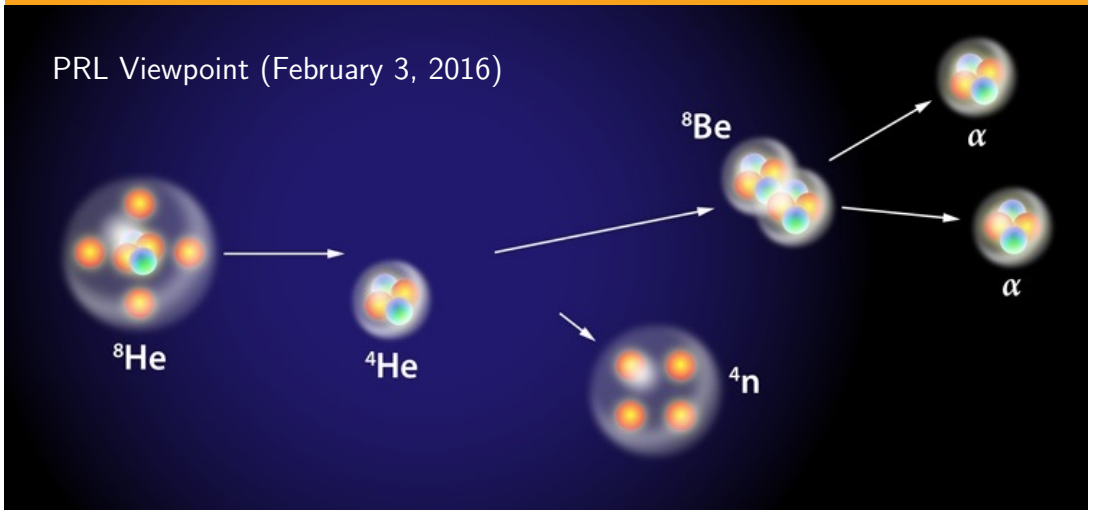
FUSTIPEN Topical Meeting

"Future directions for nuclear structure and reaction theories: Ab initio approaches for 2020"

March 14-18, 2016, GANIL (France)

Can Four Neutrons Tango?



F. Miguel Marqués

lpc caen
Laboratoire de physique corpusculaire

Outline

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- extremely difficult to produce
- potential impact in many fields
- experimental program for 50 years !

  → two-step processes (bound state)

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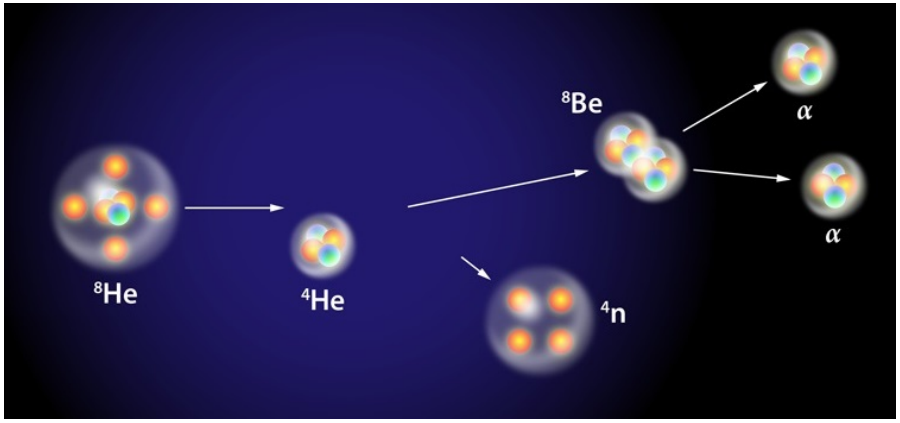

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- theory cannot predict 4n states ...
- need order(s) of magnitude improvement

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- SHARAQ 2.0
- NEBULA+NeuLAND & MINOS :

  → (p,pα) : 4n without FSI

  → ^{7}H 4n-decay : sensitive to any $(E,\Gamma)_{\mathrm{R}}$

⇨ short-term solution to ^{4}n & ^{7}H !

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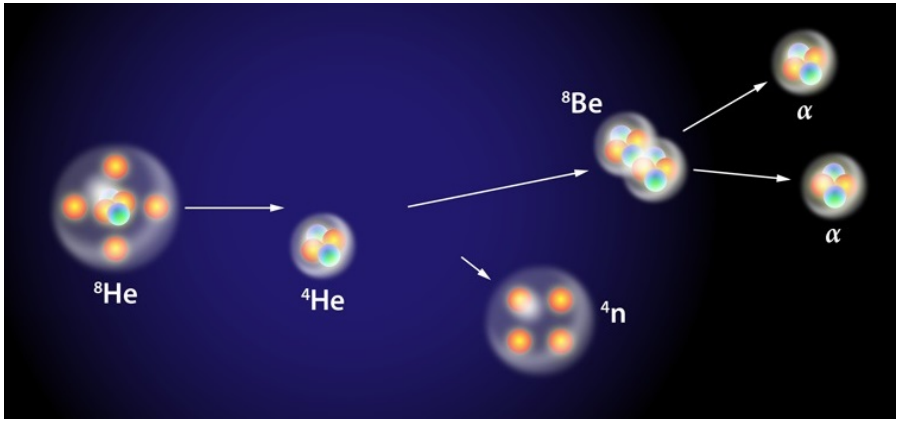

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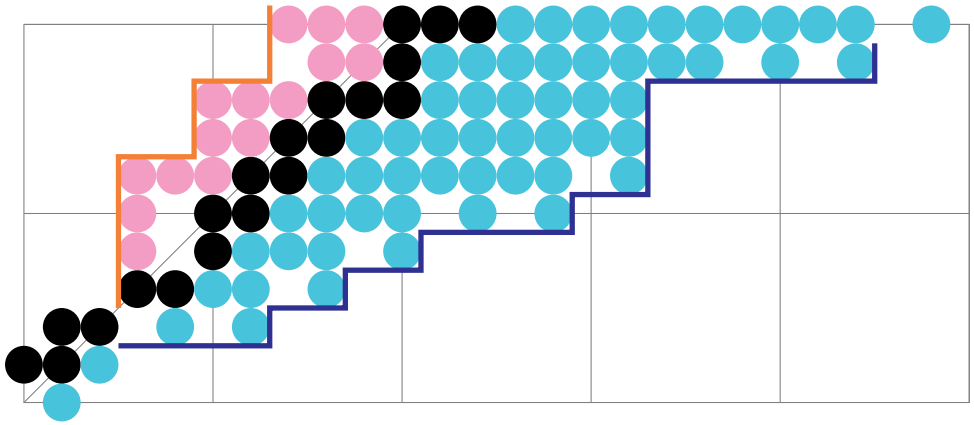

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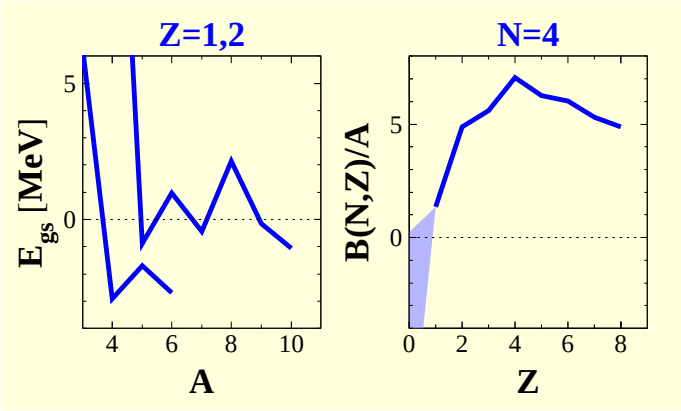
  - neutron stars are bound
  - masses of light nuclei :



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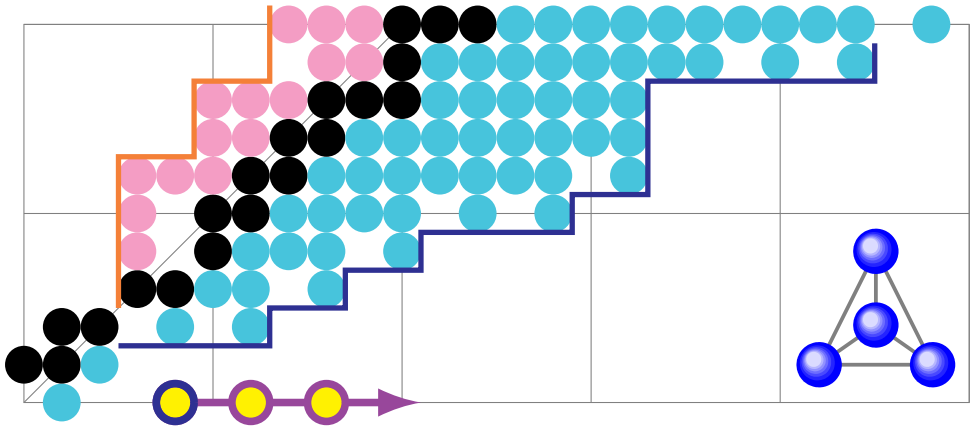

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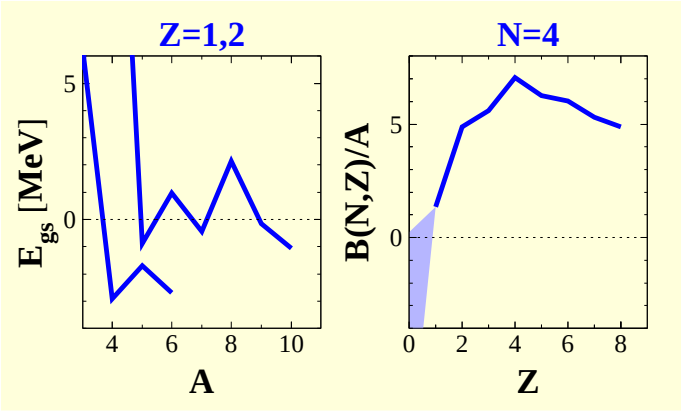

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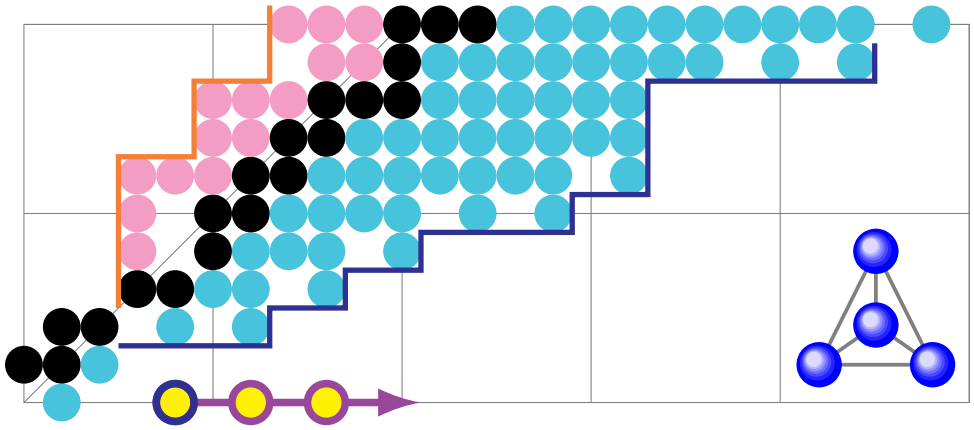

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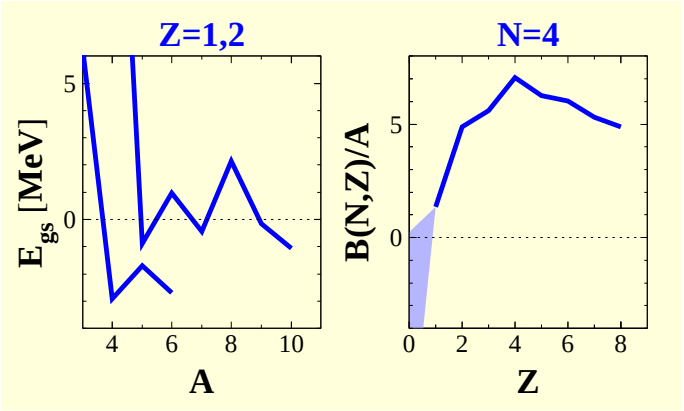

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- Implications ?
  - bound multi-neutrons :

    → Big Bang nucleosynthesis

    → neutral ('dark') matter
  - any multi-neutron :

    → n-n interaction

    → few-body (3-4) effects

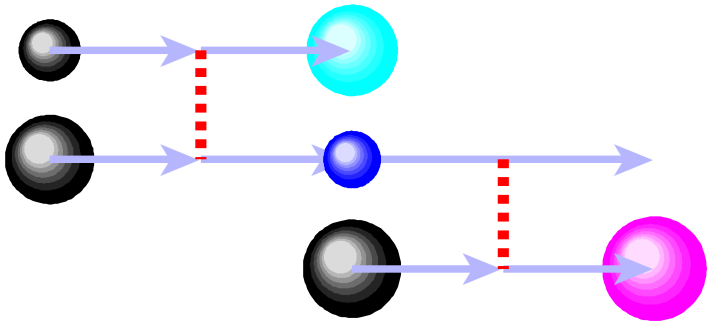
    → neutron stars ...

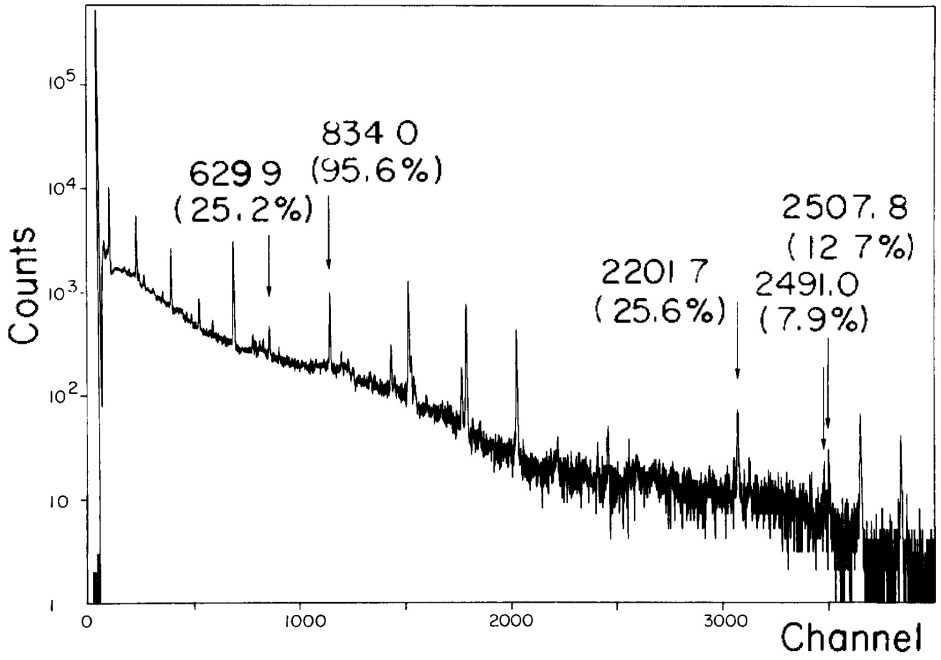
    → multi-neutron + few protons ?

Experimental Program since 1960s !

- Two-step reactions :
  - $p + W \longrightarrow {}^{A}n + {}^{70}Zn \rightarrow {}^{72}Zn$ $(\rightarrow {}^{72}Ga)$!!!

    Detraz, PLB 66 (1977) 33 ☜





✗ ^{70}Zn (t,p) ^{72}Zn through Aluminium ...

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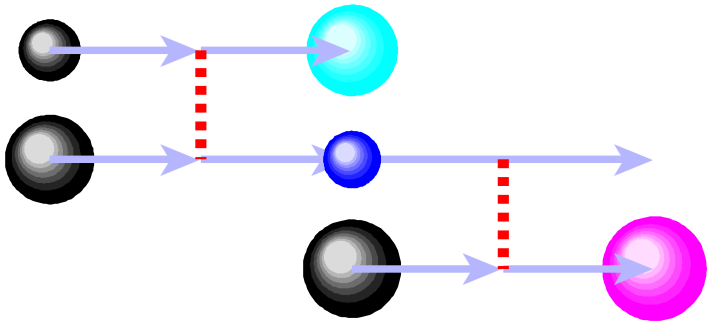

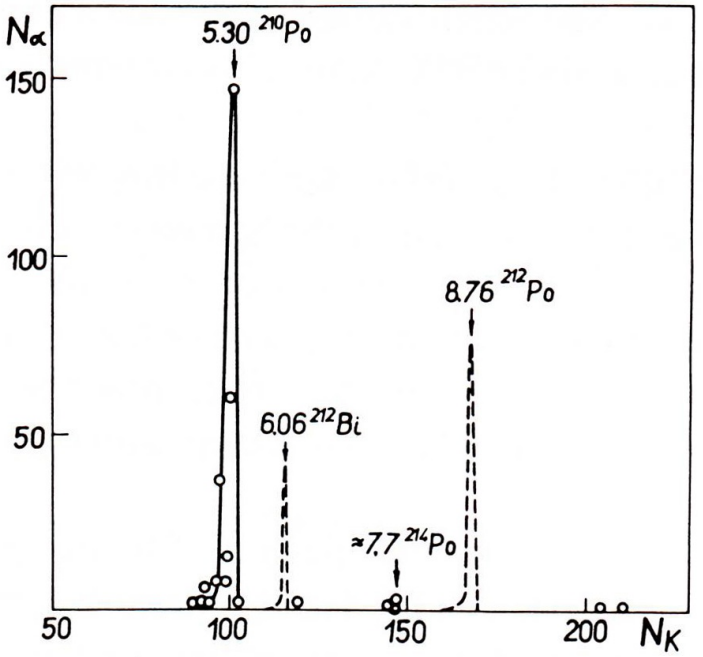

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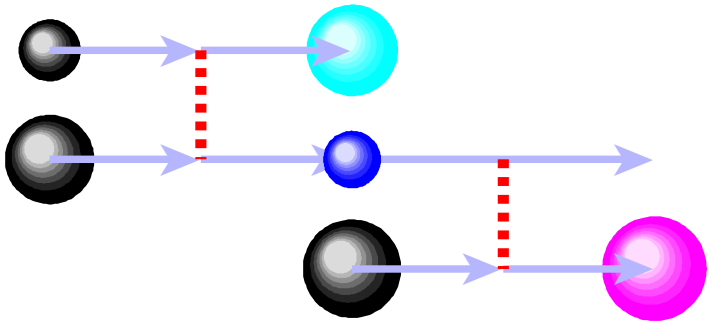

- Pion charge-exchange :
  - ${}^{3}H\,(\pi^-, \gamma)\,3n$
    Miller, NPA 343 (1980) 347
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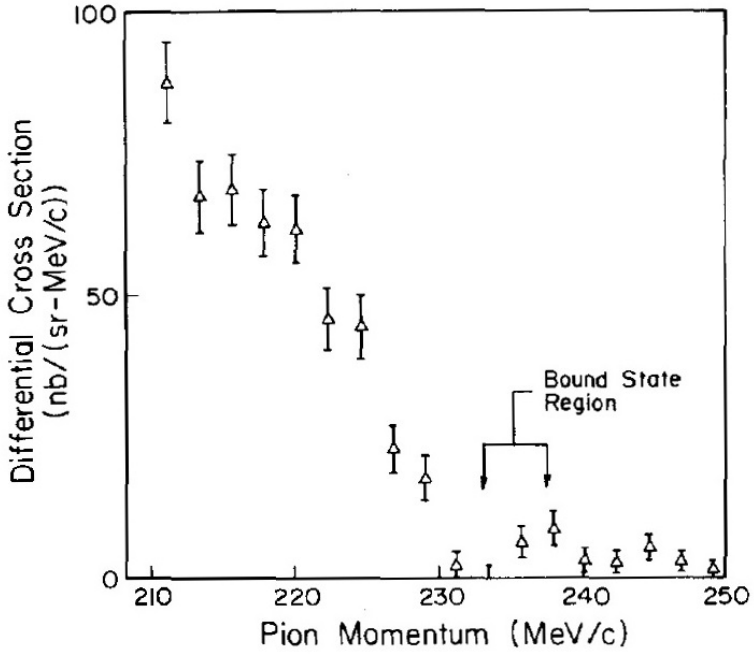
    Ungar, PLB 144 (1984) 333



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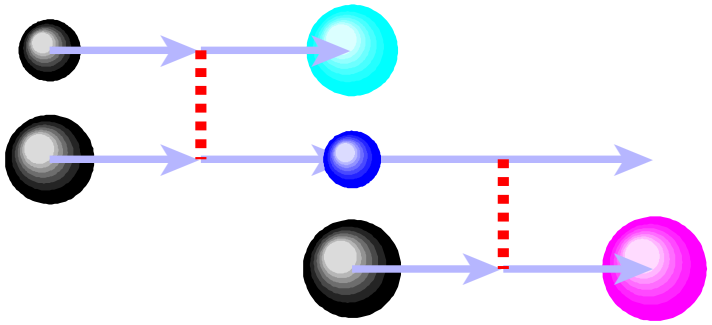

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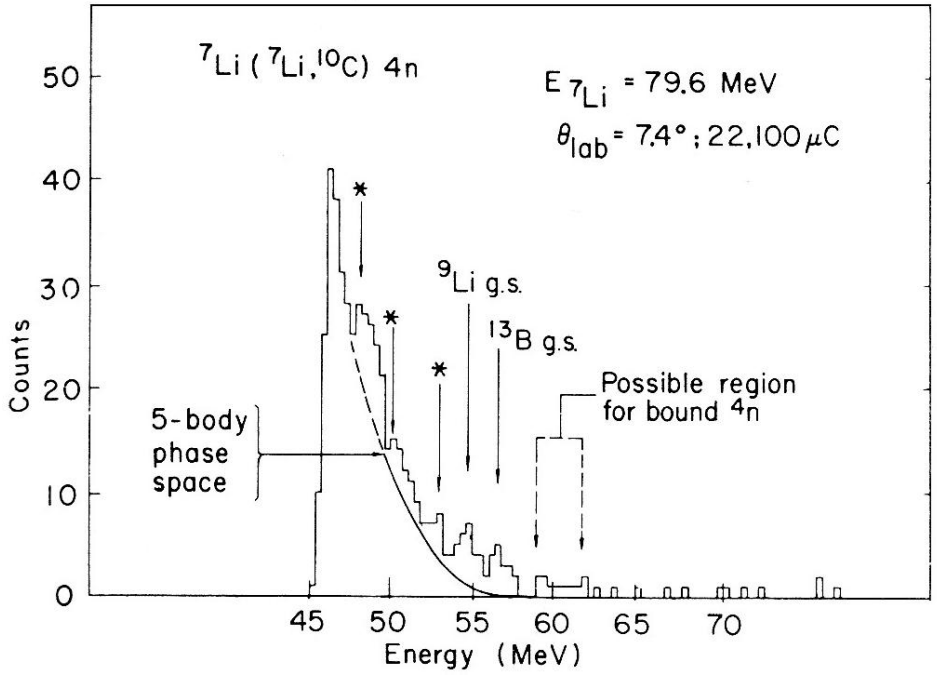


- Multinucleon transfer :
  - ${}^{7}Li + {}^{11}B \rightarrow {}^{14}O + 4n$
    - Belozyorov, NPA 477 (1988) 131
  - ${}^{7}Li + {}^{7}Li \rightarrow {}^{10(11)}C + 4(3)n$
    - Cerny, PLB 53 (1974) 247

☜

⇨ XX century : cross-sections & backgrounds ...

