PHYSICS AT THE DRIP LINES (Topics addressed in GT1 of GDR Resanet)

1) Shell evolution far from stability and related theory -> see also Matta, Nowacki

2) Evolution of pairing towards the drip line

3) Clustering towards the drip line (di-proton, di-neutron, quasi-molecular states)

4) Study of in-medium clustering

5) Emergence of halo & Borromean states and related properties

6) Broken mirror symmetries -> see also Nowacki

7) Giant and pigmy modes in exotic nuclei -> see Hammache, Gulminelli

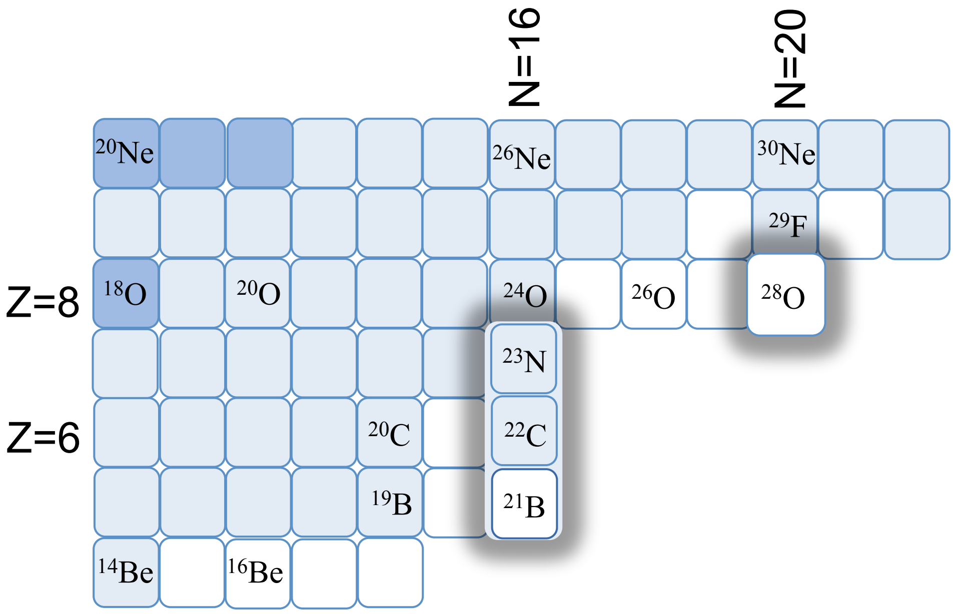
8) Synergy with other quantum systems.

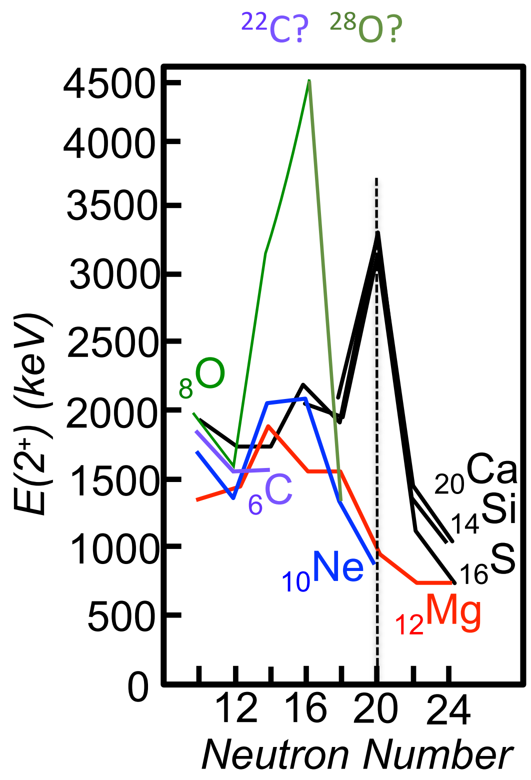
Mild changes / almost same models

OR

Drastics change / new models and concepts needed

Evolution of nuclear structure far from stability (RIKEN)





Change of paradigm in nuclear physics:

Systematic disappearance of magic nuclei 8, 20, 28 far from stability

Is N=16 a truly new magic number ?

-> Study of excited states of N=16 isotones below ^{24}O

@ RIKEN/SAMURAI

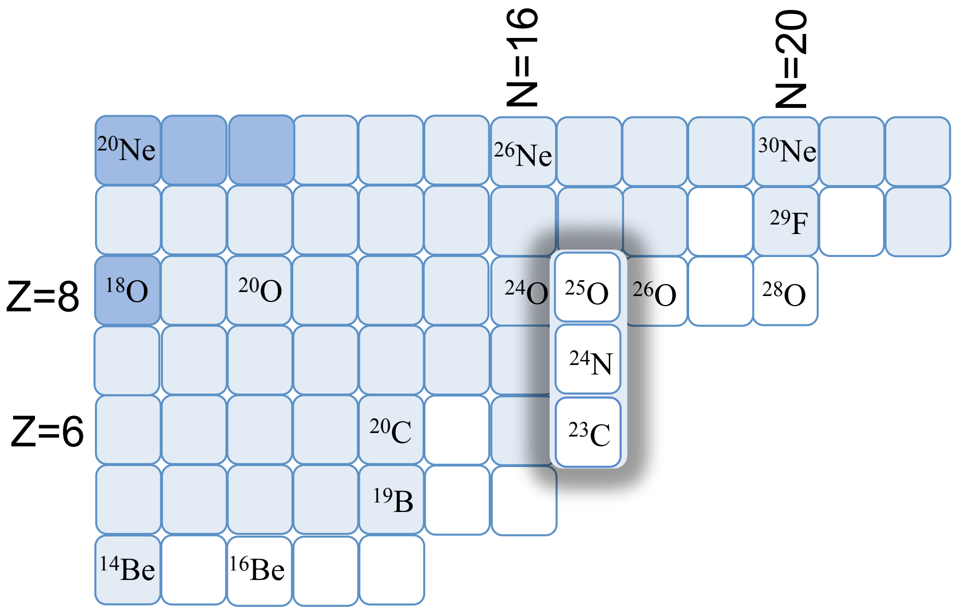
To which extent does N=20 disappears as well in ^{28}O, supposed to be DOUBLY magic?

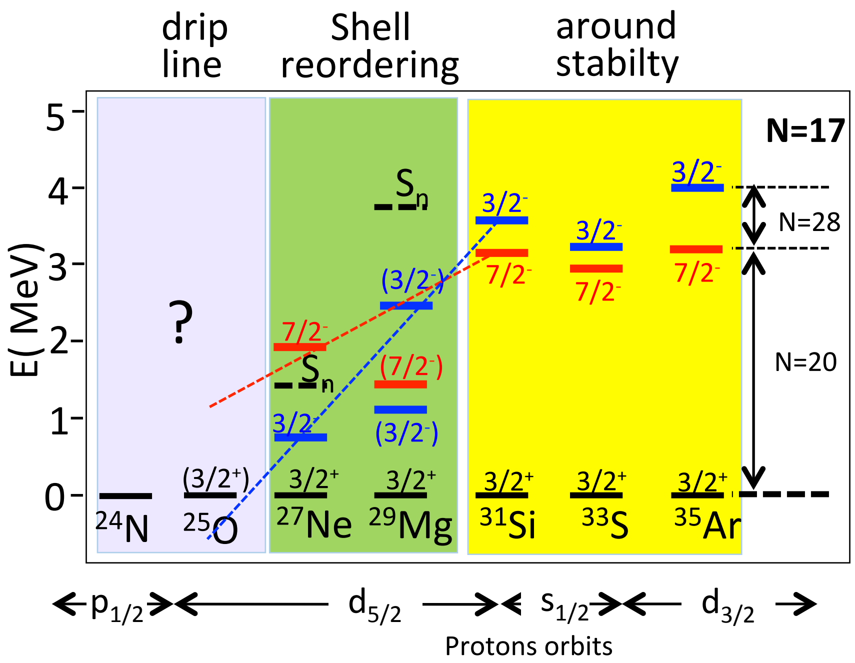
-> Study of excited states in ^{28}O

Future: Benefit from higher neutron efficiency and RIBF intensity (x10) in 2025

N.L. Achouri, F. Delaunay, F. Flavigny, J. Gibelin, F. M. Marquès, F. de Oliveira Santos, N. Orr, O. Sorlin, M. Parlog...

Evolution of nuclear structure: the role of nuclear forces / contiunuum





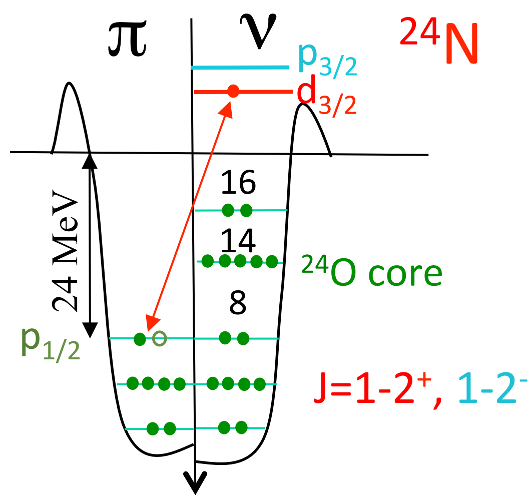
What are the underlying mechanisms for this substantial shell changes ?

How pn forces are modified with large pn binding asymmetry ?

