INSTITUTO GALEGO
DE FÍSICA
DE ALTAS ENERXÍAS

Experimental Studies of Nuclear Open Quantum Systems
(*with transfer reactions*)

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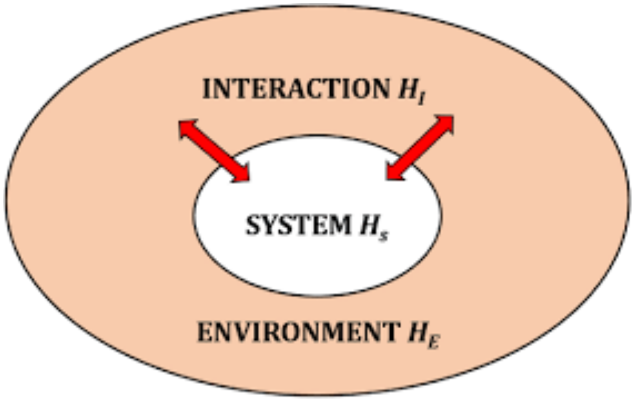
Disclaimer

- *Selected examples based on my experience and activity*
- *Experimental & analysis limitations in open quantum systems*
- *Synergies with other fields*

Open quantum systems

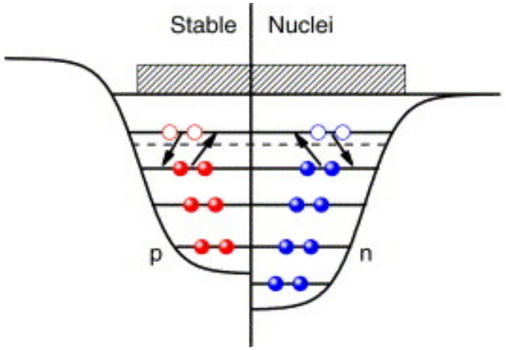
- **Decoherence** : loss of quantum superposition → quantum objects behave classically

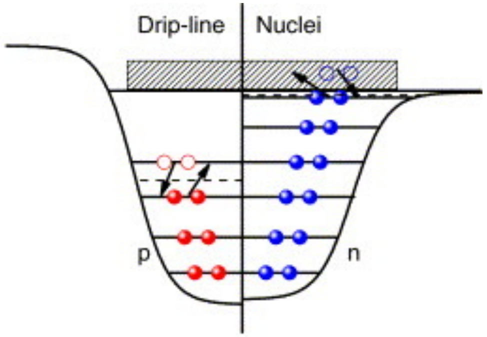
- **Dissipation** : energy & information loss



Nuclear Physics : Weakly-bound and unbound nuclei

- Core system : inert core + valence nucleons → discrete shell model states
- Environment: continuum states (scattering, decaying states) ← no external
- Interaction : coupling between core + bath → resonances, particle emission..



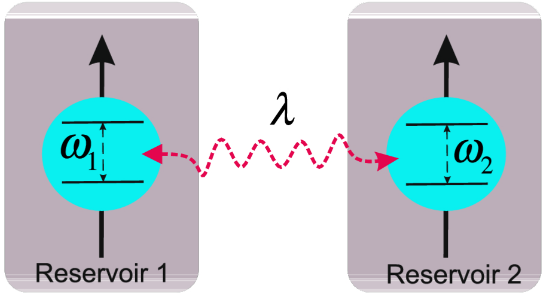


Scale
- Energy ~ keV-MeV
- Distance ~ fm
- Interaction strength ~ MeV

Open quantum systems

Atomic physics/CM/Quantum optics

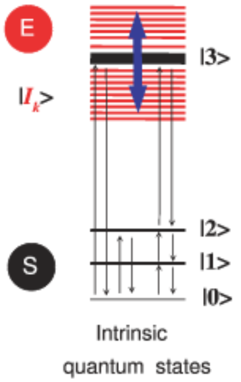
Environment is externally designed :
Engineer the conditions : T, EM-mode, noise



- Atom coupled to an external electromagnetic mode
- A qubit coupled to a thermal reservoir

Nuclear physics

Emergent environment :
generated by the nucleus

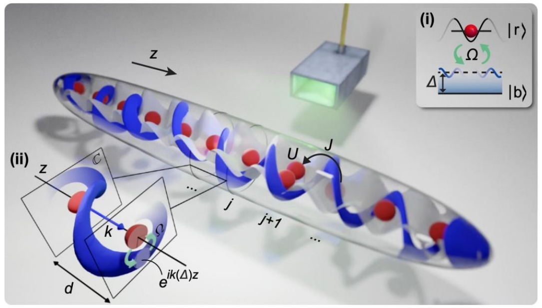


A. Diaz-Torres

Regimes where the cont. coupling becomes stronger or weaker

- Excitation energy
- Thresholds
- Isotopic composition
- Angular momentum
- Reactions : transfer, scattering

Open quantum systems

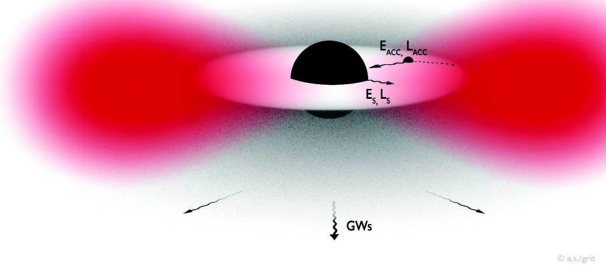


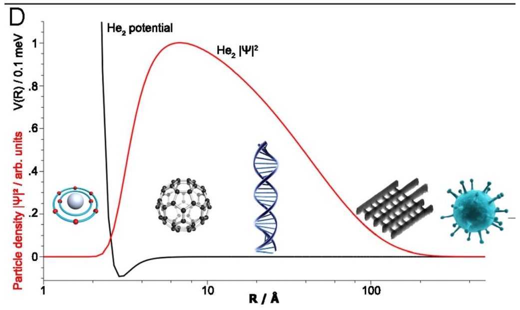
→ Quantum optics

L. Kirnner,M. Stewart, A. Pazmiño, J. Kwon & D. Schenebele Nature 559 (2018) 589-592
Kim, Y., Lanuza, A., & Schneble, D. (2024). . Nature Physics.