ISSN 0021 3640, JETP Letters, 2013, Vol. 98, No. 11, pp. 656–660. © Pleiades Publishing, Inc., 2013.
Original Russian Text © B.G. Novatsky, S.B. Sakuta, D.N. Stepanov, 2013, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2013, Vol. 98, No. 11, pp. 747.

Detection of Light Neutron Nuclei in the Alpha-Particle-Induced Fission of ^{238}U by the Activation Method with ^{27}Al

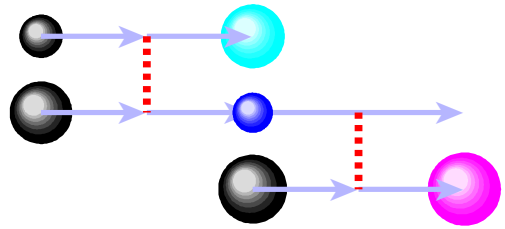
B. G. Novatsky, S. B. Sakuta*, and D. N. Stepanov

National Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia

** e mail: sbsakuta@mail.ru*

Received October 30, 2013

Light nuclear-stable multineutrons among products of the fission of ^{238}U nuclei that is induced by 62-MeV alpha particles have been searched by the activation method with a ^{27}Al sample. These multineutrons have been detected by characteristic gamma rays emitted by the nuclei from the beta-decay chain ^{28}Mg $\longrightarrow$ ^{28}Al $\longrightarrow$ ^{28}Si. The ^{28}Mg parent nucleus can be formed in the ^{27}Al + ^{x}n $\longrightarrow$ ^{28}Mg + $p(x-2)n$ process. The gamma-ray spectra of the irradiated sample exhibit lines of 1342- and 1779-keV photons accompanying the beta decay of the ^{28}Mg and ^{28}Al nuclei, respectively. The decrease in the activity corresponds within the measurement accuracy with the half-life $T_{1/2}$ ~ 21 h of ^{28}Mg, which certainly indicates the detection of nuclear-stable multineutrons ^{x}n with $x \geq 6$.



$$\alpha + {}^{238}\mathrm{U} \longrightarrow {}^{A}\mathrm{n} + {}^{27}\mathrm{Al} \rightarrow {}^{28}\mathrm{Mg}$$

1. INTRODUCTION

The problem of stability of nuclei consisting of neutrons only has long been actively studied both experimentally and theoretically. Interest in this problem is quite understandable, since the discovery of neutron nuclei would be revolutionarily important for nuclear physics and would radically change our representations on the nucleon–nucleon interaction with far-reaching consequences not only for nuclear physics but also for other fields of science, in particular, astrophysics. This discovery would be applied with the appearance of the possibility of the accumulation of neutron matter.

It is well known that two neutrons do not form a bound nuclear system. The overwhelming majority of experimental investigations indicate that the systems of three and four neutrons are also unstable.

Thus, the negative result of numerous searches for ^{2}n–^{4}n nuclei [5–9] does not exclude the existence of heavier neutron clusters.

2. DESCRIPTION OF THE EXPERIMENT

The primary target (a ^{238}U foil 160 μm thick) placed at the center of a scattering chamber was bombarded with a beam of 62-MeV alpha particles accelerated at the cyclotron of the Kurchatov Institute.

An aluminum sample with a mass of 2.8 g was placed in a hermetically sealed container installed in a vacuum scattering chamber at an angle of 20° with respect to an incident alpha-particle beam. An additional beryllium filter 1 mm thick was placed upstream of the aluminum sample in order to suppress the background of scattered alpha particles, tritons from the ^{238}U(α,t) reaction, and other charged particles. In view of a high activity in the room, the irradiated samples were transported and processed half an hour after irradiation.

In this case, the intense 1368- and 2754-keV gamma lines of the ^{24}Na isotope from the ^{27}Al (n, α) ^{24}Na (Q =3.13 MeV) reaction and the corresponding Compton background are the only factors hindering the reliable identification of gamma rays from the chain of nuclei ^{28}Mg → ^{28}Al → ^{28}Si.

4. CONCLUSIONS

To conclude, nuclear-stable multineutrons among products of the ternary fission of ^{238}U nuclei that is induced by 62-MeV alpha particles have been sought by the activation method.

The reported measurements confirm the results of our previous work [10], where the possible emission of multineutrons from the ternary fission of ^{238}U was established by characteristic 1384-keV gamma rays from the ^{88}Sr + ^{x}n → $(x-4)n$ + ^{92}Sr → ^{92}Y process in the activated strontium sample. Comparison showed that the yield of ^{28}Mg in the case of the interaction of multineutrons with ^{27}Al is an order of magnitude higher than the yield of ^{92}Sr.

The results of two independent experiments indicate that nuclear-stable multineutrons (most likely, ^{6}n) are emitted from the alpha-particle-induced ternary fission of ^{238}U. In the future, we are going to improve the statistics of the measurements by increasing the intensity of the beam and irradiation time of sample.

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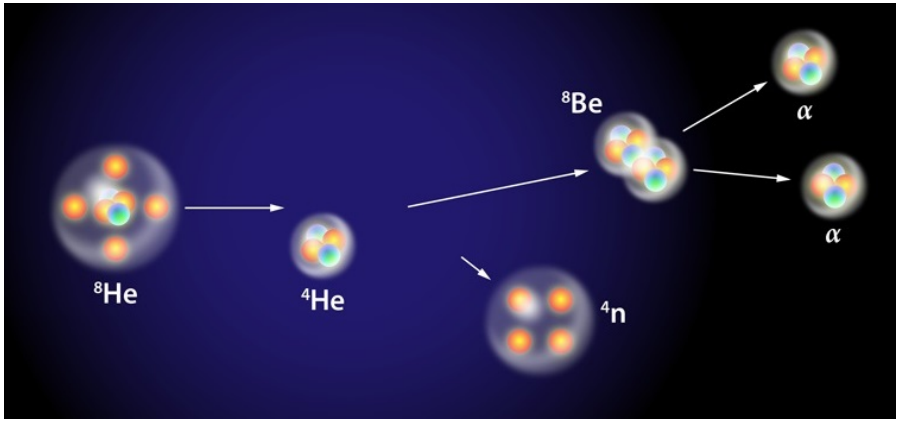

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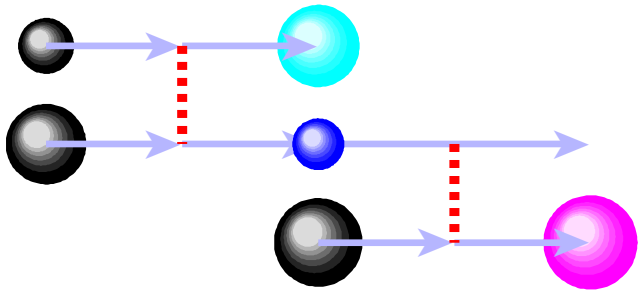

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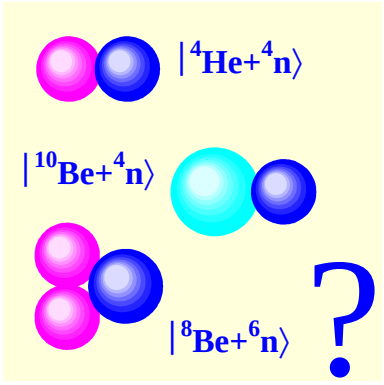
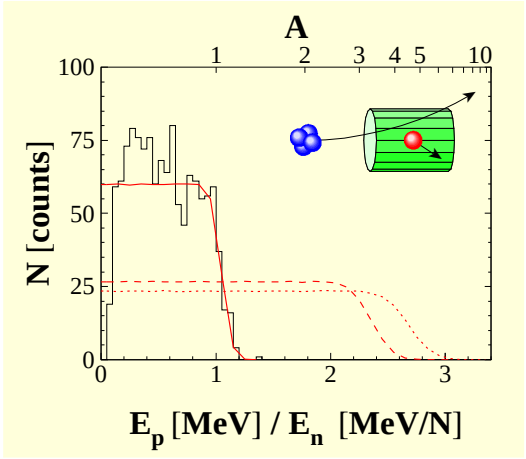
  - 2nd step : sensitive probe !





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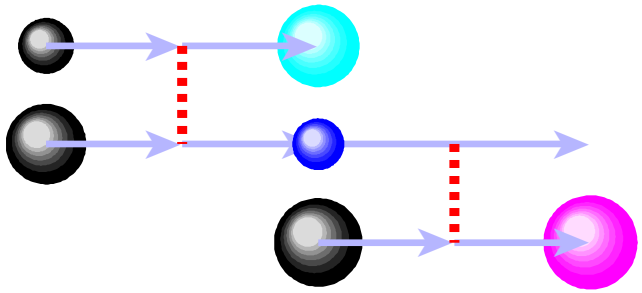

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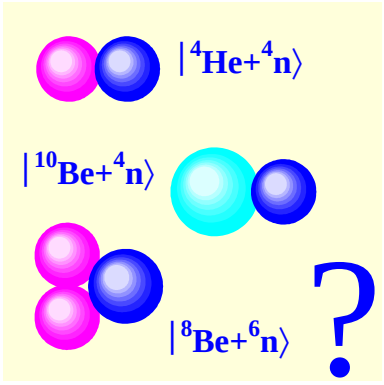

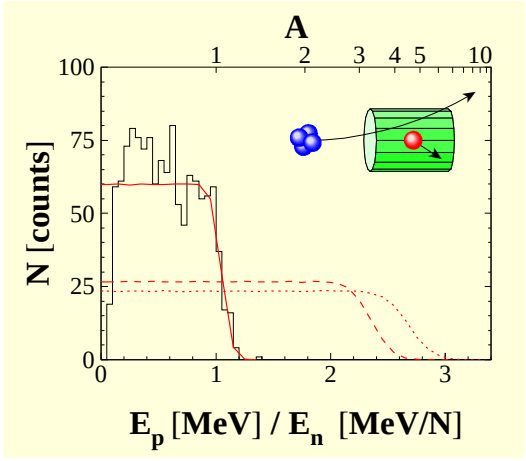

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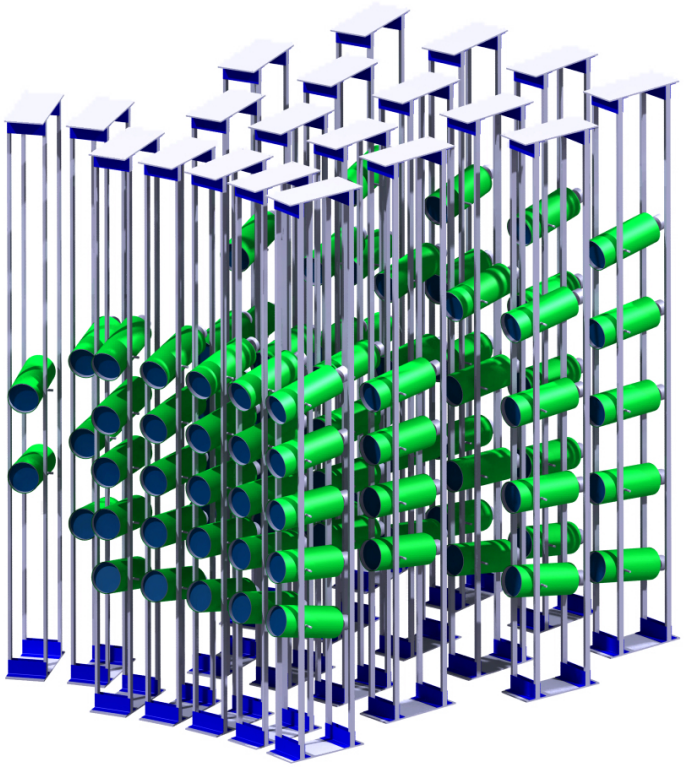

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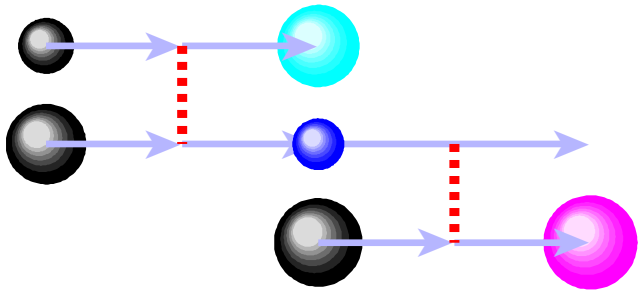

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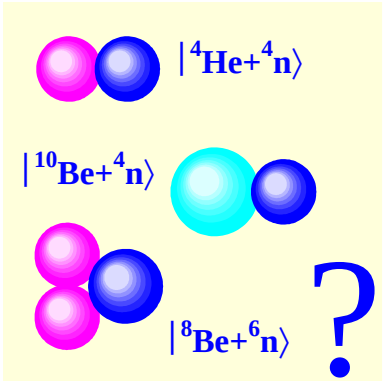

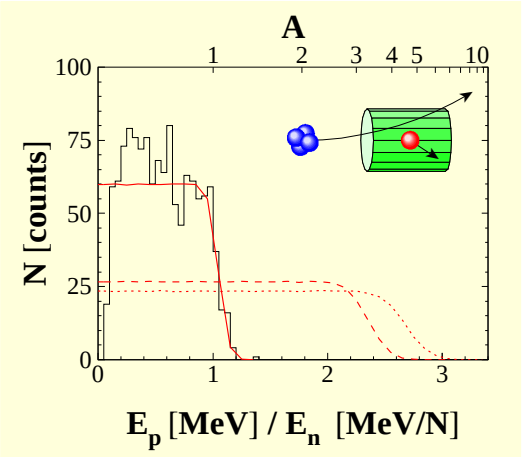

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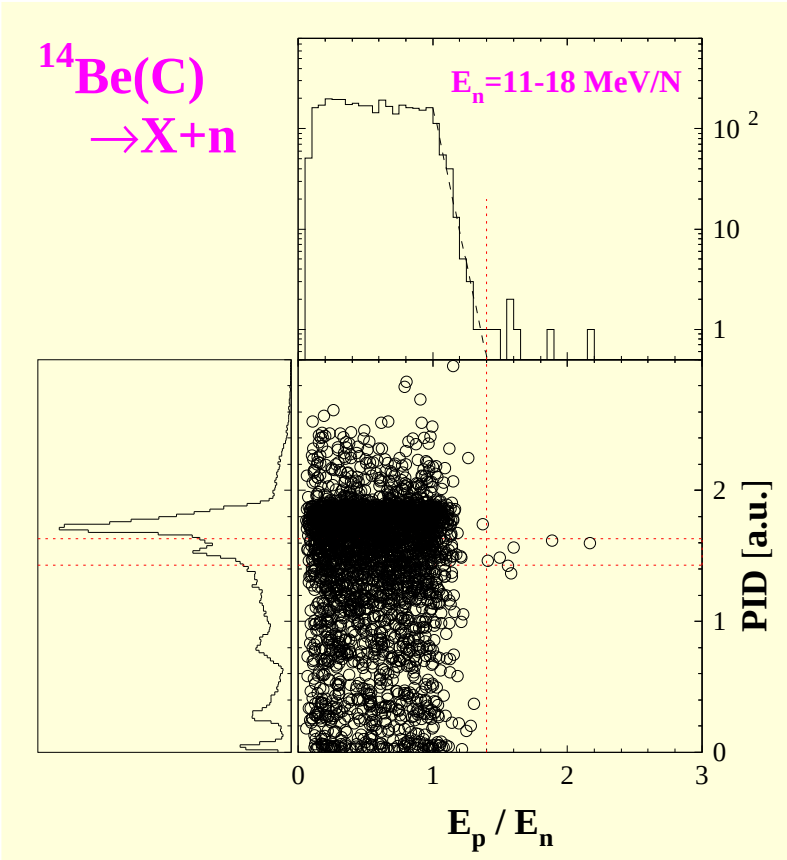

FMM, PRC 65 (2002) 044006

→ first positive claim !

→ trigger of calculations & experiments

Is the Tetraneutron Possible ?

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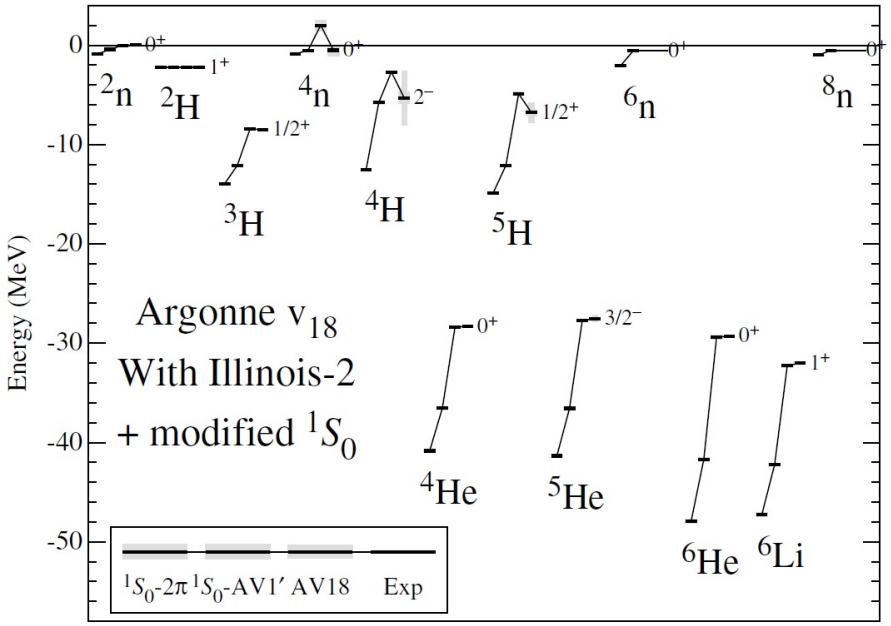
  - (^{4}n,p) elastic scattering ?

    Bertulani, PRC 69 (2004) 027601

  - bound or resonance (or nothing) ?



Pieper, PRL 90 (2003) 252501

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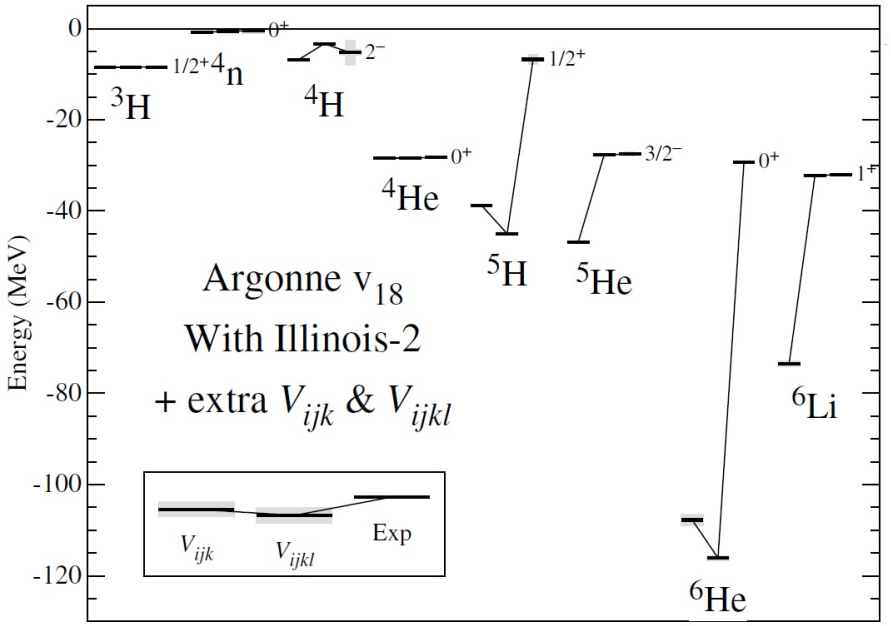

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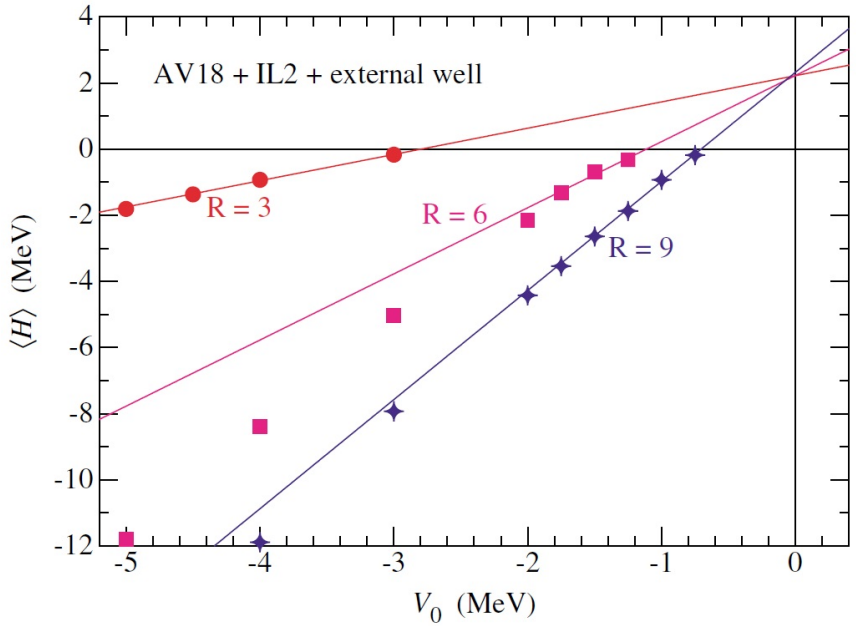

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Lazauskas, Carbonell, PRC 71 (2005) 044004

Lazauskas, Carbonell, PRC 72 (2005) 034003

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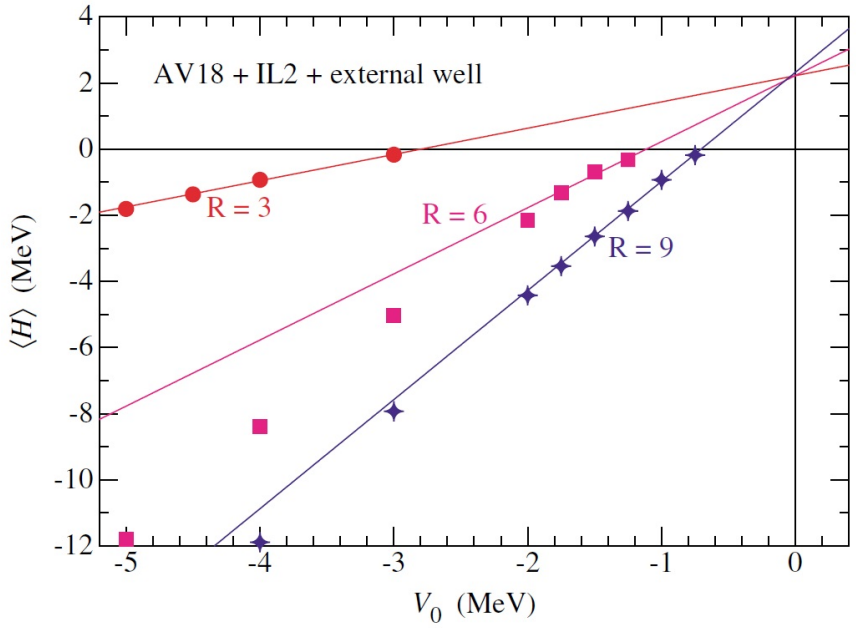


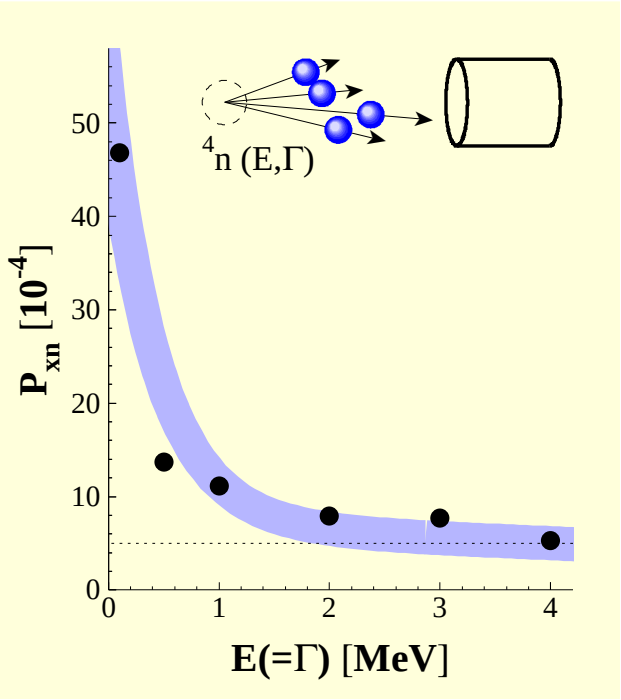
Pieper, PRL 90 (2003) 252501

Lazauskas, Carbonell, PRC 71 (2005) 044004

Lazauskas, Carbonell, PRC 72 (2005) 034003

- Candidate evts also compatible with :
  - (^{4}n,p) breakup
  - $E_R(^4n) \lesssim 2$ MeV !