-> Study shell evolution of N=17 isotones

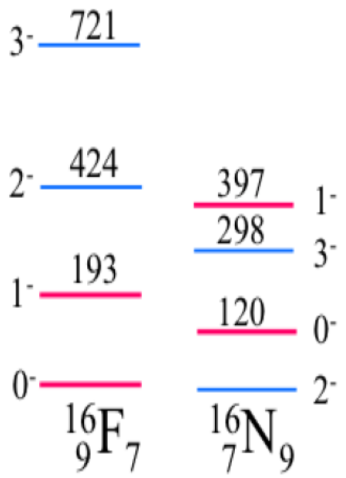
@ RIKEN/SAMURAI

Are there new expected magic nuclei ?



Unique way to understand nuclear forces for a better predictability in heavier nuclei

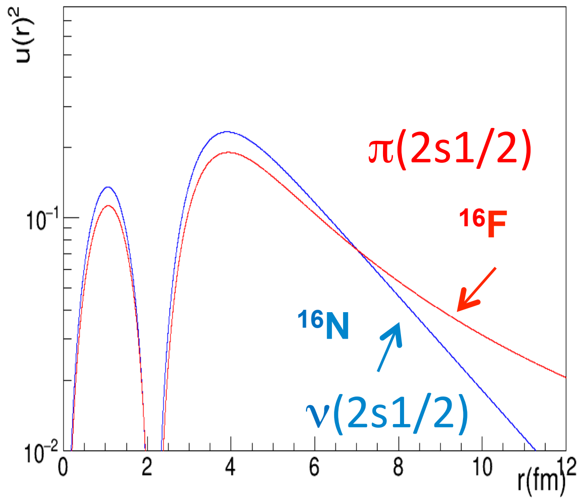
Breaking of mirror symmetry in open quantum systems



^{16}F unbound by 535 keV

Complete reordering of the orbits between the A=16 mirror nuclei

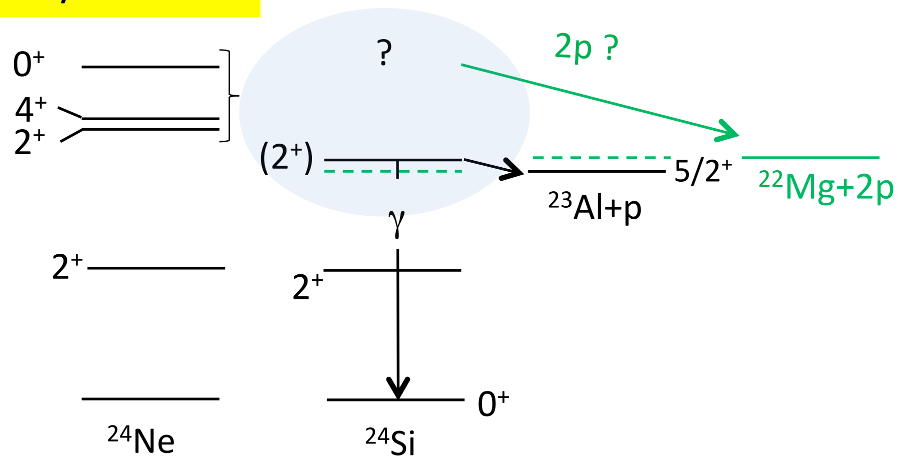
Effective pn interaction reduced by 50% owing to the continuum

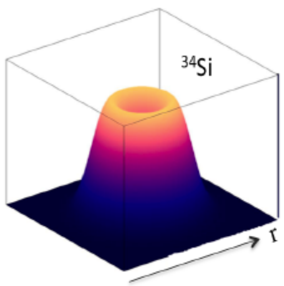


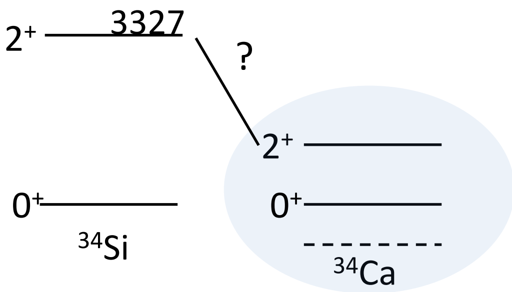
Perspectives @ GANIL/GRIT ...

Would the vibrational character of a nucleus be preserved in its mirror nucleus ?

Drastic influence on p captures in X-ray bursts
Study of 2p decay and correlations



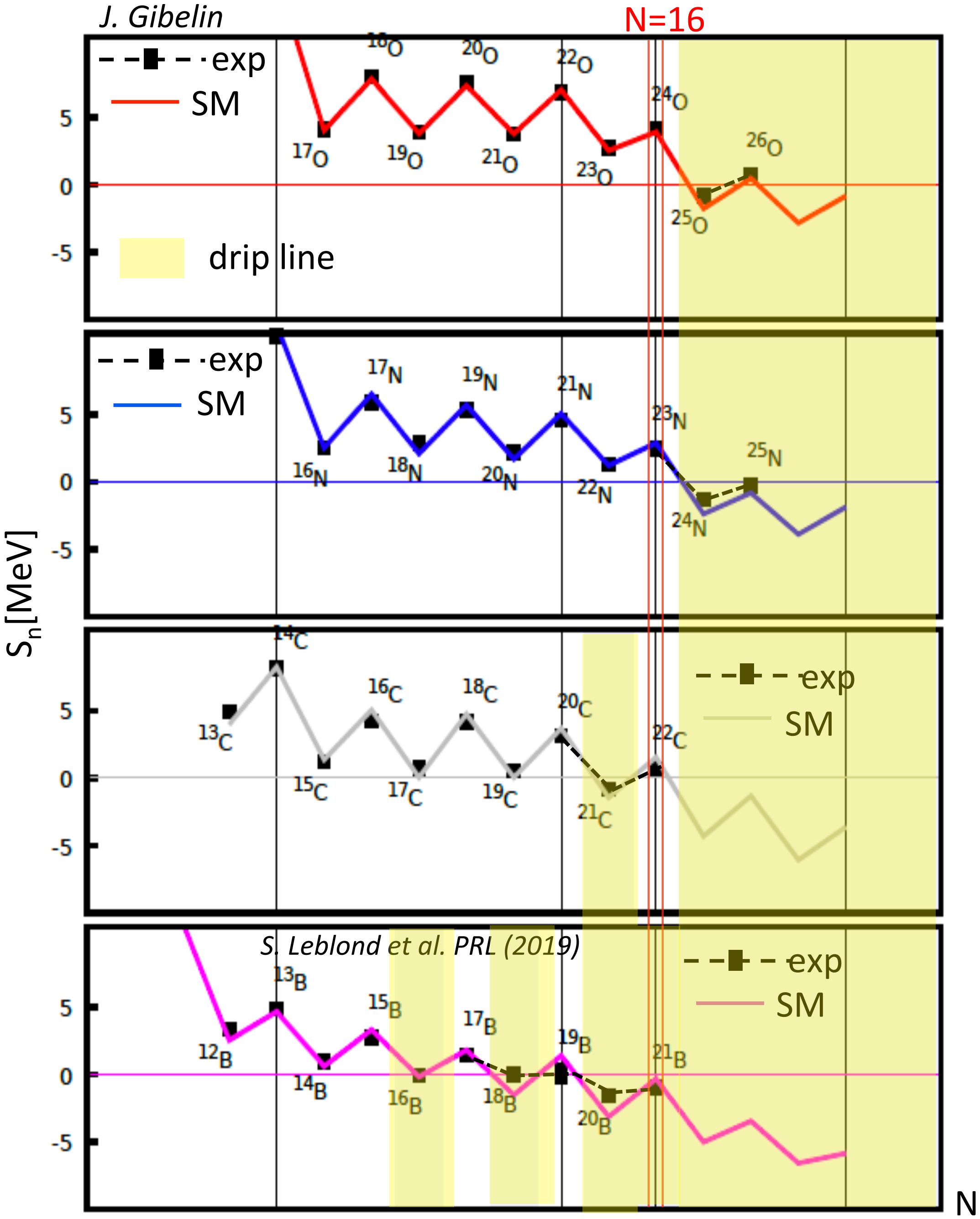


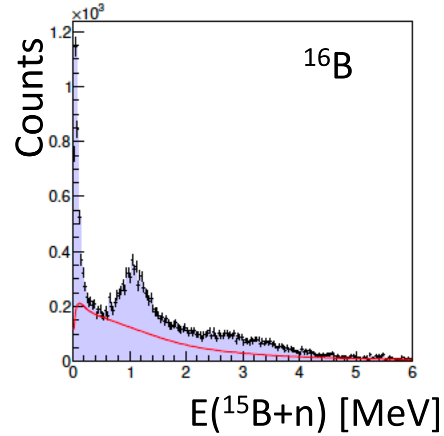


Could a doubly magic nucleus become deformed in its mirror reflexion ?

N.L. Achouri, M. Assié, D. Beaumel, Y. Blumenfeld, F. Flavigny, J. Gibelin, S. Grévy, F. Hammache, A. Matta, F. de Oliveira Santos, O. Sorlin, I. Stefan ...

Trend of $S_n(N)$ as a probe of shell-closure and pairing





Study of 1n and 2n decays of unbound nuclei allows accurate determinations of S_n beyond the drip line

Reduced odd-even S_n oscillations at the drip line as compared to calculations

-> change of pairing regime?
-> Role of pn interaction?
-> analogy with gapless supracond ?

Extend studies further away from Stability at RIKEN

N.L. Achouri, F. Delaunay, F. Flavigny, J. Gibelin, F. M. Marquès, N. Orr, M. Parlog, O. Sorlin ...