Quantum Cosmology ←

P. Pani, R. Brito and V. Cardoso 2015 Class. Quantum Grav. 32 134001
R. Brito et al 2015 Class. Quantum Grav. 32 134001



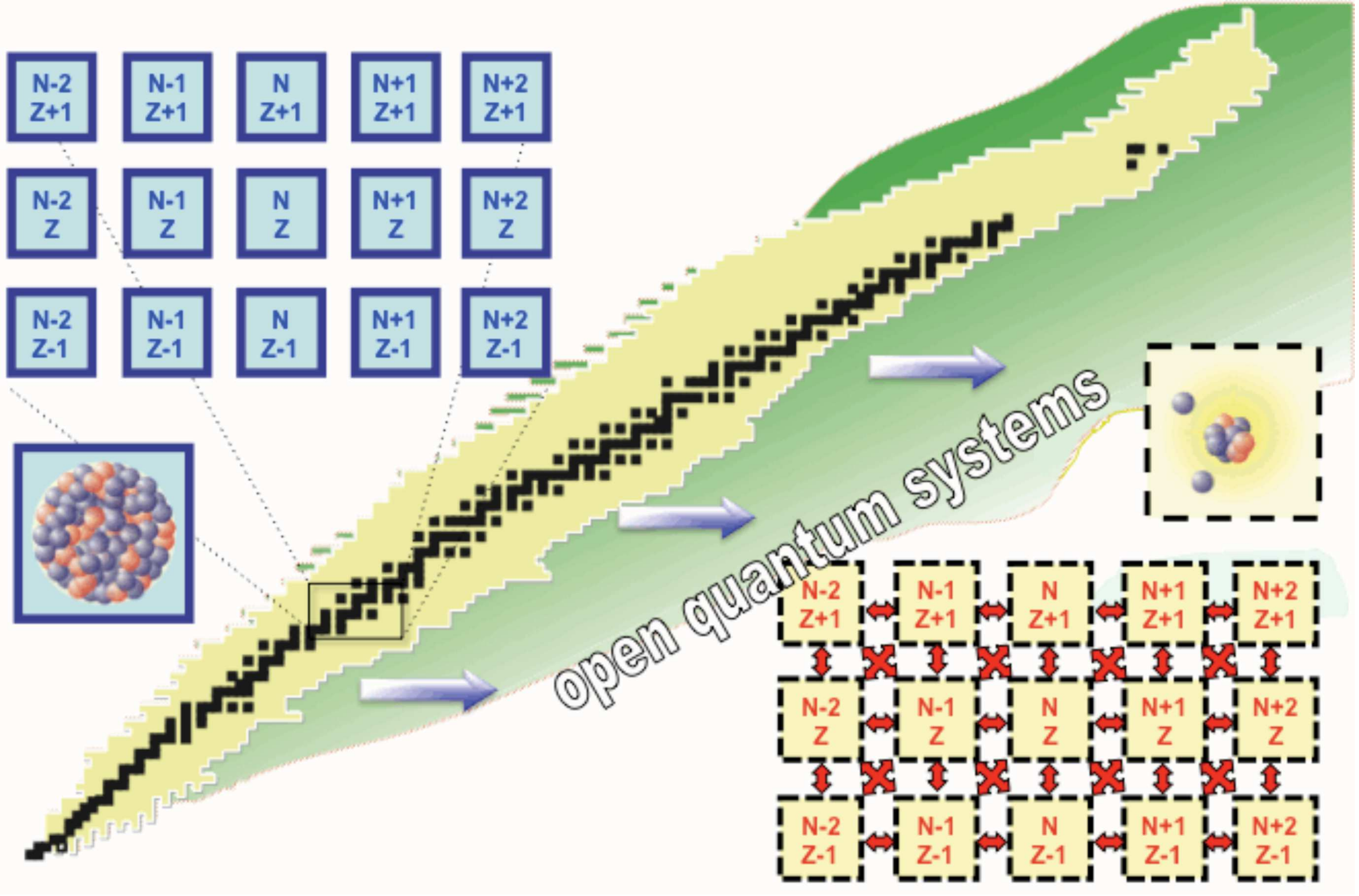


→ Atomic Physics

S. Zeller et al., PNAS 113 (2016) 14651

Nuclear open quantum systems

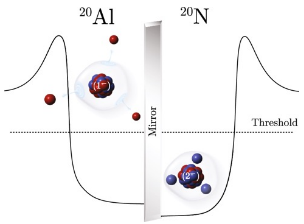
N. Michel, W. Nazarewicz, J. Okolowicz and M. Ploszajczak J. Phys. G: Nucl. Part. Phys. 37 064042



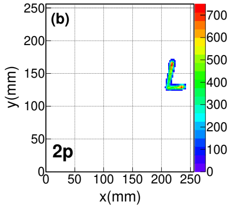
- Nuclear structure changes near particle thresholds
- Nuclei communicate with each other

