

PKU-CUSTIPEN Nuclear Reaction Workshop (China-U.S. Theory Institute for Physics with Exotic Nuclei)

“Reactions and Spectroscopy of Unstable Nuclei”

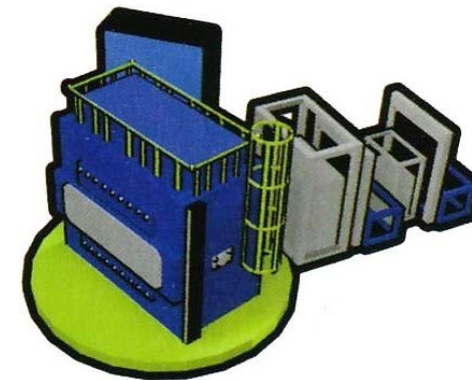
August 10-14, 2014, Peking University, Beijing (China)

The Far Side of Boron and Beryllium

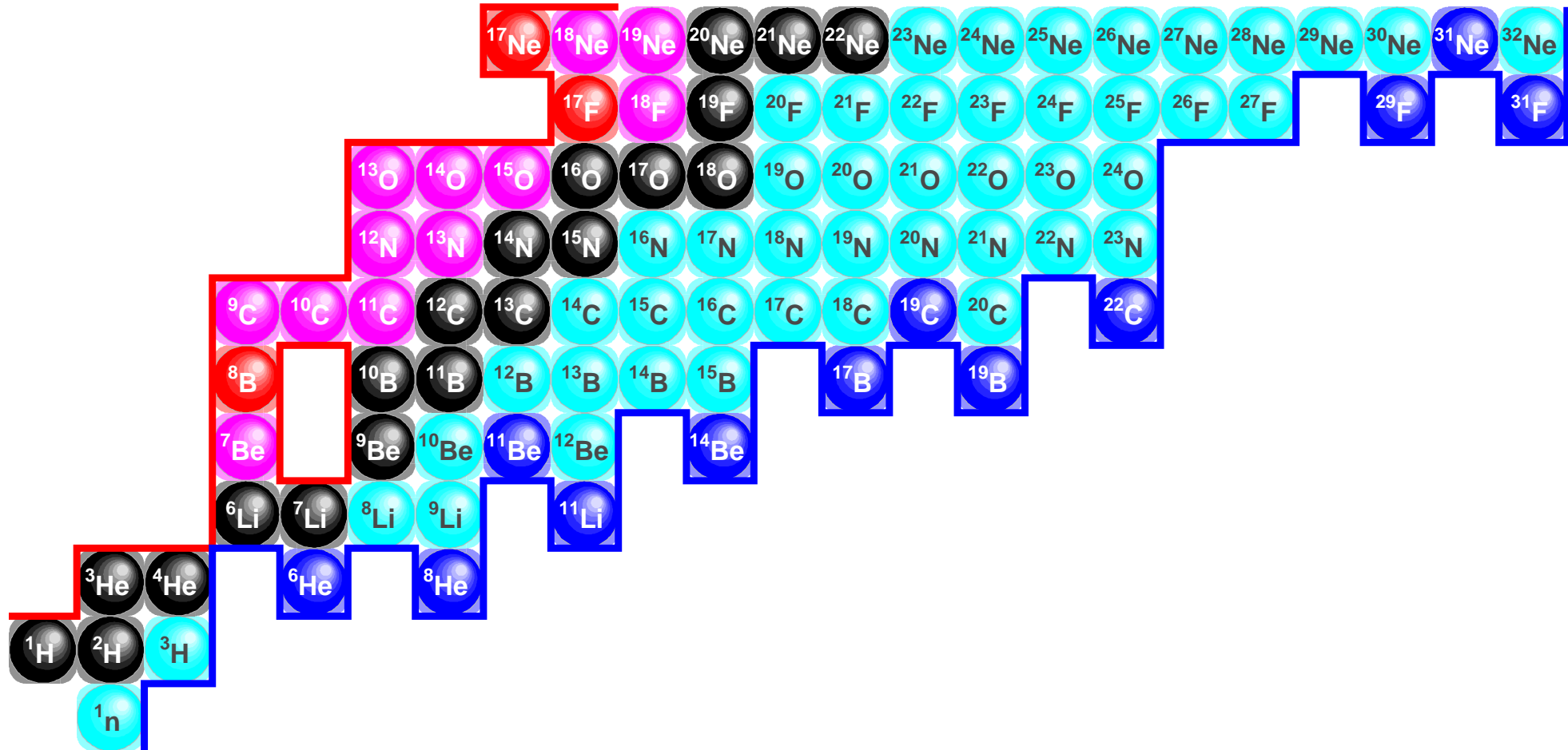
F. Miguel Marqués



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N. Nakatsuka⁸, T. Nakashima², A. Navin⁹, S. Nishi², H. Otsu⁴, H. Sato⁴, Y. Satou⁵,
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⁶Tohoku University, ⁷Rikkyo University, ⁸Kyoto University, ⁹GANIL, ¹⁰GSI, ¹¹University of York, ¹²IPN-Orsay

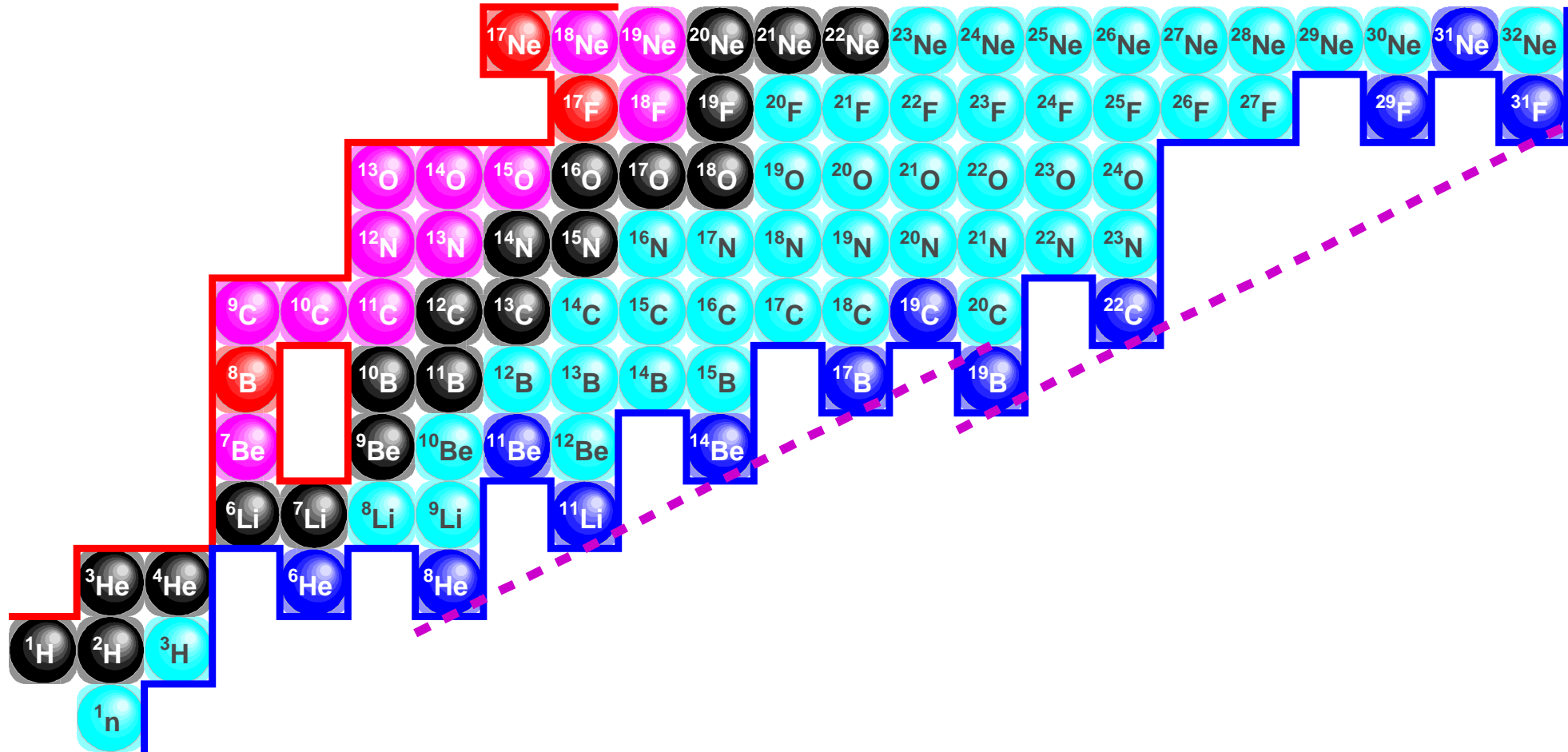


- Fundamental questions :

- ⇒ **where** are the limits ?

- ⇒ **why** are they located there ?

- ⇒ **how** does the far side look like ?

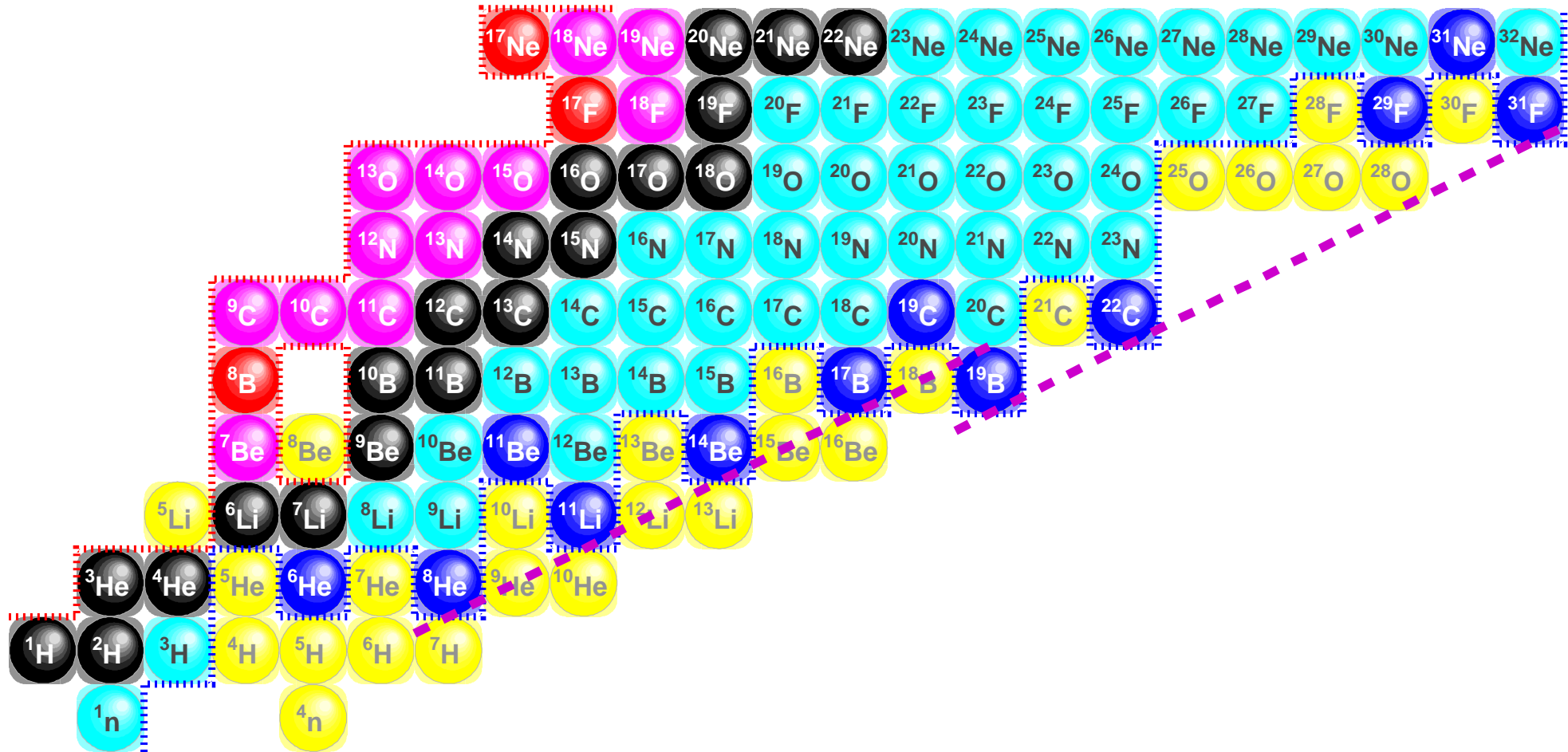


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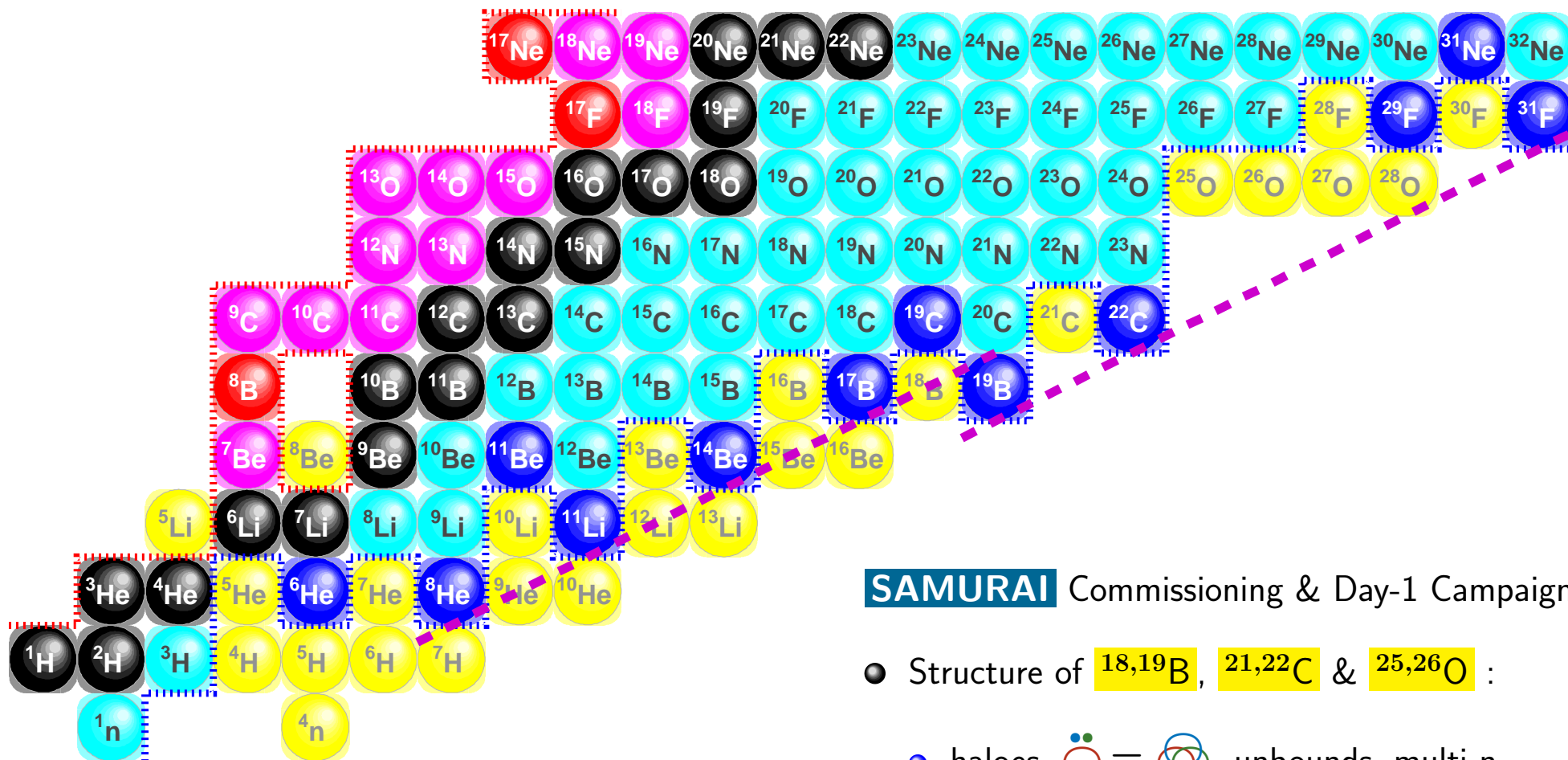
⇒ **why** are they located there ?

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SAMURAI Commissioning & Day-1 Campaign

- Structure of $^{18,19}\text{B}$, $^{21,22}\text{C}$ & $^{25,26}\text{O}$:

- haloes, $\text{O} \equiv \text{O}$, unbounds, multi-n ...