Evolution of pairing between BCS and BEC

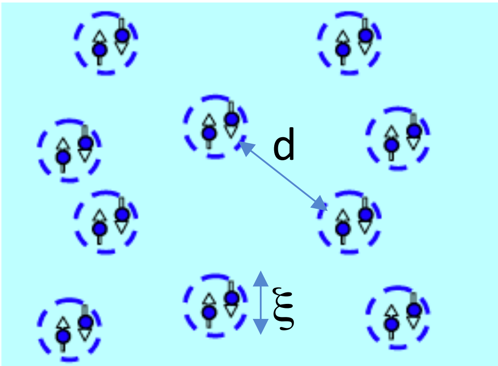
BEC

Strong interaction

Bound pairs (bosons) in free space

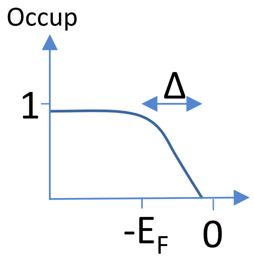
Boson condensate in medium

$\xi/d \ll 1$, $\Delta/E_F > 1$



Cross over

Light
n-rich nuclei



$1.3 > \Delta/E_F > 0.2$

$0.2 < \xi/d < 1$

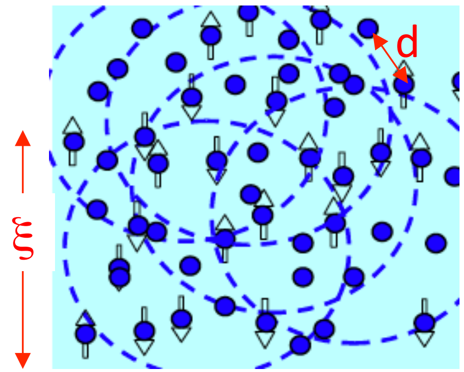
BCS

Weak interaction

No bound pair in free space

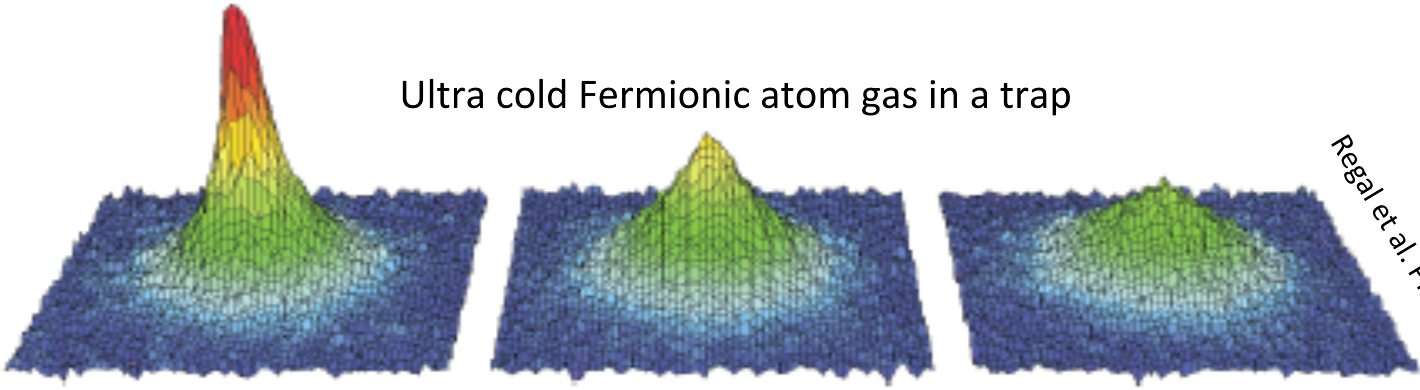
Cooper pairs formed in medium

$\xi/d > 1$, $\Delta/E_F \ll 1$



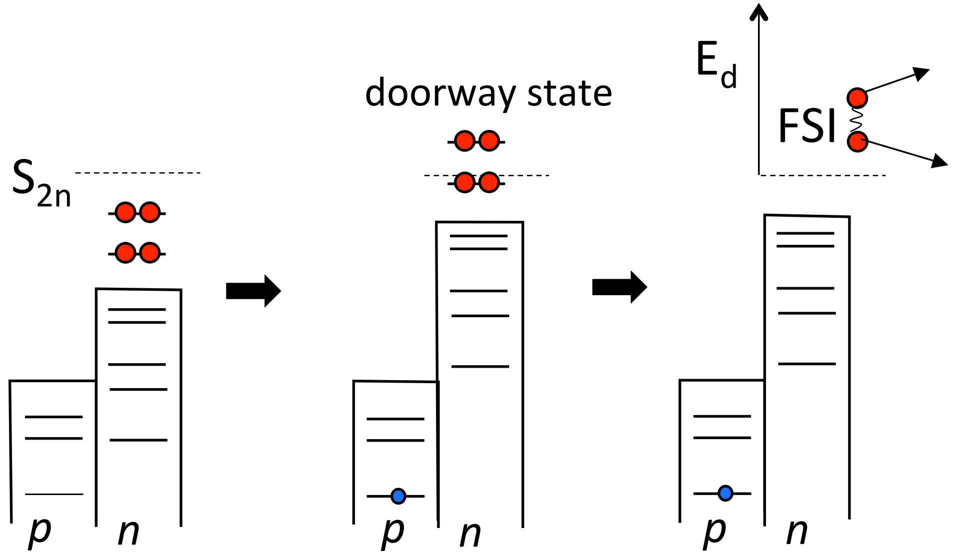
From Matsuo

Ultra cold Fermionic atom gas in a trap

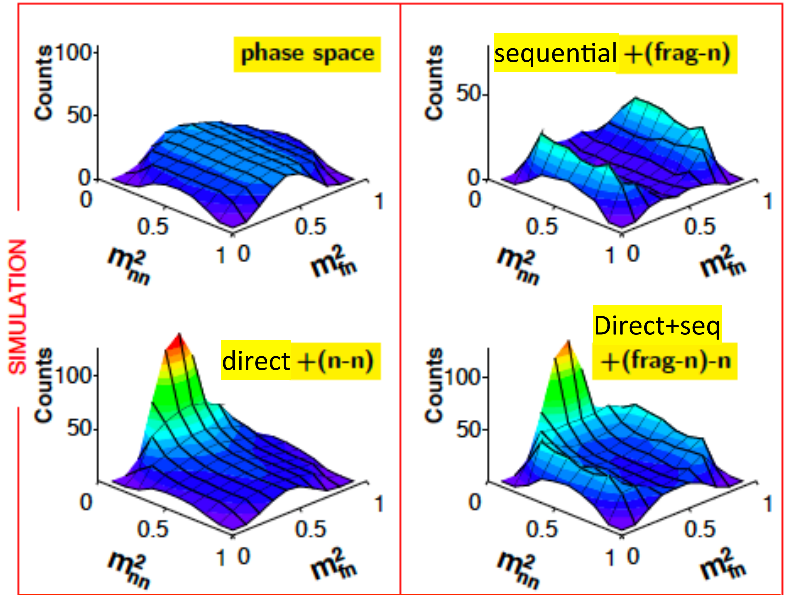


Regal et al. PRL (2014)

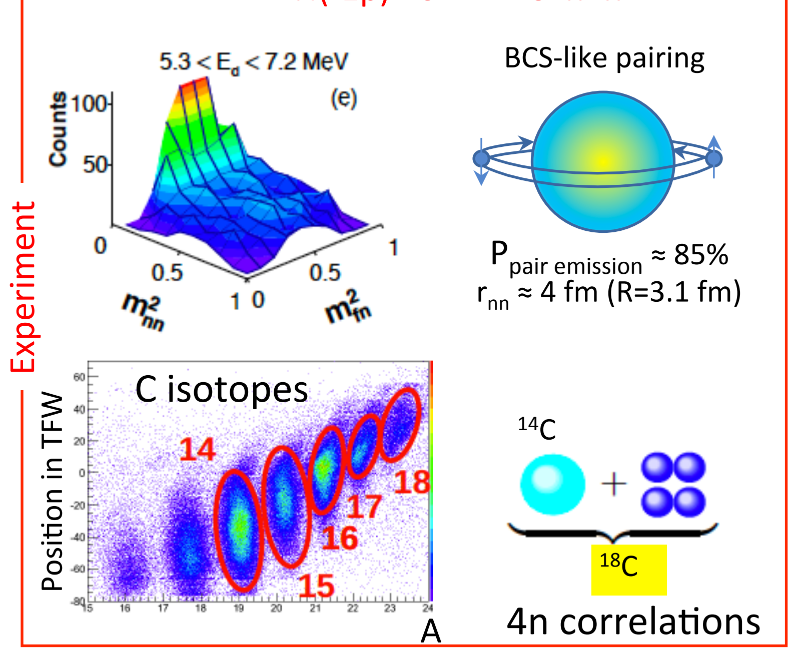
Study of 2n and 4n correlations towards the drip line



Analogy with photoemission of Cooper pairs *Wehlitz PRL (2012)*



^{19}N(-1p)^{18}C* -> ^{16}C+n+n



A. Revel et al. PRL (2018)

Use deeply-bound nucleon quasi-free knockout

-> Promote 2n and 4n in the continuum

-> Study 2n and 4n decays (direct/sequential)

