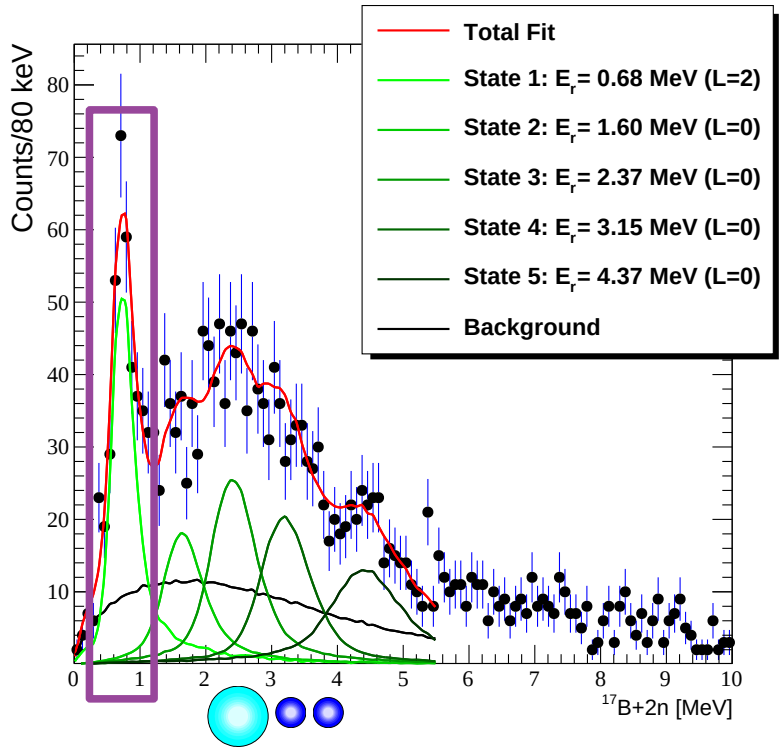



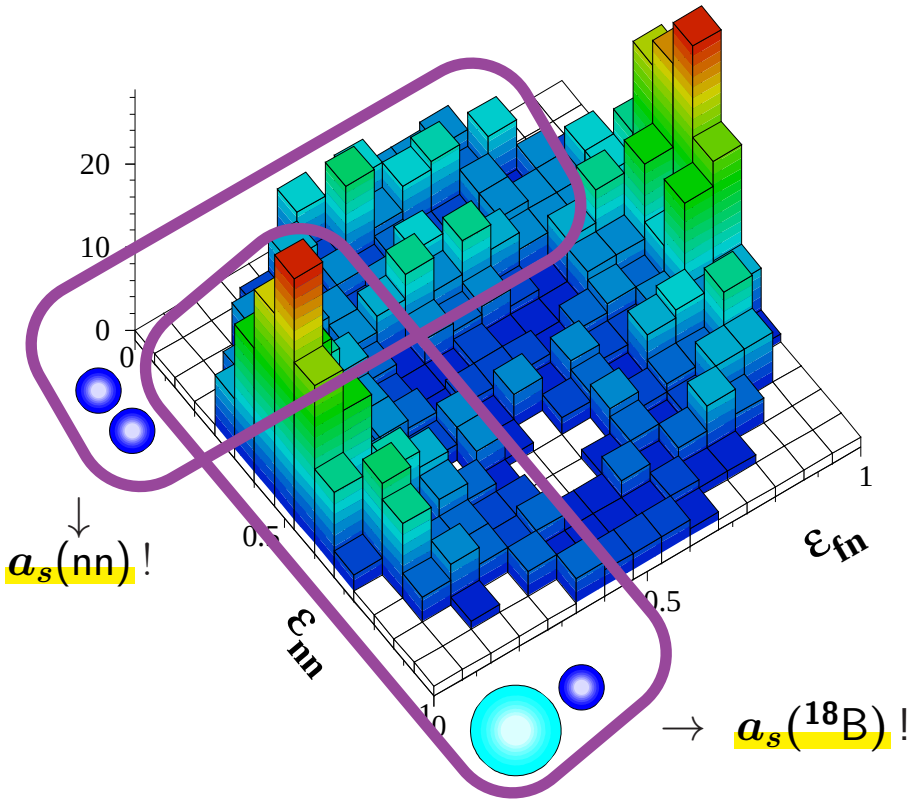



# Boron 19 : two large $a_s$ ! [Gibelin]



# 17B+n+n : Efimov trimers ? [Hiyama, Lazauskas, Carbonell]

- Efimov effect :