Nuclear open quantum systems

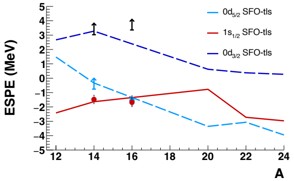
- Broken mirror symmetries



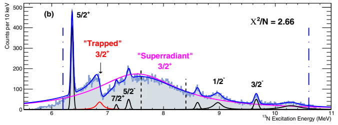
- One/two proton radioactivity



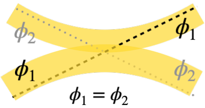
- Shell evolution drip-line

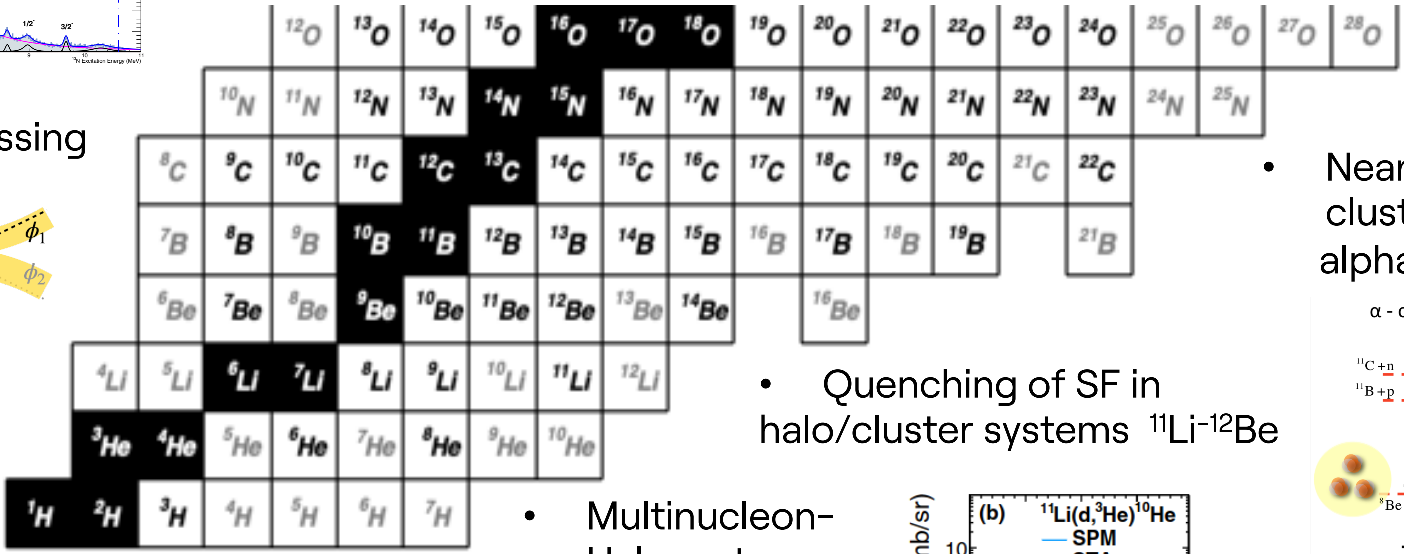


- Superradiance

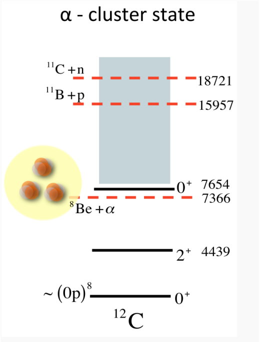


- Level crossing
^{8}Be

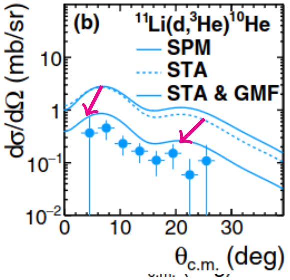




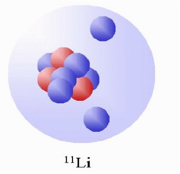
- Near threshold clustering
alpha clustering



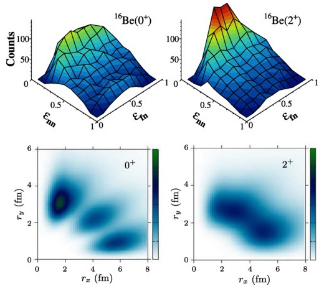
- Quenching of SF in halo/cluster systems ^{11}Li-^{12}Be