@ FAIR/R3B/NeuLAND, RIKEN/SAMURAI/NEBULA

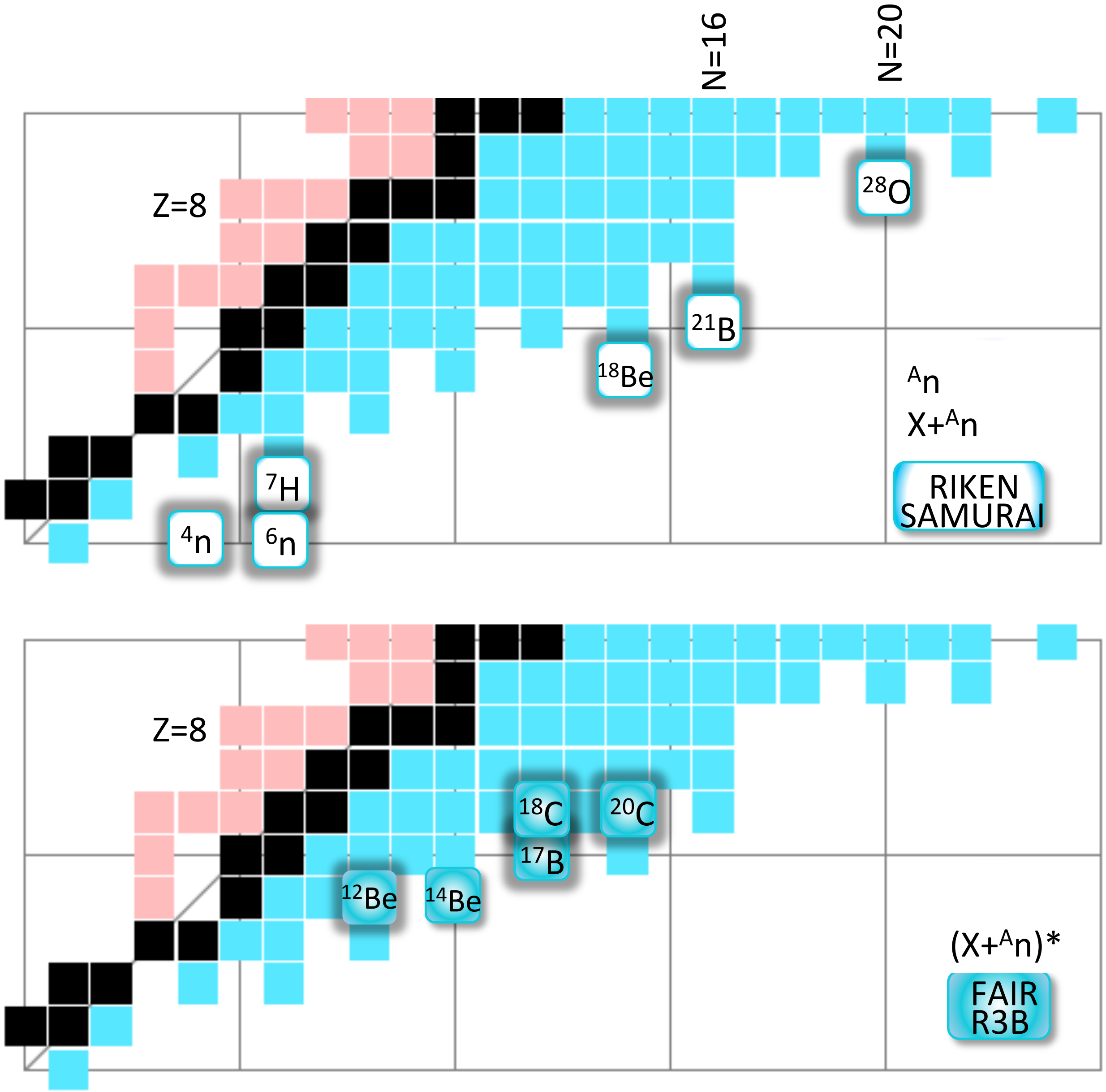
-> Evolution of r_{nn} with binding energy and A

-> Study the role of the reaction mechanism

Complete the neutron wall, Si tracker and CALIFA

M. Assié, D. Beaumel, A. Chbihi, F. Flavigny, M. Marques, F. de Oliveira Santos, O. Sorlin, G. Verde...

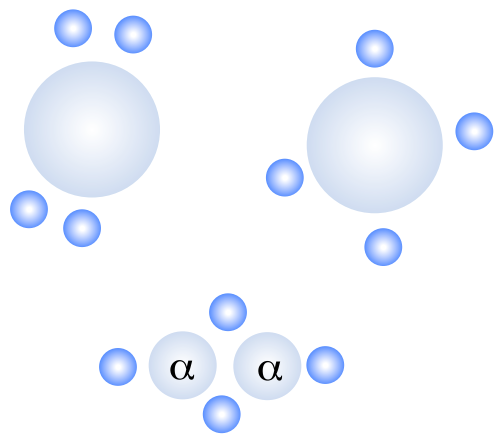
Study of multi-neutron emission from ground and excited states



^{A}n: Better modelling of ab-initio nuclear forces

X+^{A}n & (X+^{A}n)*:
Characterize An decays and correlations

Identify molecular states e.g. correlations between clusters and neutrons

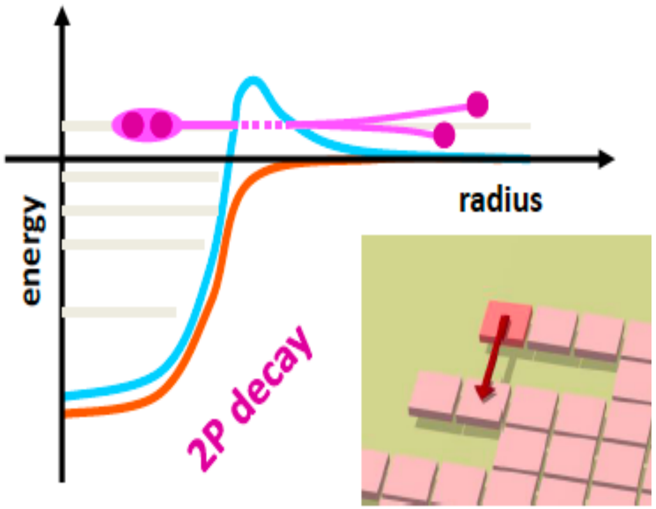


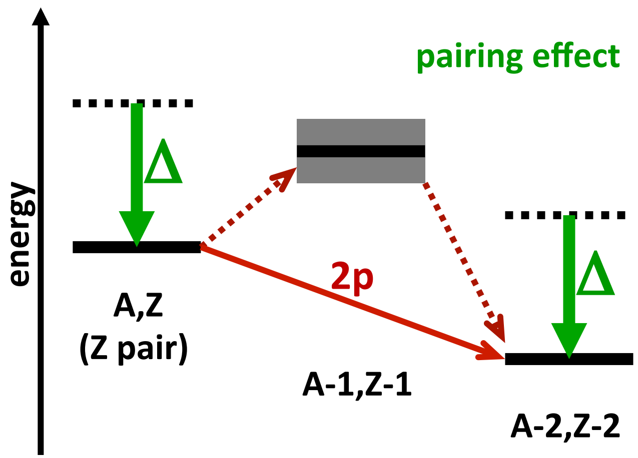
Need of very high granularity and efficiency neutron arrays
-> upgrade of Nebula at RIKEN, more double planes and larger distance of NeuLAND at FAIR

Goals and prospects on 2p decay radioactivity

The 2p radioactivity is very a rare process.
The lifetime of the nucleus should be long enough to call it ‘radioactivity’.

It is found when the 1p daughter is unbound and when the 2p are trapped inside a barrier

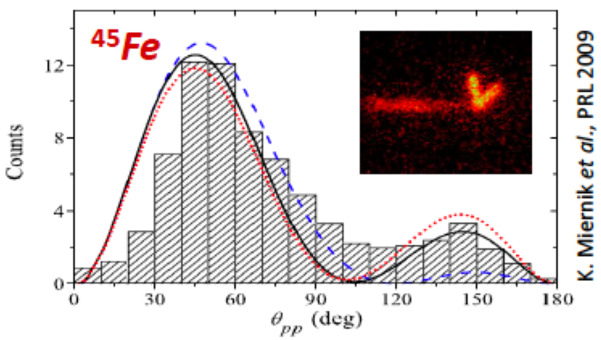


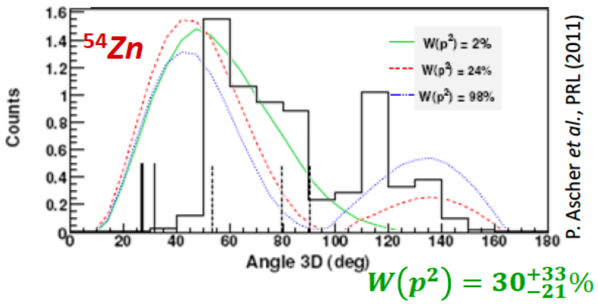


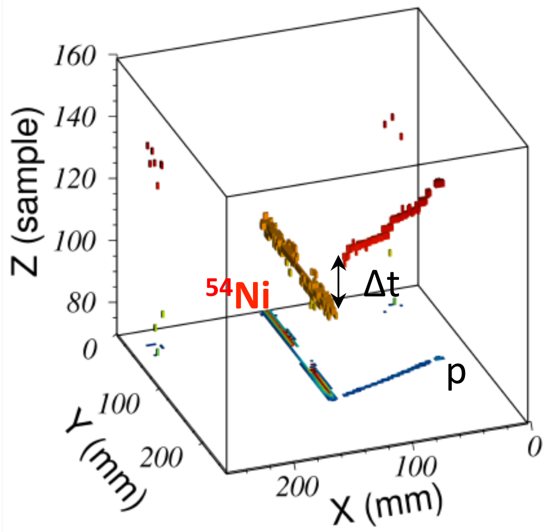
Understanding the 2p process requires modeling of the nuclear structure and the dynamics