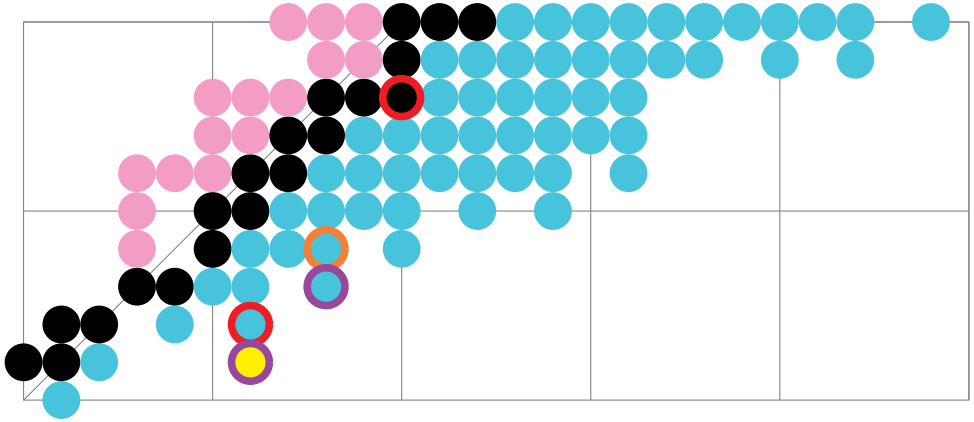
FMM, arXiv:nucl-ex/0504009

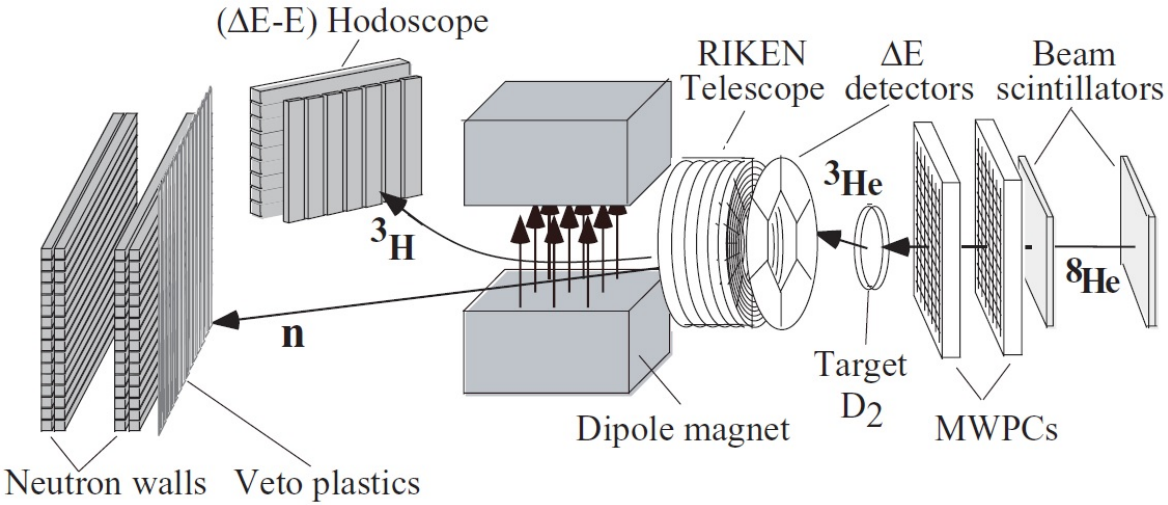


→ P_{xn} due to ^{4}n resonance : $\times 10$!

→ 4n phase space : lower limit ...

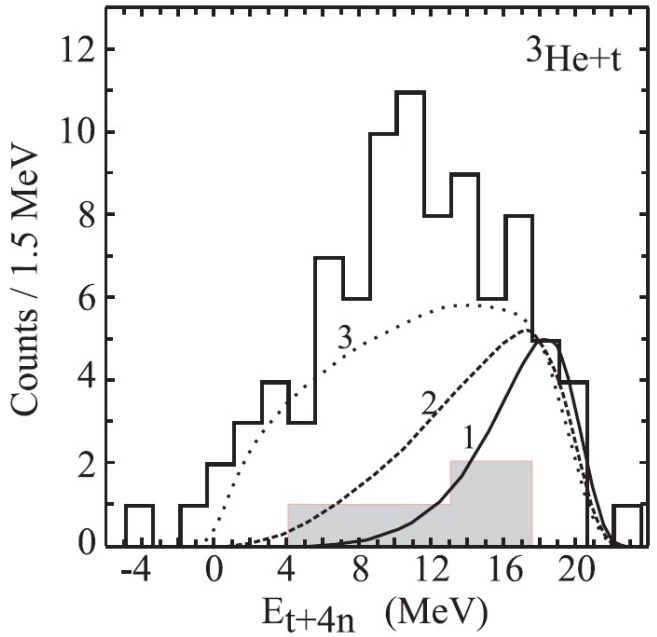
'Russian' Hydrogen 7 [E.Yu. Nikolskii]





Nikolskii, PRC 81 (2010) 064606

▶ ^{8}He (d,^{3}He) ^{7}H @ 42 MeV/N :

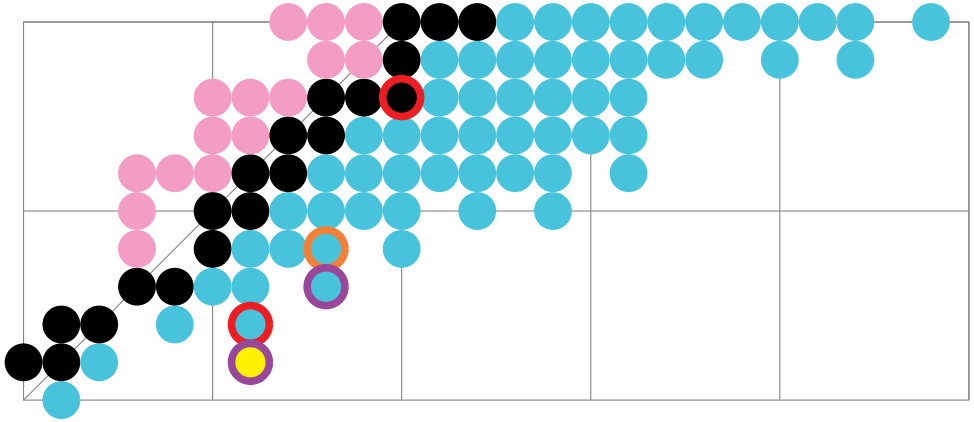


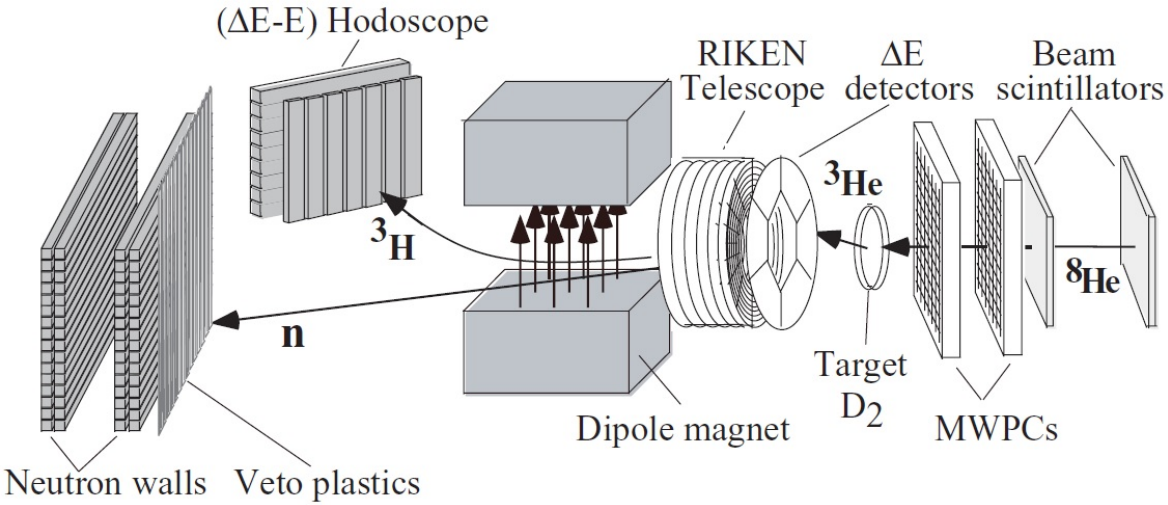
"a peculiarity at ∼ 2 MeV" ?

1) 5-body (t+n+n+n+n) PS

2) 3-body (t+2n+2n) PS

'Russian' Hydrogen 7 [E.Yu. Nikolskii]





Nikolskii, PRC 81 (2010) 064606

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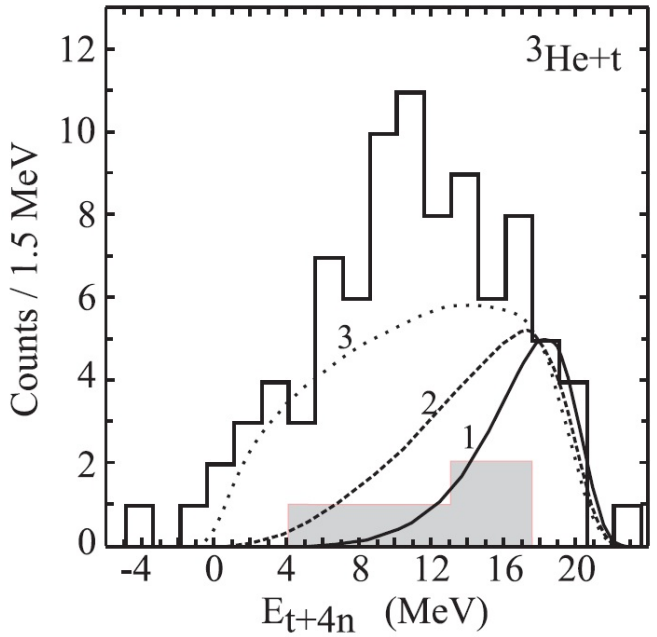


"a peculiarity at ∼ 2 MeV" ?

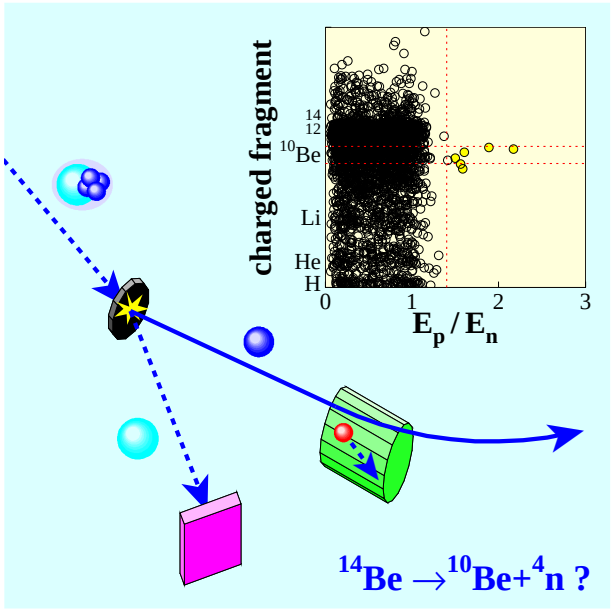
1) 5-body (t+n+n+n+n) PS

2) 3-body (t+2n+2n) PS

3) 2-body (t+4n) PS !

"extreme, unrealistic case" !!!

- The DEMON campaigns :



$$^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n} \qquad (\text{'01,'02})$$

$$^{8}\mathrm{He} \xrightarrow{(C)} {}^{4}\mathrm{He} + {}^{4}\mathrm{n} \qquad (\text{'02})$$

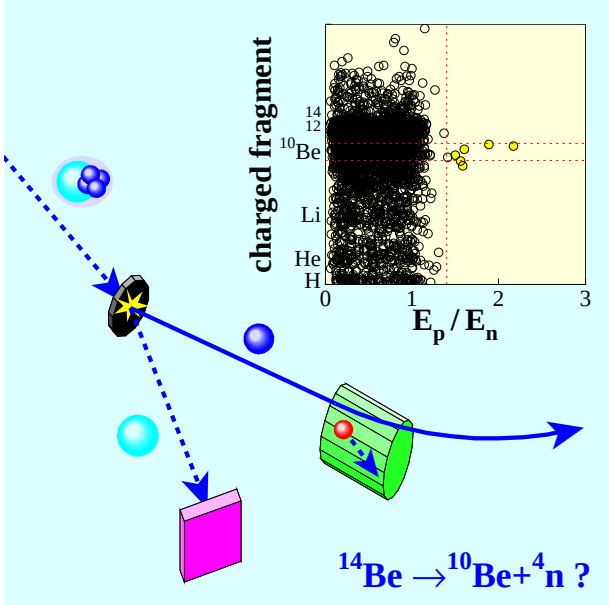
$$^{12/14}\mathrm{Be} \xrightarrow{(C)} \alpha\alpha + {}^{4/6}\mathrm{n} \qquad (\text{'02})$$

$$^{15}\mathrm{B} \xrightarrow{(C)} {}^{14}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{n} \qquad (\text{'05,'06})$$

⇨ experimental program stopped ...

New Experiments at GANIL ... and RIKEN

- The DEMON campaigns :



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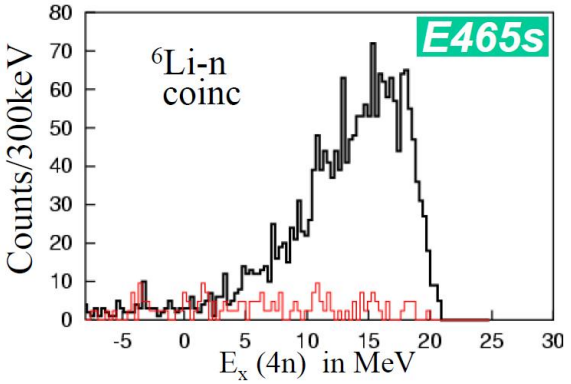
$$^{15}\mathrm{B} \xrightarrow{(C)} {}^{14}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{n} \quad (\text{'05,'06})$$

$\Rightarrow$ experimental program stopped ...

- MUST collaboration :

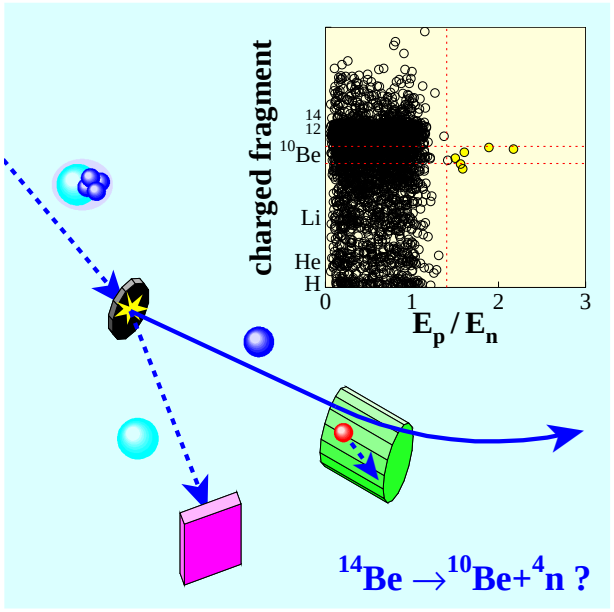
$$^{8}\mathrm{He} \xrightarrow{(d)} {}^{6}\mathrm{Li}\ [+{}^{4}\mathrm{n}] \quad (\text{'02,'04})$$

$$^{8}\mathrm{He} \xrightarrow{(d)} {}^{4}\mathrm{He} + \mathrm{d}\ [+{}^{4}\mathrm{n}] \quad (\text{'04})$$



. . . . . .

- The DEMON campaigns :



$^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n}$ ('01,'02)

$^{8}\mathrm{He} \xrightarrow{(C)} {}^{4}\mathrm{He} + {}^{4}\mathrm{n}$ ('02)

$^{12/14}\mathrm{Be} \xrightarrow{(C)} \alpha\alpha + {}^{4/6}\mathrm{n}$ ('02)

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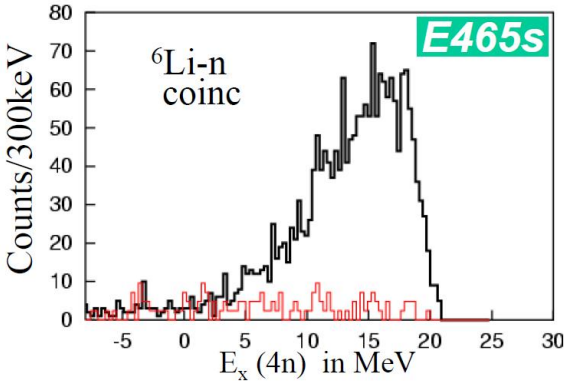
⇨ experimental program stopped ...

- MUST collaboration :

$^{8}\mathrm{He} \xrightarrow{(d)} {}^{6}\mathrm{Li}\ [+{}^{4}\mathrm{n}]$ ('02,'04)

$^{8}\mathrm{He} \xrightarrow{(d)} {}^{4}\mathrm{He} + \mathrm{d}\ [+{}^{4}\mathrm{n}]$ ('04)



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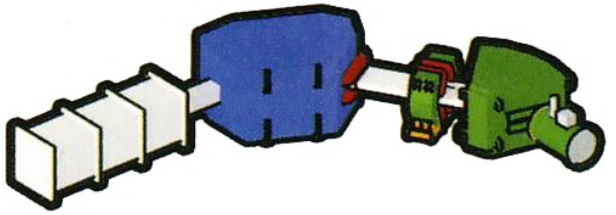
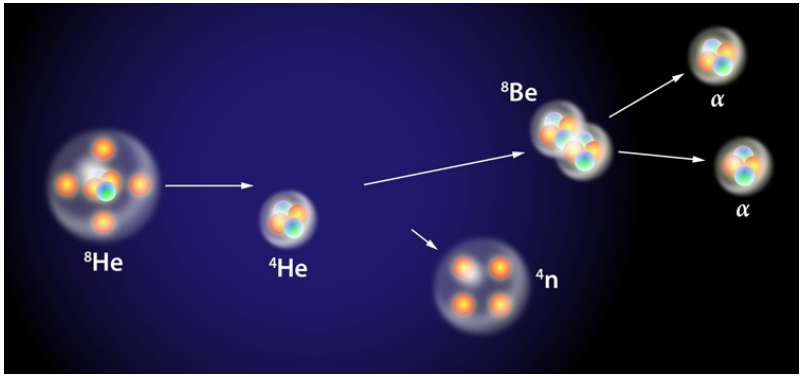
- Shimoura et al (SHARAQ) :



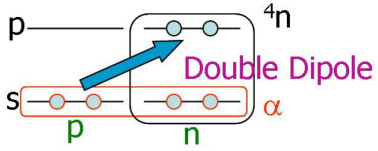
$^{4}\mathrm{He}\,(^{8}\mathrm{He}, \alpha\alpha)\,{}^{4}\mathrm{n}$ ('12)

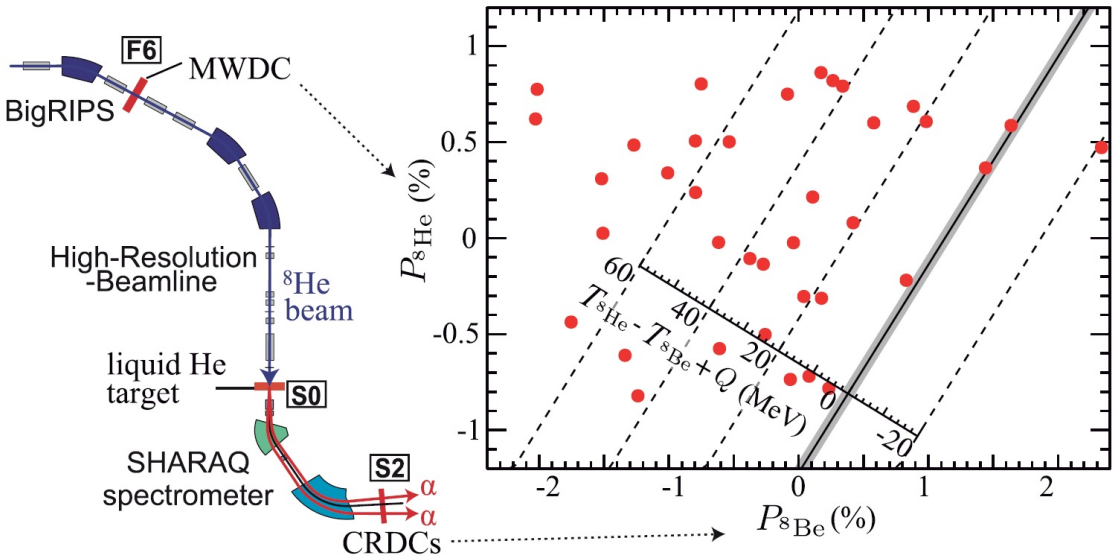
"Candidate Resonant Tetraneutron" [K. Kisamori]