- complete survey of the far side :

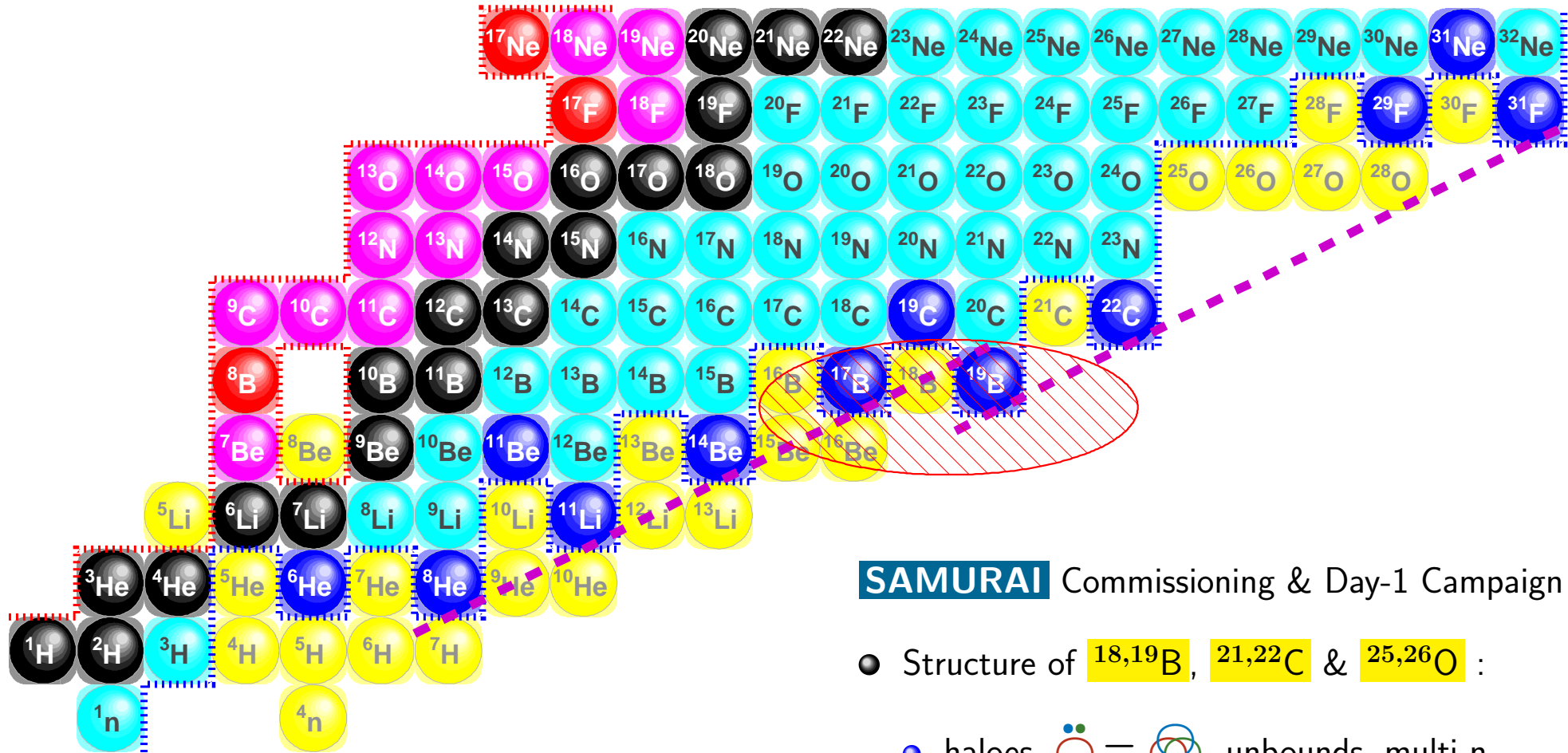
- $^{12,13}\text{Li} \longleftrightarrow ^{25,26}\text{O}$ in almost one shot !

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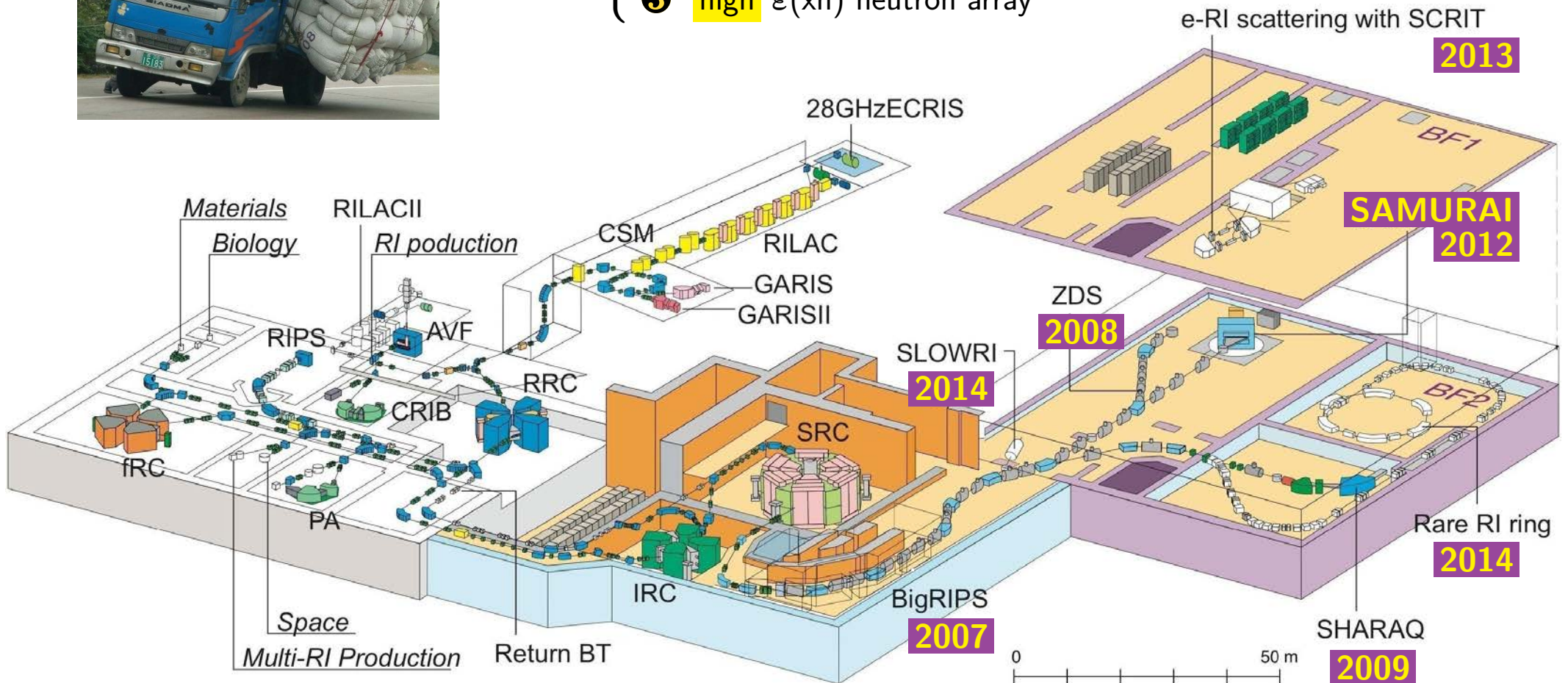
⇒ **how** does the far side look like ?

⇒ PRELIMINARY results on $^{16,18,20,21}\text{B} / ^{15,16}\text{Be}$



Access to very high A/Z !!!

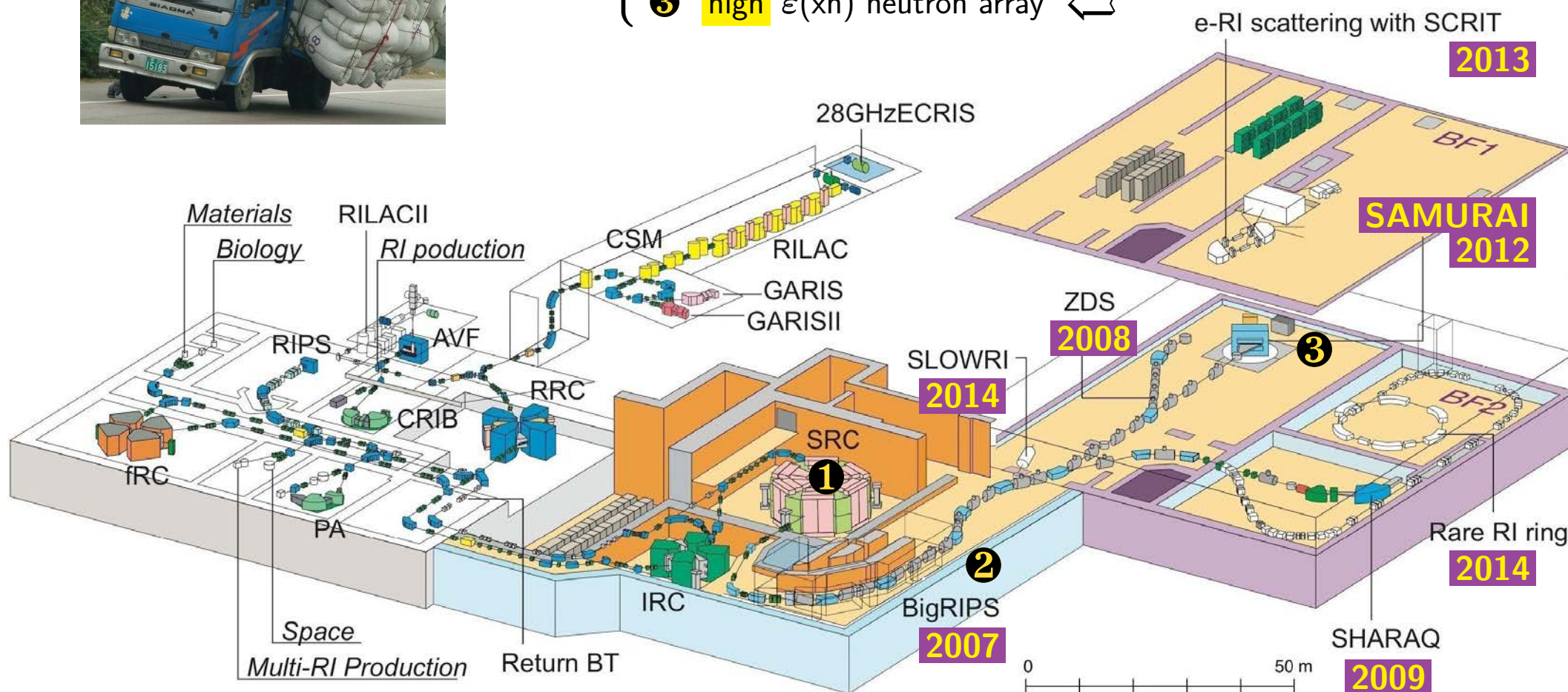
- ⇒
- ① **intense** primary beams
 - ② **strong** B fields (A/Z)
 - ③ **high** $\epsilon(xn)$ neutron array

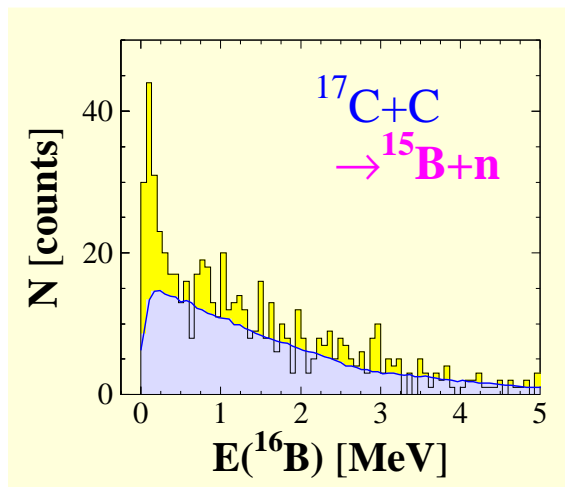
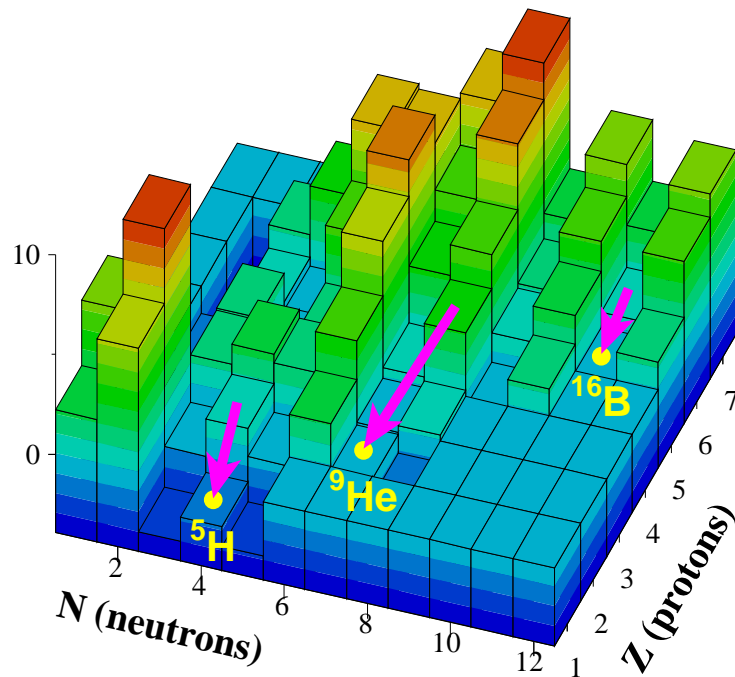




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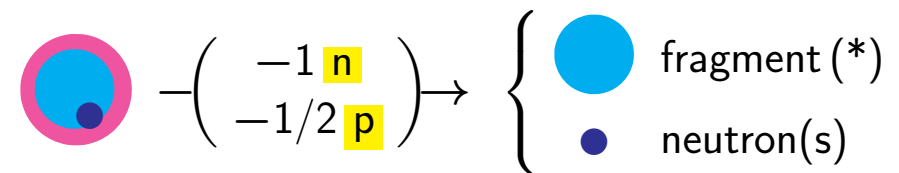


Lecouey, PLB 672 (2009) 6

- Shell evolution **around** the limits
- Three-body systems (interactions) :

$${}^{17}\text{B} ({}^{15}\text{B}-n-n \text{ (diagram)}) \equiv {}^{16}\text{B} \otimes 2n$$

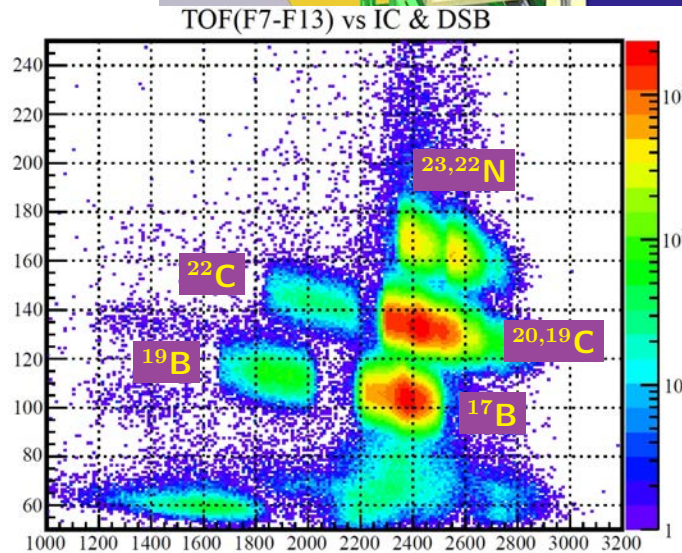
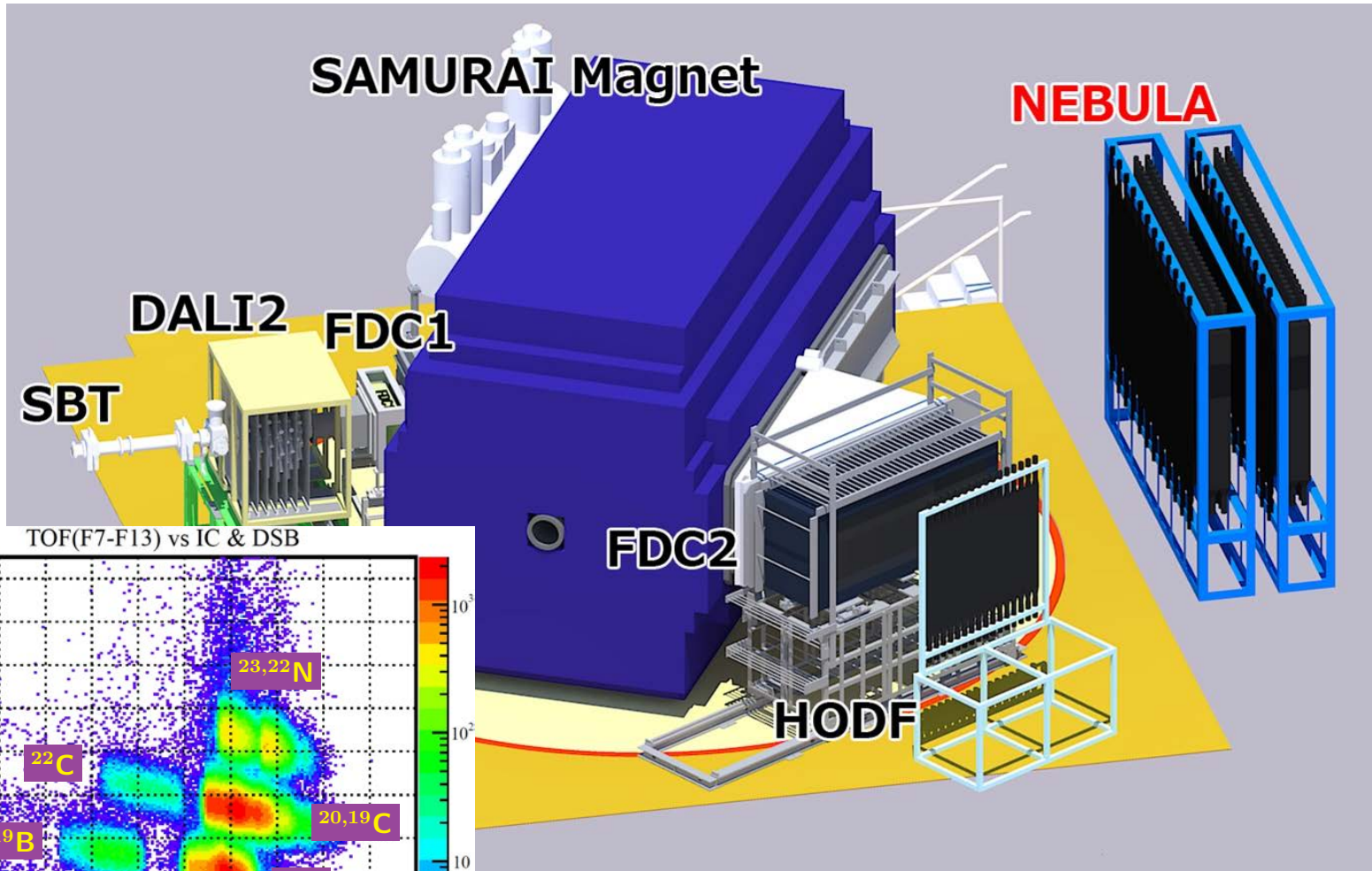
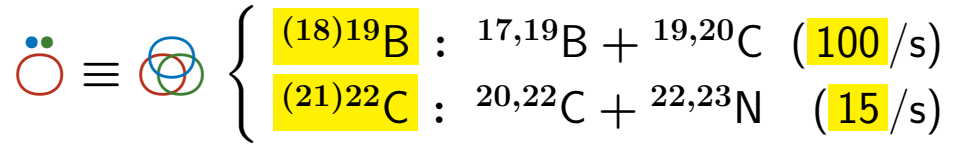
- Knock out from the dripline :