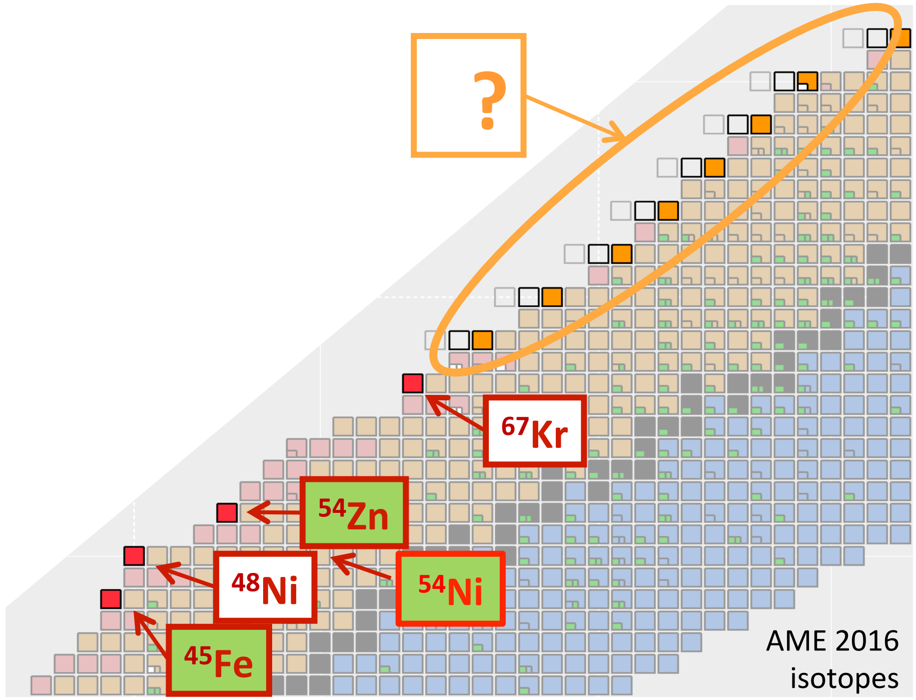
P. Ascher, B. Blank, M. Gerbaux, J. Giovinazzo, S. Grévy, T. Kurtukian-Nieto, F. de Oliveira Santos, T. Roger, J.C. Thomas...

Perspectives on the study of 2p decay radioactivity









GANIL, RIKEN, GSI

Studies of doubly magic ^{48}Ni, of ^{54}Zn and the deformed ^{67}Kr

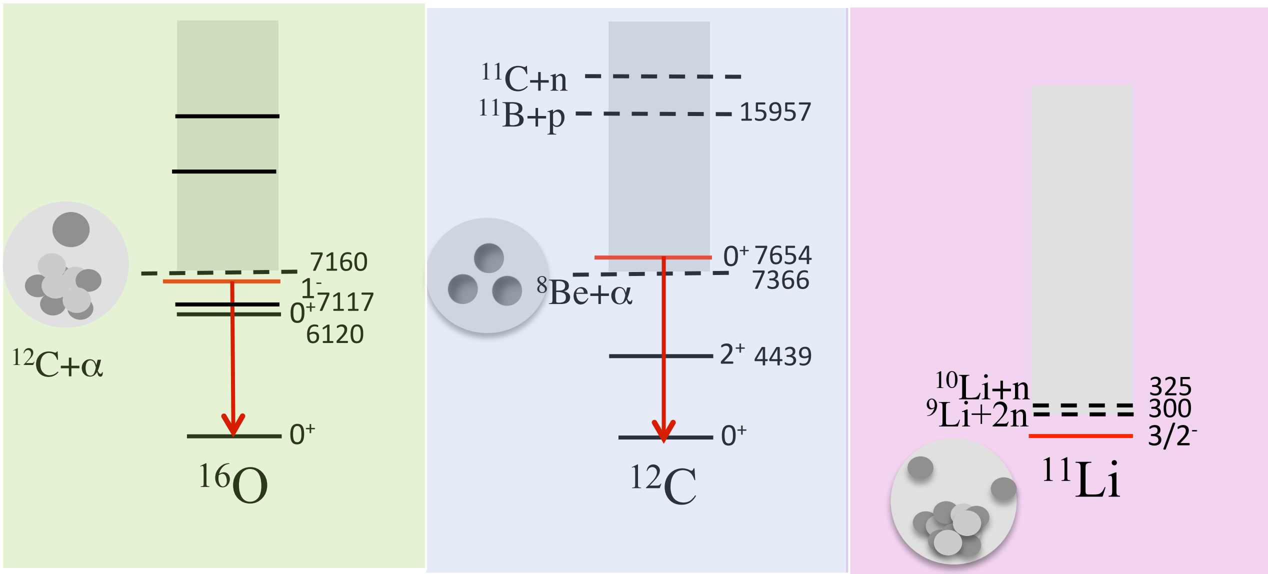
Identify new (heavier) 2p emitters

Measure the corresponding 2p decays and properties

Strong connexions with theories to interpret the decay patterns

Does the ikeda conjecture apply to di- or tetra- nucleon configurations?

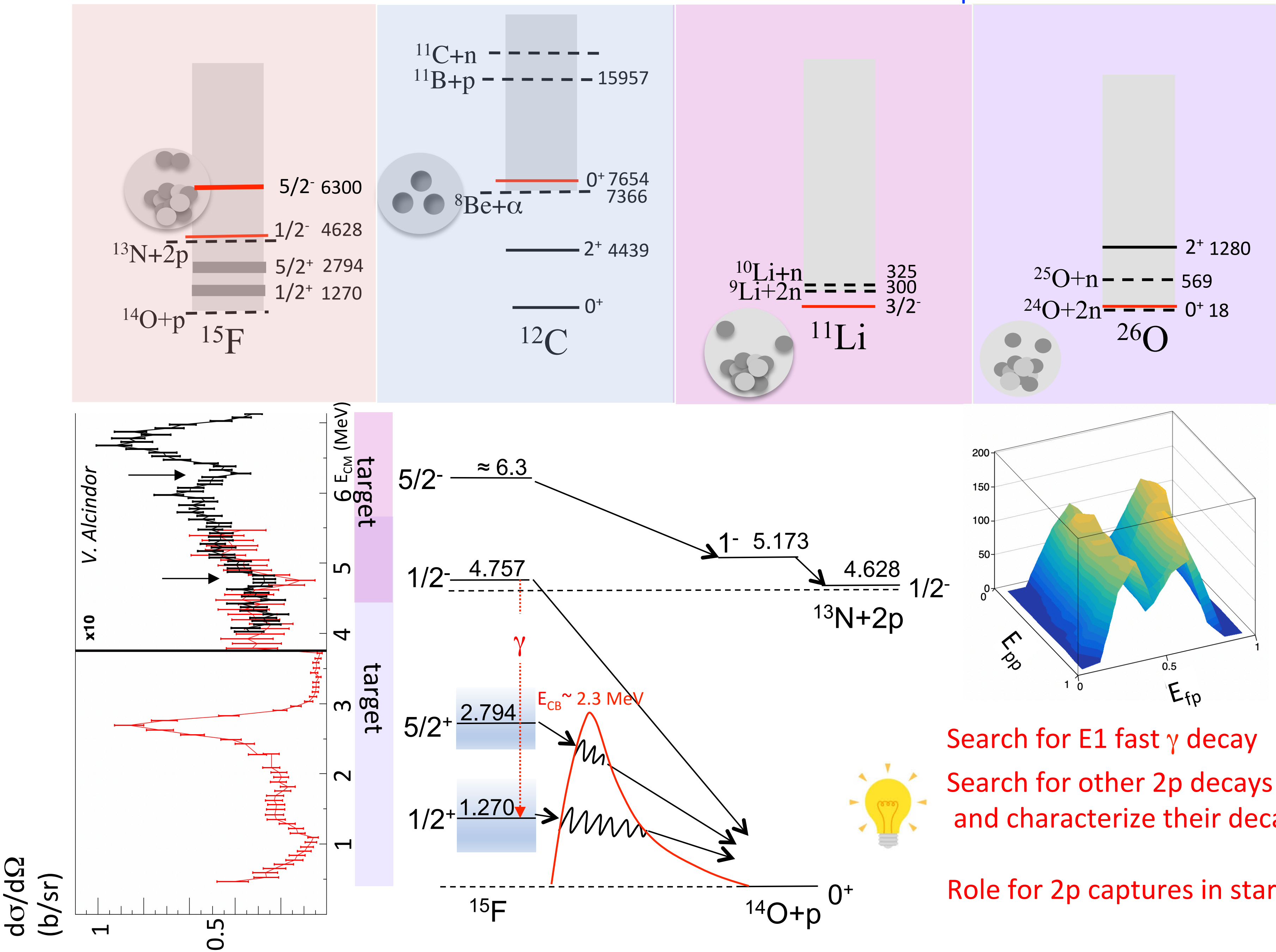
(J. Okolowicz, et al. Prog. Th. Phys. Supp. 196 (2012))



Ikeda conjecture : Existence of narrow cluster states at the corresponding energy thresholds

-> Decisive impact for ^{12}C and ^{16}O production in massive stars by α captures