Kisamori, Shimoura, PRL 116 (2016) 052501



^{4}He $(^{8}$He, $\alpha\alpha)$ ^{4}n





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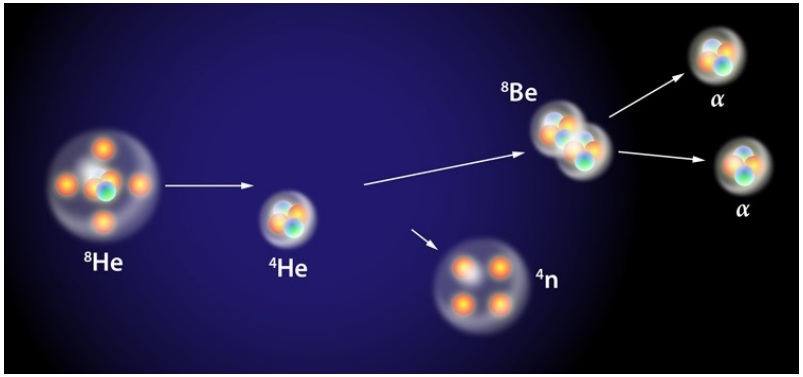
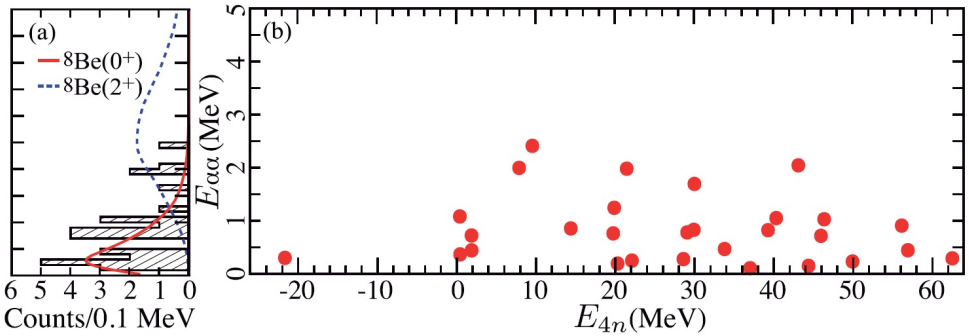
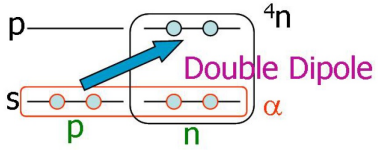
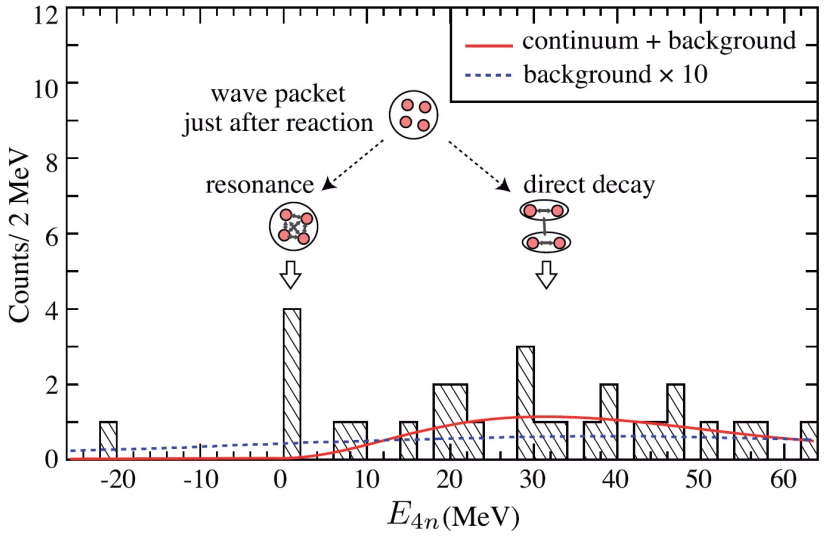
Kisamori, Shimoura, PRL 116 (2016) 052501

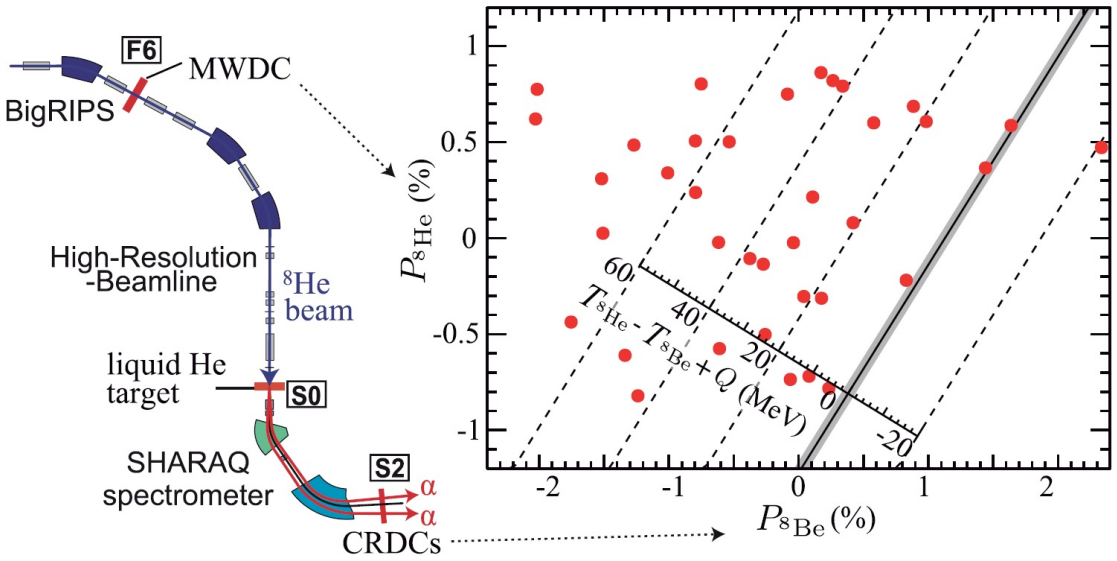




^{4}He (^{8}He, $\alpha\alpha$) ^{4}n







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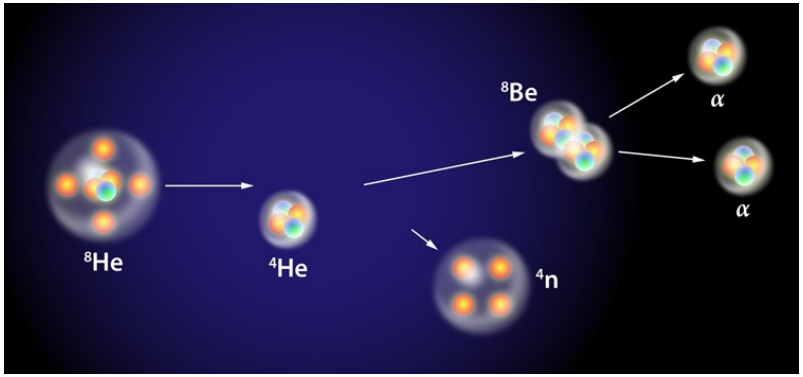
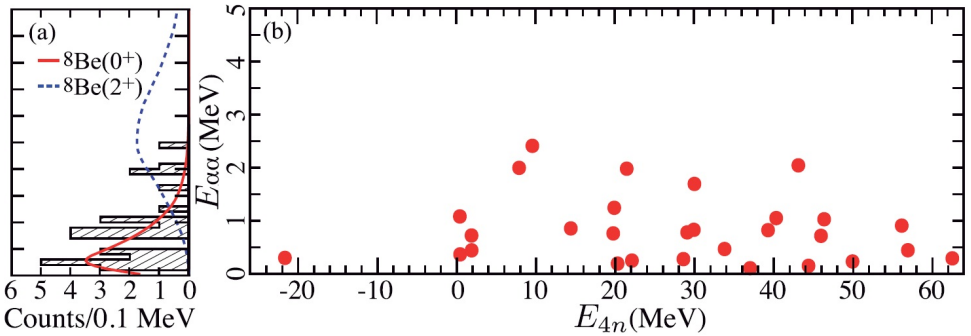
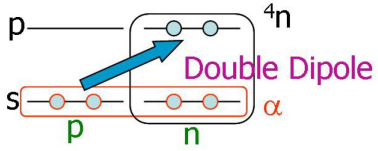
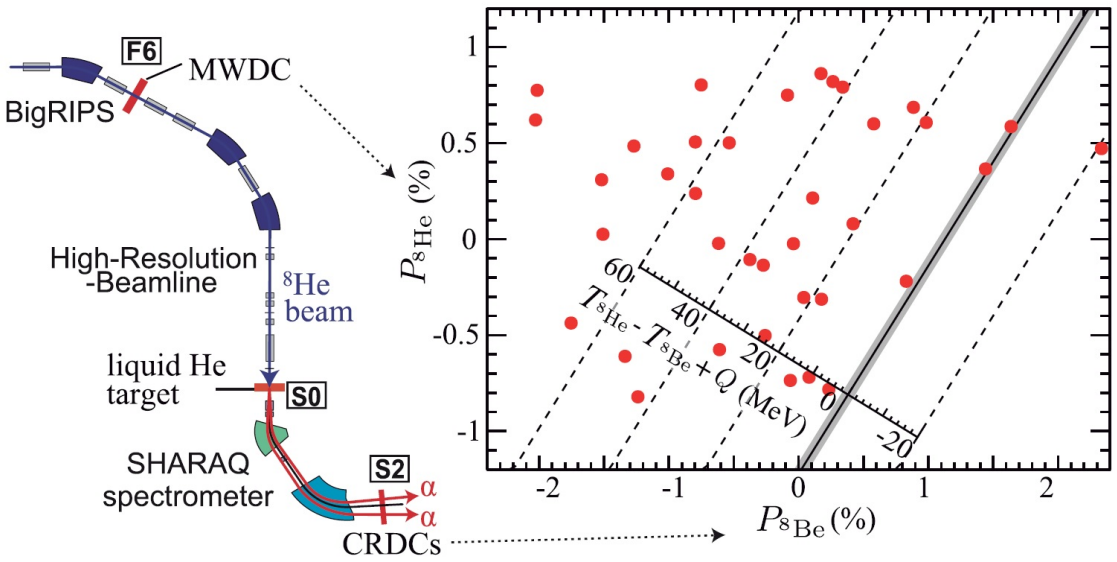
Kisamori, Shimoura, PRL 116 (2016) 052501

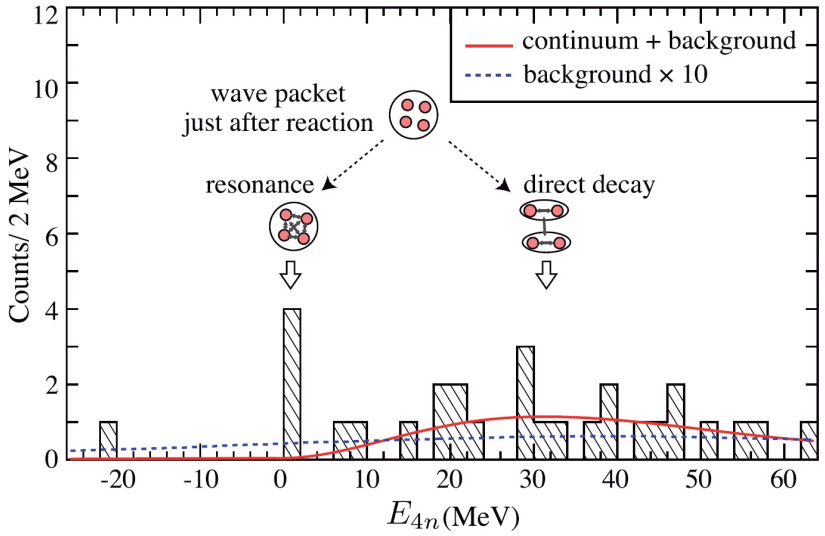




^{4}He (^{8}He, $\alpha\alpha$) ^{4}n







→ E(^{4}n) = 0.8 ± 1.3 MeV !

→ $\Gamma(^{4}\mathrm{n}) < 2.6$ MeV

→ $\sigma(^{4}\mathrm{n}) \sim 4$ nb

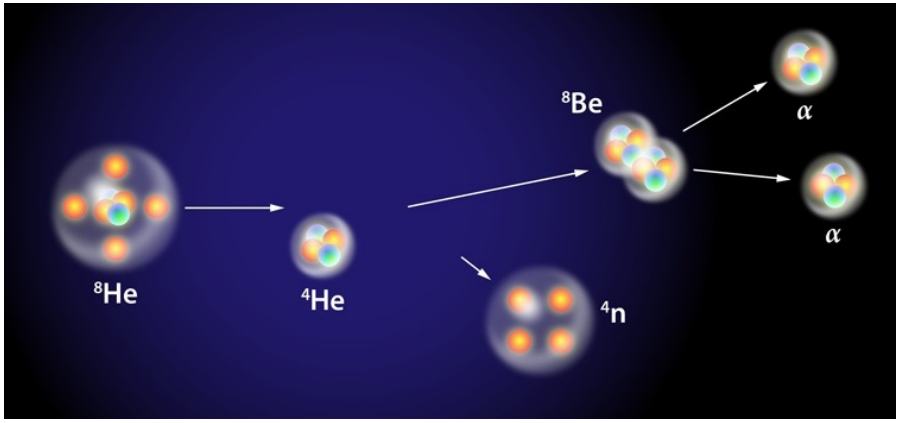
Outline

❶ **A very long quest** :

- extremely difficult to produce
- potential impact in many fields
- experimental program for 50 years !

  → two-step processes (bound state)

  → binary partners (any state)



❷ **The end of the quest ?**

- first 4n signals : DEMON & SHARAQ !
- low statistics, but no background ...
- theory cannot predict 4n states ...
- need order(s) of magnitude improvement

❸ **Coming next** (2016-17) :

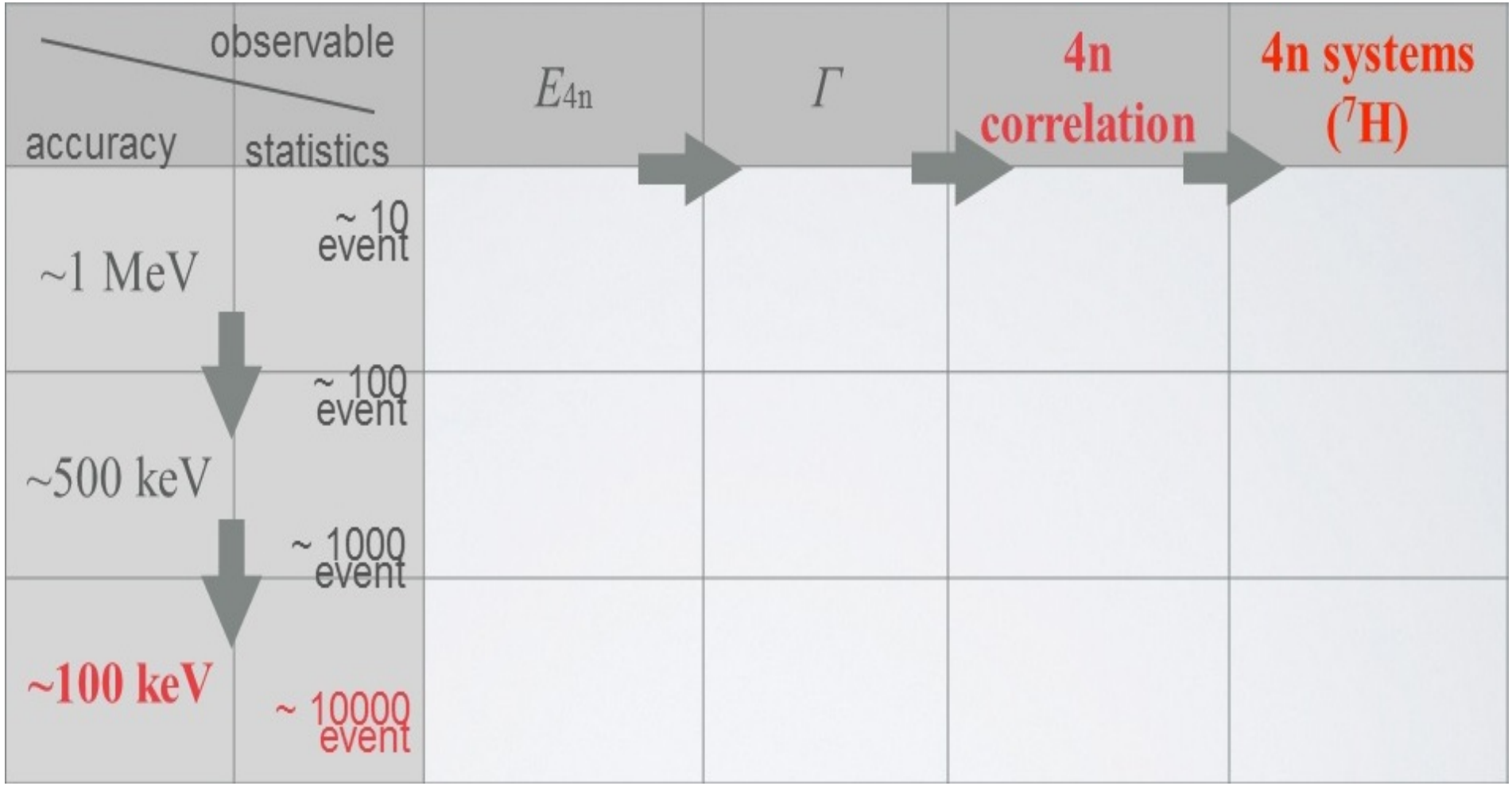
- SHARAQ 2.0
- NEBULA+NeuLAND & MINOS :

  → (p,pα) : 4n without FSI

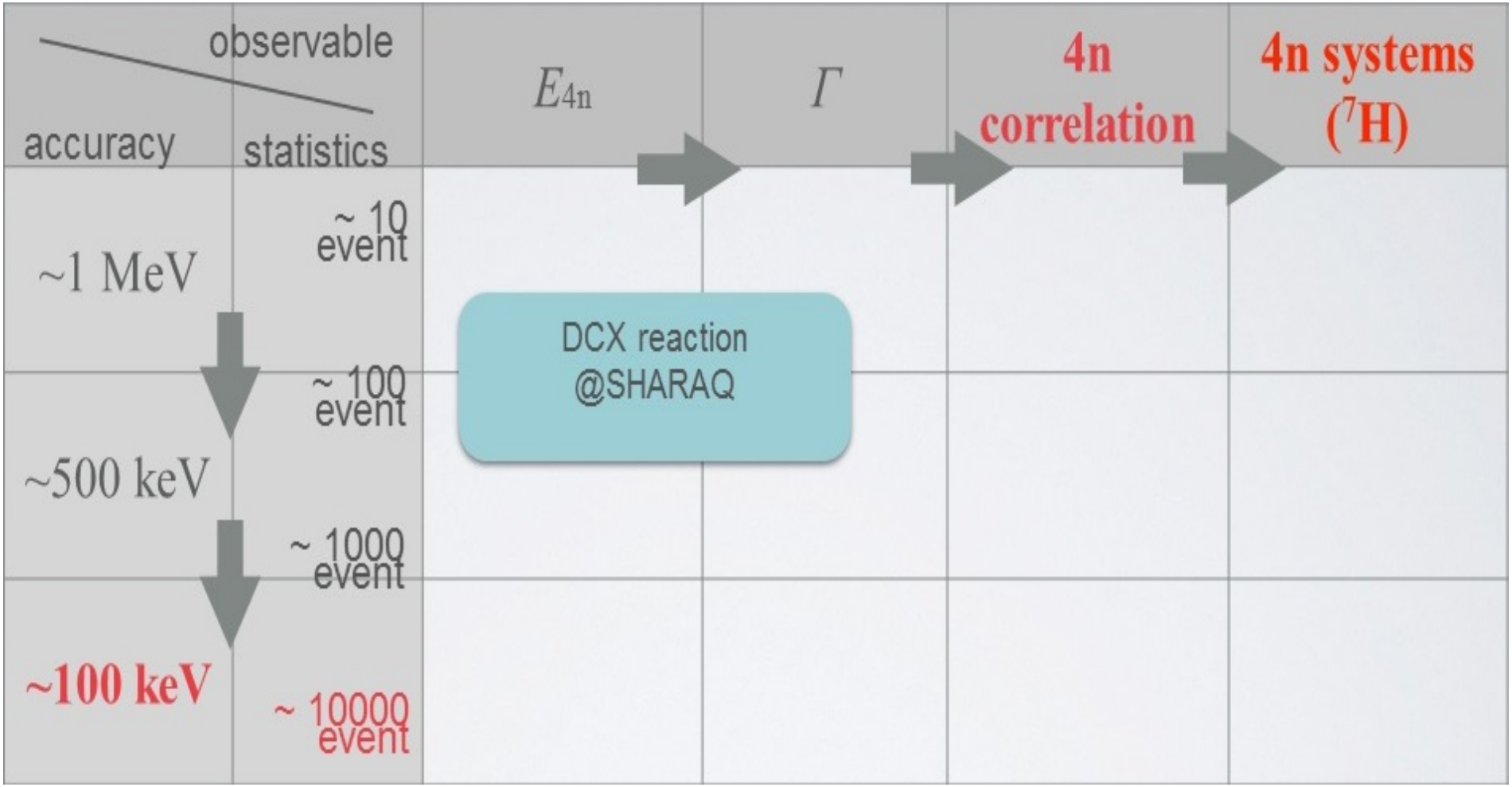
  → ^{7}H 4n-decay : sensitive to any $(E,\Gamma)_{\mathrm{R}}$

⇨ short-term solution to ^{4}n & ^{7}H !