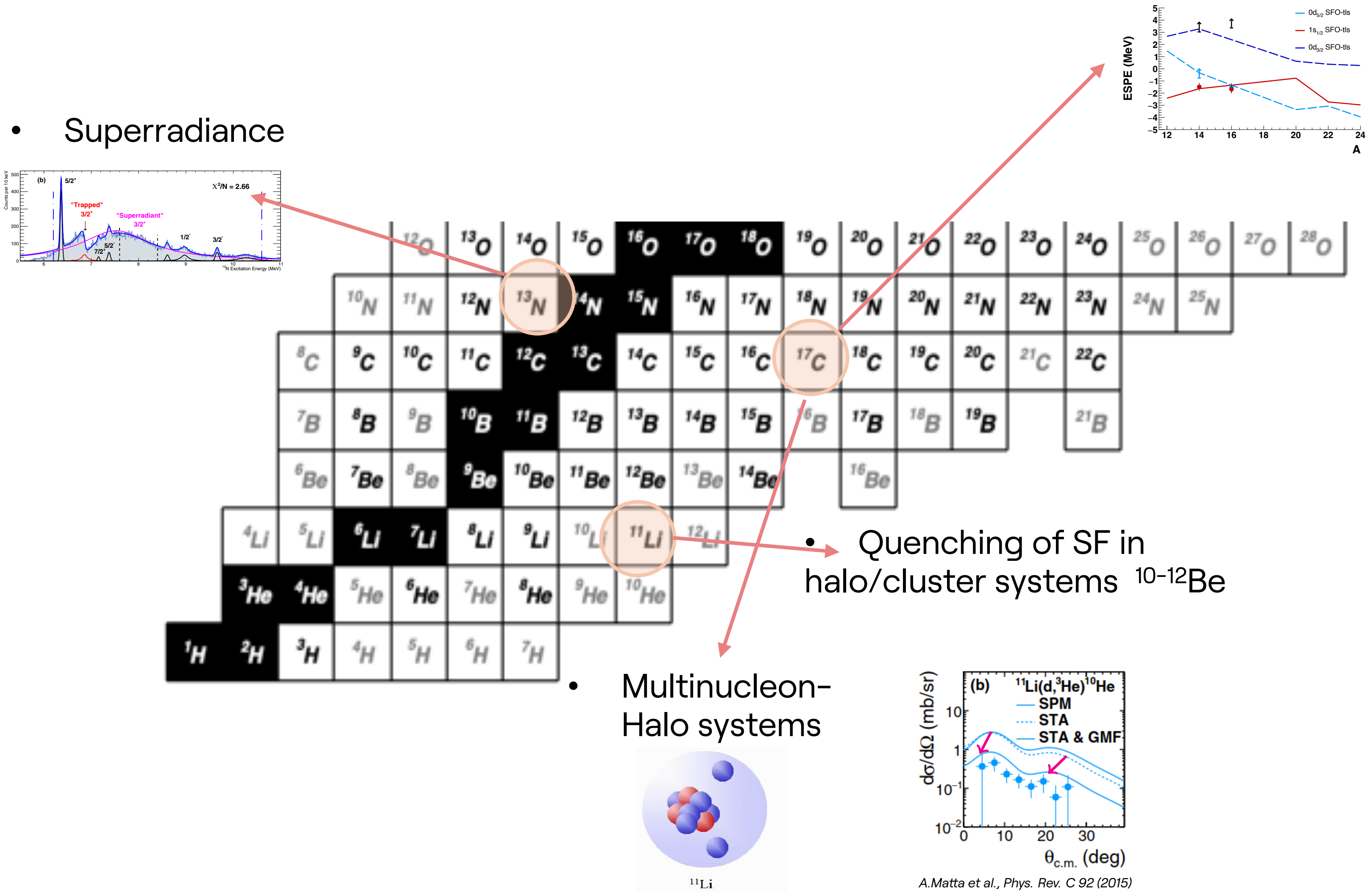
- Multinucleon-Halo systems



- One/two-four n- emission



Nuclear open quantum systems



- Shell evolution drip-line

- Superradiance

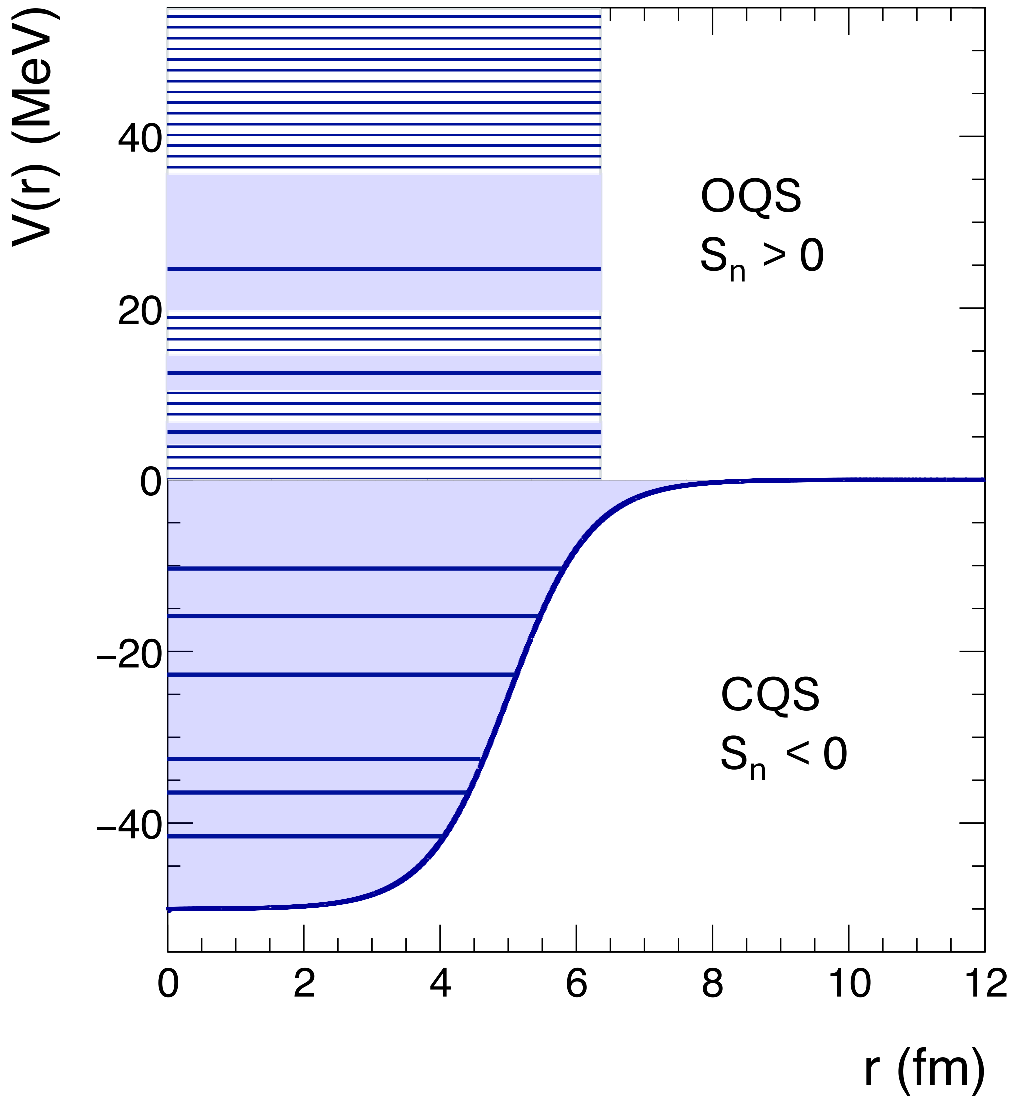
- Quenching of SF in halo/cluster systems $^{10-12}$Be

- Multinucleon-Halo systems

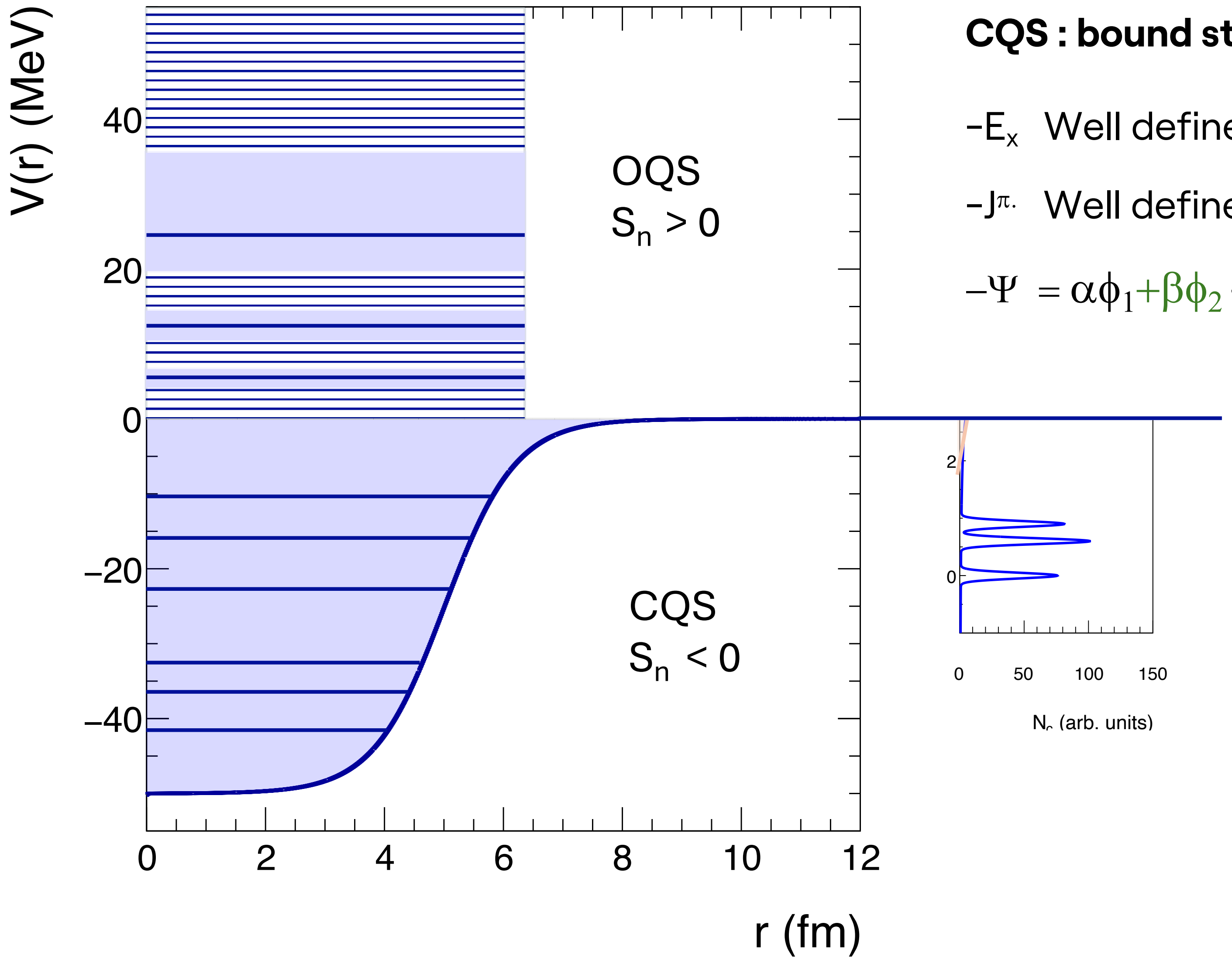
A.Matta et al., Phys. Rev. C 92 (2015)

Nuclear open quantum systems

What can experimentalists measure ?



Nuclear open quantum systems



What can experimentalists measure ?