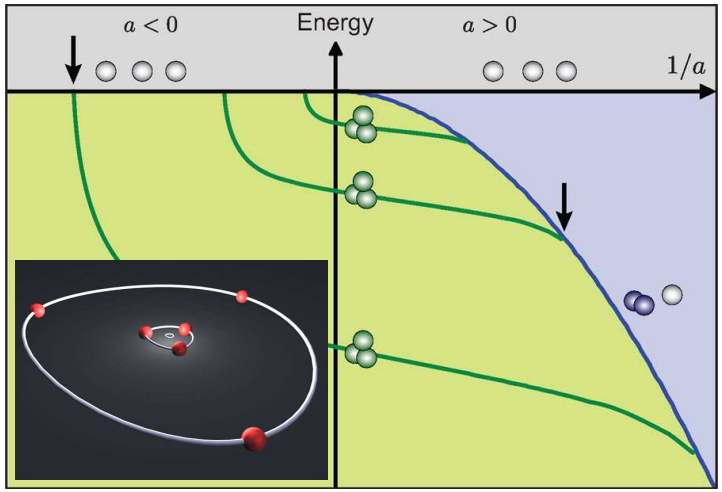
  "*a scale-invariant 3-body attraction*"

  Naidon & Endo, Rep Prog Phys 80, 5 (2017)

  → induced long-range interaction

  → discrete scale invariance

  → Borromean binding ( )



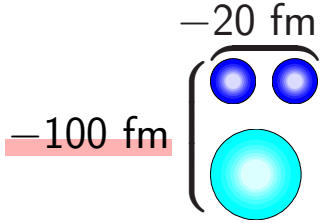

- Efimov physics :

  → Universality if $|a_s| \gg r_0$ ...

  → number of trimers $\gtrsim 1$ ...

- Three-body calculation :

Hiyama, PRC 100 (2019) 011603R




$\Longrightarrow$ $S_{2n}(^{19}B) = 0.14 \pm 0.39$ MeV

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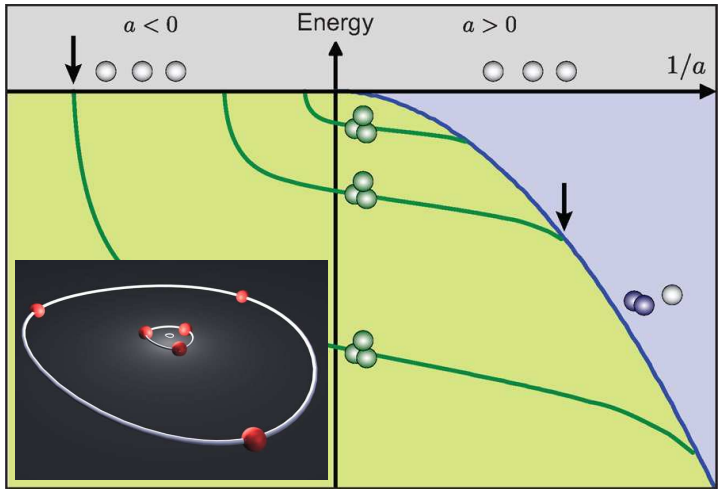


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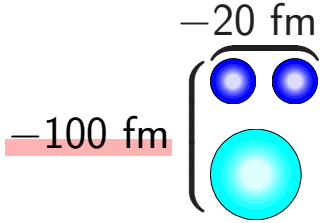
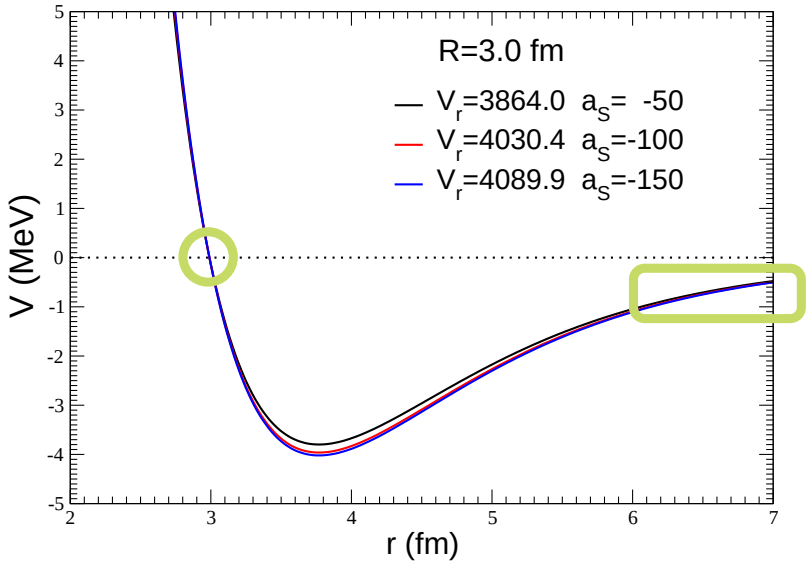