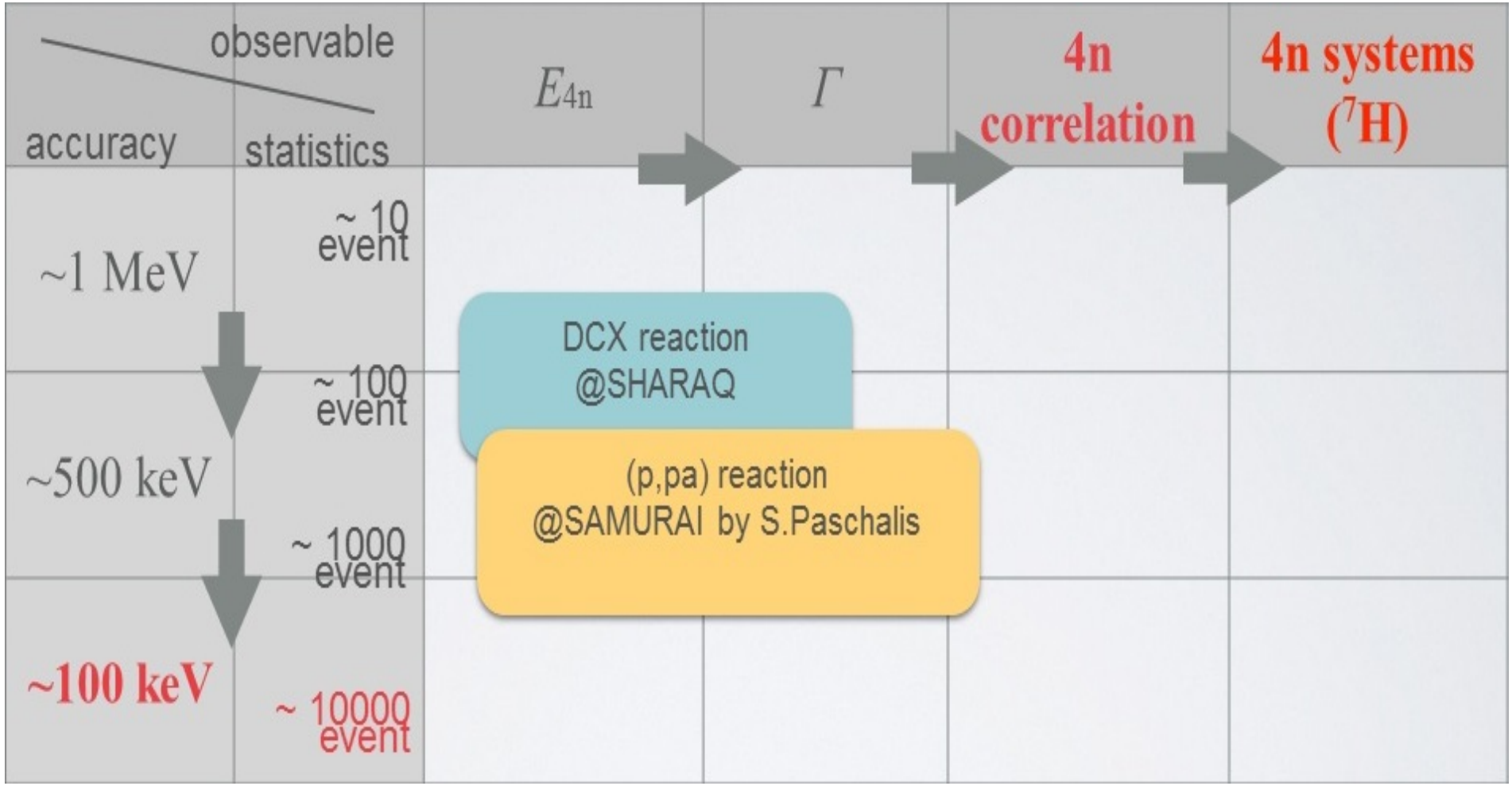
Experimental Context @ RIKEN



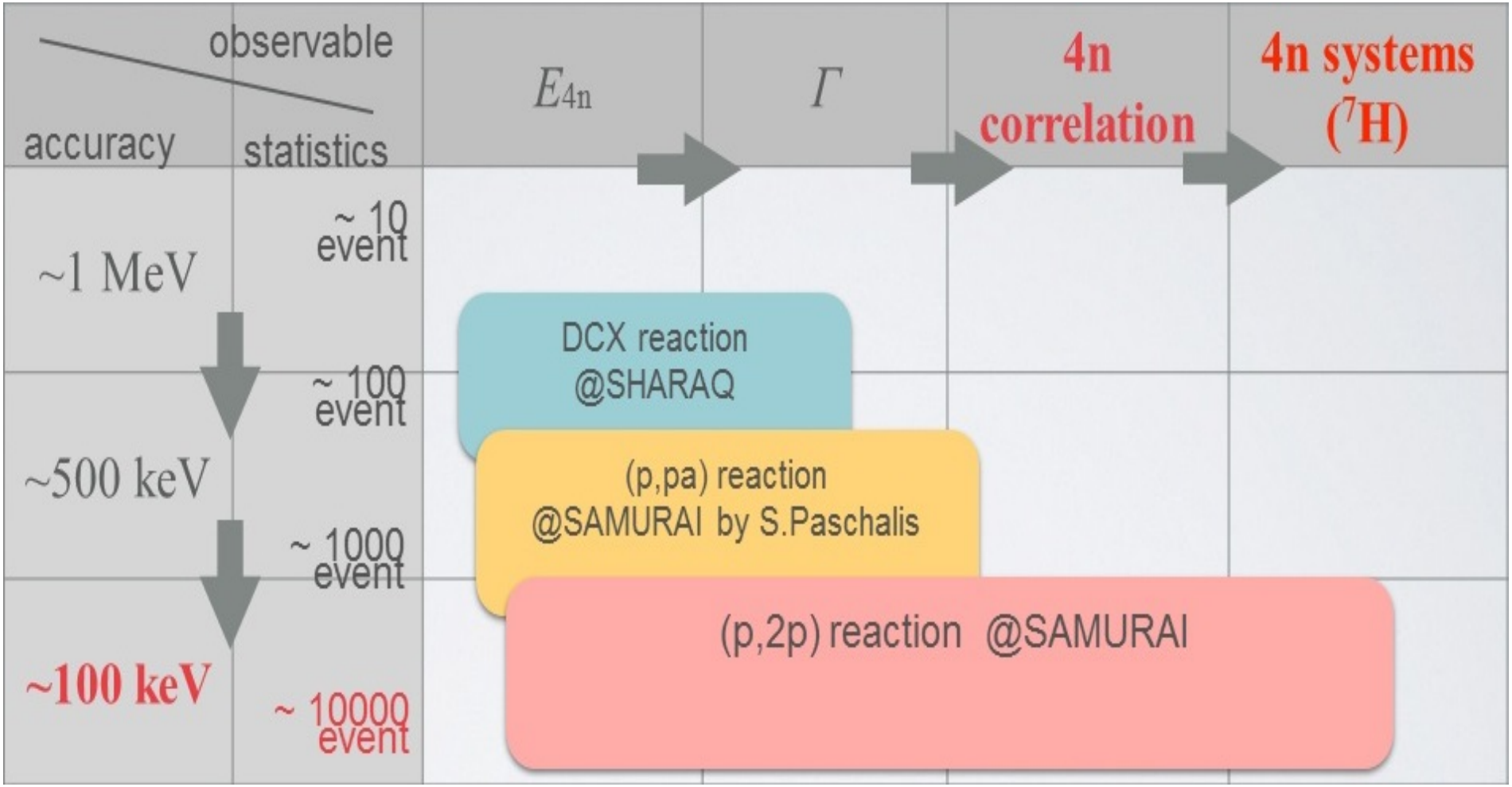
Experimental Context @ RIKEN



Experimental Context @ RIKEN



Experimental Context @ RIKEN



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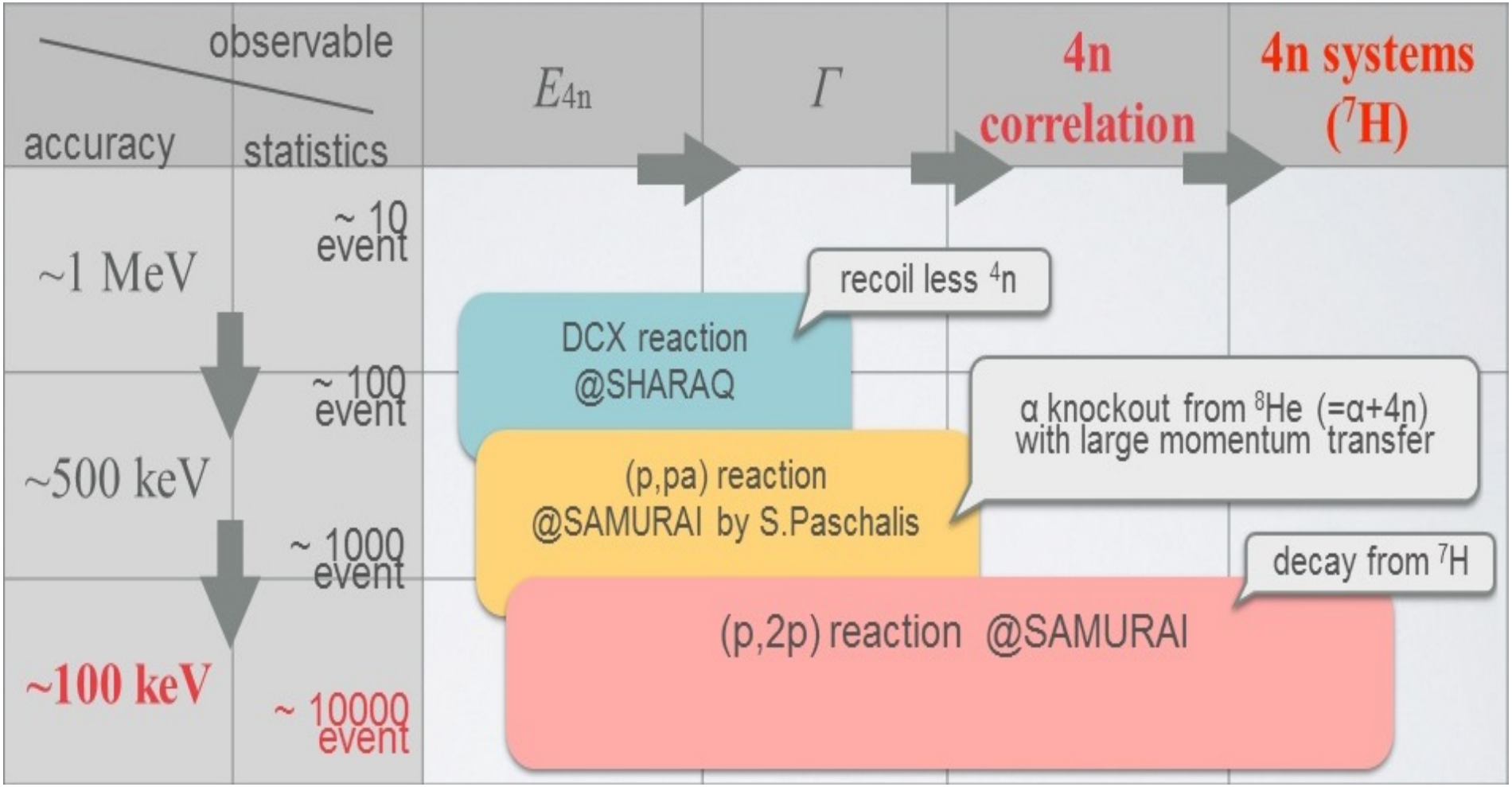
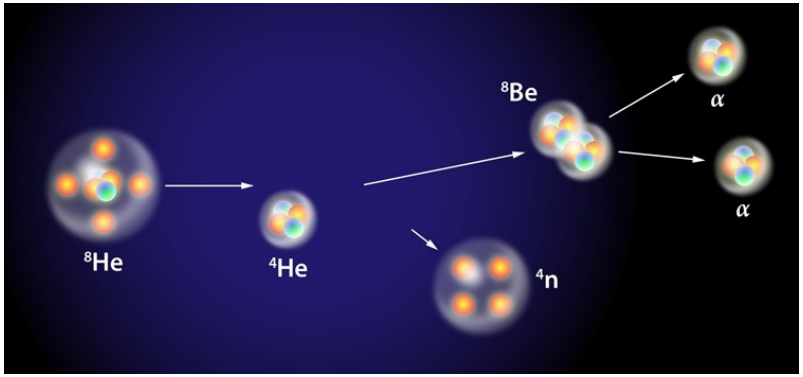


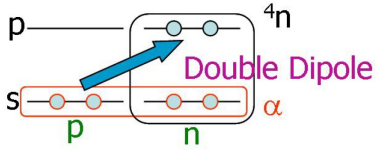
RIビームファクトリー全体図
RIビームファクトリーではさまざまな実験装置を使って、原子核の構造と反応を研究しておるのじゃ。
加速する原理
超伝導リングサイクロトロン(SRC)
生成分離装置(BigRIPS)
加速装置
超電導磁石
強い磁力で原子核の進路を曲げて、円運動させて加速
1兆個以上の原子核
光速の70%のスピード
標的物質
壊れた原子核(RIビーム)
分離電磁石
スリット
同じ種類の原子核を集めて研究
RI BEAM FACTORY 01
RRC RIKEN RING CYCLOTRON
(理研リングサイクロトロン)
第1のリングサイクロトロン。RIビームファクトリーのサイクロトロンの中では一番の古株。
重さ 2,300t
直径 12.6m
RI BEAM FACTORY 02
fRC FIXED-FREQUENCY RING CYCLOTRON
(固定加速周波数型リングサイクロトロン)
第2のリングサイクロトロン。ウランを加速するために必要不可欠な装置。
重さ 1,500t
直径 10.8m
RI BEAM FACTORY 03
IRC INTERMEDIATE-STAGE RING CYCLOTRON
(中間段リングサイクロトロン)
第3のリングサイクロトロン。SRCにビームを送る他、実験装置へもビームを送る。
重さ 2,800t
直径 14.0m
RI BEAM FACTORY 04
SRC SUPERCONDUCTING RING CYCLOTRON
(超伝導リングサイクロトロン)
第4のリングサイクロトロン。最終加速。6基の超伝導電磁石を持つ史上最強のリングサイクロトロン。
重さ 8,300t
直径 18.5m
偏極RIビーム生成装置
回して調べる
ビーム発射
GARIS
RILAC
AVFサイクロトロン
RILAC2
RIPS
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32%
光速の47%
光速の70%
原子核を壊す
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。
BigRIPS
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

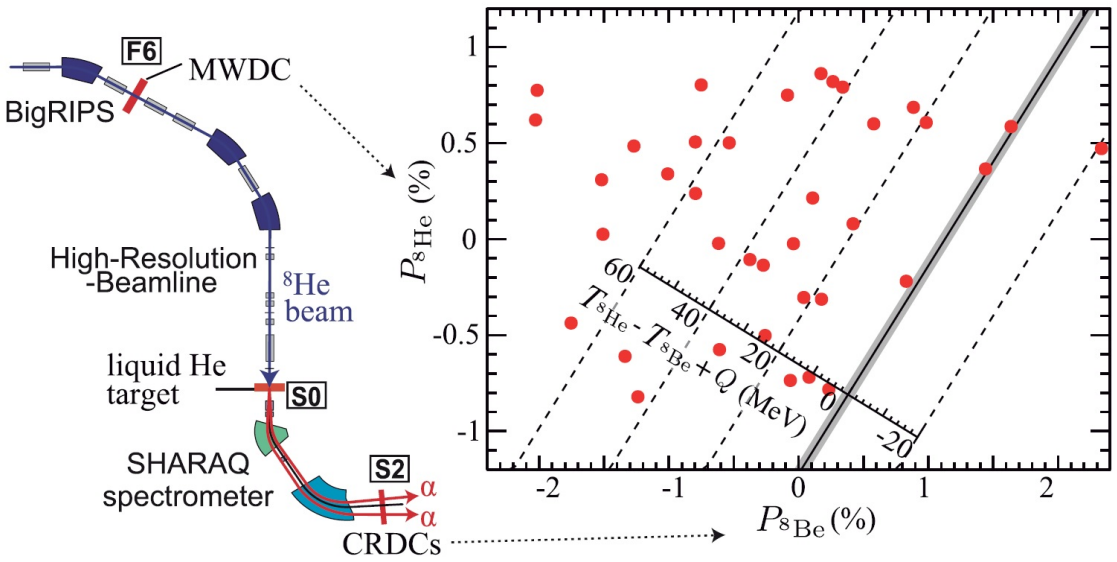
Exothermic DCX on Hellium 4 [S. Shimoura]

Kisamori, Shimoura, PRL 116 (2016) 052501

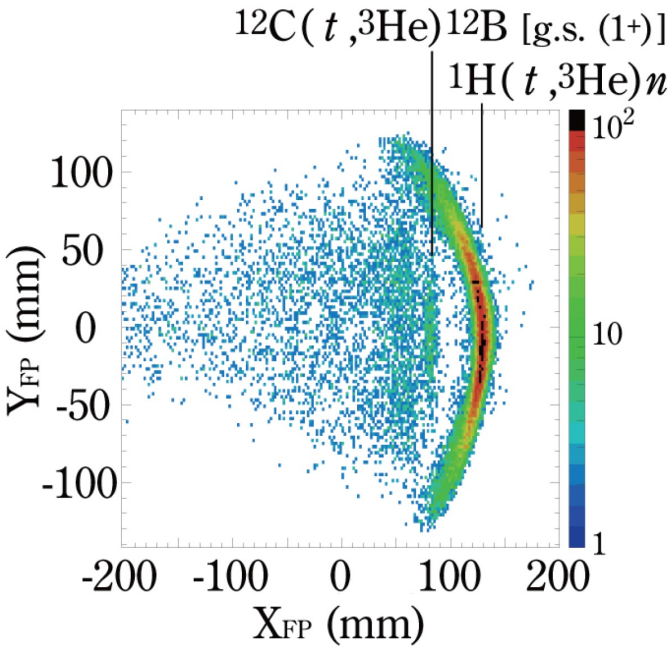


^{4}He (^{8}He, $\alpha\alpha$) ^{4}n





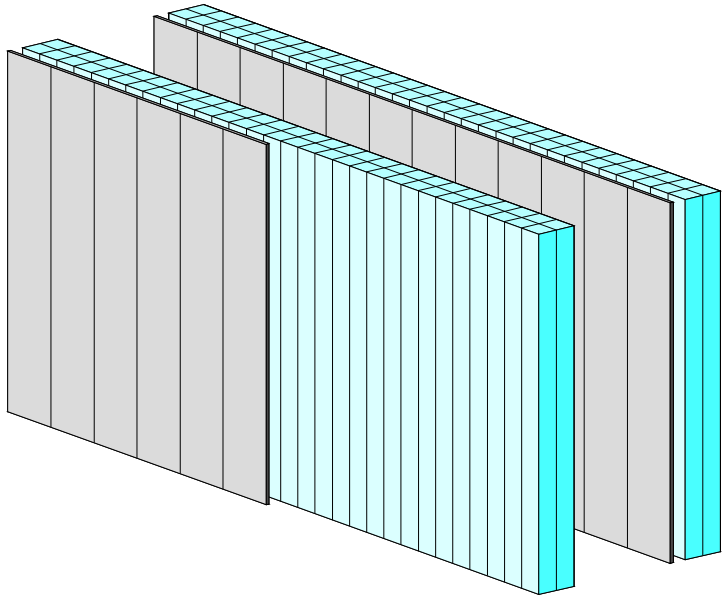
- Increase statistics & accuracy ×10 !
  - DAQ system & beam time
  - tracking & trigger efficiencies
  - ^{3}H beam with same rigidity :

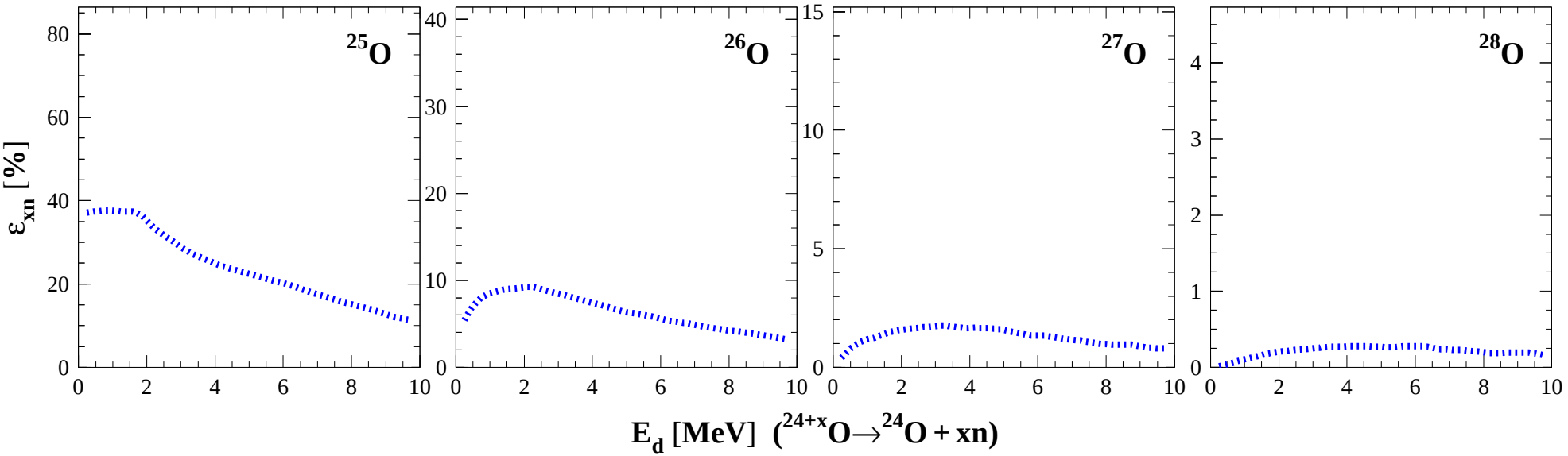


→ tentative schedule next June ...

EXPAND : French ANR Funding

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





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

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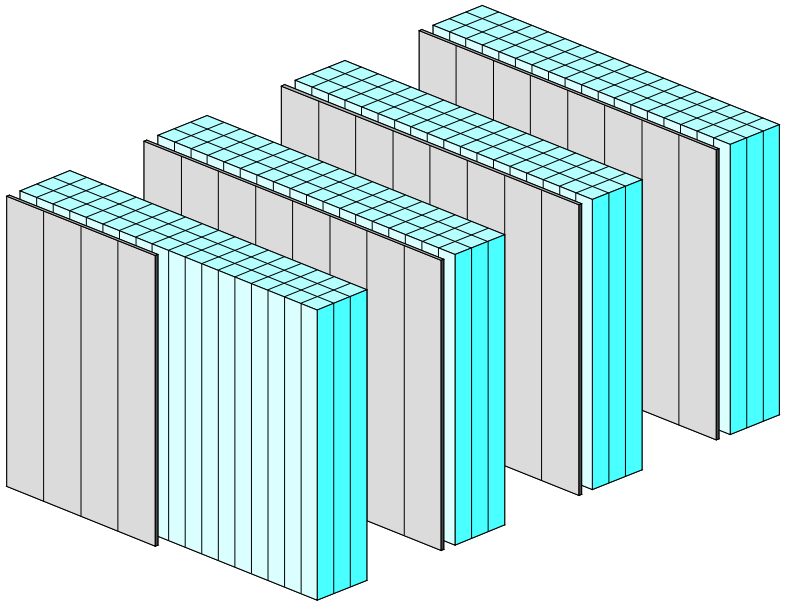
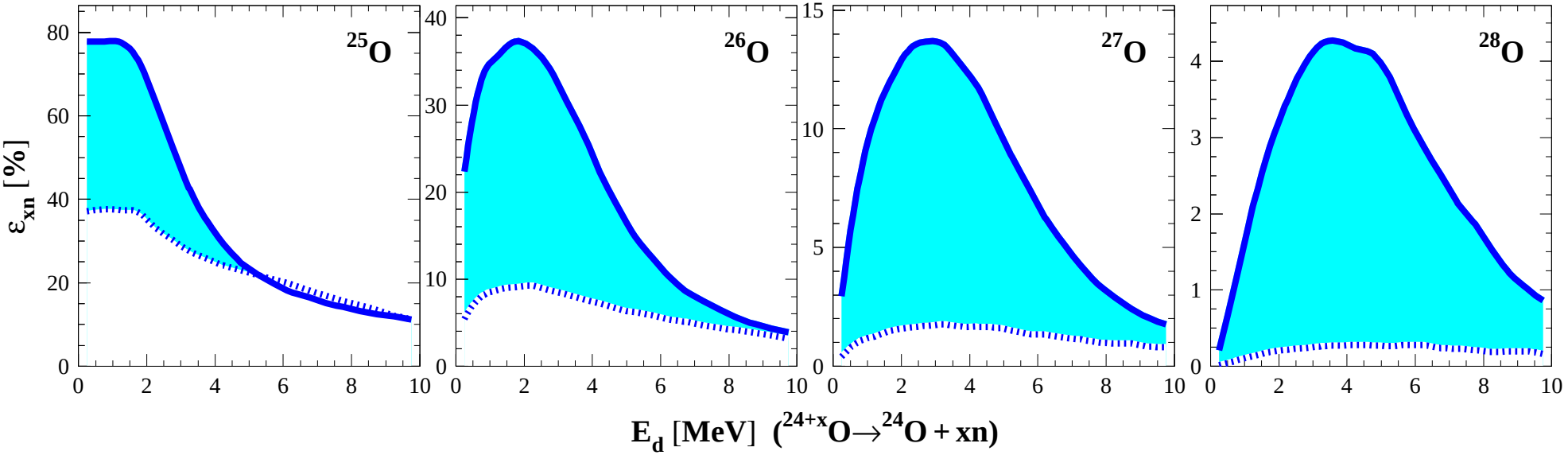
  - France : LPC, IRFU, IPNO
  - Japan : TITech, RIKEN
  - +90 bars : Comm. & Day-1 in 2017
  - suggested configuration :

    ⇨ ε(4n) enhanced $\sim \times 16$!





