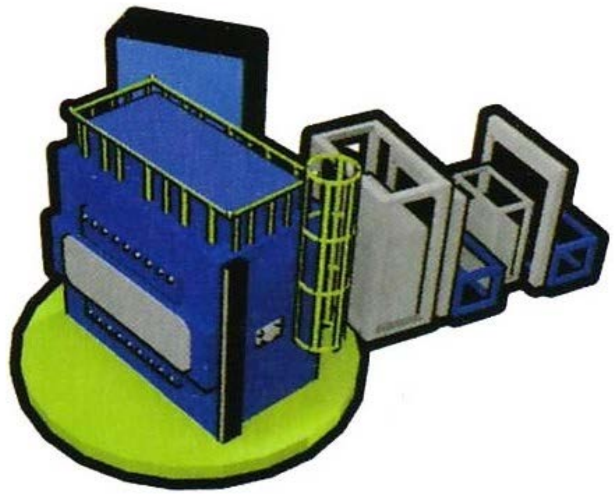
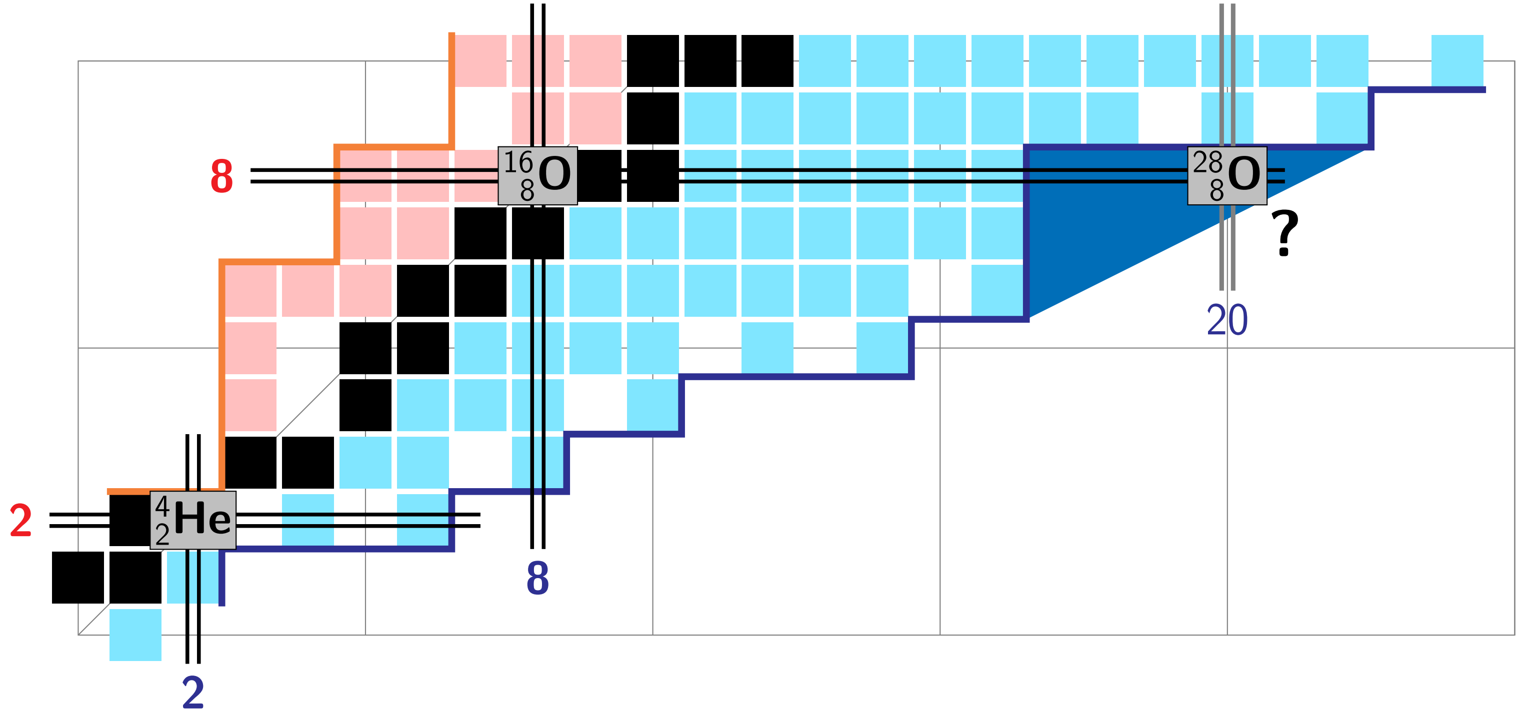
NUSTAR Annual Meeting 2021

(Planet Earth, February 25, 2021)

Results on very n-rich nuclei from SAMURAI@RIKEN

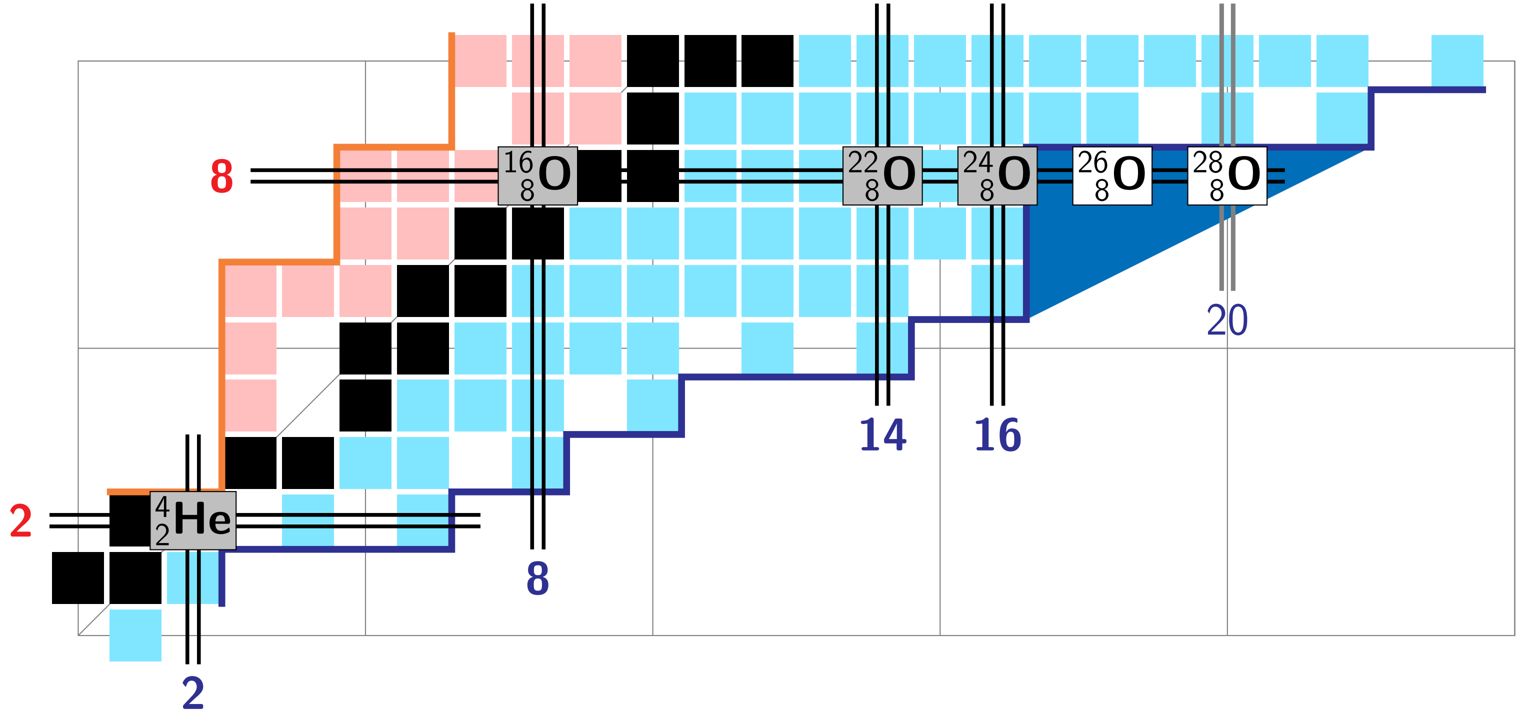


F. Miguel Marqués



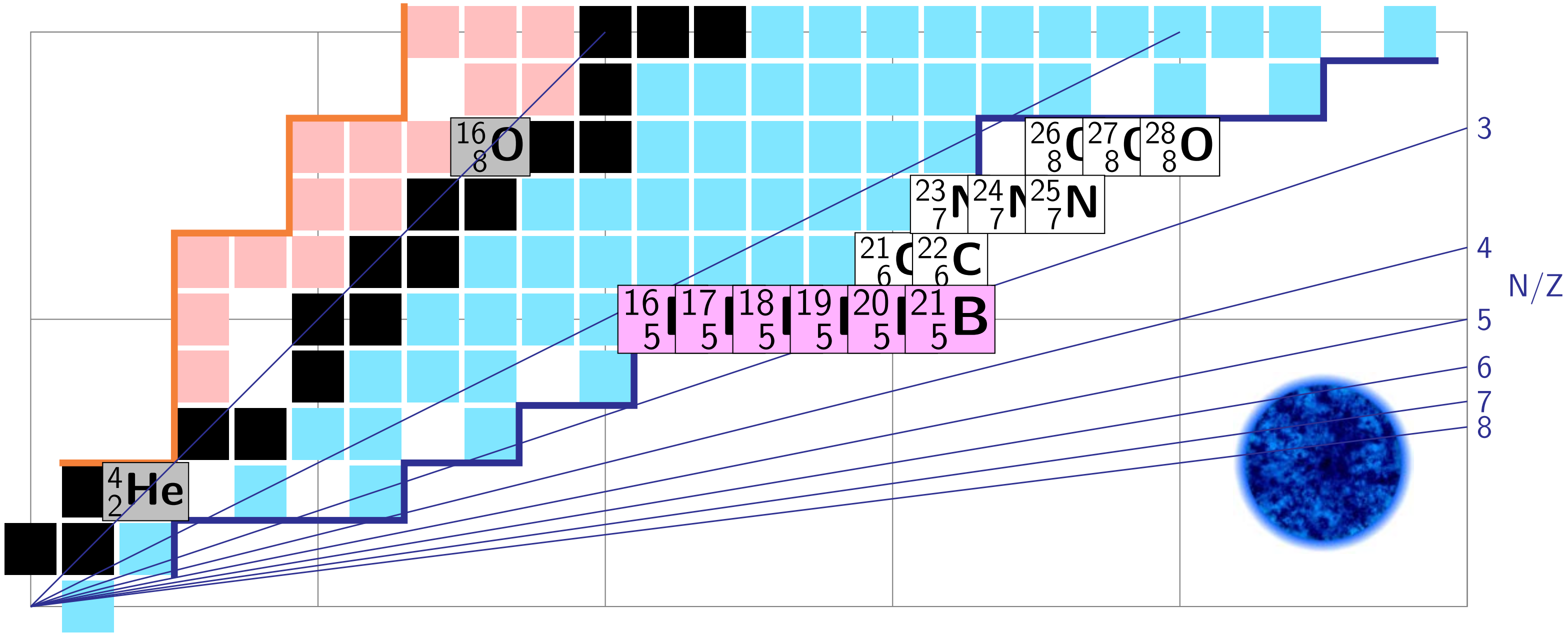
- "**Oxygen anomaly**" ?

The exotic limits of exotic nuclei



- "**Oxygen anomaly**" : N = 20 → **14** & **16**

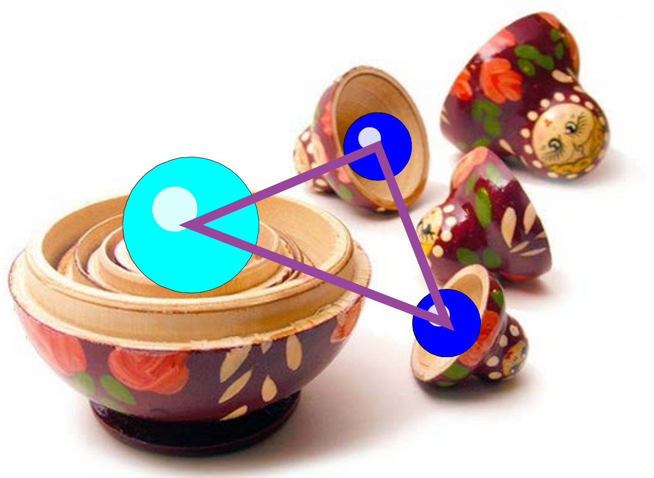
The exotic limits of exotic nuclei



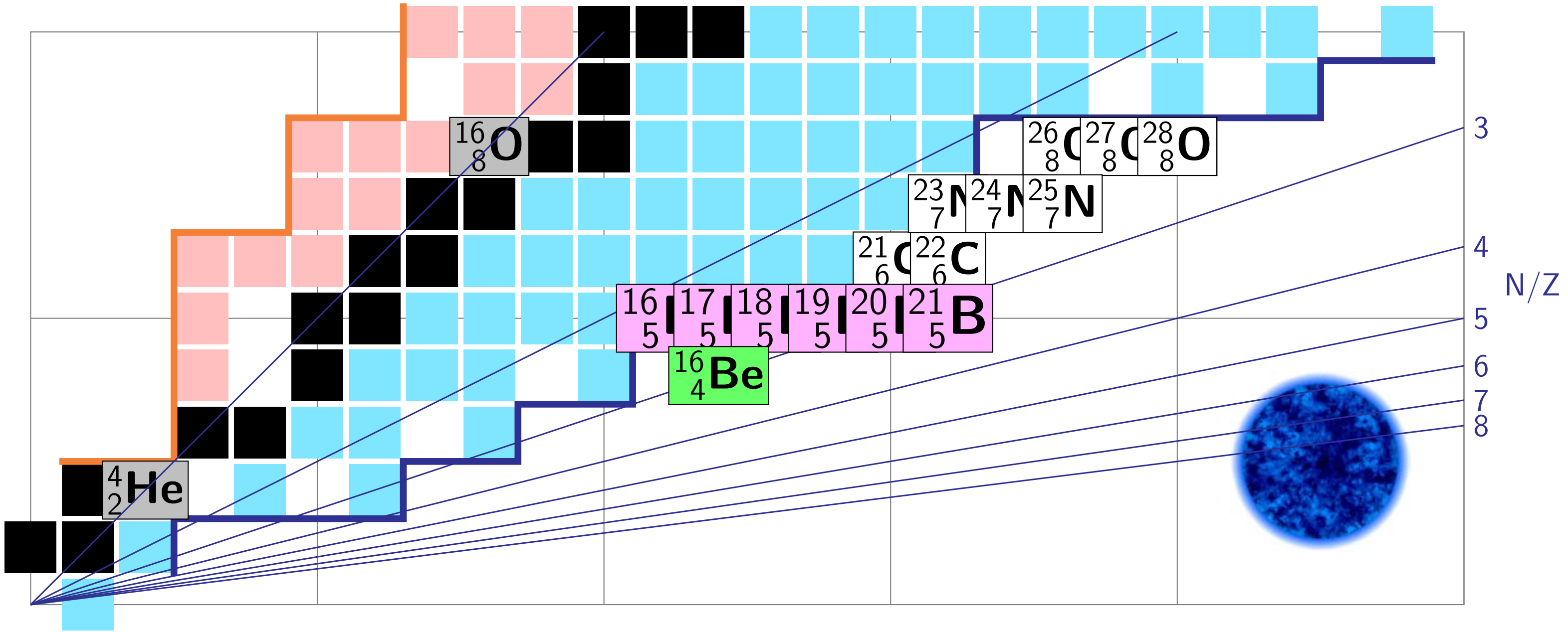
- Access to extreme N/Z ratios :

❶ $Z = 5$ (**S04**, Day-One) :

→ literally exotic structures !



The exotic limits of exotic nuclei



- Access to extreme N/Z ratios :

  ❶ $\boxed{Z=5}$ (**S04**, Day-One) :

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  ❷ $\boxed{Z=4}$ (**S18**, +MINOS) :

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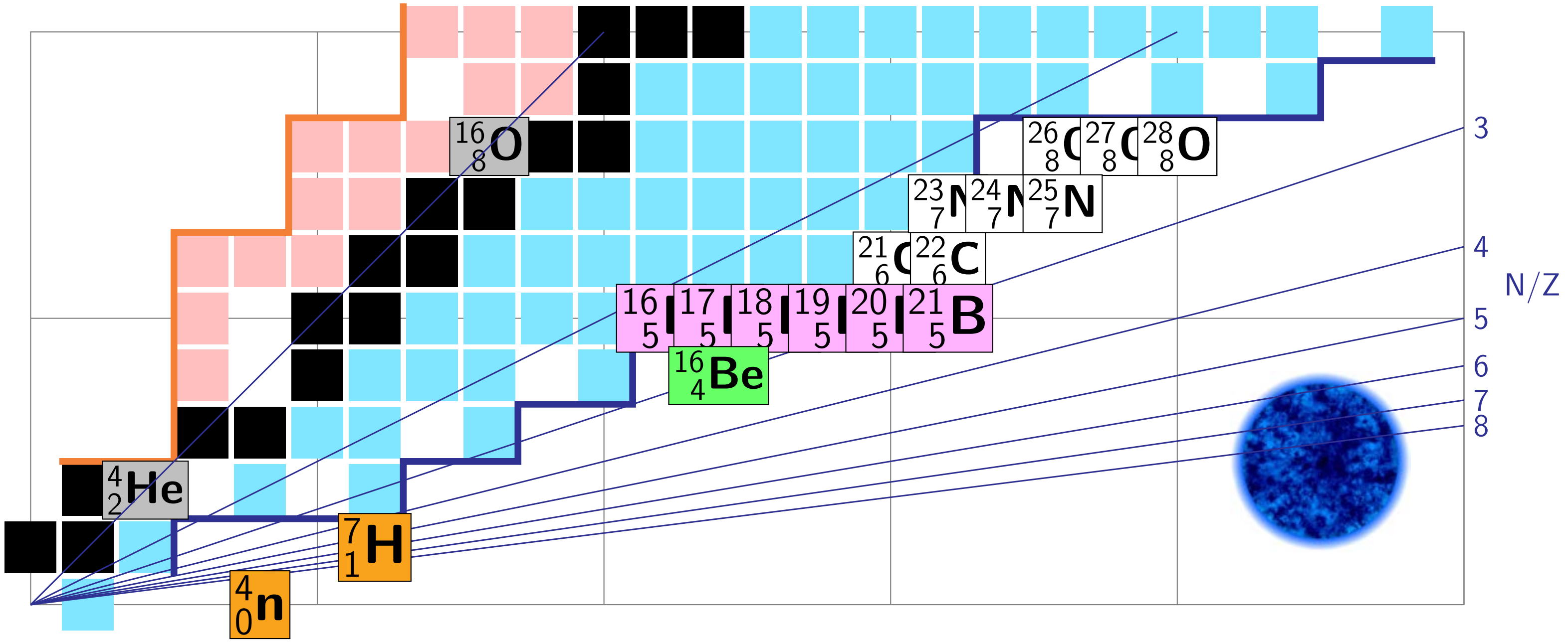
The exotic limits of exotic nuclei



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  ❶ Z = 5 (**S04**, Day-One) :

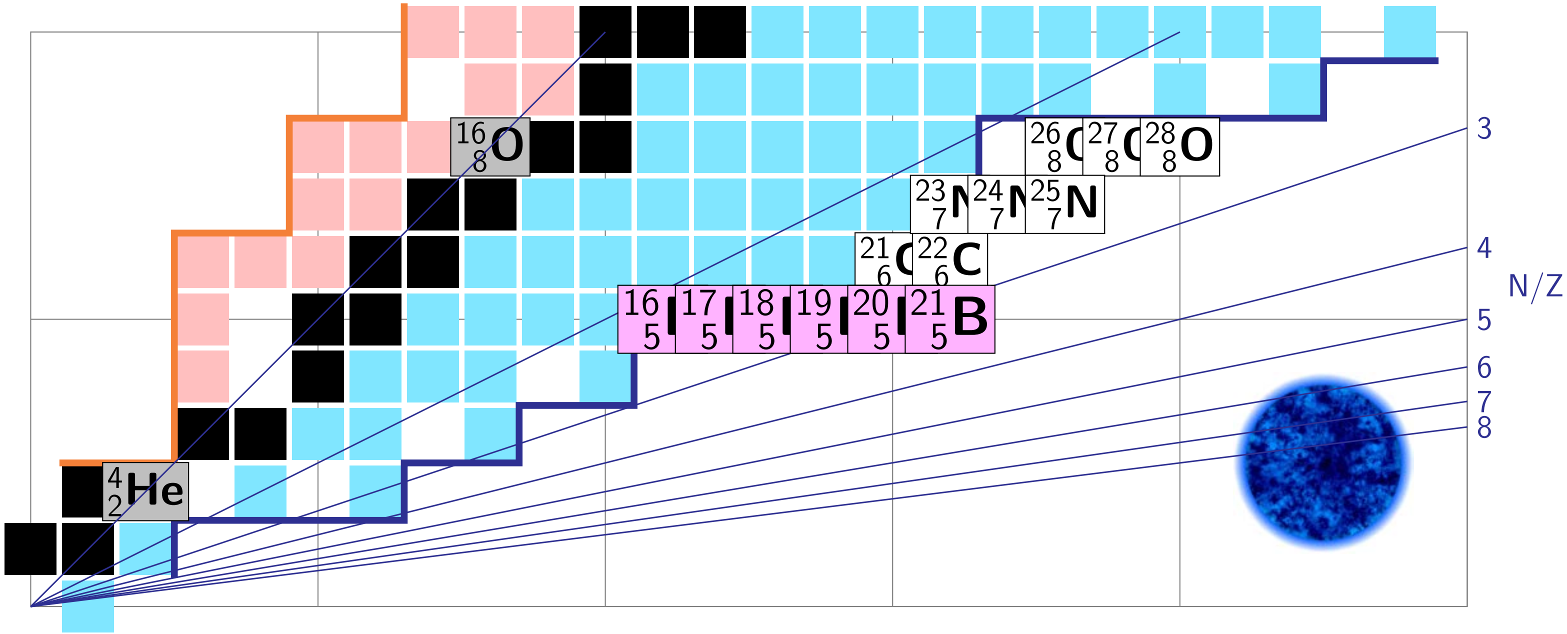
  → literally exotic structures !

  ❷ Z = 4 (**S18**, +MINOS) :

  → 2n emission/decay ?

  ❸ Z = 1 & Z = 0 (**S34**, +NeuLAND) :

  → multineutron physics !



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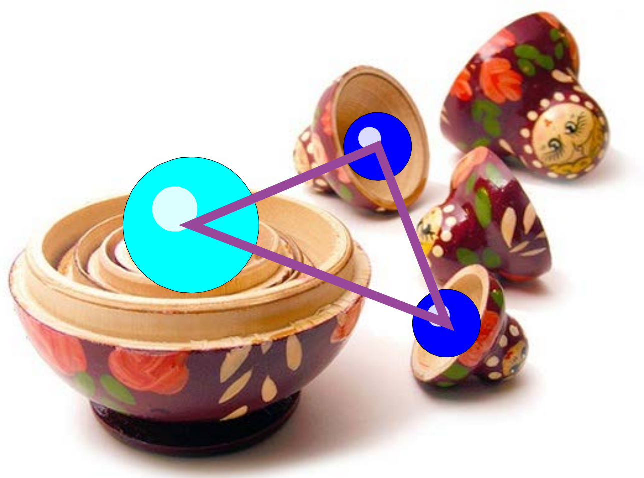
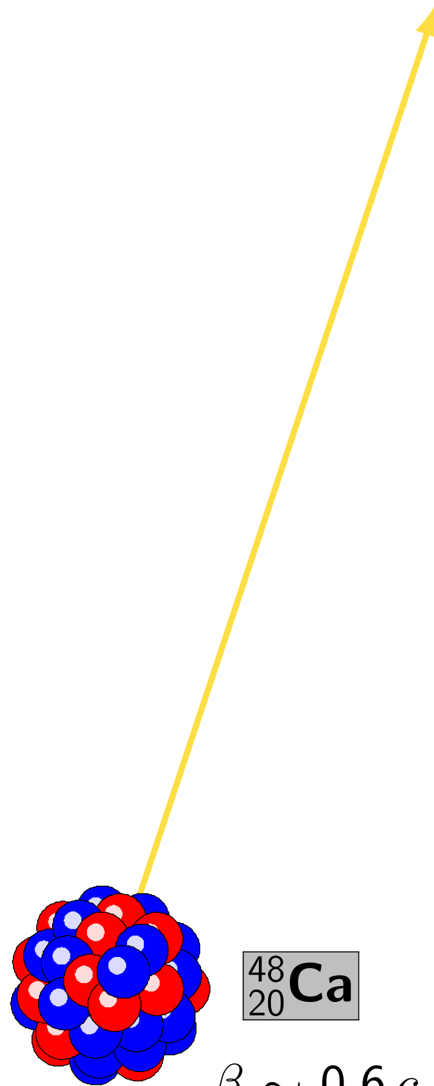
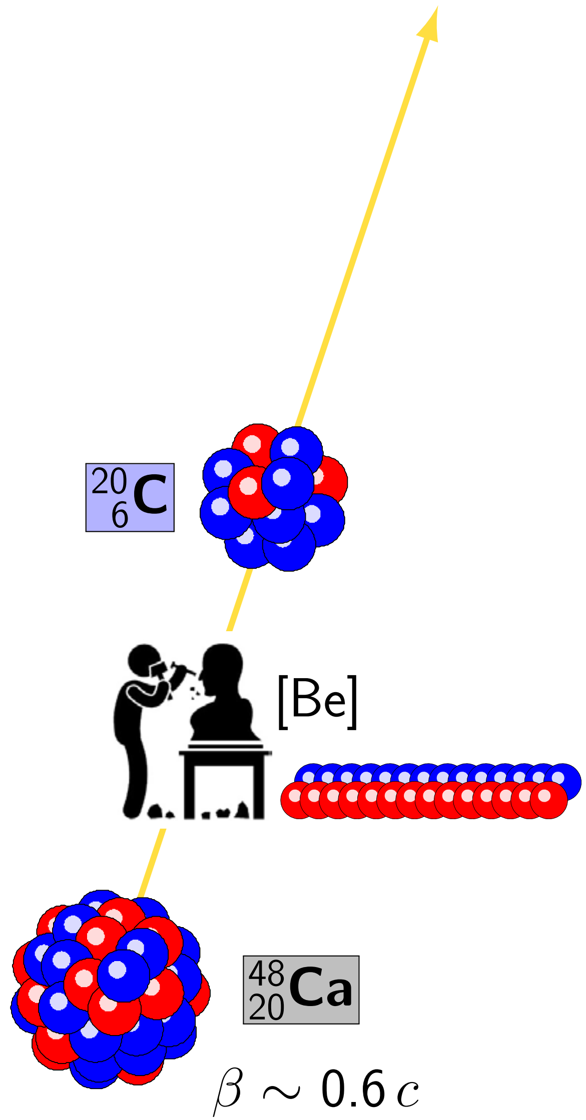


Sculpting exotic structures [S04, Orr/Gibelin]

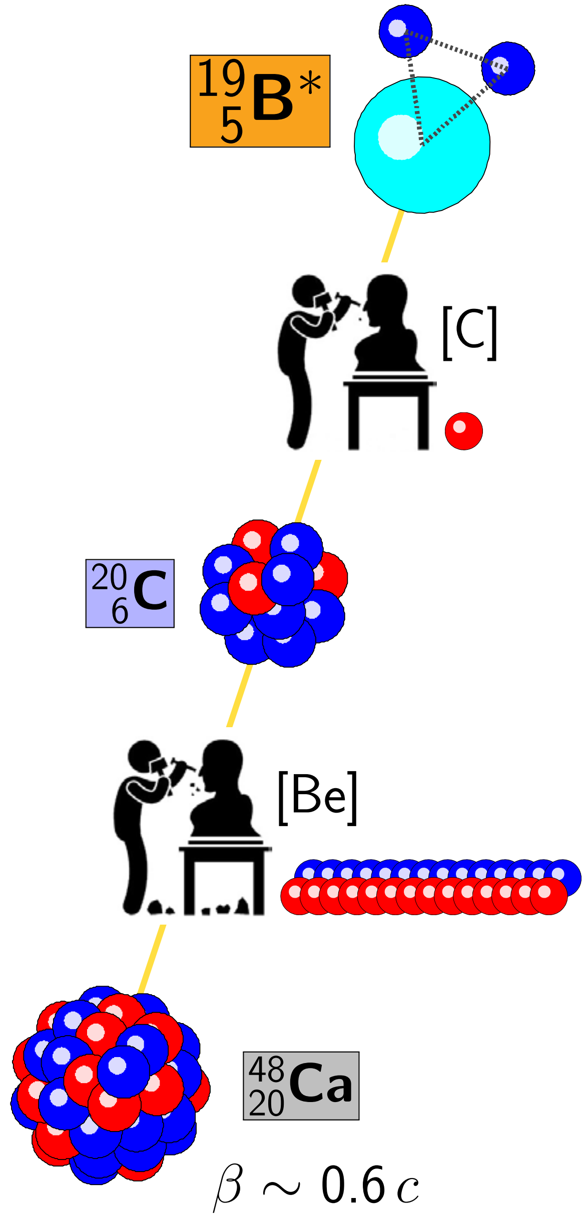


$\beta \sim 0.6\,c$

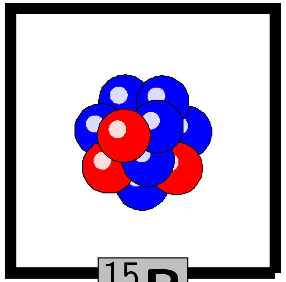

RIビームファクトリー全体図
RIビームファクトリーではさまざまな実験装置を使って、原子核の構造と反応を研究しておるのじゃ。
RI BEAM FACTORY 01
RRC RIKEN RING CYCLOTRON
(理研リングサイクロトロン)
重さ 2,300t
直径 12.6m
ビーム発射
GARIS
RILAC
AVFサイクロトロン
RILAC2
光速の4%
数値は地点通過時のビーム速度を表しています。
光速の16%
光速の70%
光速の47%
原子核を壊す
ゼロ度スペクトロメータ
形を調べる
SAMURAI
反応を調べる
SCRIT
大きさをはかる
地下1階
稀少RIリング
重さをはかる
地下2階
叩いて調べる
SHARAQ
SLOWRI
止まれ
止めて調べる
BigRIPS
RI BEAM FACTORY 04
SRC SUPERCONDUCTING RING CYCLOTRON
(超伝導リングサイクロトロン)
重さ 8,300t
直径 18.5m
ここには「ビームダンプ」という装置があって、重イオンビームからRIビームに変わるところなんだよ。


$^{20}_{6}$C
[Be]
$^{48}_{20}$Ca
$\beta \sim 0.6\,c$

Sculpting exotic structures [S04, Orr/Gibelin]



The Boron ‘Matryoshka’



$^{15}_{5}\mathrm{B}$

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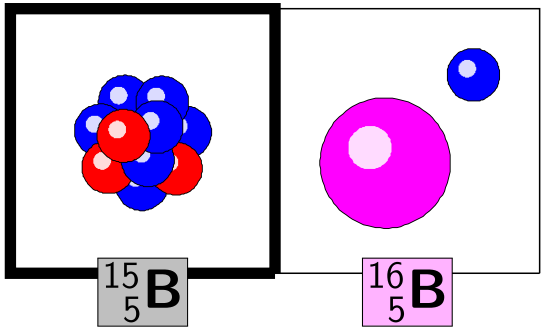
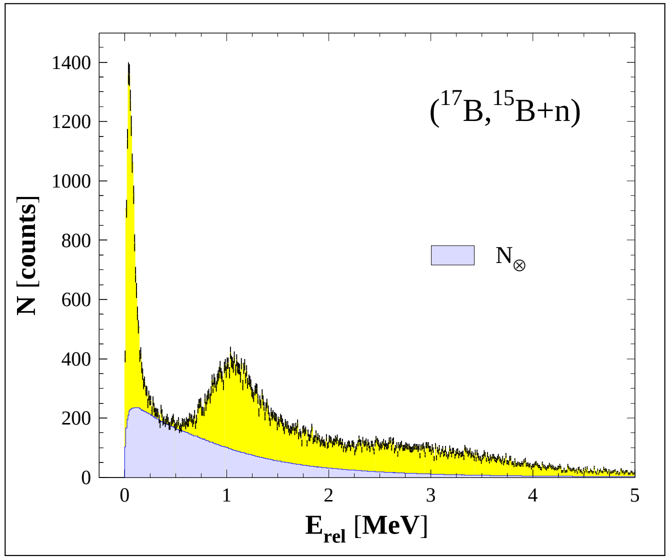


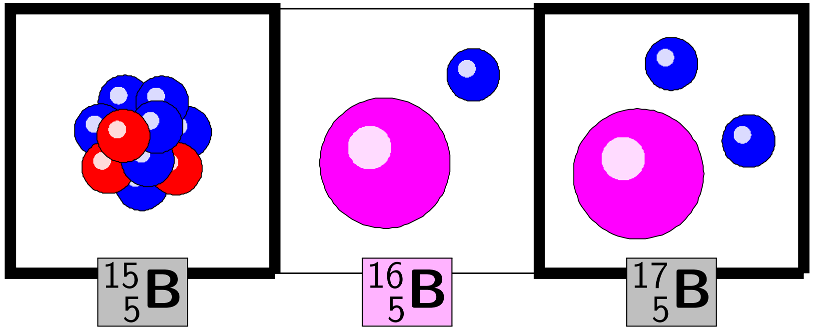


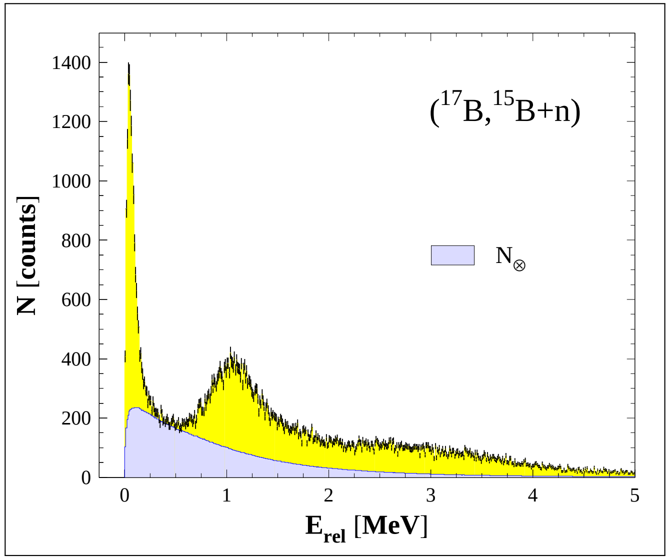
$\rightarrow$ $E_{gs} = 46(3)$ keV

$\rightarrow$ $\frac{\delta m}{m} \sim 10^{-7}$!