$\Longrightarrow$ $S_{2n}(^{19}\mathrm{B}) = 0.14 \pm 0.39$ MeV

- $V(^{17}\mathrm{B}\text{-n}) = V_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r}$

  → $\mu = 1/m_\pi \sim 0.7$ fm$^{-1}$

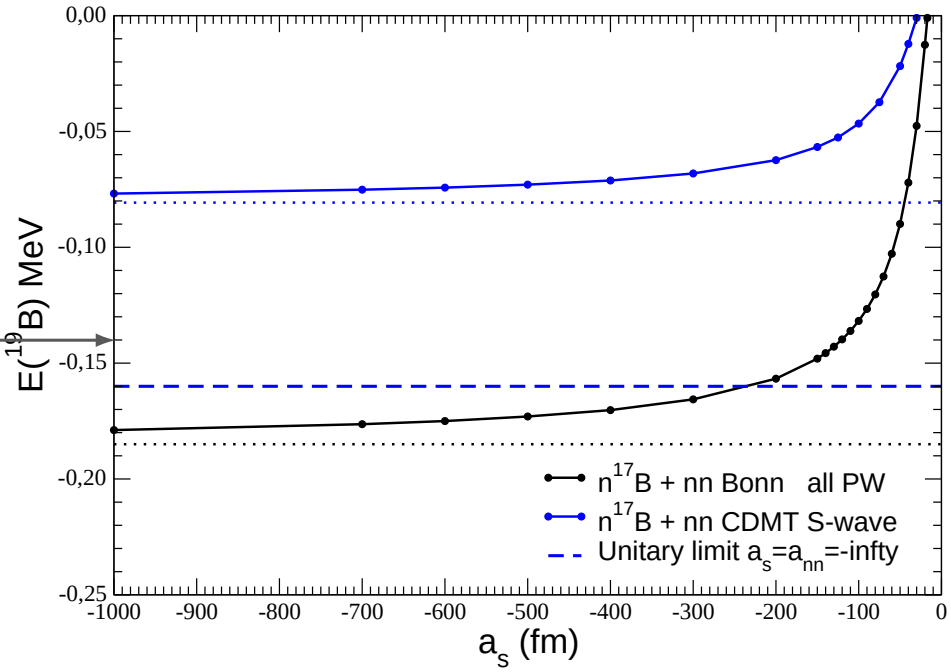
  → $R = R_{\mathrm{rms}}(^{17}\mathrm{B}) \sim 3$ fm




- n-n : Bonn A (all waves) / CD MT13 ($s$ wave)

# 17B+n+n : Unitary Limit

- Faddeev/GEM : Hiyama, PRC 100 (2019) 011603R




- ✔ $^{19}$B bound state !
- ✔ unbound excited states !

# 17B+n+n : Unitary Limit

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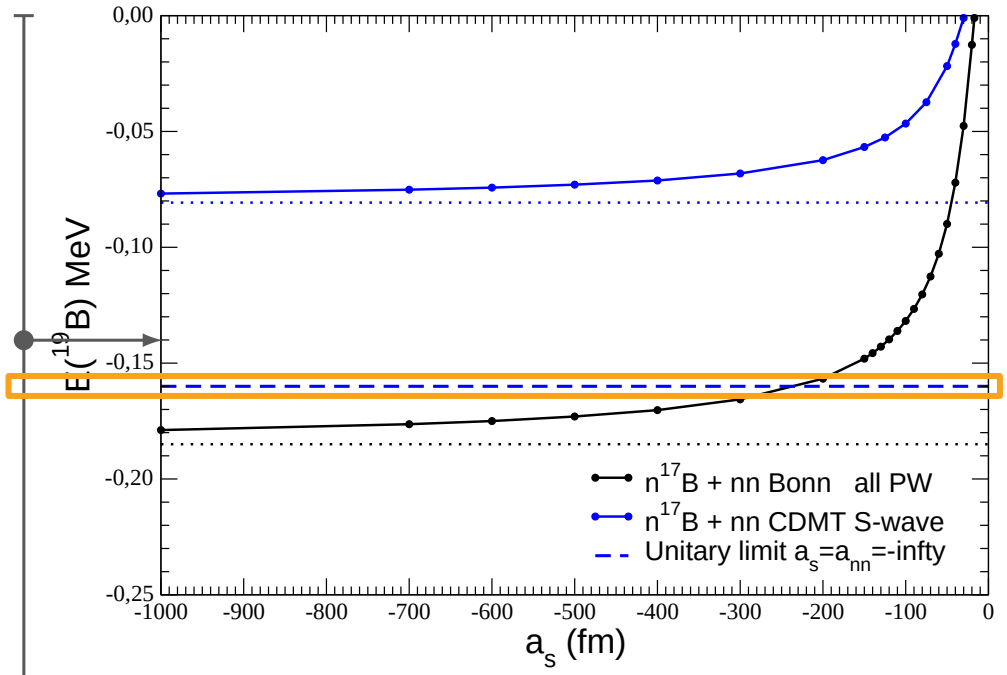


