

7th International and Interdisciplinary Workshop on the Dynamics of Critically Stable Quantum Few-Body Systems

Critical Stability 2014

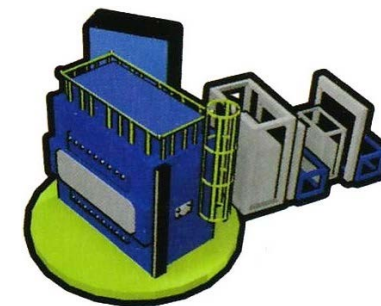
October 12-17, 2014, Santos (Brazil)

The Far Side of the Neutron Dripline at RIKEN

F. Miguel Marqués



S. Leblond¹, J. Gibelin¹, N.A. Orr¹, S. Ogoshi², R. Minakata², Y. Kondo², T. Nakamura², R. Tanaka², N.L. Achouri¹, T. Aumann³, H. Baba⁴, F. Delaunay¹, P. Doornenbal⁴, N. Fukuda⁴, J.W. Hwang⁵, N. Inabe⁴, T. Isobe⁴, D. Kameda⁴, D. Kanno², S. Kim⁵, N. Kobayashi², T. Kobayashi⁶, T. Kubo⁴, J. Lee⁴, T. Motobayashi⁴, D. Murai⁷, T. Murakami⁸, K. Muto⁶, N. Nakatsuka⁸, T. Nakashima², A. Navin⁹, S. Nishi², H. Otsu⁴, H. Sato⁴, Y. Satou⁵, Y. Shimizu⁴, H. Suzuki⁴, K. Takahashi⁶, H. Takeda⁴, S. Takeuchi⁴, Y. Togano¹⁰, A.G. Tuff¹¹, M. Vandebrouck¹², K. Yoneda⁴



¹LPC-Caen, ²Tokyo Institute of Technology, ³Technische Universität Darmstadt, ⁴RIKEN, ⁵Seoul National University, ⁶Tohoku University, ⁷Rikkyo University, ⁸Kyoto University, ⁹GANIL, ¹⁰GANIL, ¹¹University of York, ¹²IPN-Orsay

I. The neutron dripline :

- Exotic nuclei & physics
- Secondary n-rich beams
- The RIBF at RIKEN
- Knockout experiments

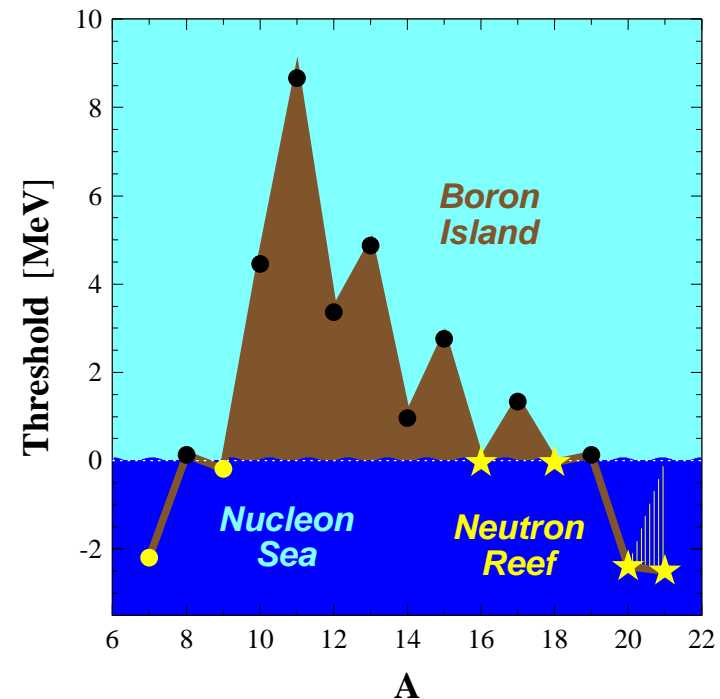


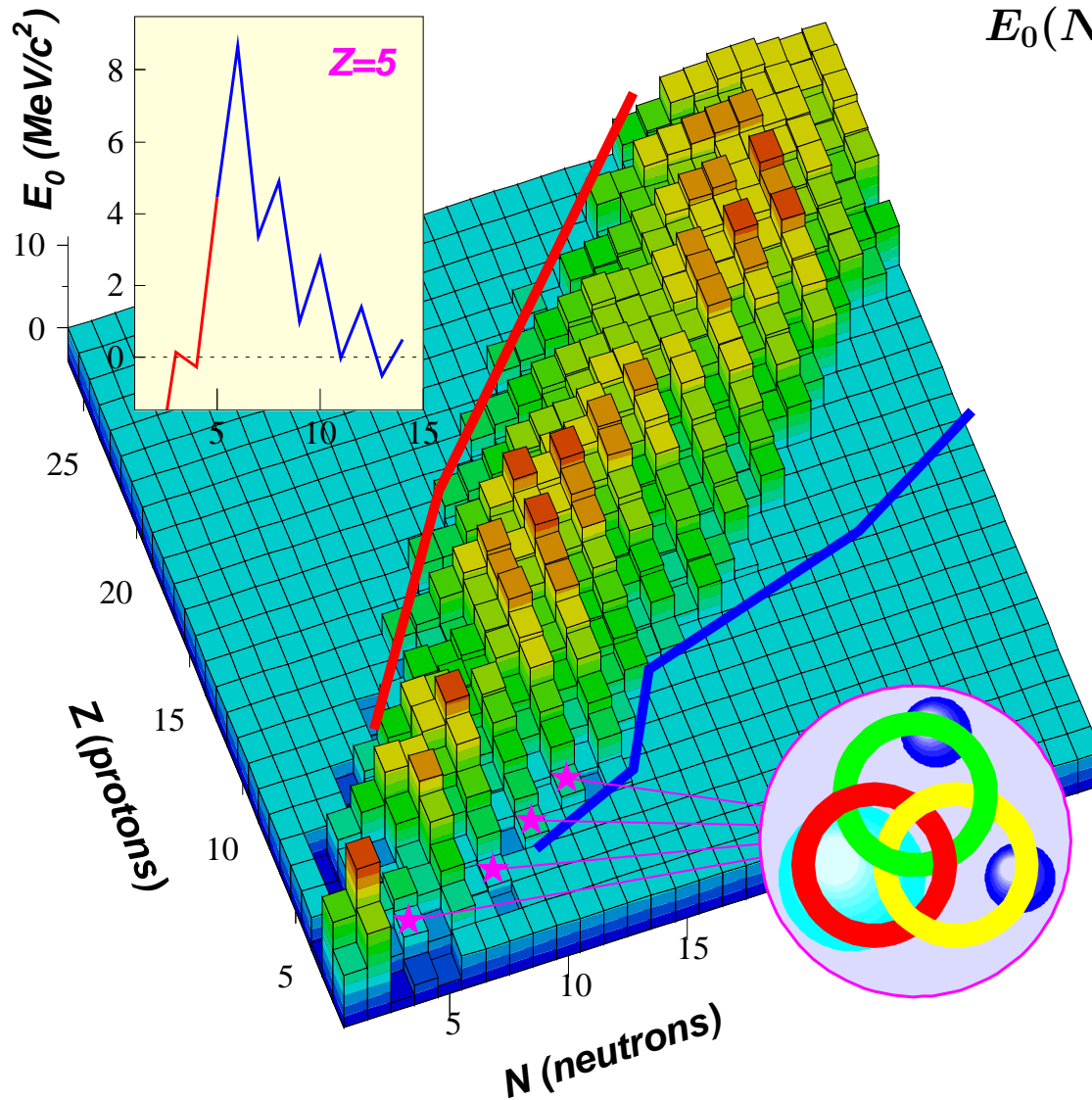
II. SAMURAI Day-1 campaign :

- SAMURAI & NEBULA
- Some (1n) examples : $^{16,18,20,21}\text{B}$
- The Beryllium 'puzzle'

III. Beyond two neutrons :

- NEBULA+ (& NeuLAND)
- Towards ^{28}O & ^4n
- Next steps around the dripline

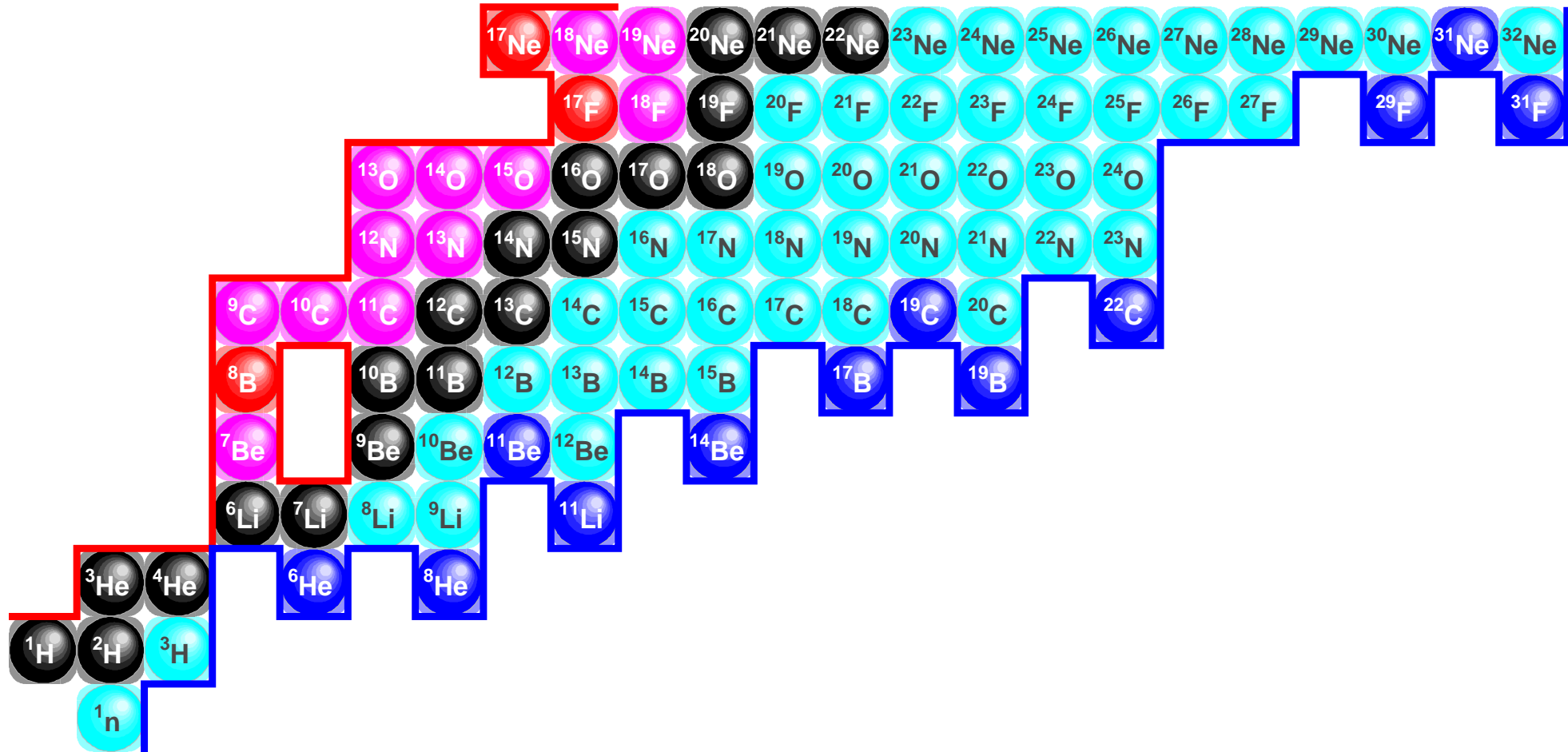




$$E_0(N, Z) = \min \left[\sum M(n_i, z_i) \right] - M(N, Z)$$

- The **neutron** dripline :
 - access to extreme (N, Z) !!!
 - limited to 'very light' nuclei
 - few-body correlations :
 - how deep is the **far side** ?



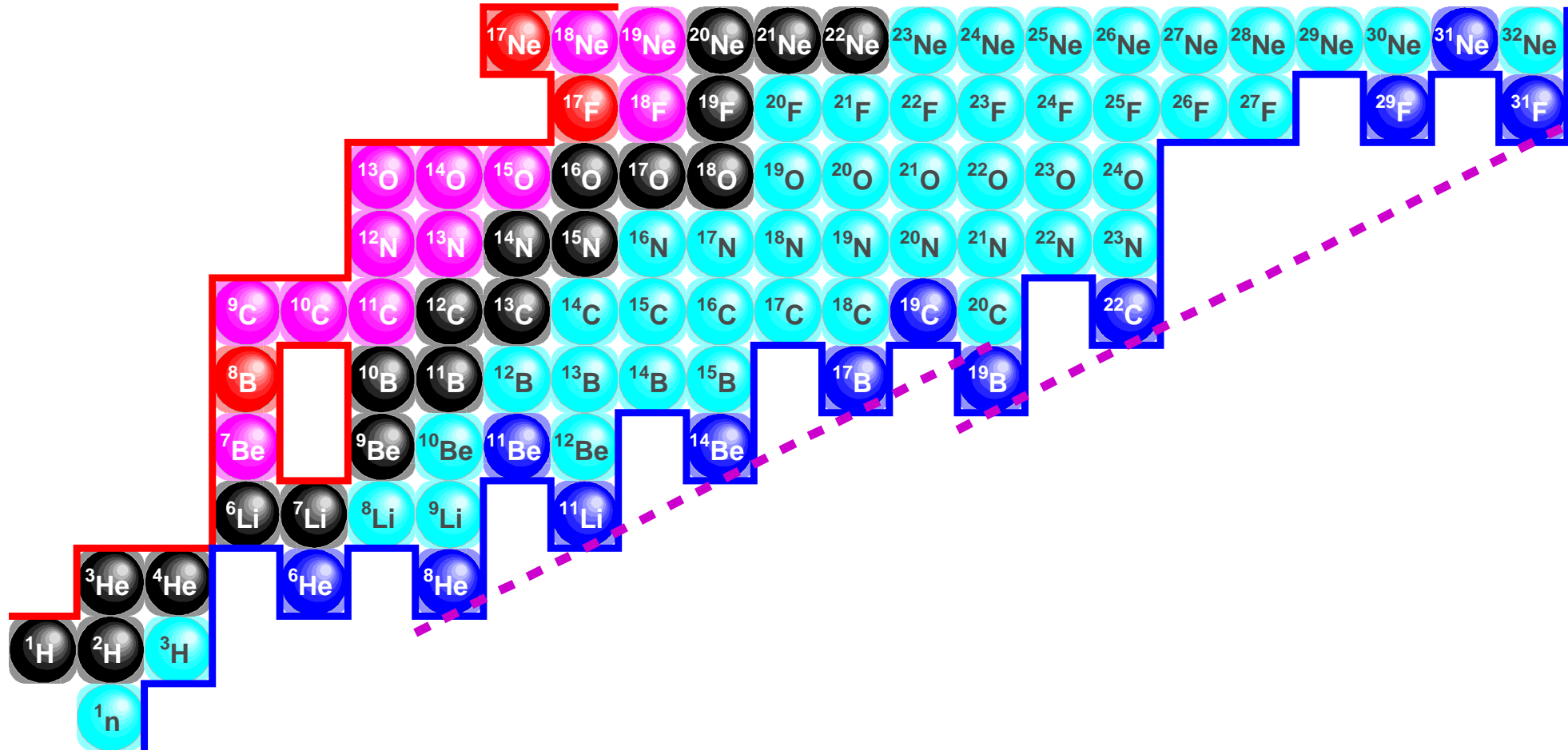


- Fundamental questions :

⇒ where are the limits ?

⇒ why are there limits ?

⇒ how do nuclei 'disappear' ?

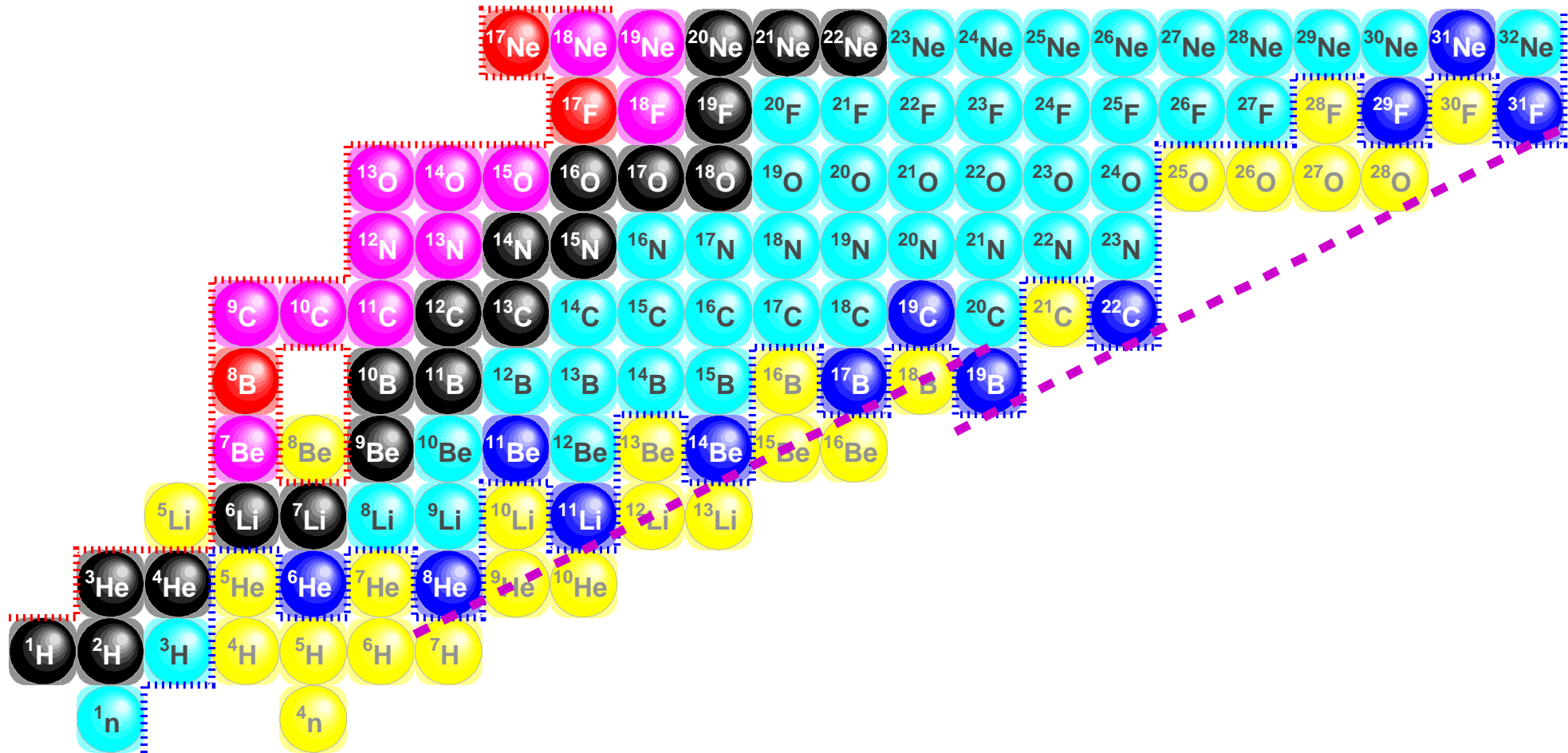


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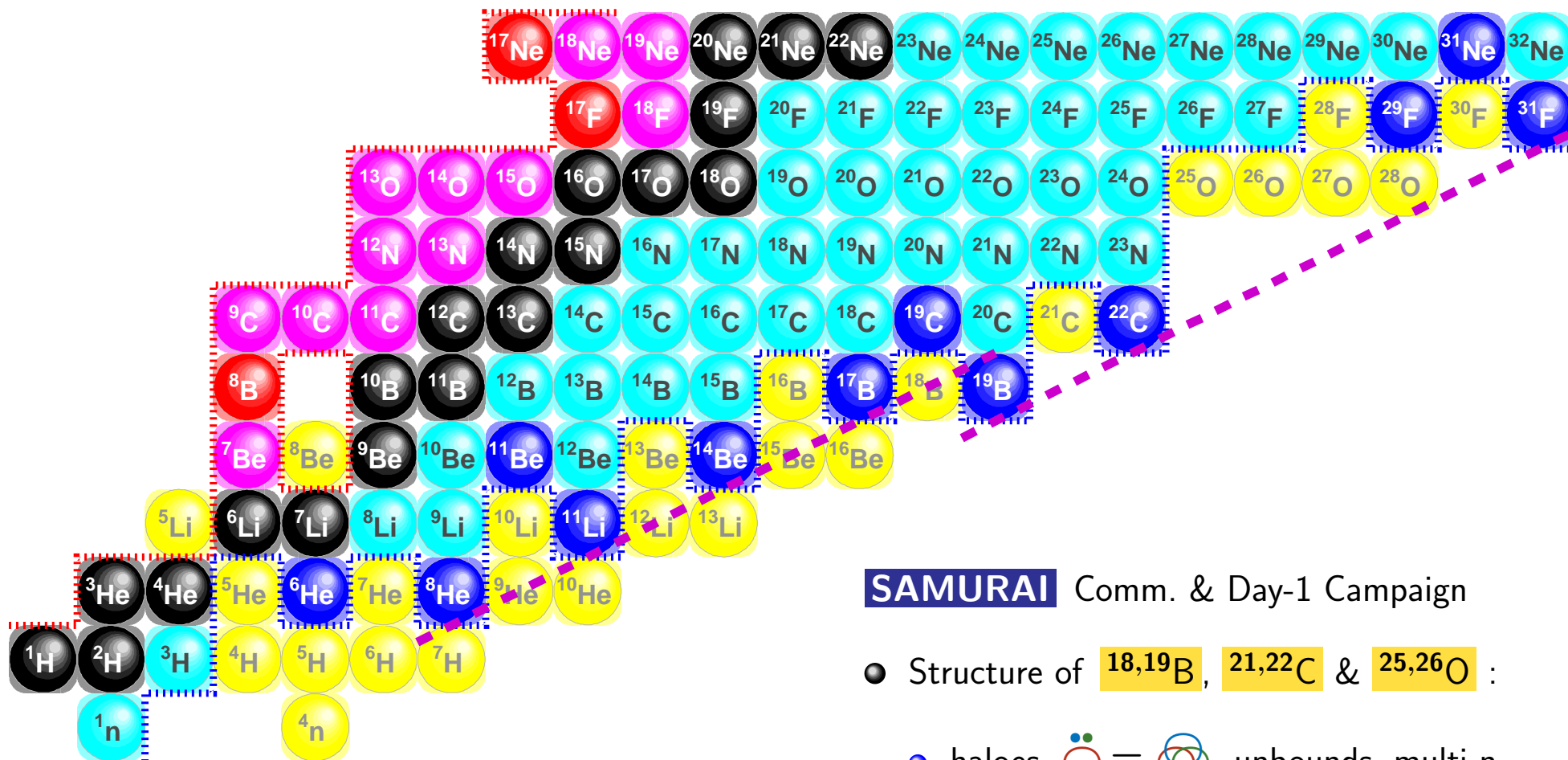
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SAMURAI Comm. & Day-1 Campaign