Search for 2p cluster configurations around S_{2p} threshold

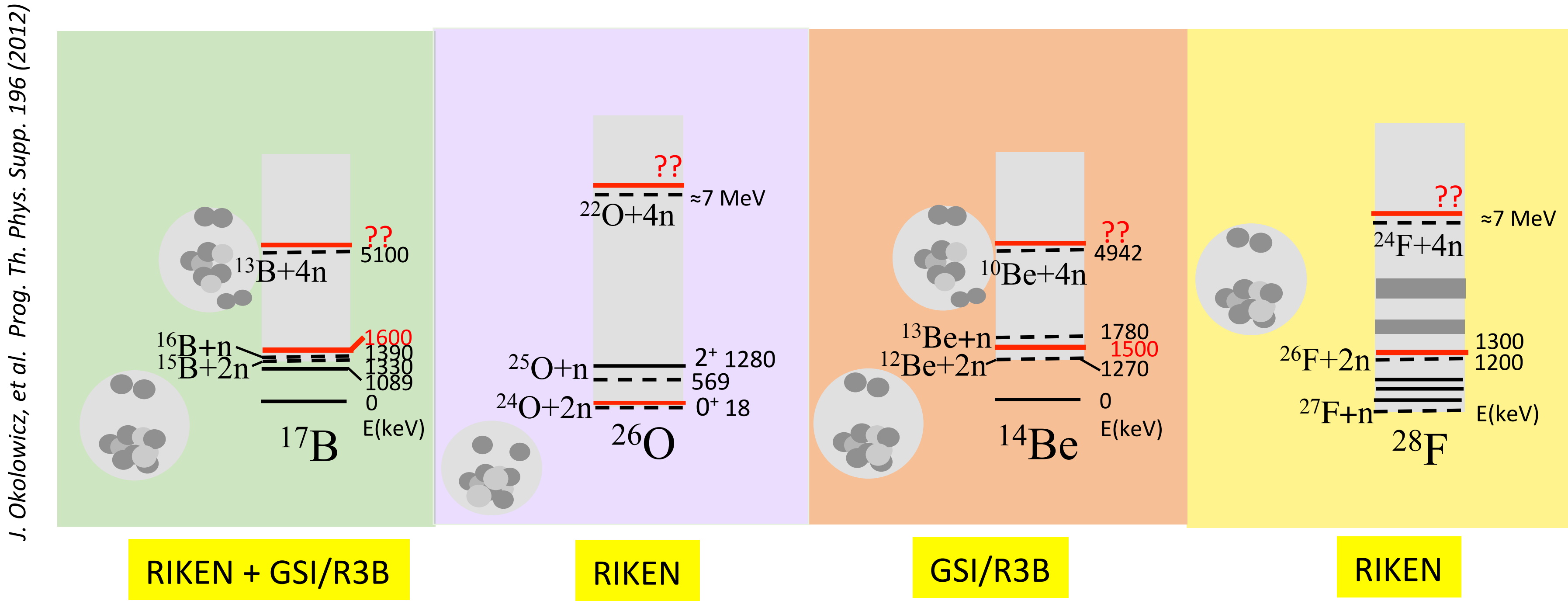


Search for E1 fast γ decay

Search for other 2p decays and characterize their decays

Role for 2p captures in stars ?

Does the ikeda conjecture apply to di- or tetra- nucleon configurations?



Narrow states ≈S_{2n} systematically present -> use models including continuum to understand

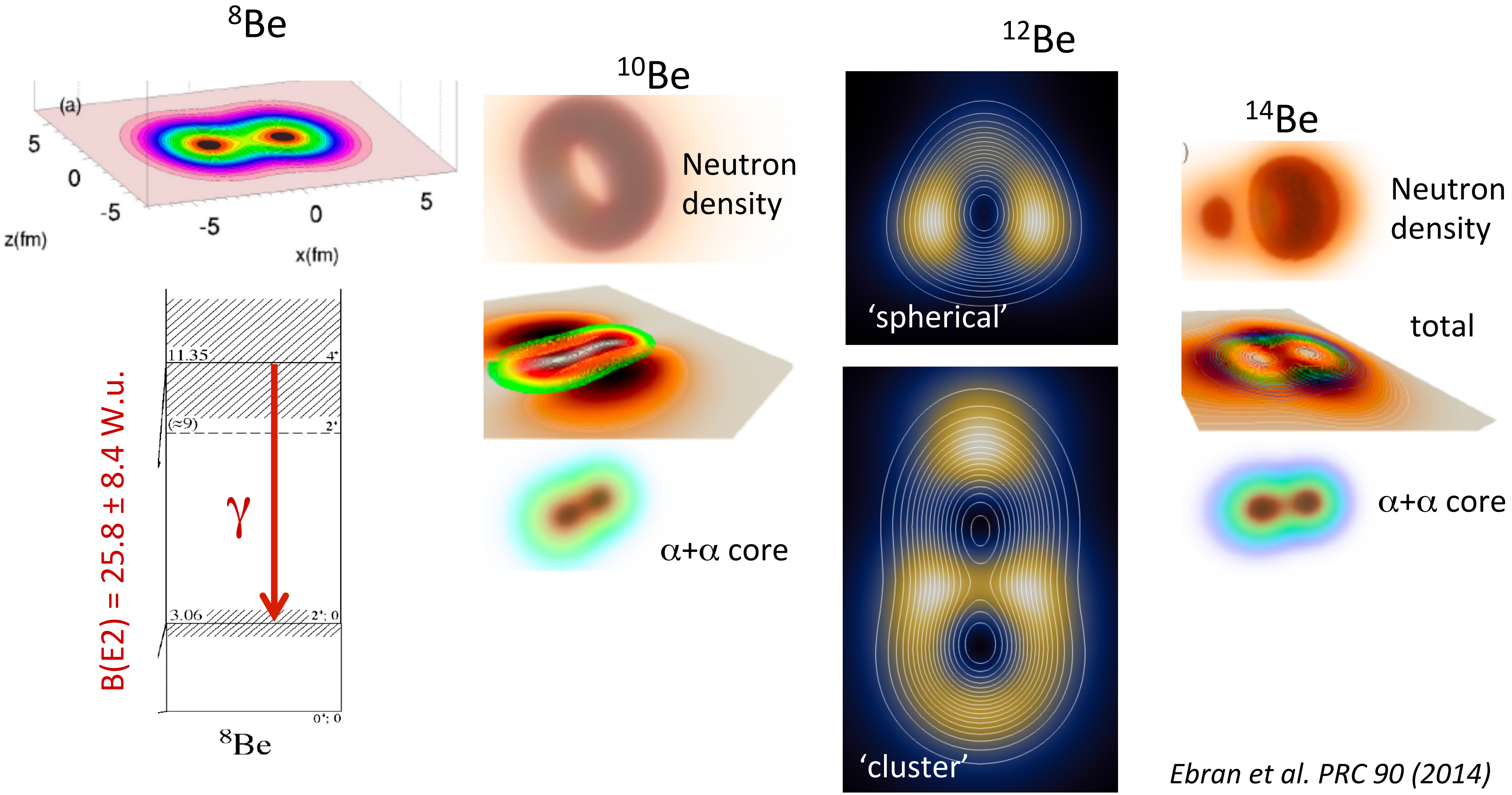
What is the γ- wrt 1n- or 2n- decay of such states, possibly spatially extended

Are there narrow resonances around S_{4n} -> 4n clustering ?

Such narrow resonances close to S_{2n} may drastically enhance n captures in the r process

N.L. Achouri, F. Delaunay, F. Flavigny, J. Gibelin, F. M. Marquès, F. de Oliveira Santos, N. Orr, O. Sorlin, M. Parlog...

Evolution of nuclear α clustering in neutron-rich nuclei



Ebran et al. PRC 90 (2014)

Decay between two unbound states of a rotational band

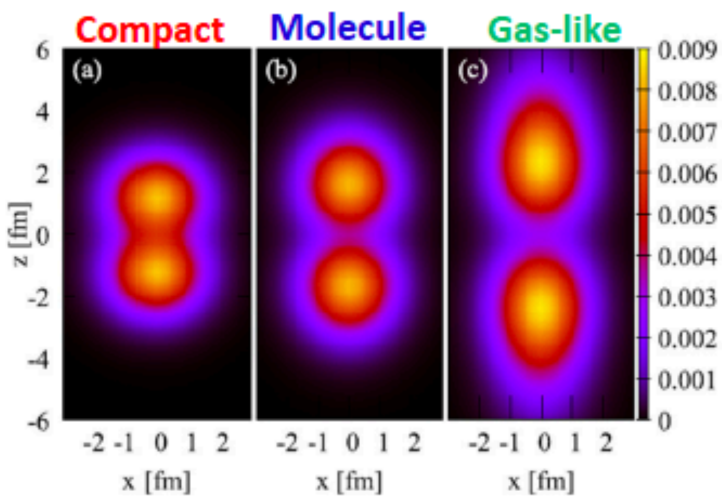
-> Search for other cases to characterize clustering

M. Assié, D. Beaumel, S. Courtin, J. Gibelin, F. Hammache...

Probing cluster structures using knockout and transfer reactions

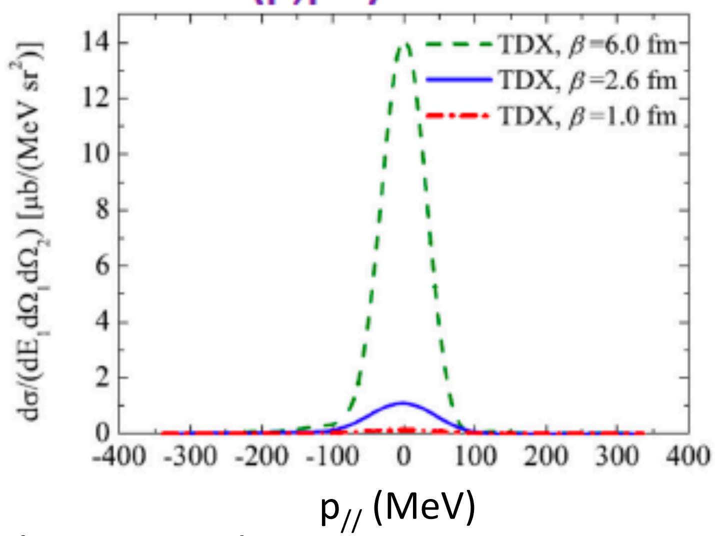
High sensitivity of the α knockout cross section to the extension of the cluster

^{10}Be GS wave function



DWIA calc.