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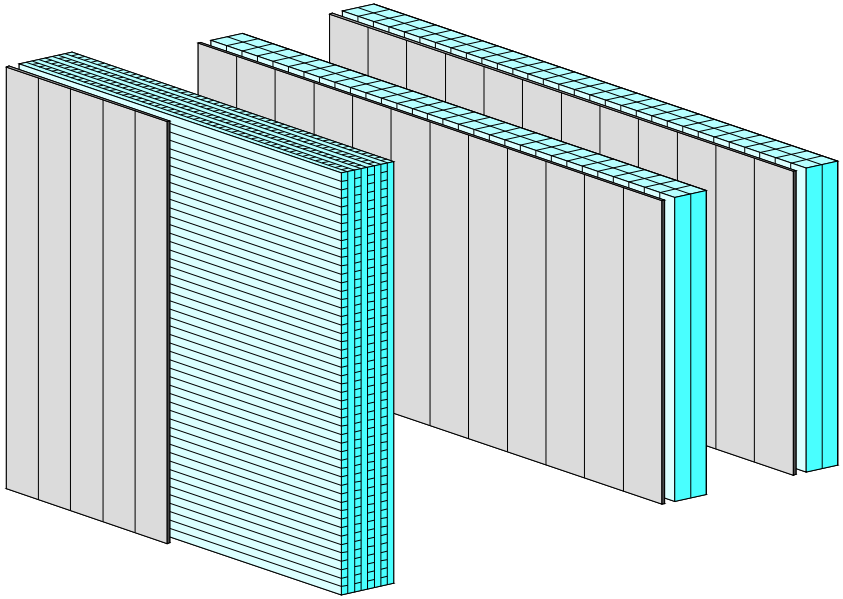
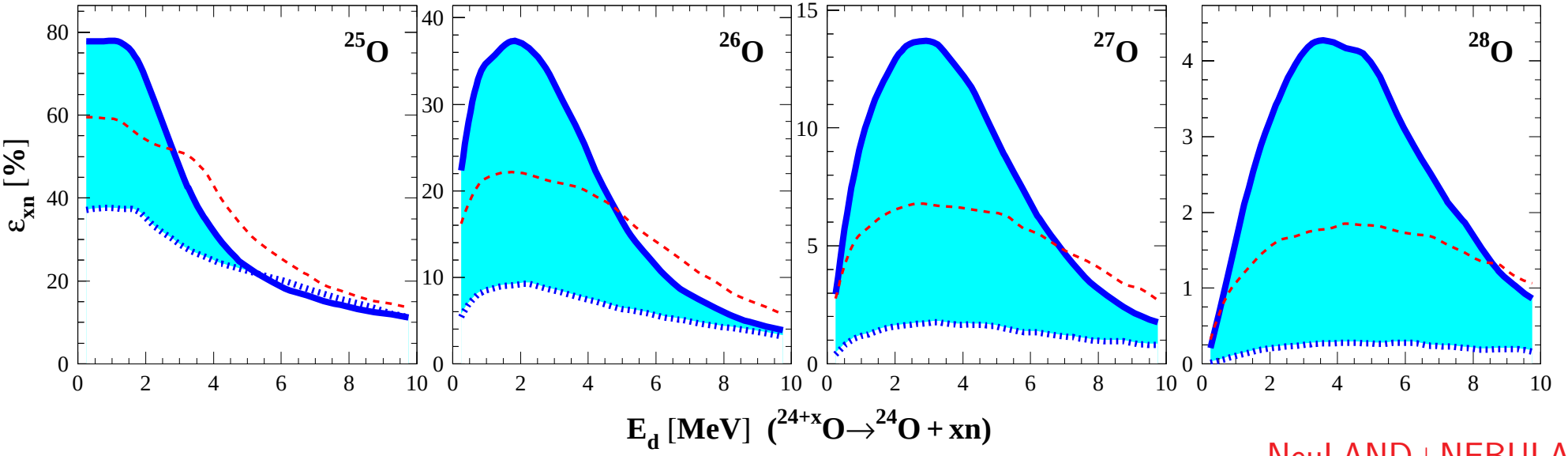
  - suggested configuration :

    ⇨ ε(4n) enhanced $\sim \times 16$!

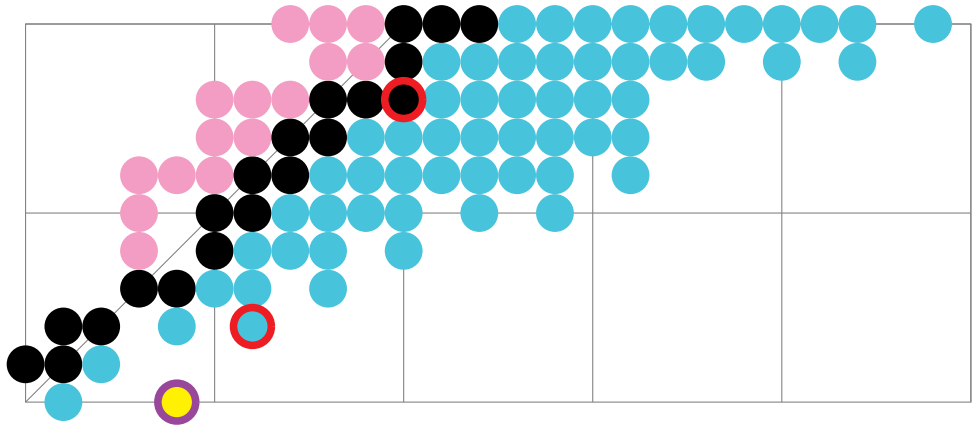




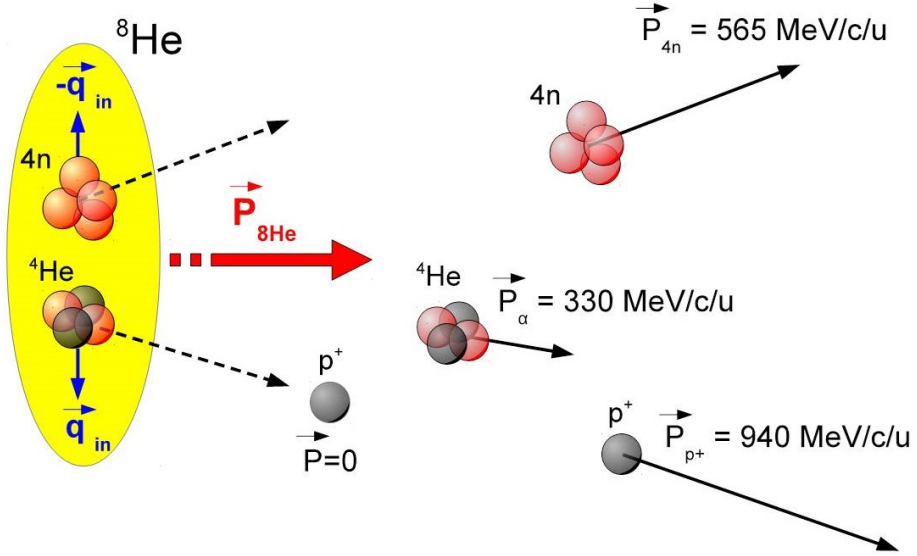
--- NeuLAND+NEBULA

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

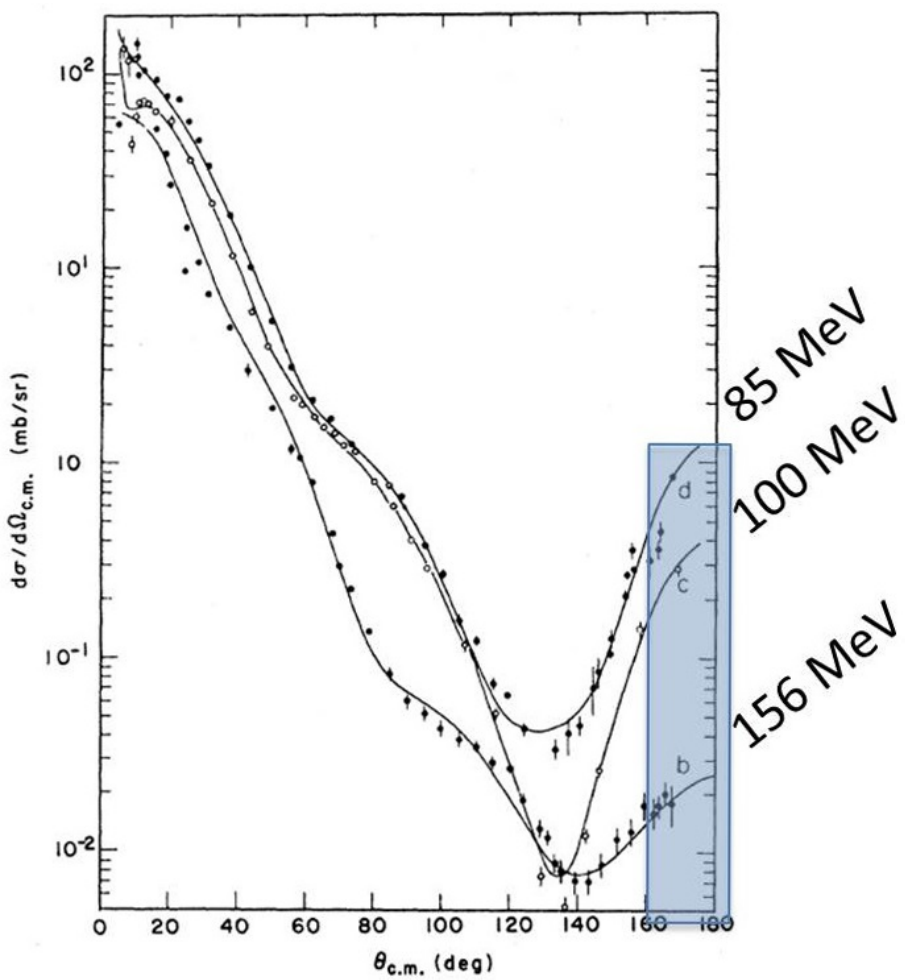
Tetraneutron @ SAMURAI [S. Paschalis]



- QFS (p,pα) on ^{8}He :



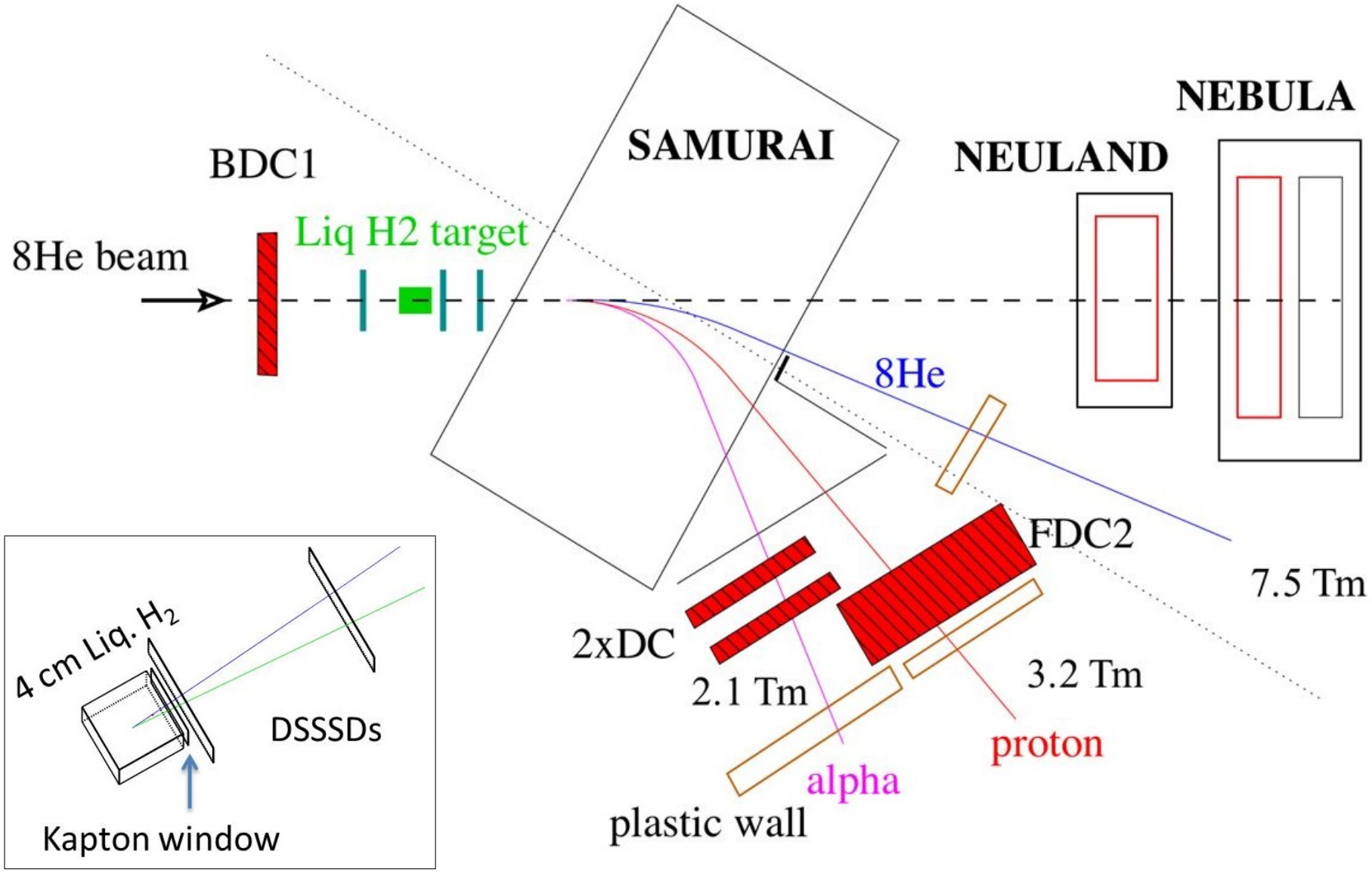
Paschalis-Shimoura, RIBF NP1406-SAMURAI19



- α knockout at large q :

  $\rightarrow$ minimize FSI between 4n and p/α

Tetraneutron @ SAMURAI [S. Paschalis]



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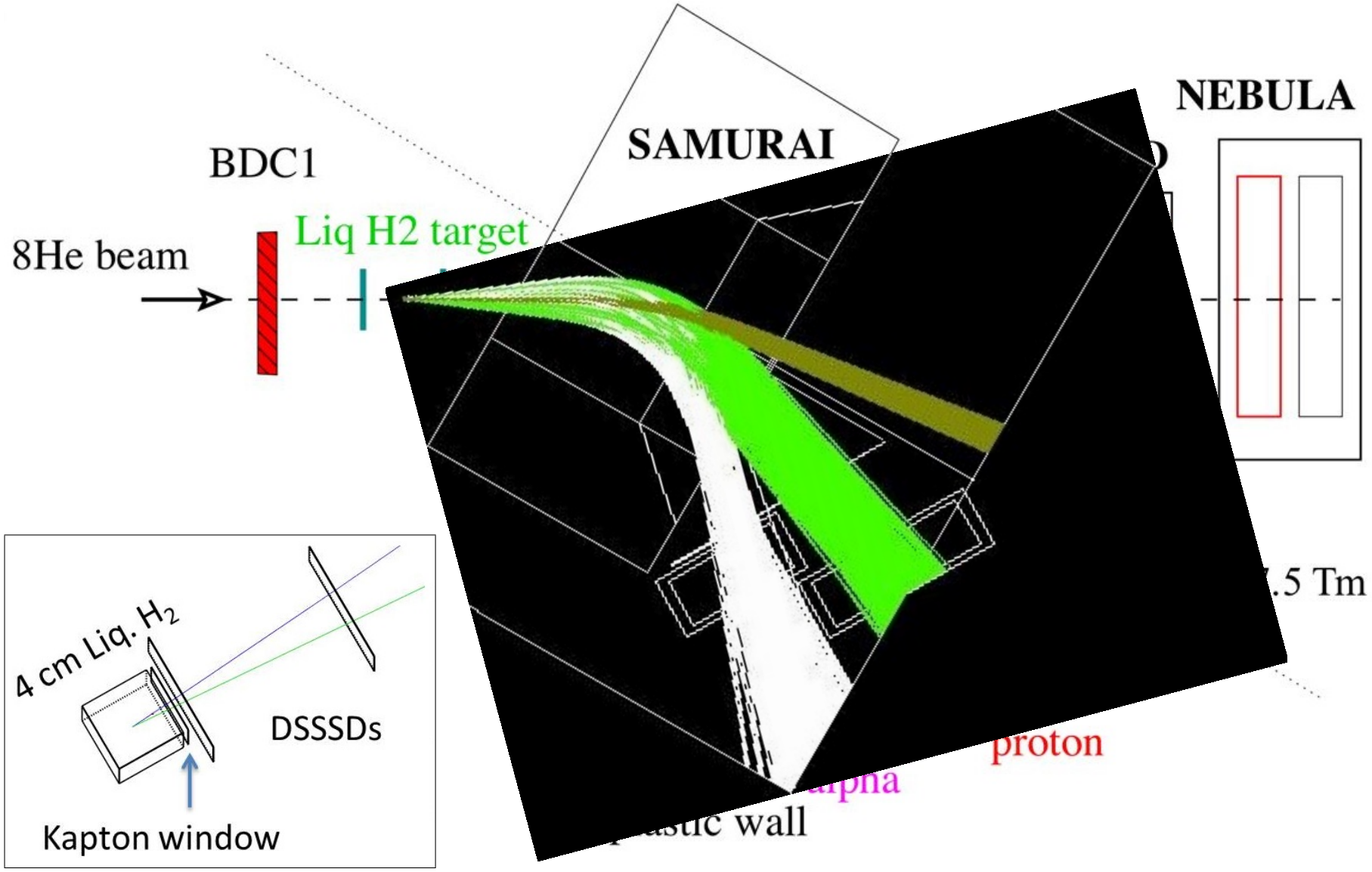
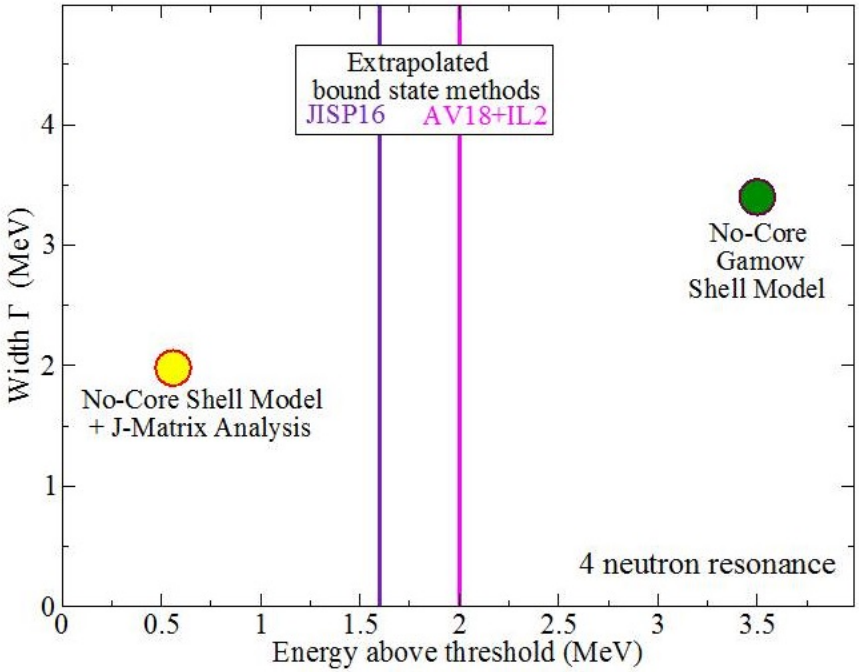


Theoretical calculations :

Paschalis-Shimoura, RIBF NP1406-SAMURAI19

- *Ab initio* estimate of ^{4}n (E,Γ) :



$\rightarrow$ E $\sim$ 2-3 MeV, $\Gamma \sim$ 3-4 MeV ...

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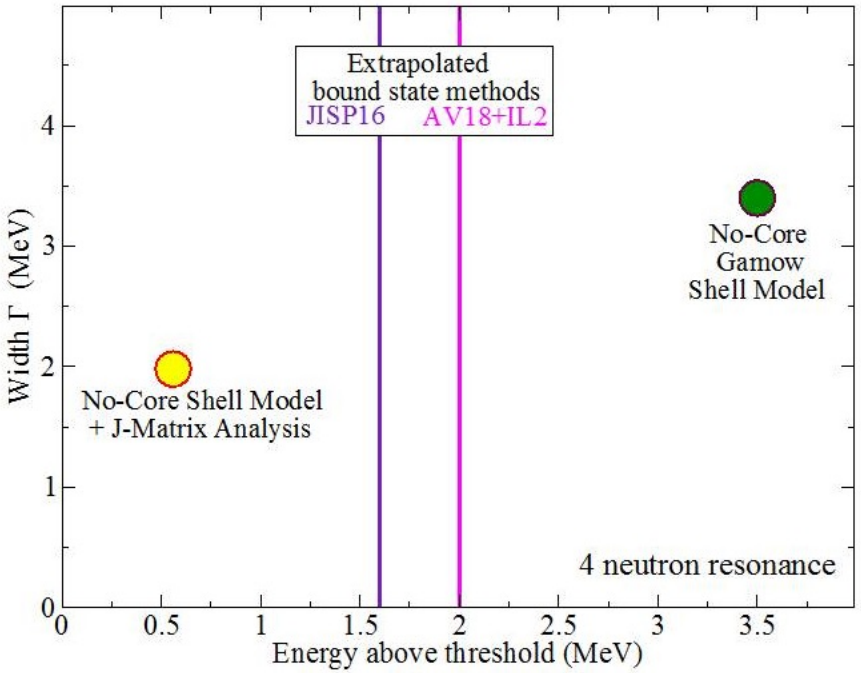

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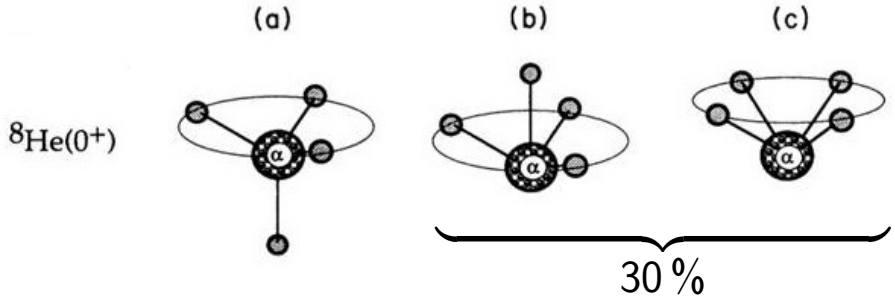
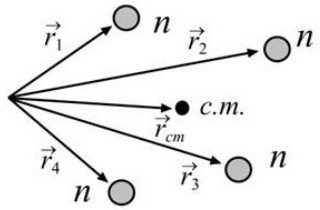
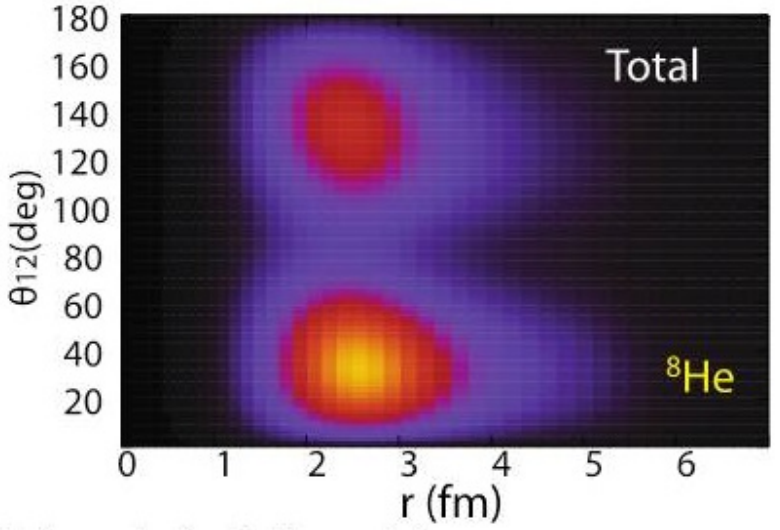
- COSMA estimate of $\langle {}^8\text{He} | {}^4\text{n} \rangle$ overlap :





$\Longrightarrow$ significant $\ell = 0$!