- ✔ $^{19}$B bound state !
- ✔ unbound excited states !
- ✔ good description @ Unitary Limit !

# 17B+n+n : Unitary Limit

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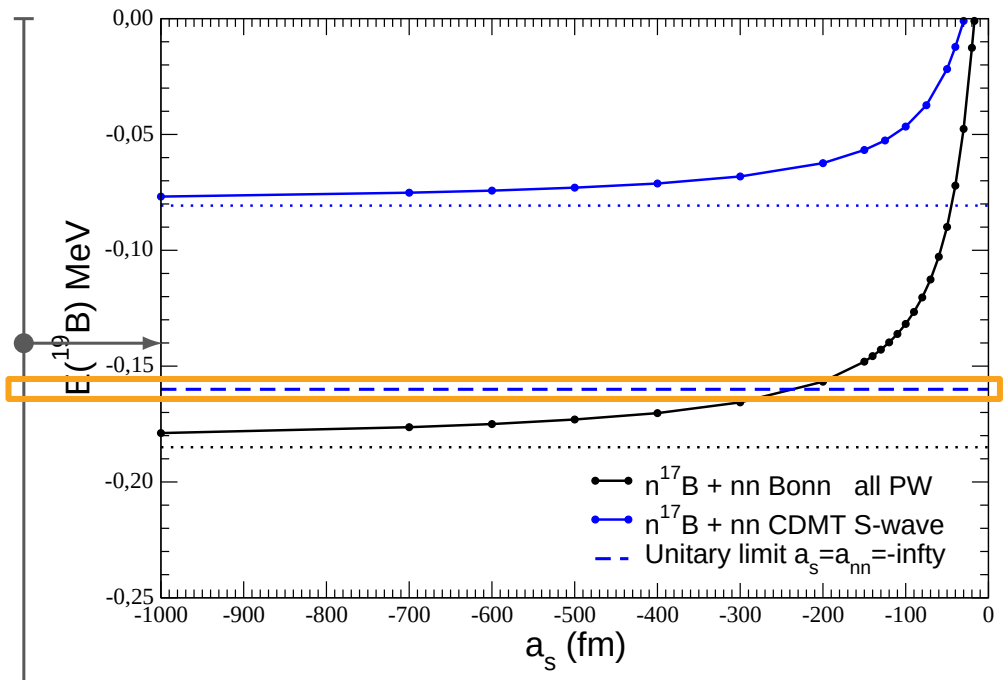