^{10}Be(p,pα) cross-section



M.Lyu et al., PRC 97 (2018)

^{10,12,14}Be (pp,α) done at 150 MeV/A, combine with neutron detection

Cluster in neutron-rich C isotopes planned to be studied RIKEN

M. Assié, D. Beaumel, F. Flavigny, F. Hammache, A. Matta...

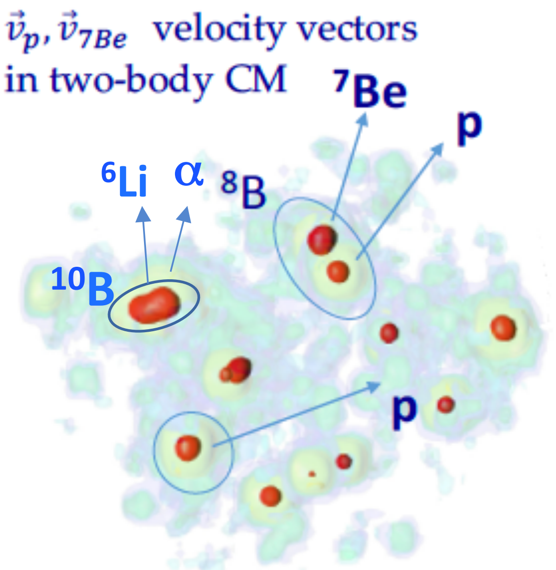
GANIL actar TPC

Clustering in ^{10}Be and ^{12}Be can be probed through ^{10}Be(p,t)2α and ^{8}He(α,α)^{8}He, respectively

M. Assié, D. Beaumel, F. Flavigny, J. Gibelin, F. de Oliveira Santos, T. Roger

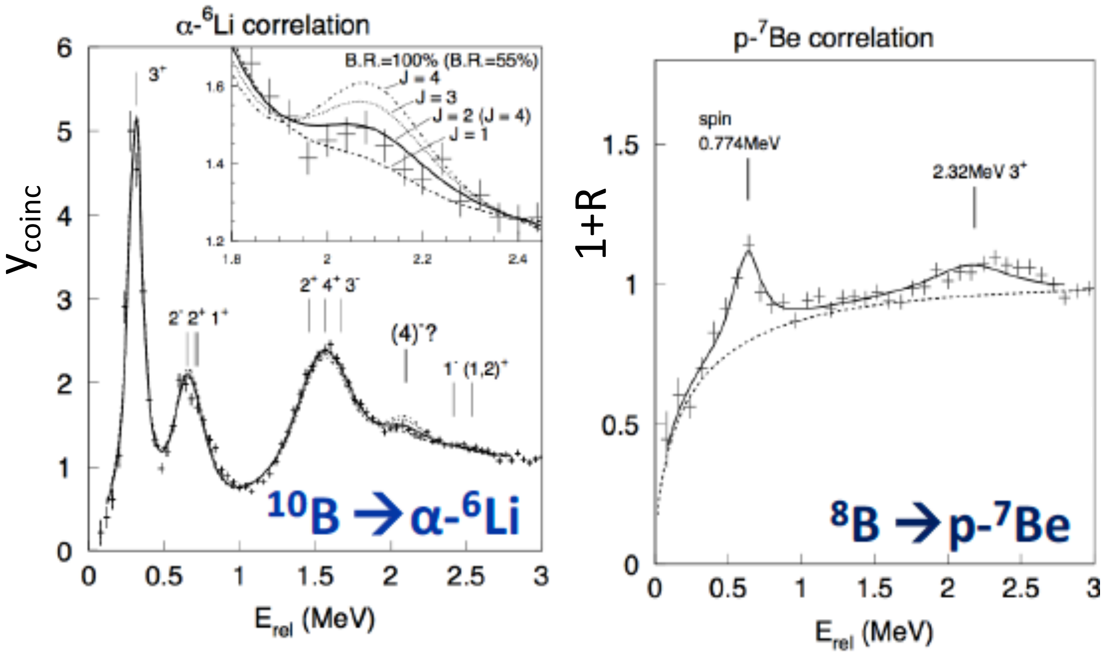
In-medium cluster formation and resonance decay spectroscopy

What are the mechanisms leading to cluster production during nuclear collisions ?
Does the environment modify the properties of resonances (decay pattern, energy, width) ?



Particle emitting sources extended in phase-space

Analogy with the production of K, Σ, Λ, Ξ resonances in heavy ion collisions



Coincidence yields

$Y_{coinc}(a,b)$

-> T, branching ratios

Correlation function

$$1+R(q)=\frac{Y_{coinc}(a,b)}{Y_{random}(a,b)}$$

-> Volume, Density, Spin

Determine the Y_{coinc} and $1+R(q_{rel})$ in different reactions **INDRA/FAZIA**

B. Borderie, A. Chbihi, J. Frankland, D. Gruyer, F. Gulminelli, N. Le Neindre, O. Lopez, G. Verde and E. Vient

In-medium cluster formation and resonance decay spectroscopy

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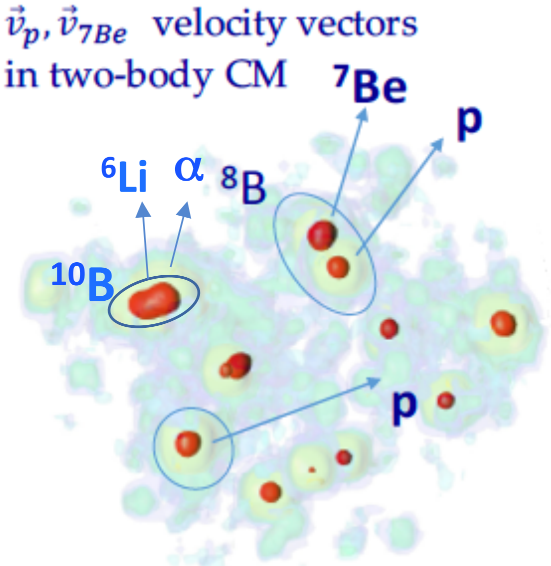
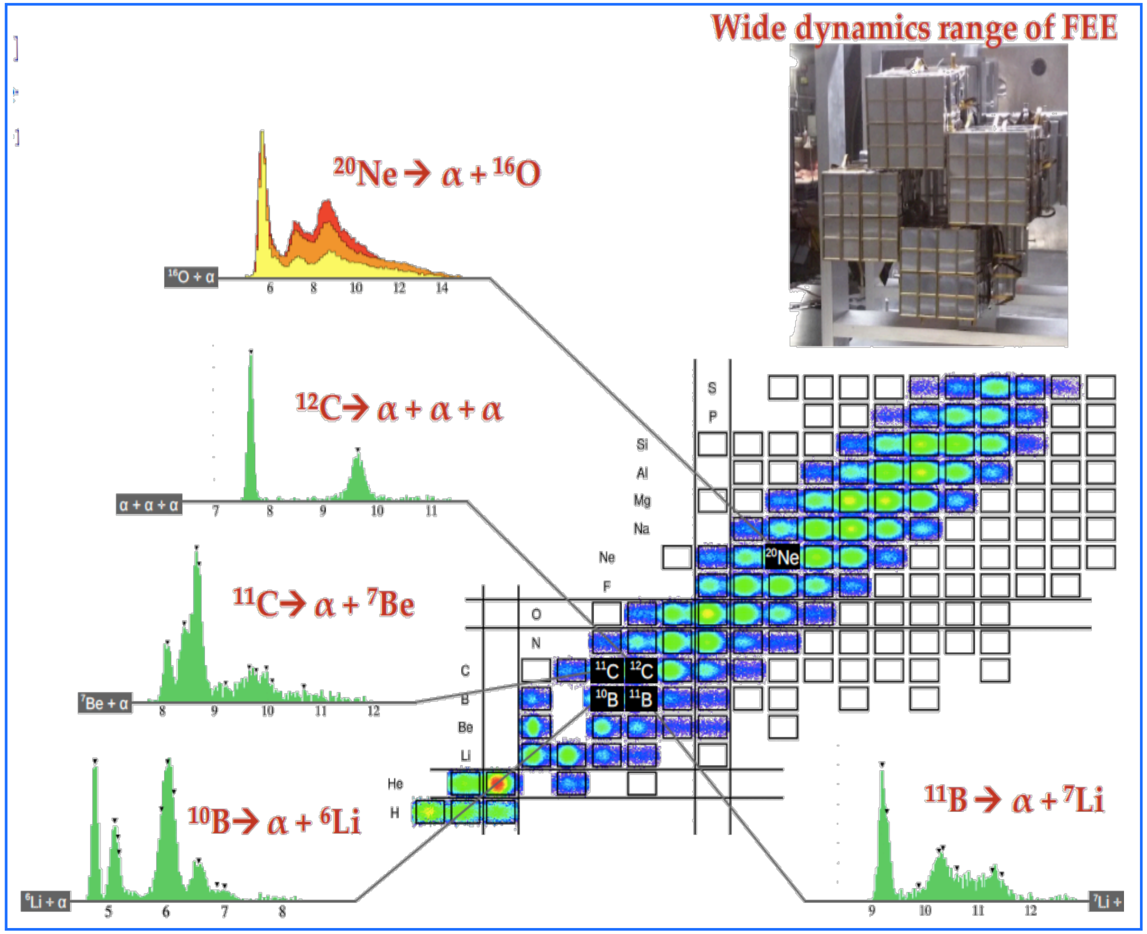


Particle emitting sources extended in phase-space

Analogy with the production of K, Σ, Λ, Ξ resonances in heavy ion collisions



Determine the Y_{coinc} and $1+R(q_{rel})$ in different reactions
Study the profiles of resonances in different medium