Yang, PRL 126 (2021) 082501

The Boron 'Matryoshka'





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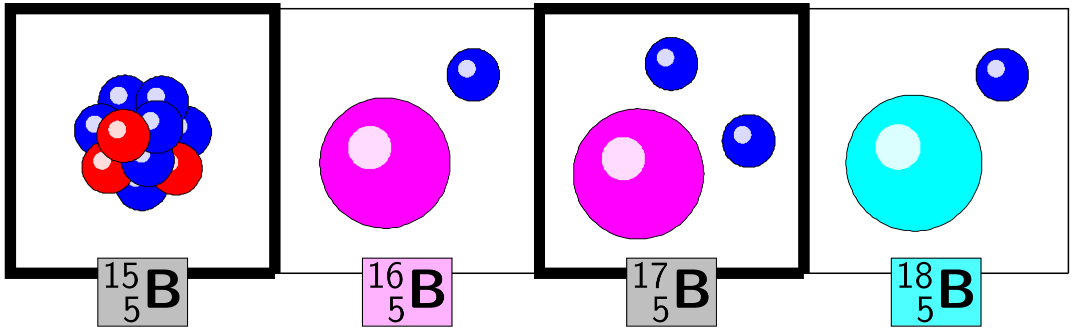

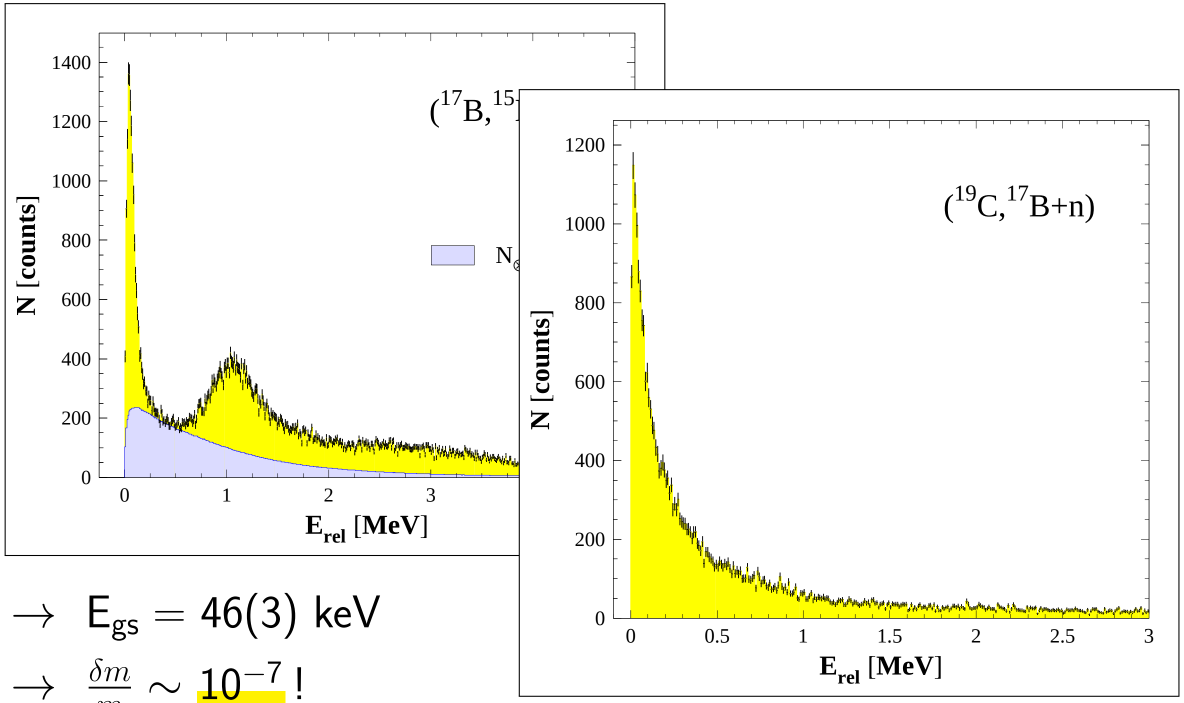

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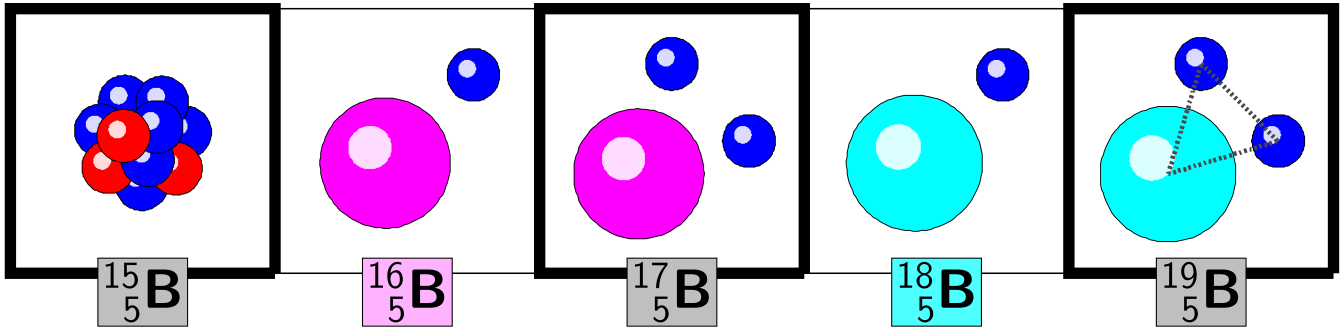

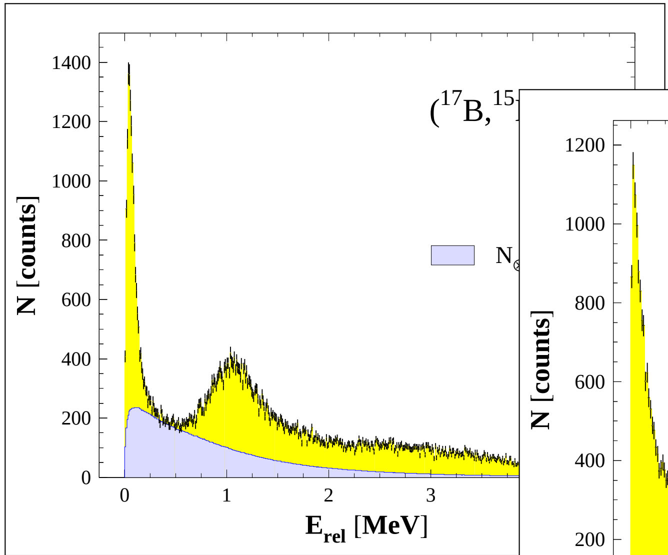

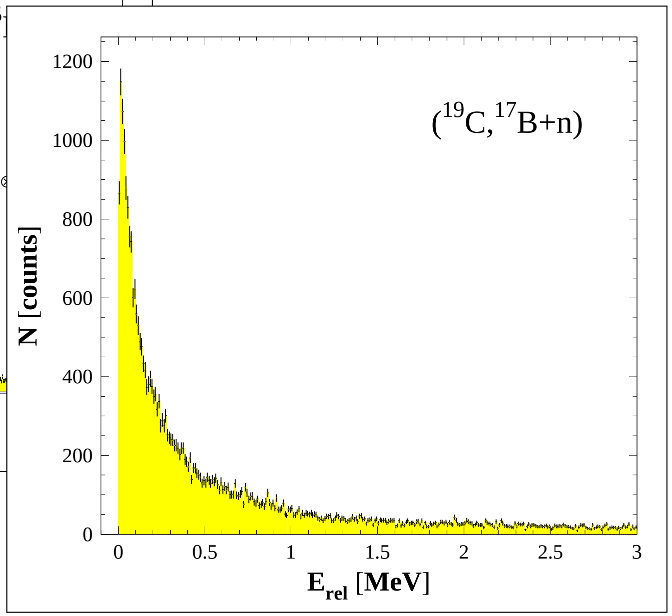

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→ Efimov states ?

Hiyama, PRC 100 (2019) 011603R

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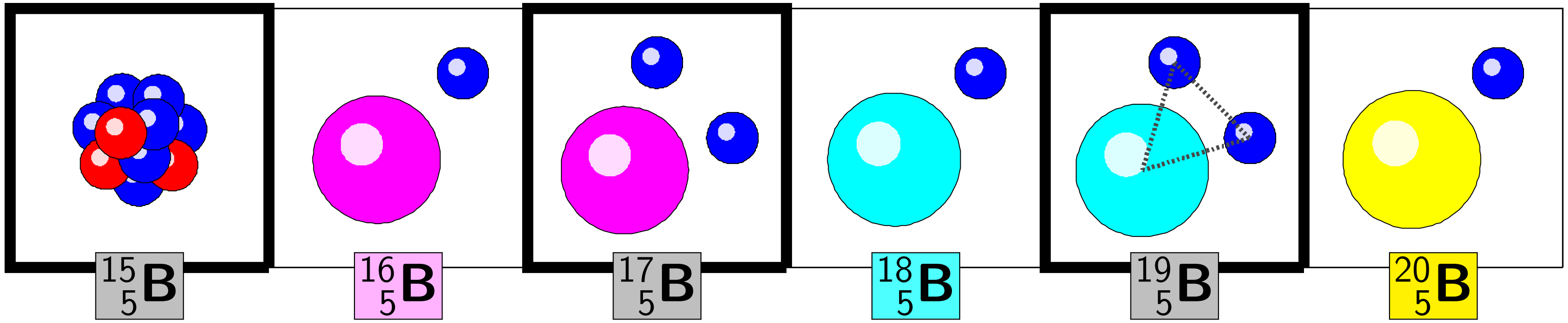

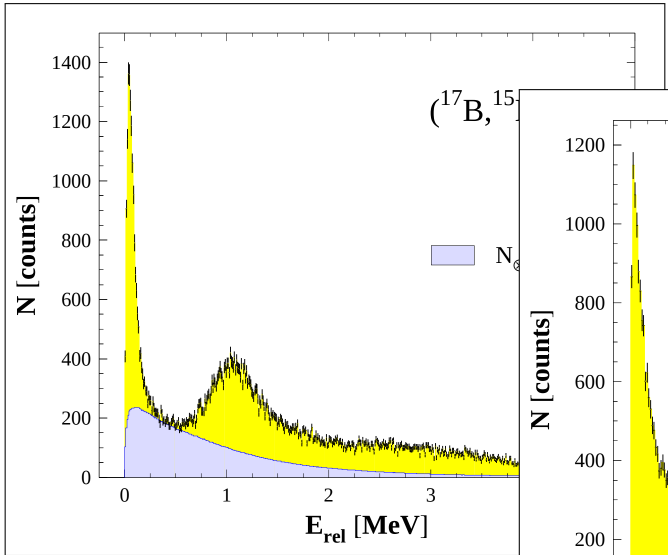

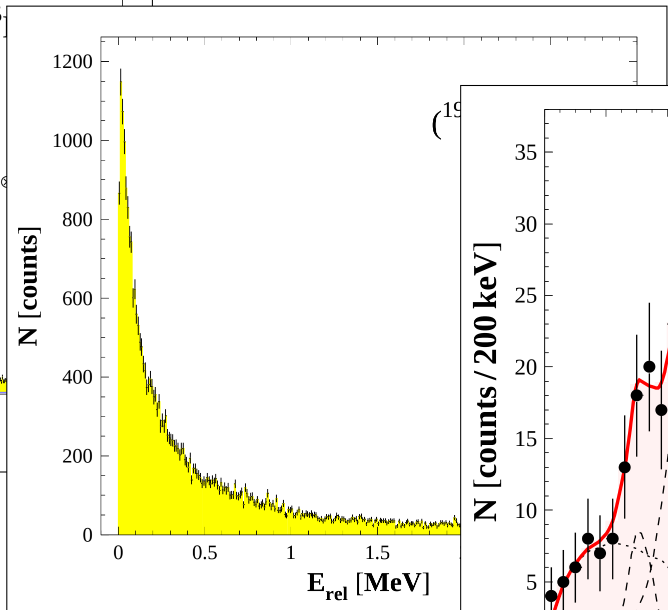

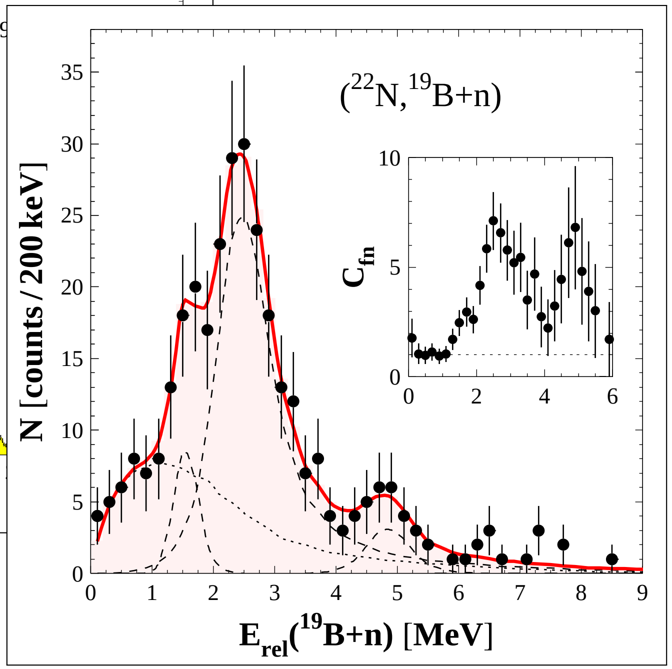

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Leblond, PRL 121 (2018) 262502

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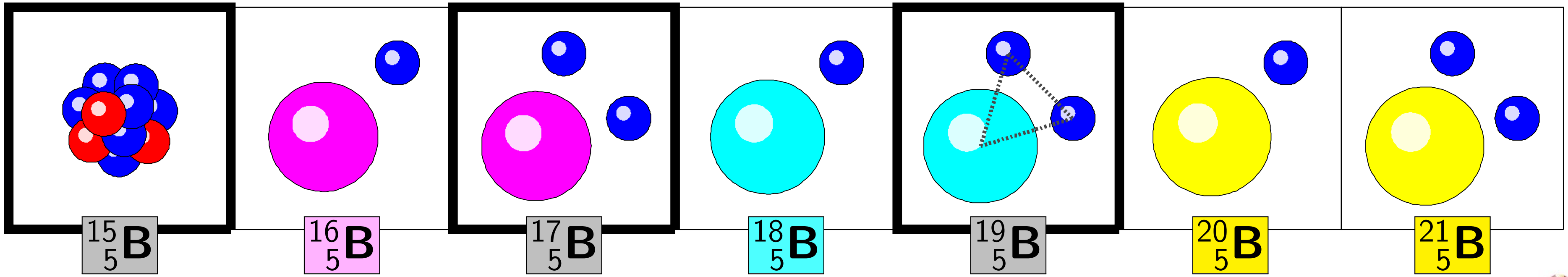

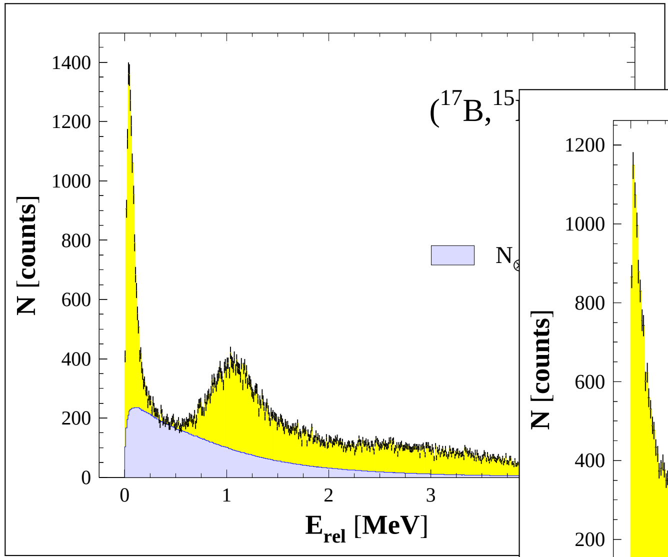

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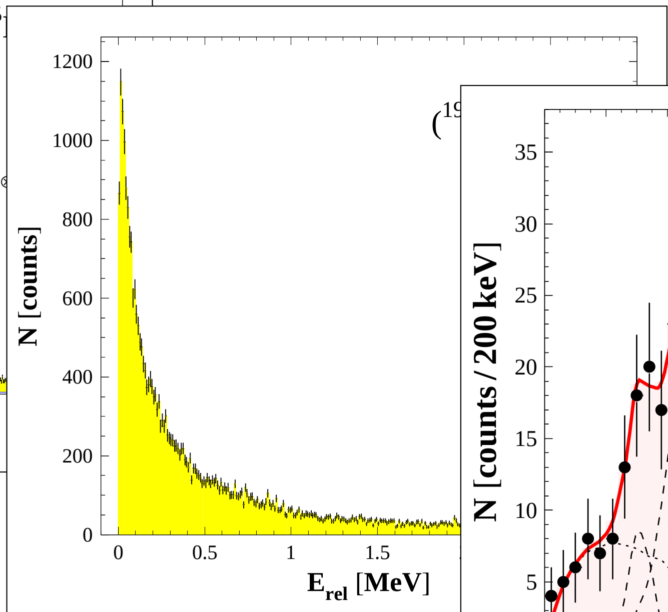

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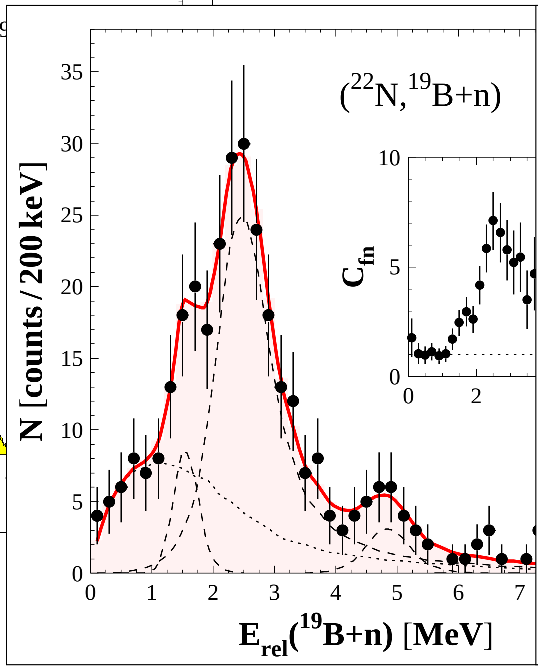
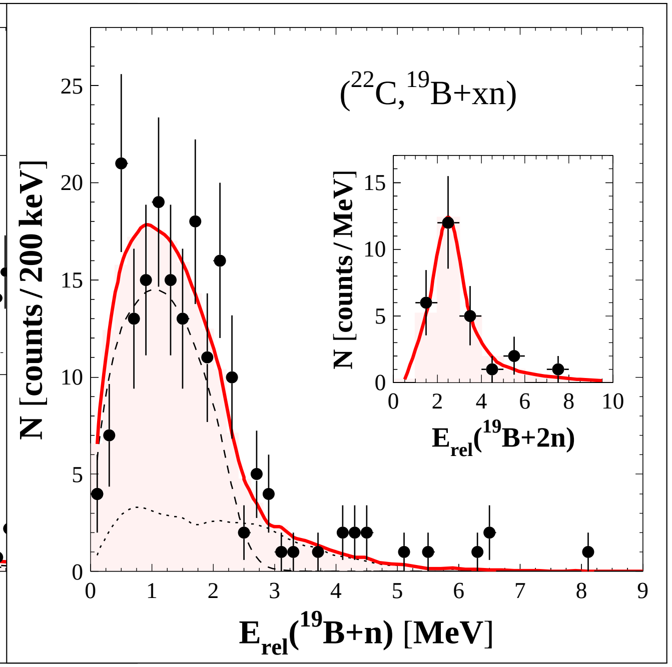
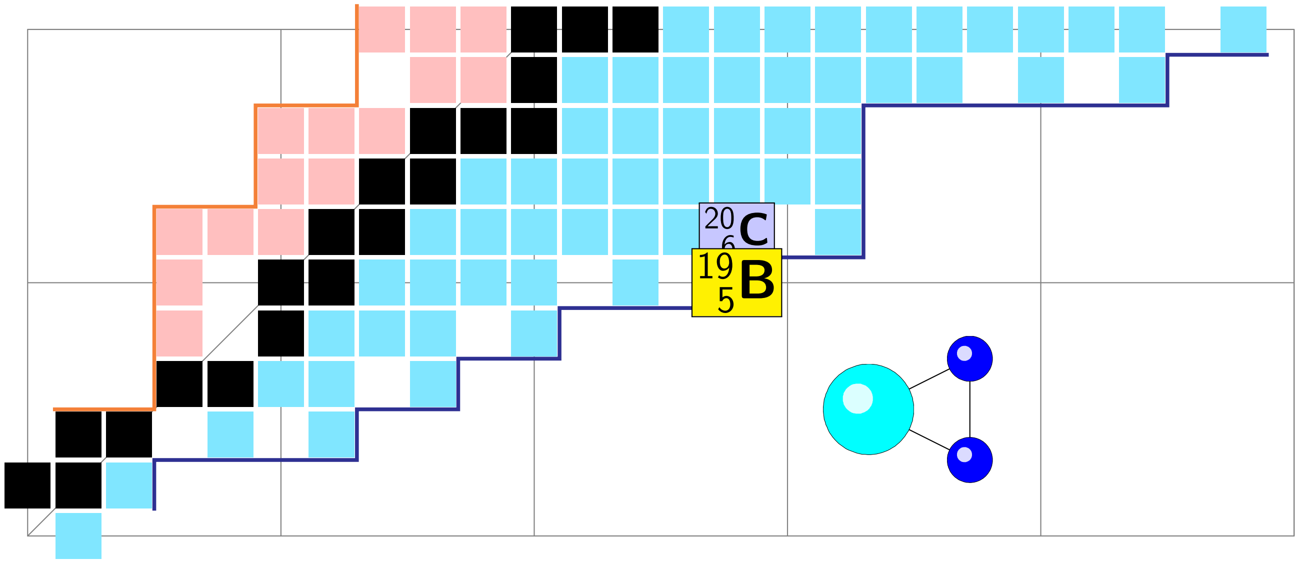


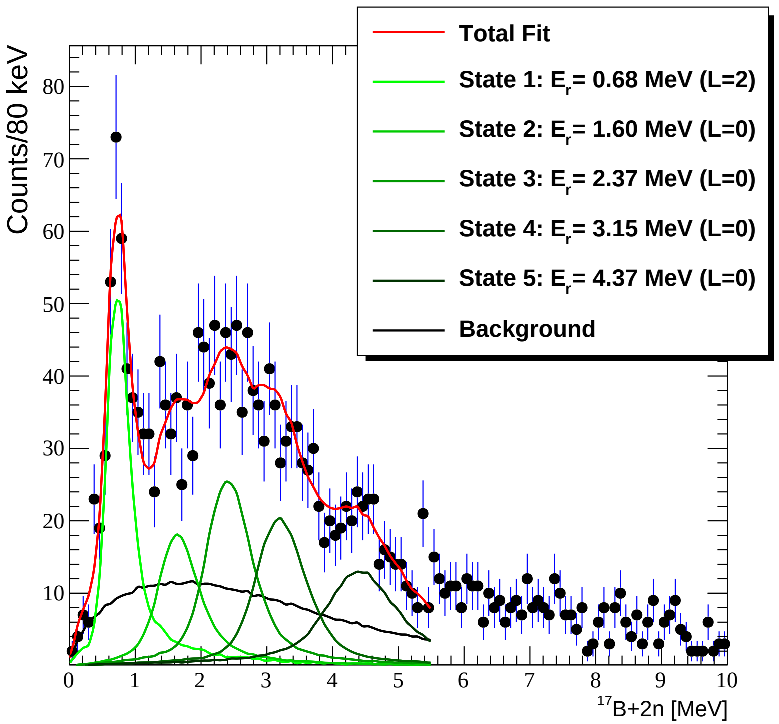


Leblond, PRL 121 (2018) 262502

→ 2n emitter !