- 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 :

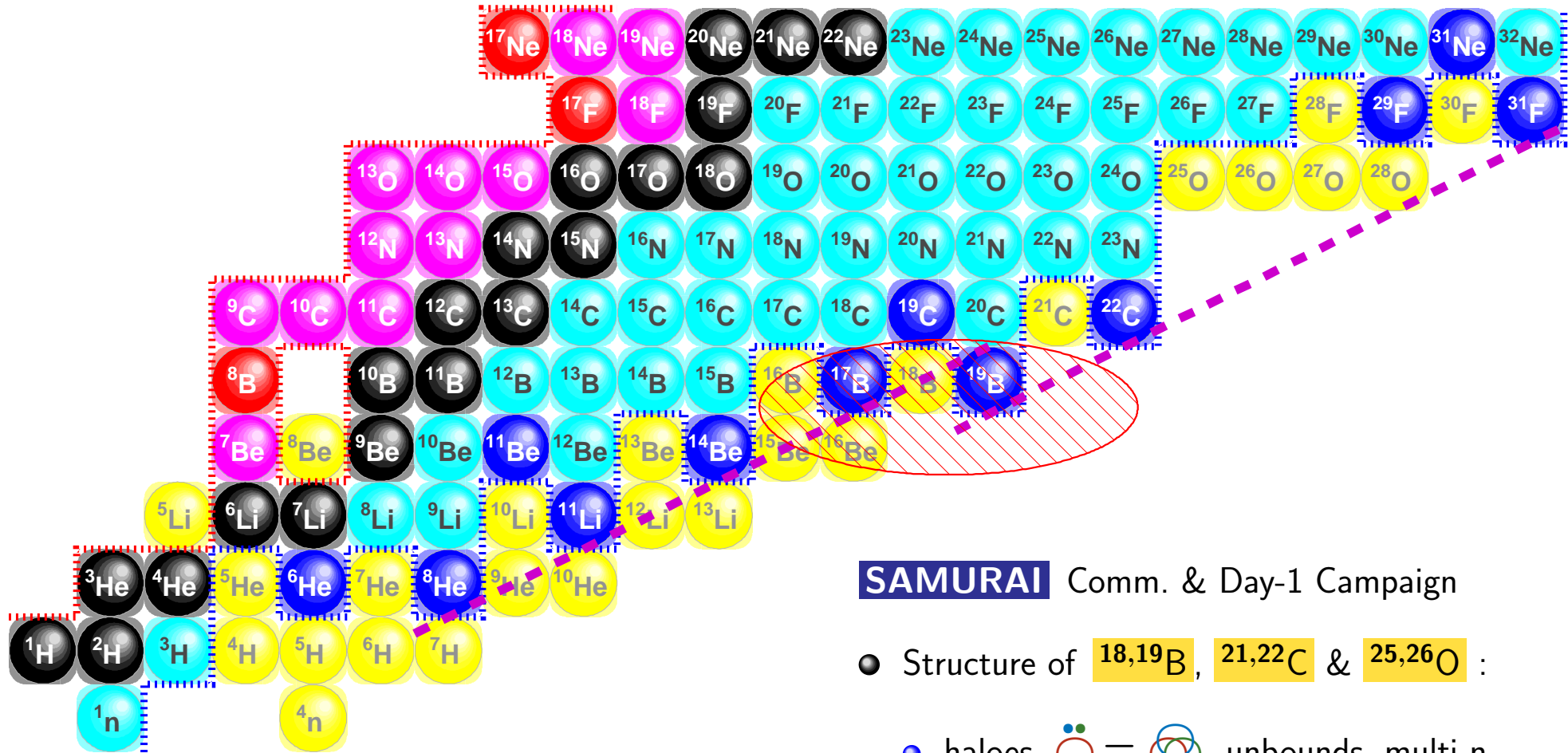
- $^{12}\text{Li} \leftarrow (25) \rightarrow ^{26}\text{O}$ in almost 1 shot !

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● $^{12}\text{Li} \leftarrow (25) \rightarrow ^{26}\text{O}$ in almost 1 shot !

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

● Fundamental questions :

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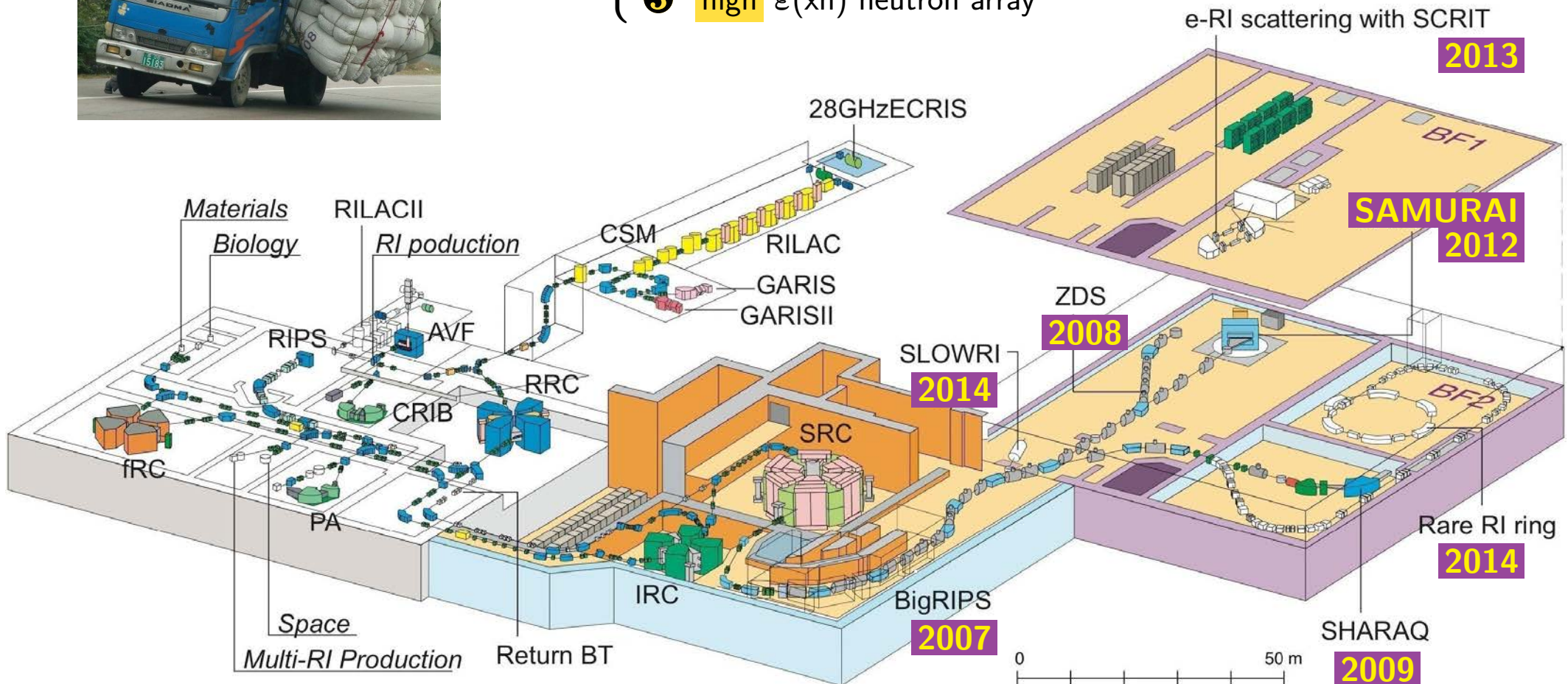
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Access to very high A/Z !!!

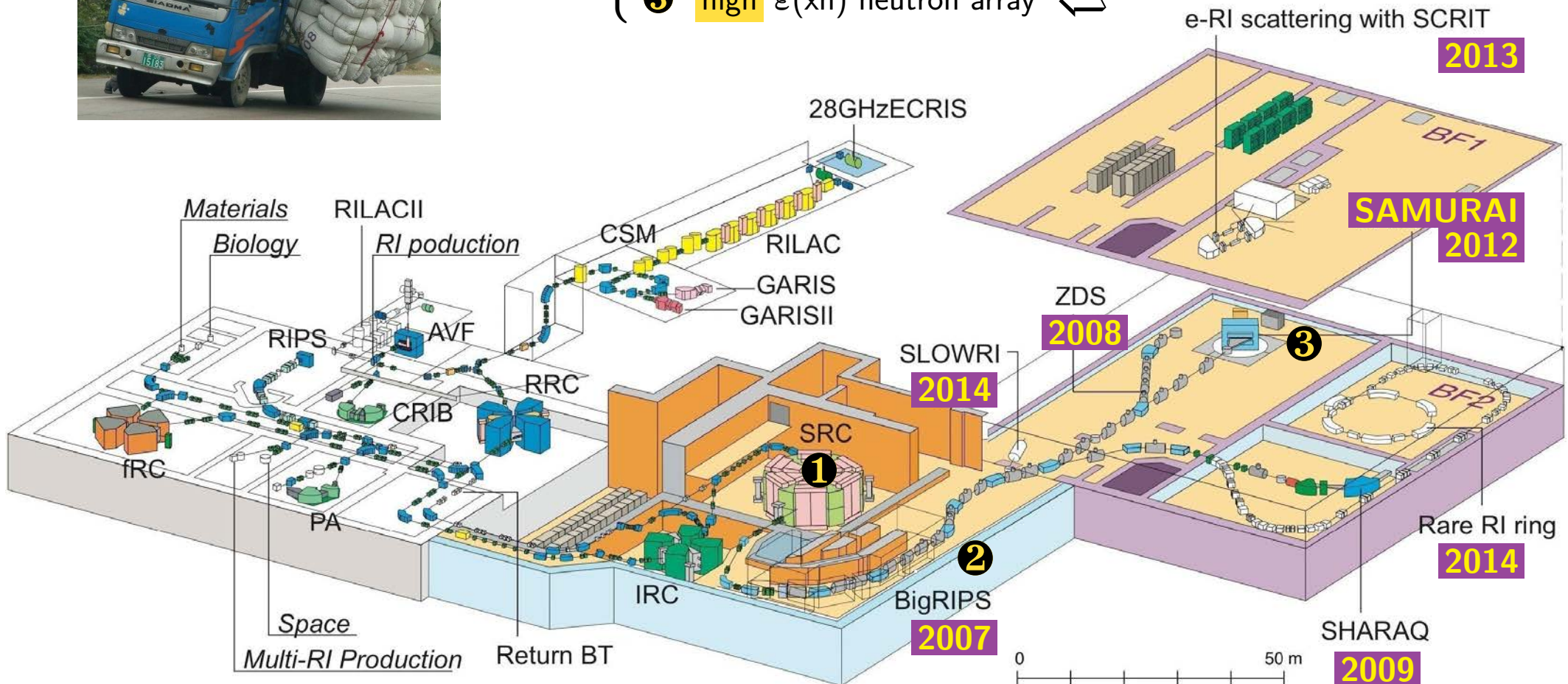
- ⇒
- ① intense primary beams
 - ② strong B fields (A/Z)
 - ③ high $\epsilon(xn)$ neutron array

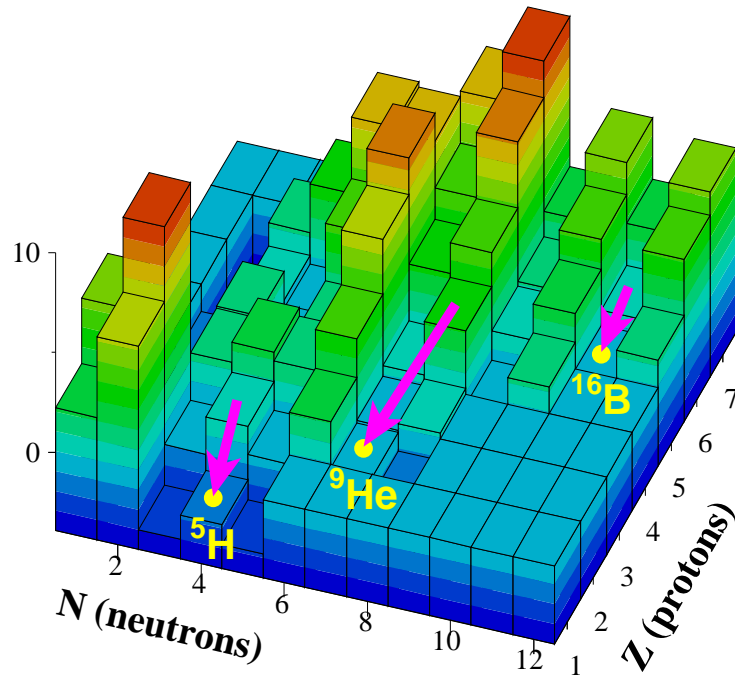




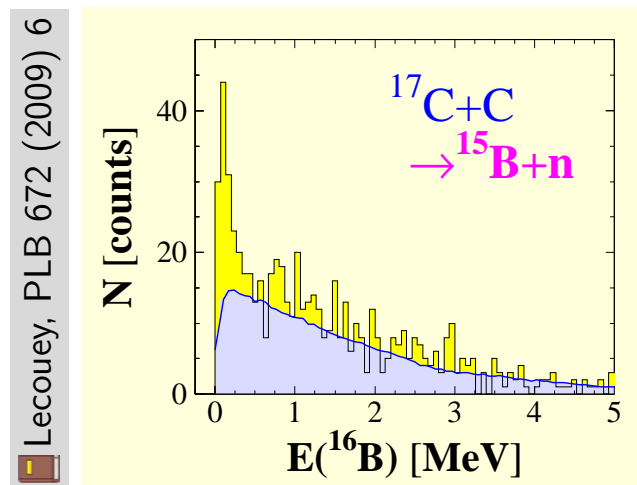
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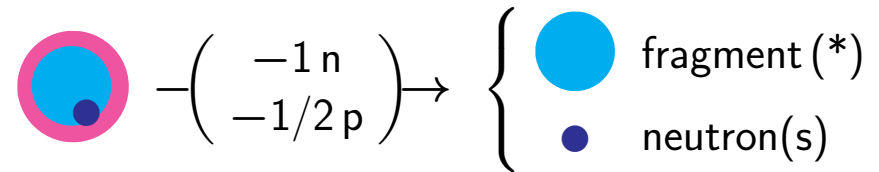




^{17}B (\otimes ^{15}B -n-n) :



● Knock out from the dripline :



● fragment (γ) + neutrons \rightarrow E_{rel}

● direct, fast reactions :

● J^π selectivity $\rightarrow |A \otimes \nu\rangle \subset$

● non-resonant distribution :

● event mixing $\rightarrow N_{\otimes}$

FMM, PLB 476 (2000) 219

● Breakup : wider range of J^π ...

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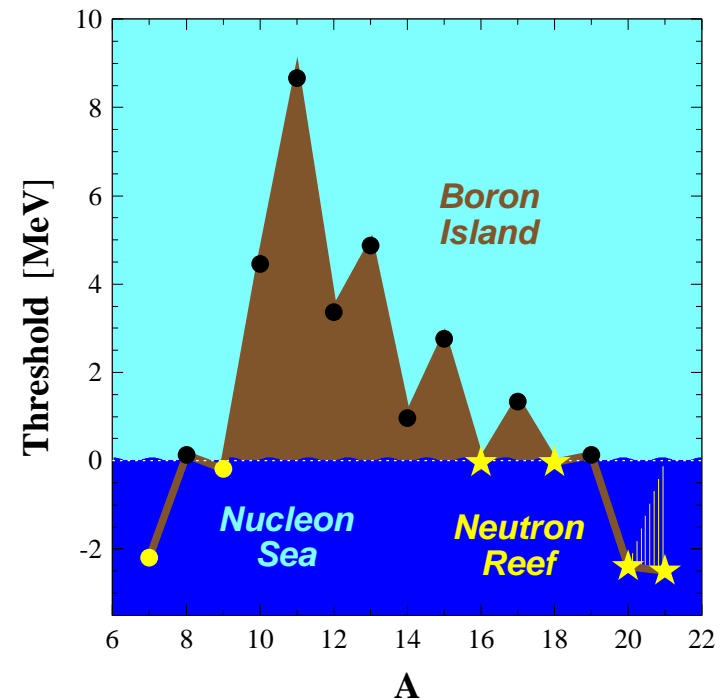


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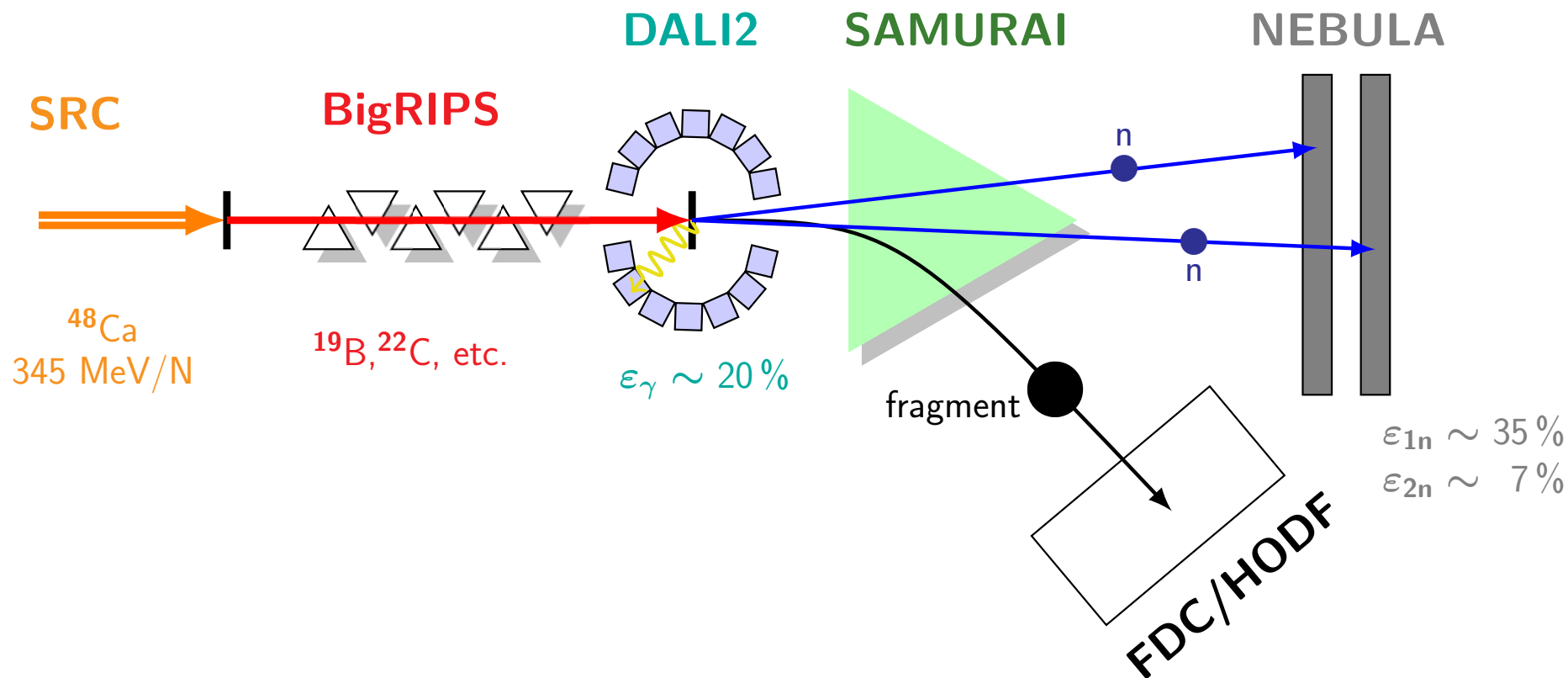
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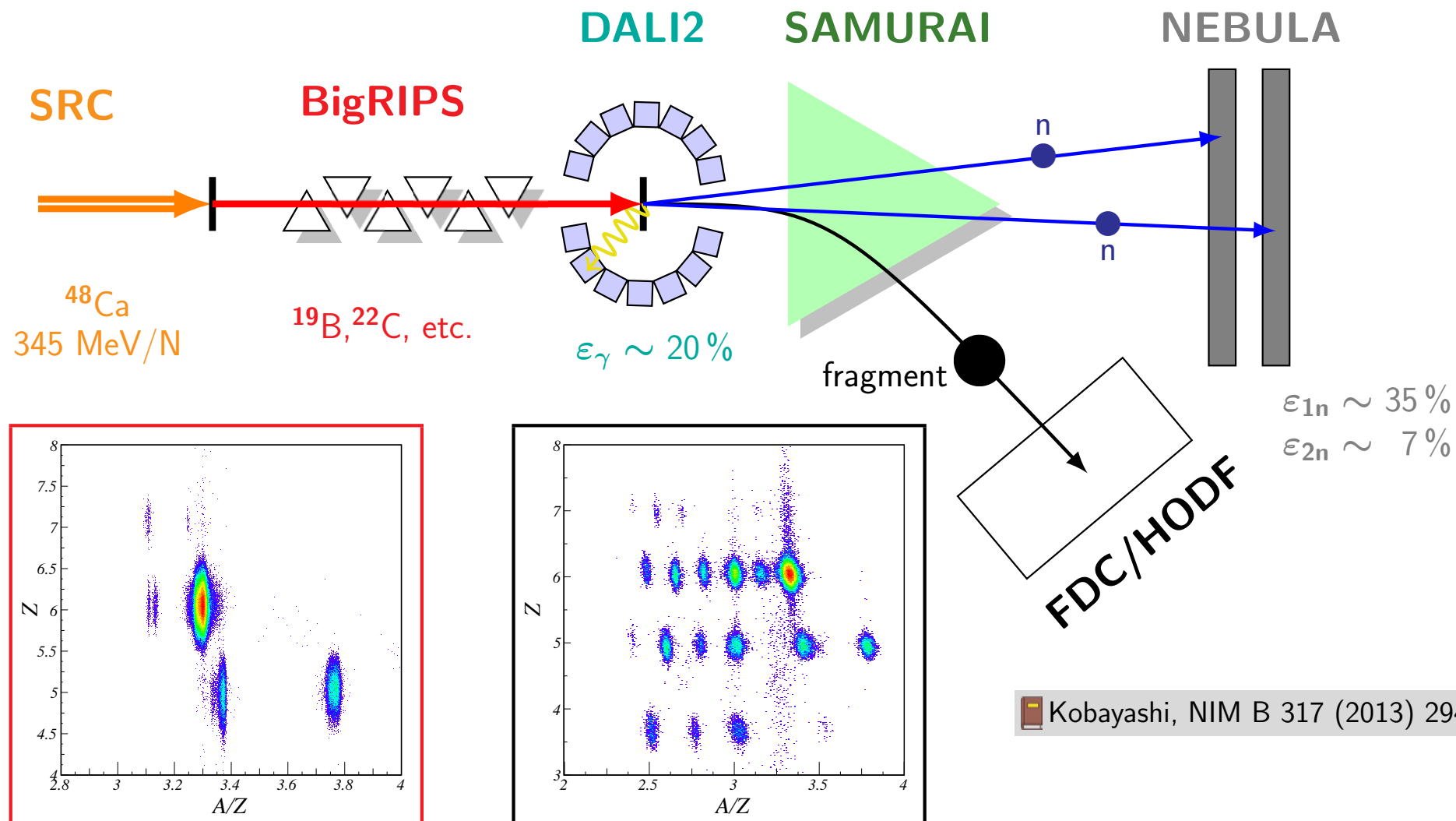
- The structure of **Boron 19** & **Carbon 22** :
(& the search for **Oxygen 26**, TITECH)