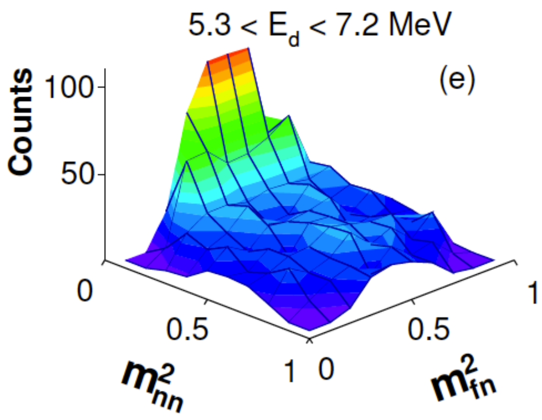
INDRA/FAZIA

Reinforce links between theory and experiments

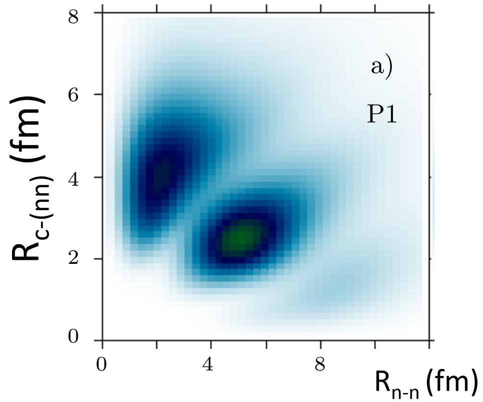
EXPERIMENT

$C_{nn}(q_{nn})$

m^2_{fn}, m^2_{nn}, θp_{n1}-p_{n2}



THEORY

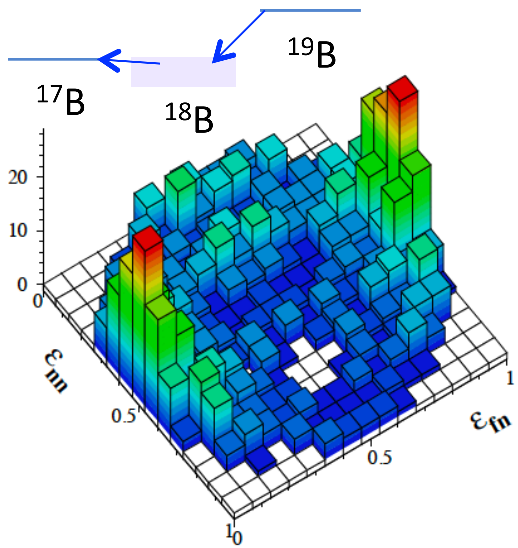


Describe nuclear stucture and reaction mechanisms within the same framework

Essential to link experimental observables with underlying physics

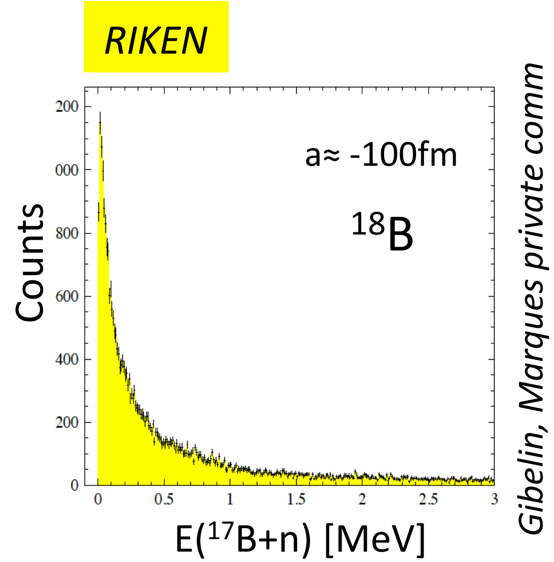
J.-P. Ebran, G. Hupin, E. Khan, D. Lacroix, M. Ploszajczak...

Could gigantic ‘nuclei’ exist ?



Sequential decay of ^{19}B through the virtual state in ^{18}B
BE(^{19}B)≈ -0.14(39)MeV

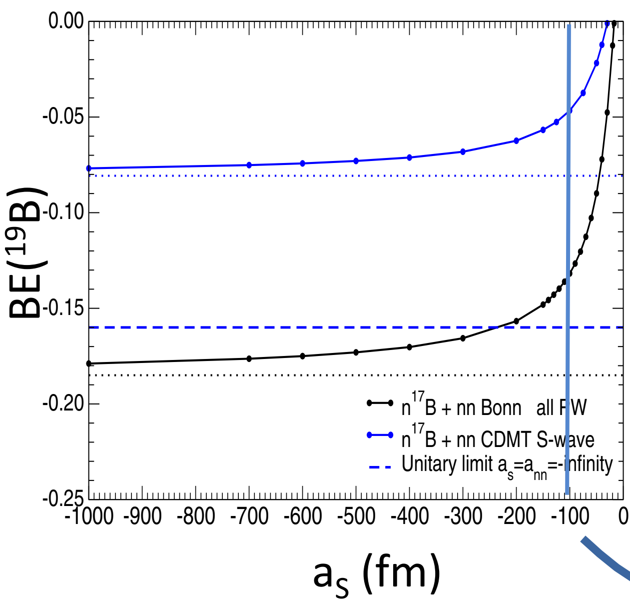
Very large n-^{17}B distance w.r.t. range of nuclear forces (a_{nn}≈ -18fm)

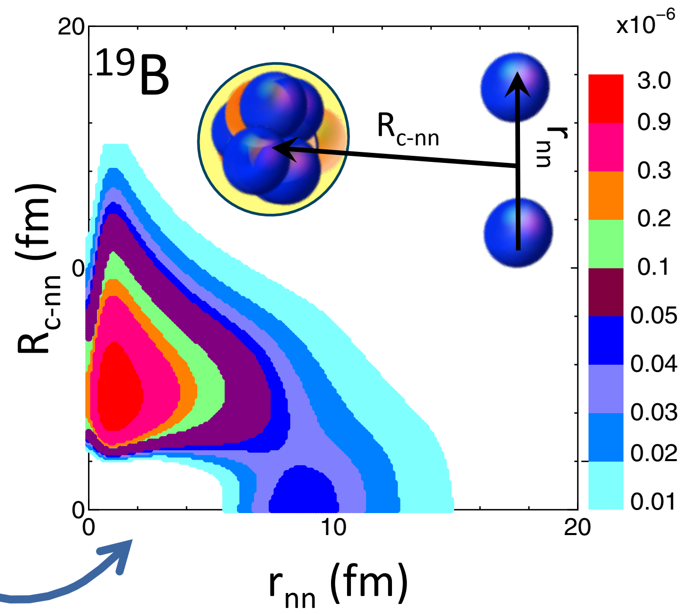


Description without using explicit 3-body forces correctly reproduce the binding energy of ^{19}B

The theory is close to the unitarity limit

Carbonell et al. (2019)





Few questions related to the working group

Would all magic nuclei eventually disappear at the drip lines ?
How effective nuclear forces evolve at the drip line?

By how much mirror symmetry can be broken when open quantum systems are involved ?

Can we better understanding pairing in atomic nuclei ?
How does it evolve towards the drip lines ?

Does the ikeda conjecture apply to di- or tetra- nucleon configurations?

How does clustering evolves with neutron enrichment ?
Does the medium modify the properties of clusters ?

Could gigantic 'nuclei' exist ?

French participation (staff only): N.L. Achouri[1], P. Ascher[2], M. Assié[3], D. Beaumel[3], B. Blank[2], Y. Blumenfeld[3], B. Borderie[3], A. Chbihi[4], A. Corsi[5], S. Courtin[6], F. Delaunay[1], J.-P. Ebran[7], F. Flavigny[1], J. Frankland[4], M. Gerbaux[2], J. Gibelin[1], J. Giovinazzo[2], S. Grévy[4], D. Gruyer[1], F. Gulminelli[1], G. Hupin[3], E. Khan[3], T. Kurtukian-Nieto[1], D. Lacroix[3], N. Le Neindre[1], O. Lopez[1], F. M. Marquès[1], A. Matta[1], F. de Oliveira Santos[4], N. Orr[1], M. Ploszajczak[4], O. Sorlin[4], M. Parlog[1], I. Stefan[3], G. Verde[4] and E. Vient[1]

[1]LPC, [2]CENBG,[3]IJCLab, [4]GANIL, [5]CEA/IRFU, [6]IPHC, [7]CEA/DAM

MID TERM FUTURE DEVELOPMENTS /STRATEGIES… 2020 - 2025

RIKEN

Nebula-plus @RIKEN : Tests and commissioning, first experiments

Strässe @RIKEN : Prototype of LH2 target (2020), Full barrel with target chamber ≥2022

GANIL /MUGAST/GRIT + PARIS/EXOGAM2 + ZDD @LISE :

Mugast campaign, Development of zero degre detection ≥2022

Development and tests of GRIT (detectors, electronics, reaction chamber, combine with γ-ray detection)

R3B@FAIR: Participation in the completion of NeuLAND and/or CALIFA and/or Si tracker ?

LONG TERM FUTURE … ≥ 2025

SAMURAI+ NEBULA-plus + gamma array: Increase in beam intensity of RIBF x10,
Nuclear stucture and correlations 20<A<40

R3B@FAIR: Fair should deliver high intensity beams
Improved neutron resolution of NeuLAND as placed at 35 m

GANIL / LISE / SPIRAL1 : New SPIRAL1 beams ?
Which experimental programs will be pursued when SPIRAL2-1 starts ?

FRIB: should be highly competitive in terms of intensity, not clear about detectors and spectrometers