Boron 19 : two huge scattering lengths ! [Gibelin]





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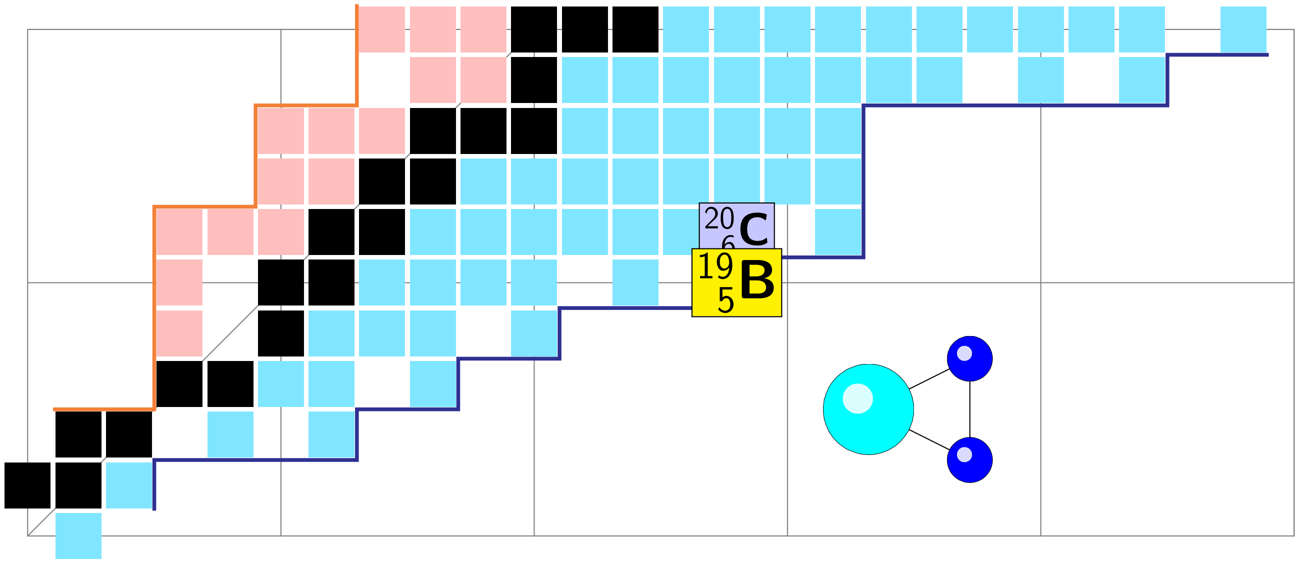

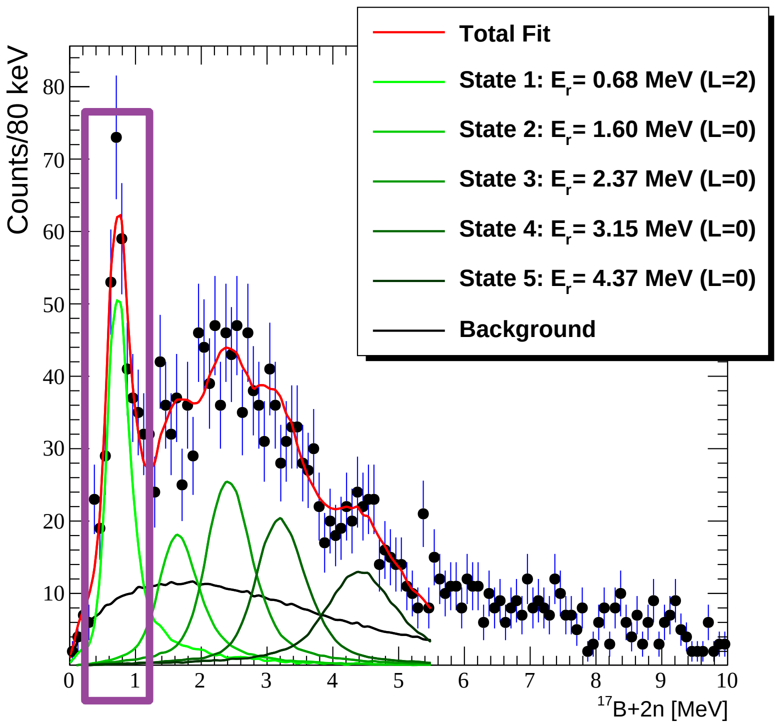

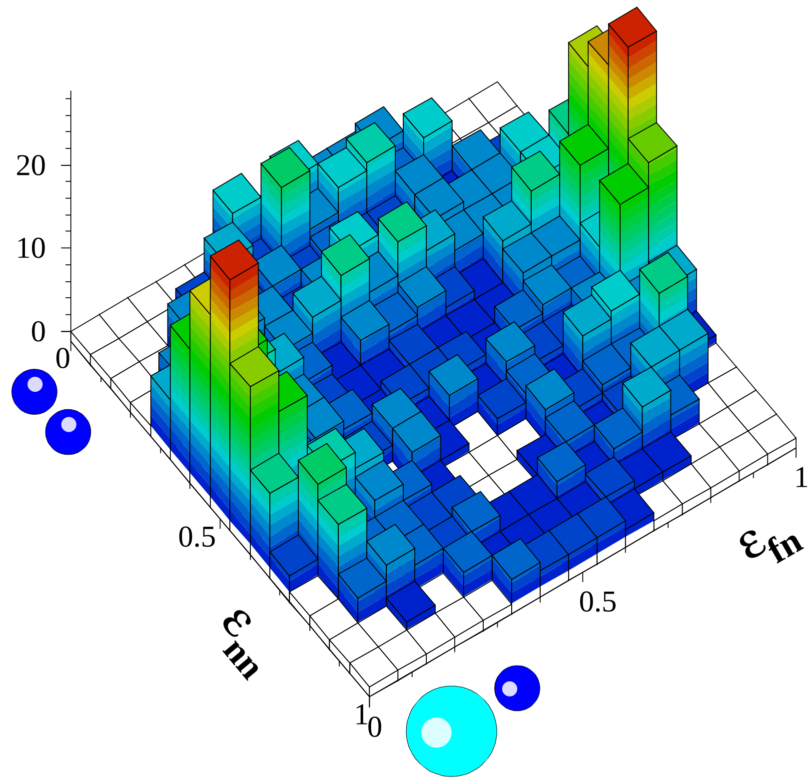

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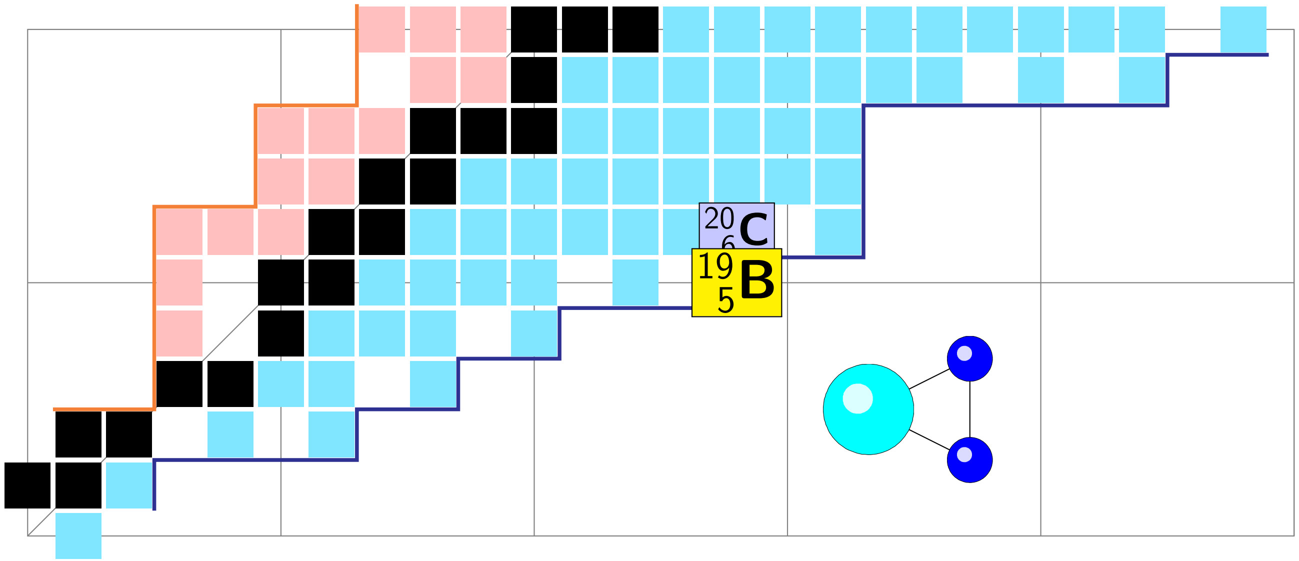
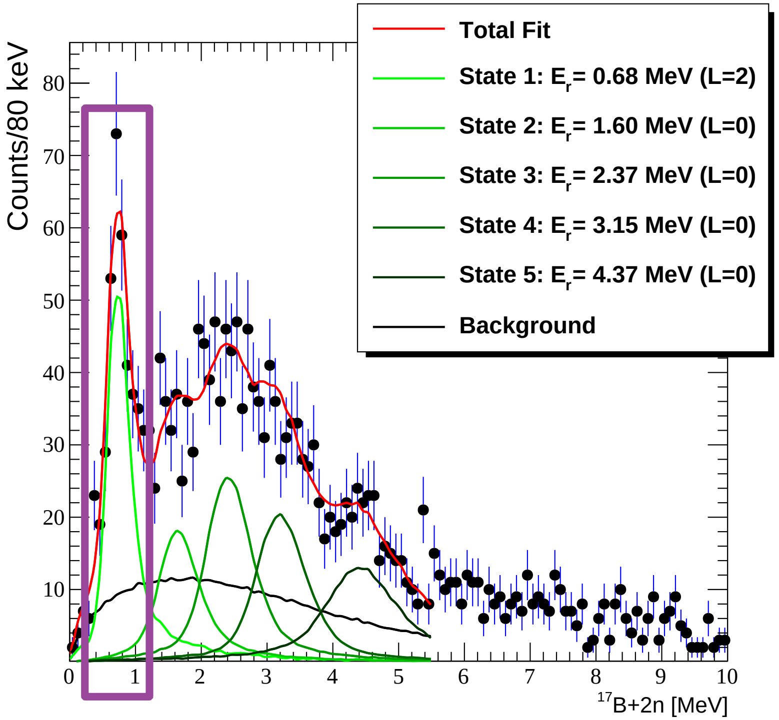
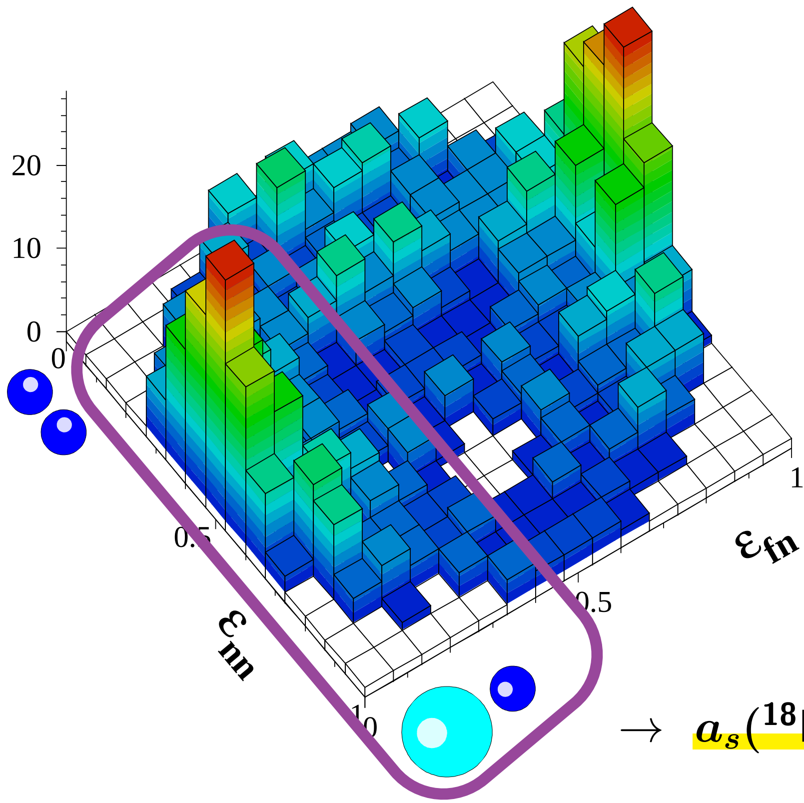
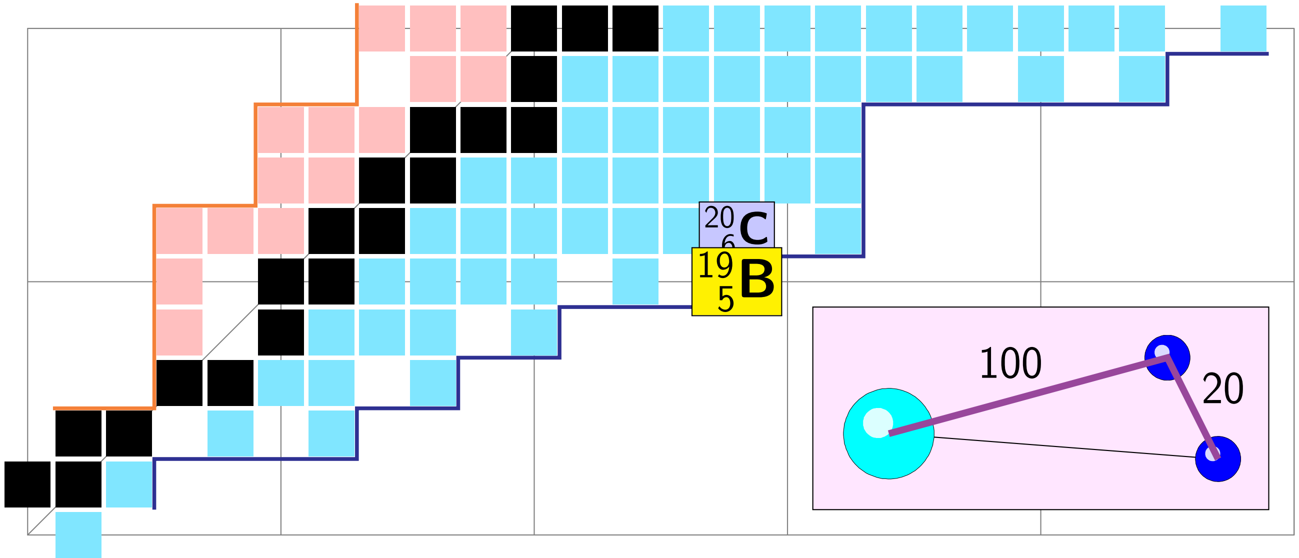


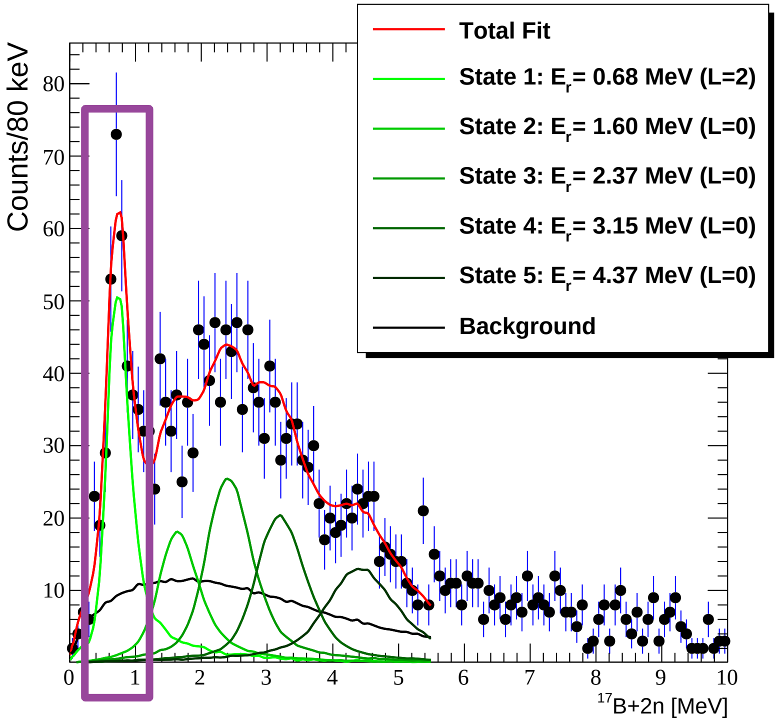


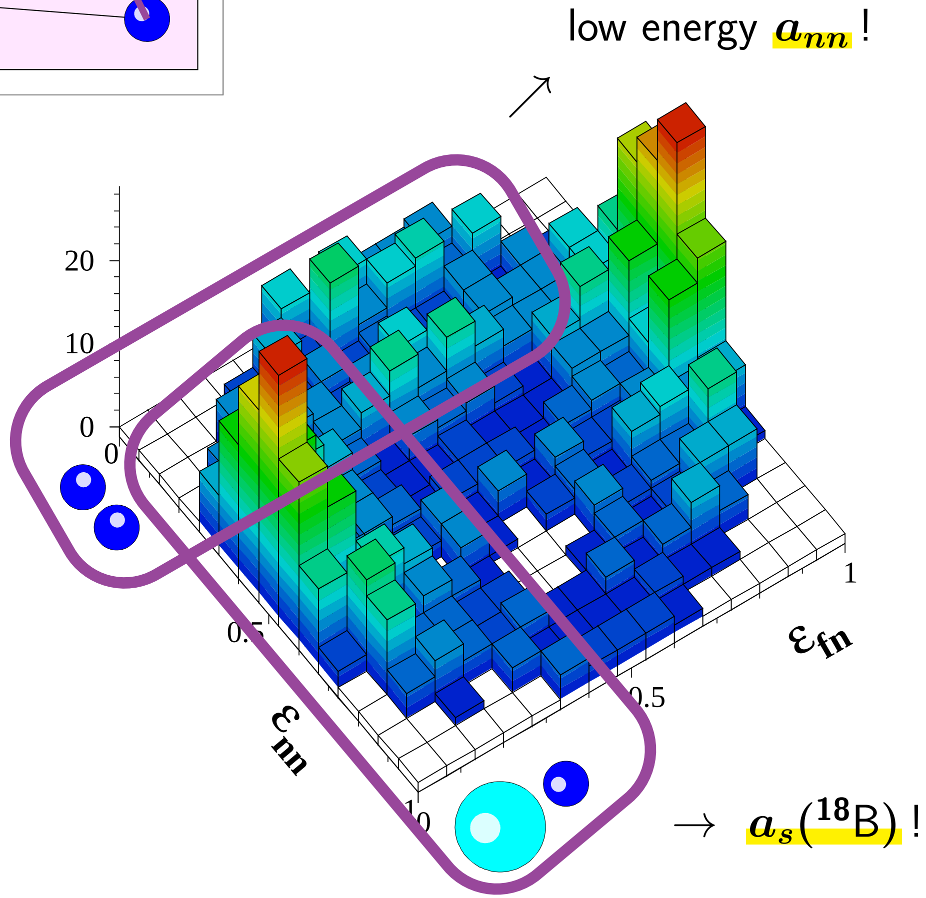


$\rightarrow a_s(^{18}\mathrm{B})$!

Boron 19 : two huge scattering lengths ! [Gibelin]







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

- Efimov effect :

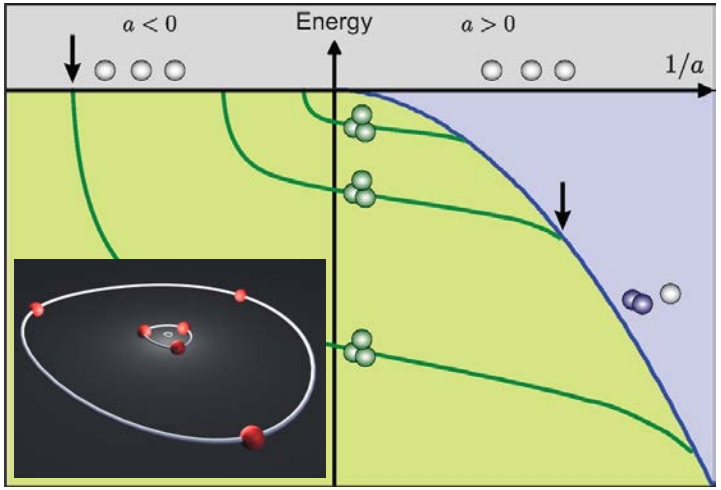
  "*a scale-invariant 3-body attraction*"

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

  → induced long-range interaction

  → discrete scale invariance

  → Borromean binding ( )



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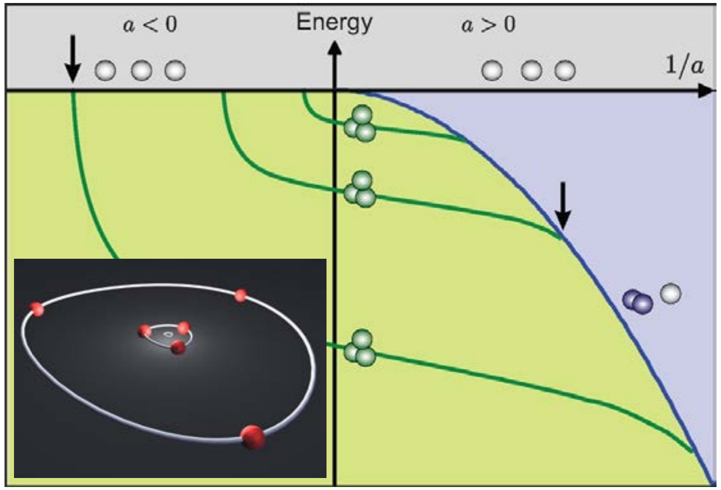
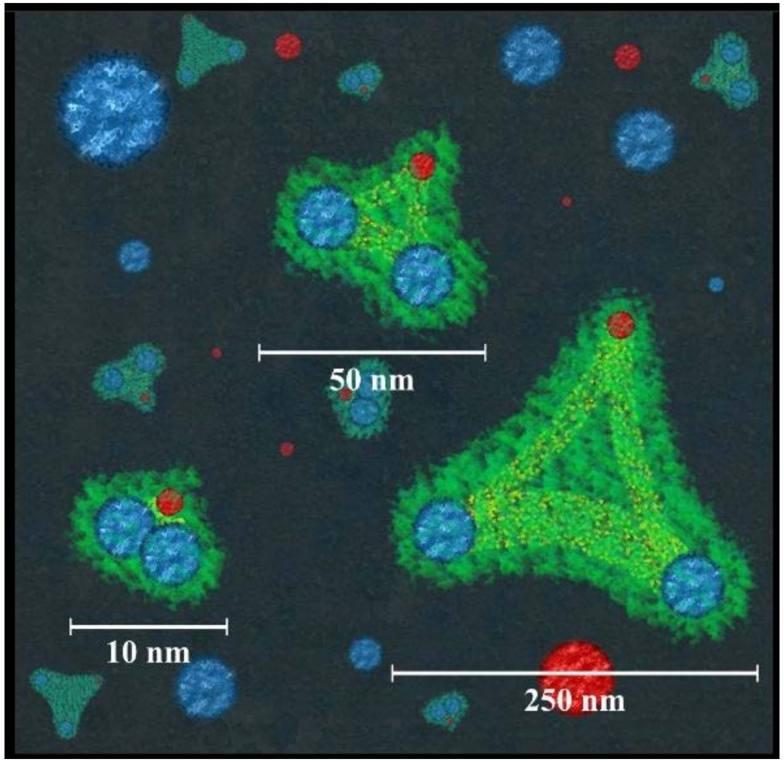


- Efimov physics :

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

  → number of trimers $\gtrsim 1$ ...

Pires, PRL 112 (2014) 250404



phys.org : Li-Cs-Cs "*exotic giant molecules*"

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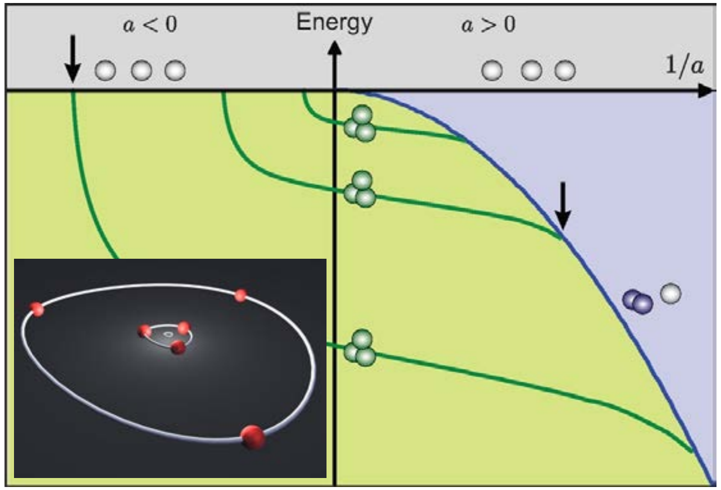

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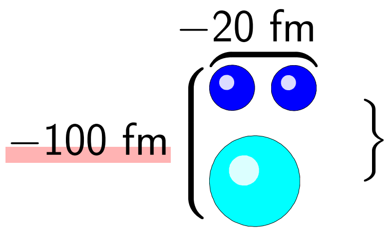
- Three-body calculation :

  Hiyama, PRC 100 (2019) 011603R



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

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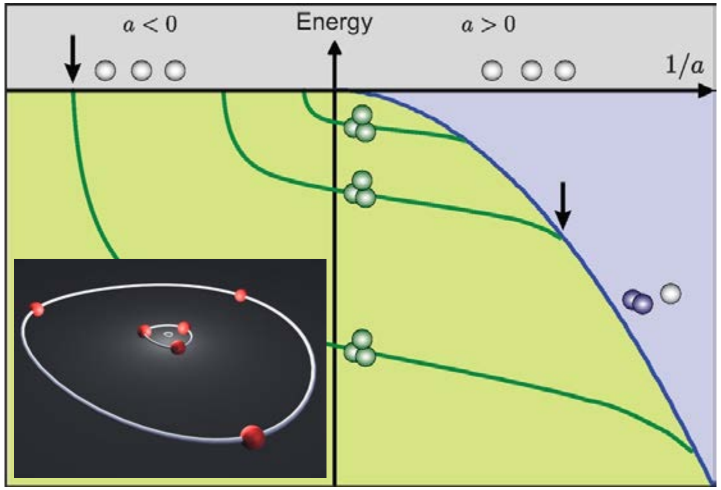

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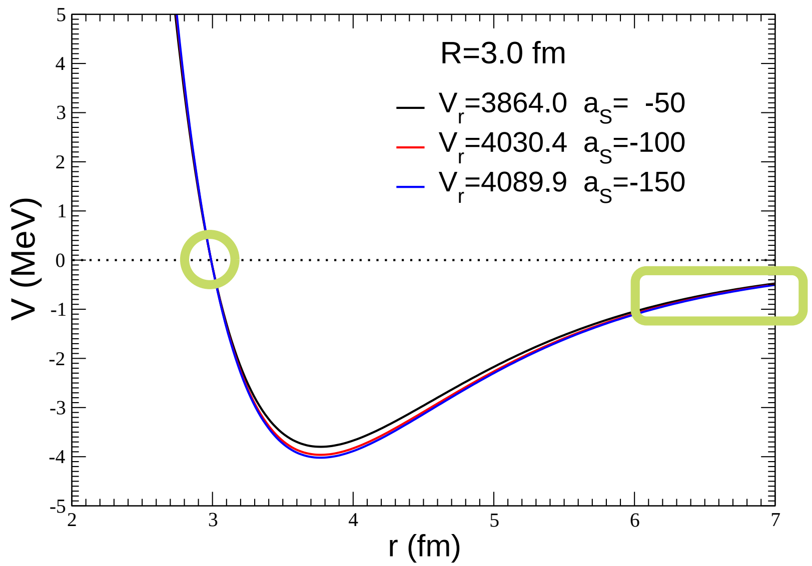
  ~20 fm, ~100 fm $\Longrightarrow$ $S_{2n}(^{19}B) = 0.14 \pm 0.39$ MeV

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

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

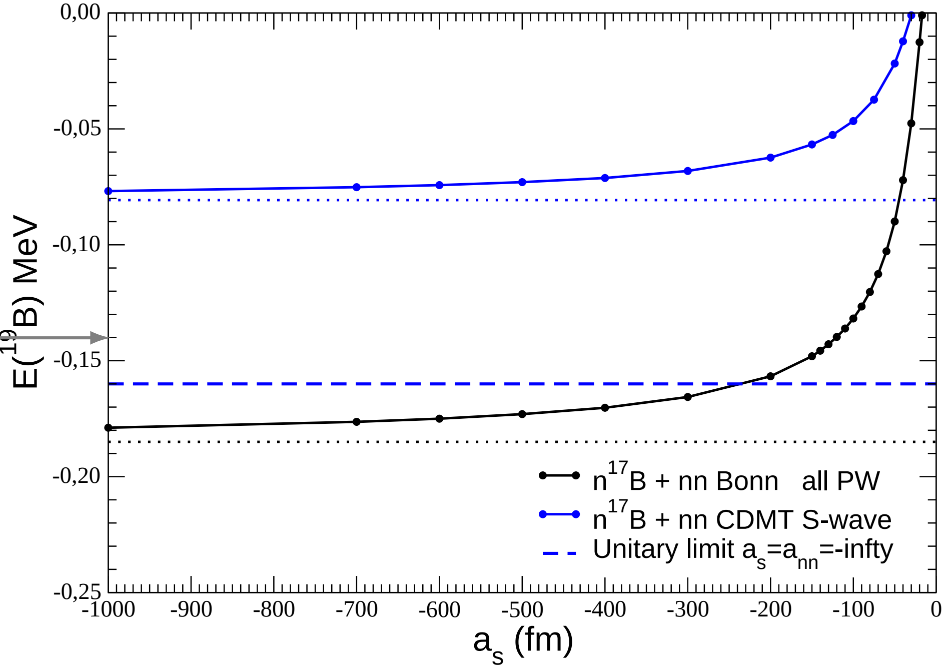
  $\rightarrow$ $R = R_{\text{rms}}(^{17}\text{B}) \sim 3$ fm



- 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 !

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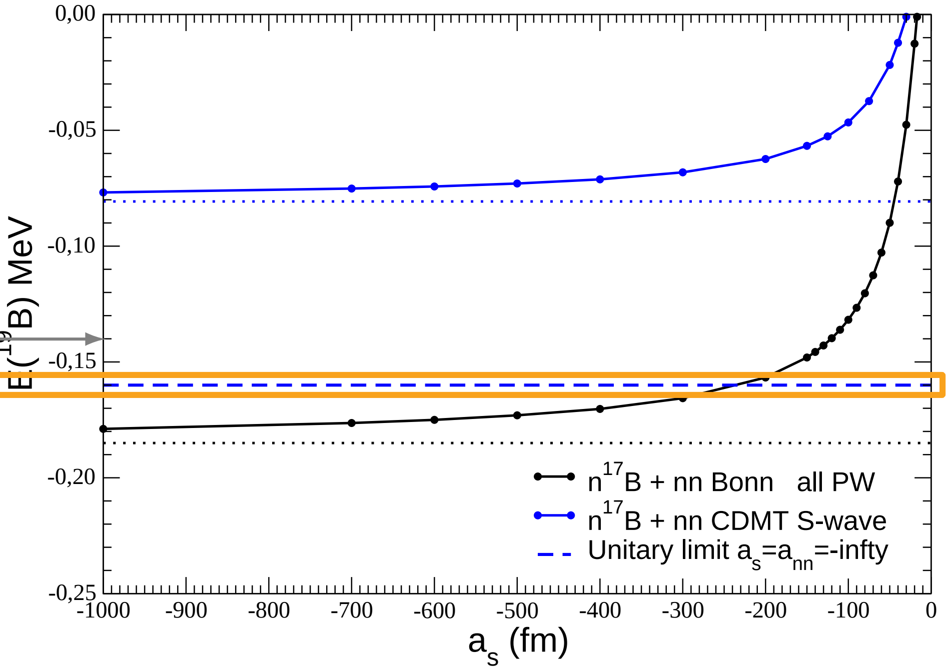

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✔ good description @ Unitary Limit !