- fragment (γ) + neutrons : E_{rel}
- direct, fast reactions : **resonances** (J^π) \subset (pink circle)
- non-resonant distribution : event mixing (N_{\otimes})

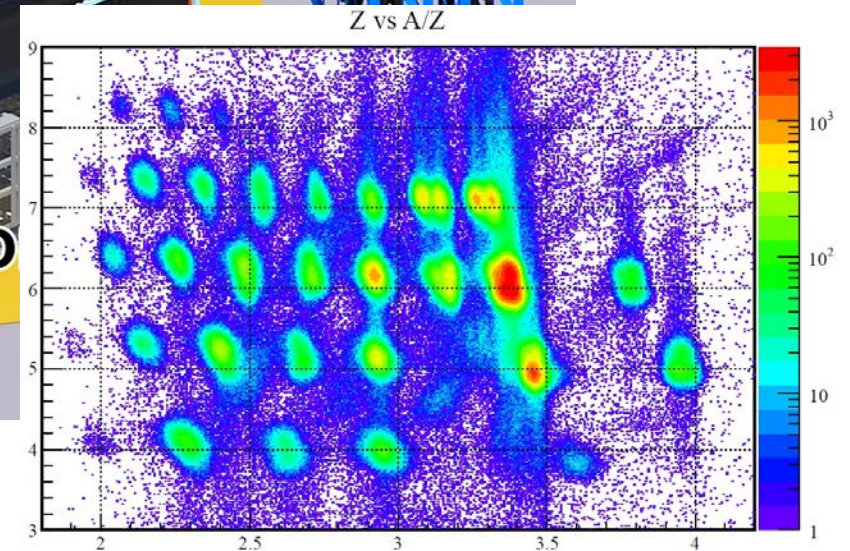
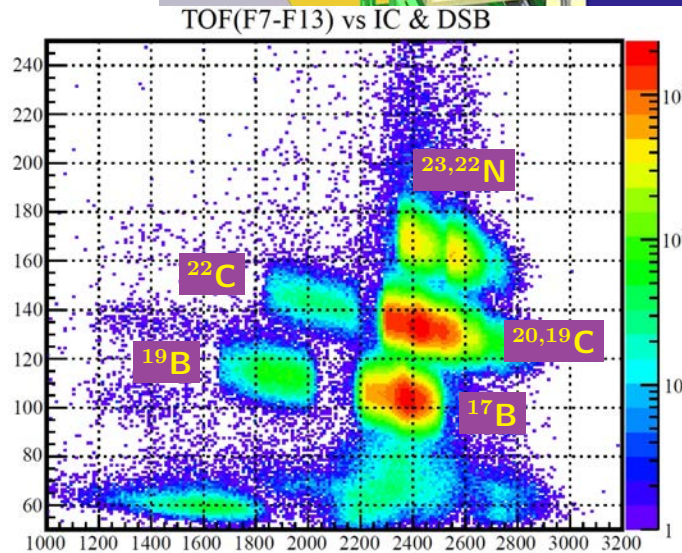
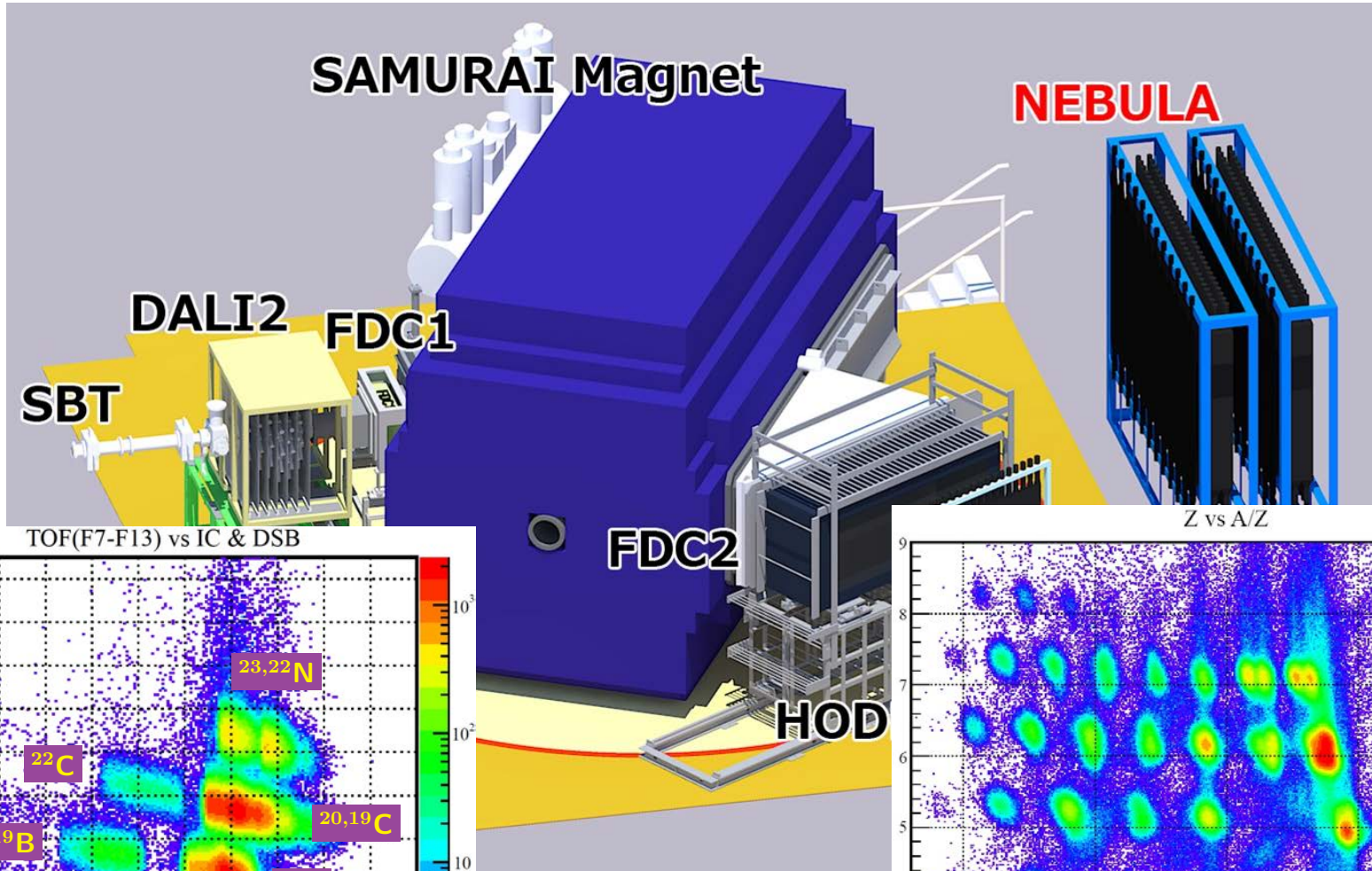
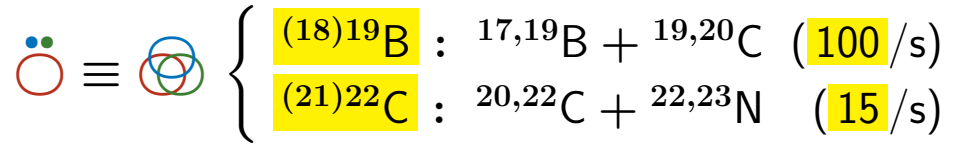
FMM, PLB 476 (2000) 219

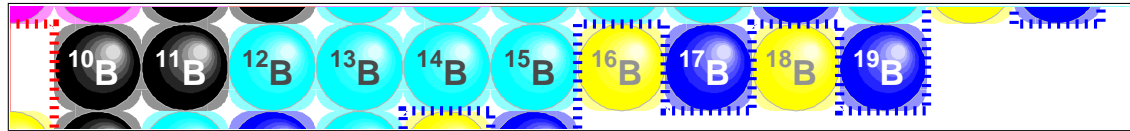
- The structure of Boron 19 & Carbon 22 :



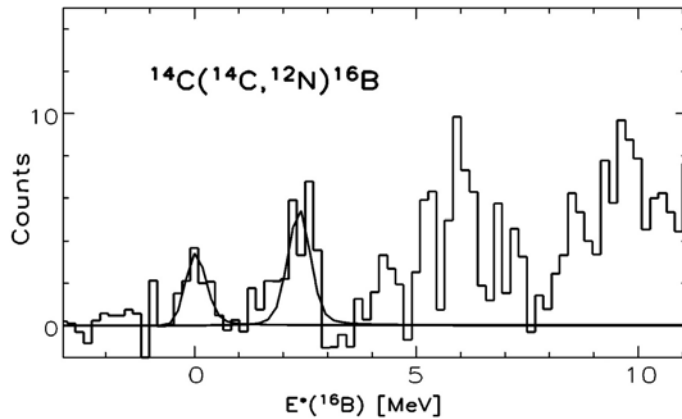
Kobayashi, NIM B 317 (2013) 294

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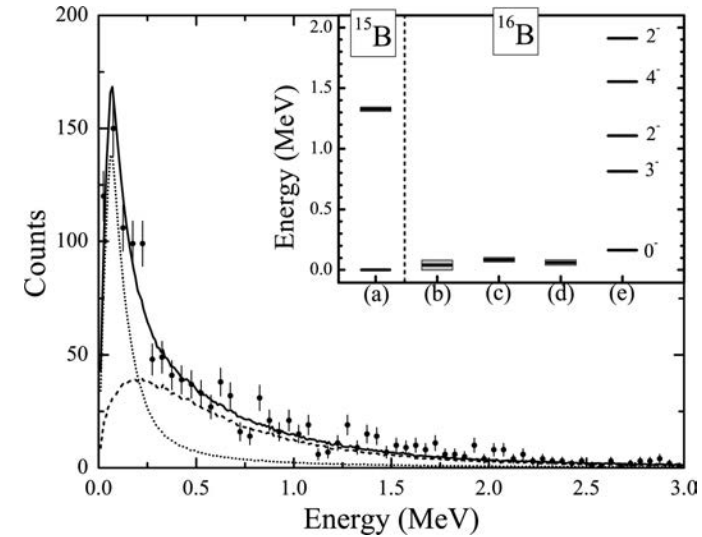




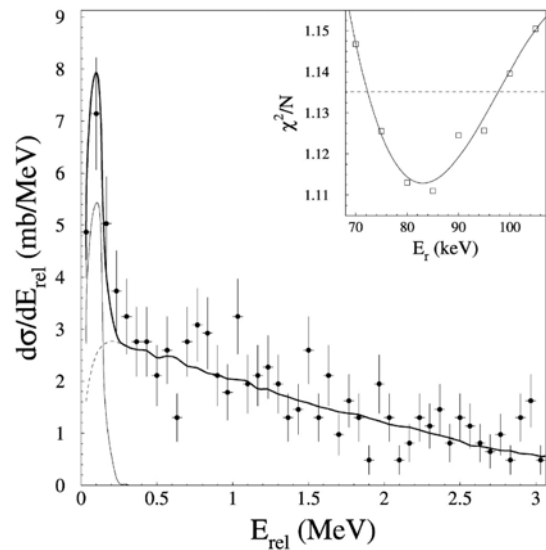
Transfer : Kalpakchieva, EPJA 7 (2000) 451



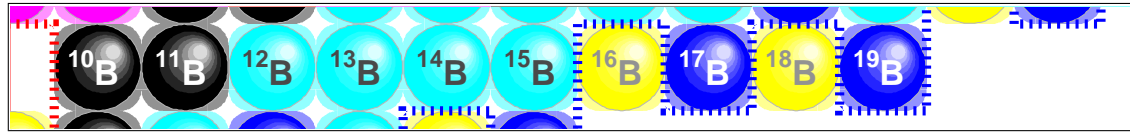
Spyrou, PLB 683 (2010) 129



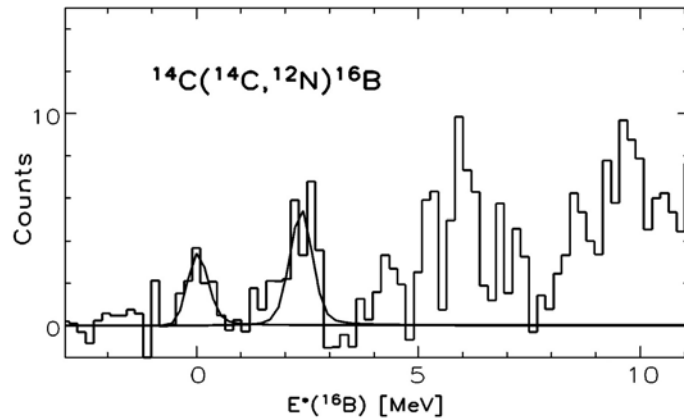
$(^{17}\text{C}, ^{15}\text{B}+n)$: Lecouey, PLB 672 (2009) 6



- Ground state at 0-100 keV
 - $-1p$: no γ detection
- Excited states ?
 - $-1p$: low statistics/acceptance
 - transfer : structure at ~ 2.4 MeV ?