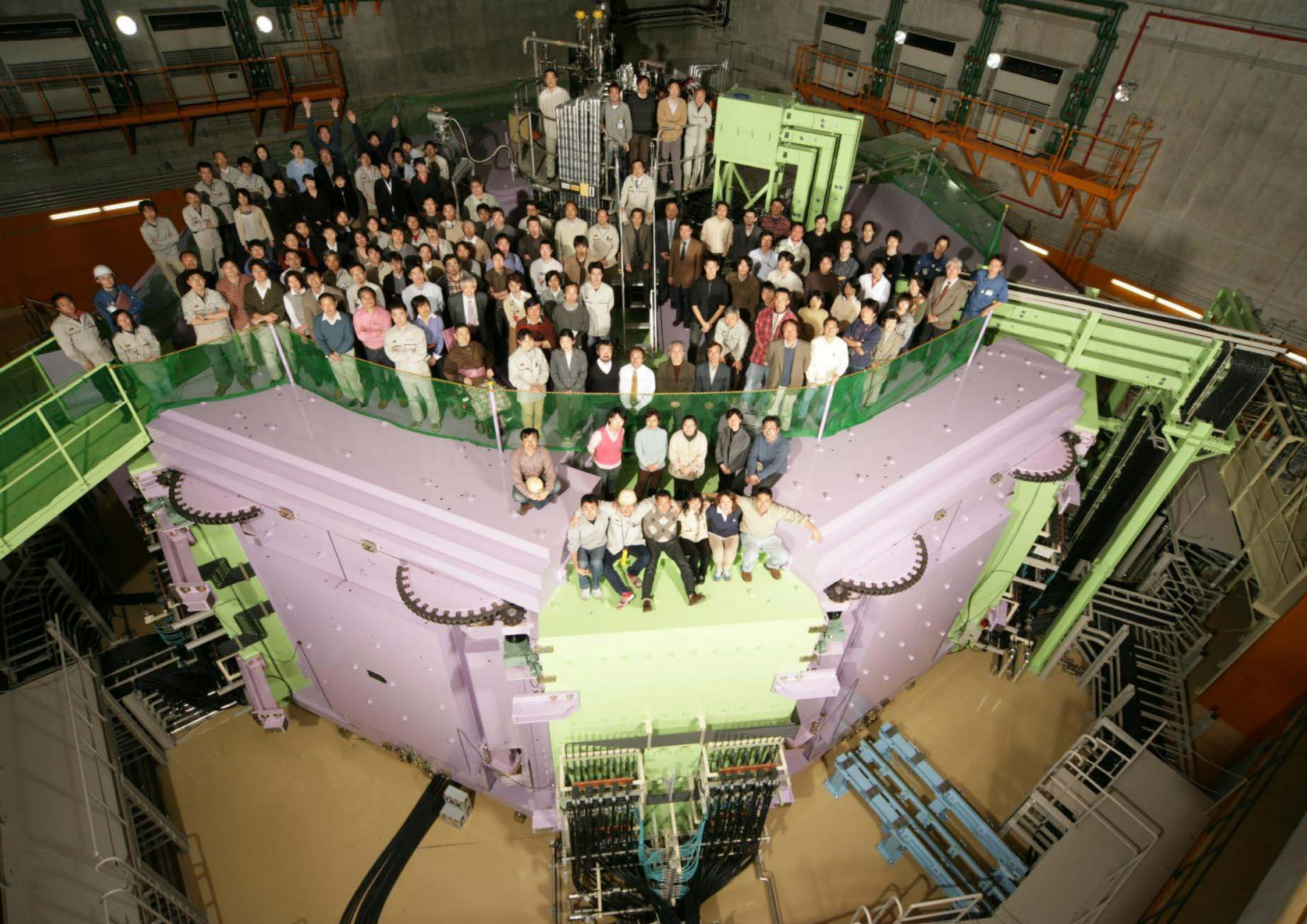
$$\begin{matrix} \text{red circle with 2 dots} \\ \text{red circle with 2 dots} \end{matrix} \equiv \begin{matrix} \text{red circle} \\ \text{blue circle} \\ \text{green circle} \end{matrix} \left\{ \begin{array}{l} \text{(18)19B} : 17,19\text{B} + 19,20\text{C} \quad (100/\text{s}) \\ \text{(21)22C} : 20,22\text{C} + 22,23\text{N} \quad (15/\text{s}) \end{array} \right.$$

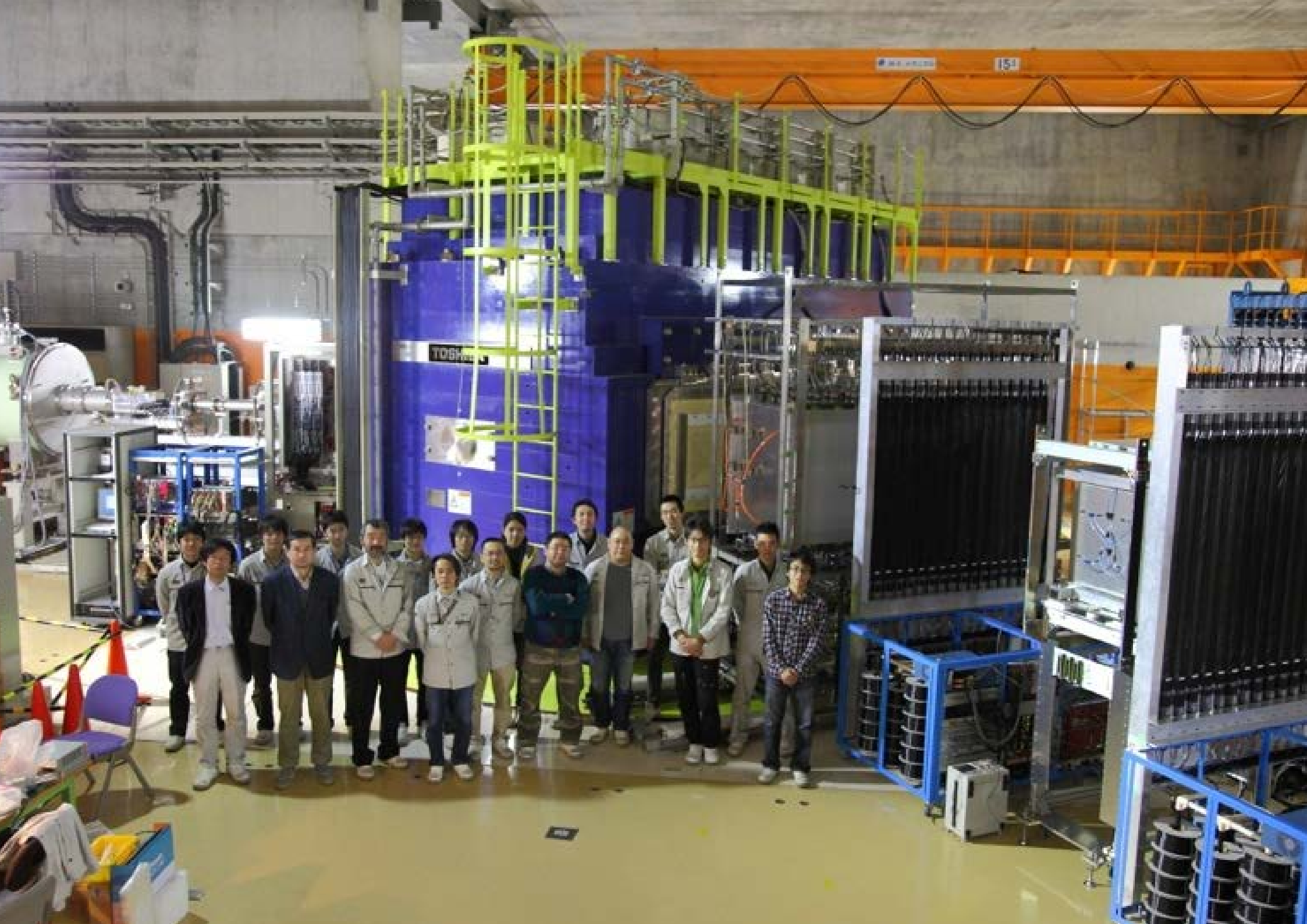


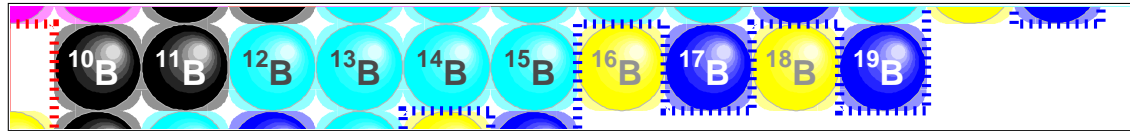
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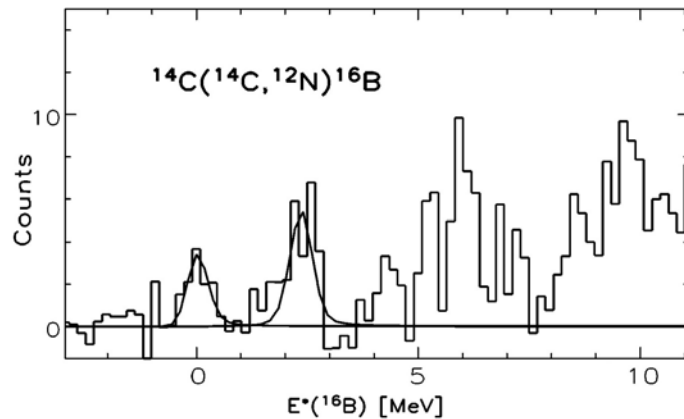




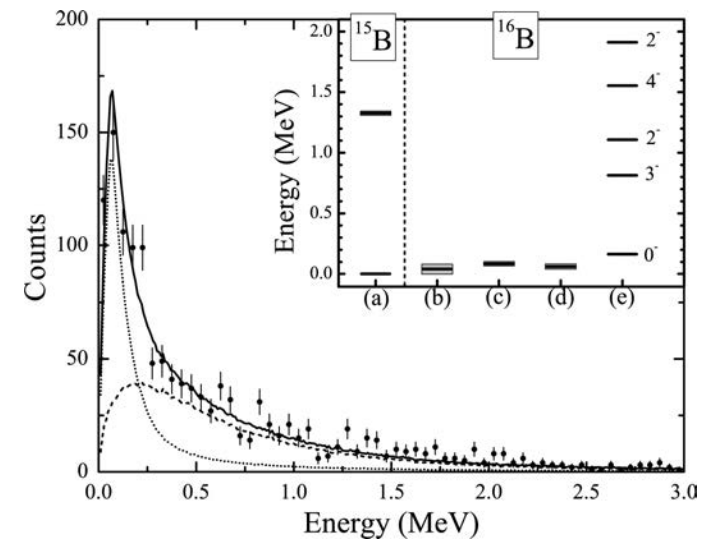




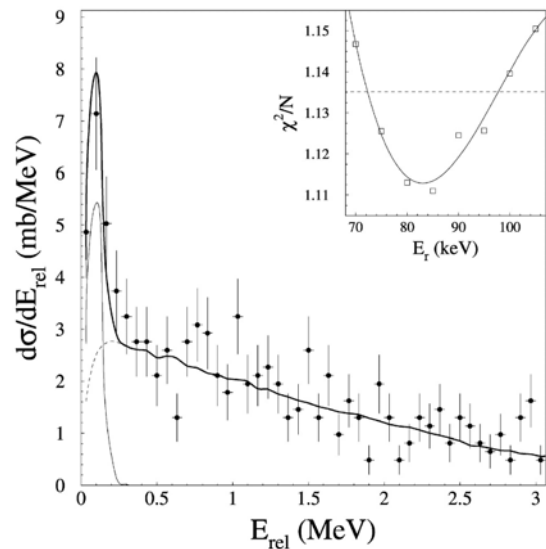
Transfer : Kalpakchieva, EPJA 7 (2000) 451



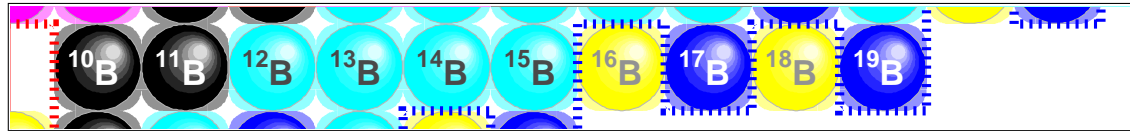
Spyrou, PLB 683 (2010) 129



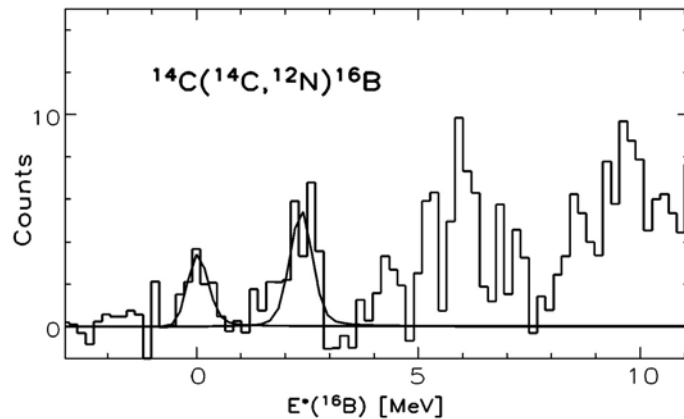
(^{17}C , $^{15}\text{B}+n$) : Lecouey, PLB 672 (2009) 6



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

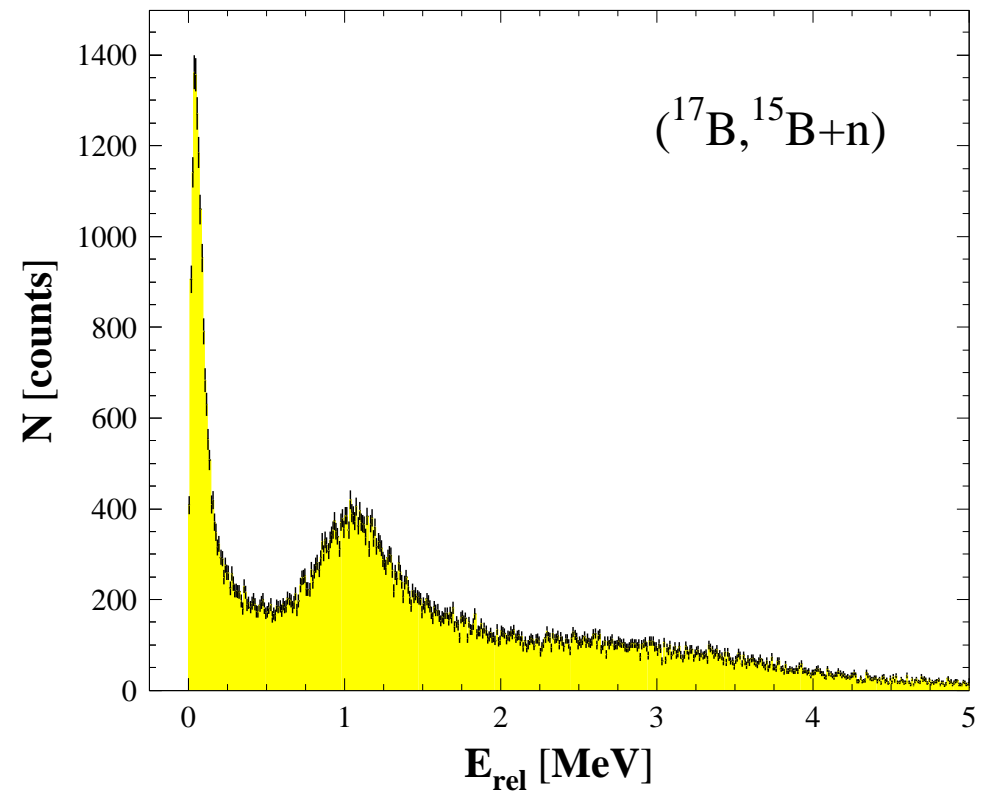


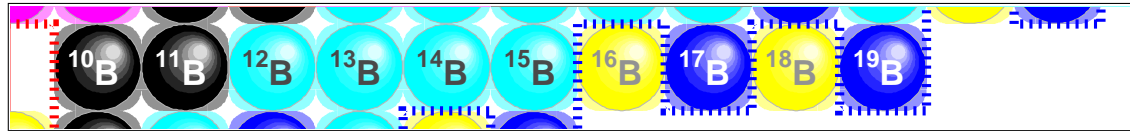
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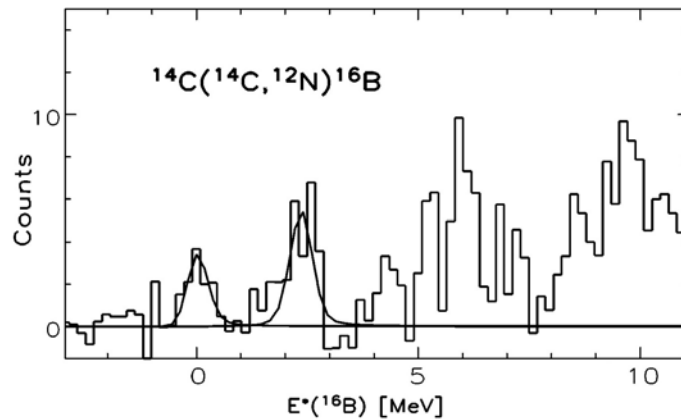
$(^{17}\text{B}, ^{15}\text{B}+n)$:

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



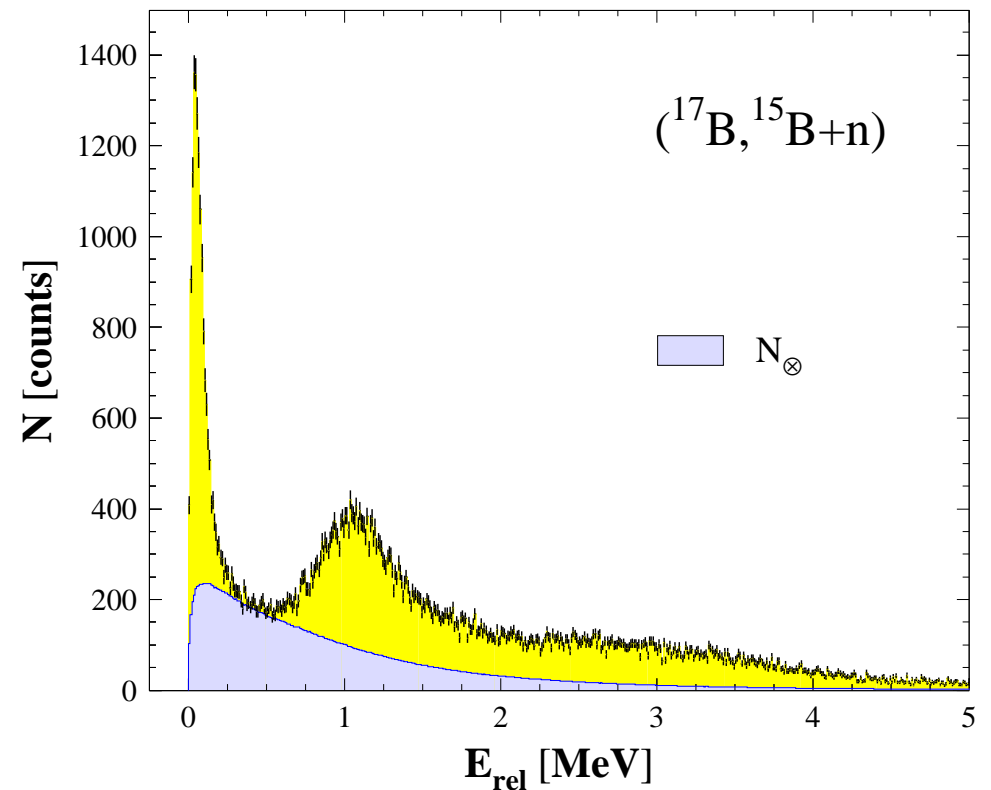


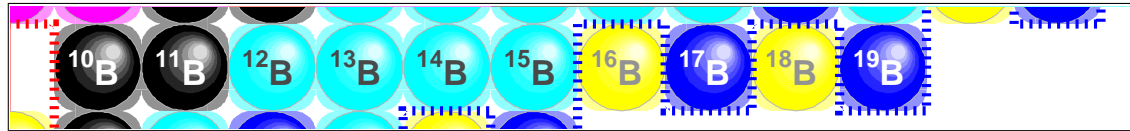
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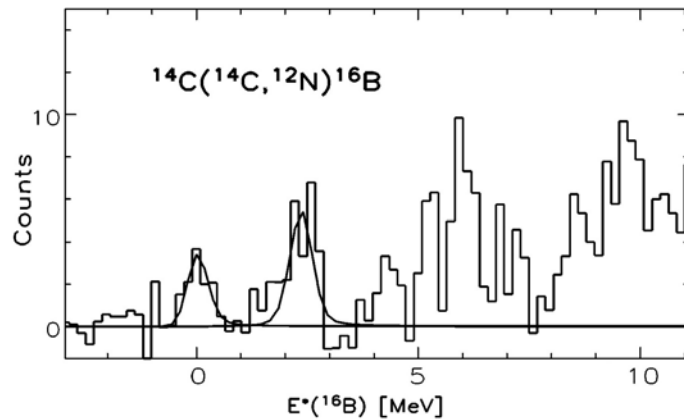
(¹⁷B, ¹⁵B+n) :