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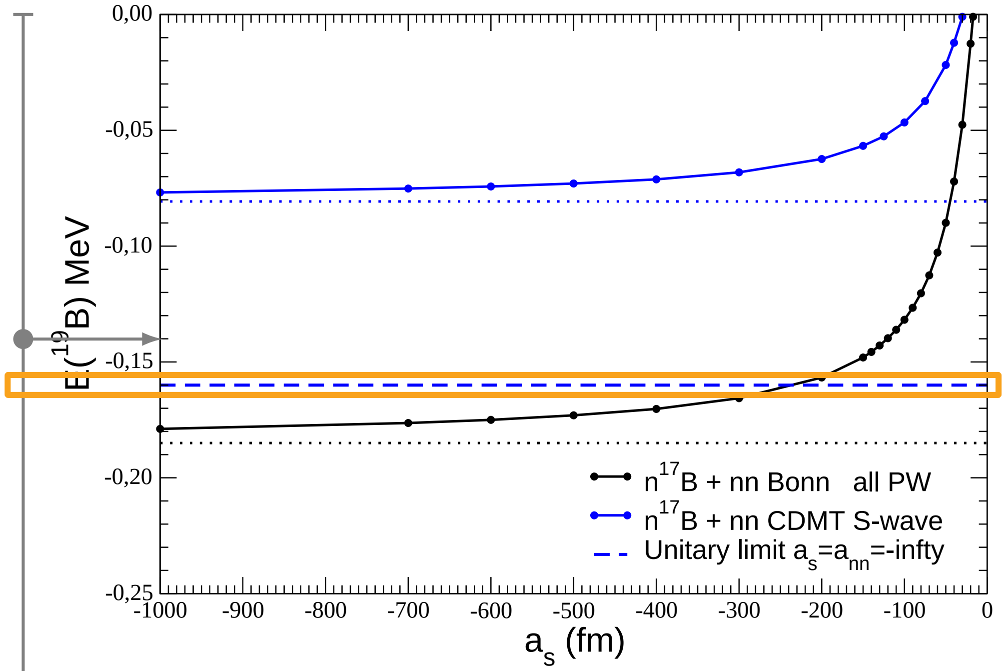
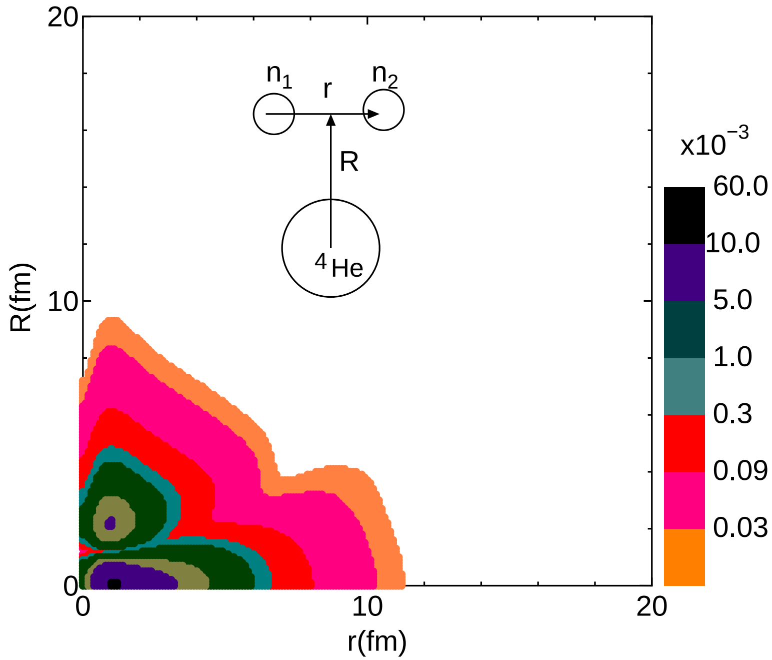
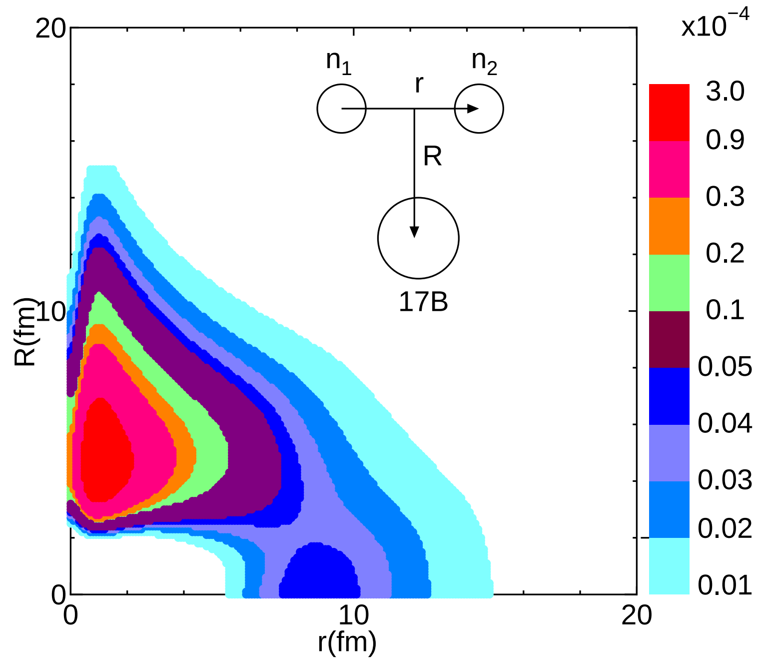


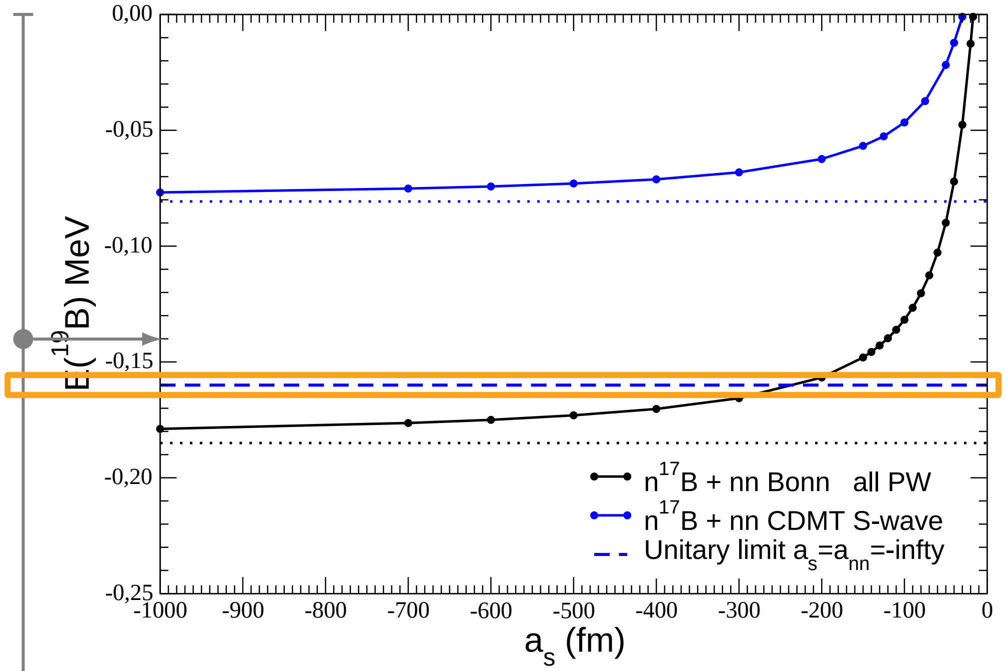


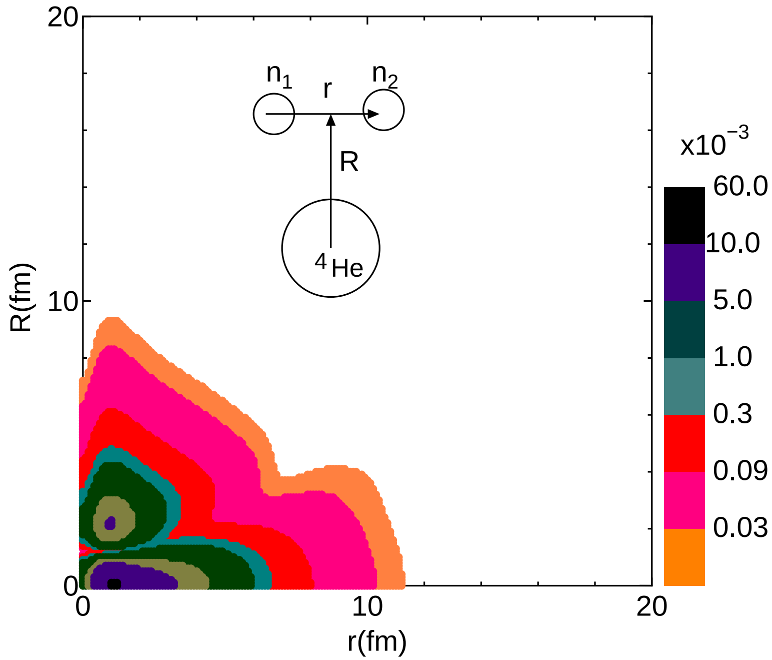


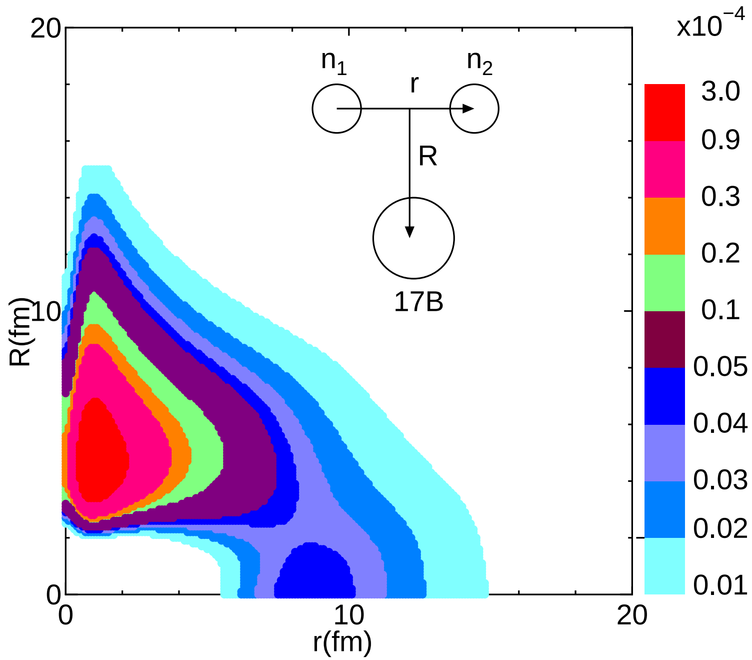
- ✔ ^{19}B bound state !
- ✔ unbound excited states !
- ✔ good description @ Unitary Limit !
- ✔ $|\Psi(r,R)|^2$: molecule-like structure !

17B+n+n : Unitary Limit

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







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

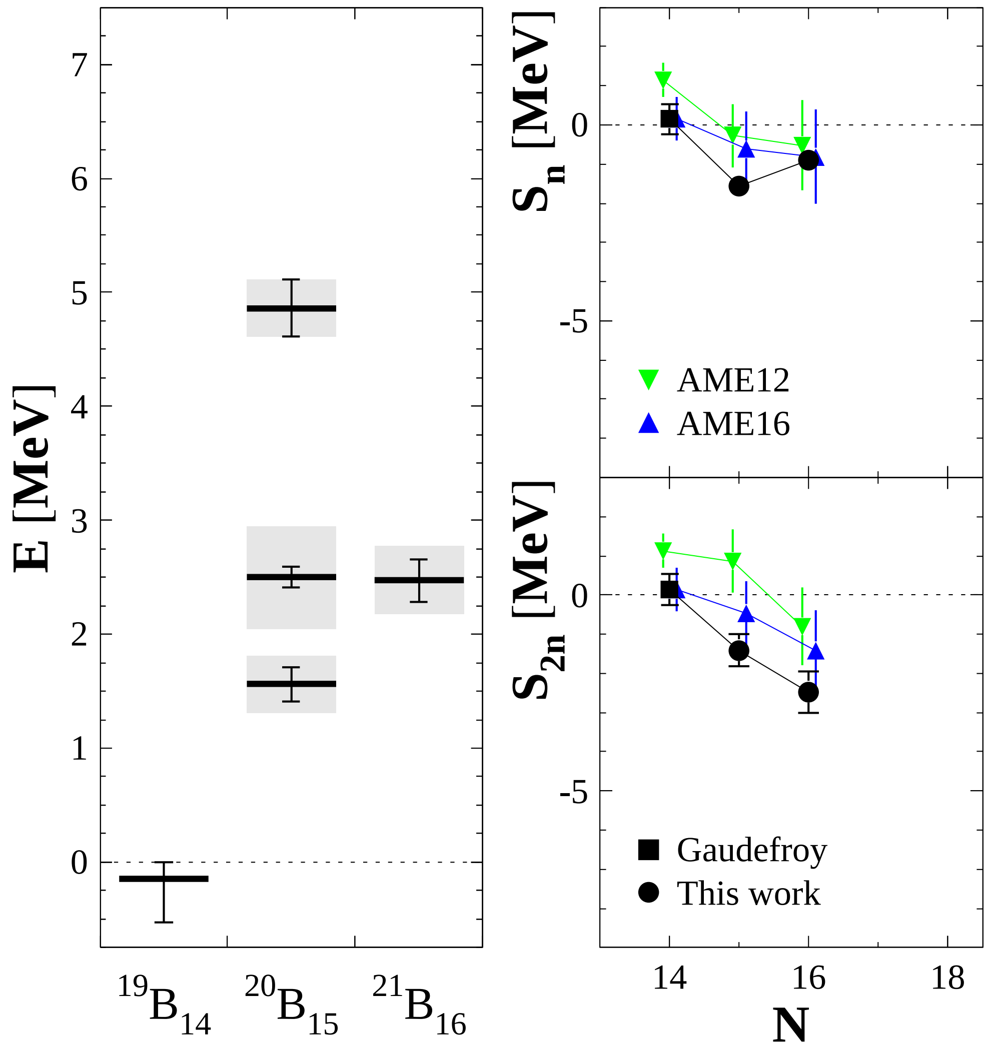
$\rightarrow$ extensible to ^{20,21}B $\equiv$ ^{17}B+3,4n ...

▶ Evaluation of mass excess :

Isotope	AME12	AME16	Experiment
^{19}B	58.78(40)	59.77(53)	59.77(35)
^{20}B	67.13(70)	68.45(80)	70.27(38)
^{21}B	75.72(90)	77.33(90)	78.38(43)

Wang, Chinese Phys. C 41 (2017) 030003

- lower by ∼3 MeV
- new data (^{19}B, ^{22}C, ^{23}N) improve trends !



Leblond, PRL 121 (2018) 262502

Boron 20 & 21 : masses & multineutron emission

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Wang, Chinese Phys. C 41 (2017) 030003

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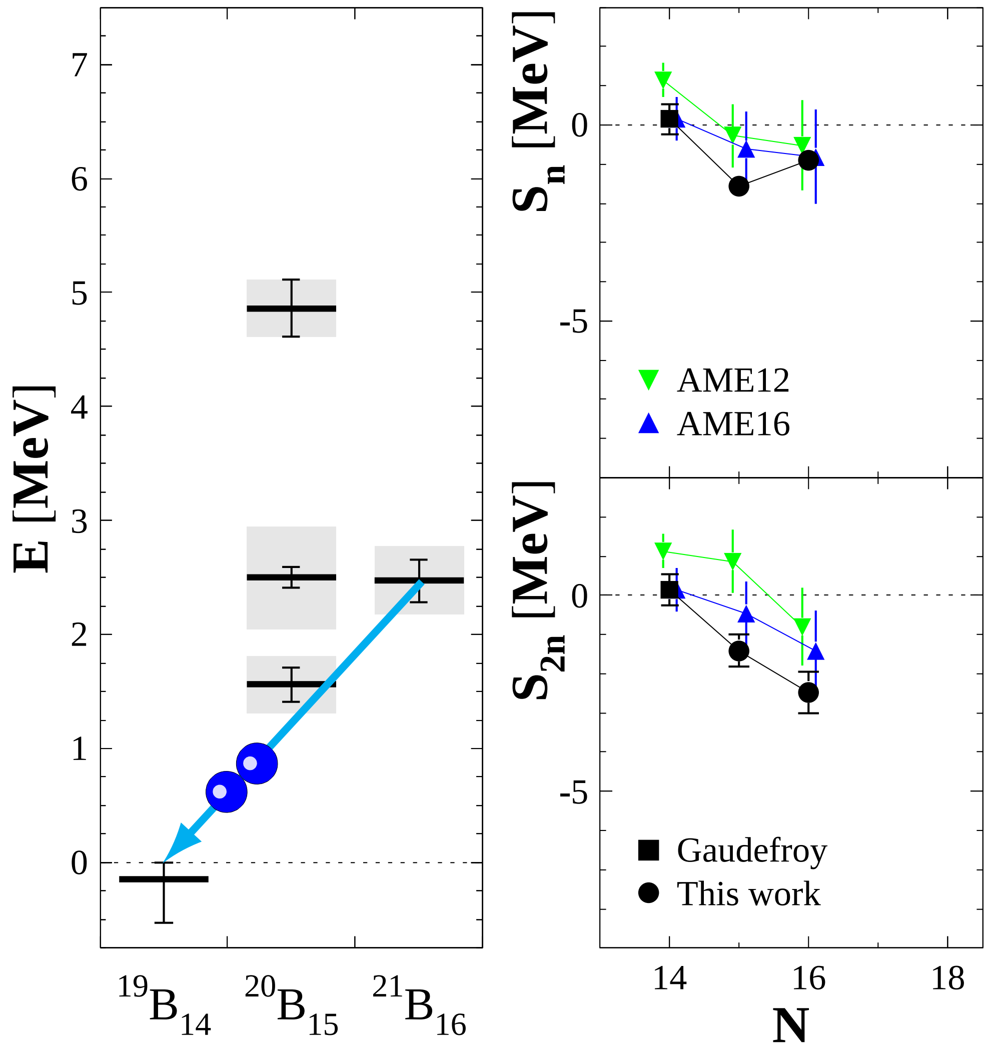
- $^{21}_{5}\mathbf{B}$ candidate for 2n emitter !



Leblond, PRL 121 (2018) 262502

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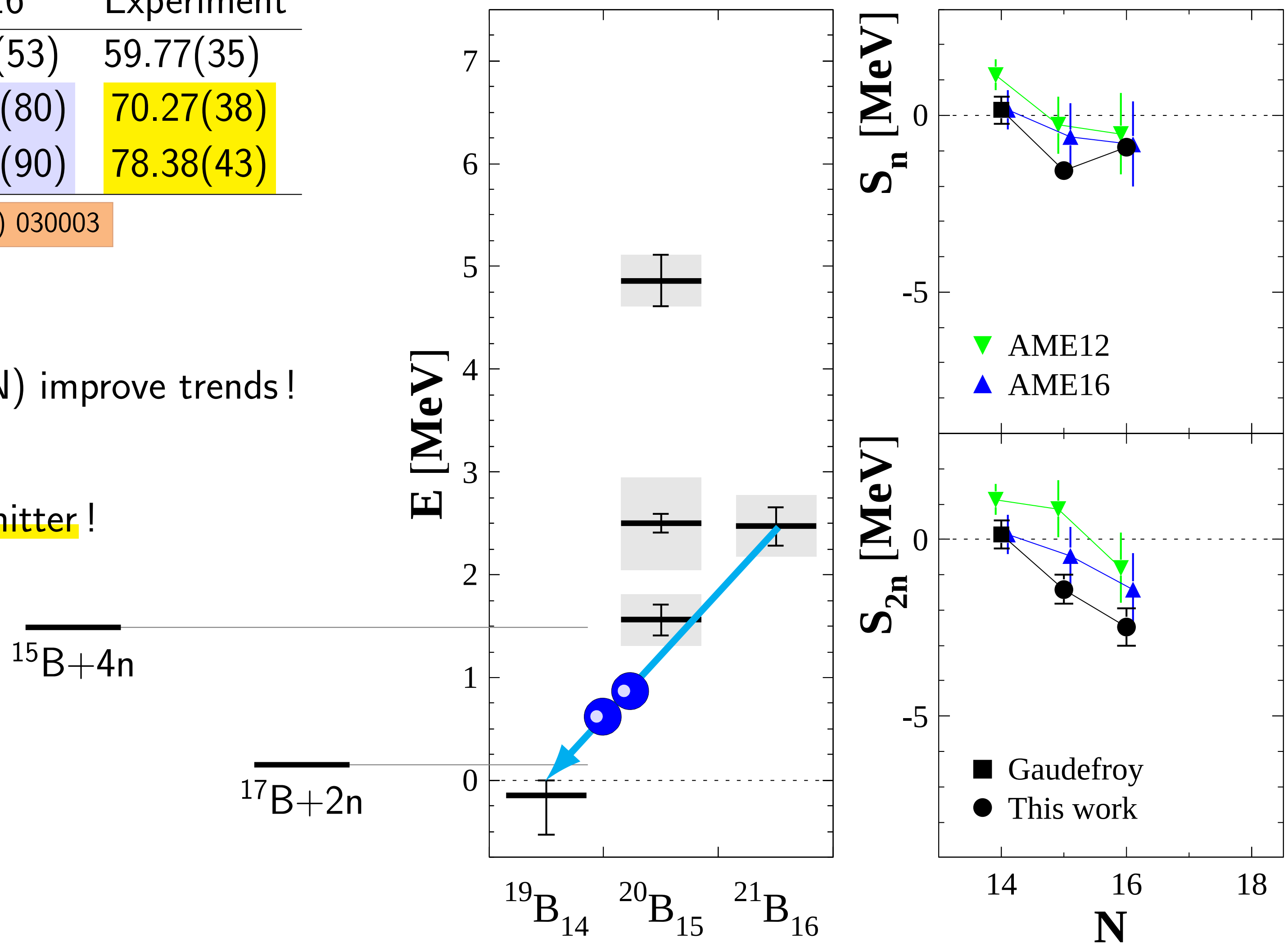

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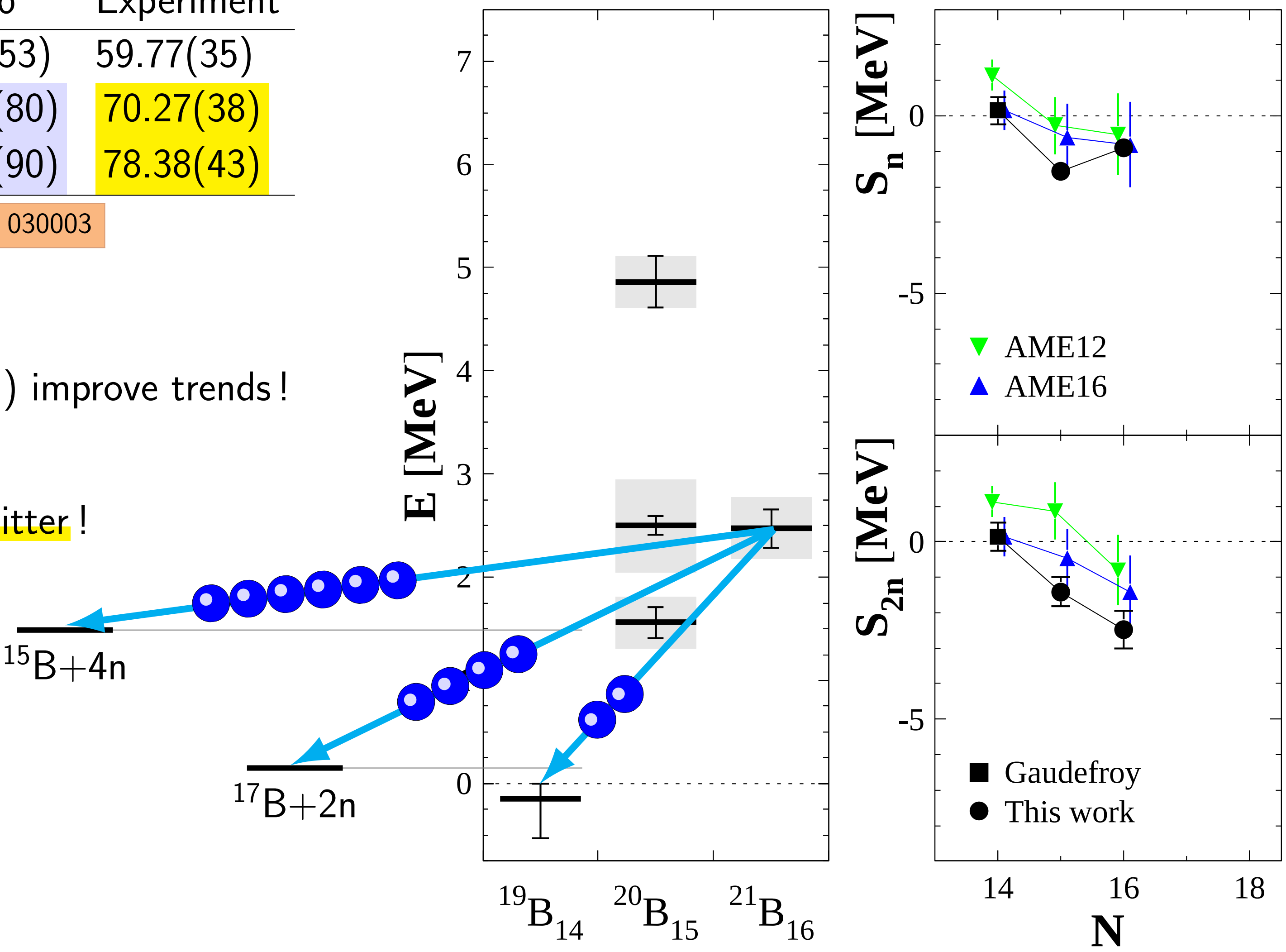
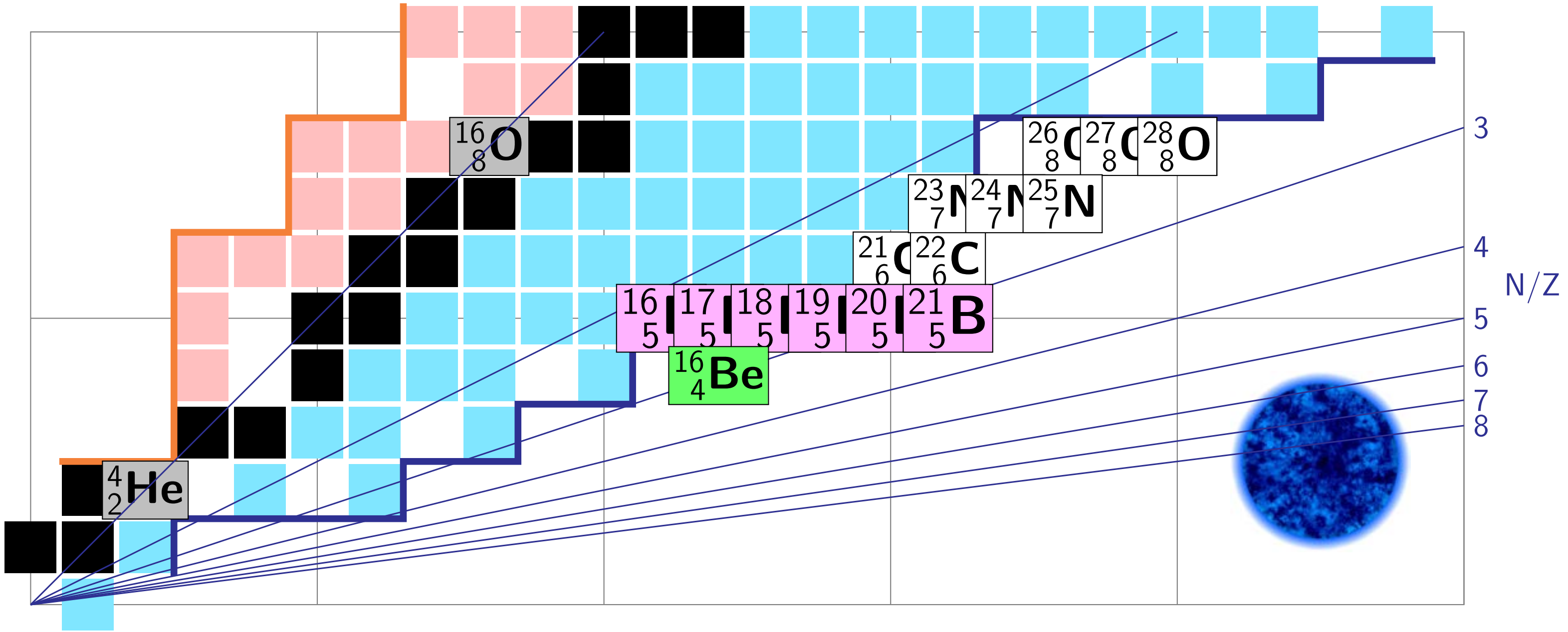


→ first candidate for 4n/6n emitter ???

Leblond, PRL 121 (2018) 262502



- Access to extreme N/Z ratios :
  - ❶ $Z = 5$ (**S04**, Day-One) :
    - $\rightarrow$ literally exotic structures !
  - ❷ $Z = 4$ (**S18**, +MINOS) :
    - $\rightarrow$ 2n emission/decay ?

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

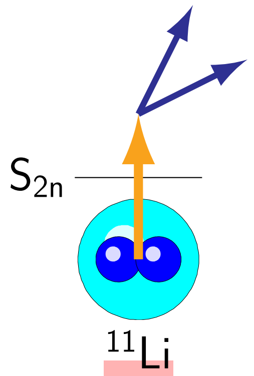
Phys. Rev. Lett. **108**, 102501 – Published 9 March 2012

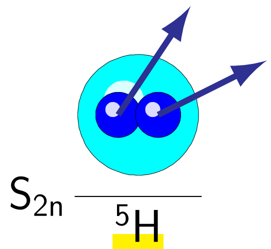
Physics See Focus story: Nuclei Emit Paired-up Neutrons

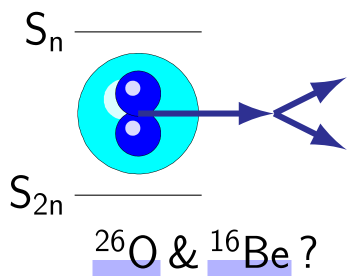
Article | References | Citing Articles (65) | PDF | HTML | Export Citation

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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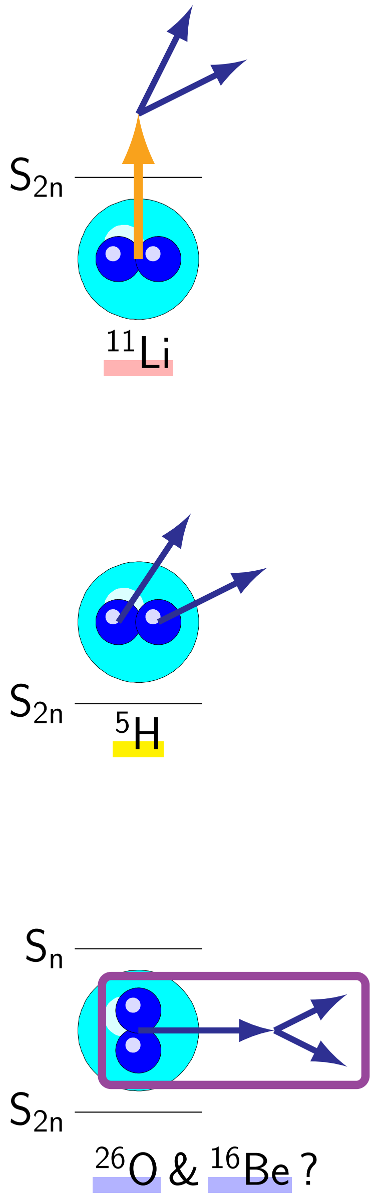

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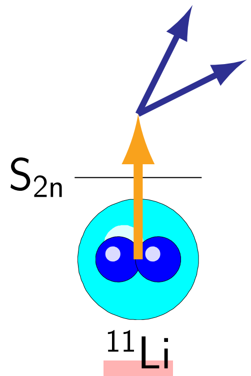
. . .