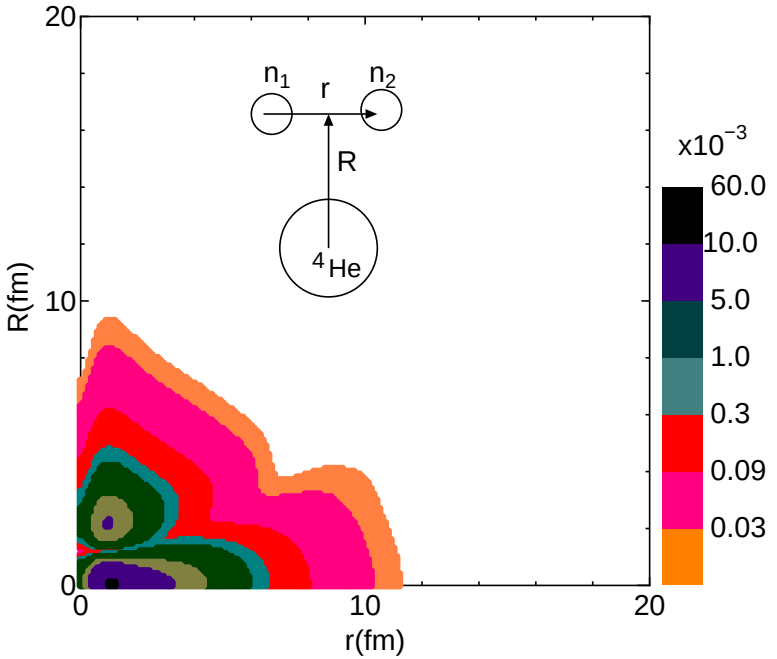


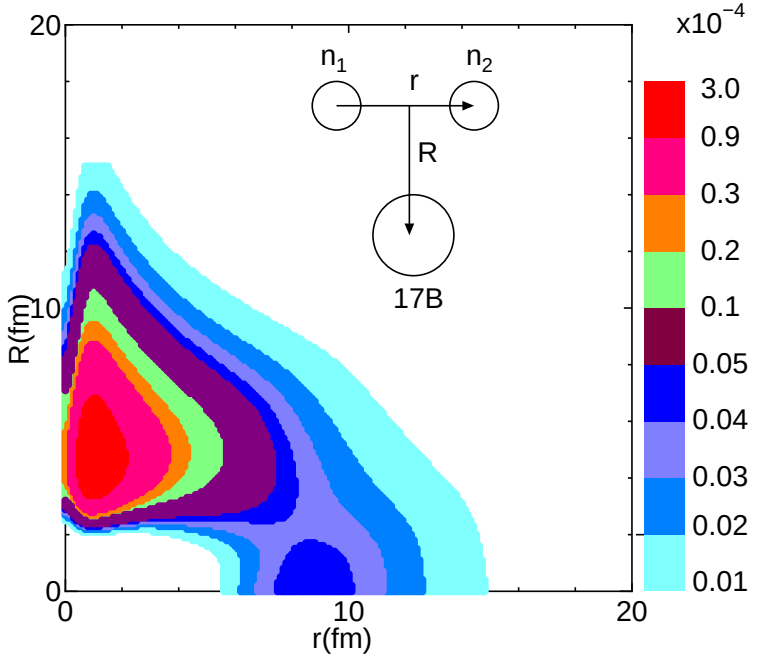


- ✔ $^{19}$B bound state !
- ✔ unbound excited states !
- ✔ good description @ Unitary Limit !
- ✔ $|\Psi(r,R)|^2$ : molecule-like !