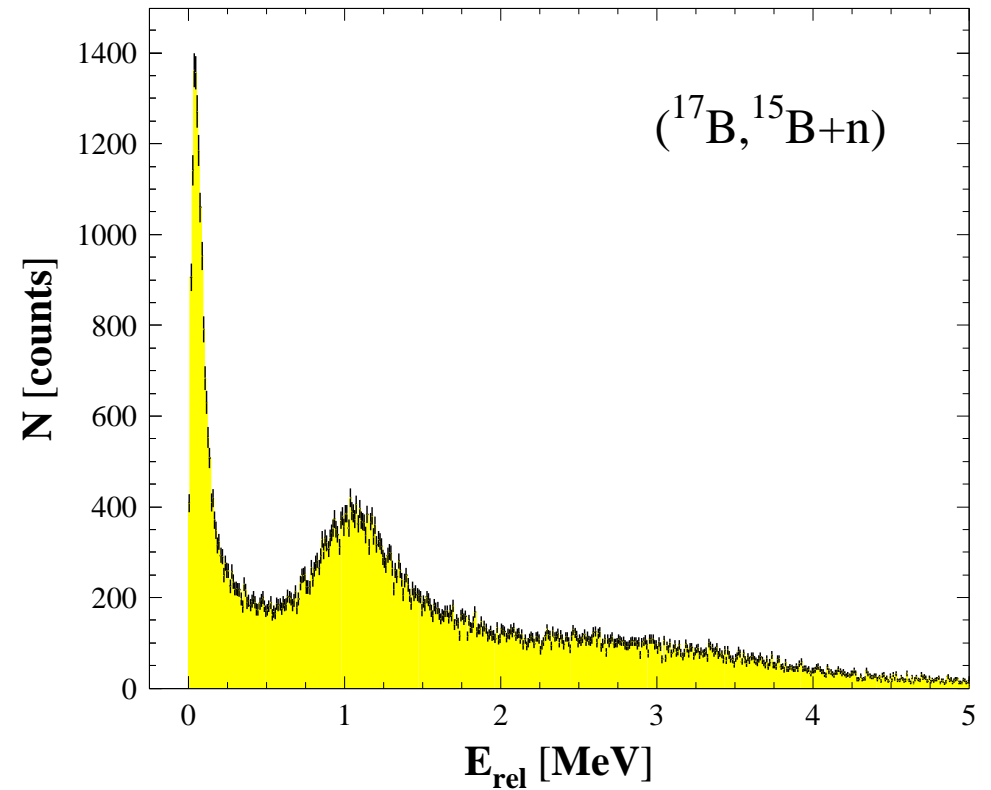


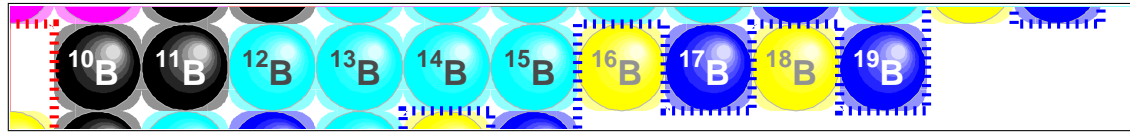
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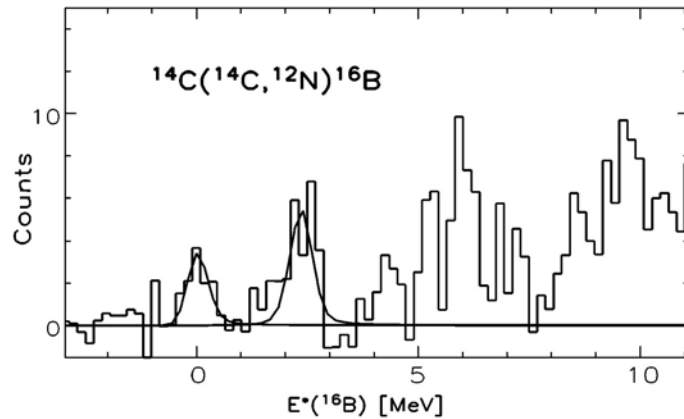
$(^{17}\text{B}, ^{15}\text{B}+n)$:

- RIKEN+NEBULA : $\sim 90\text{k}$ evts !
- global cross-check of analyses



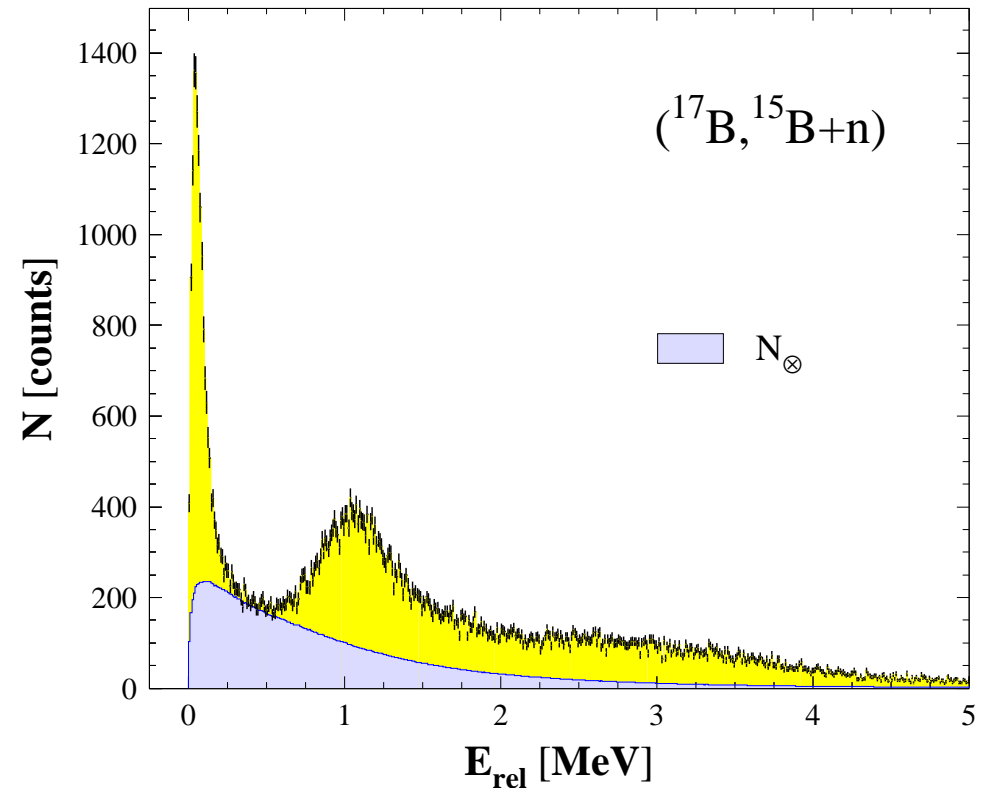


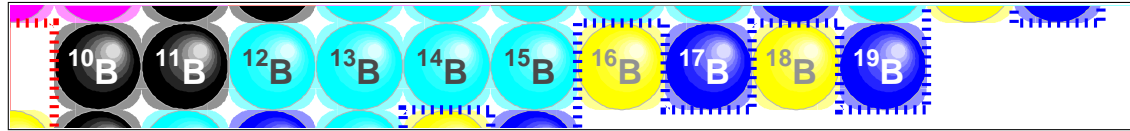
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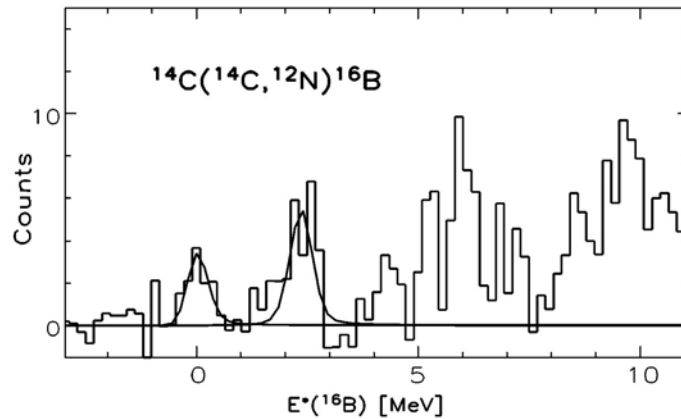
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- event mixing provides N_{\otimes}
- $E_{\text{gs}}(^{16}\text{B}) \sim (40 \pm \text{few}) \text{ keV} ?$
- very clear excited states ...



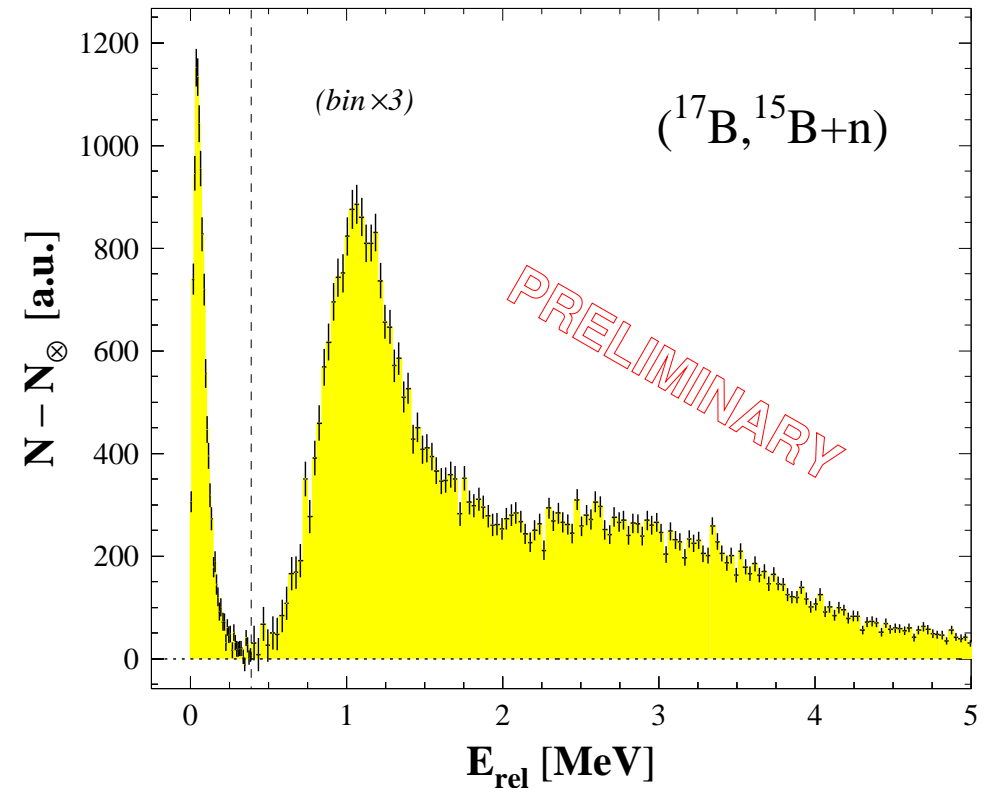


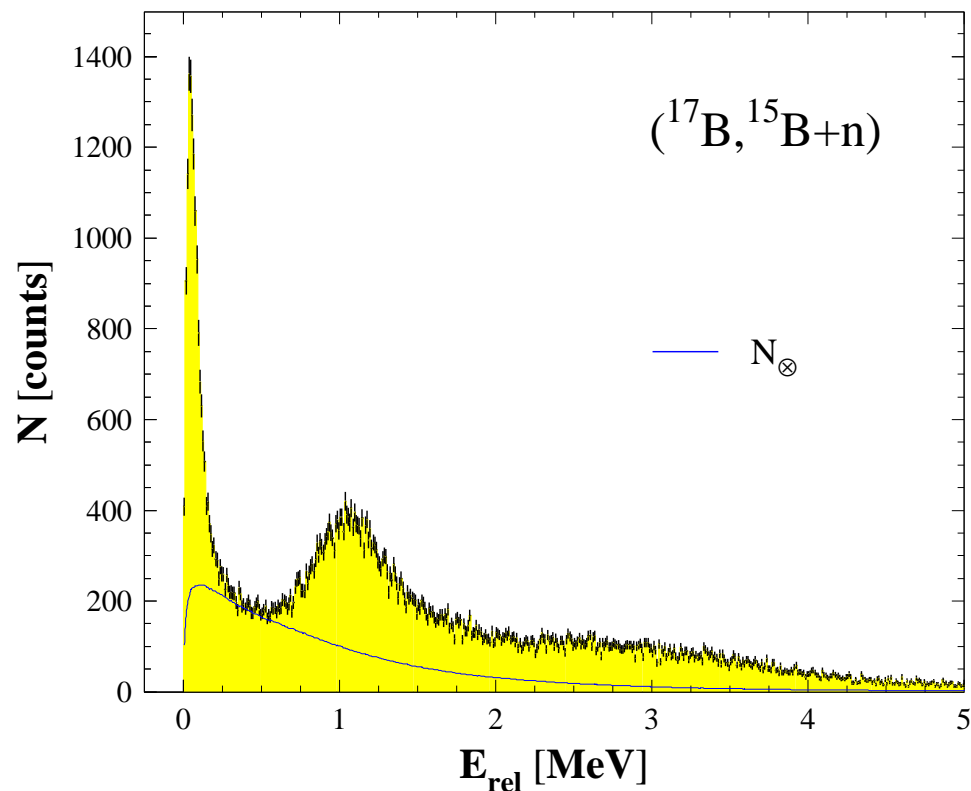
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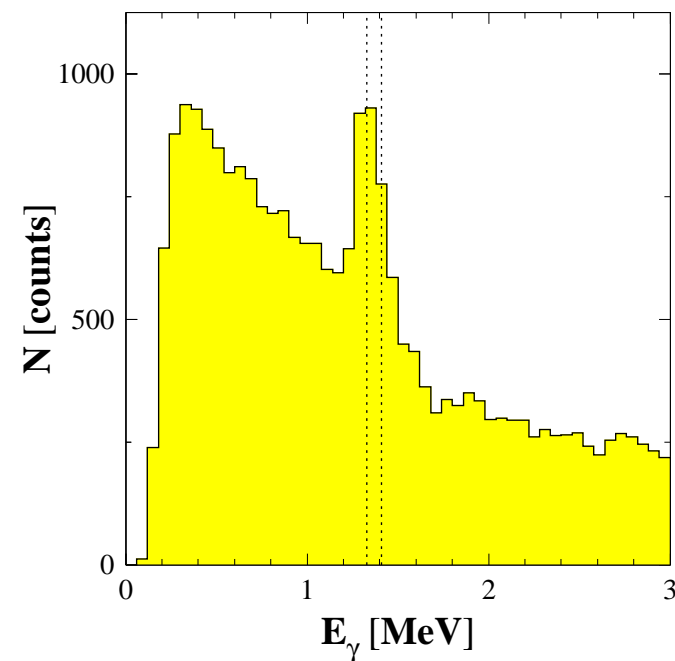




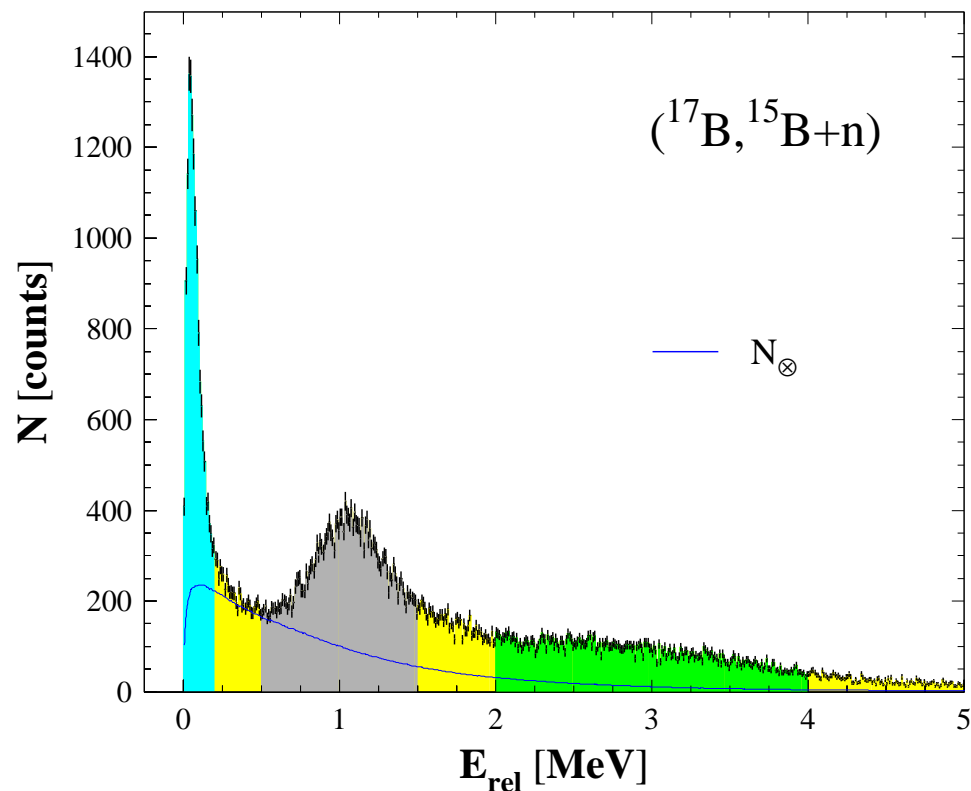
Kondo, PRC 71 (2005) 044611

↓ 1.41
↓ 1.33
 ^{15}B

DALI2 $\{^{15}\text{B}+n+\gamma\}$ events :



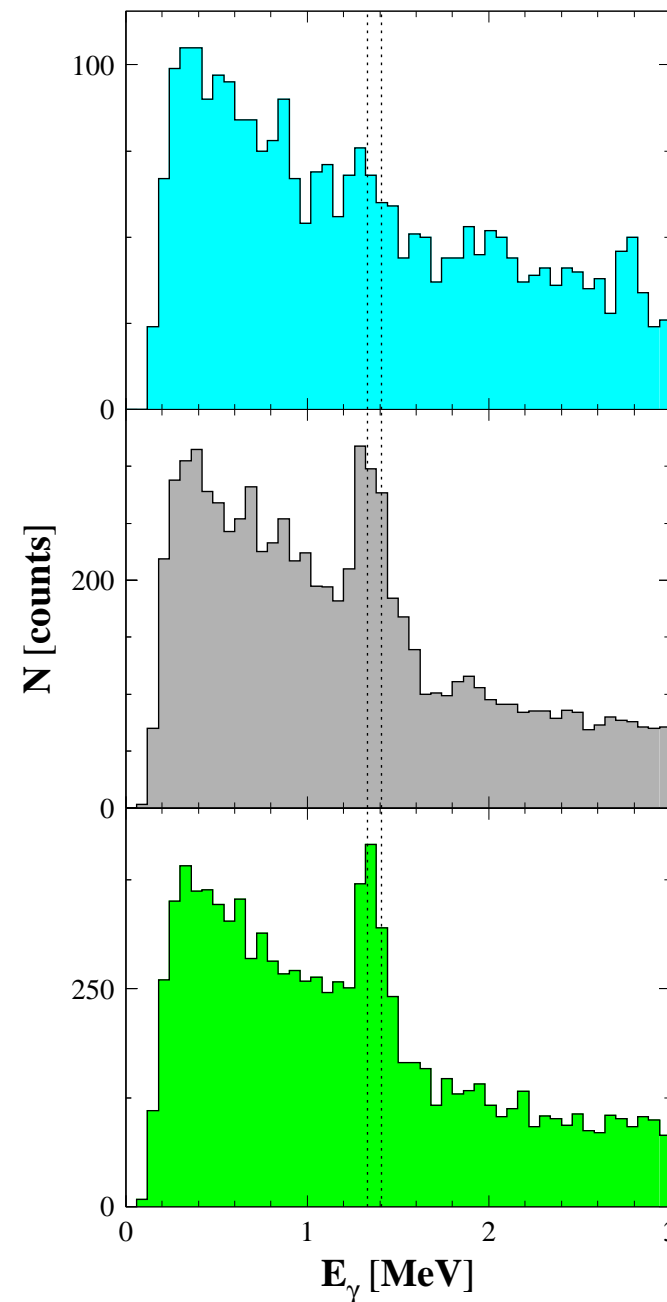
- significant $^{15}\text{B}^*$ to 1st/2nd state !
- E_{rel} vs E_{γ} correlations ?