Papdimitriou, PRC 84 (2011) 051304R

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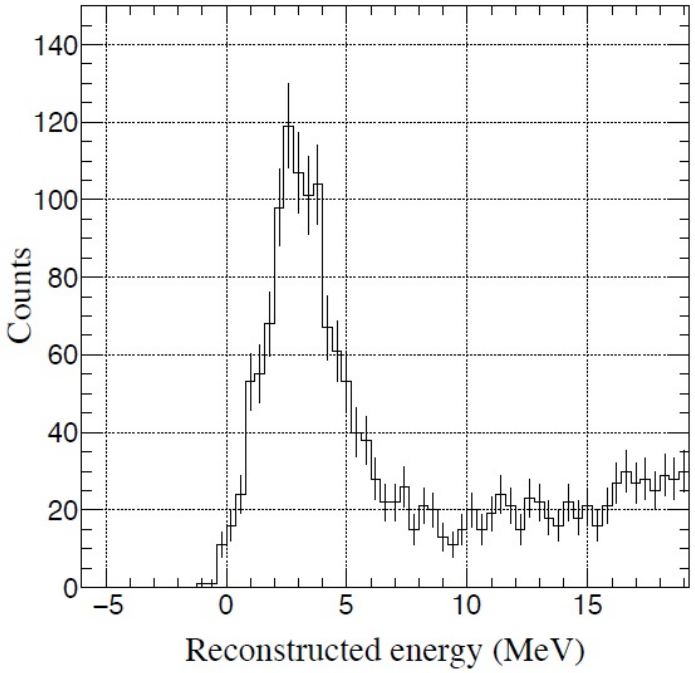

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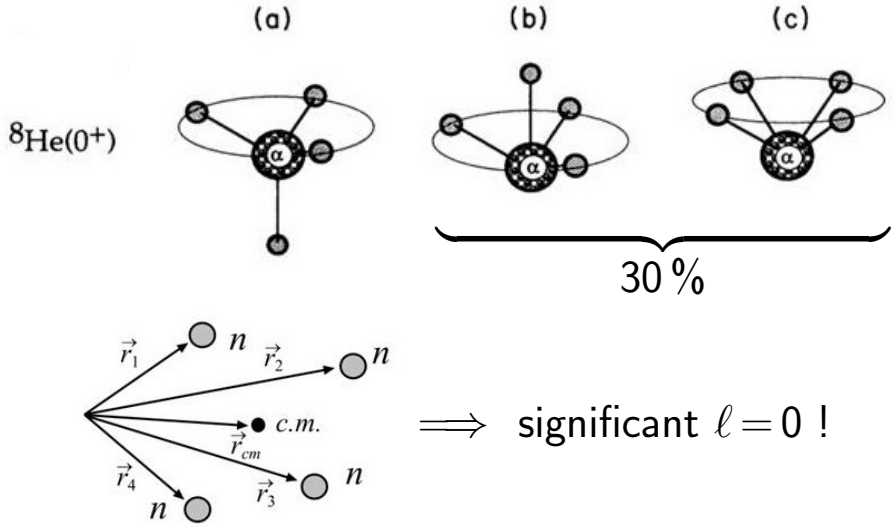

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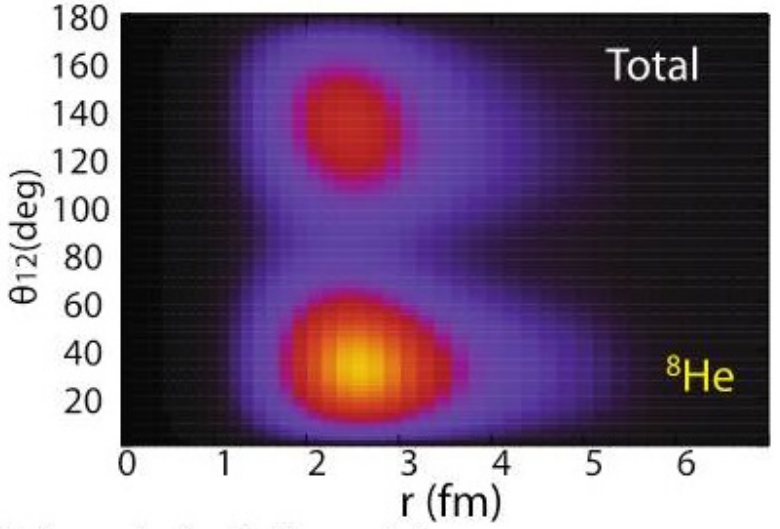
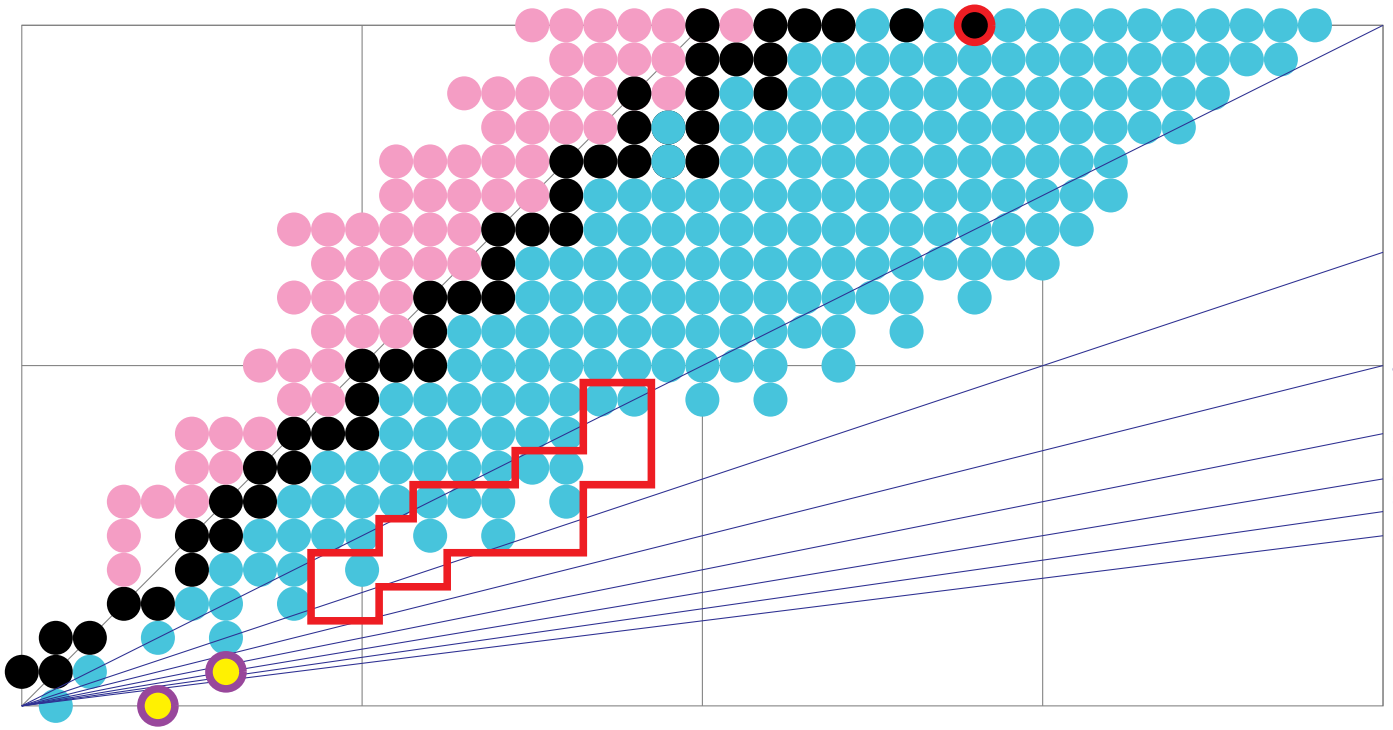
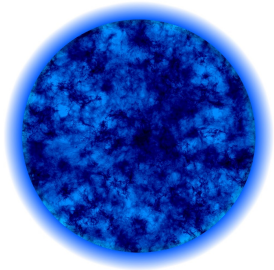


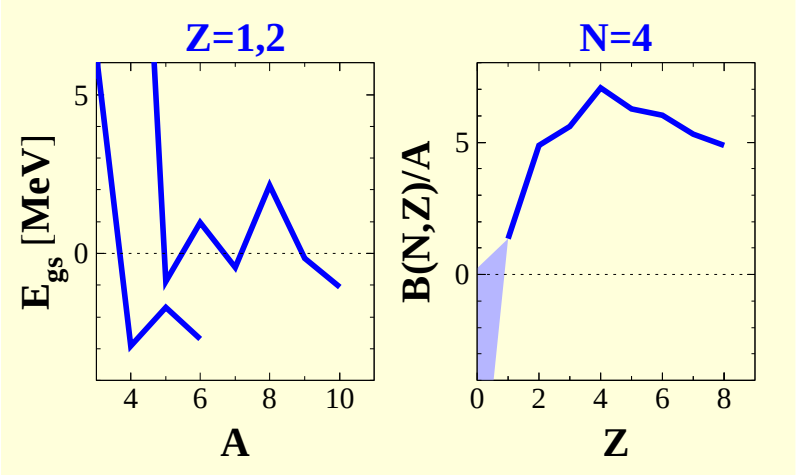
Papdimitriou, PRC 84 (2011) 051304R

Hydrogen 7 : a Tetraneutron with a Triton



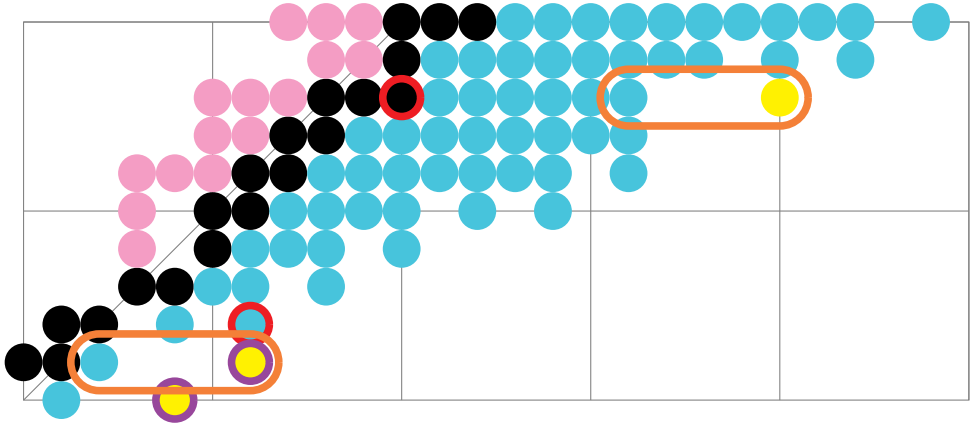


(N/Z ∼ 8)



- Low-lying ^{7}H ?
  - ambiguous and contradictory signals :
    - → resolutions ∼ 2-3 MeV
    - → low statistics & high backgrounds
    - → missing mass : no neutrons detected ...

Hydrogen 7 & Tetraneutron [K. Kisamori, FMM]



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

"Many-neutron systems:
search for superheavy Hydrogen 7
and its Tetraneutron decay"

Kisamori-FMM, RIBF NP1512-SAMURAI34

- follow up of Orr, RIBF NP1306-LOI08

  → ^{28}O [Y. Kondo] already done !

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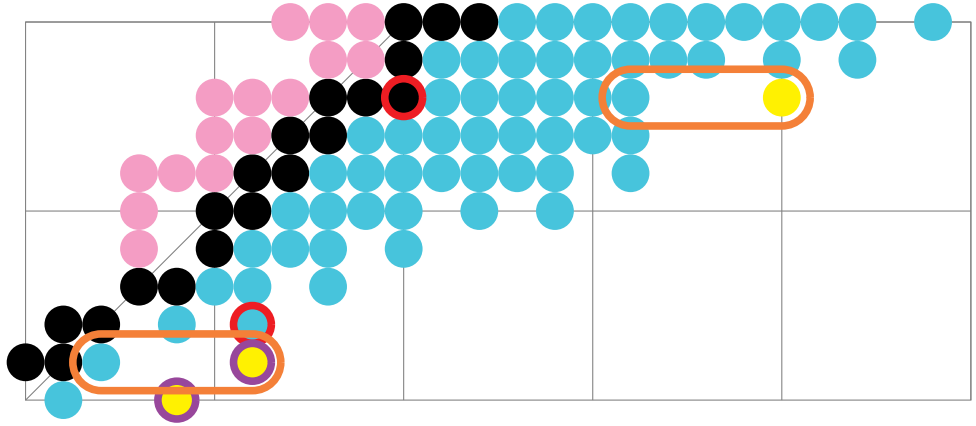

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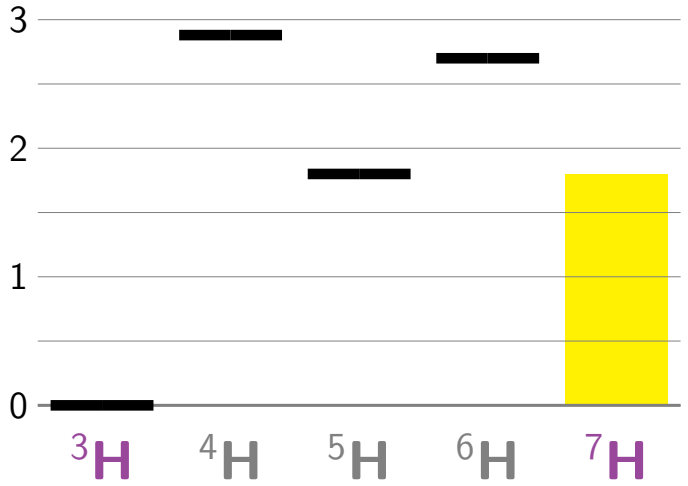

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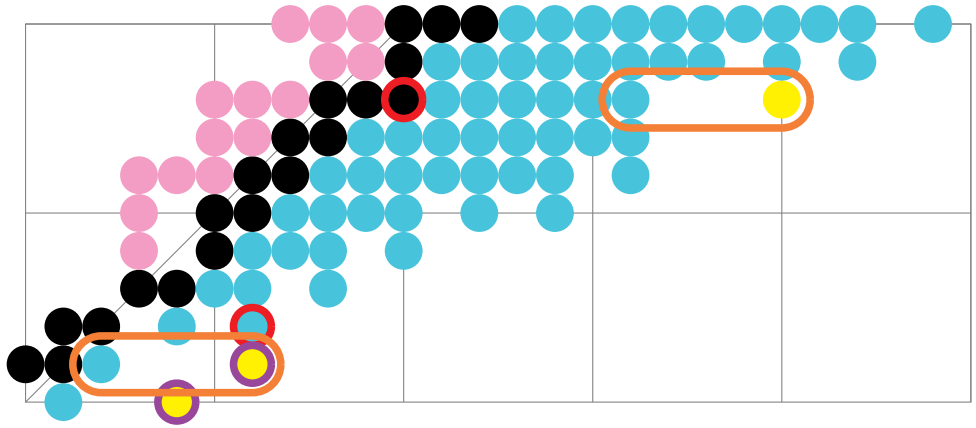

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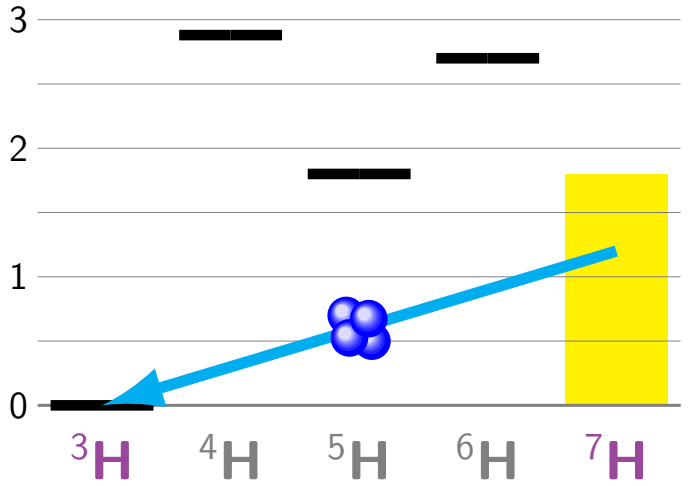
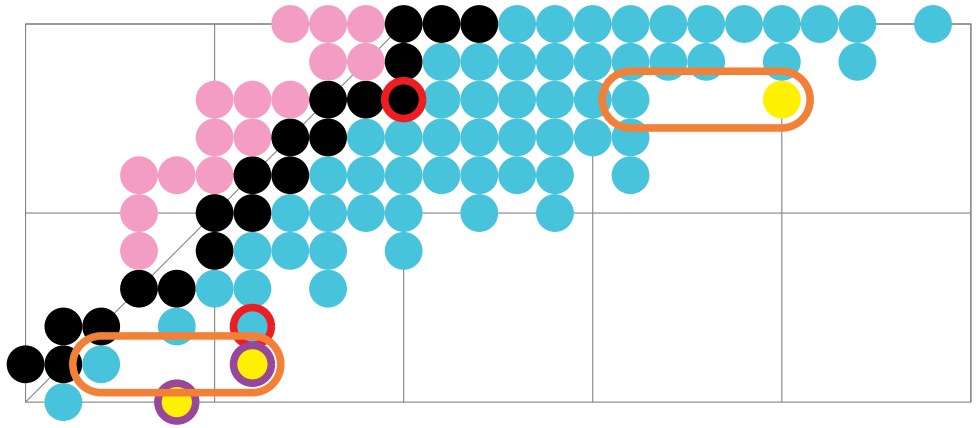


- direct 4n decay ?

  → ^{3}H + ^{4}n → 4n detection

  → angular correlations : E_R !

Hydrogen 7 & Tetraneutron [K. Kisamori, FMM]



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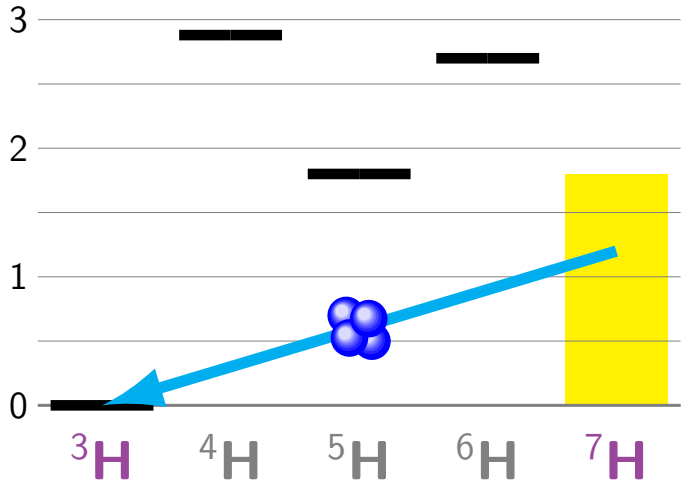

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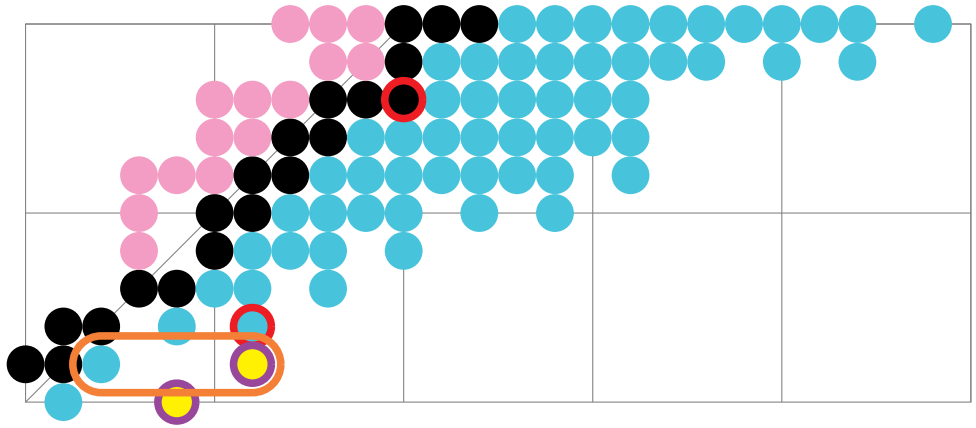
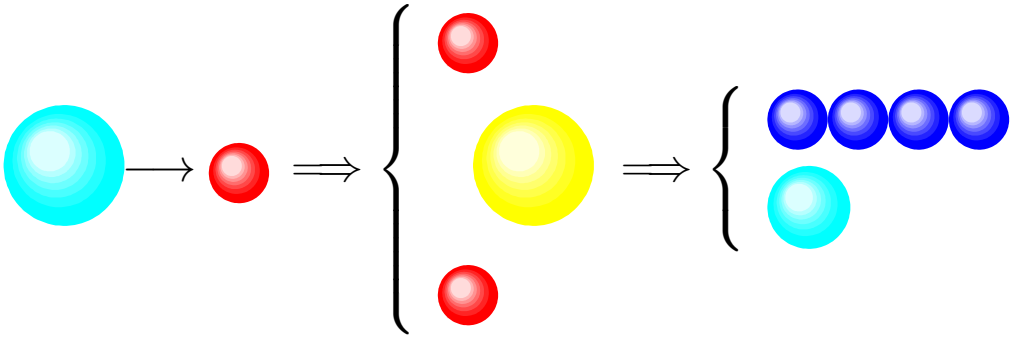
- low-lying ^{7}H / ^{4}n : bound $^{8}_{\Lambda}$H / $^{5}_{\Lambda}$n ?

Hiyama, PRC 89 (2014) 061302(R)

Hydrogen 7 & Tetraneutron : Complete Kinematics



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



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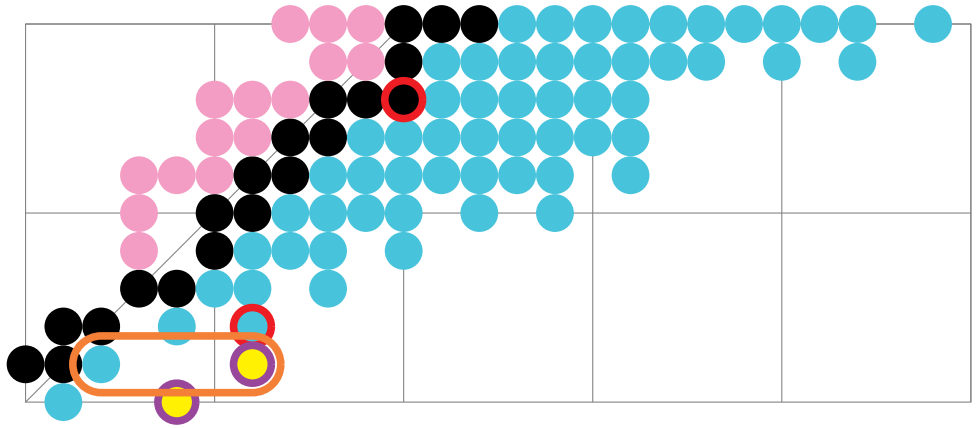

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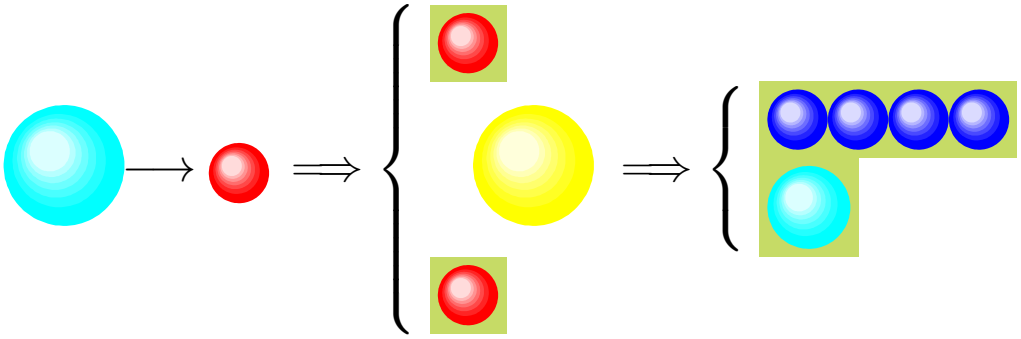
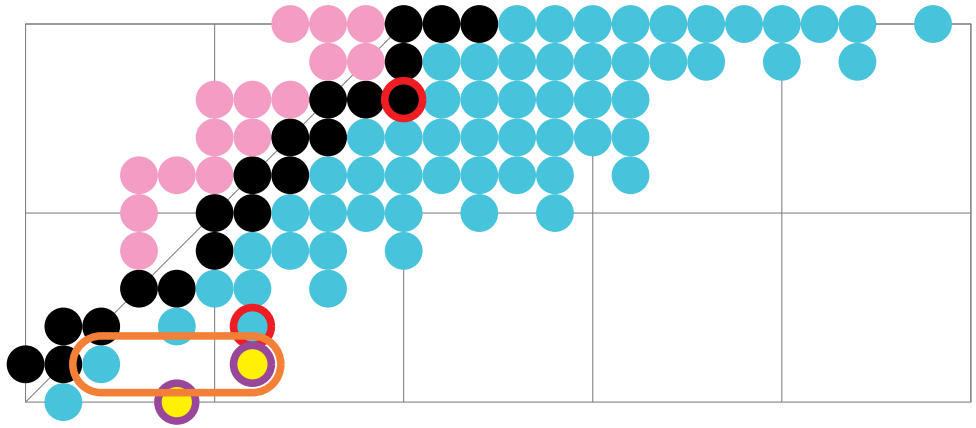


→ detection of the 7-body final state !