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



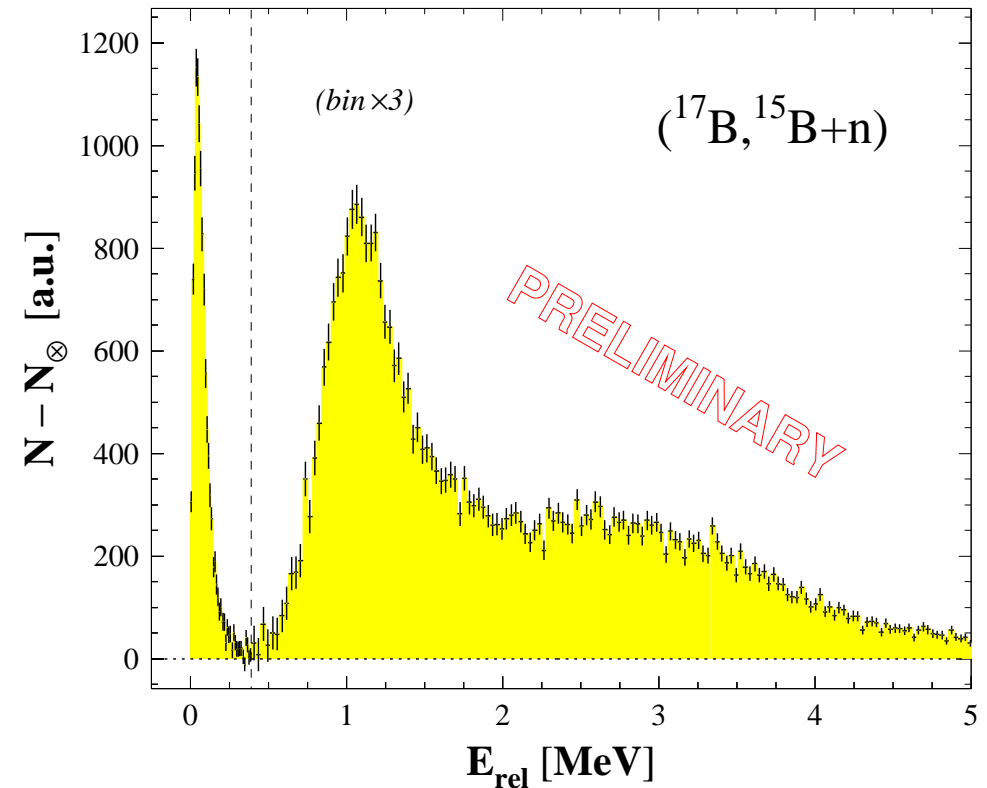


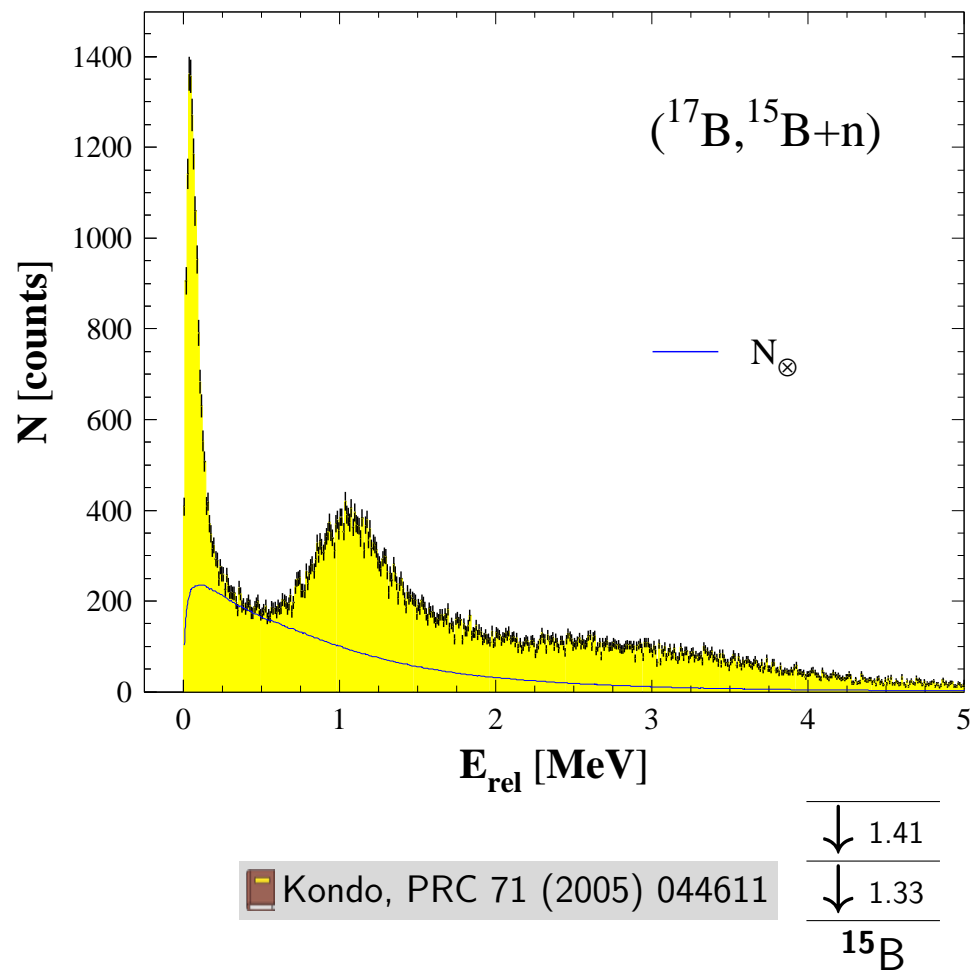
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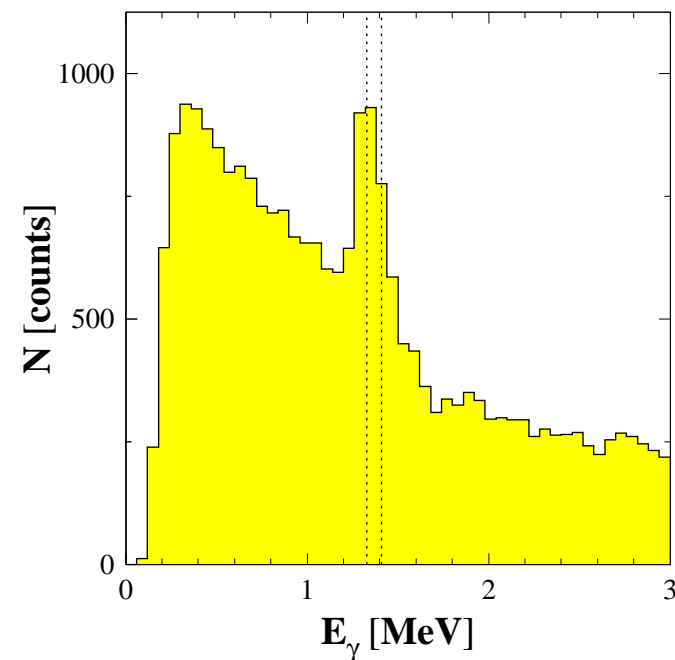
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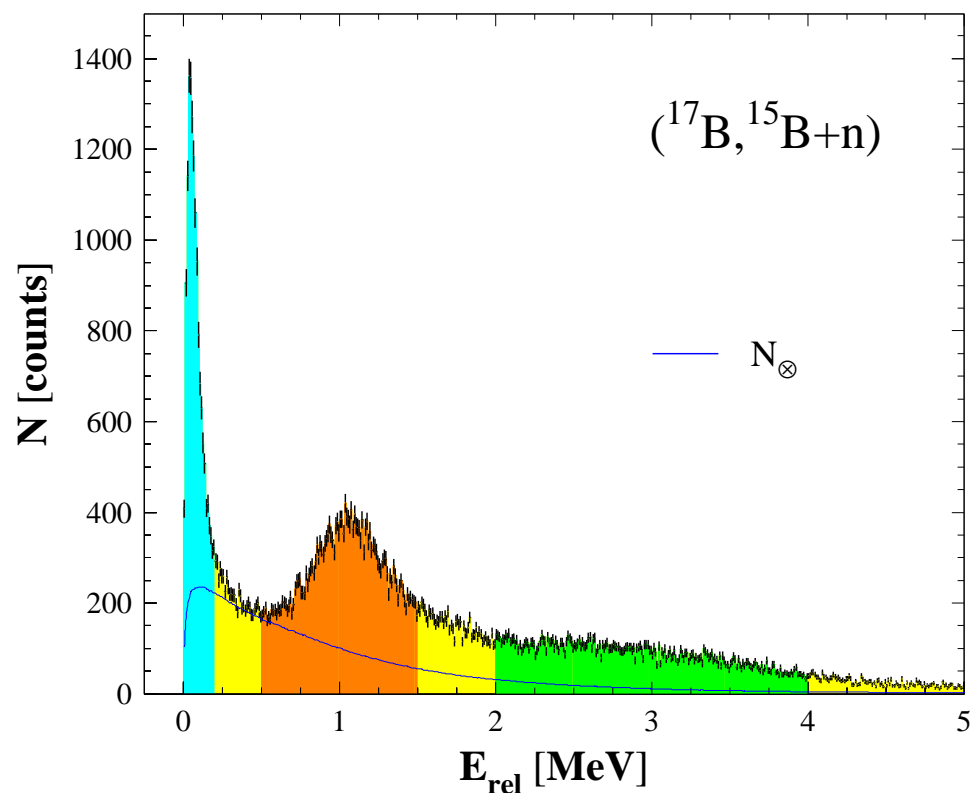




DALI2 $\{^{15}\text{B}+n+\gamma\}$ events :



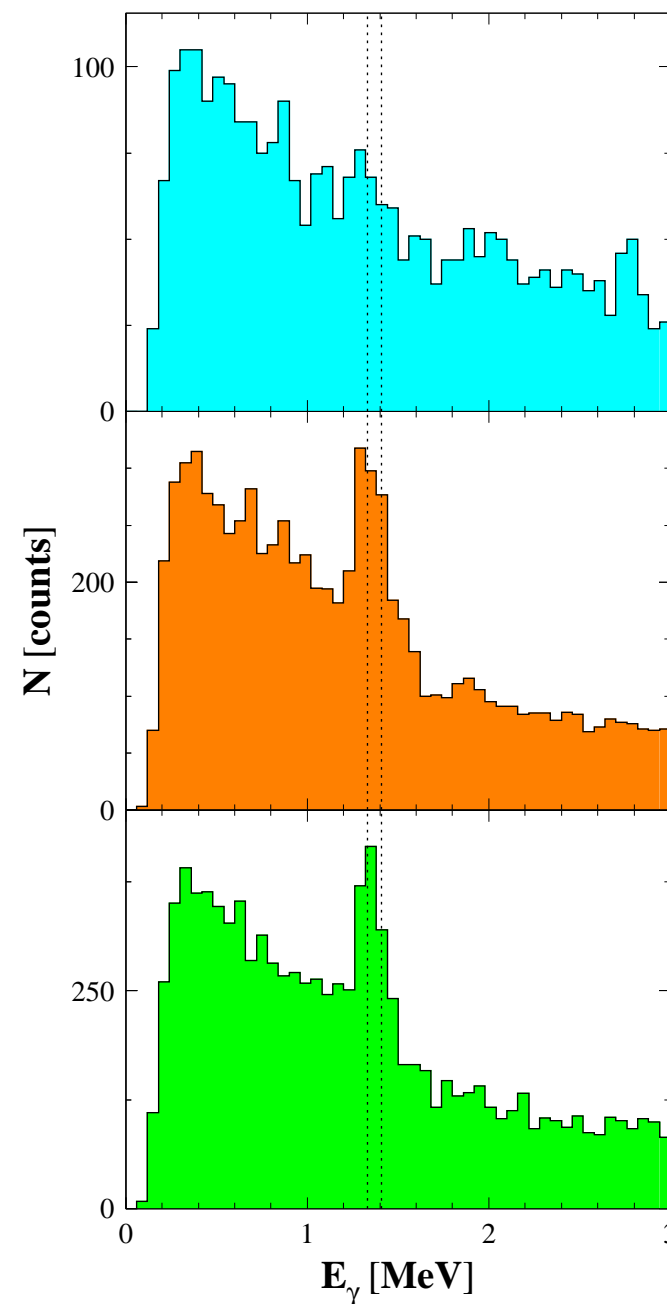
- significant $^{15}\text{B}^*$ to 1st/2nd state !
- E_{rel} vs E_{γ} correlations ?

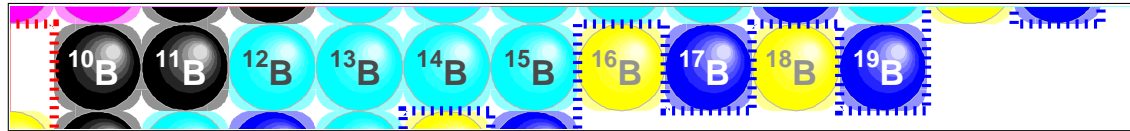


▣ Kondo, PRC 71 (2005) 044611

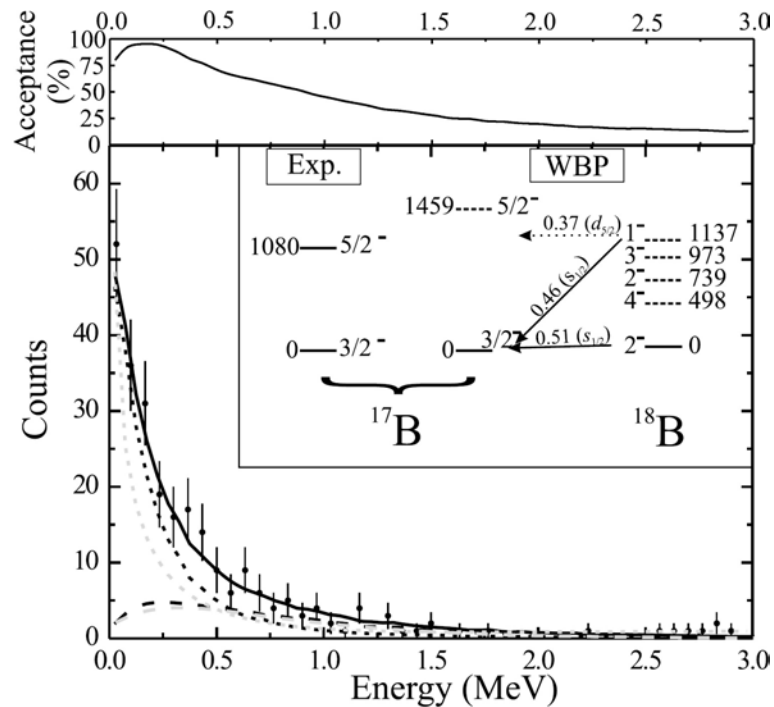
↓ 1.41
↓ 1.33
 ^{15}B

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

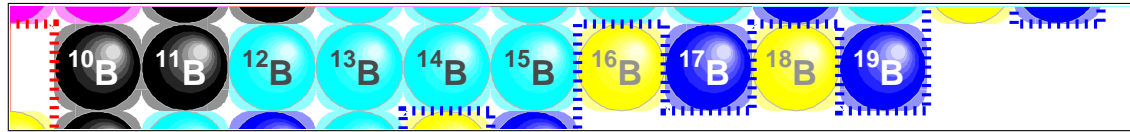




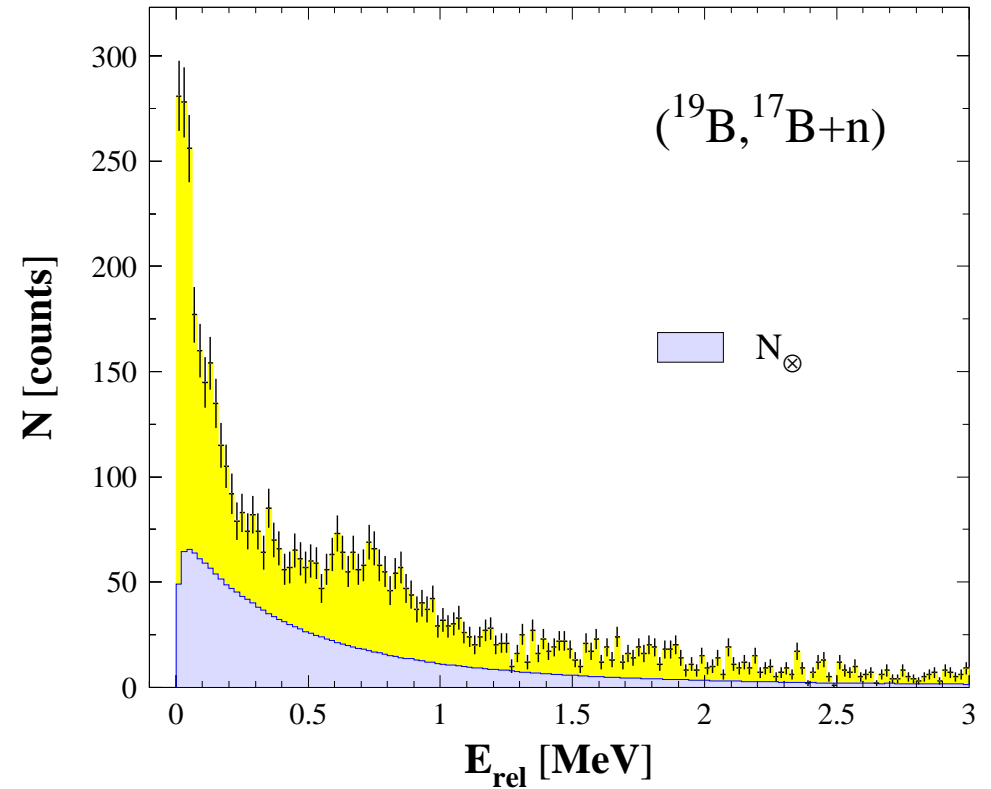
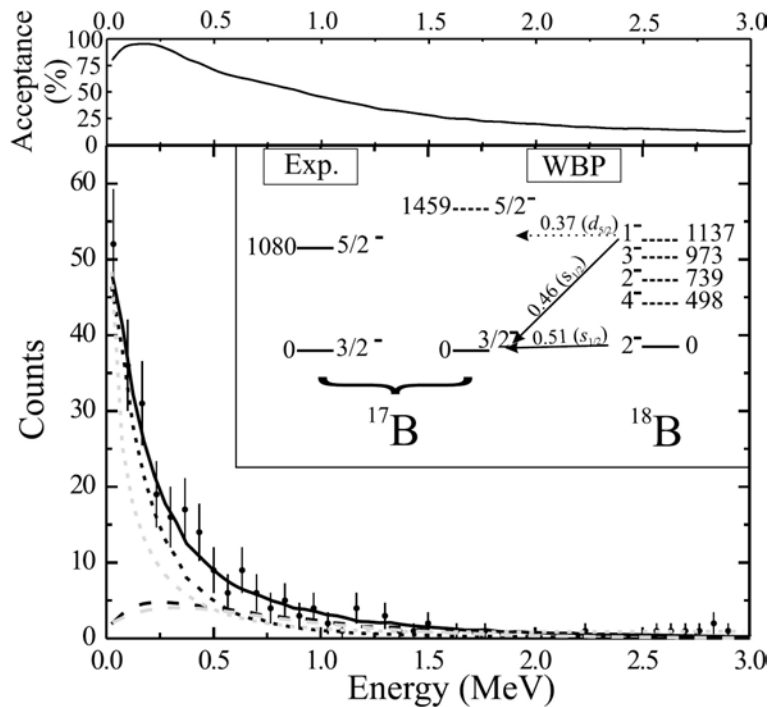
(^{19}C , $^{17}\text{B}+n$) : Spyrou, PLB 683 (2010) 129



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

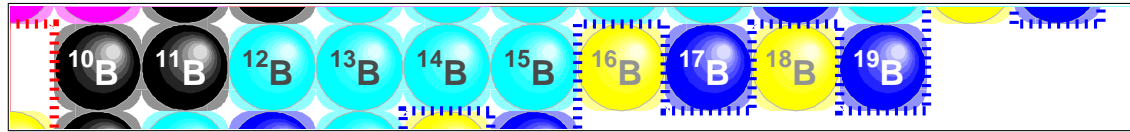


(¹⁹C, ¹⁷B+n) : Spyrou, PLB 683 (2010) 129

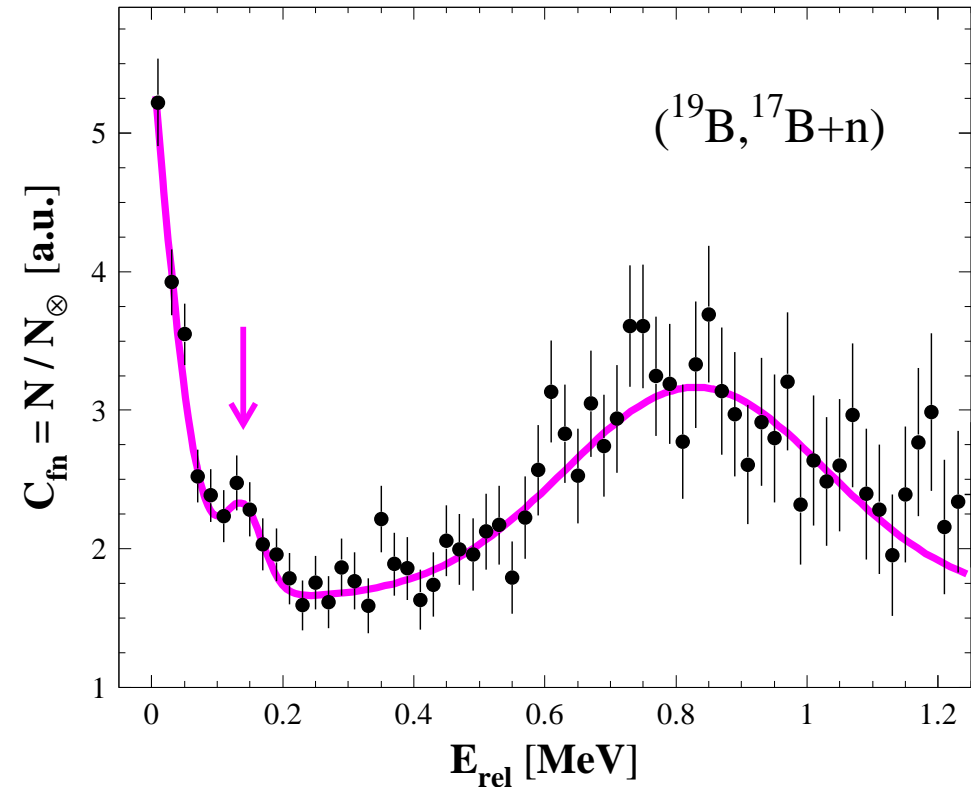
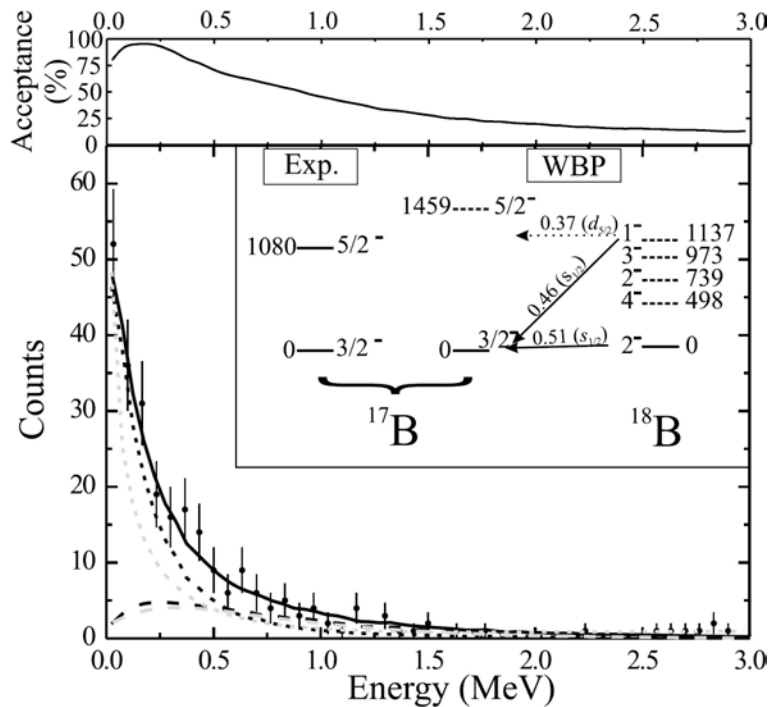


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- also other channels (& structures)
- threshold state(s) $\lesssim 150$ keV !
- very clear excited states ...