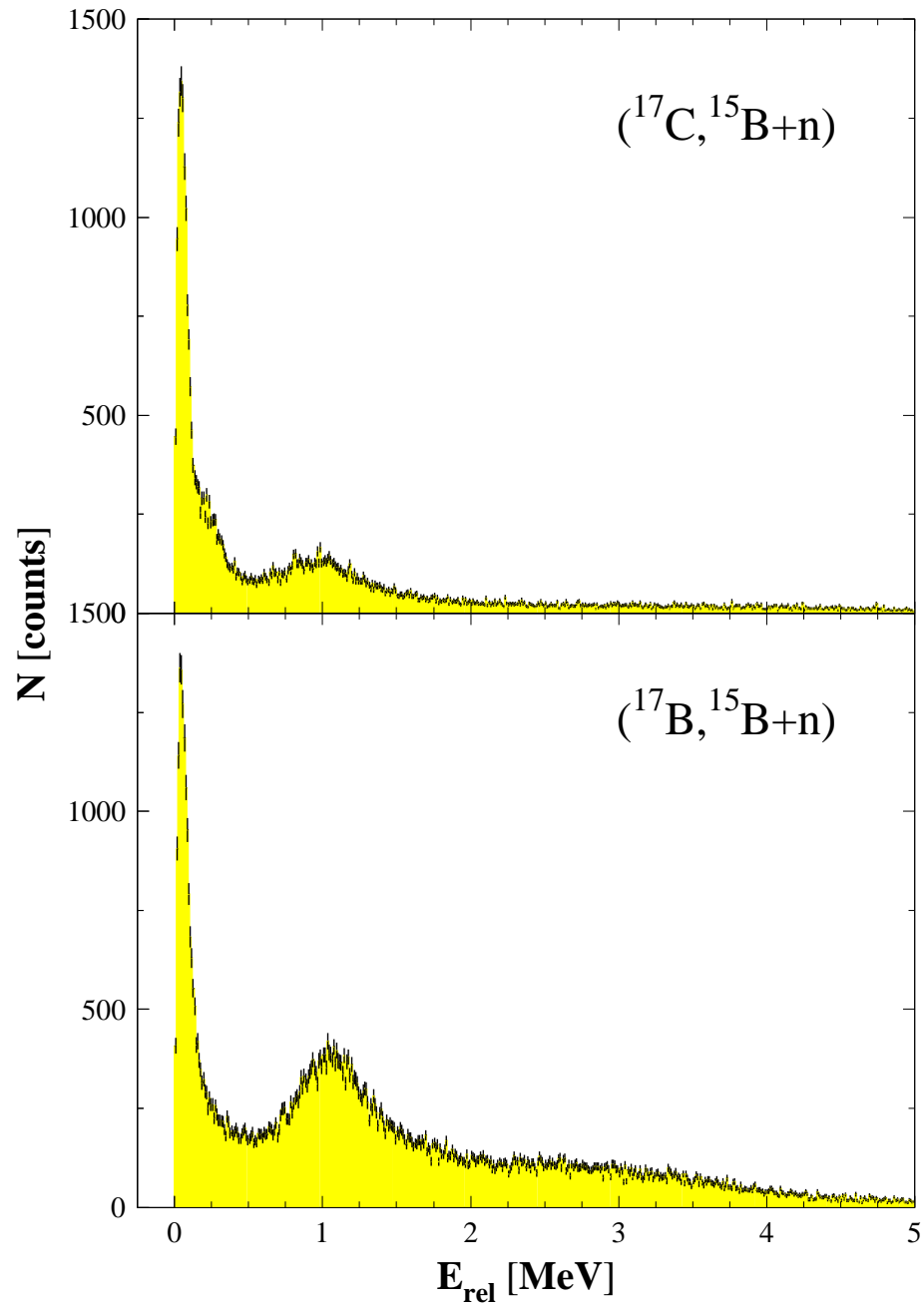


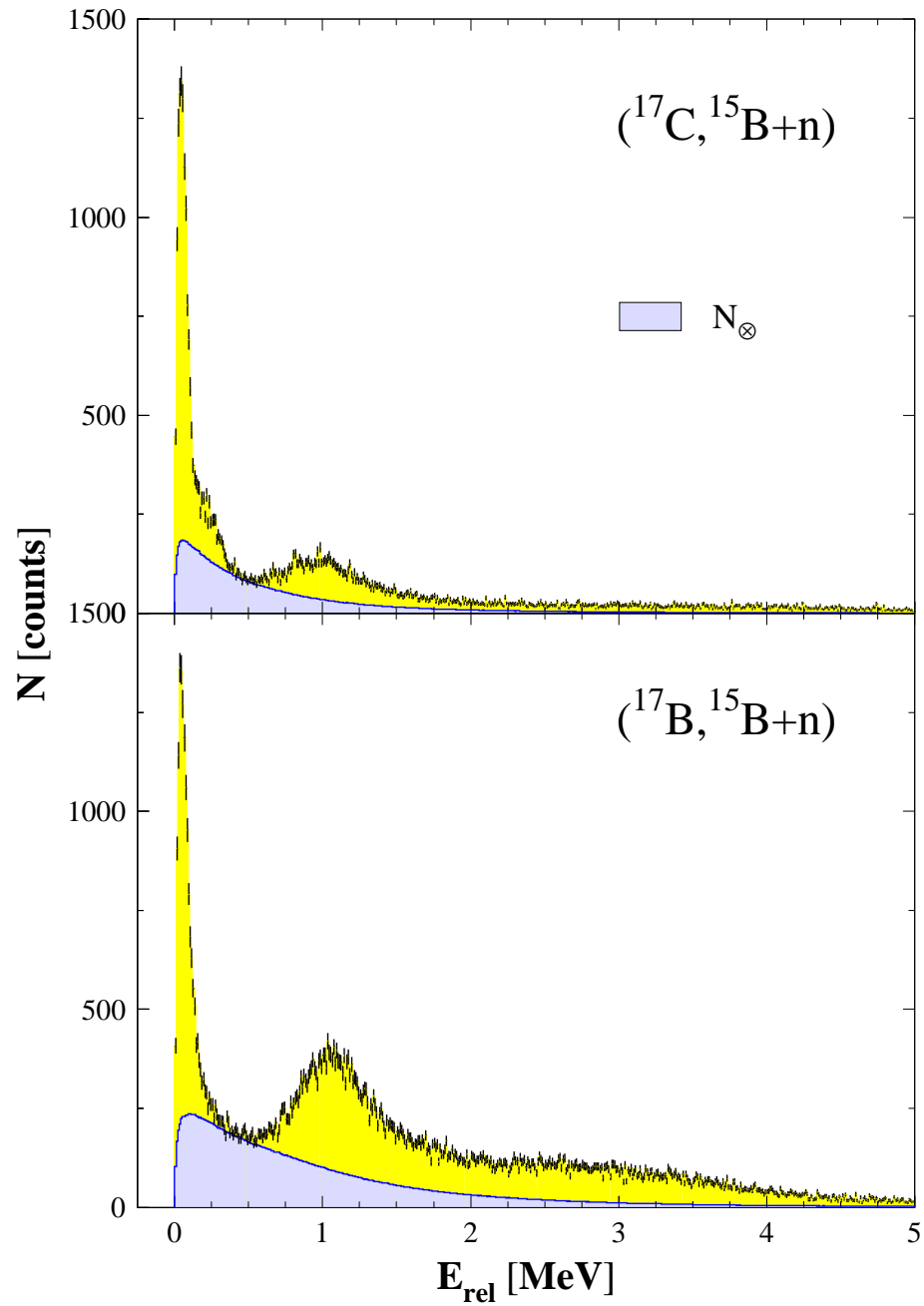
Kondo, PRC 71 (2005) 044611

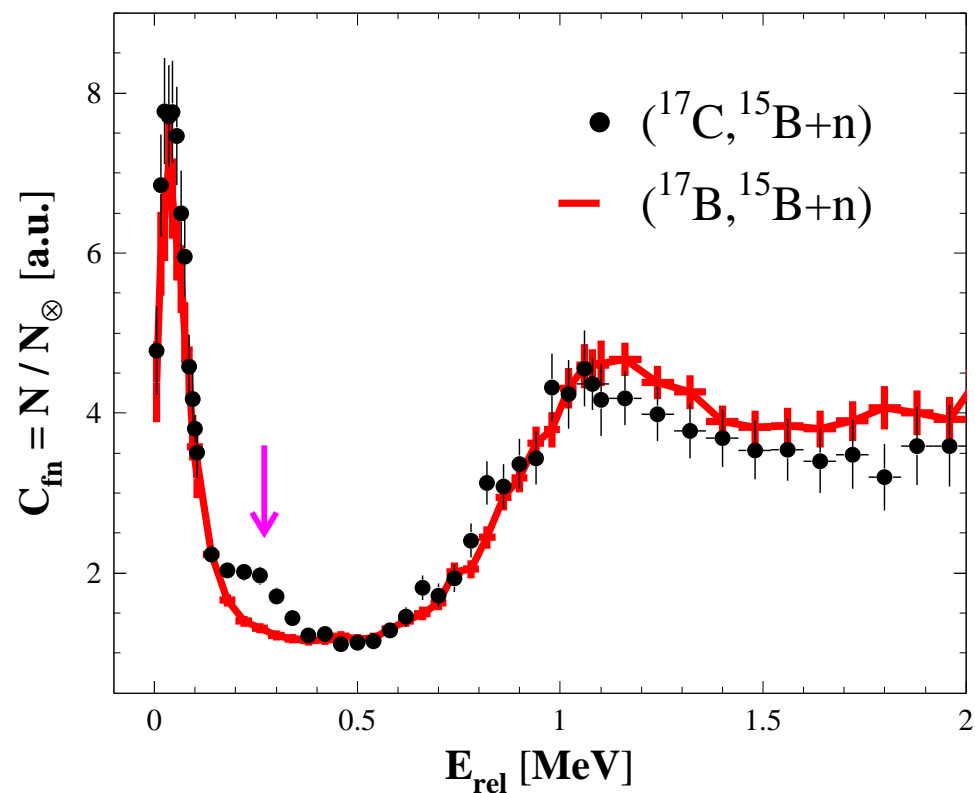
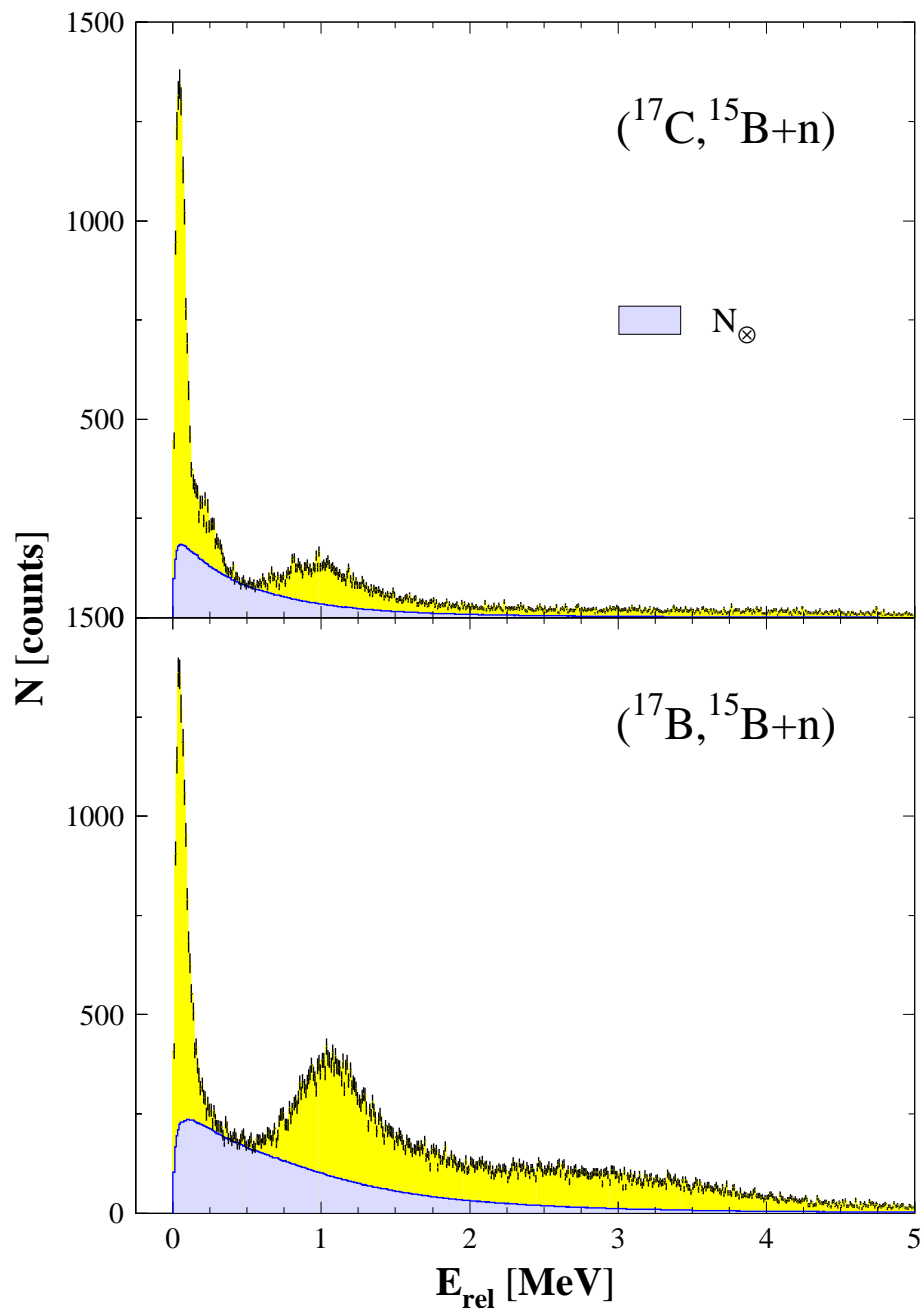
$\downarrow 1.41$
 $\downarrow 1.33$
 ^{15}B

- $M(^{16}\text{B}) \sim (M_{15}+m_n) + 40 \pm 20 \text{ keV} !$
- $^{16}\text{B}^* \equiv |^{15}\text{B}^* \otimes \nu\rangle$ excited states ...
- 1st at $\sim (1.1+1.3) \text{ MeV}$ Kalpakchieva ?