CQS : bound states (E < Threshold)

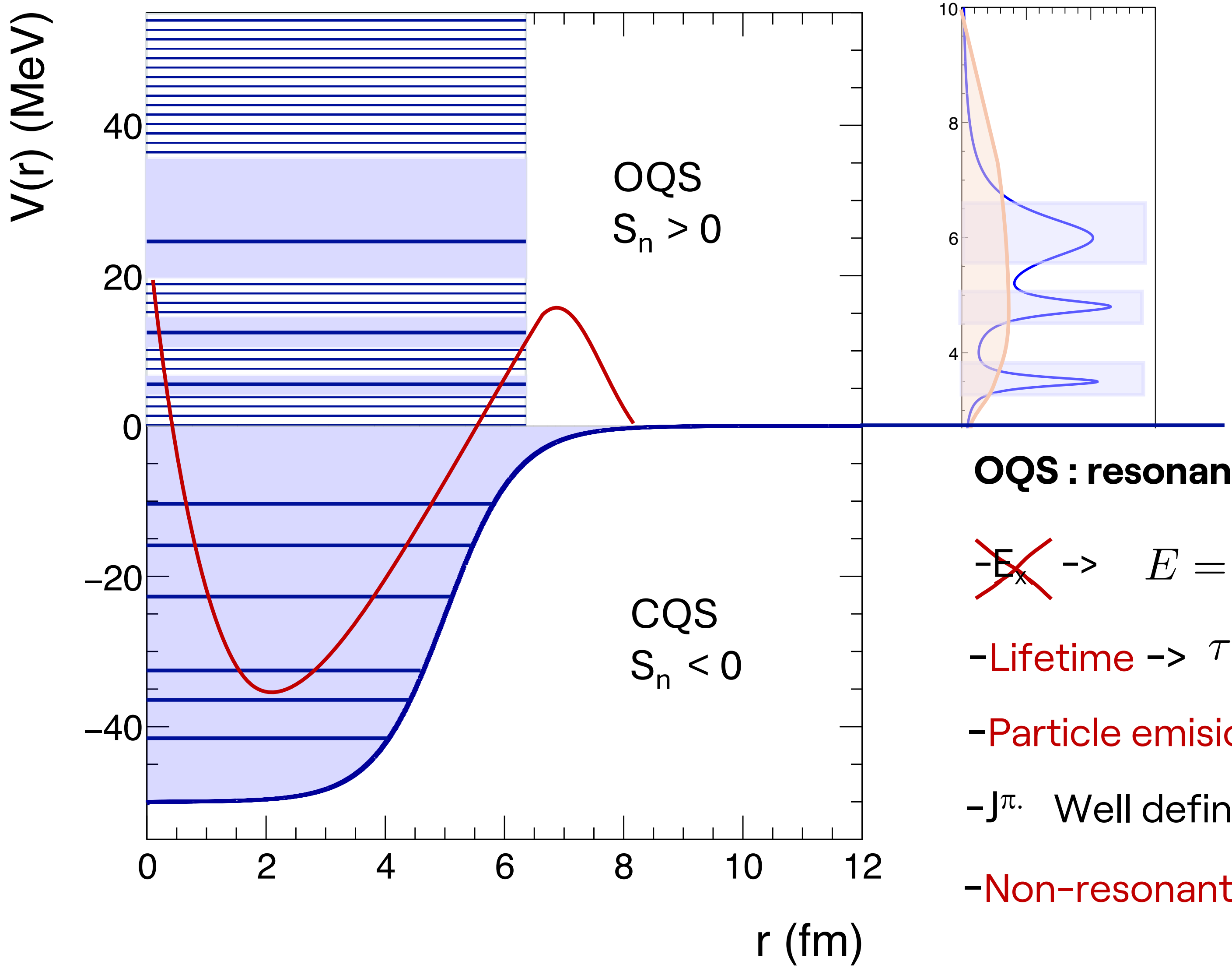
-E_x Well defined energy

-J^{π}. Well defined spin & parity

$-\Psi = \alpha\phi_1+\beta\phi_2$ -> not measurable

Nuclear open quantum systems

What can experimentalists measure ?