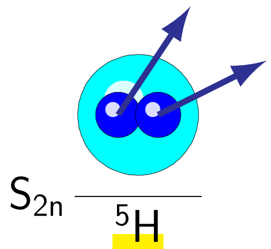
COMMENTS & REPLIES

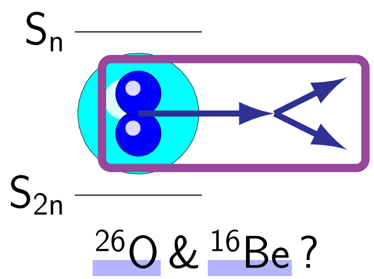
Comment on "First Observation of Ground State Dineutron Decay: ^{16}Be"

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

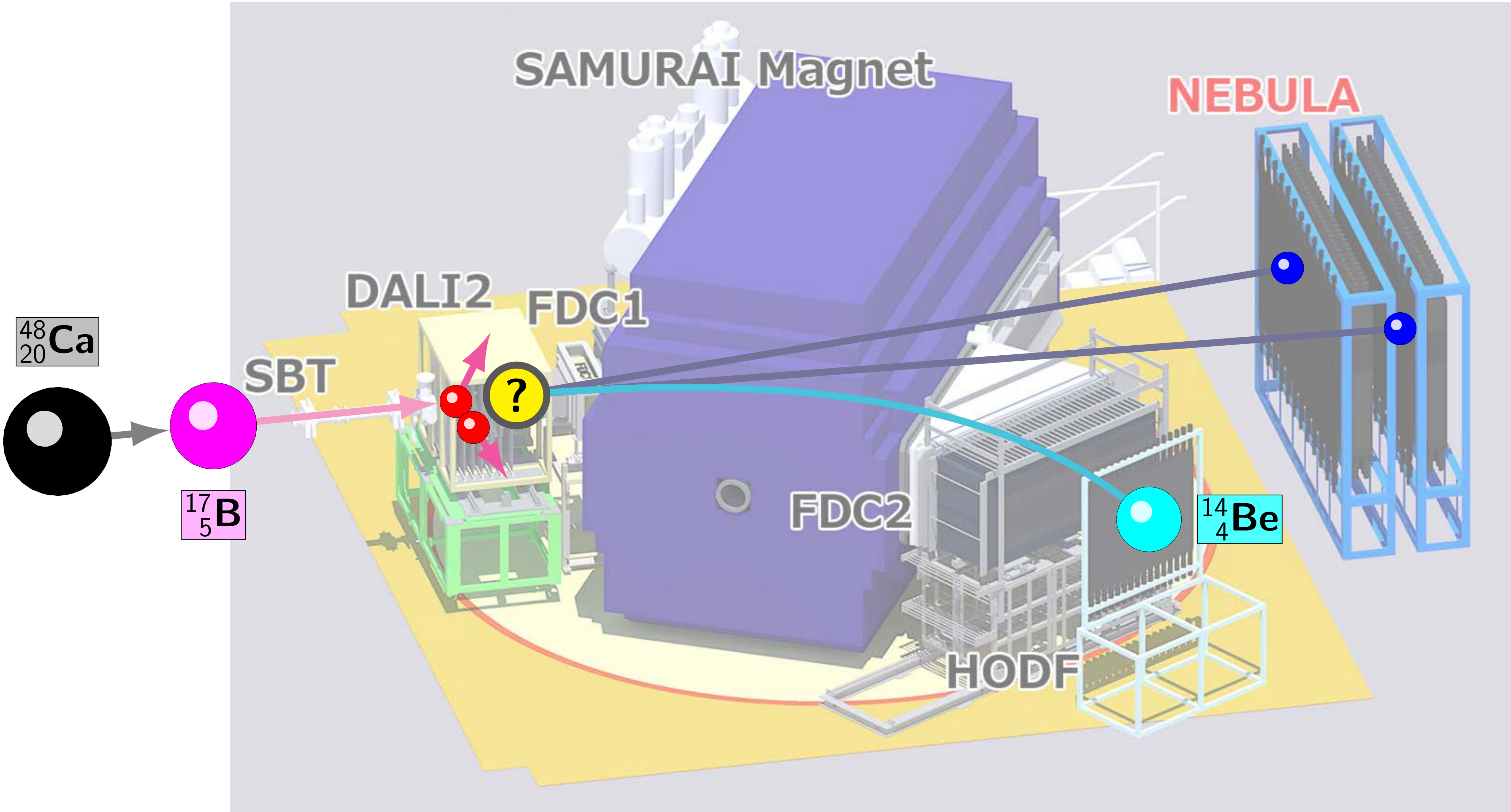
Phys. Rev. Lett. **109**, 239201 (2012)

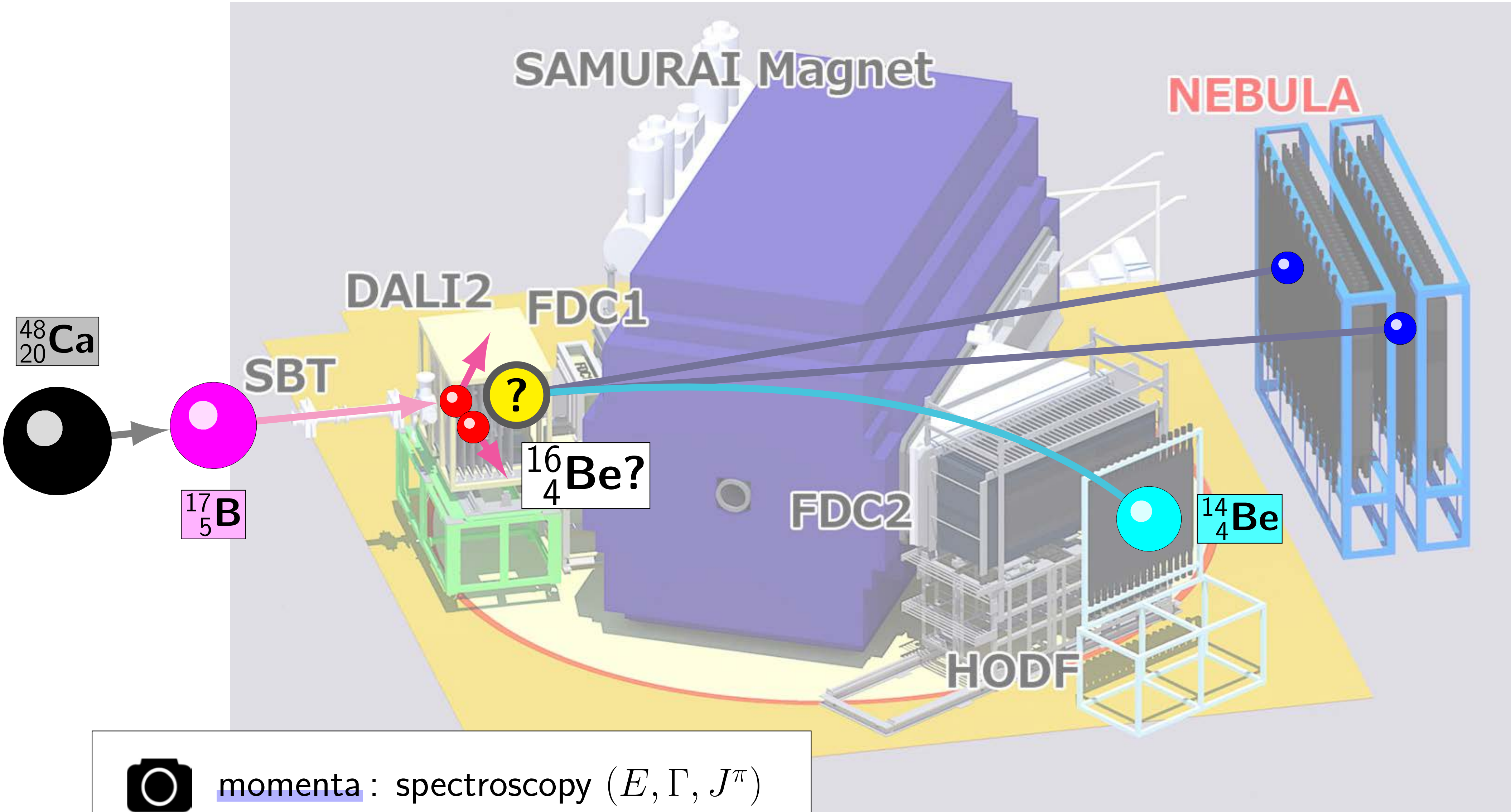






Zoom on Beryllium 16 [S18, Kubota/Corsi]


SAMURAI Magnet
NEBULA
DALI2
FDC1
SBT
FDC2
HODF
$^{48}_{20}$Ca
$^{17}_{5}$B
$^{14}_{4}$Be
?



momenta : spectroscopy (E, Γ, J^π)

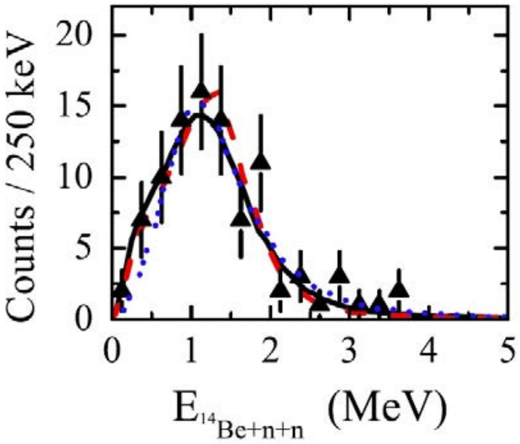
correlations : decay, sequentiality ...

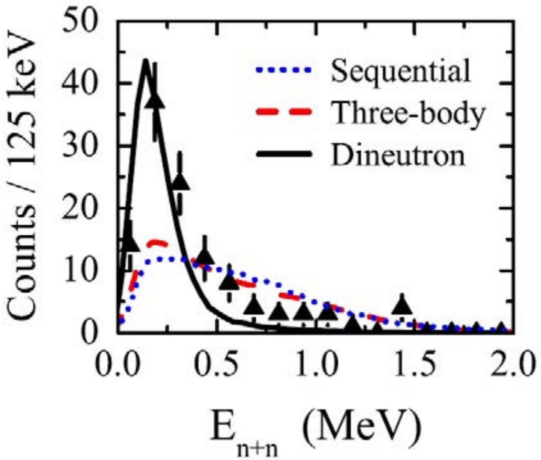
Corsi, PLB 797 (2019) 134843 : QFS into ^{13}Be

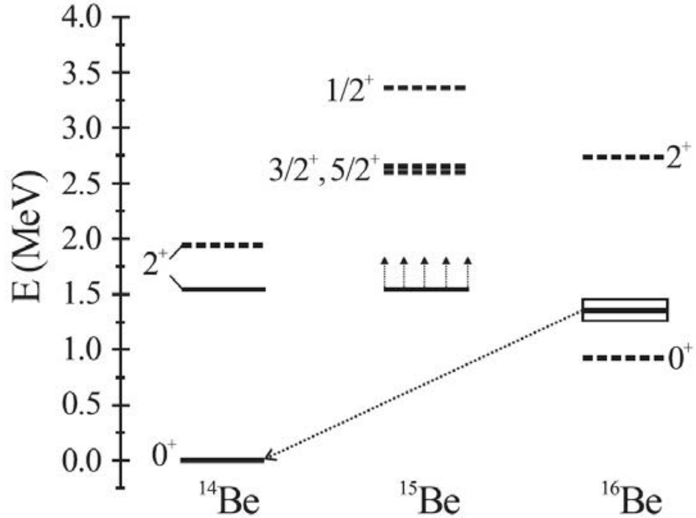
Kubota, PRL 125 (2020) 252501 : 2n in ^{11}Li

The new Beryllium 16 [Monteagudo]

Spyrou, PRL 108 (2012) 102501







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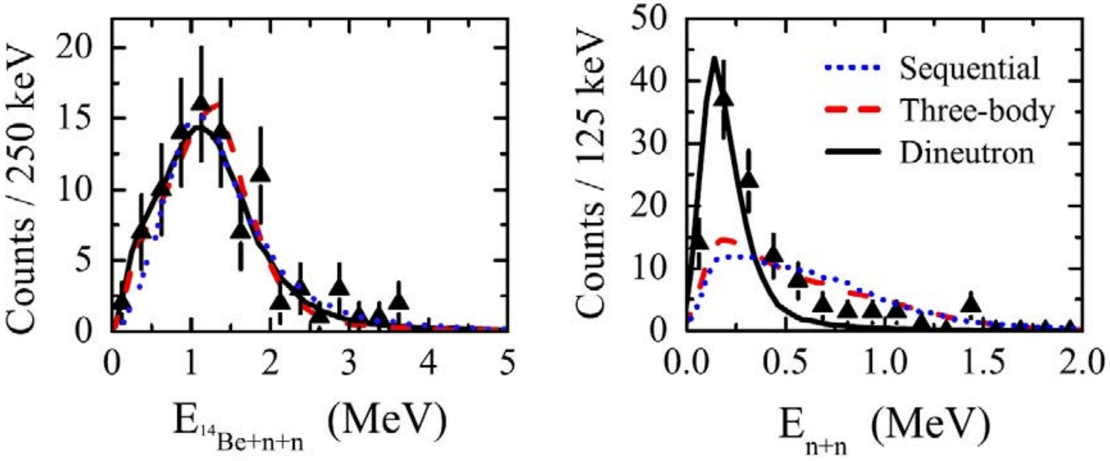

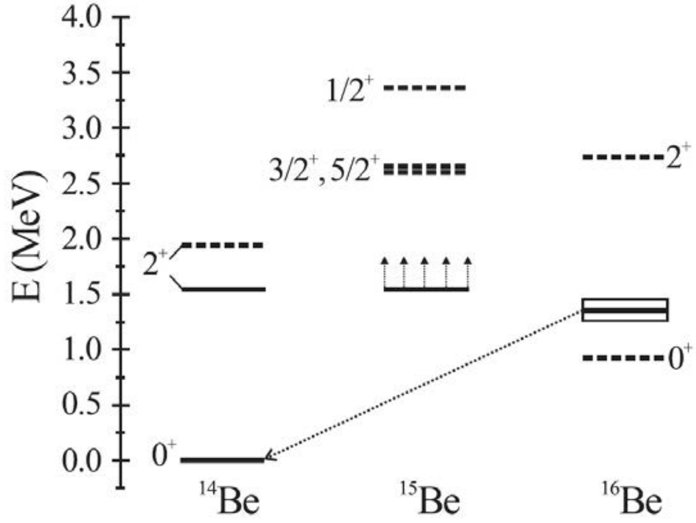

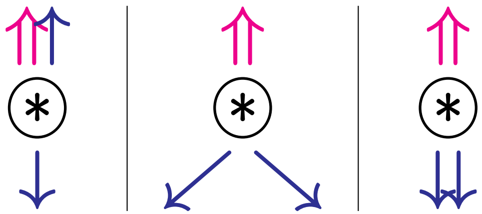

FMM, PRL 109 (2012) 239201

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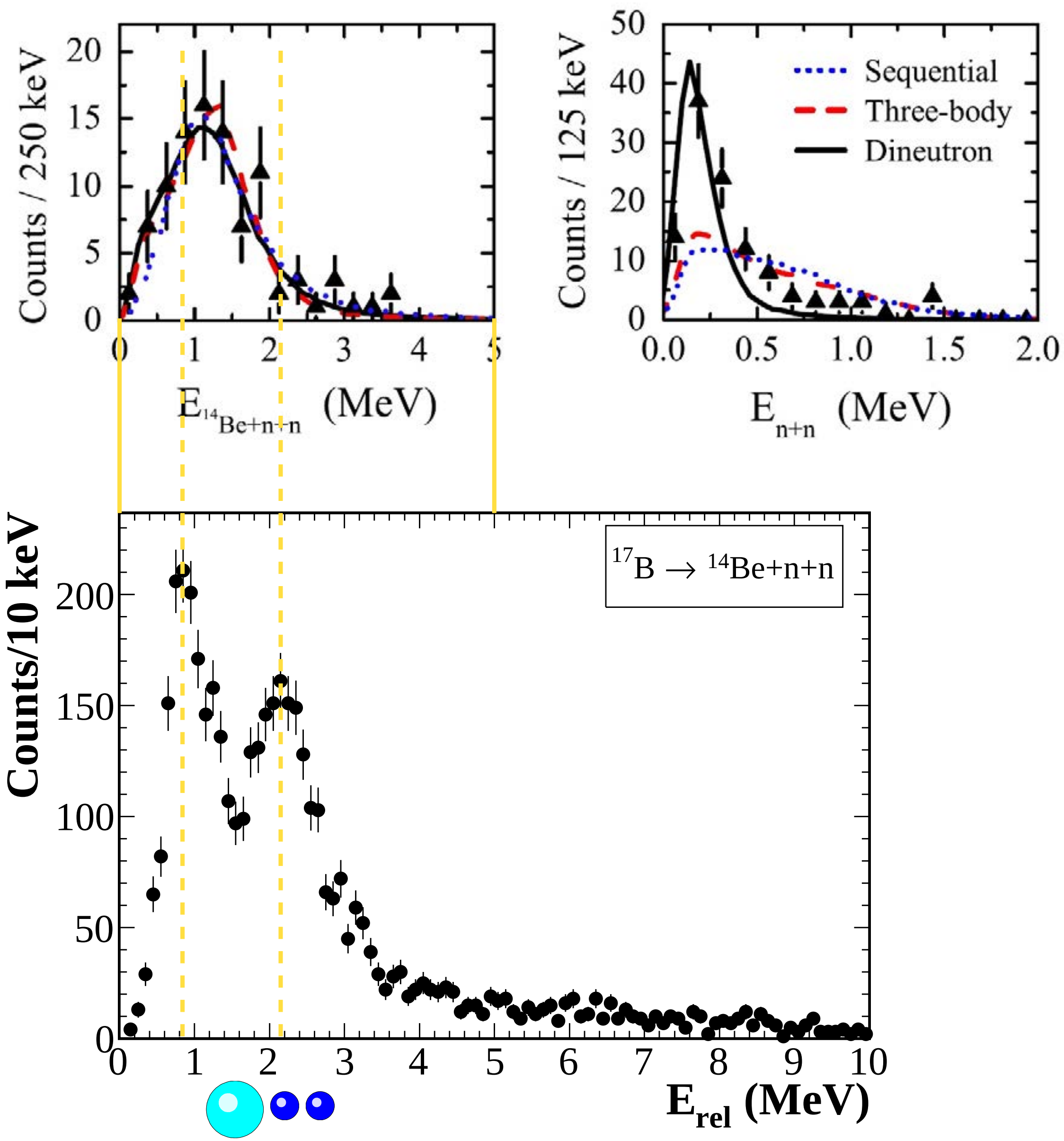
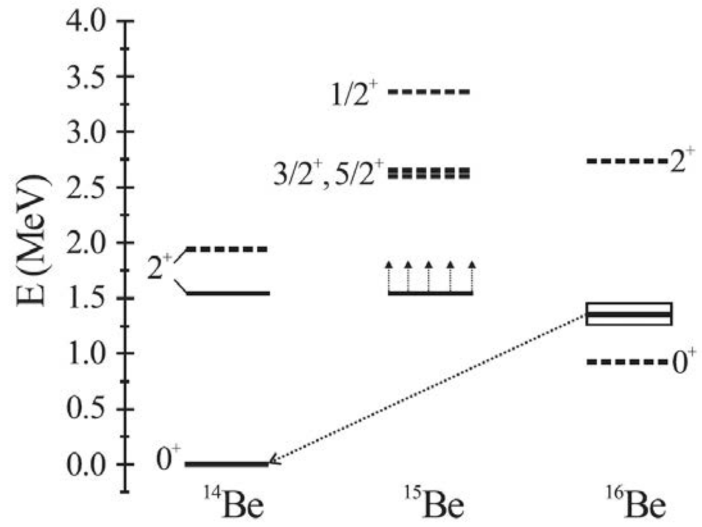
Spyrou, PRL 108 (2012) 102501





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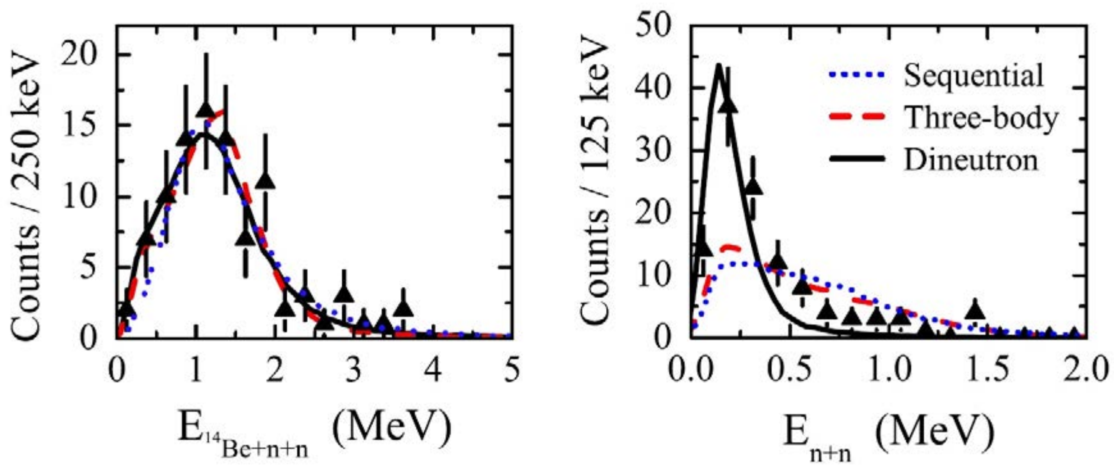

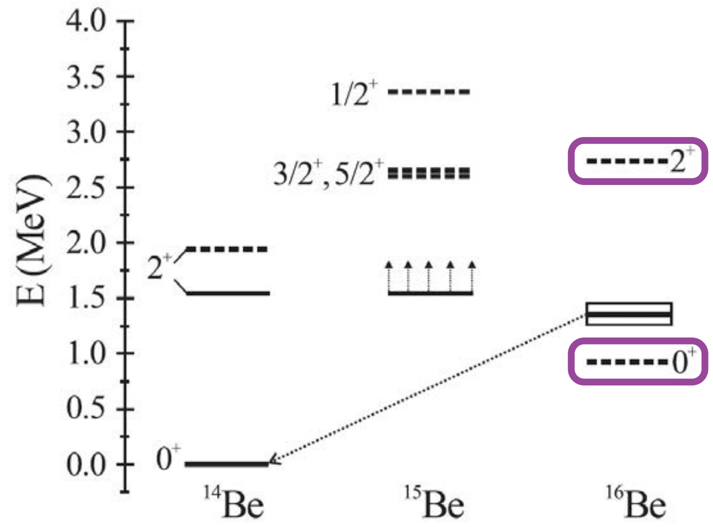

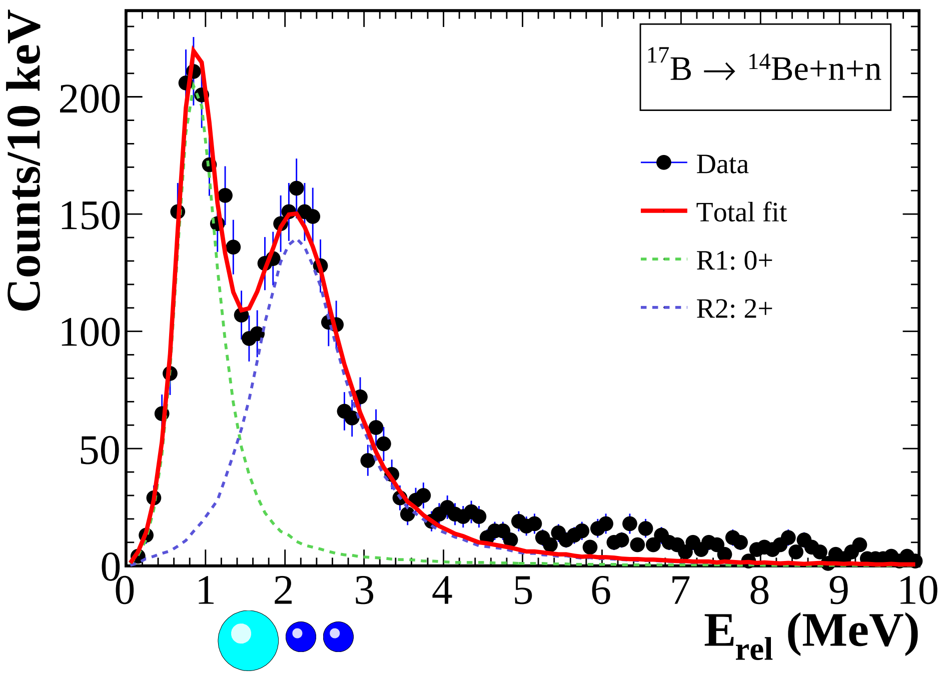

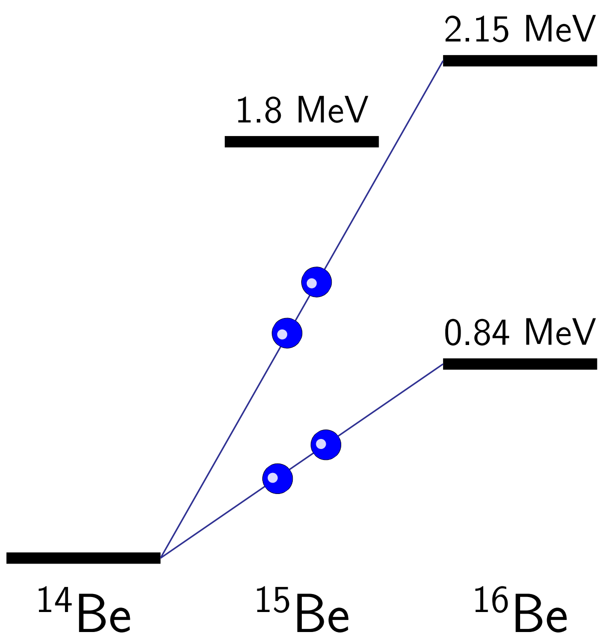

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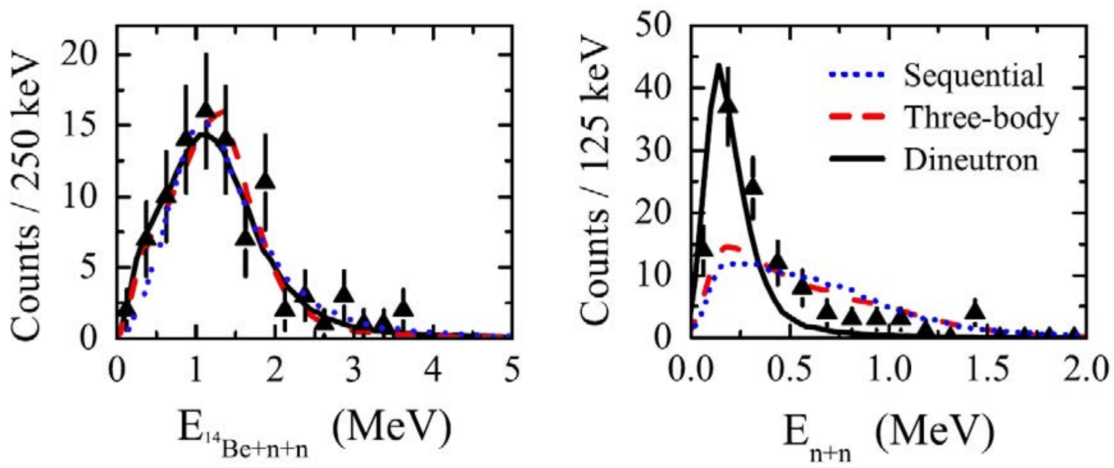
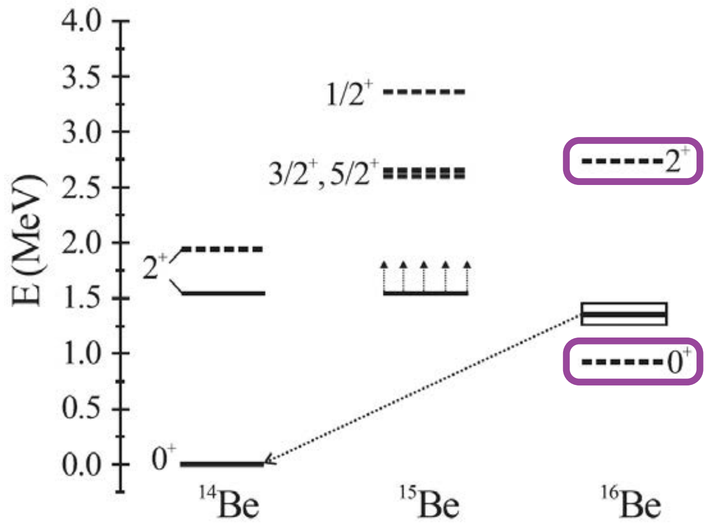
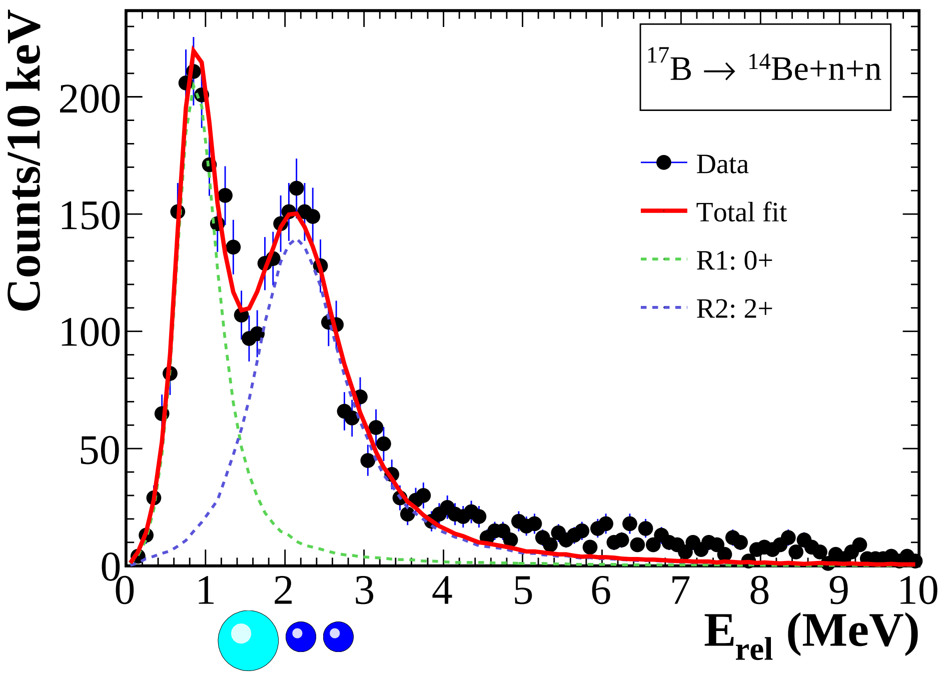
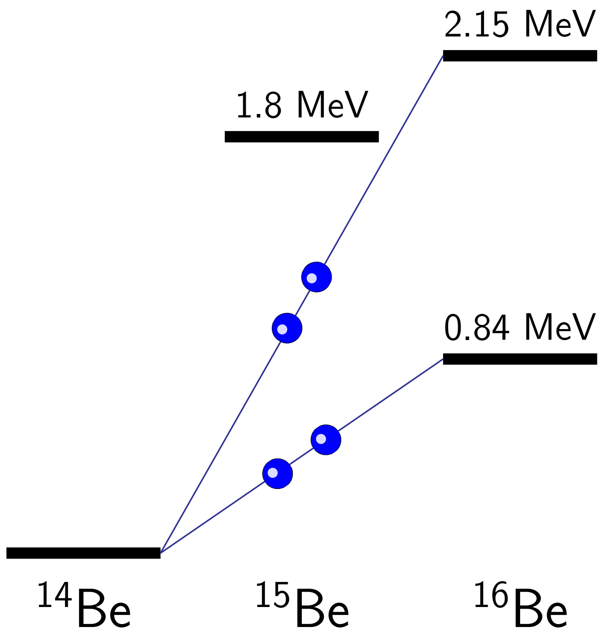
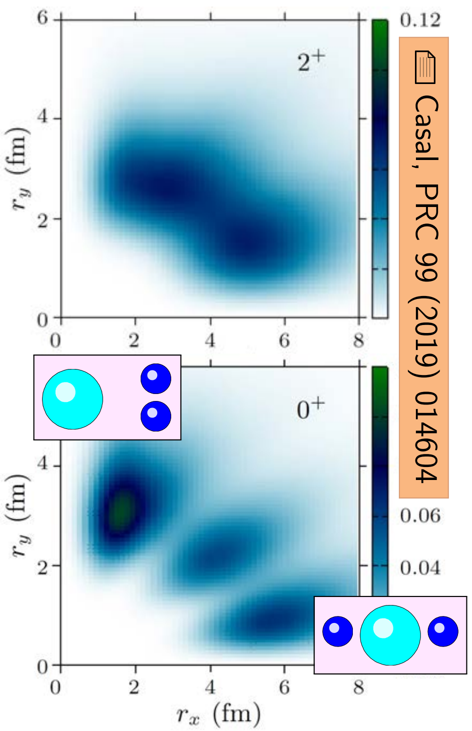