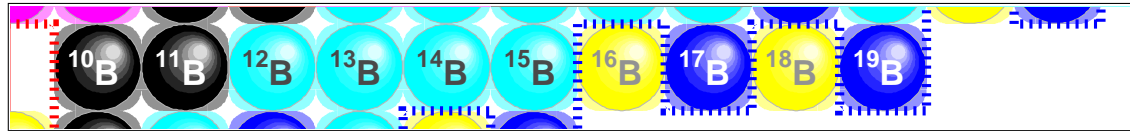




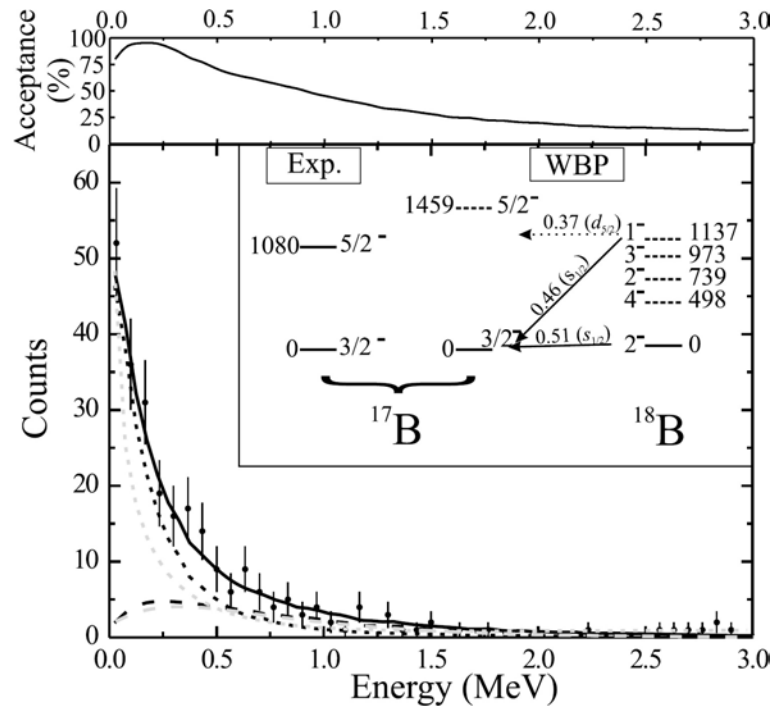




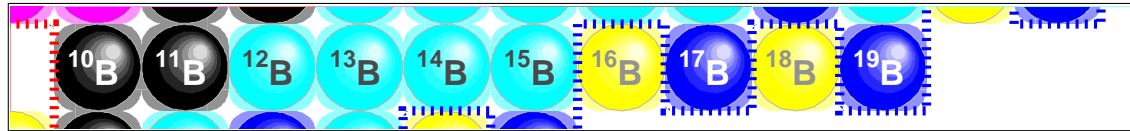
- same low-lying (ground) state
- lower '1st', no '2nd' excited state ...
- new structure at ~ 250 keV ?



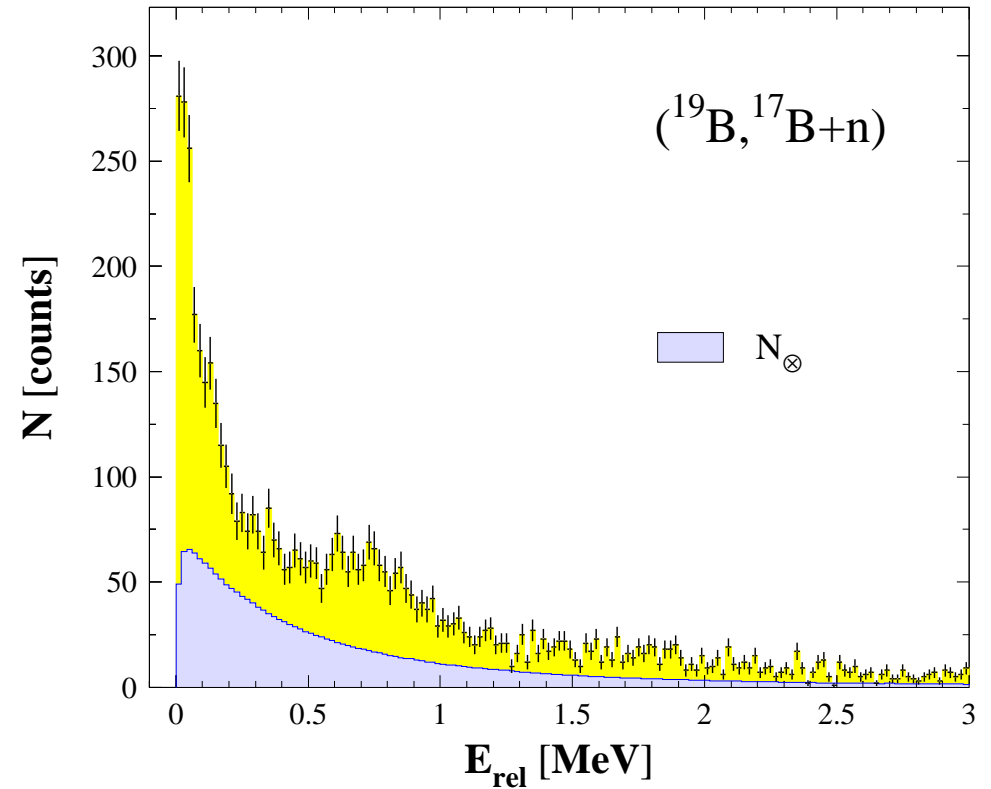
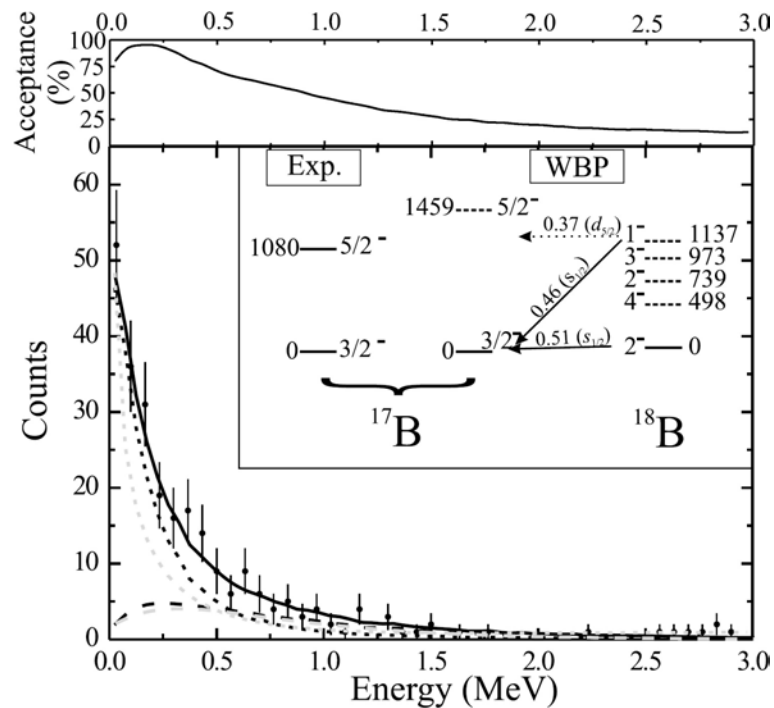
(^{19}C , $^{17}\text{B}+n$) : Spyrou, PLB 683 (2010) 129



- Virtual state with $a_s < -50$ fm :
 - arbitrary background
 - small acceptance
 - no γ detection

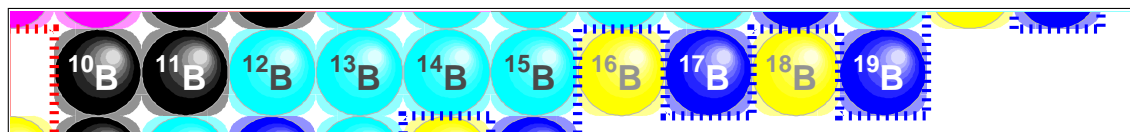


(^{19}C , $^{17}\text{B}+n$) : Spyrou, PLB 683 (2010) 129

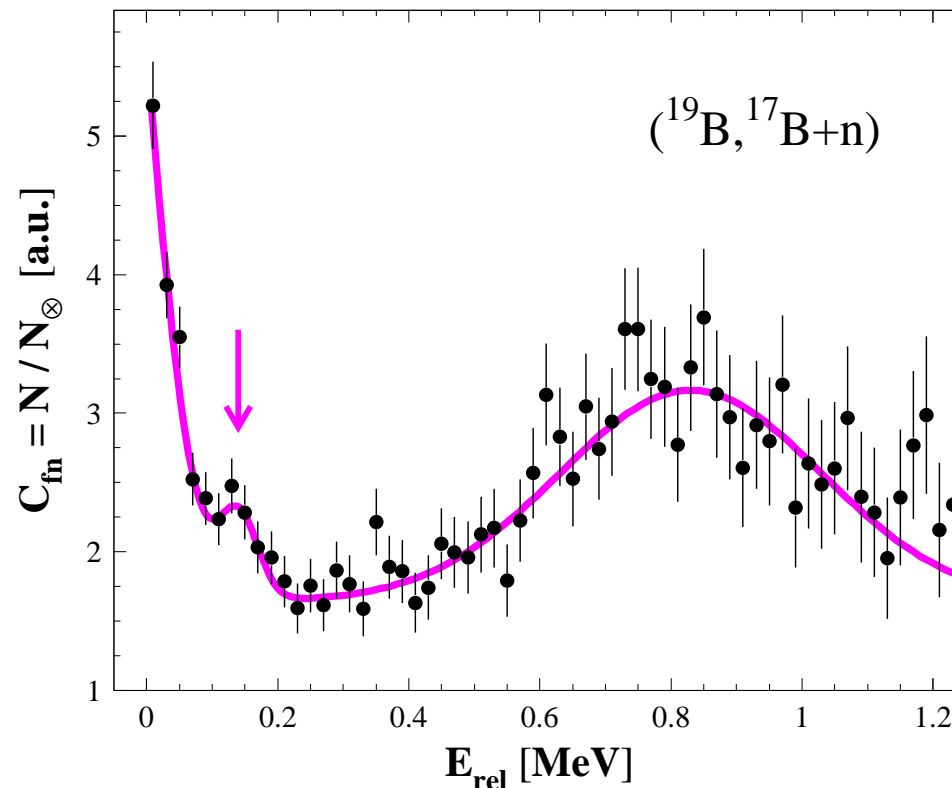
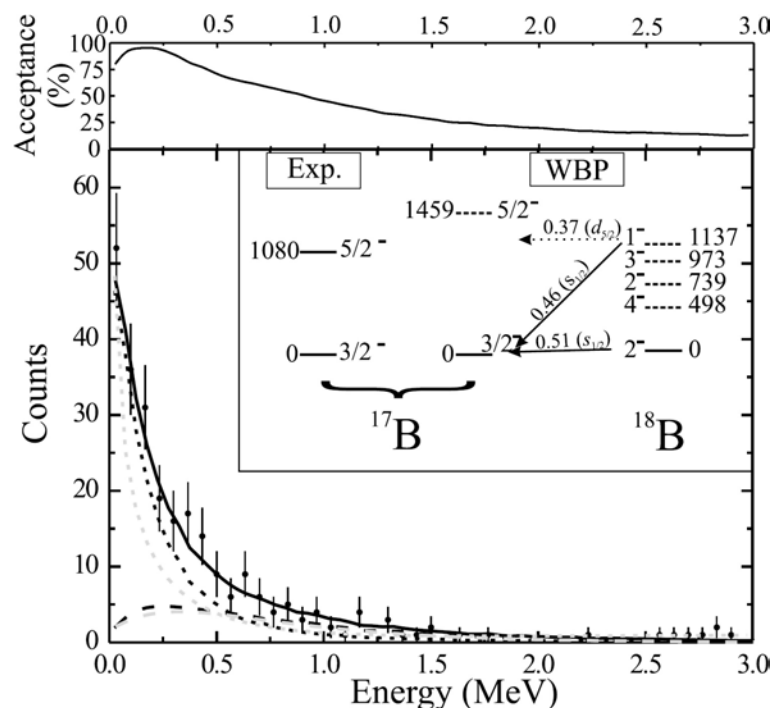


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- also other channels : different N_x
- threshold state(s) $\lesssim 150$ keV !
- very clear excited states ...

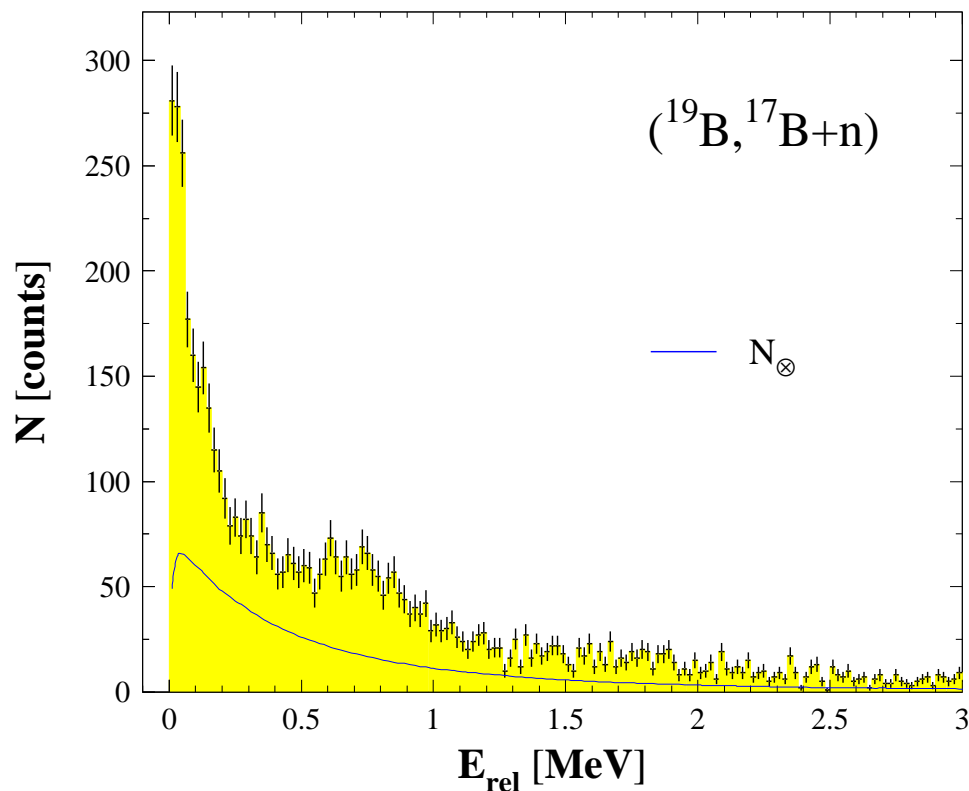


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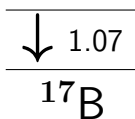


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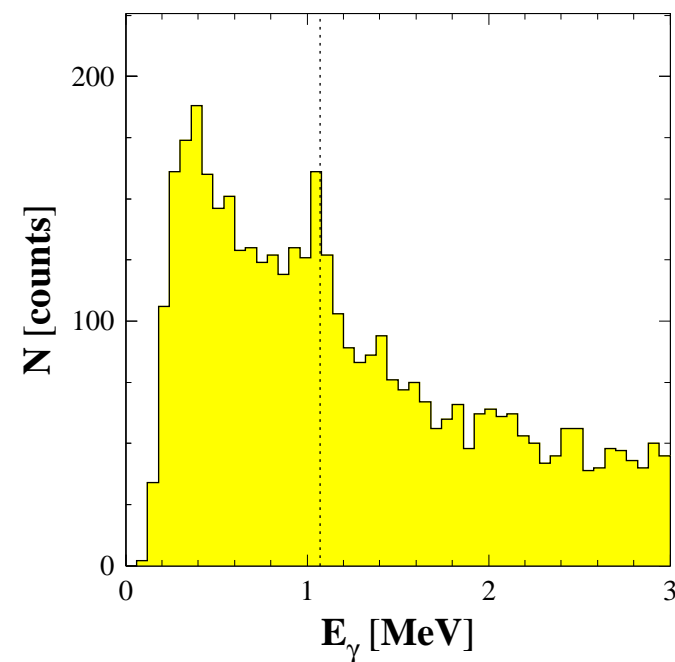
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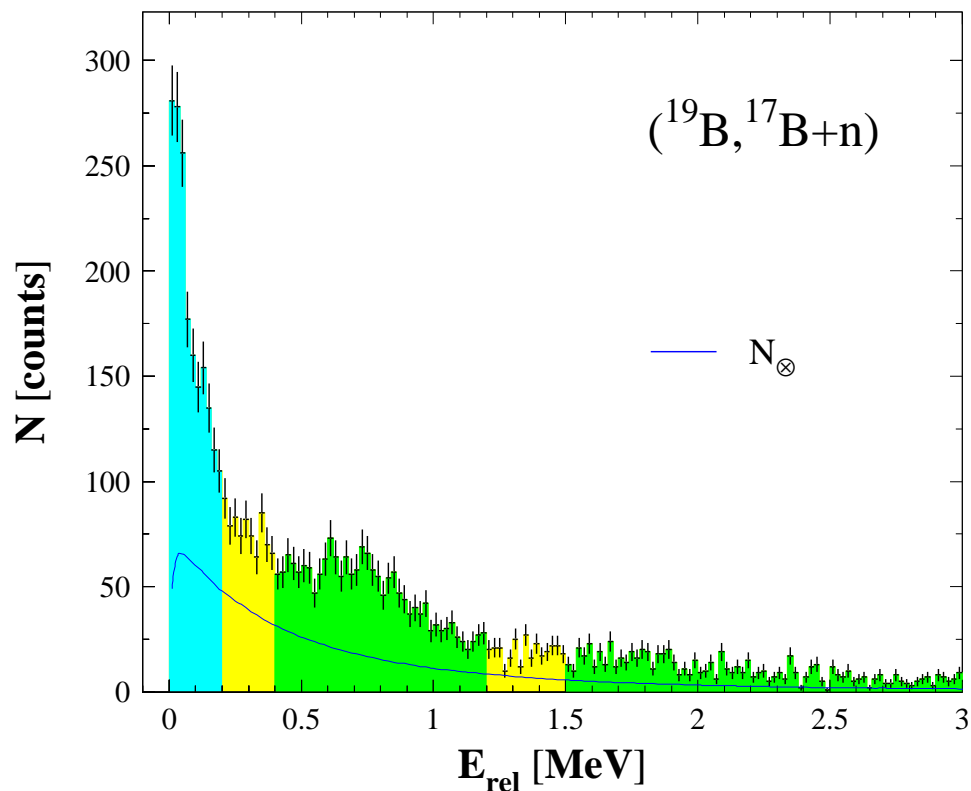
Kondo, PRC 71 (2005) 044611