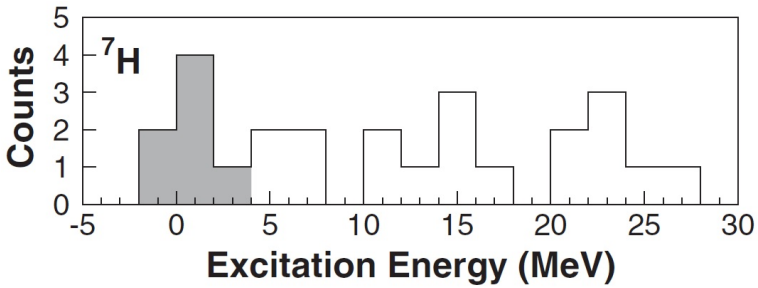
- **MINOS** liquid H target :
  - → high luminosity (*statistics*)
  - → proton angles (*resolution*)
- **CATANA** CsI crystals :
  - → proton energies (*efficiency*)
- **SAMURAI** :
  - → triton momentum (*resolution & correlations*)
- **NEBULA** + **NeuLAND** :
  - → 3/4 neutron momenta (*efficiency,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

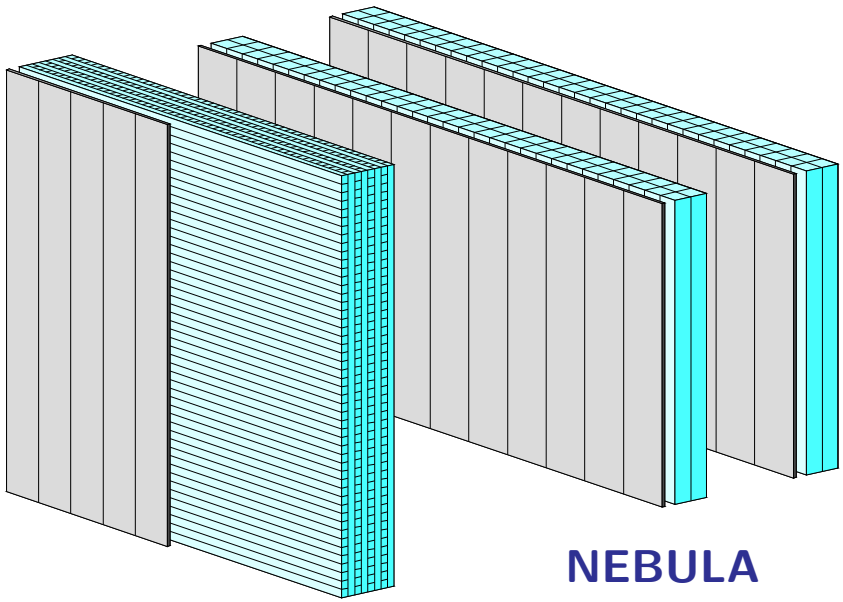
$$\text{FWHM} \sim \begin{cases} 5 \text{ MeV} & (2p) \\ 150 \text{ keV} & (2p+t+3n) \\ 100 \text{ keV} & (t+4n) \text{ !!!} \end{cases}$$

Expected Statistics & Resolution (4 days)



Caamaño, PRL 99 (2007) 062502





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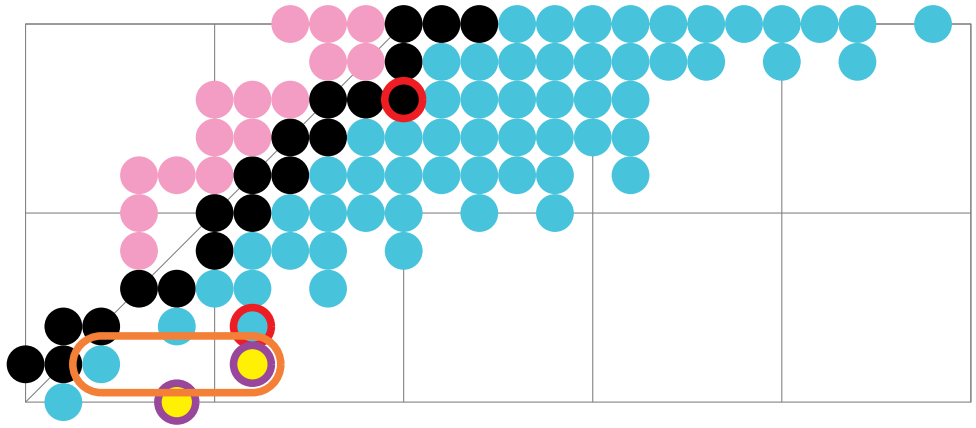
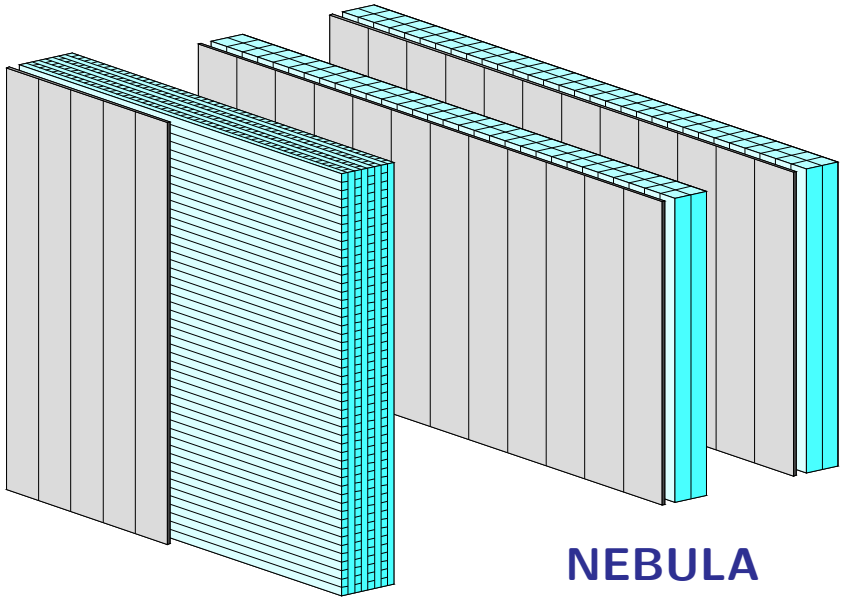
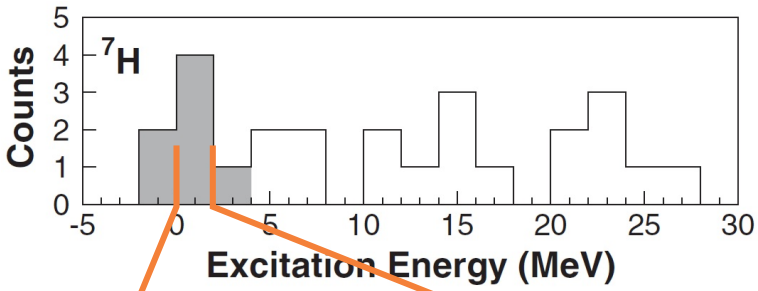
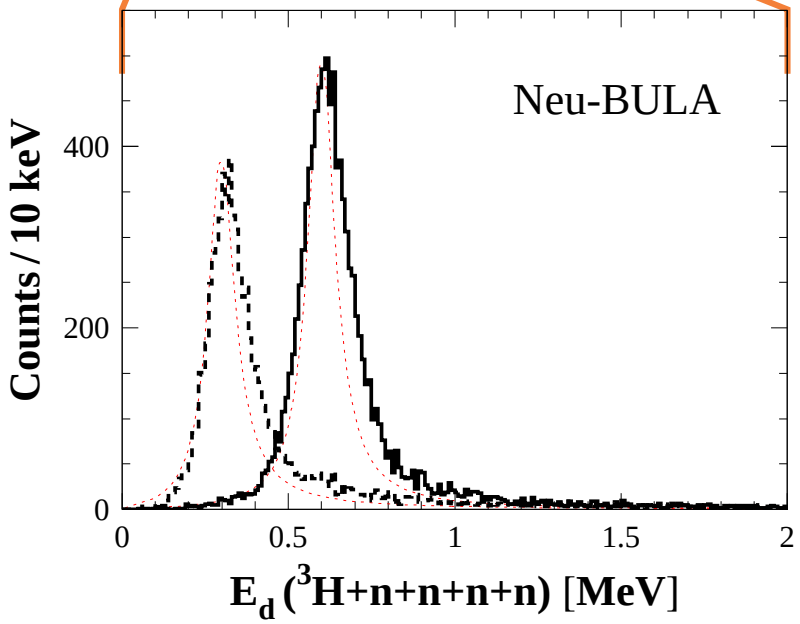


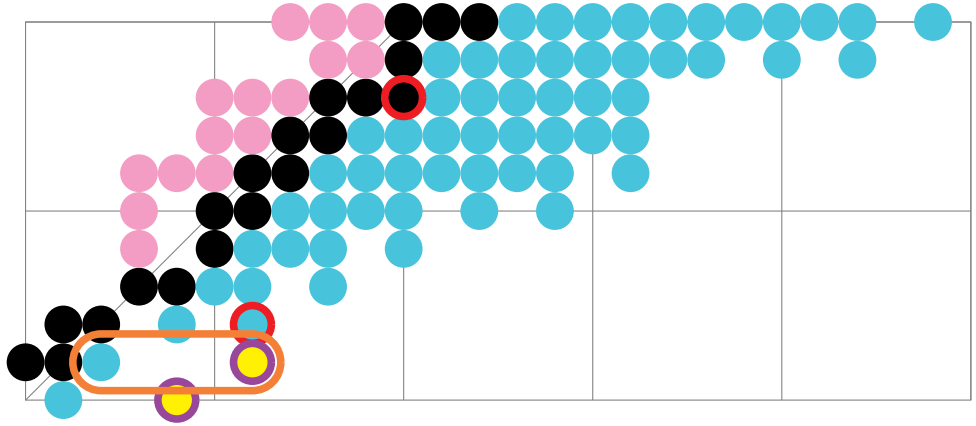


Caamaño, PRL 99 (2007) 062502

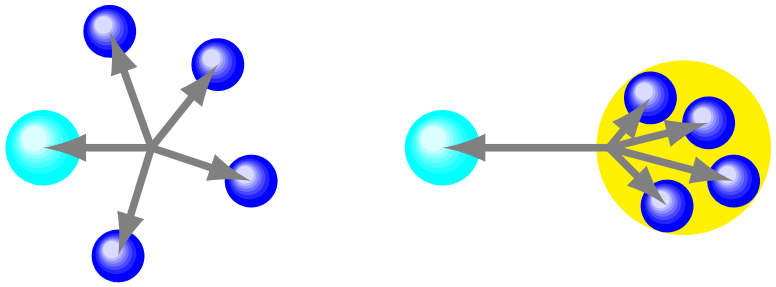




Direct 4n Decay : Sensitivity



- Angular correlations :



(a)
5-body PS

(b)
t-^{4}n PS

- very sensitive to $E_R(^4n)$!

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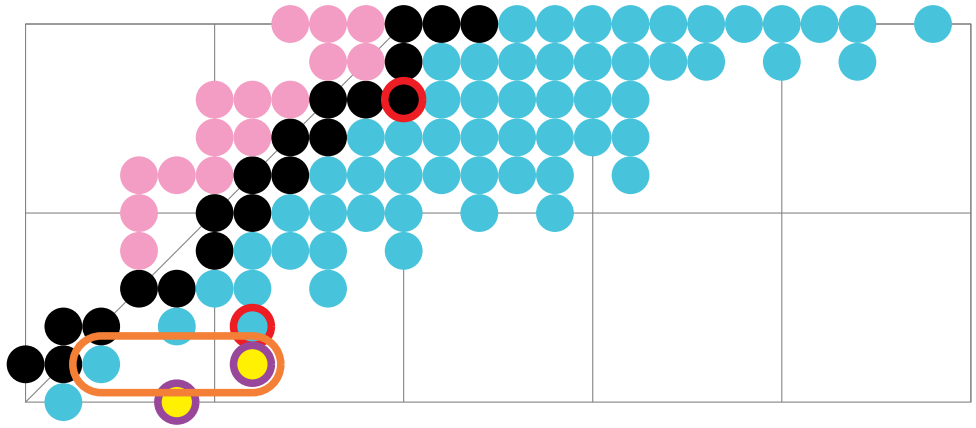

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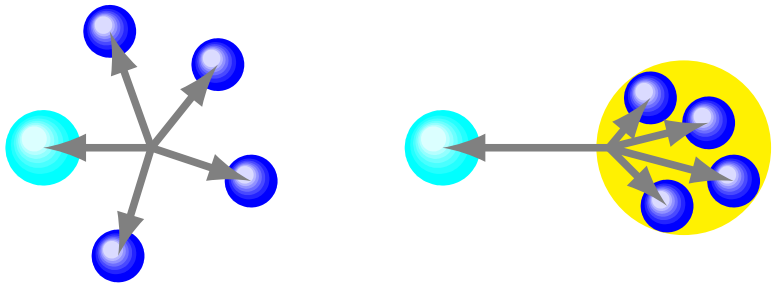

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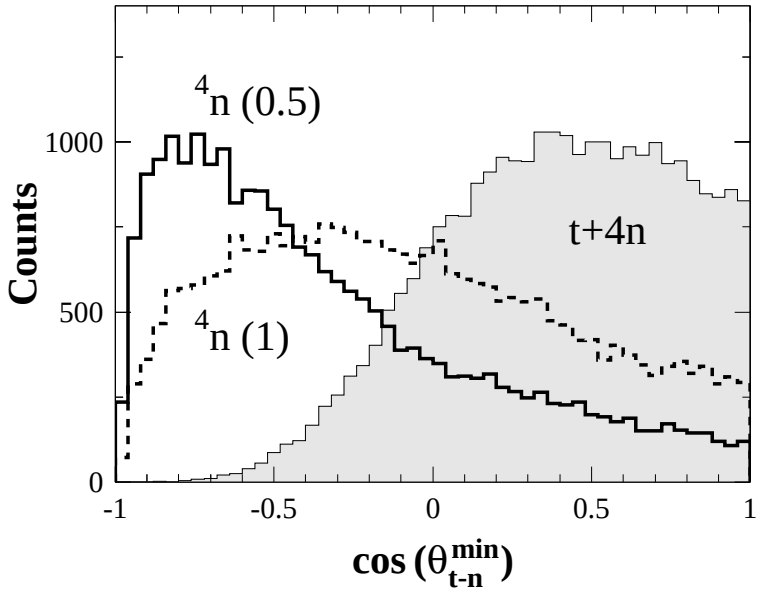
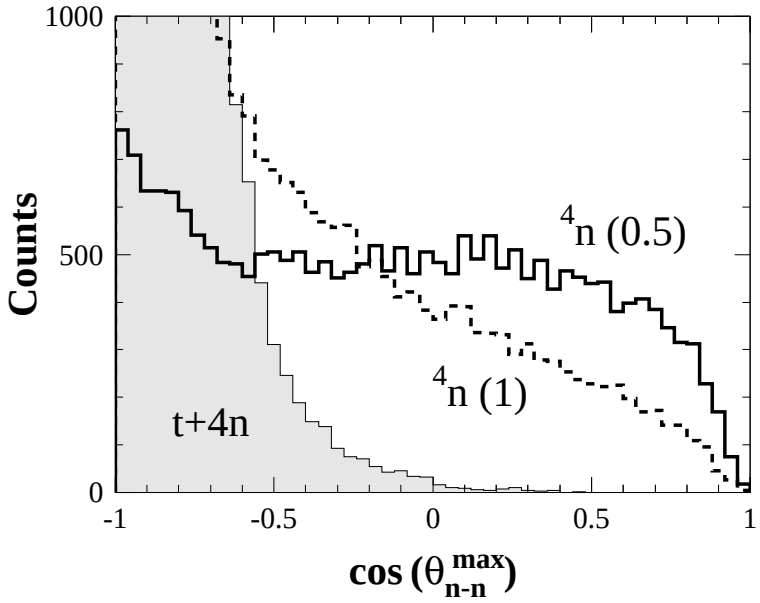
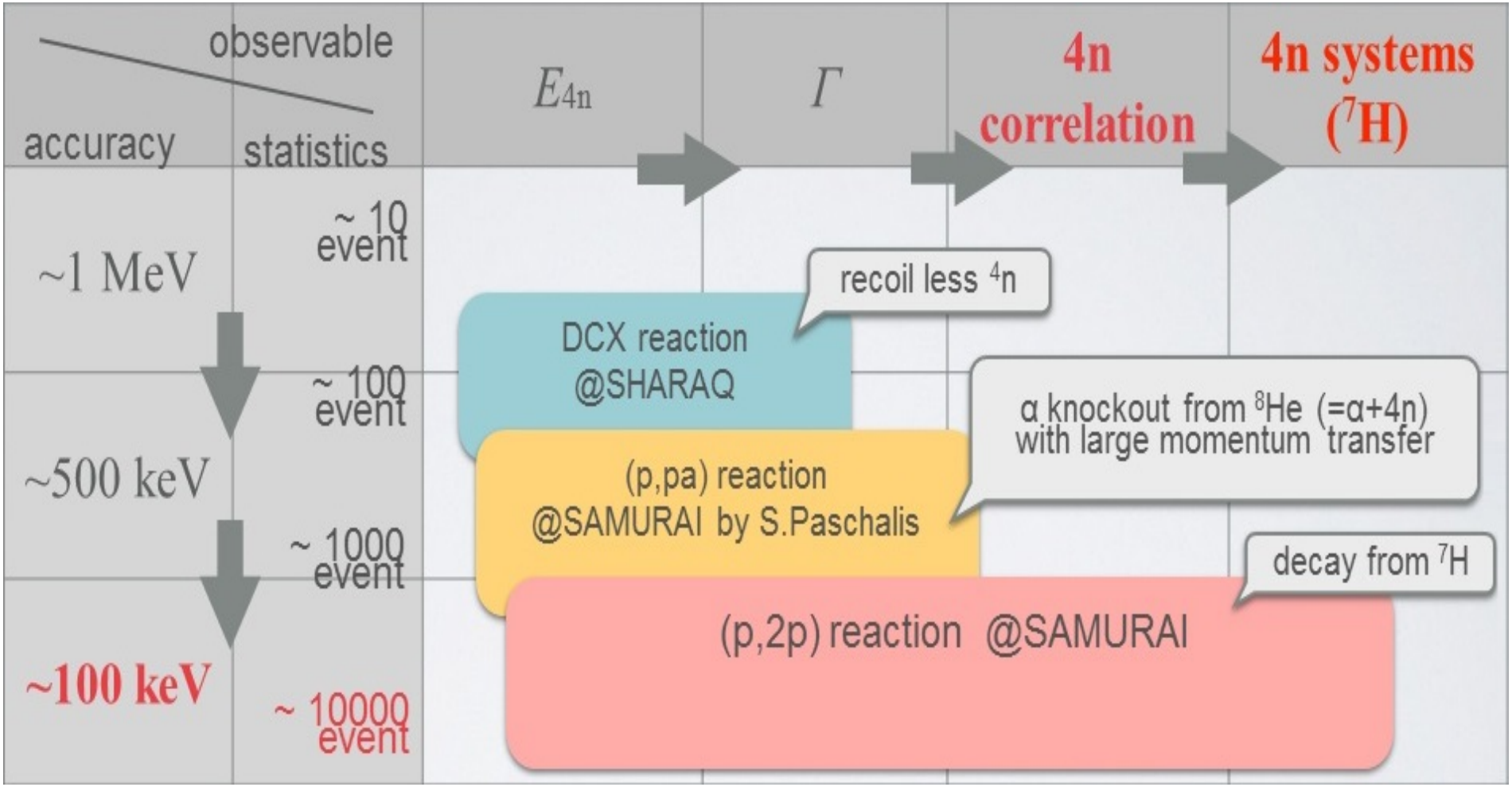




FMM, arXiv:nucl-ex/0504009

Kisamori, PRL 116 (2016) 052501

Experimental Context @ RIKEN



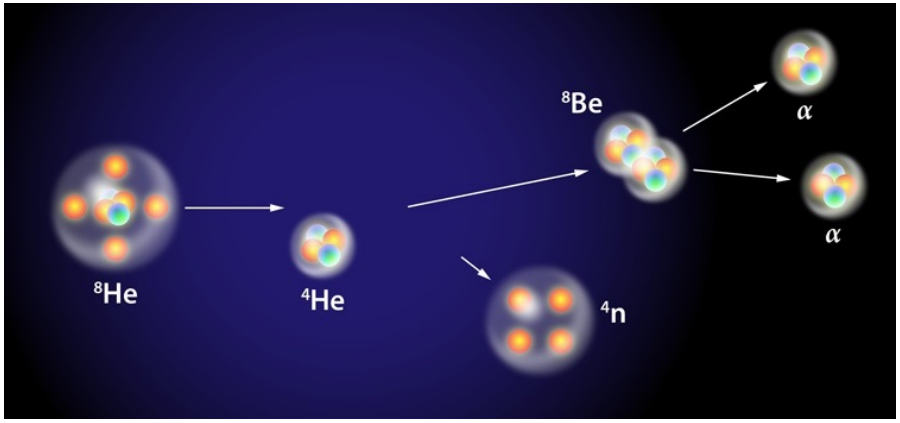
Summary

❶ A very long quest :

- extremely difficult to produce
- potential impact in many fields
- experimental program for 50 years !

  → two-step processes (bound state)

  → binary partners (any state)



❷ The end of the quest ?

- first 4n signals : DEMON & SHARAQ !
- low statistics, but no background ...
- theory cannot predict 4n states ...
- need order(s) of magnitude improvement

❸ Coming next (2016-17) :

- SHARAQ 2.0
- NEBULA+NeuLAND & MINOS :

  → (p,pα) : 4n without FSI

  → ^{7}H 4n-decay : sensitive to any $(E,\Gamma)_{R}$

⇨ short-term solution to ^{4}n & ^{7}H !