OQS : resonances near threshold

~~-E_x~~ -> $E = E_0 - i\frac{\Gamma}{2}$

-Lifetime -> $\tau = \frac{\hbar}{\Gamma}$ ~10^{-16}–10^{-22} s

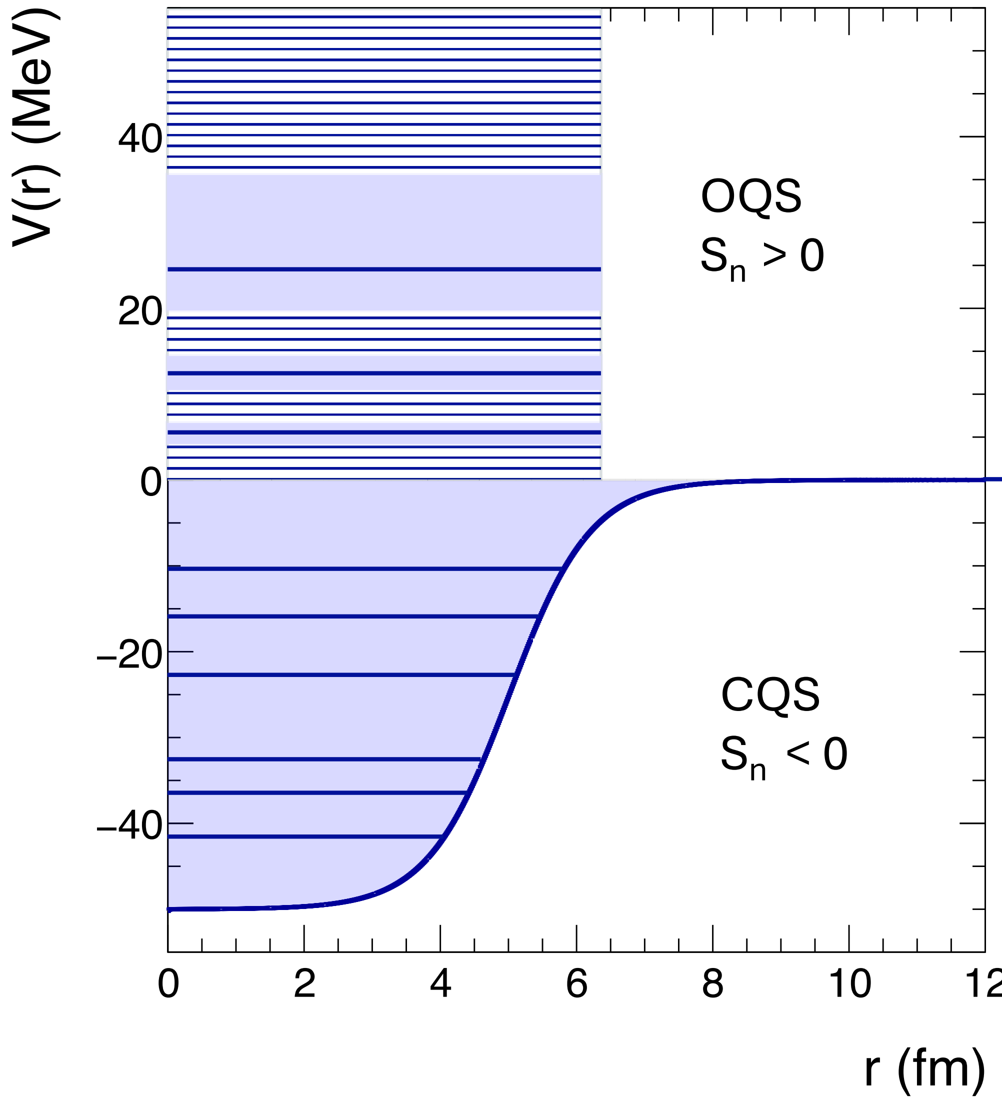
-Particle emision

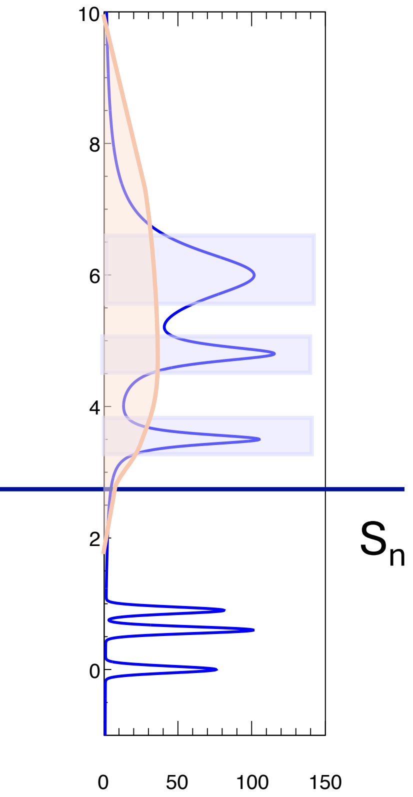
-$J^{\pi.}$ Well defined spin & parity

-Non-resonant continuum

Nuclear open quantum systems

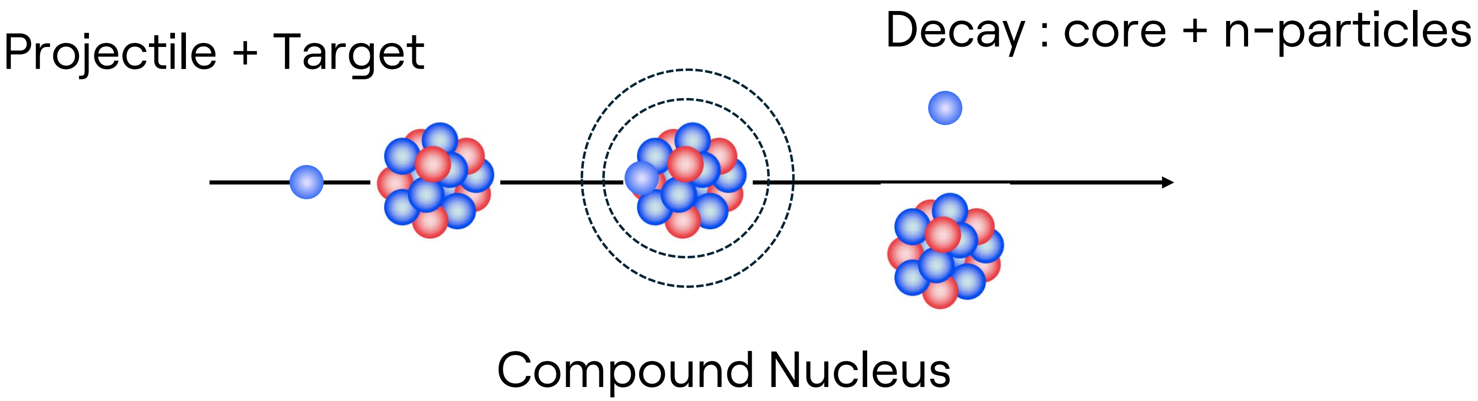
What can experimentalists measure ?



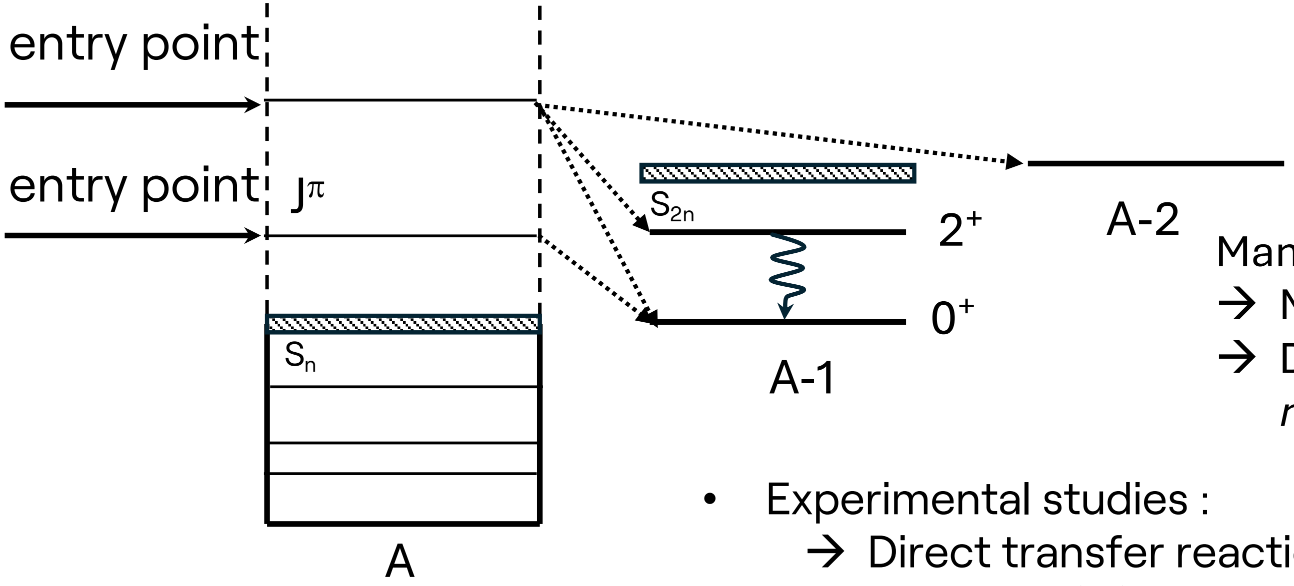


- Widths + lifetimes
- Height of peaks in the scattering cross section
- Shapes of the resonances → l & E_r
- Decaying particles
- Phase shifts if a scan of E across resonance

OQC : How do we measure them ?