DALI2 $\{^{17}\text{B}+n+\gamma\}$ events :



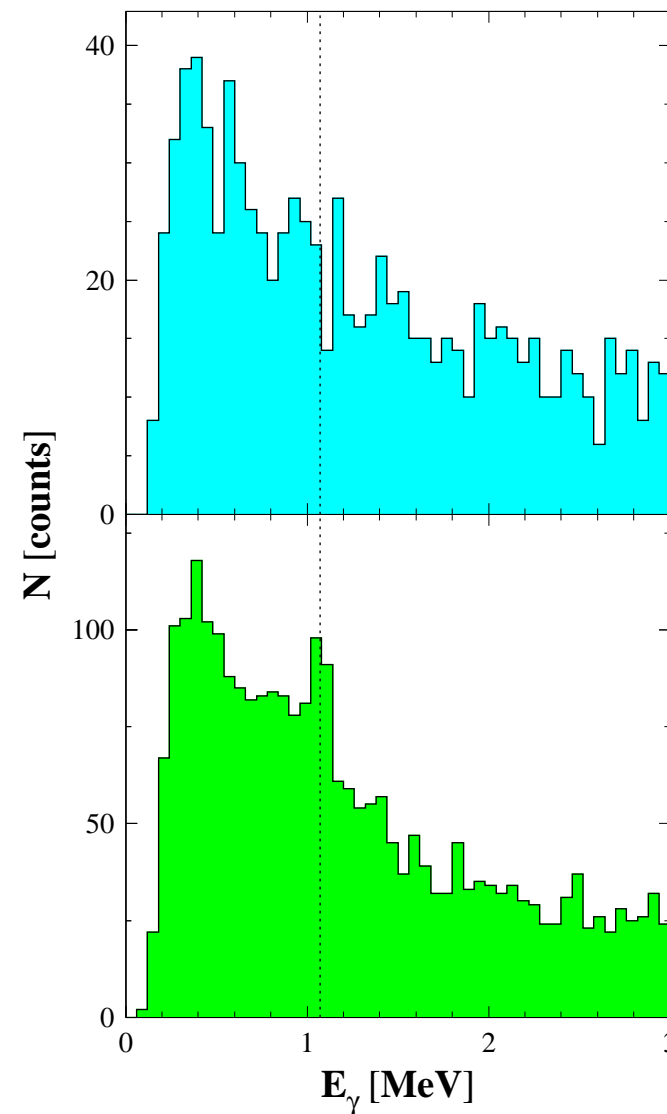
- some $^{17}\text{B}^*$ to 1st excited state !
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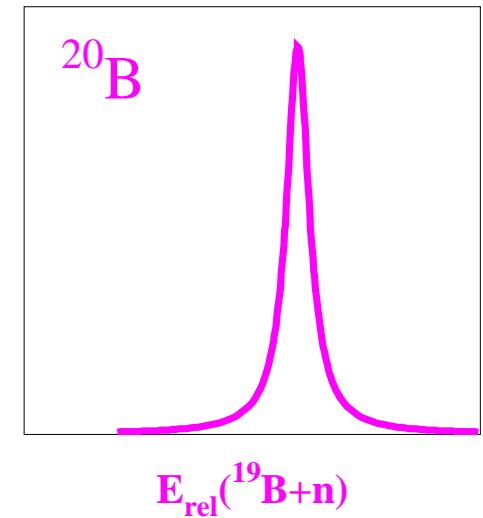
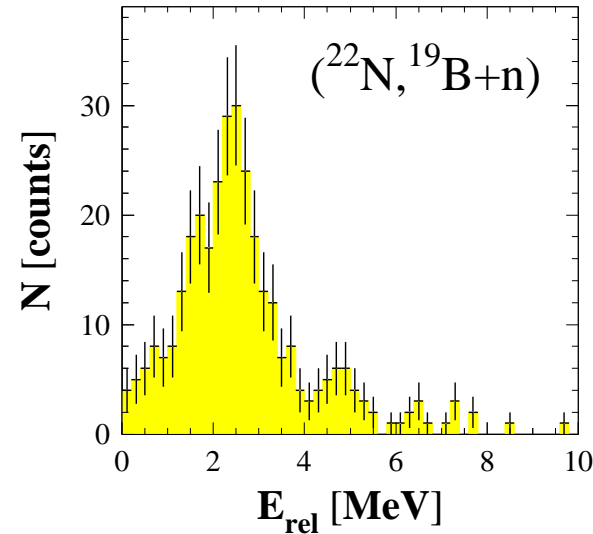
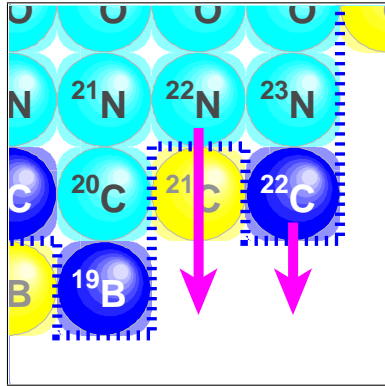


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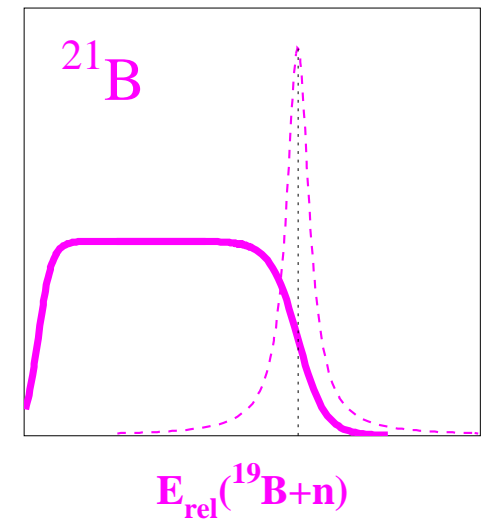
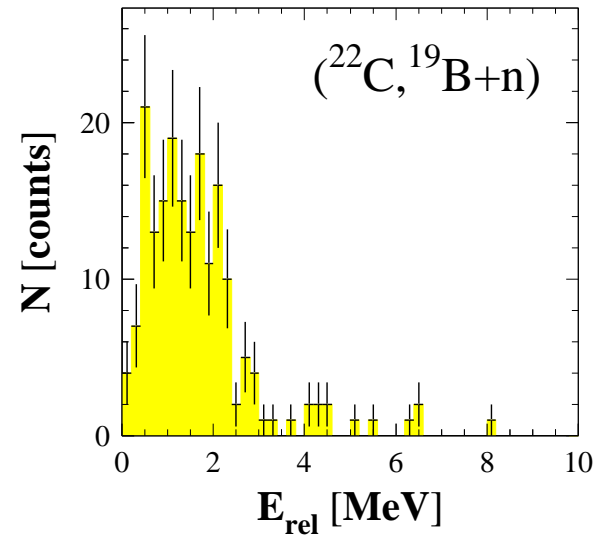
$\downarrow 1.07$
 ^{17}B

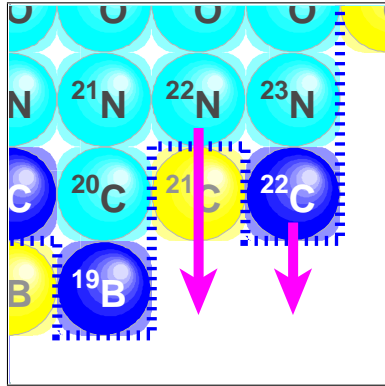
- precise characterization of g.s. !
- $^{18}\text{B}^* \equiv |^{17}\text{B}^* \otimes \nu\rangle$ excited states ...





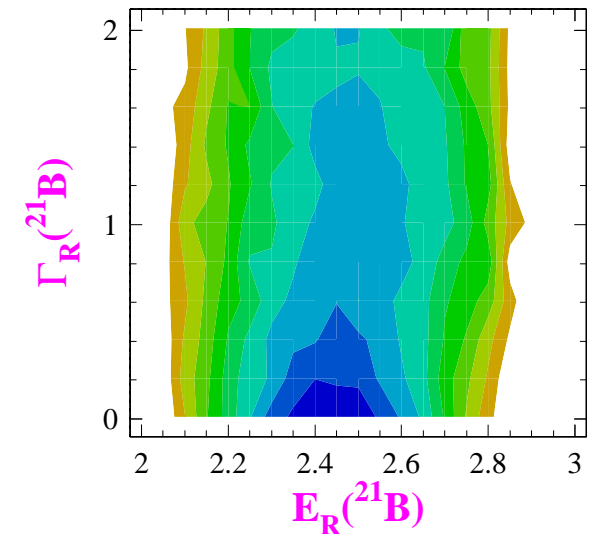
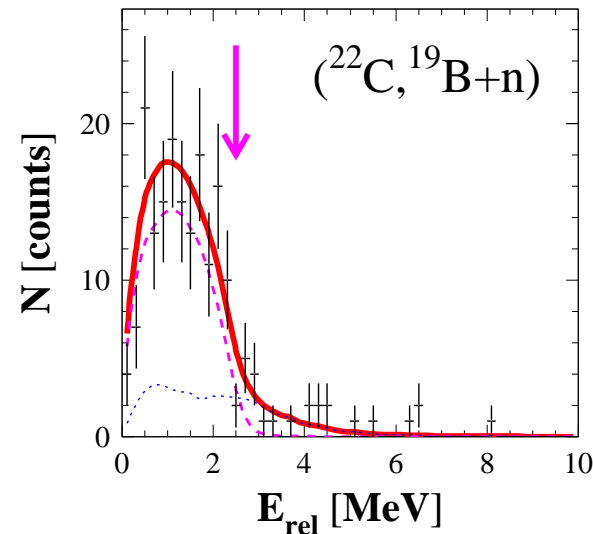
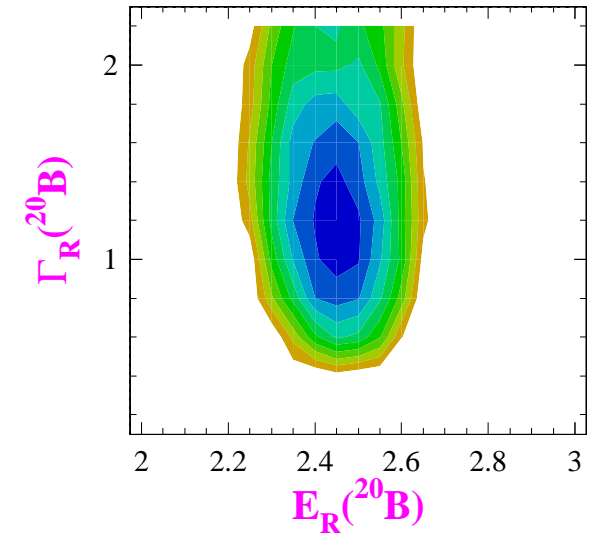
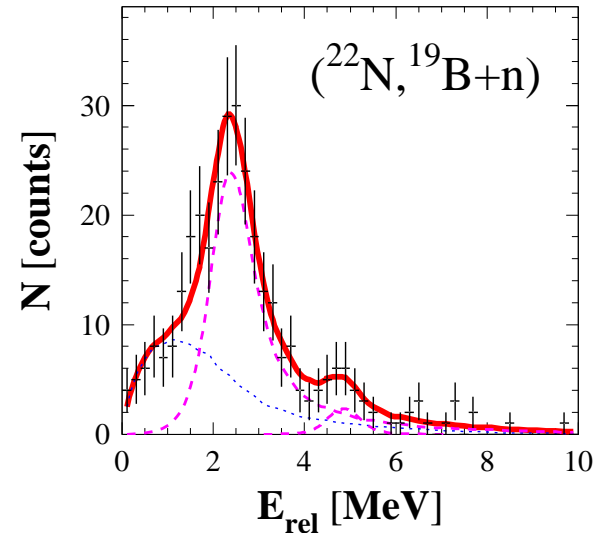
- $\{^{19}\text{B}+n\}$ events : \neq structures ...
 - $^{22}\text{N}(-2p)$: peak(s) $\sim 2(5)$ MeV ?
 - $^{22}\text{C}(-1pn)$: plateau $\sim 0-2$ MeV ...
 - \rightarrow 3-body $^{19}\text{B}+n(+n)$ decay ?
- **Fit** = $K[N_{\otimes}] + [(E_R, \Gamma_R)_{20/21}]_{\text{MC}}$
 - minimize χ^2 for $\{E, \Gamma, K\}$...





- $\{^{19}\text{B}+n\}$ events : \neq structures ...
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PRELIMINARY results \Rightarrow

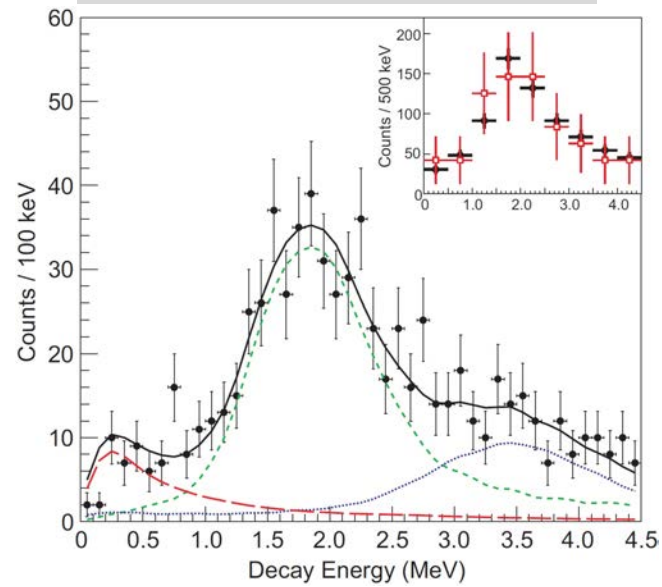


Boron 20 $E(\Gamma) \sim 2.4$ (1) MeV & $E^* \sim 4.8$ MeV

Boron 21 $E_{\text{gs}} \lesssim 2.5$ MeV ($^{19}\text{B}+n+n \dots$)

$d/C(^{14}\text{Be}, ^{14}\text{Be}+n)$:

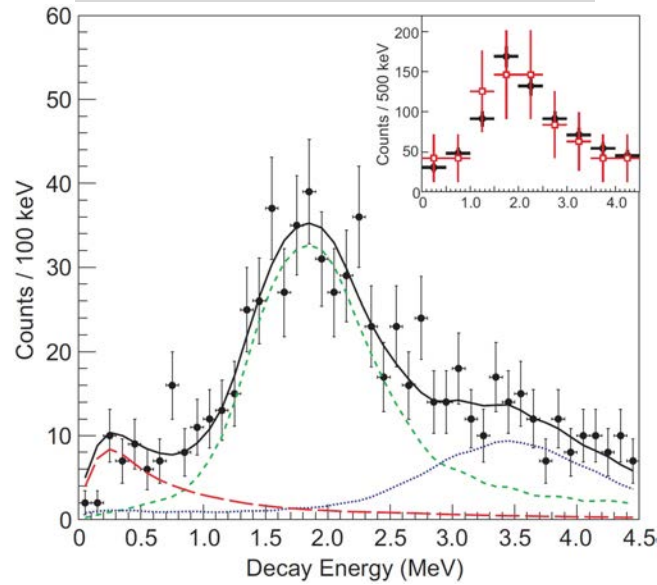
Snyder, PRC88 (2013) 031303R



- arbitrary background(s) !