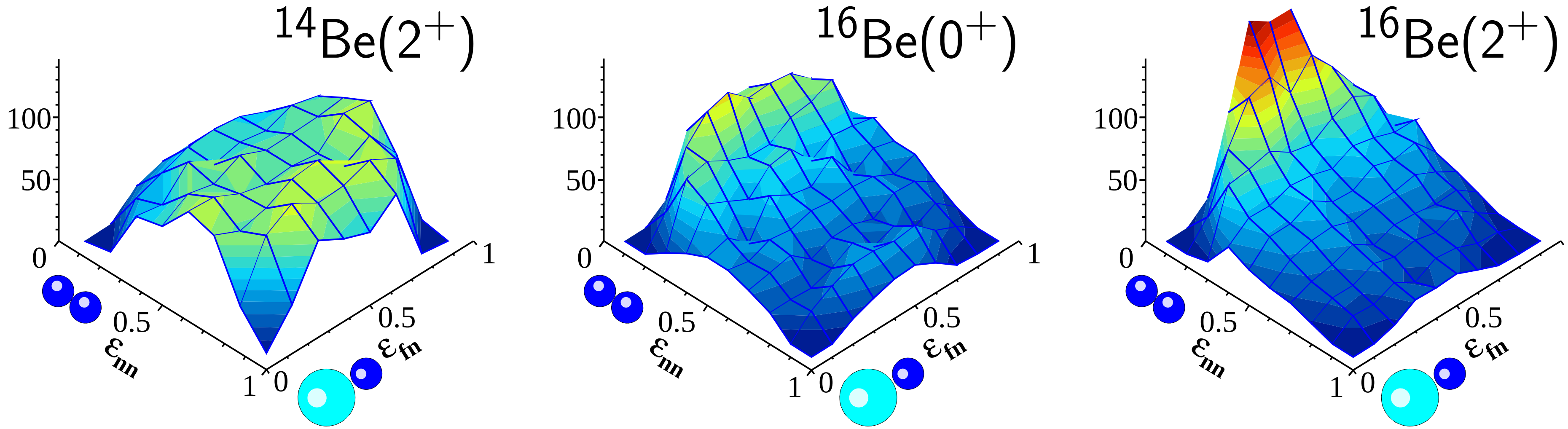






Probing the 2n wave function [Monteagudo, Casal]

- Dalitz plot of 2n decay :



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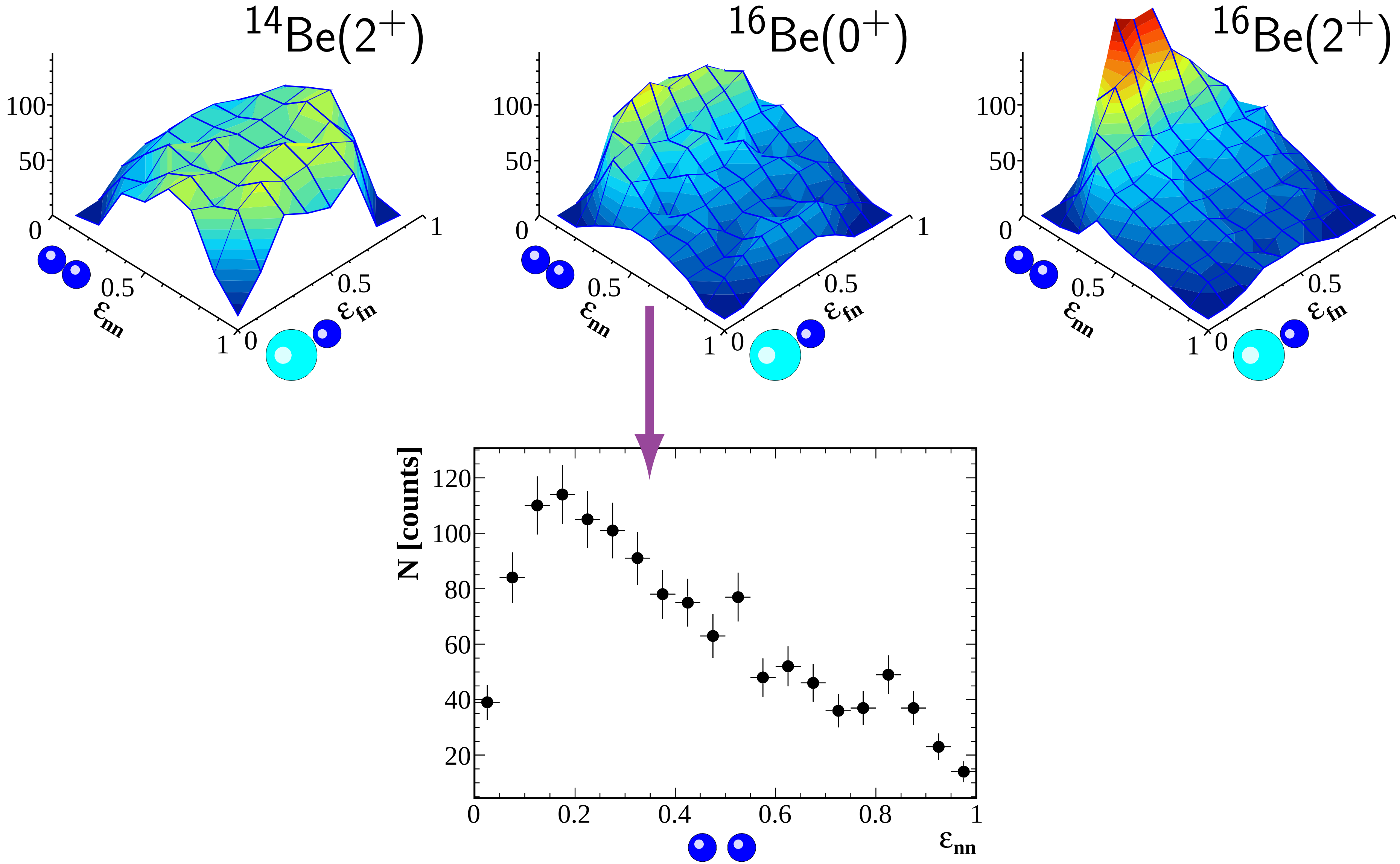

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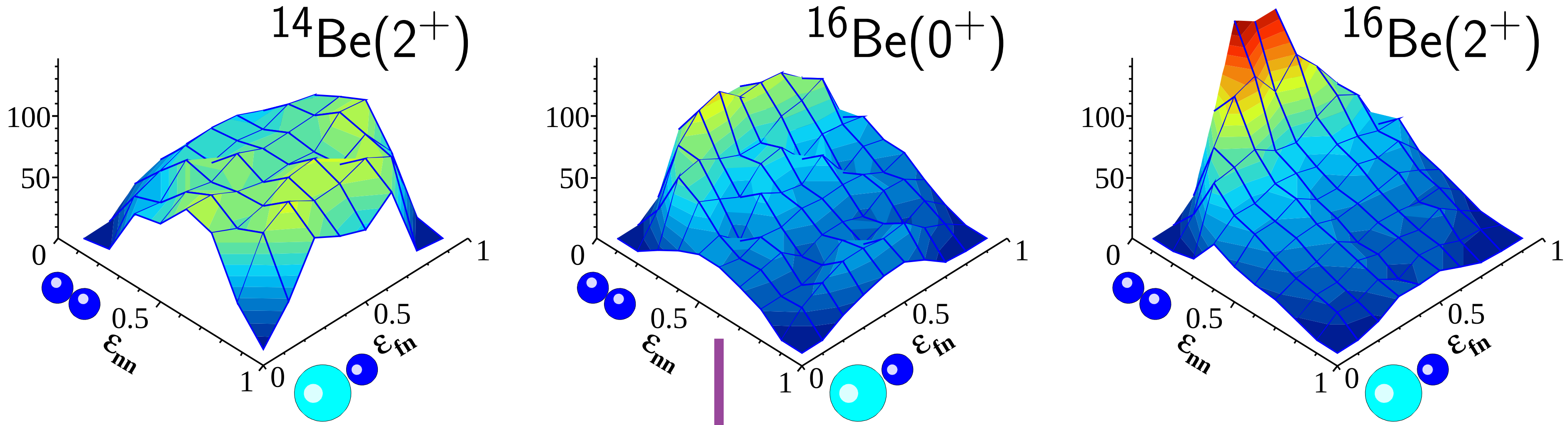

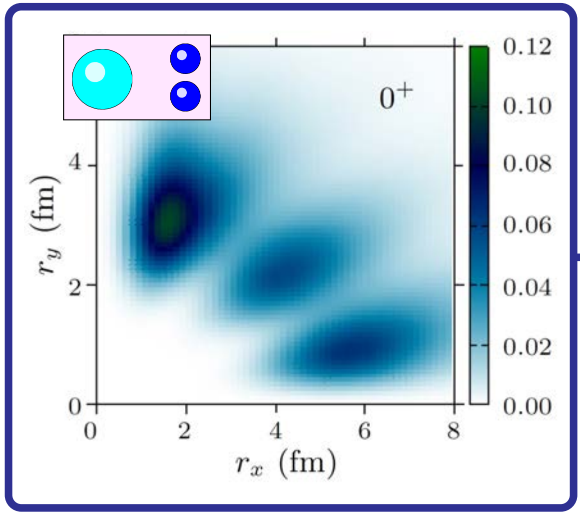

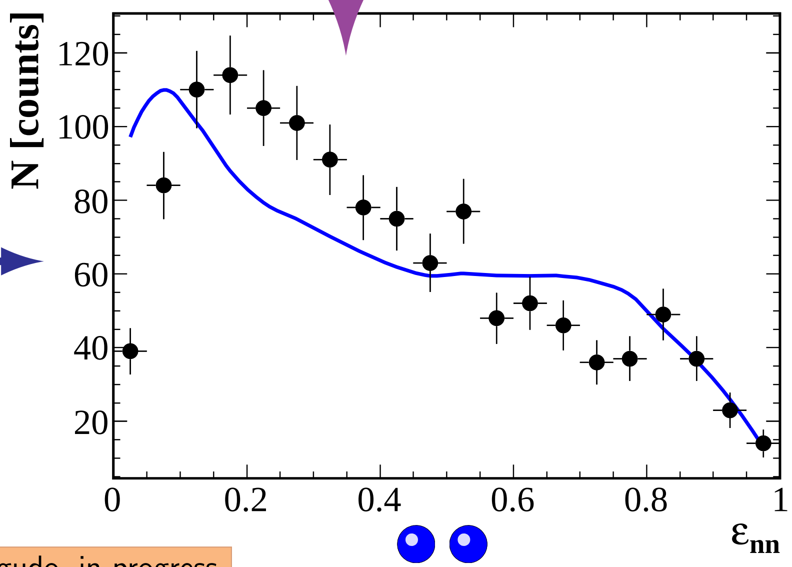

Casal & Monteagudo, in progress

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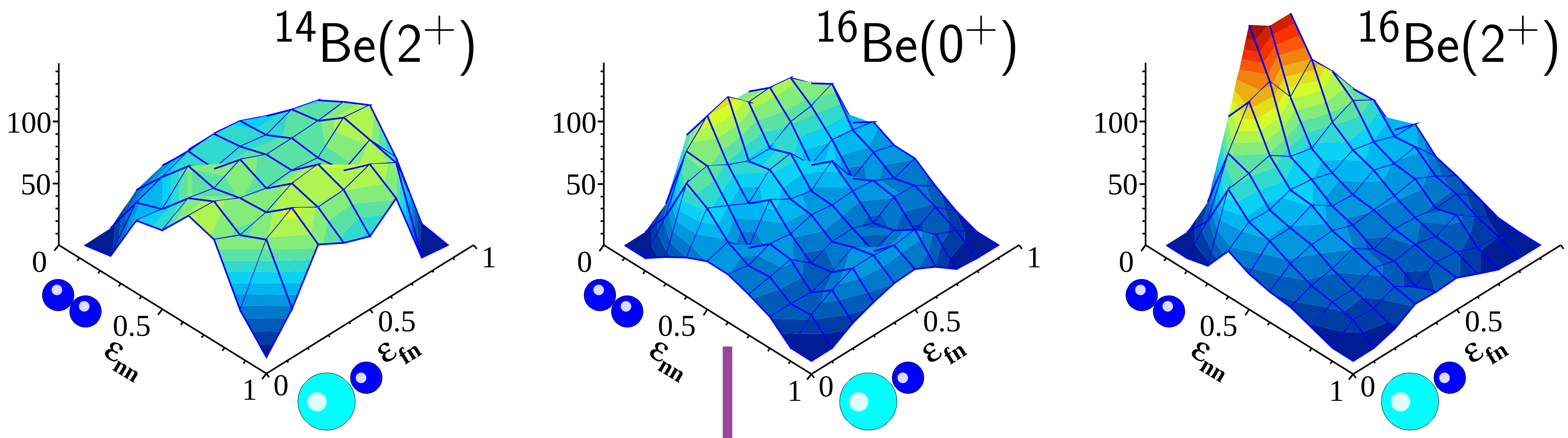
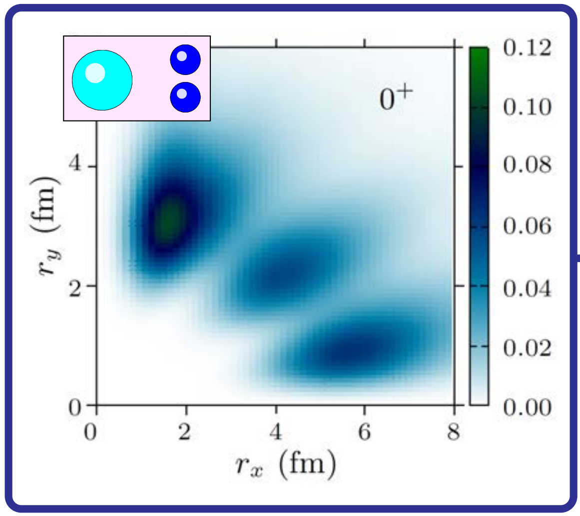
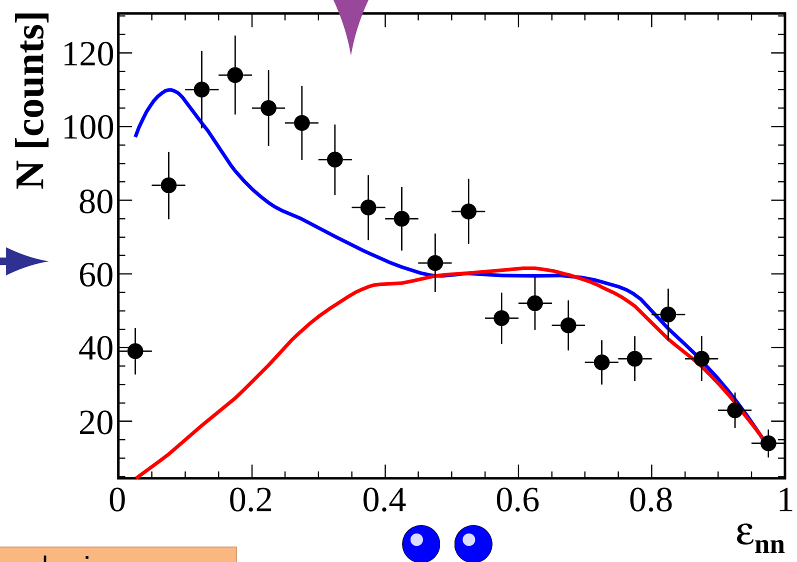
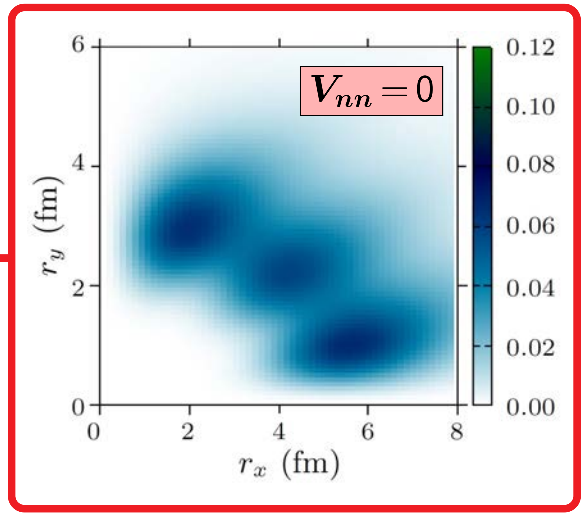


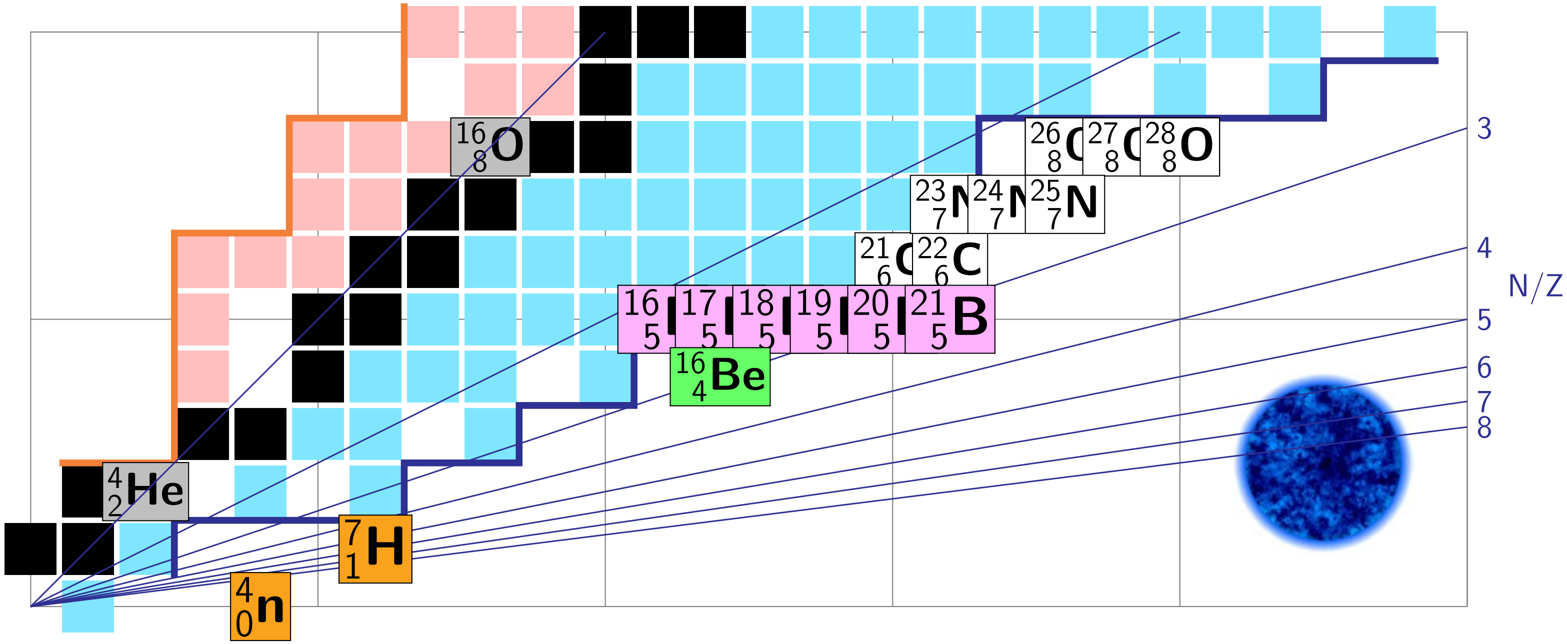






Casal & Monteagudo, in progress

The exotic limits of exotic nuclei



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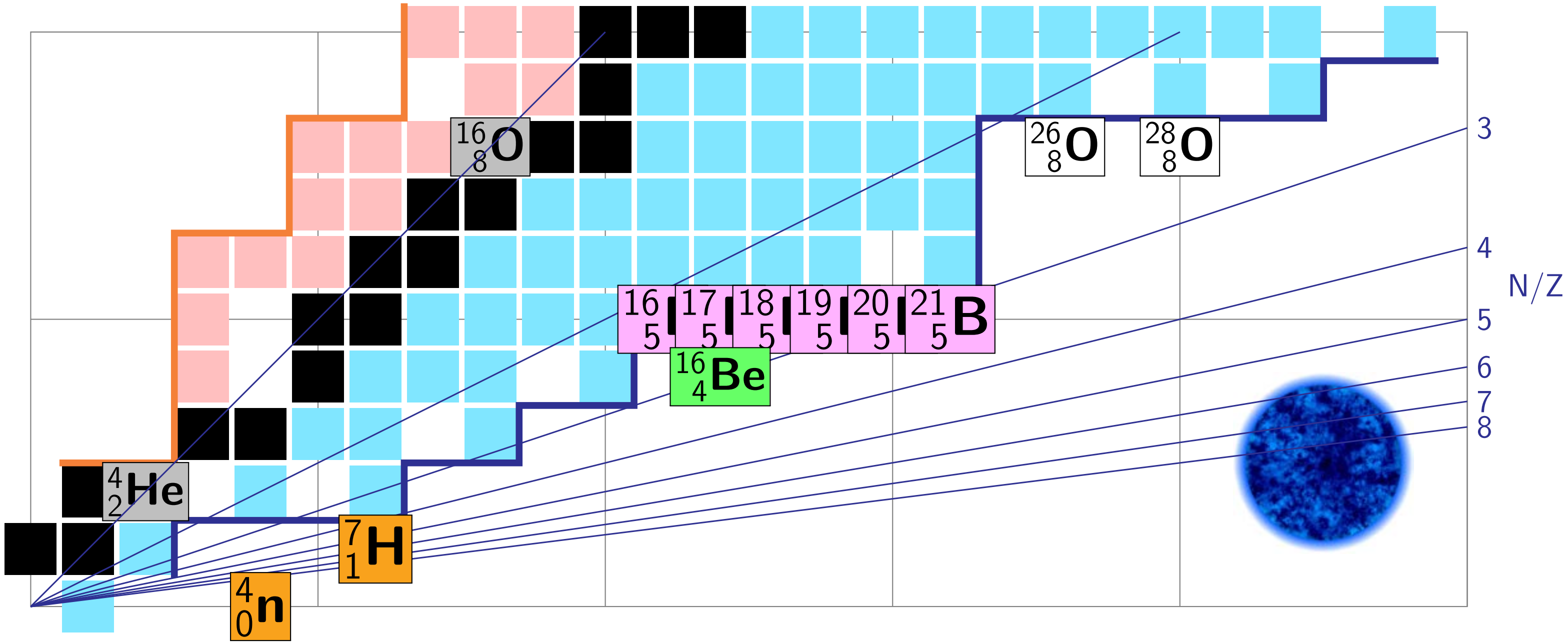
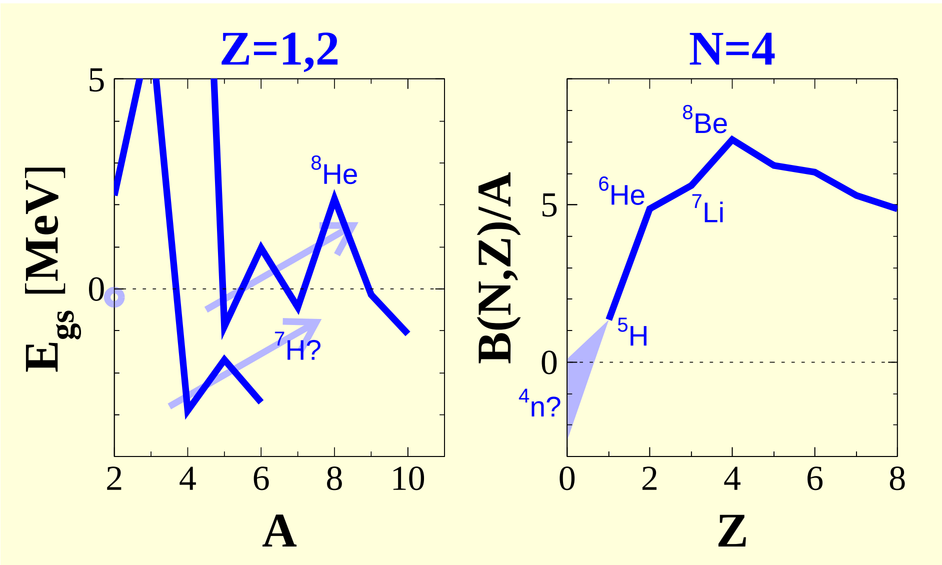
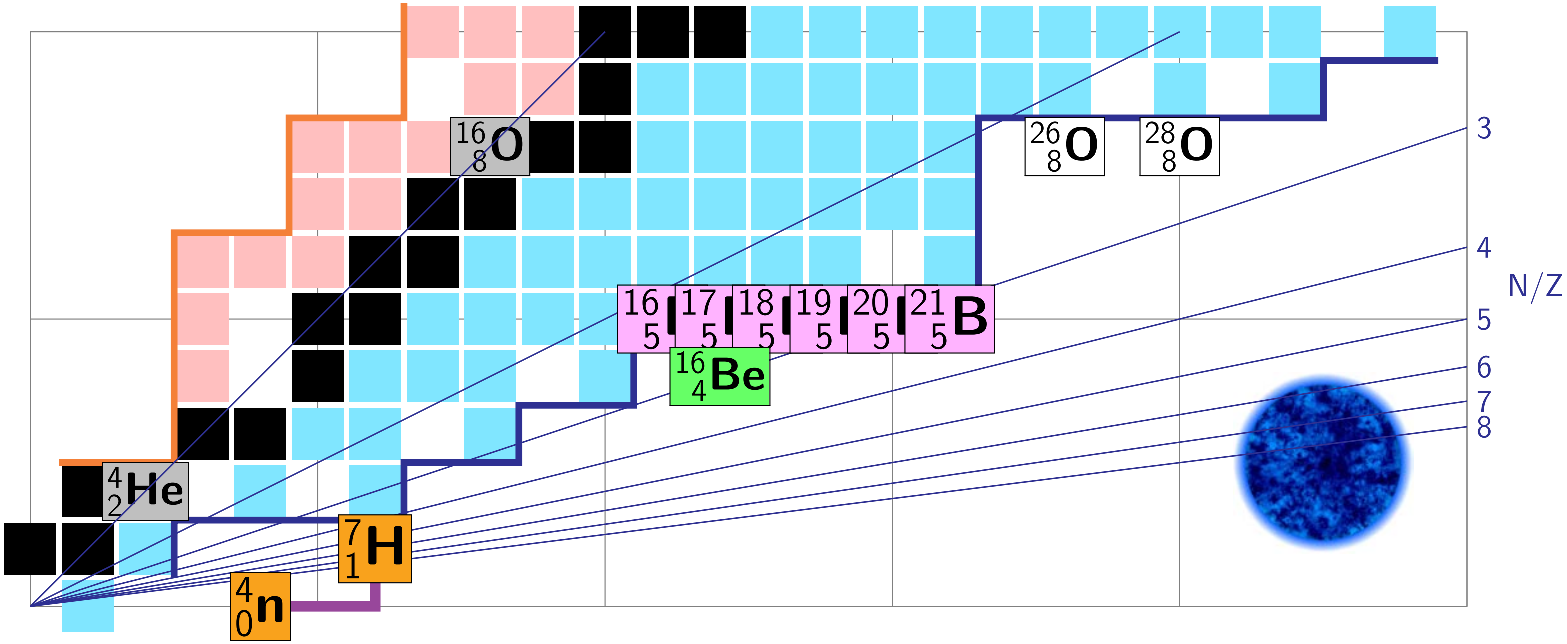
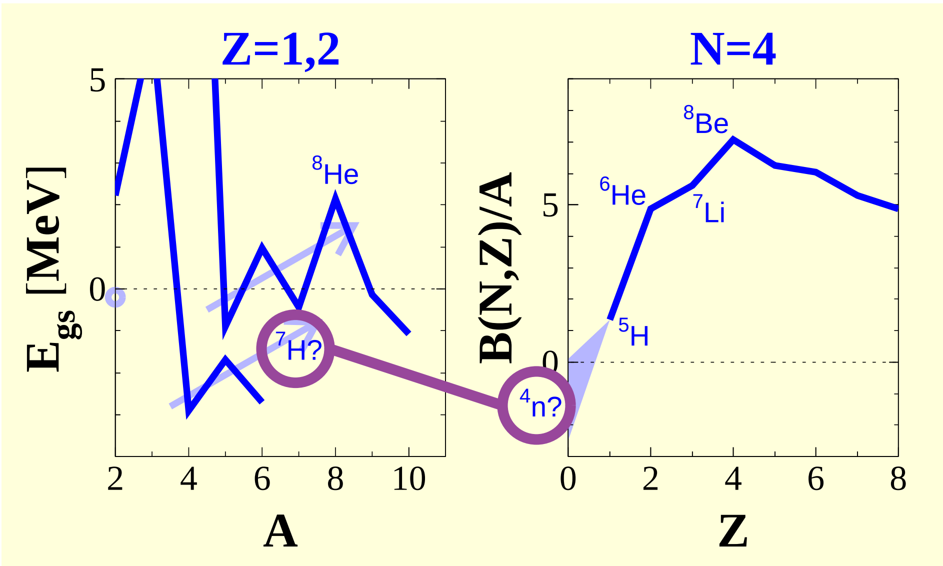
  - ❶ Z = 5 (**S04**, Day-One) :
    - → literally exotic structures !
  - ❷ Z = 4 (**S18**, +MINOS) :
    - → 2n emission/decay ?
  - ❸ Z = 1 & Z = 0 (**S34**, +NeuLAND) :
    - → multineutron physics !