Populate weakly-bound/unbound



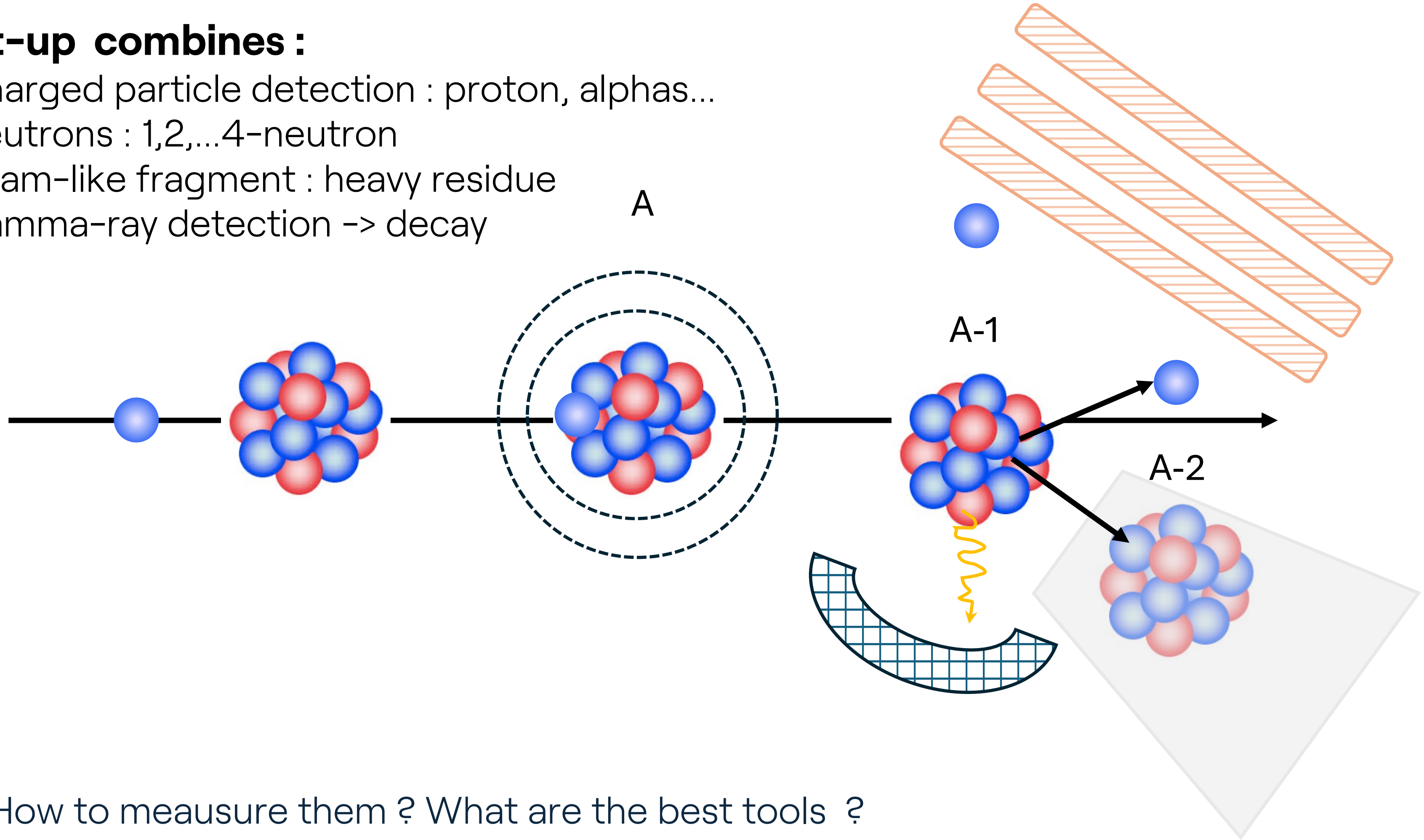
Many open channels :
→ Many types of particles
→ Different combinaisions
nlj x core

- Experimental studies :
  → Direct transfer reactions
  → Resonant (in)elastic scattering
  → Knockout or quasi-frese scattering reactions
  → Fussion evaporation

OQC : How do we measure them ?

Set-up combines :

-Charged particle detection : proton, alphas…
-Neutrons : 1,2,…4-neutron
-Beam-like fragment : heavy residue
-Gamma-ray detection -> decay

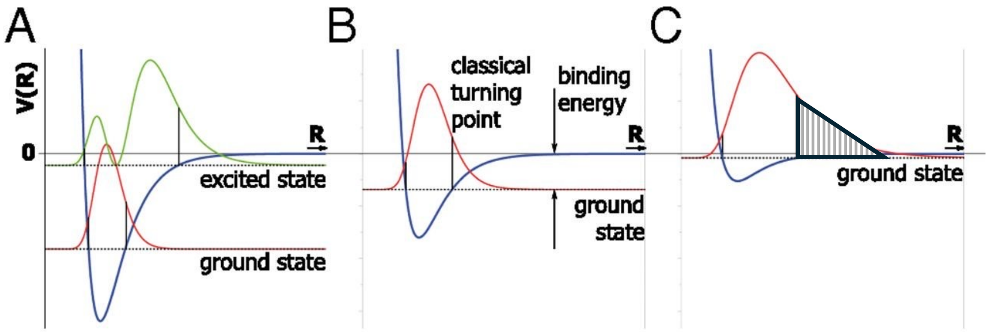


- How to meausure them ? What are the best tools ?
- How to analyse them to provide meaningful nuclear structure information ?
- Are we interested in the same information as for the bound states E_x, and J^{π}. ?
- Can we still use the same tools/detectors ?

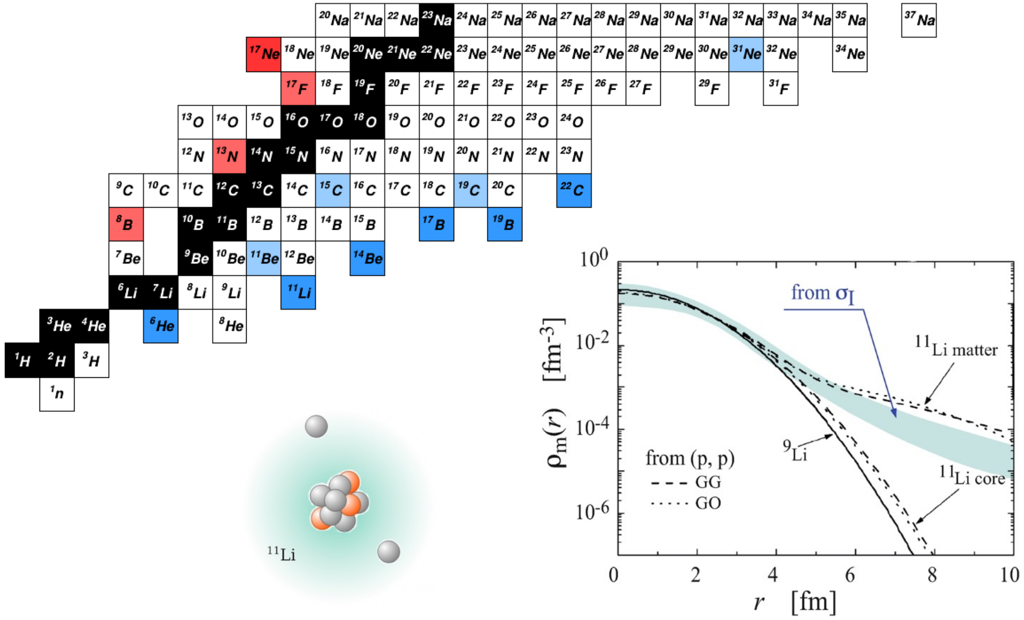
OCS: Halo systems

Halo systems

K. Riisager et al., , Phys Scr. T 152 (2013) 014001



Nuclear Physics : ^{11}Li



Effects from continuum :