$d/C(^{14}\text{Be}, ^{14}\text{Be}+n)$:

Snyder, PRC88 (2013) 031303R



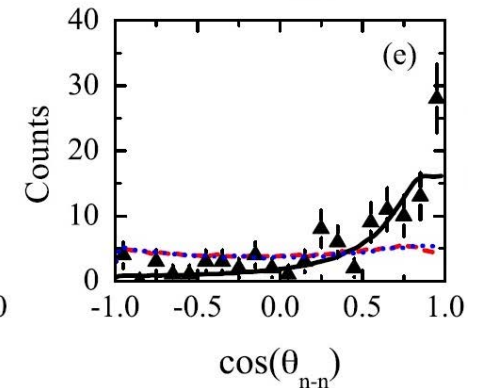
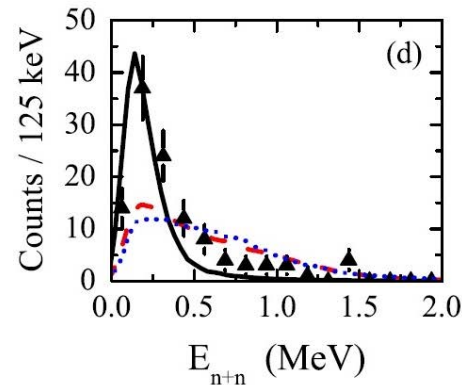
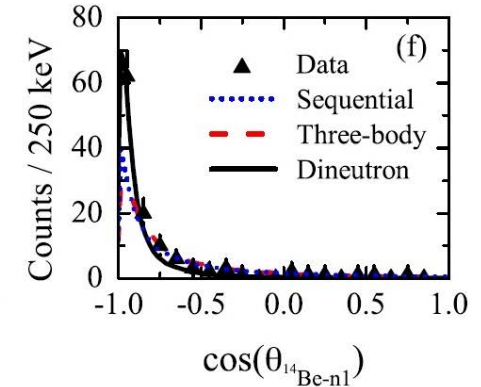
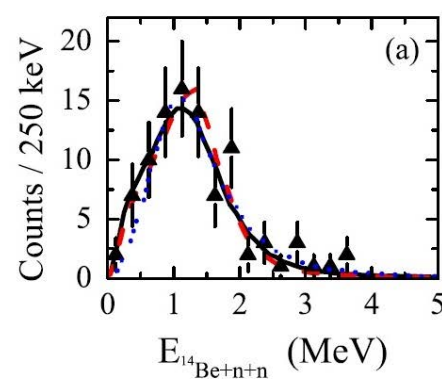
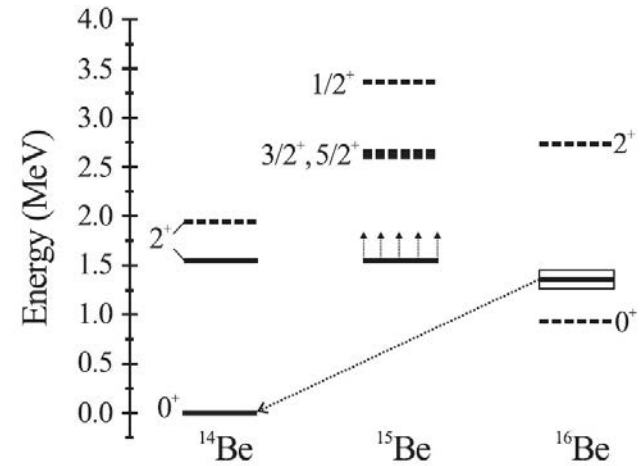
- arbitrary background(s) !

$(^{17}\text{B}, ^{14}\text{Be}+n+n)$:

Spyrou, PRL 108 (2012) 102501

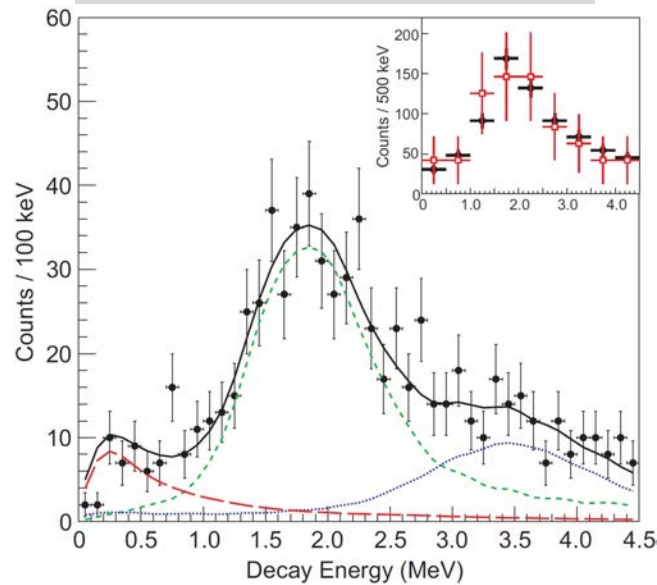
- "dineutron emission" from ^{16}Be ...
- no low-lying ^{15}Be ($S_n < 0$) ? \leftarrow
- neutron-neutron FSI

FMM, PRL 109 (2012) 239201



$d/C(^{14}\text{Be}, ^{14}\text{Be}+n)$:

Snyder, PRC88 (2013) 031303R



- arbitrary background(s) !

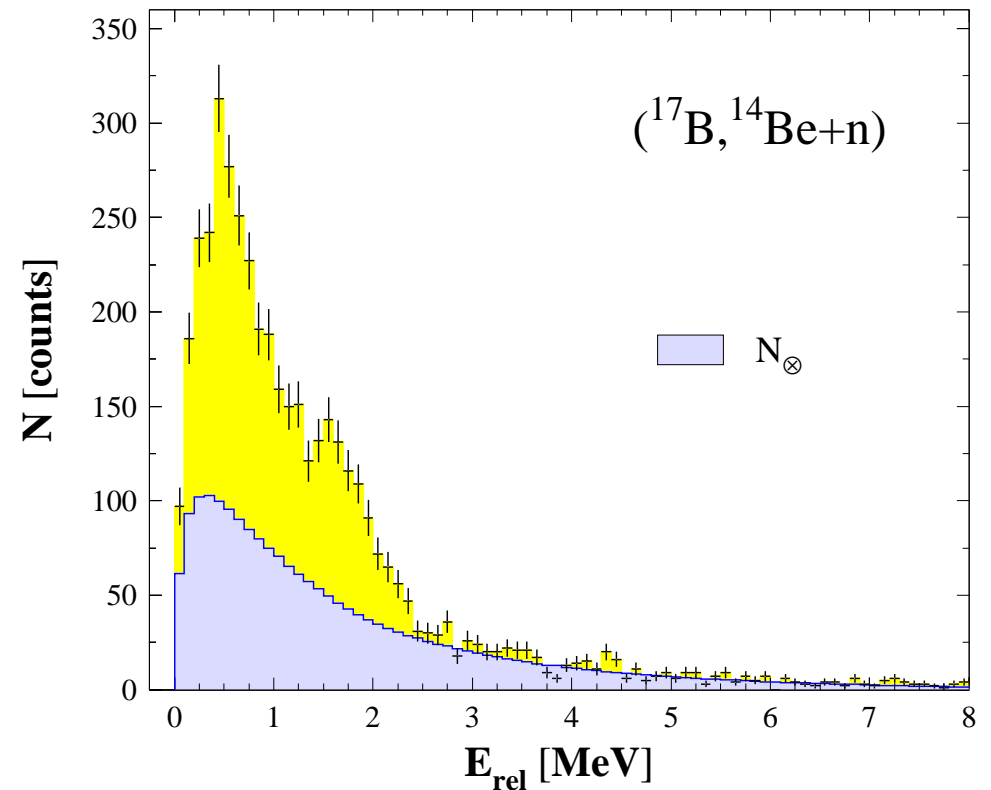
$(^{17}\text{B}, ^{14}\text{Be}+n+n)$:

Spyrou, PRL 108 (2012) 102501

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FMM, PRL 109 (2012) 239201

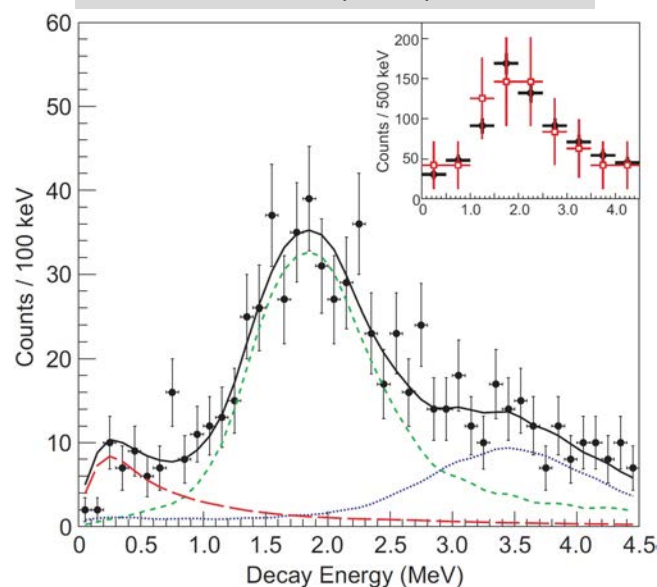
$(^{17}\text{B}, ^{14}\text{Be}+n)$:



- significant low-lying strength :
 - above non-resonant distribution

$d/C(^{14}\text{Be}, ^{14}\text{Be}+n)$:

Snyder, PRC88 (2013) 031303R



- arbitrary background(s) !

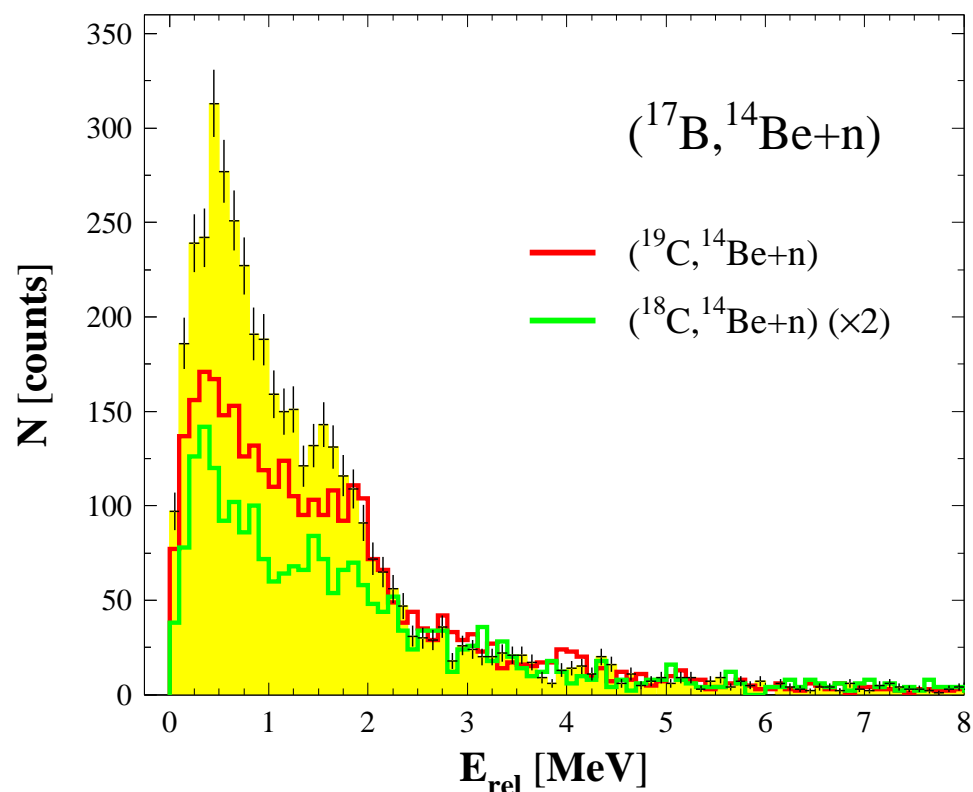
$(^{17}\text{B}, ^{14}\text{Be}+n+n)$:

Spyrou, PRL 108 (2012) 102501

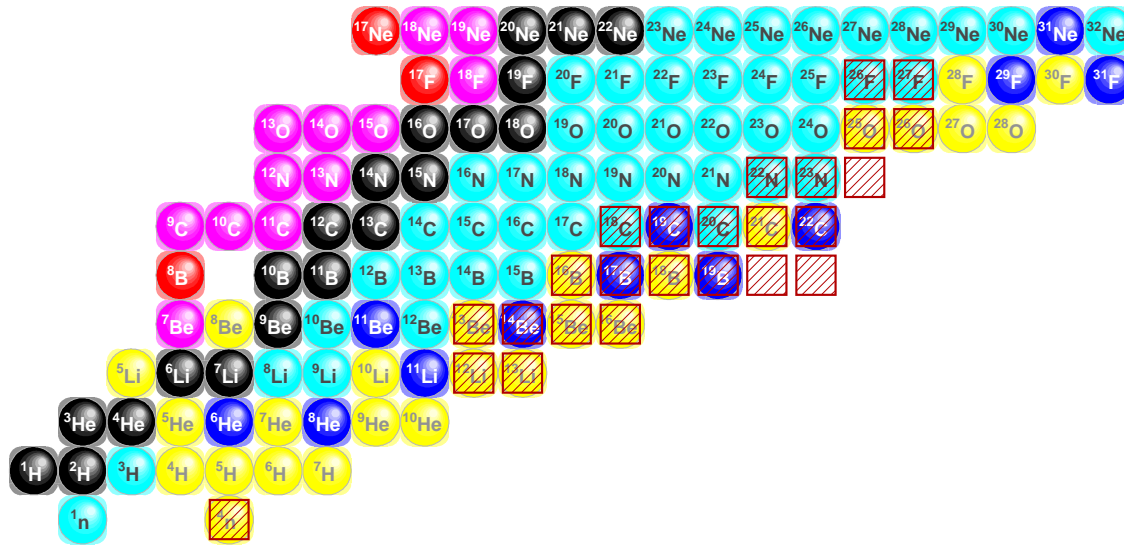
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FMM, PRL 109 (2012) 239201

$(^{17}\text{B}, ^{14}\text{Be}+n)$:

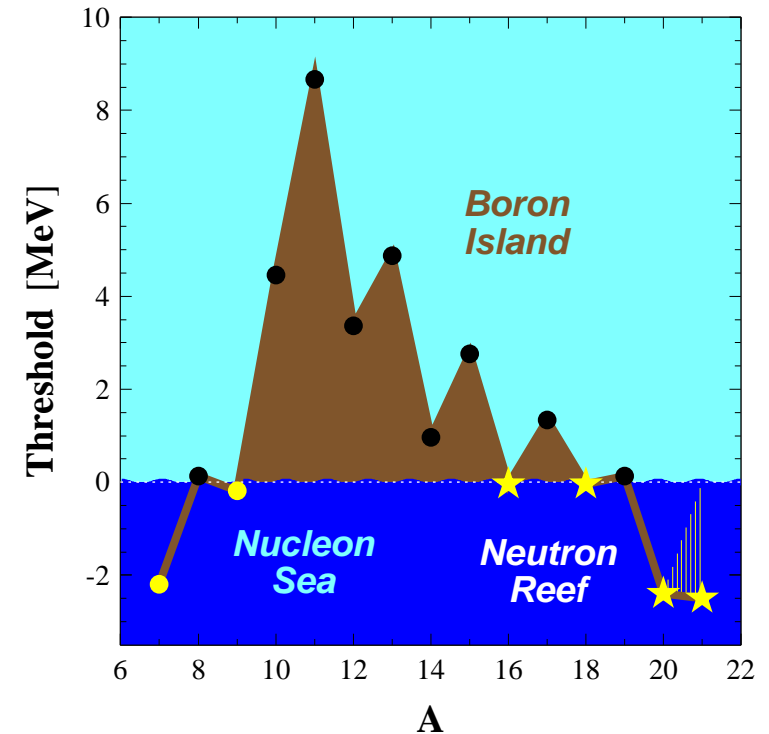


- significant low-lying strength :
 - above non-resonant distribution
 - also in other channels, though $N > 1$...
- influence of ^{16}Be decay ?
 - $\sim 1\text{k}$ $\{^{14}\text{Be}+n+n\}$, analysis ongoing ...



SAMURAI Commissioning & Day-1 Campaign :

- Structure of $^{18,19}\text{B}$, $^{21,22}\text{C}$ & $^{25,26}\text{O}$...
- Extended survey of the 'neutron reef' :
 - wide E_{rel} range + non-resonant N_{\otimes}
 - $^{16,18}\text{B}$ improved mass & new excited states (+ γ)
 - $^{20,21}\text{B}$ measured for the first time !
 - other systems in progress ($^{15,16}\text{Be}$, $^{12,13}\text{Li}$...)
- Even further : { **NeuLAND** + NEBULA } ('15/16) & **NEBULA-Plus** ('17)



- Expand NEBULA **multi-neutron** capabilities :

- France : LPC-Caen, IRFU, IPN-Orsay
- Japan : TITECH, RIKEN
- +90 bars, comm. & 1st exps. early 2017
- suggested configuration :

⇒ $\epsilon(4n)$ enhanced $\sim \times 16$!