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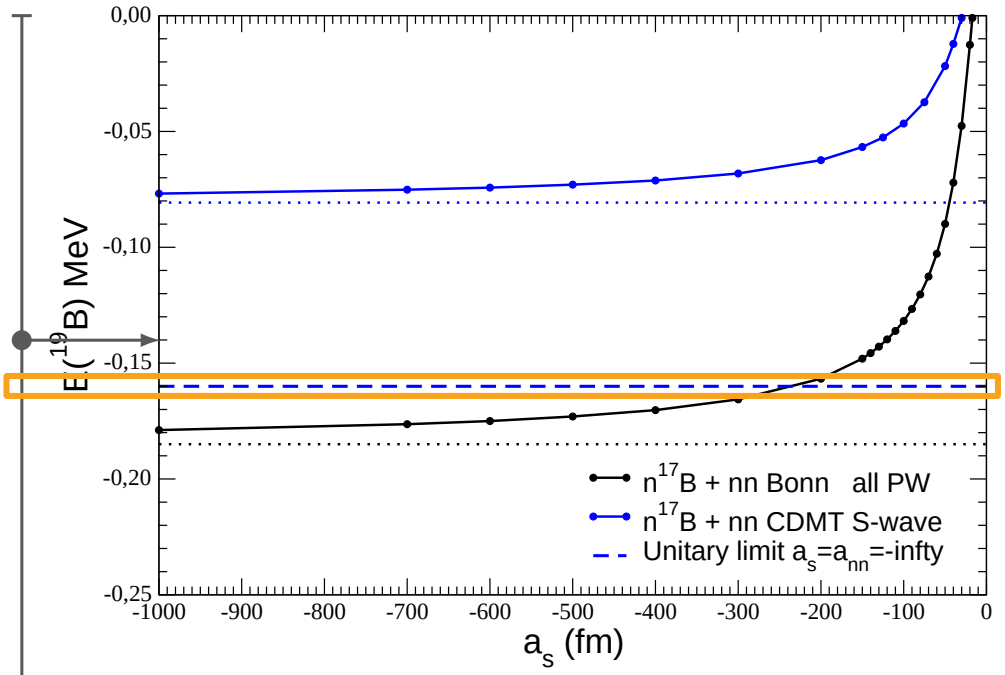