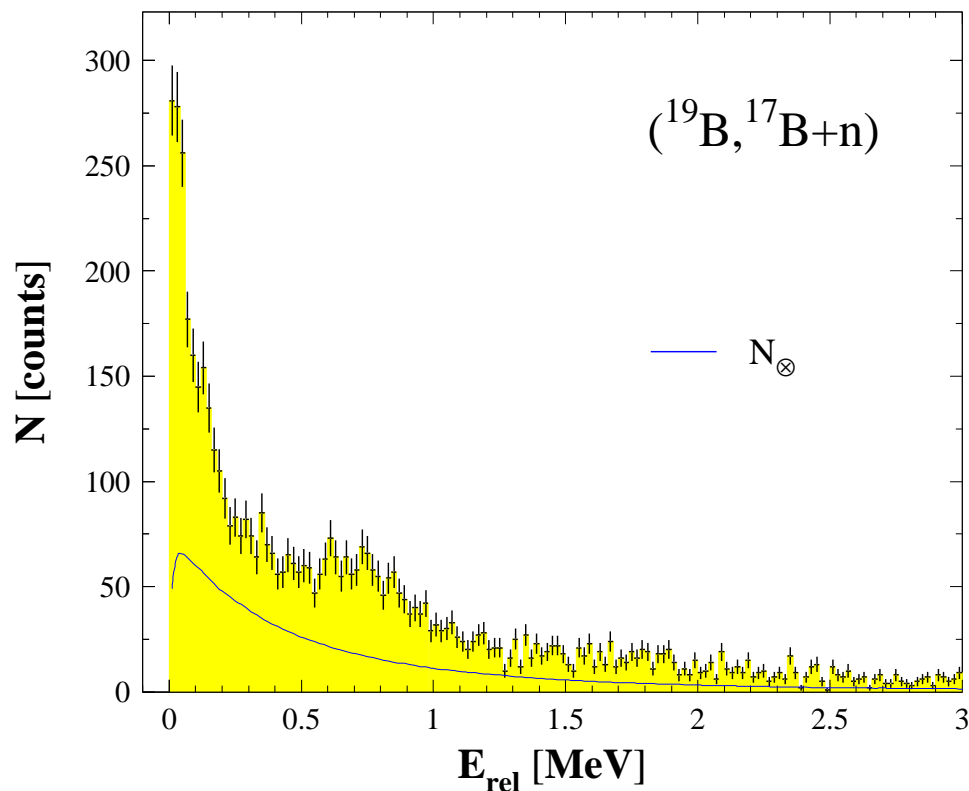


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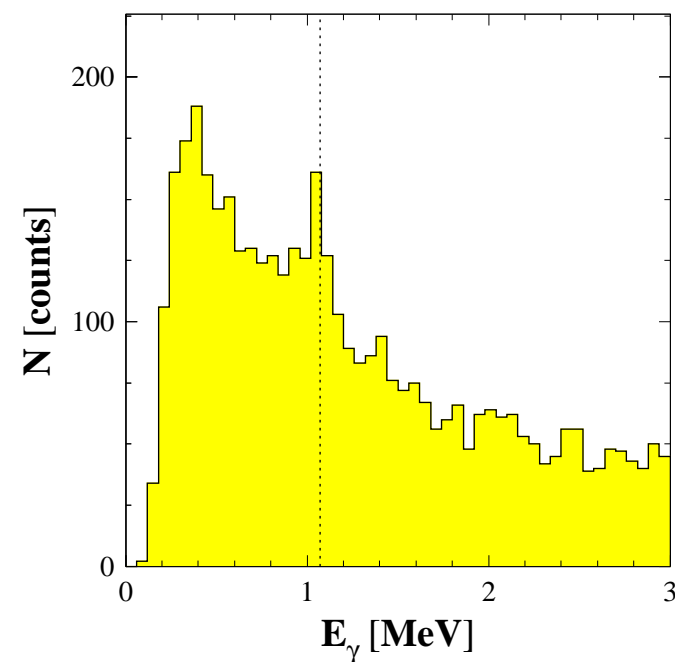
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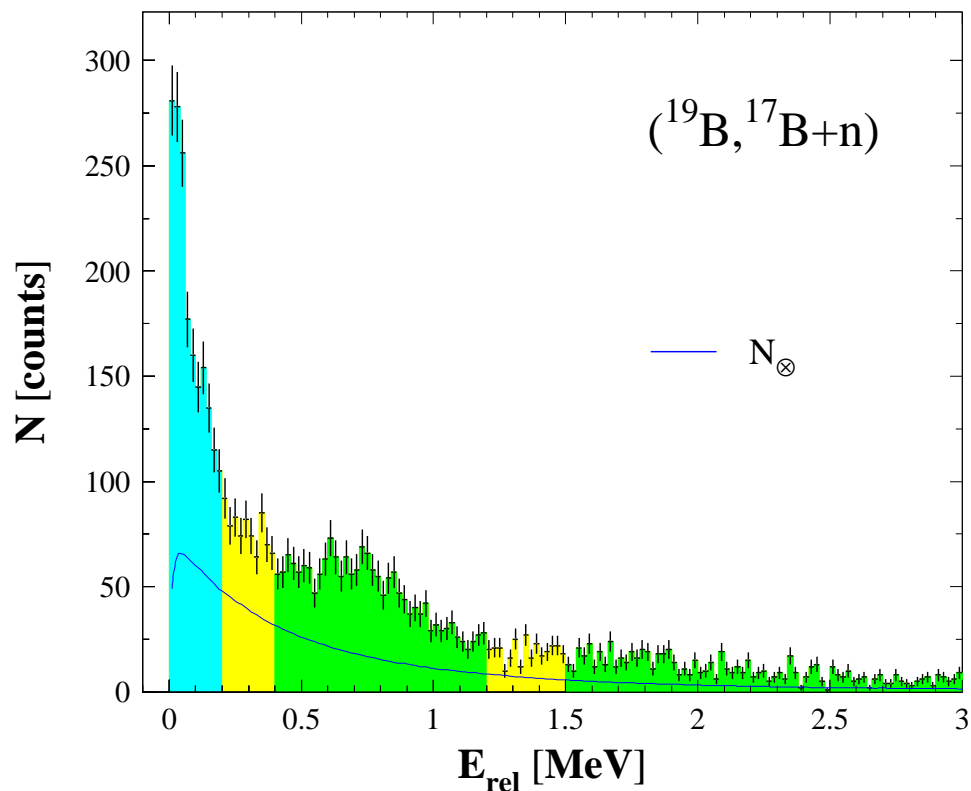
Kondo, PRC 71 (2005) 044611

$$\frac{\downarrow 1.07}{^{17}\text{B}}$$

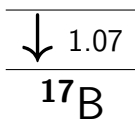
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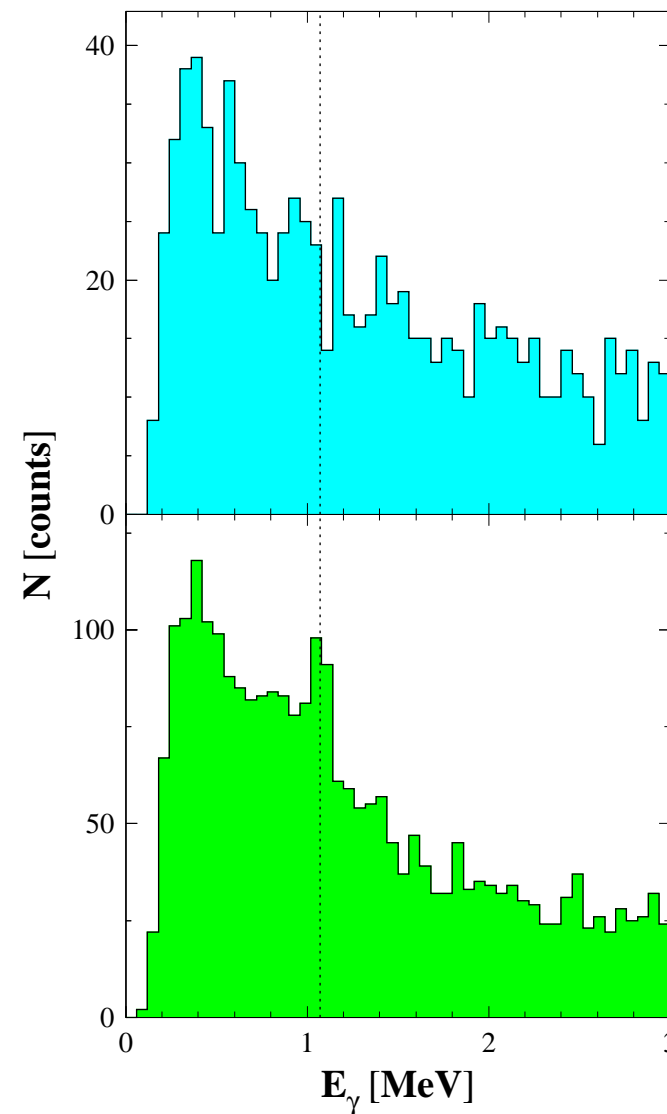
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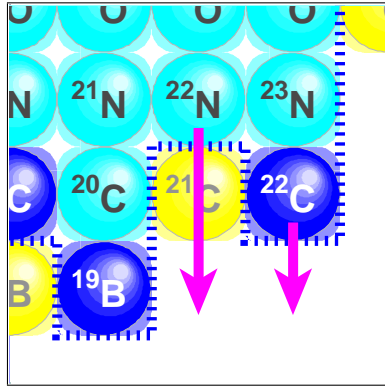


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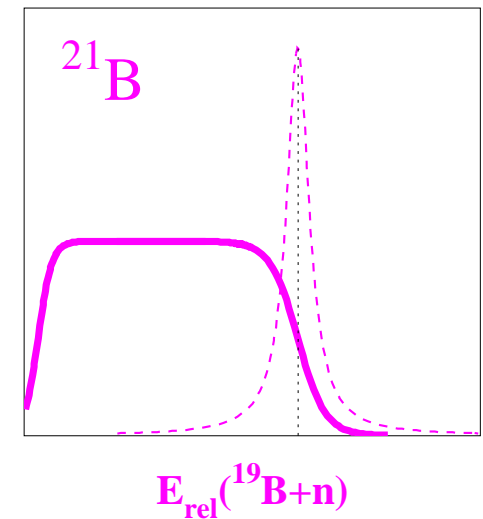
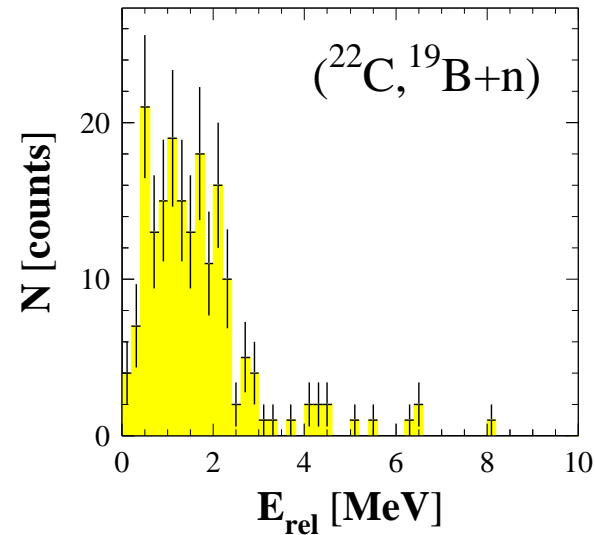
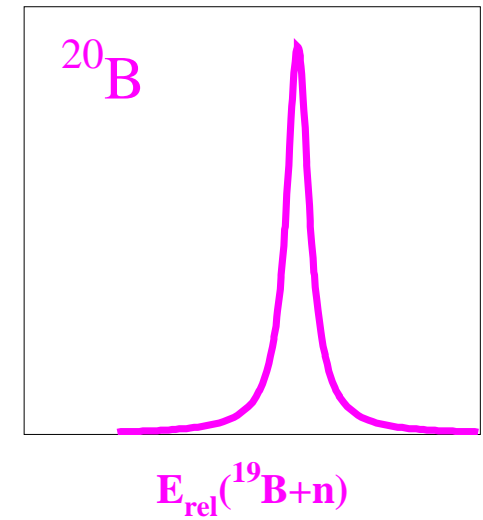
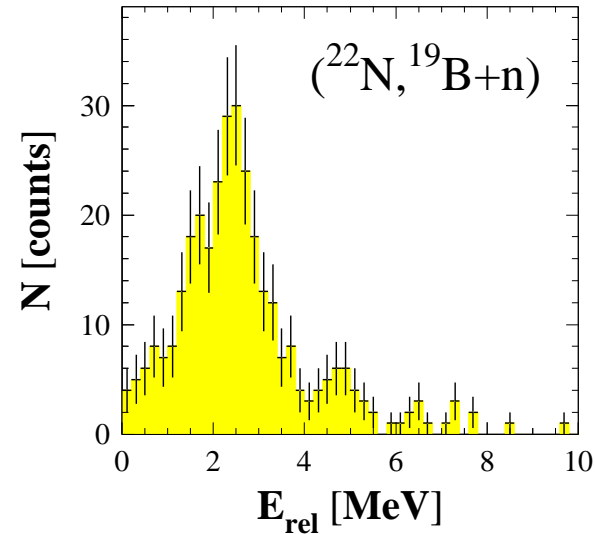


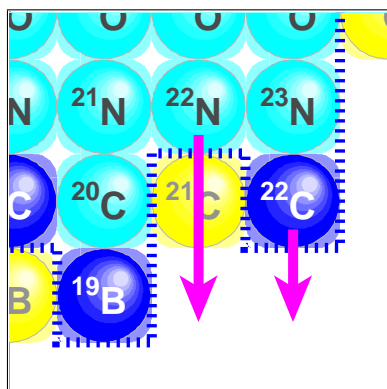
- precise characterization of g.s. !
- $^{18}\text{B}^* \equiv |^{17}\text{B}^* \otimes \nu\rangle$ excited states ...





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





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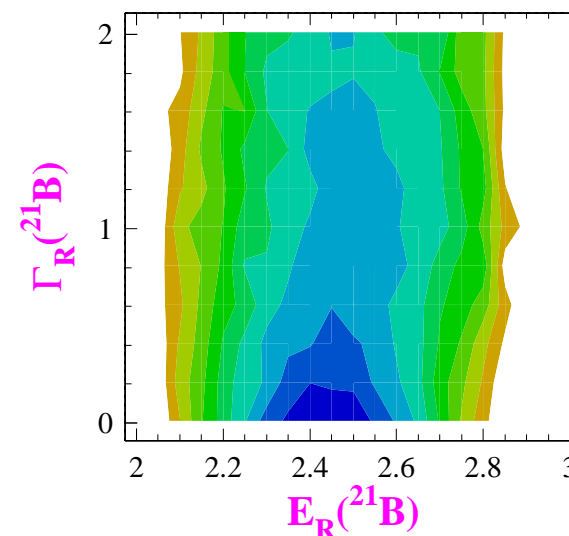
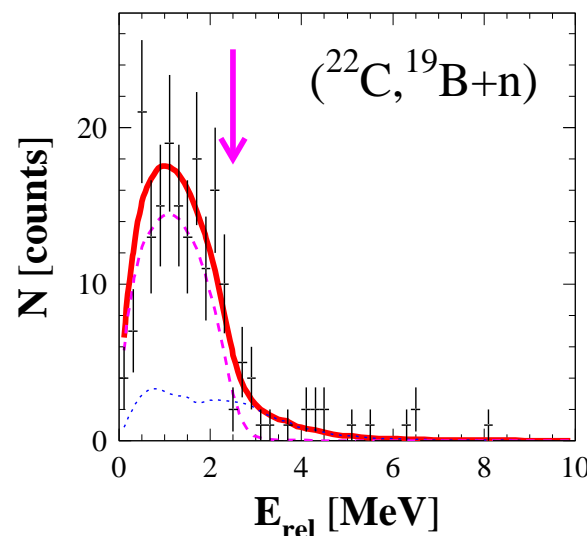
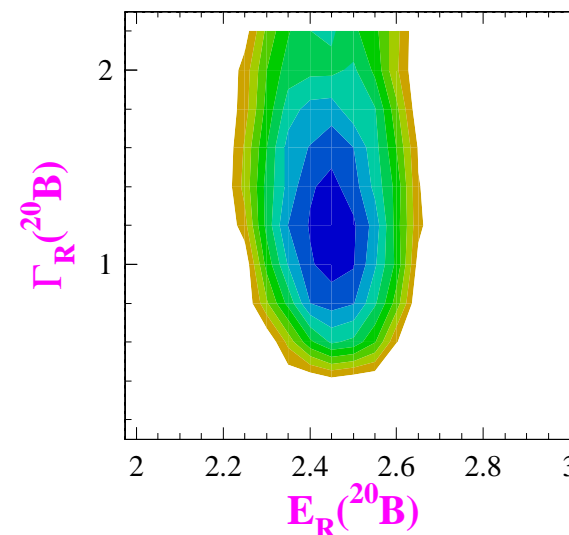
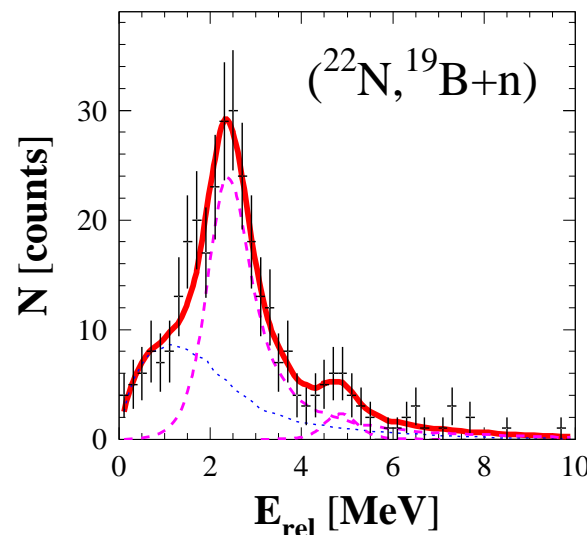
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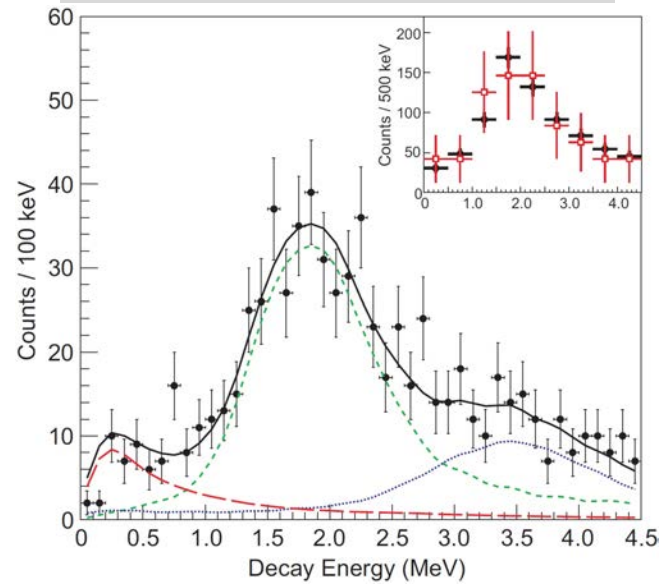
PRELIMINARY \Rightarrow

^{20}B $E_{\text{gs}} \sim 2.4$ MeV & $E^* \sim 4.8$ MeV

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

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

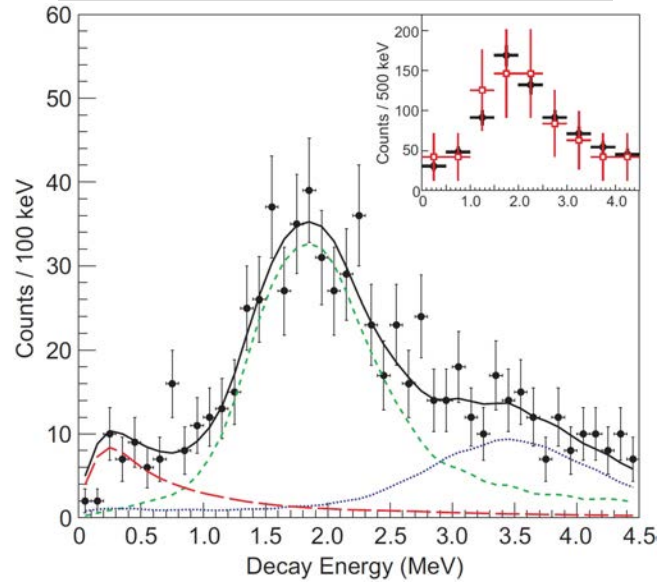
■ Snyder, PRC88 (2013) 031303R



- arbitrary background(s) !