Hydrogen 7 & Tetraneutron [S34, FMM/Yang]









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

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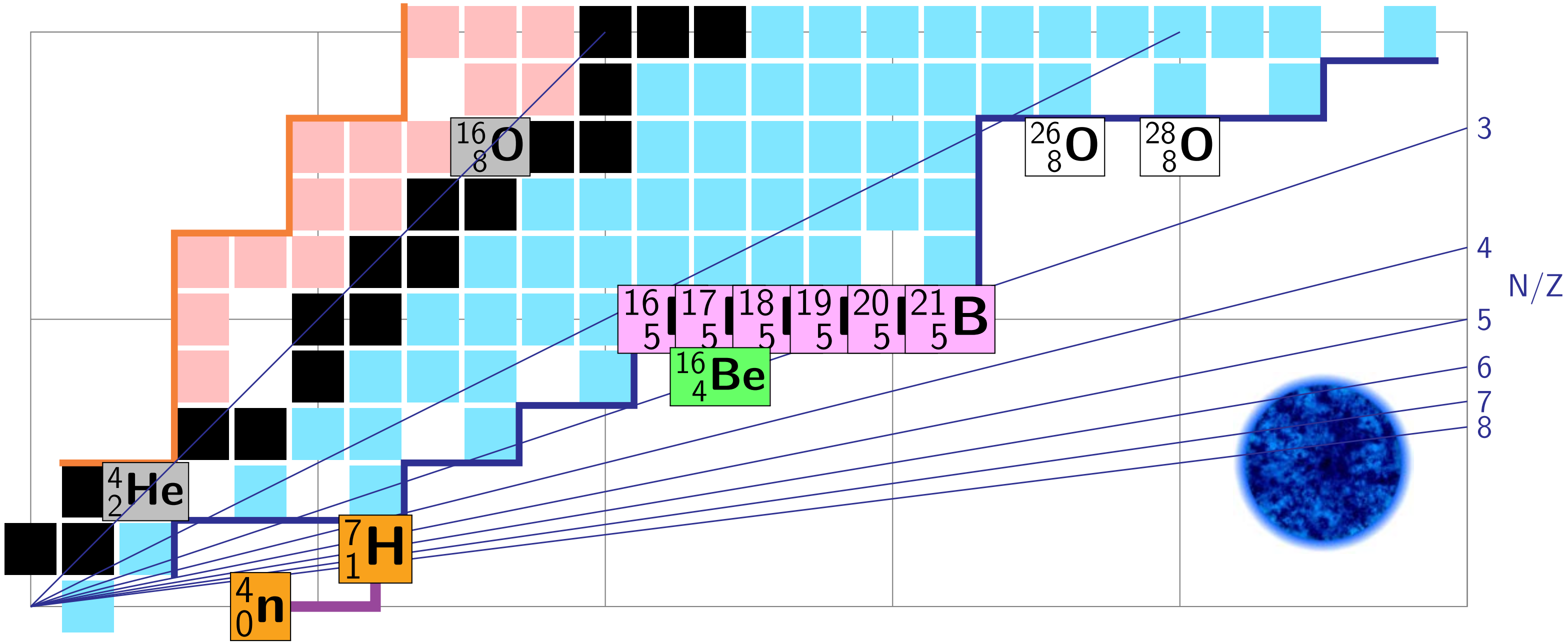

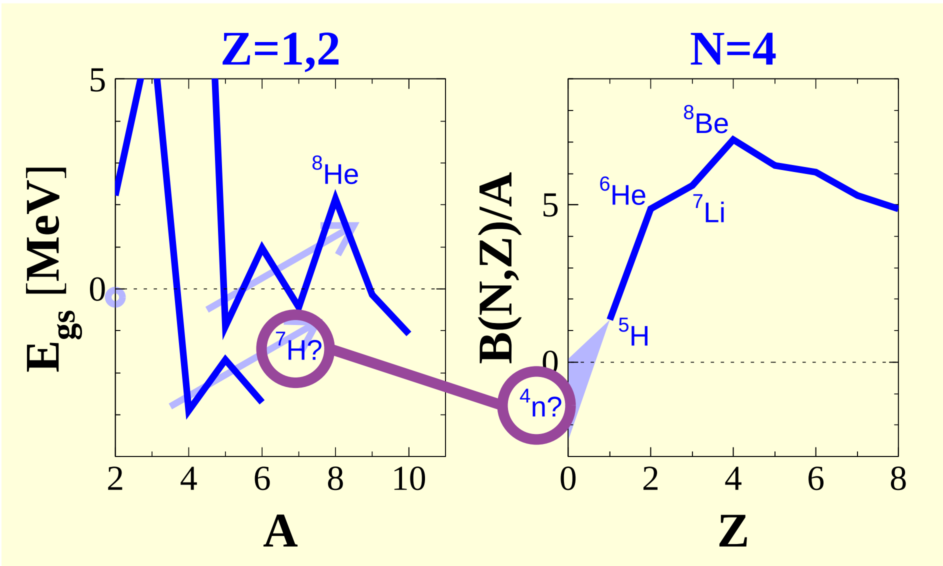

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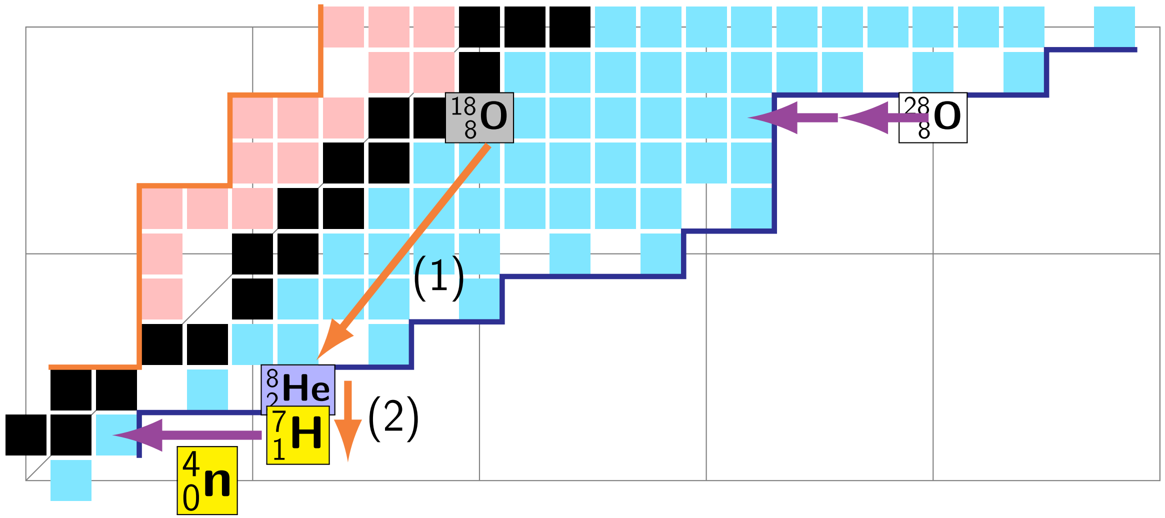
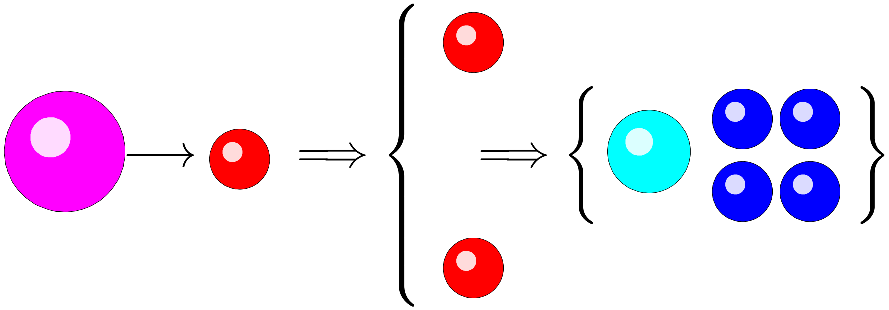
  ⟹ ^{7}H & ^{4}n proposal with $\varepsilon(4n) \gg 0$!

Hydrogen 7 & Tetraneutron ‘emission’ ?

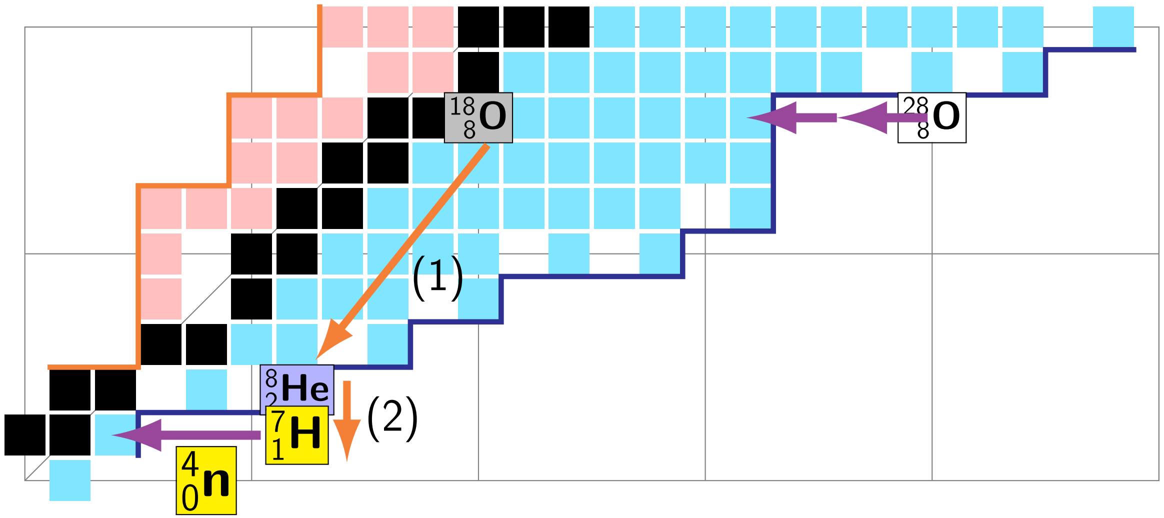


^{8}He (p,2p) ^{7}H @ 150 MeV/N :

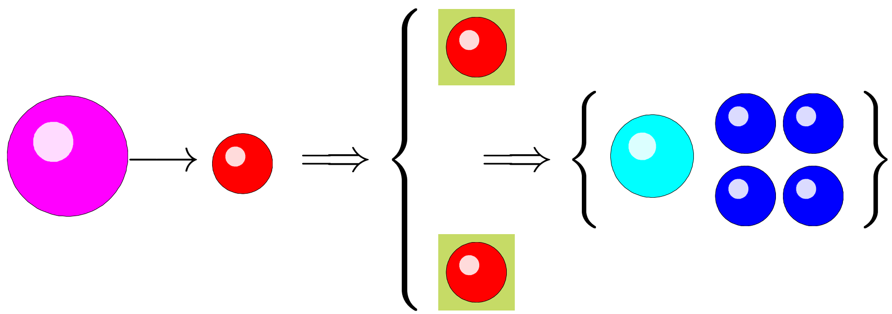


$\rightarrow$ 7-body final state !

Hydrogen 7 & Tetraneutron 'emission' ?

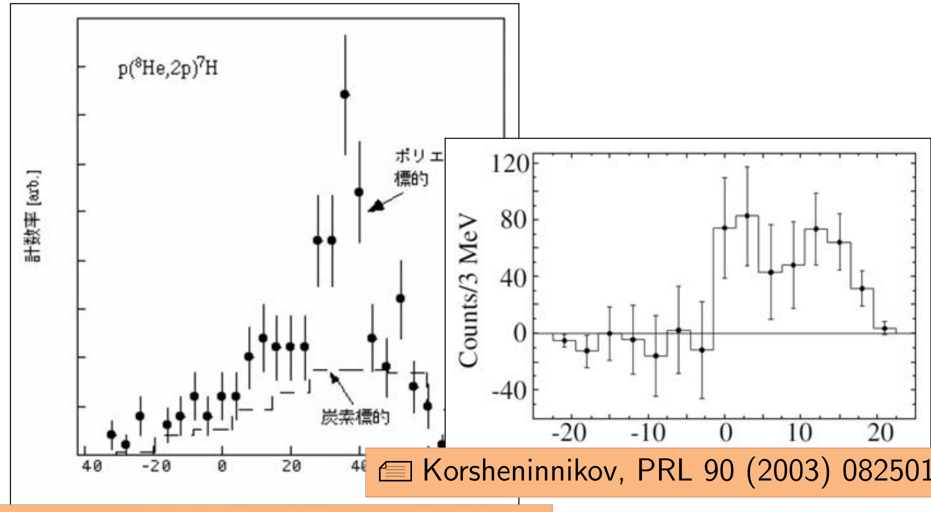


^{8}He (p,2p) ^{7}H @ 150 MeV/N :



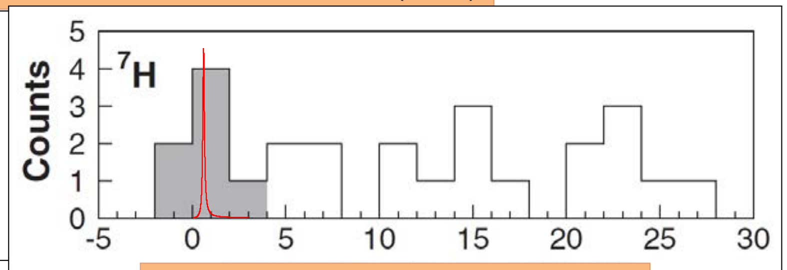
→ 7-body final state !

→ FWHM ∼ few MeV

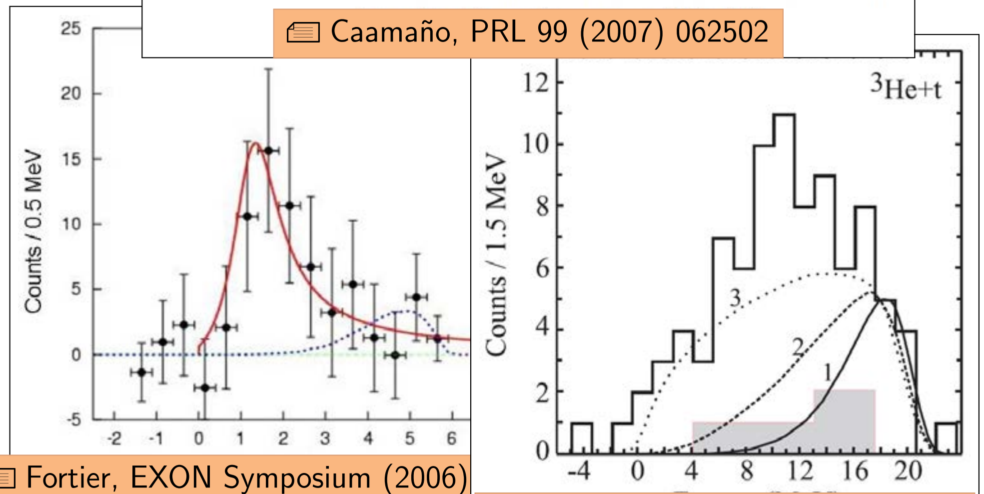


Korsheninnikov, PRL 90 (2003) 082501

Kobayashi, HIMAC Report H12 (2000)



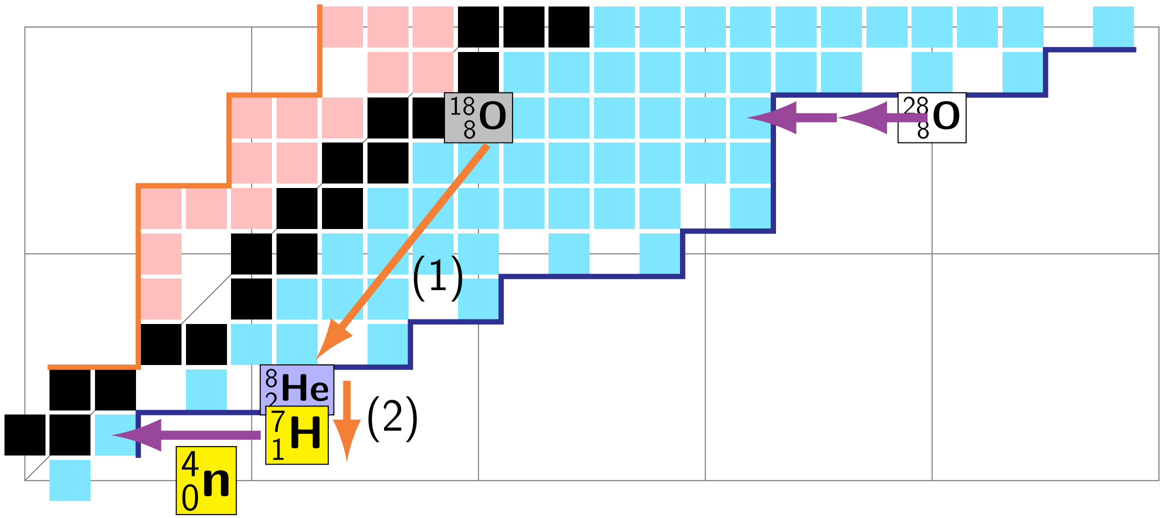
Caamaño, PRL 99 (2007) 062502



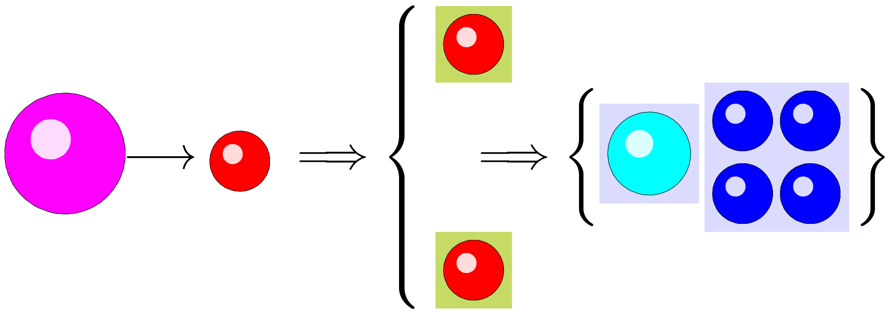
Fortier, EXON Symposium (2006)

Nikolskii, PRC 81 (2010) 064606

Hydrogen 7 & Tetraneutron 'emission' ?



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

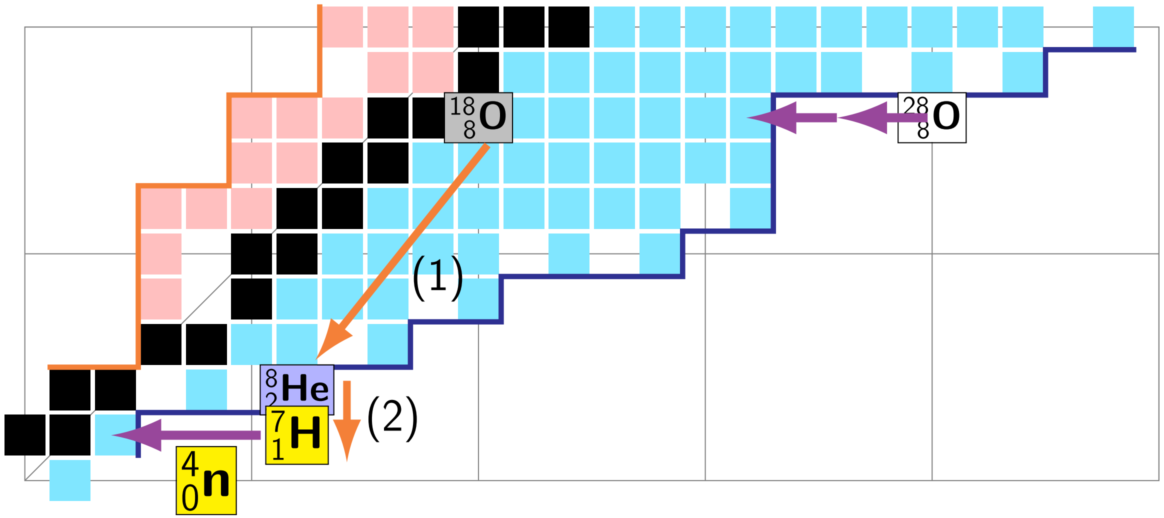


→ 7-body final state !

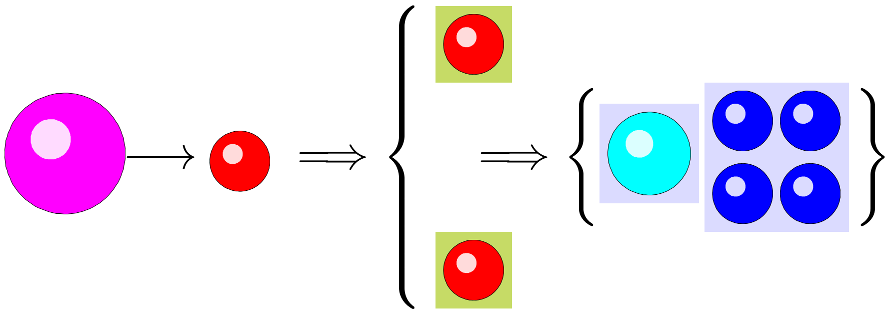
→ FWHM ∼ few MeV → 100 keV !

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

Hydrogen 7 & Tetraneutron 'emission' ?



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



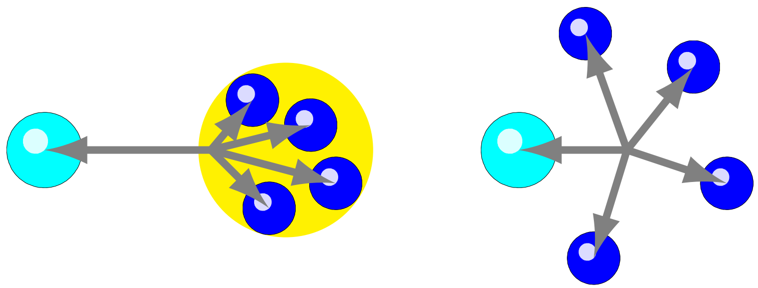
→ 7-body final state !

→ FWHM ∼ few MeV → 100 keV !

→ (2p+t+3n) ∼ 150 keV !

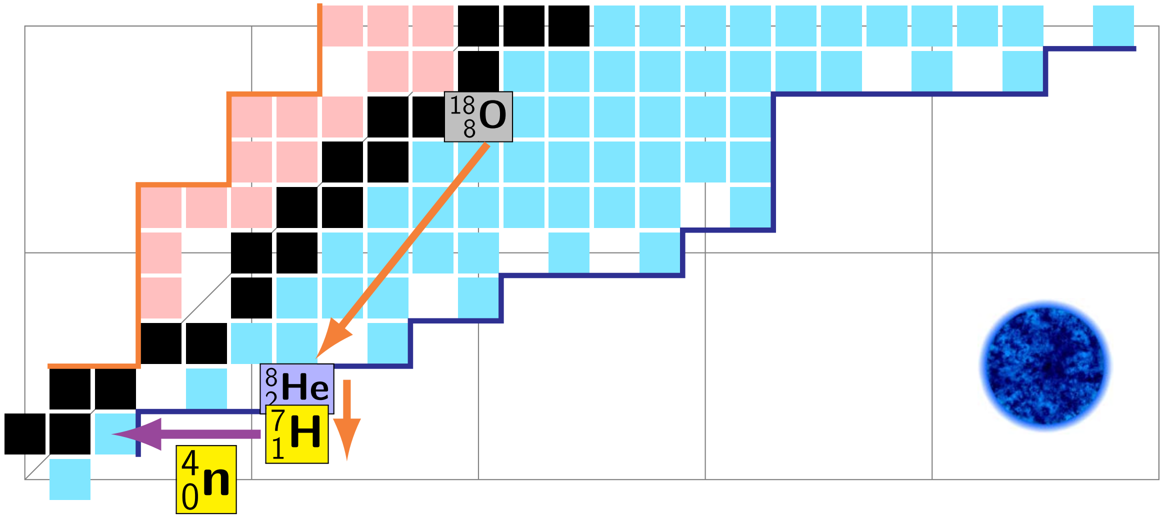
- **MINOS** liquid H target :
  → high luminosity (*statistics*)
  → proton angles (*resolution*)
- **DALI** NaI crystals :
  → proton energies (*efficiency*)
- **SAMURAI** :
  → triton momentum (*resolution & correlations*)
- **NEBULA** + **NeuLAND** :
  → 3/4 neutron momenta (*efficiency, resolution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

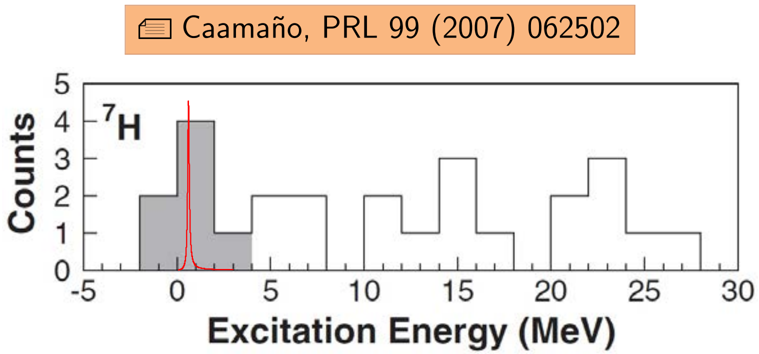
angular correlations → E(4n) !