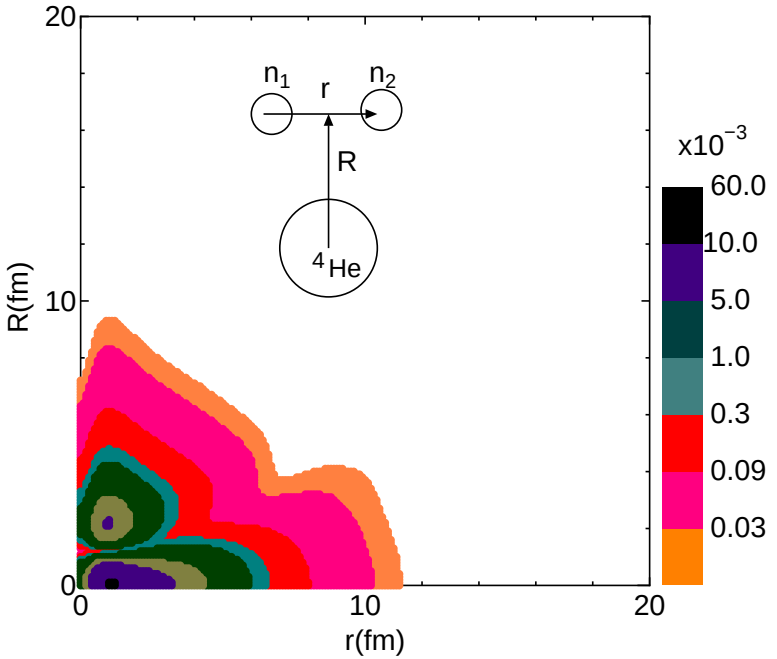
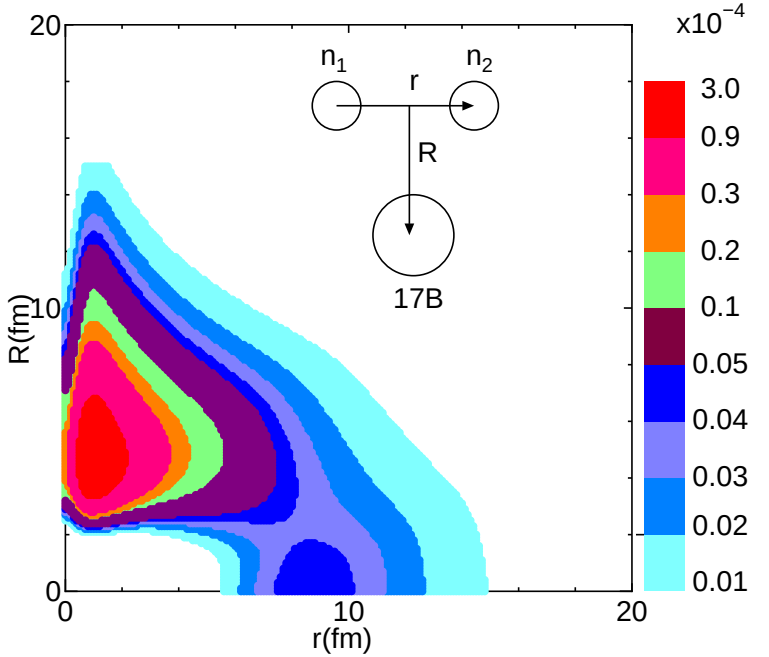
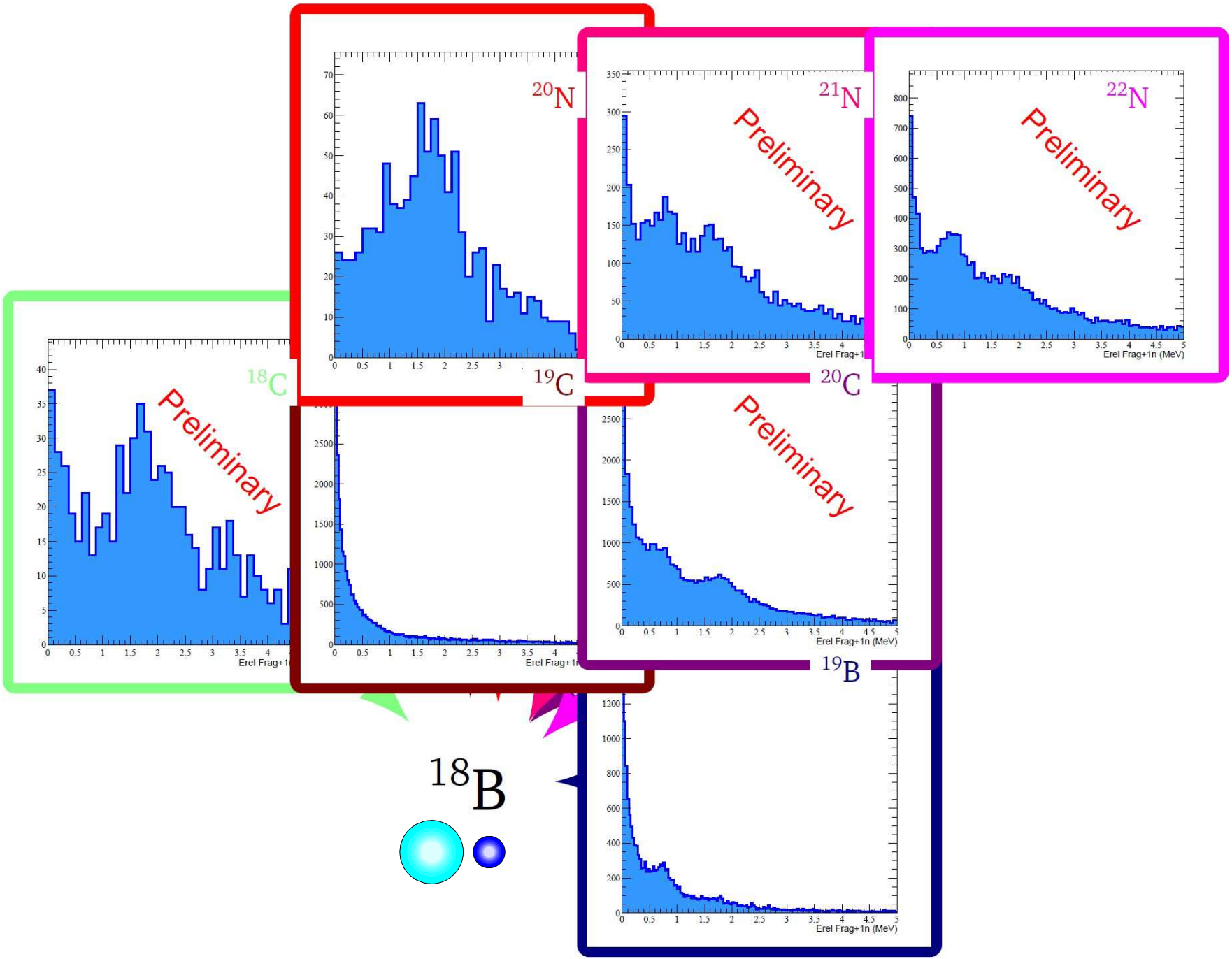