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

Snyder, PRC88 (2013) 031303R



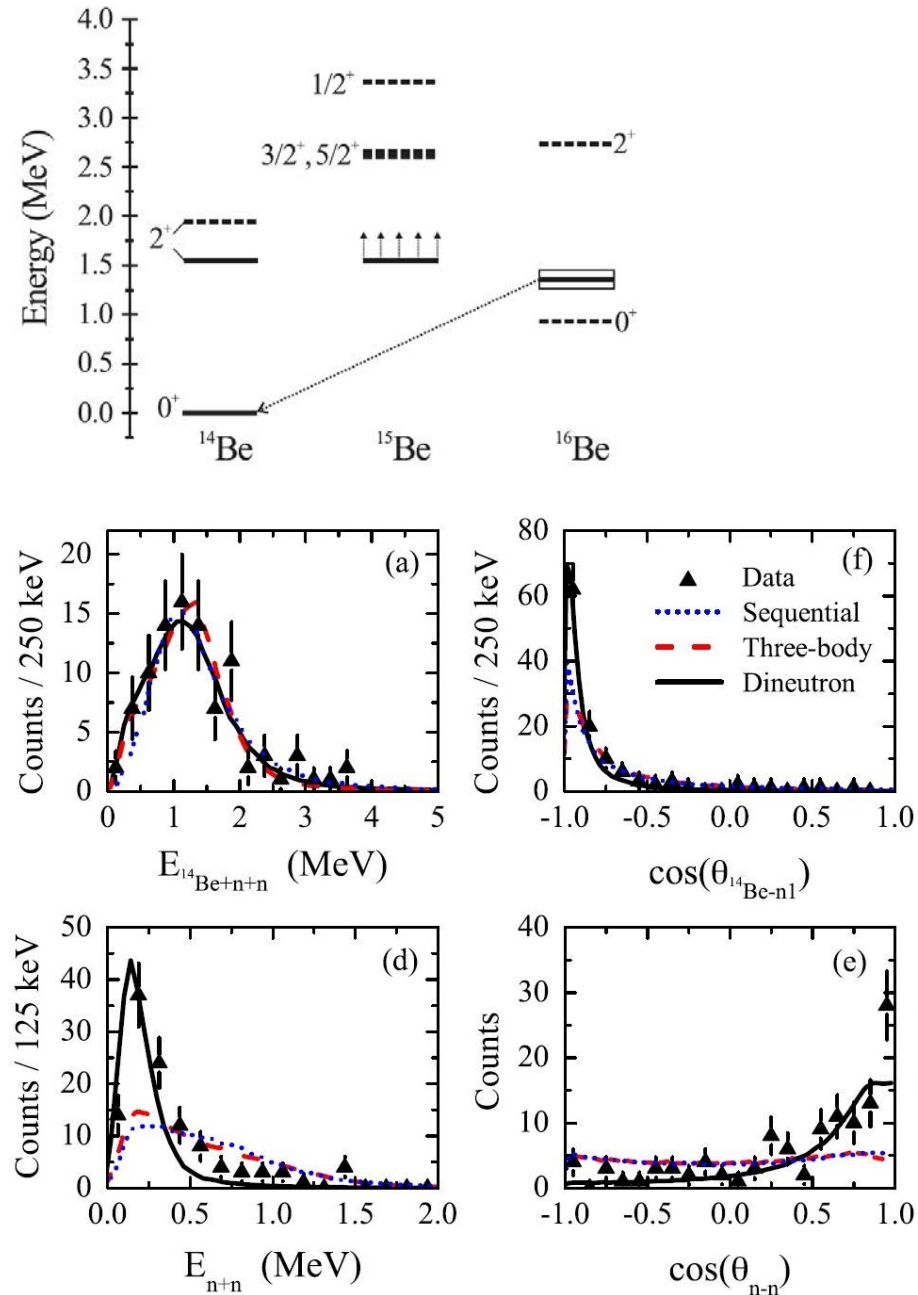
● arbitrary background(s) !

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

Spyrou, PRL 108 (2012) 102501

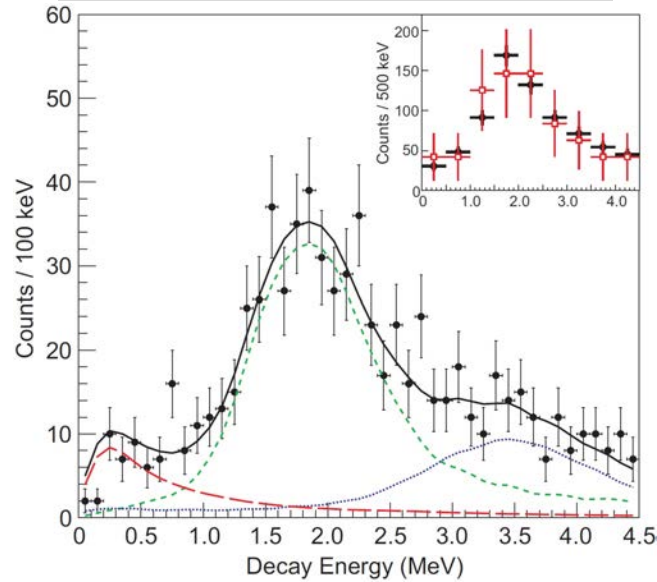
- "dineutron emission" claim !
- no low-lying ^{15}Be ($S_n < 0$) ? \leftarrow
- no n-n FSI :

FMM, PRL 109 (2012) 239201



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

■ Snyder, PRC88 (2013) 031303R



- arbitrary background(s) !

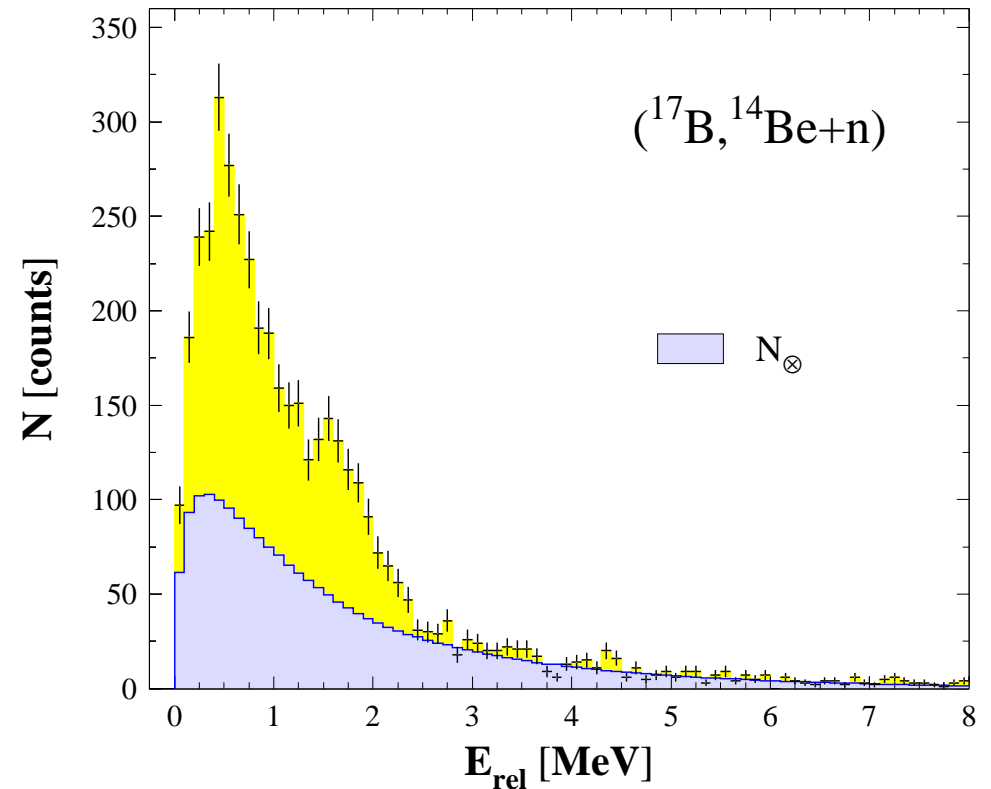
$(^{17}\text{B}, ^{14}\text{Be}+n+n)$:

■ Spyrou, PRL 108 (2012) 102501

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■ FMM, PRL 109 (2012) 239201

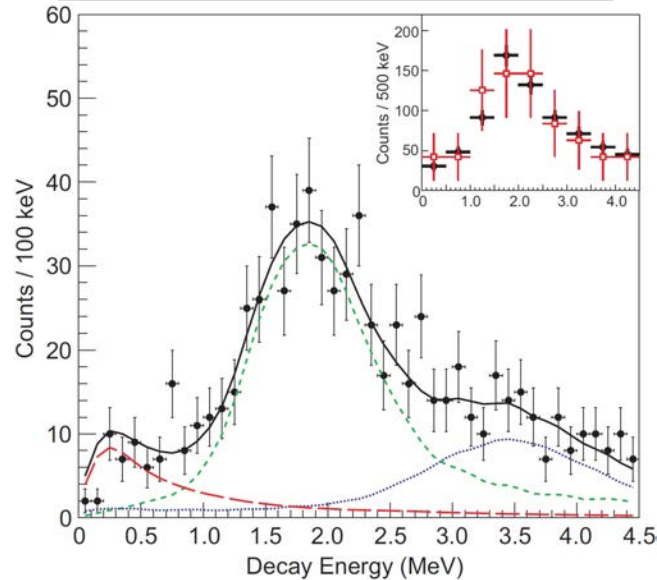
$(^{17}\text{B}, ^{14}\text{Be}+n)$:



- significant low-lying strength !

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

■ Snyder, PRC88 (2013) 031303R



- arbitrary background(s) !

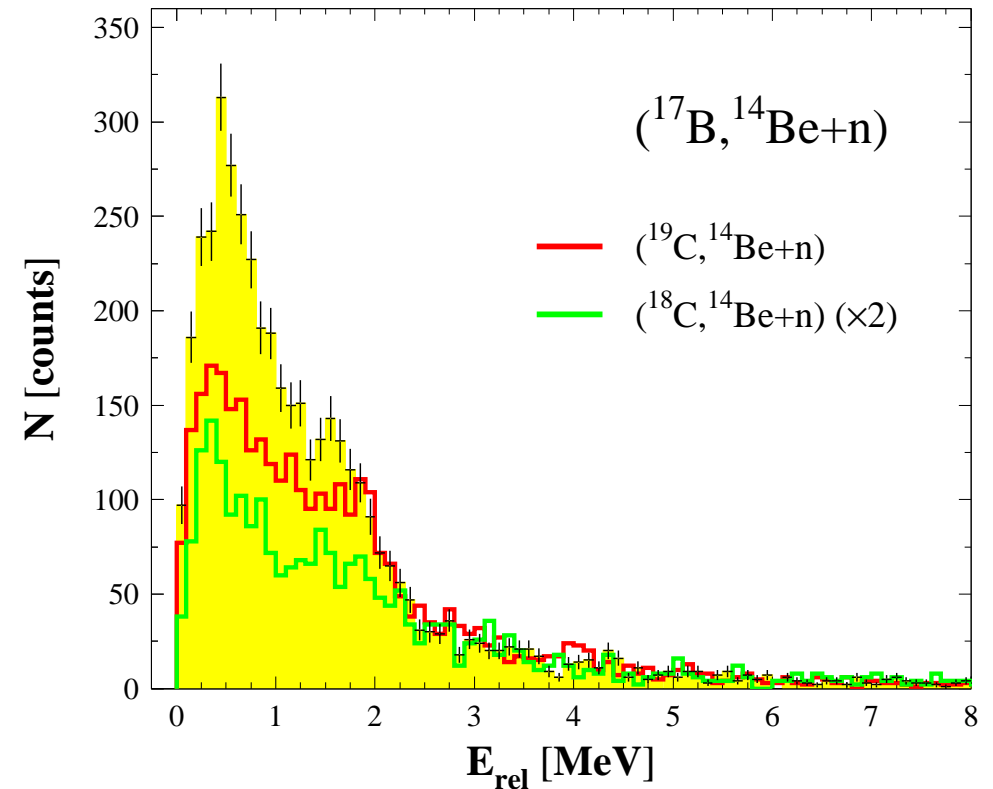
$(^{17}\text{B}, ^{14}\text{Be}+n+n)$:

■ Spyrou, PRL 108 (2012) 102501

- "dineutron emission" claim !
- no low-lying ^{15}Be ($S_n < 0$) ? \leftarrow
- no n-n FSI :

■ FMM, PRL 109 (2012) 239201

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



- significant low-lying strength !
- present in other channels, $N > 1$...
- influence of ^{16}Be decay ?
- $\sim 1\text{k}$ $\{^{14}\text{Be}+n+n\}$, analysis ongoing ...

I. The neutron dripline :

- Exotic nuclei & physics
- Secondary n-rich beams
- The RIBF at RIKEN
- Knockout experiments

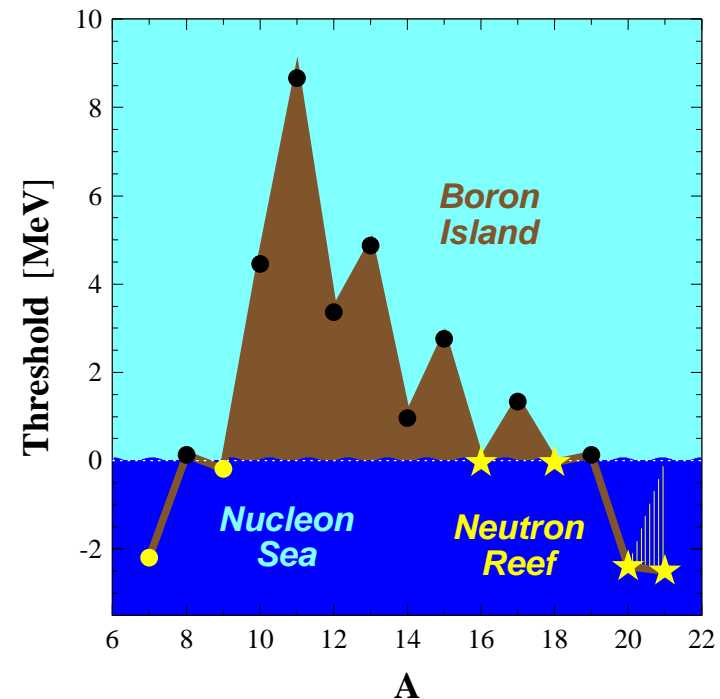


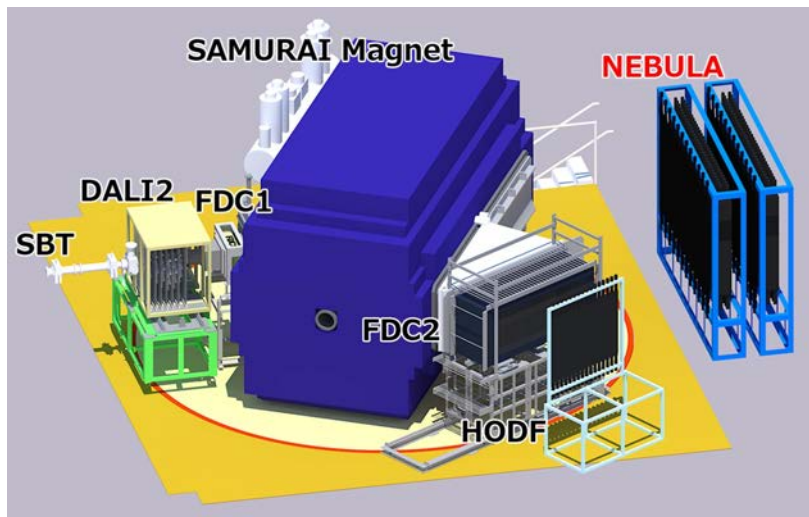
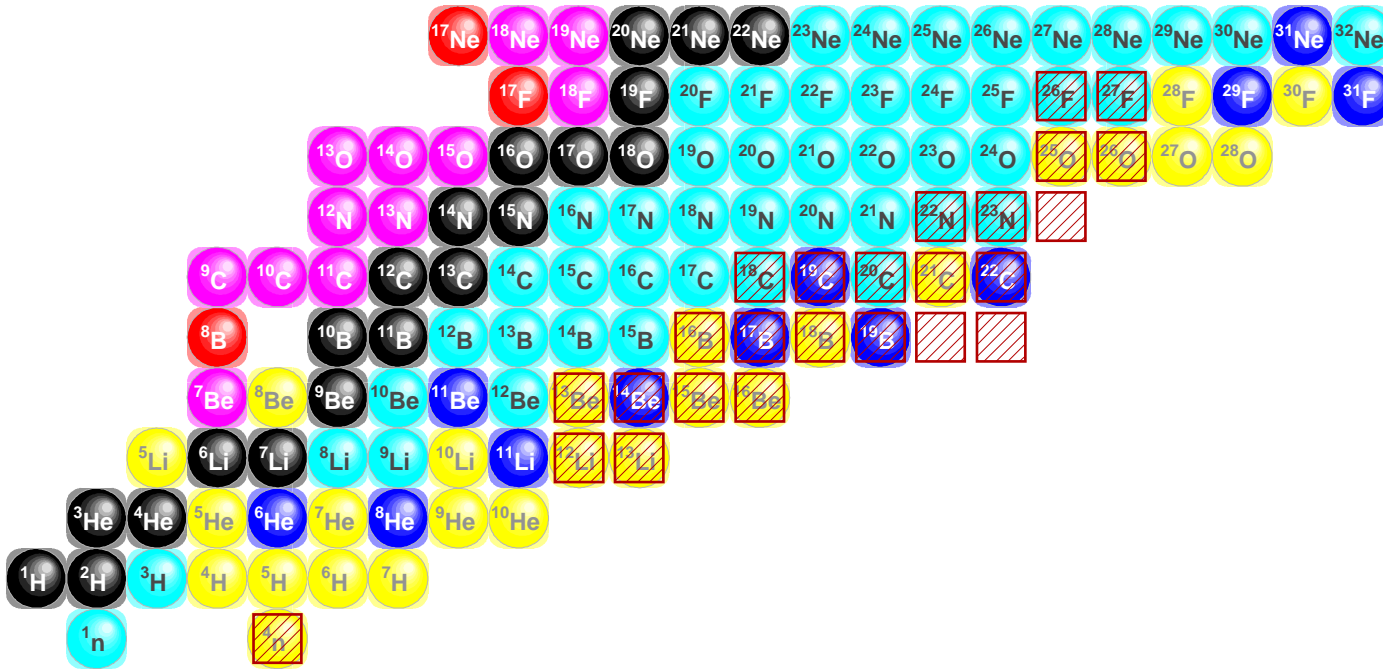
II. SAMURAI Day-1 campaign :

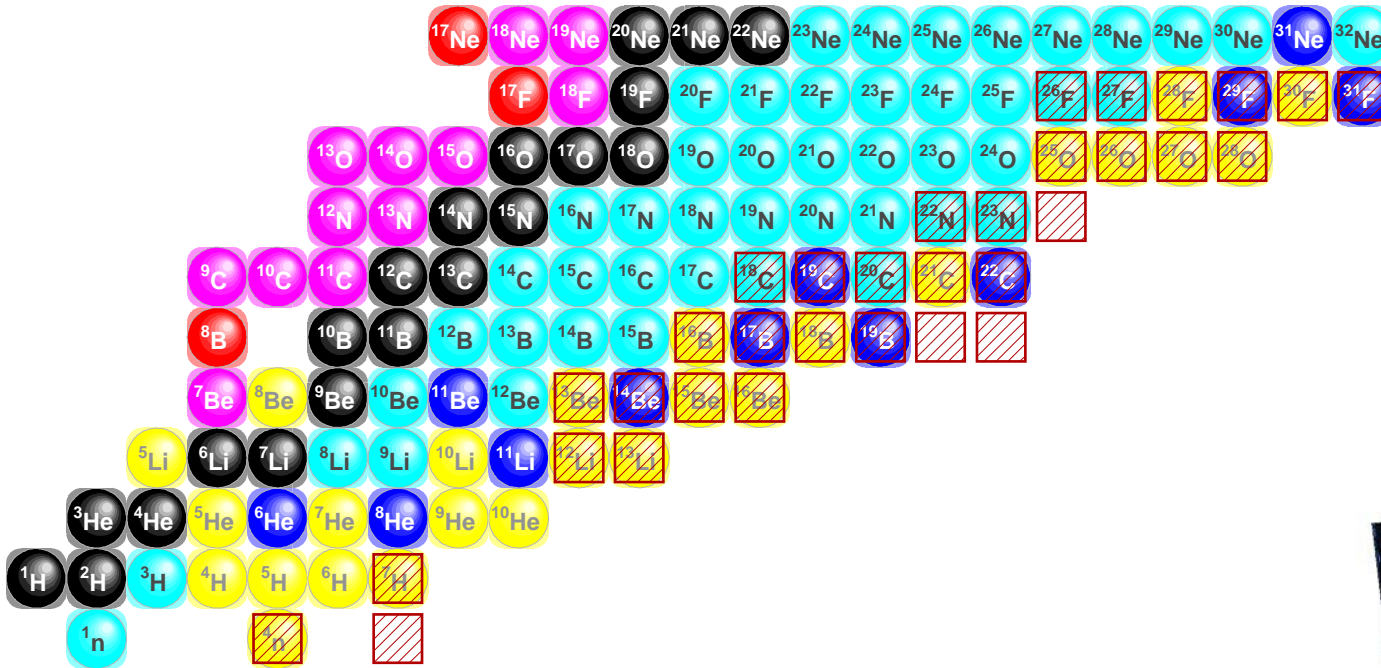
- SAMURAI & NEBULA
- Some (1n) examples : $^{16,18,20,21}\text{B}$
- The Beryllium 'puzzle'

III. Beyond two neutrons :

- NEBULA+ (& NeuLAND)
- Towards ^{28}O & ^4n
- Next steps around the dripline

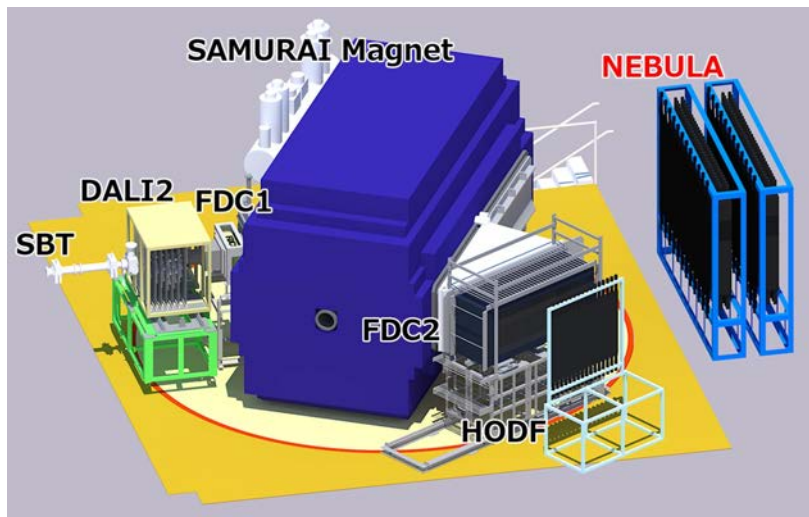
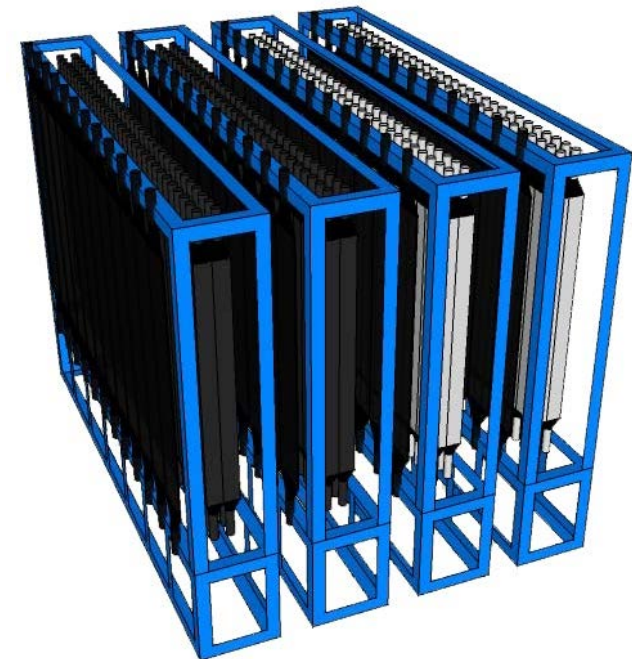