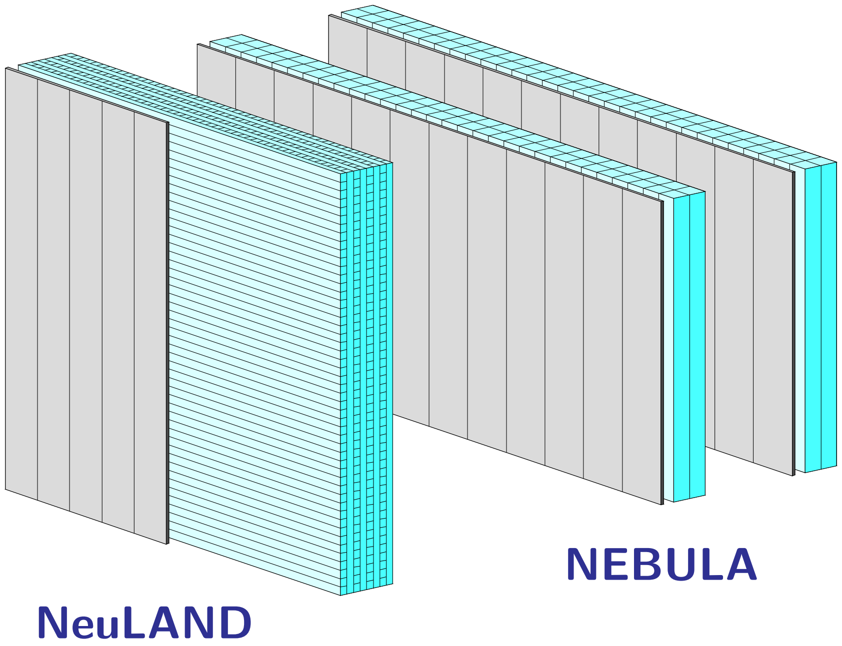


(2-body PS) (5-body PS)

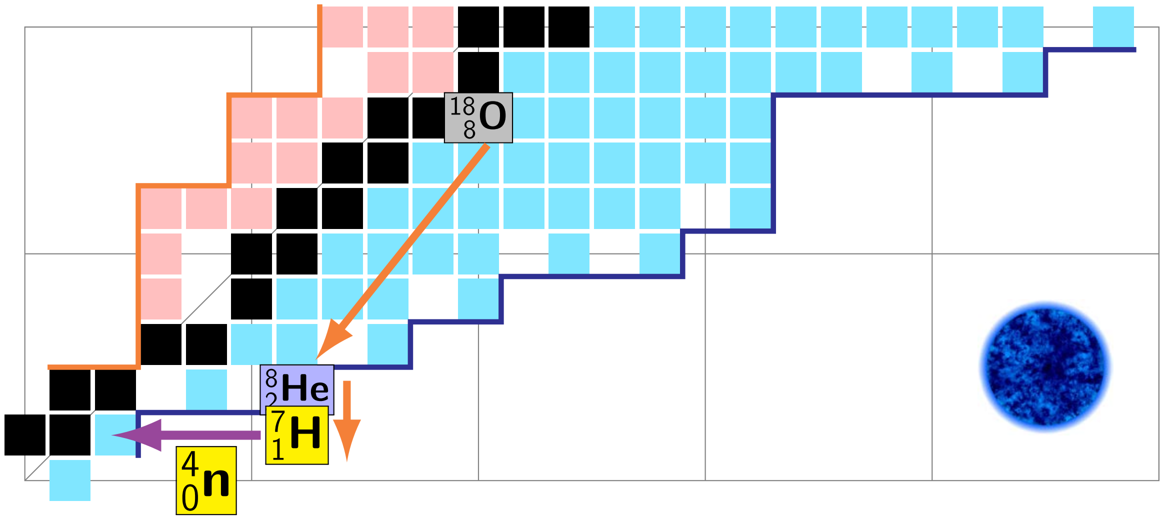
Expected results : MC simulations

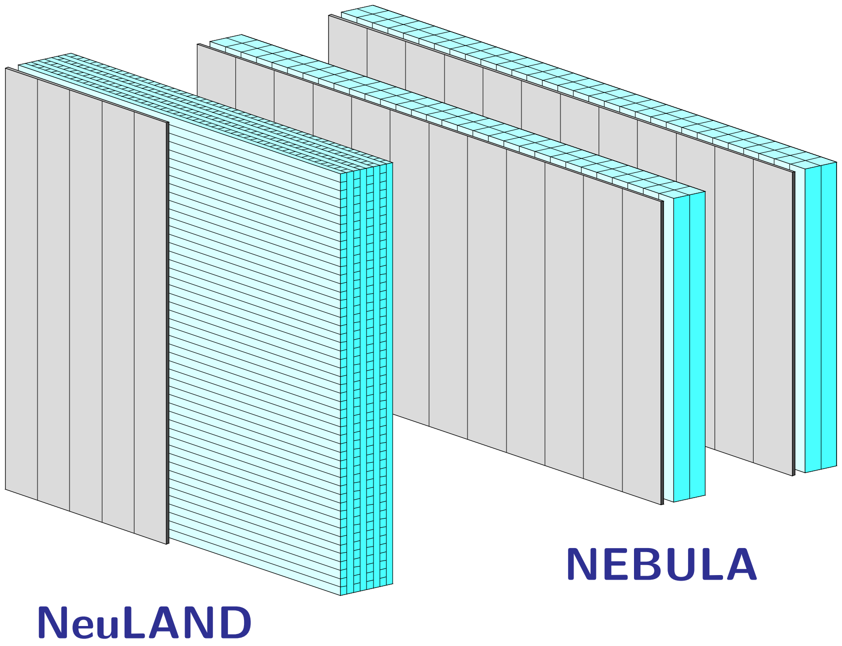


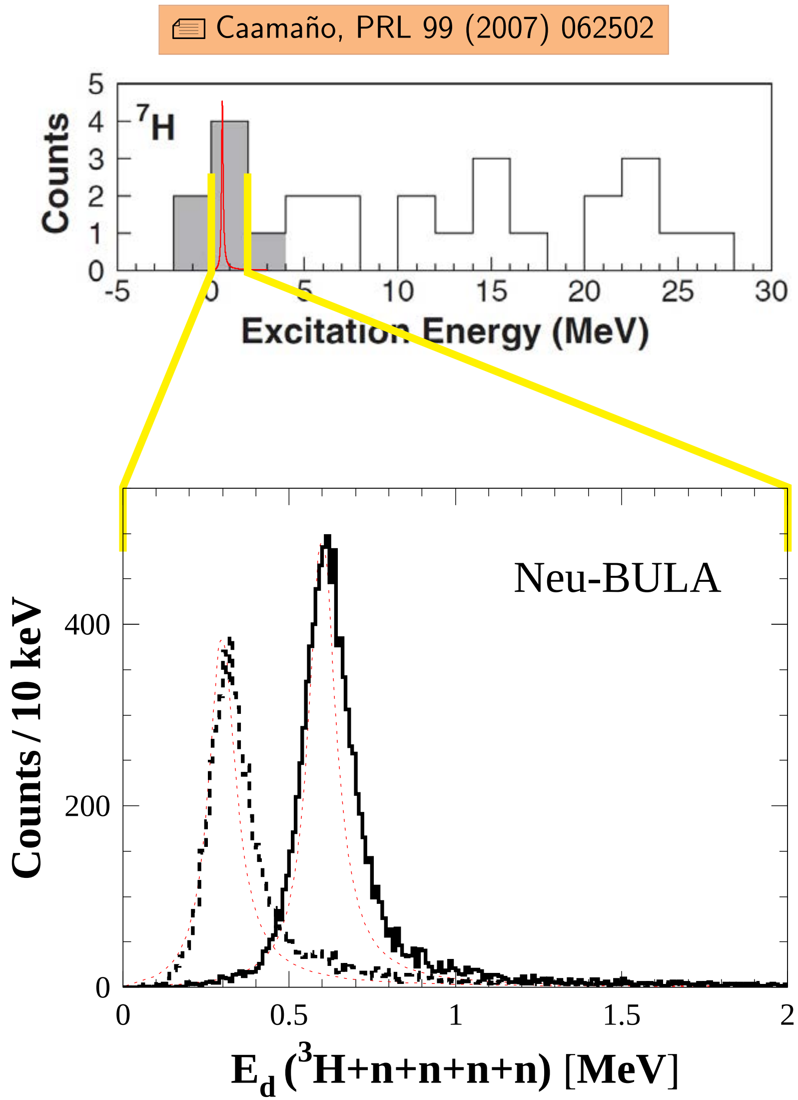




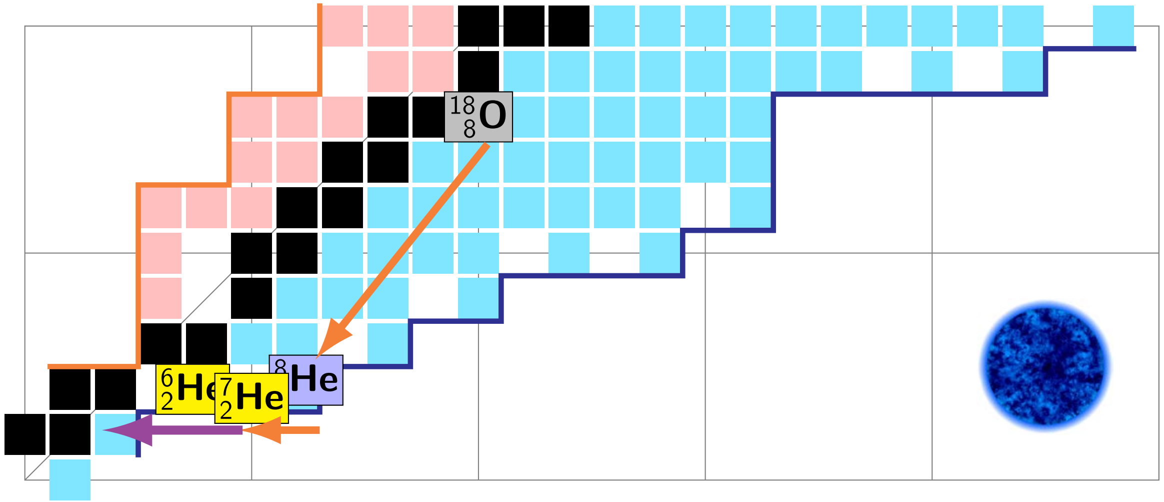
Expected results : MC simulations

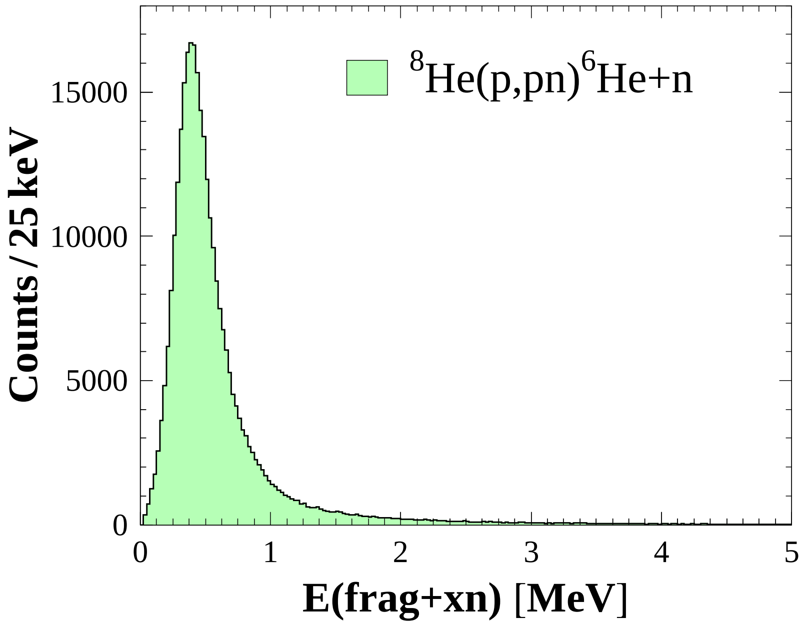


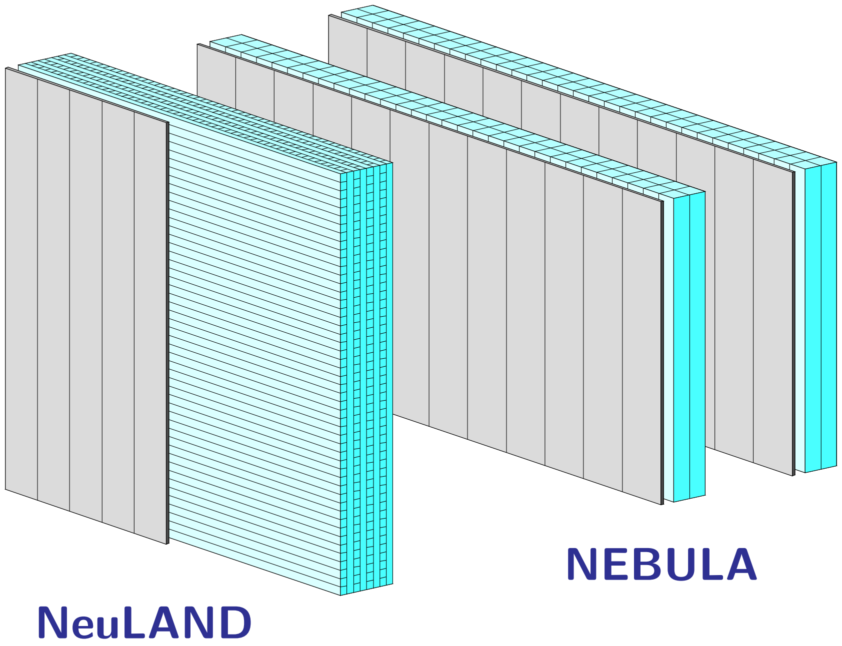


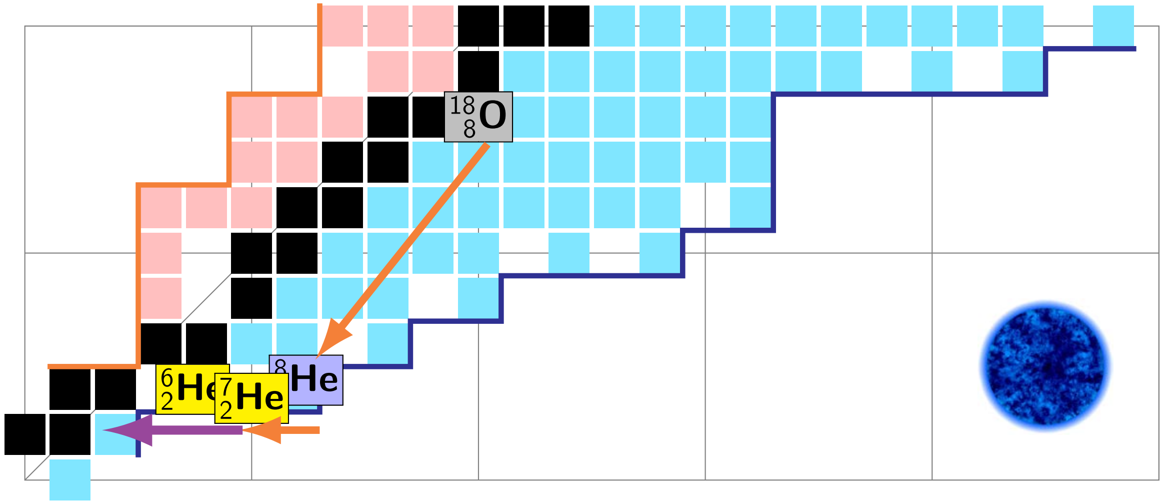


VERY PRELIMINARY results [Lenain]

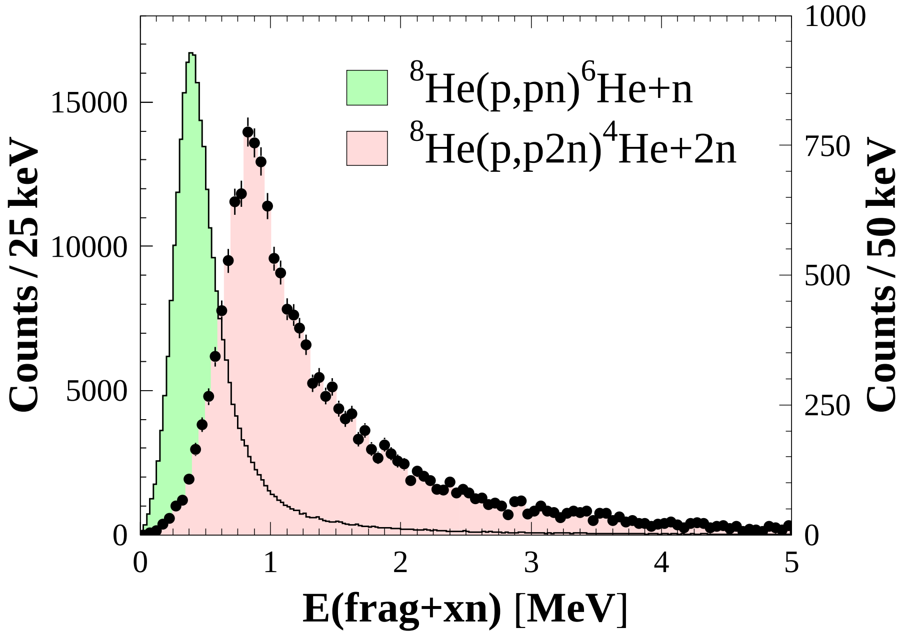




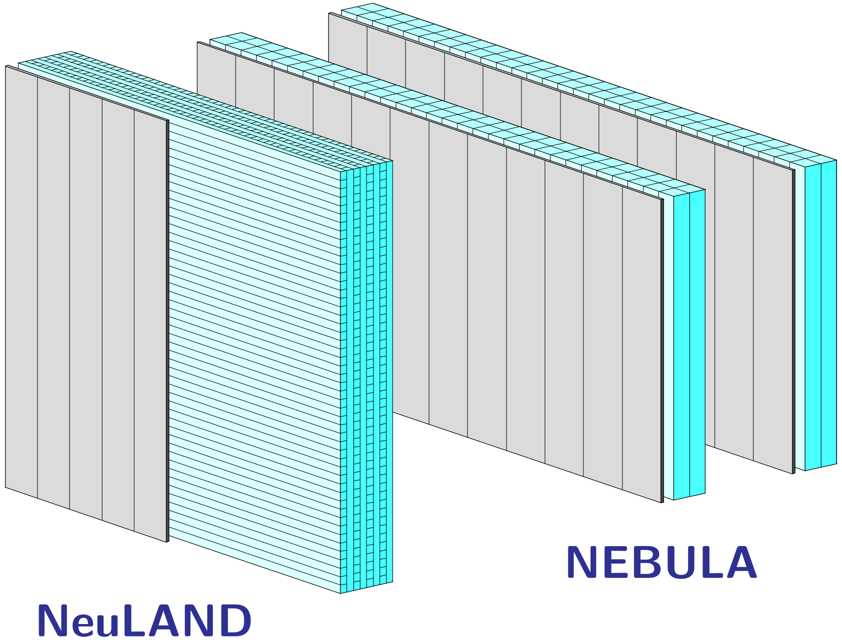




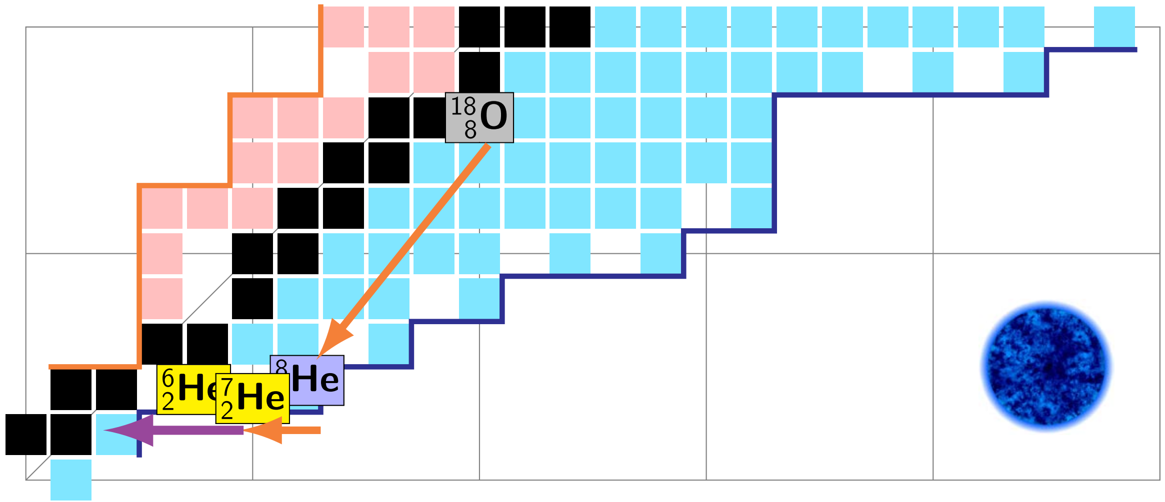
$^{18}_{8}$O
$^{6}_{2}$He
$^{7}_{2}$He
^{8}He



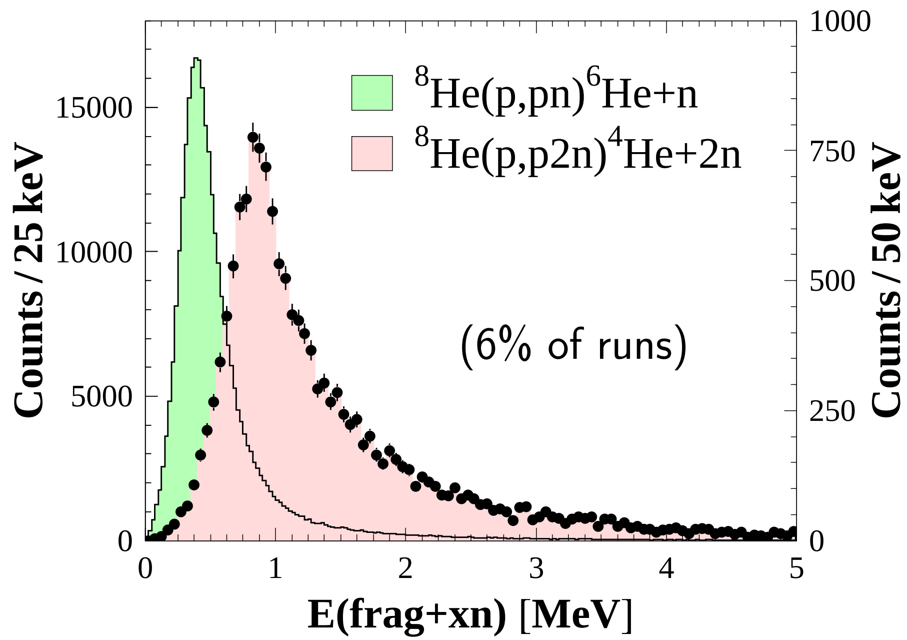
^{8}He(p,pn)^{6}He+n
^{8}He(p,p2n)^{4}He+2n
Counts / 25 keV
Counts / 50 keV
E(frag+xn) [MeV]



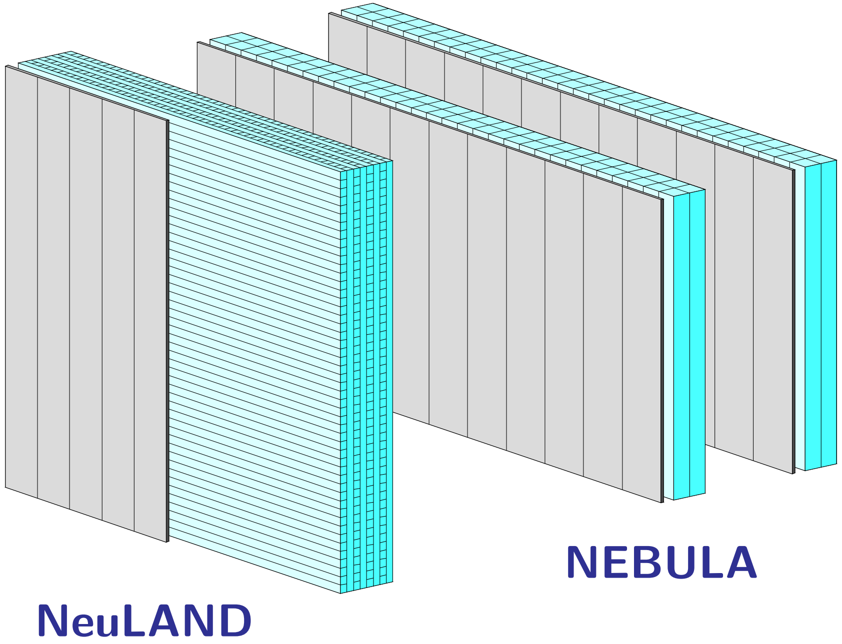
NEBULA
NeuLAND



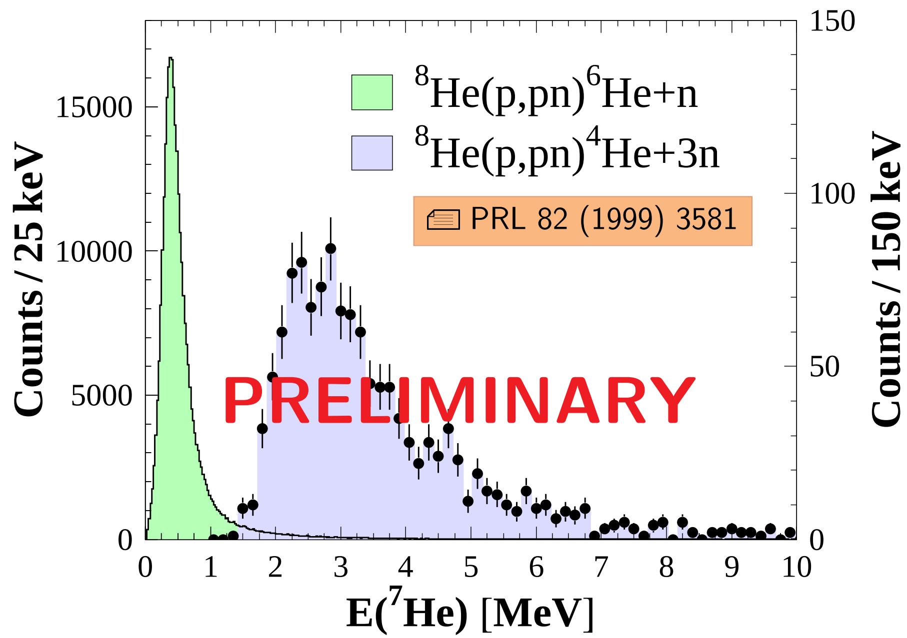
$^{18}_{8}$O
^{8}He
$^{6}_{2}$He
$^{7}_{2}$He



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

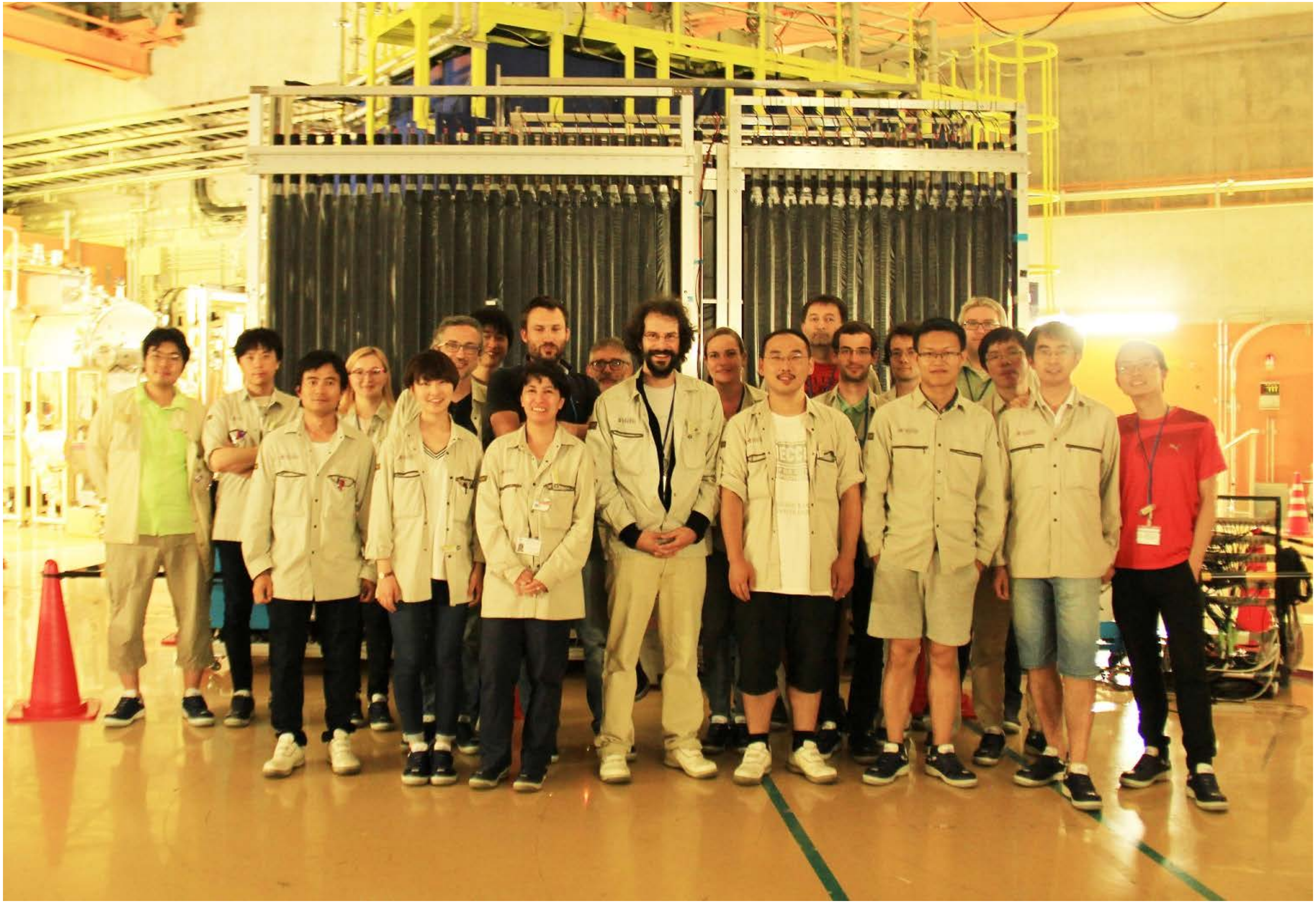


NeuLAND
NEBULA



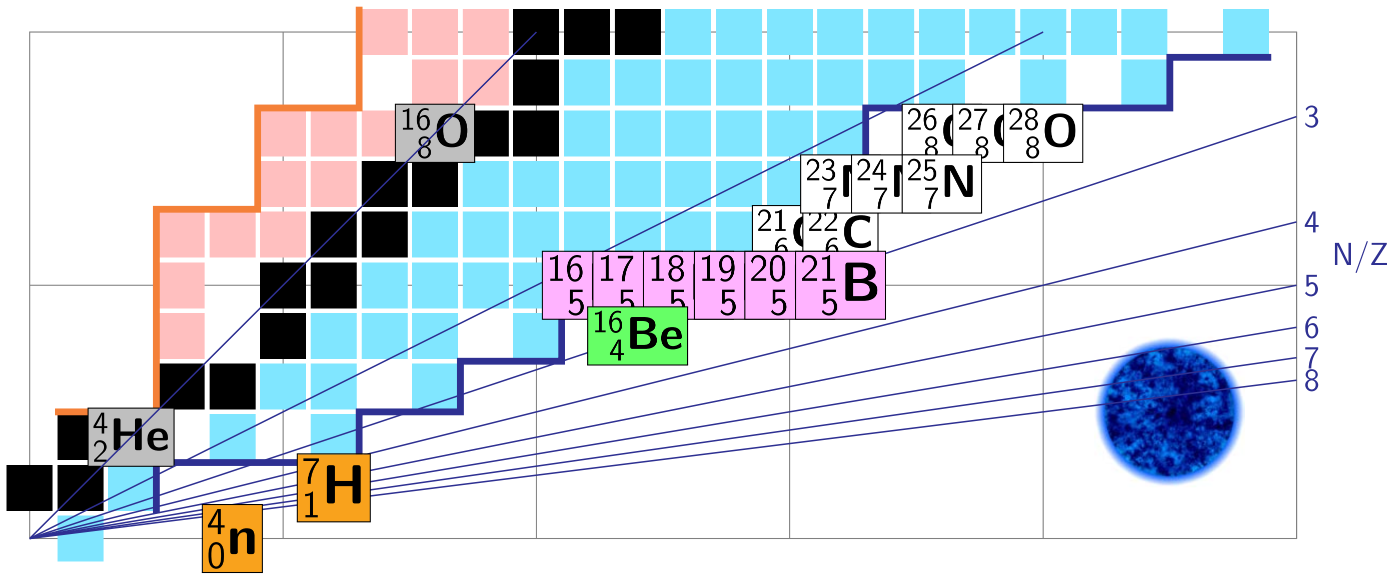
^{8}He(p,pn)^{6}He+n
^{8}He(p,pn)^{4}He+3n
PRL 82 (1999) 3581
PRELIMINARY
Counts / 25 keV
Counts / 150 keV
E(^{7}He) [MeV]

SAMURAI S34 collaboration (part)




TOSHIBA

SAMURAI@RIKEN



- Extreme N/Z regime :
  - $\boxed{Z=5}$: exotic phenomena !
    - → Efimov trimers ?
    - → 2/4/6n emission ...
  - $\boxed{Z=4}$: 2n emission from ^{16}Be(s) !
  - $\boxed{Z=1}$ & $\boxed{Z=0}$: multineutron physics !
    - → definitive location of ^{7}H & ^{4}n ...
    - → benchmark for many-neutron models

EXPAND project (French ANR)

- Expand NEBULA multineutron capabilities :
  - France : LPC, IRFU, IPNO
  - Japan : TITech, RIKEN
  - +90 bars : Commissioning & Day-1 in 2021 (?)