- ✔ $^{19}$B bound state !
- ✔ unbound excited states !
- ✔ good description @ Unitary Limit !
- ✔ $|\Psi(r,R)|^2$ : molecule-like !
- ✘ other bound trimers unlikely ($a_s \sim$ kfm )
- ✔ only binary inputs (no 3NF) !!!

# Boron 18 : better constraint on $a_s$ [Gibelin]



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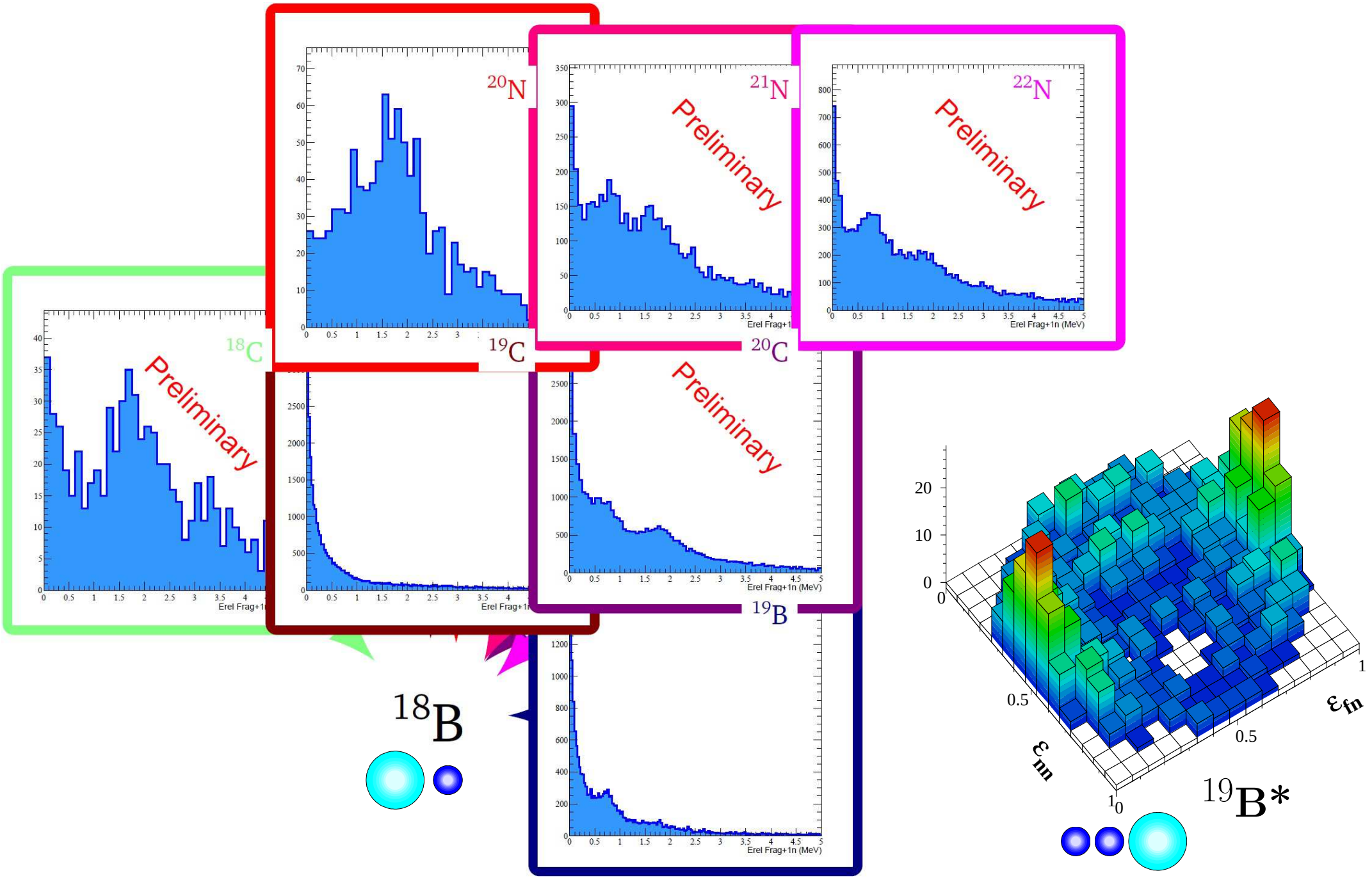
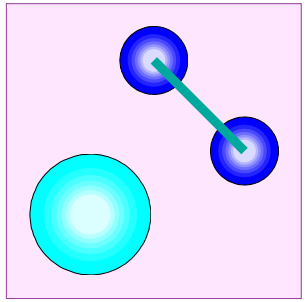
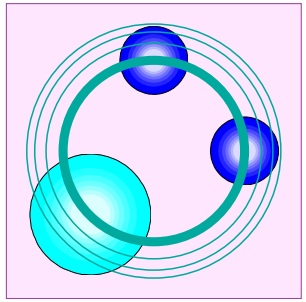


# Summary & Conclusions



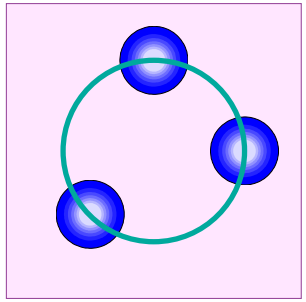
$^{16}_{4}$**Be** : $^{14}$Be+n+n  Belén Monteagudo, PhD

- there is no "dineutron" emission
- probe of the 2n wave function !



$^{19}_{5}$**B** : $^{17}$B+n+n  Hiyama, PRC 100 (2019) 011603R

- short answer : no Efimov trimers
- long answer : good description @ Unitary Limit !



$^{3}_{0}$**n** : n+n+n  Cyril Lenain, PhD

- first direct detection of 3n emission !
- no trineutron (yet), but no money was wasted ...