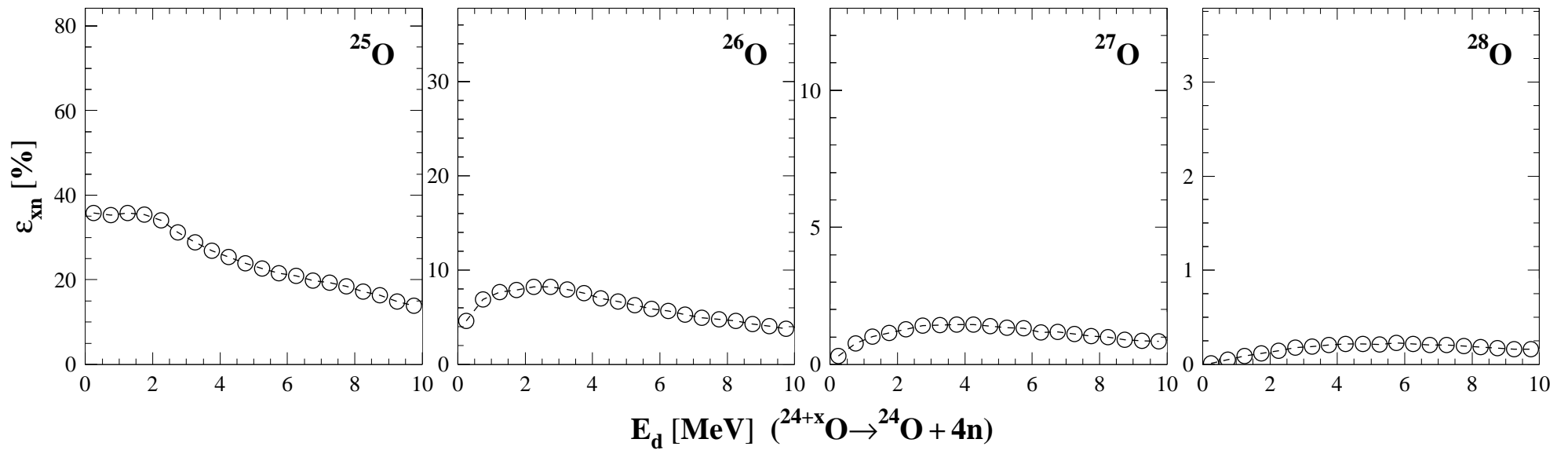
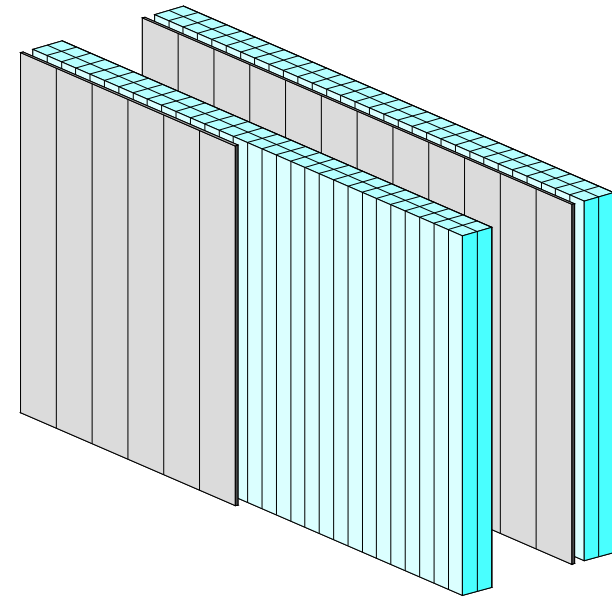
NEBULA+

- 240 neutron modules
- 48 veto modules
- 2+2 walls : ^{28}O , ^7H , $^{4,6}\text{n}$!



⇒ ANR funding request ...

- Expand NEBULA **multi-n** capabilities :
 - France : LPC, IRFU, IPNO
 - Japan : TITECH, RIKEN

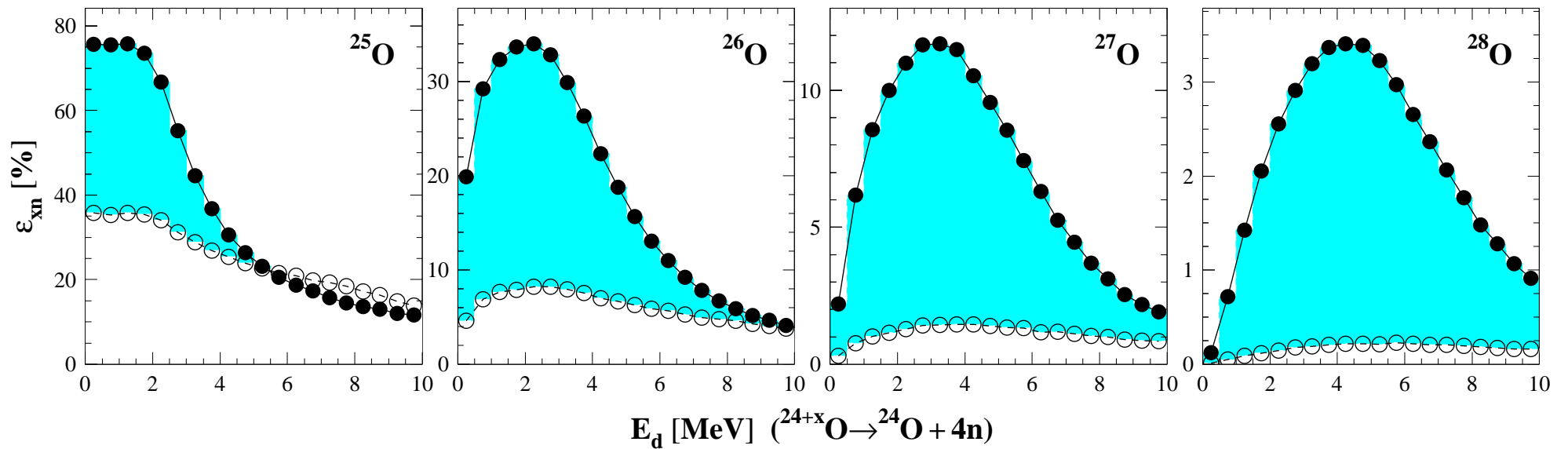
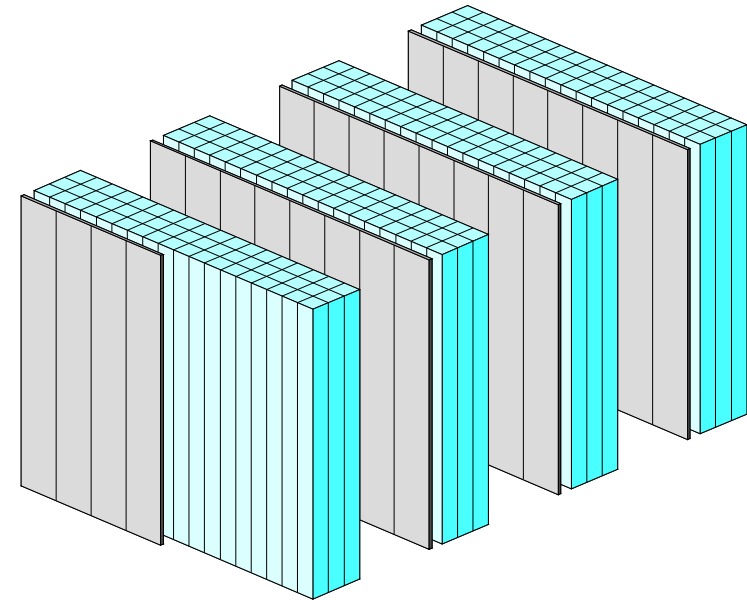


($\epsilon_{xn} < \epsilon_n^x$ due to neutron cross-talk  FMM, NIM A 450 (2000) 109)

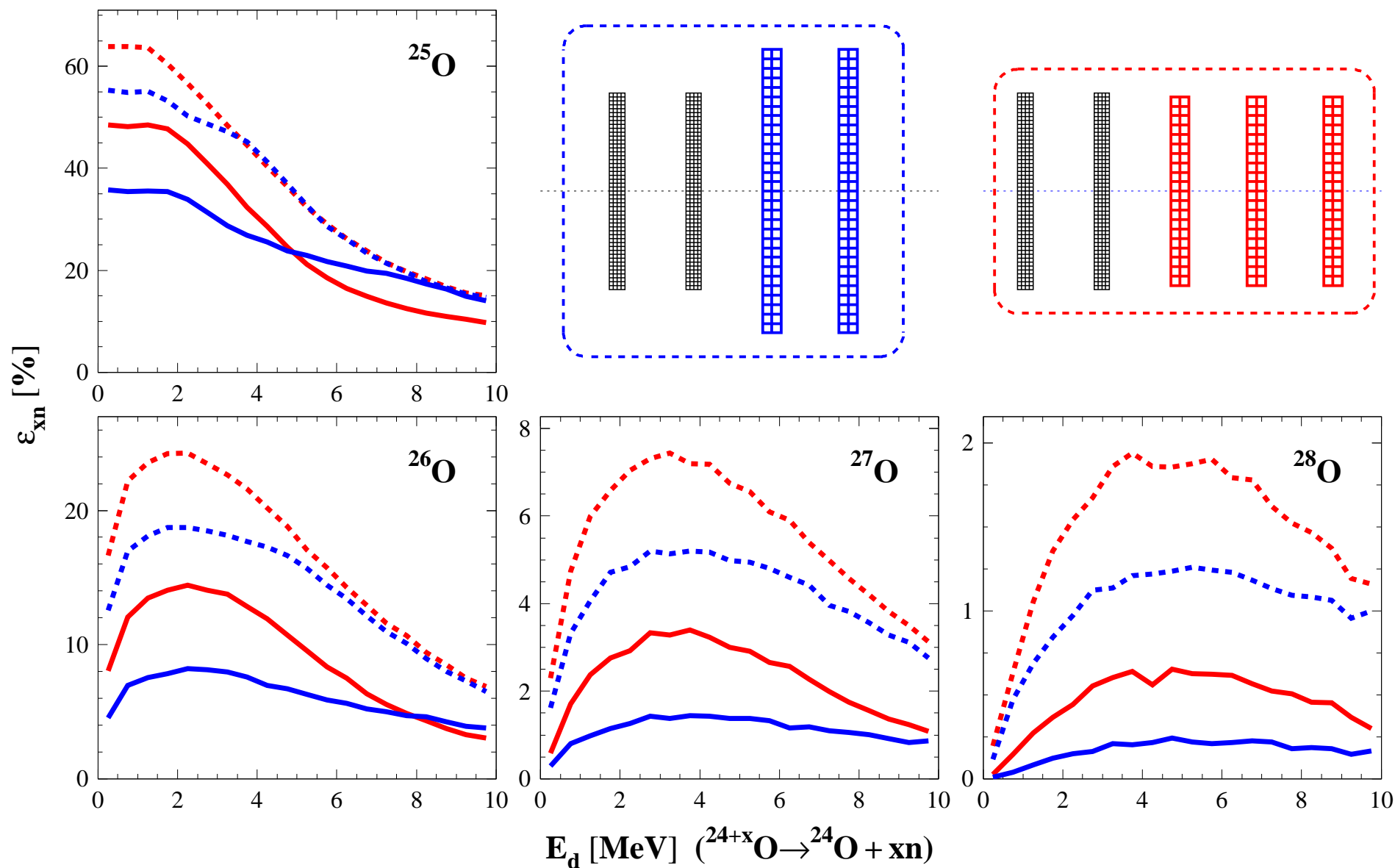
● Expand NEBULA **multi-n** capabilities :

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

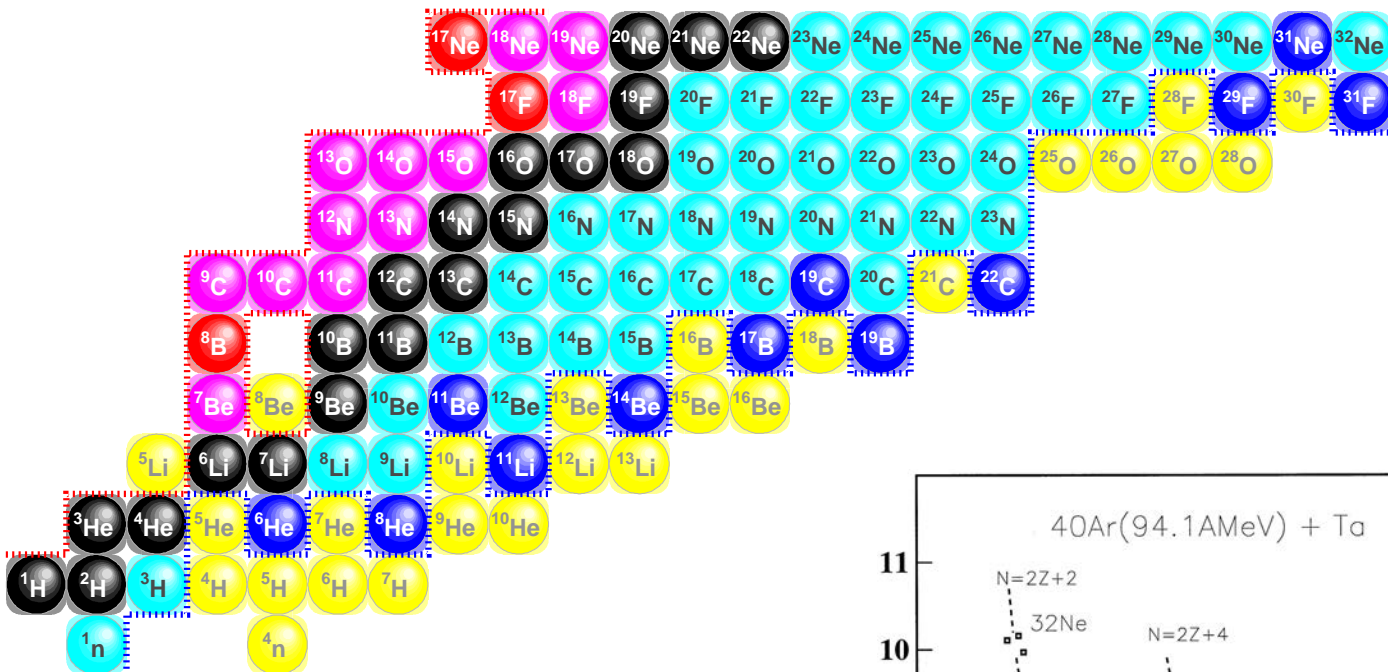
⇒ $\epsilon(4n)$ enhanced $\sim \times 16$!



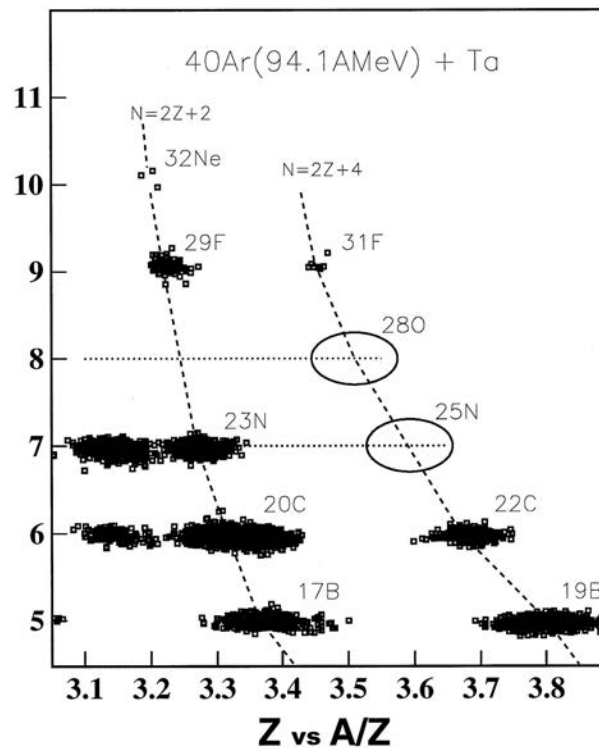
($\epsilon_{xn} < \epsilon_n^x$ due to neutron cross-talk FMM, NIM A 450 (2000) 109)



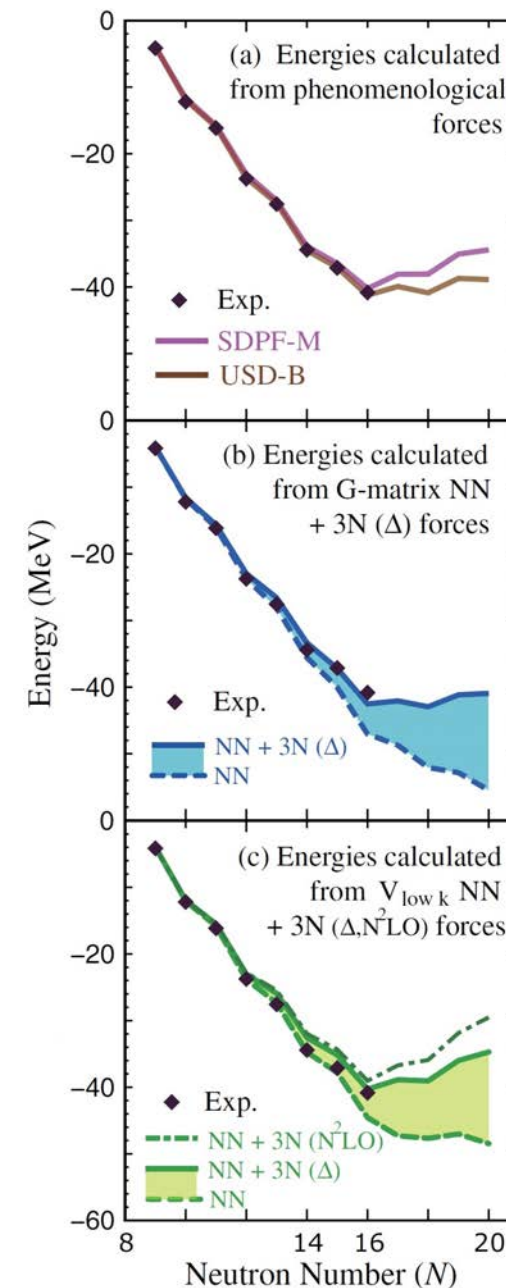
Oxygen 28 & the Tetraneutron



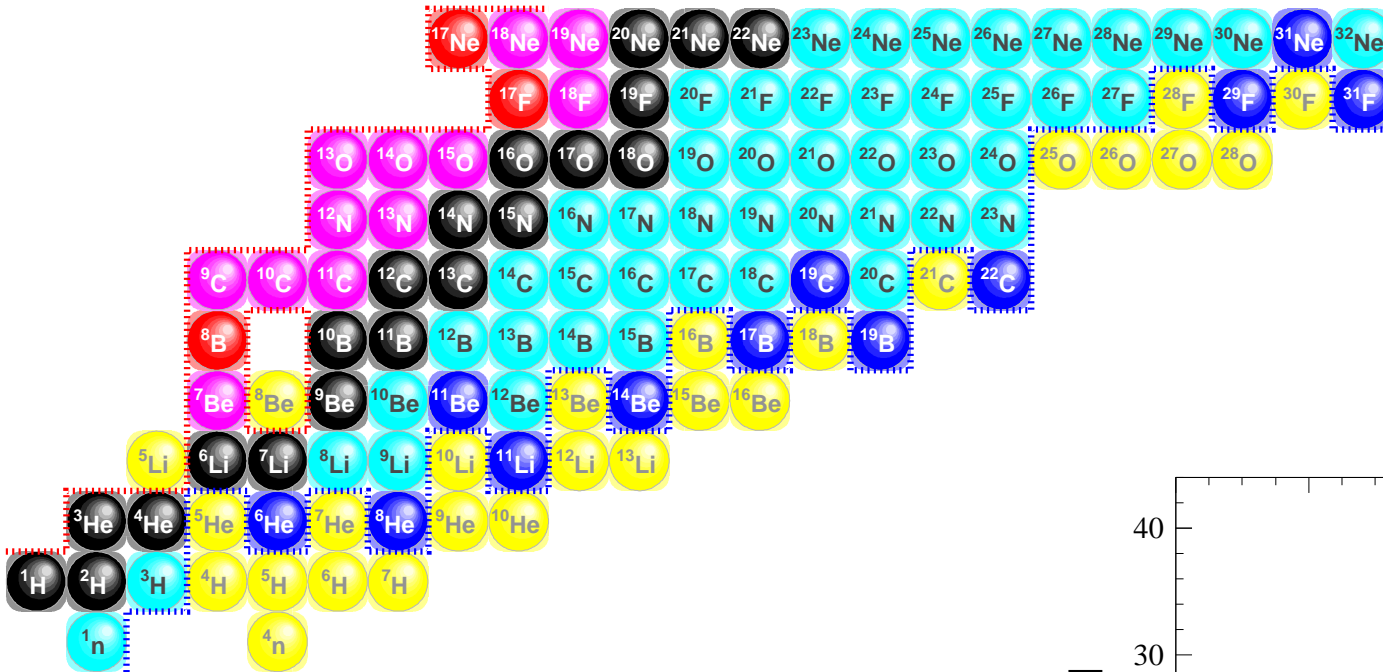
● The “Oxygen anomaly” :



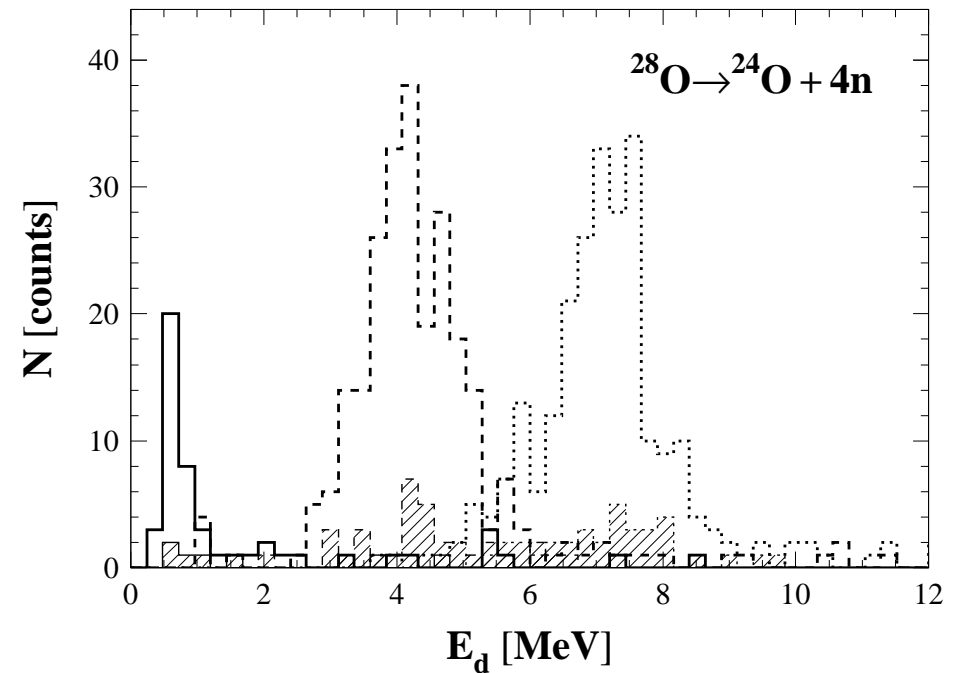
Sakurai, PLB 448 (1999) 180



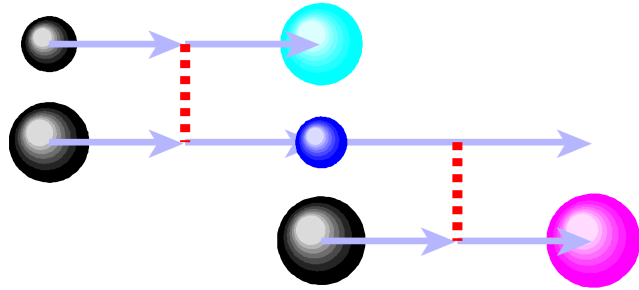
Otsuka, PRL 105 (2010) 032501



- The “Oxygen anomaly” :
 - ^{29}F beam at 25/s
 - MINOS Hydrogen target
 - (p,2p) about 1 mb
 - 10 days ~ 150 $^{24}\text{O}+4\text{n}$!
 - heaviest O : $^{29,31}\text{F}$!!!

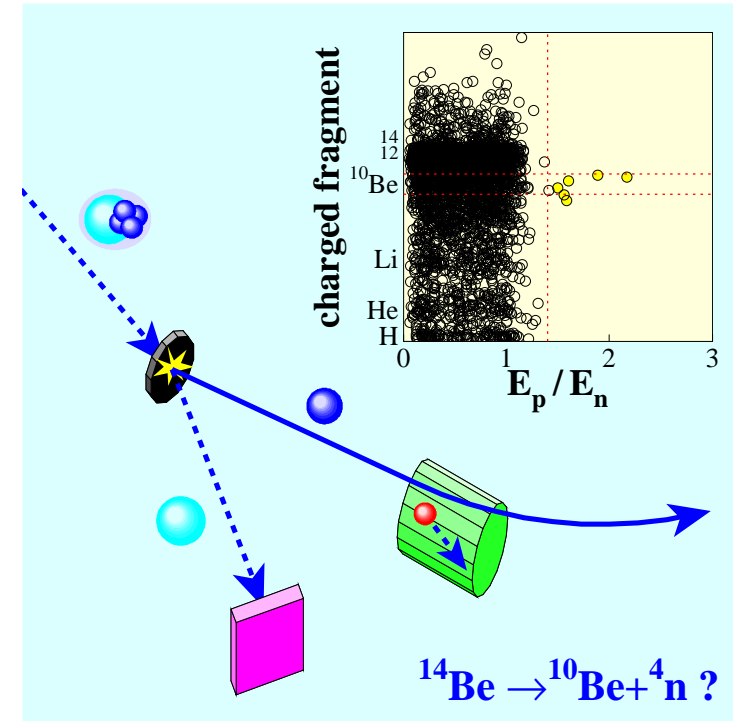
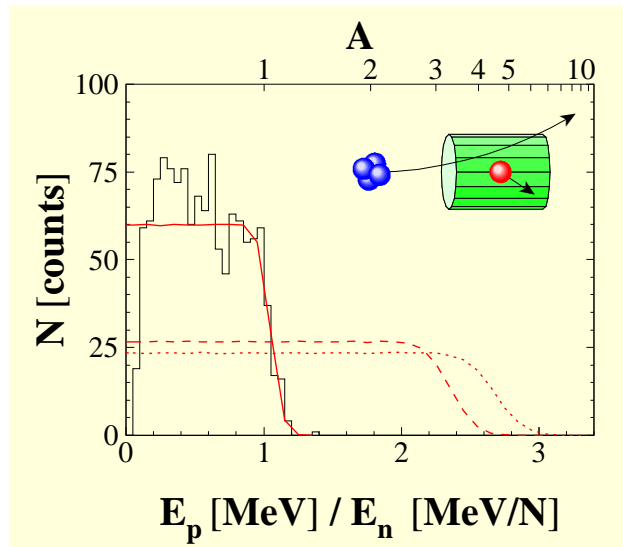


- 1960s-2000s :



⇒ all **binary** or **two-step** reactions

- GANIL+ **DEMON** :



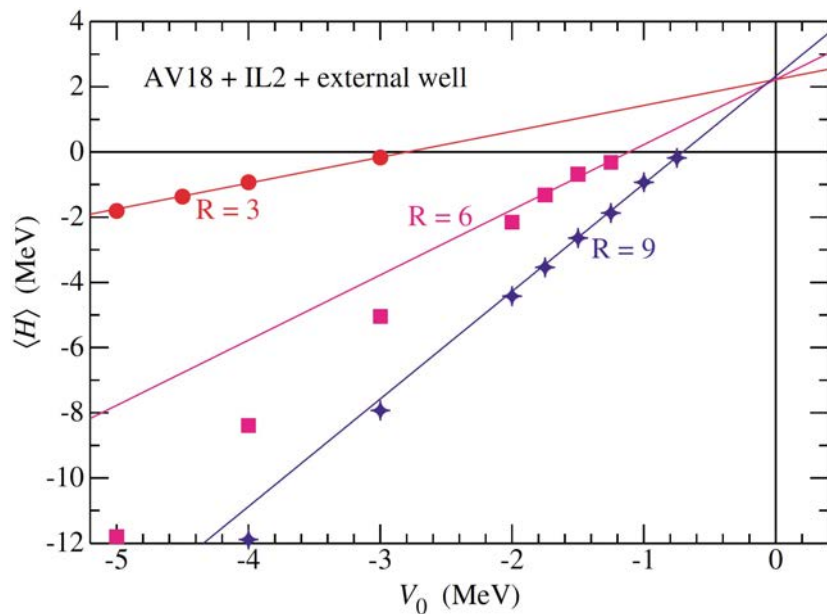
FMM, PRC 65 (2002) 044006

- Trigger of calculations :

- ($^4n, p$) scattering ?

■ Bertulani, PRC 69 (2004) 027601

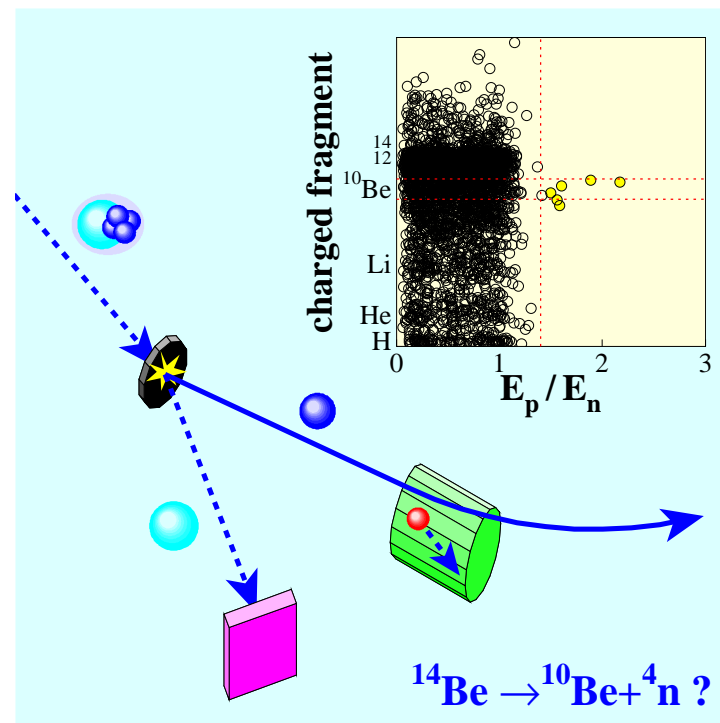
- bound, resonance (or nothing) ?



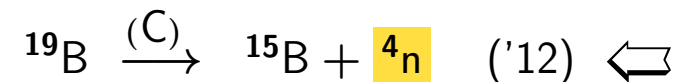
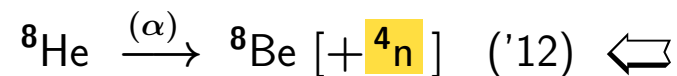
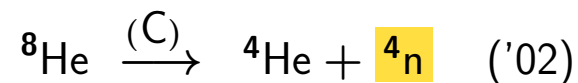
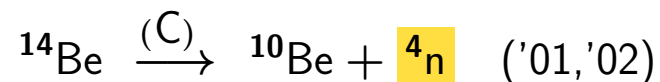
■ Pieper, PRL 90 (2003) 252501

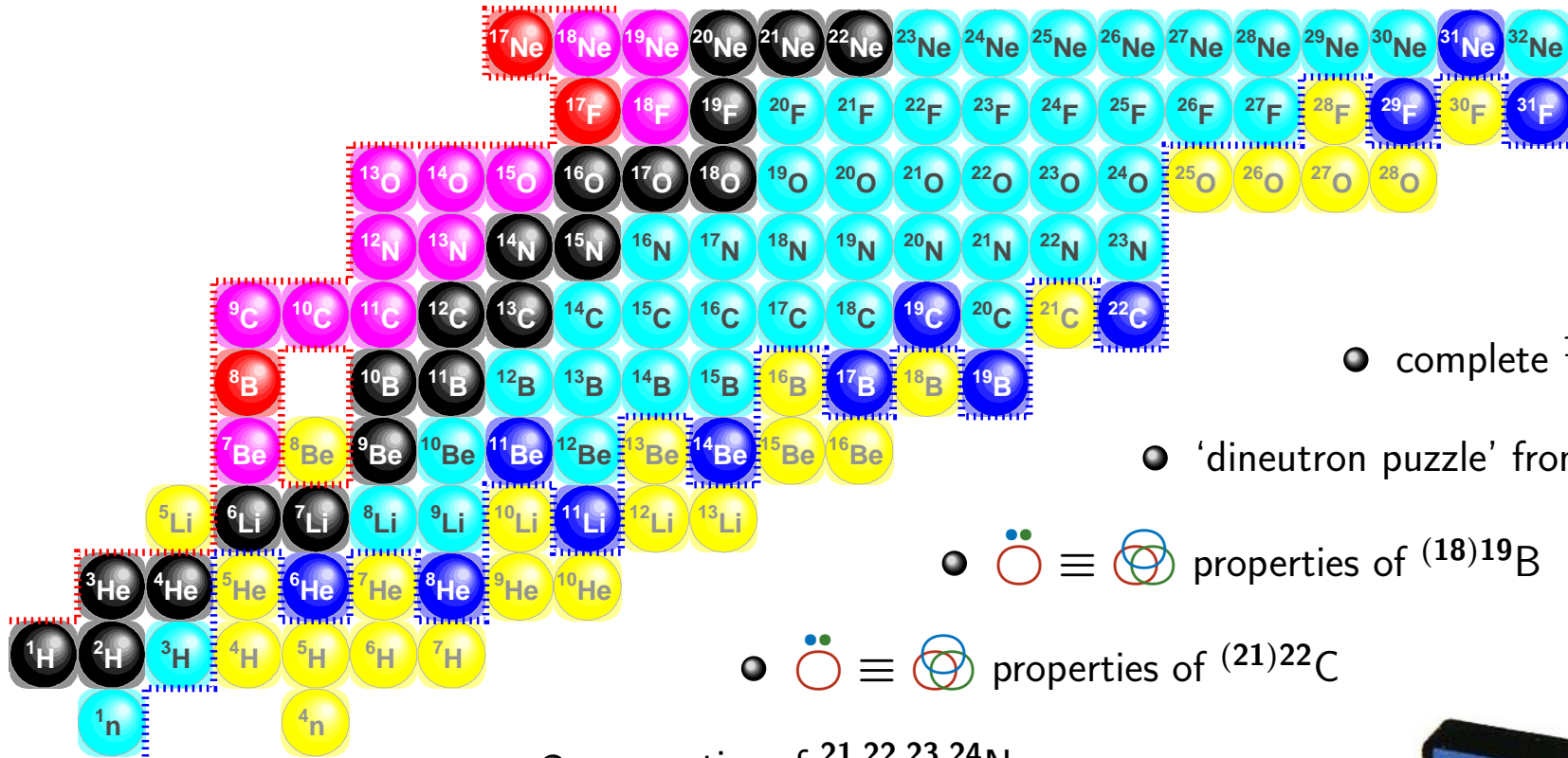
⇒ compatible with $E_R(^4n) \lesssim 2$ MeV !

■ FMMM, arXiv:nucl-ex/0504009

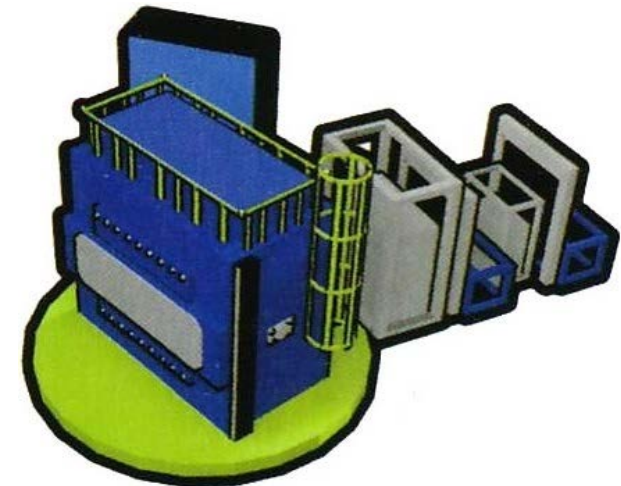


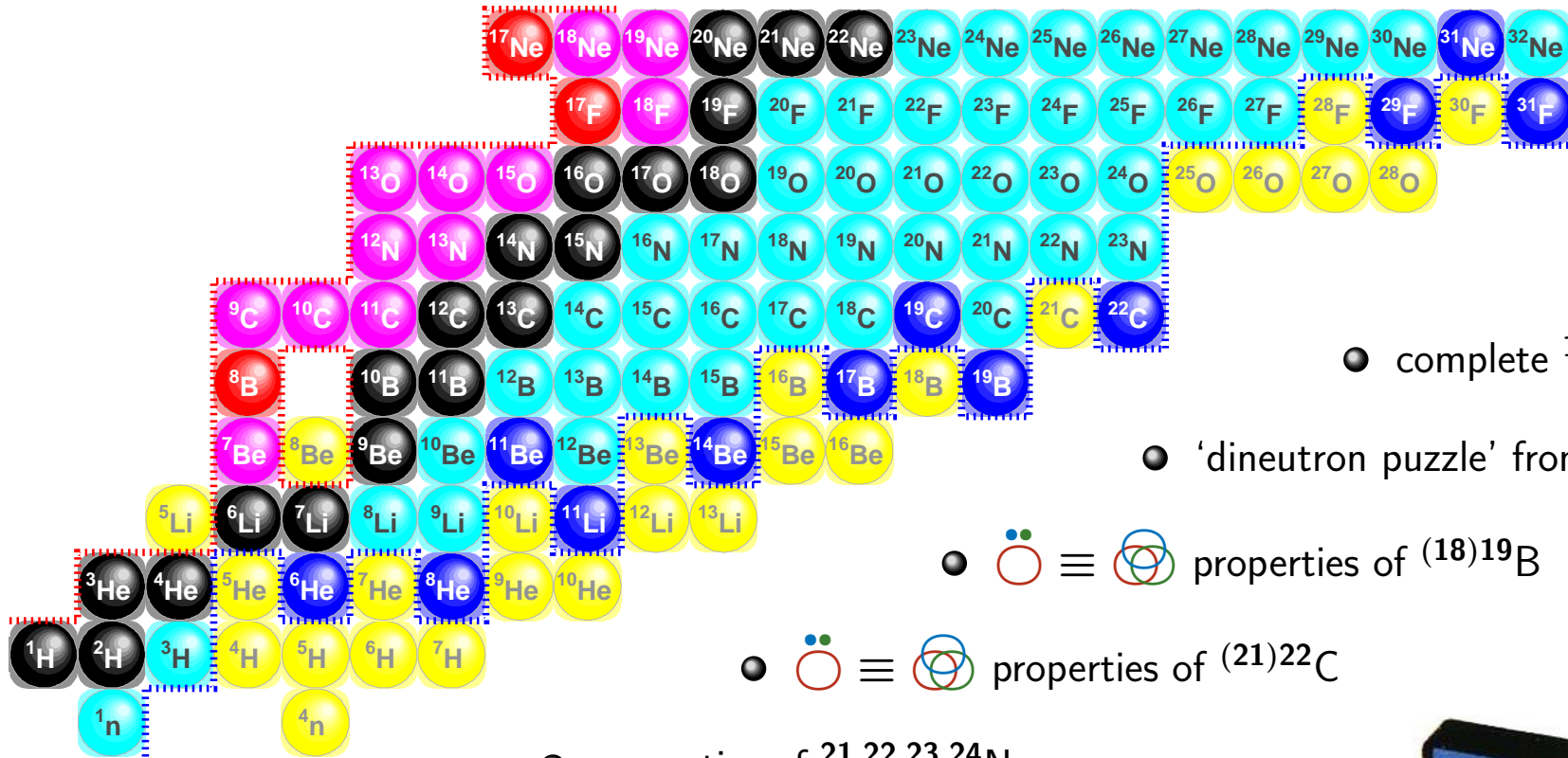
■ FMM, PRC 65 (2002) 044006





- complete $^{16,18,20,21}\text{B}$ analysis
- 'dineutron puzzle' from $^{(15)}^{16}\text{Be}$
- $\text{O} \equiv \text{O}$ properties of $^{(18)}^{19}\text{B}$
- $\text{O} \equiv \text{O}$ properties of $^{(21)}^{22}\text{C}$
- properties of $^{21,22,23,24}\text{N}$





- complete $^{16,18,20,21}\text{B}$ analysis

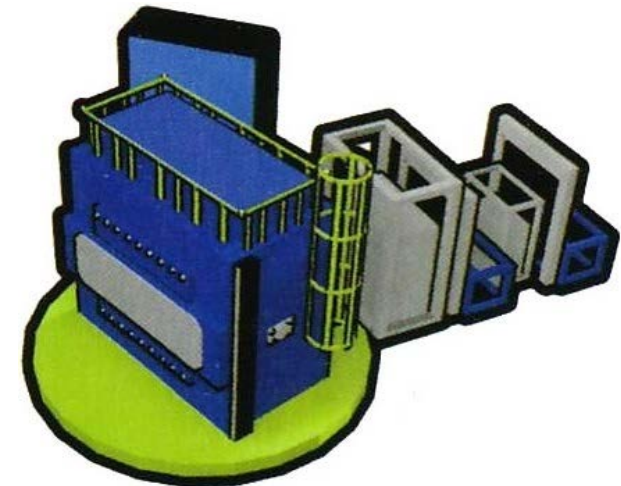
- 'dineutron puzzle' from $^{(15)}^{16}\text{Be}$

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- $\text{O} \equiv \text{C}$ properties of $^{(21)}^{22}\text{C}$

- properties of $^{21,22,23,24}\text{N}$

- proposal/LOI (NEBULA+)
- ^{28}O , ^4n & heavy F/Ne
 - ^{23}C & $^{24,25}\text{N}$
 - ^7H & ^4n , high statistics
 - ^{39}Mg ...



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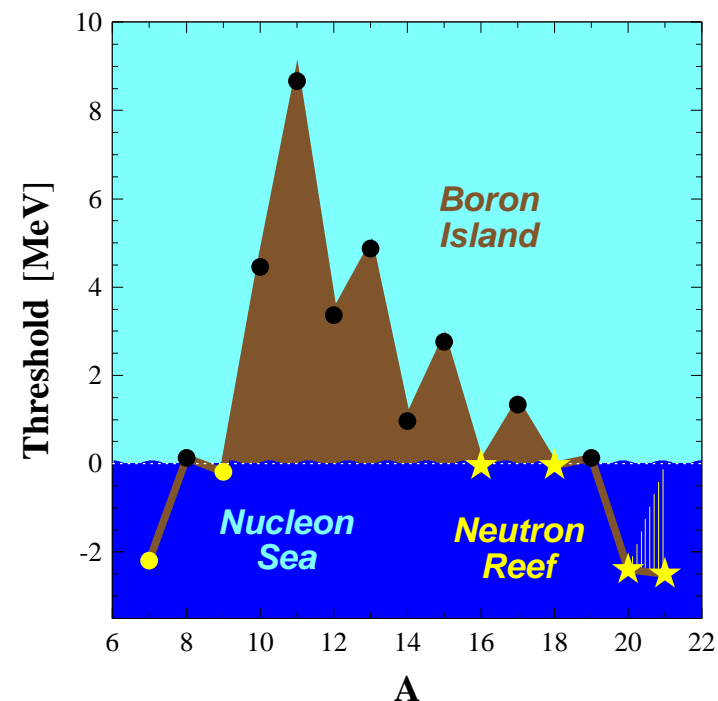


II. SAMURAI Day-1 campaign :

- SAMURAI & NEBULA
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GEANT4 / MENATE ...

- A simple 'toy' alternative ?
 - NEBULA geometry
 - MENATE_R interaction **probabilities**
 - $\sigma(E, \theta)$ from QFS + p recoil ...
 - check with ${}^7\text{Li}(p,n){}^7\text{Be}$ data :

Algorithms for
Neutron
Identification in
Modular
Experiments