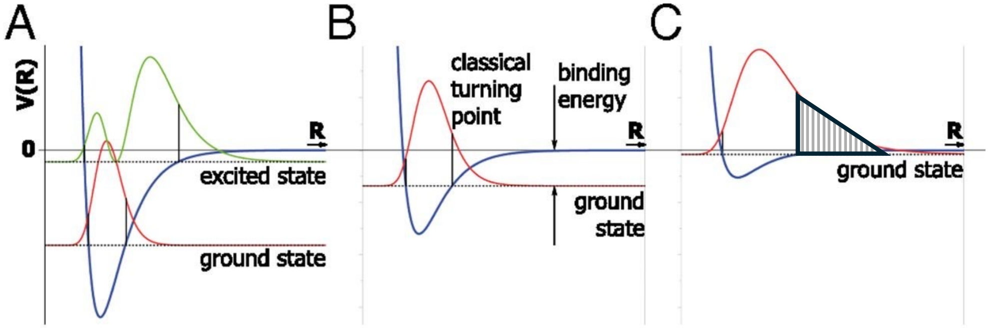
- Near threshold : 2p,p,n,2n and 4n
- Low binding energy ~few keV
- Low relative (l=0,1)
- Extended spatial range

Observables :

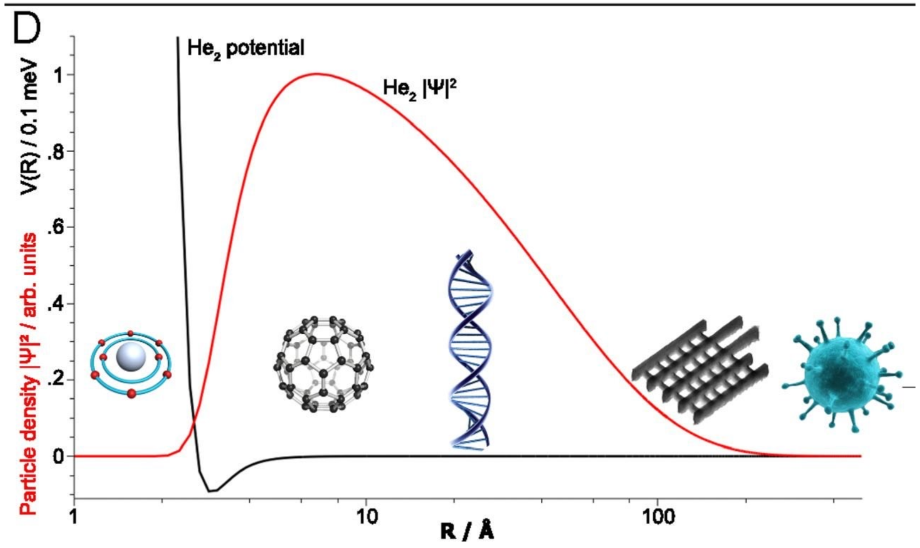
- Nuclear/charge matter radii $<r^2>$
- **Prob. particle outside the classic R**
- Nucleon-nucleon correlations

OCS: Halo systems

Halo systems



Molecular Physics : He$_2$ dimmer



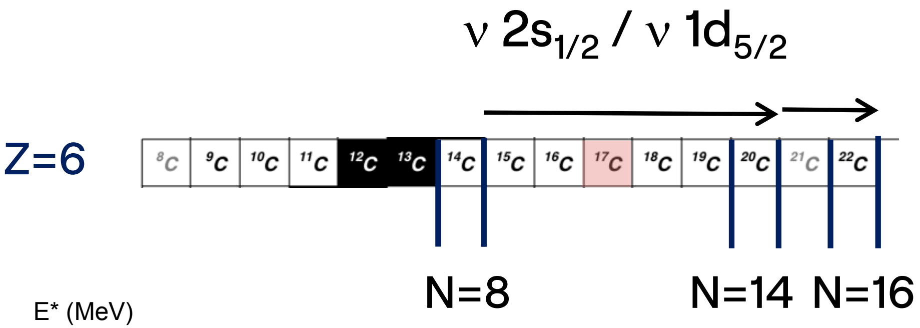
Effects from continuum :

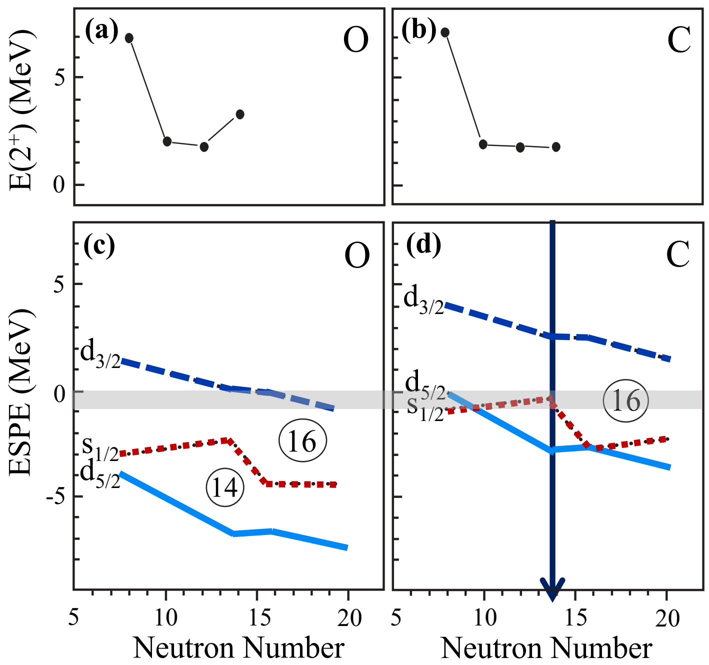
- Low binding energy : 151.9 ± 13.3 neV
- Low temperature : ultra cold
- Shallow potential <-- weak Van der Waals for
- Interdistance: 50 A ~100 atomic Diam.

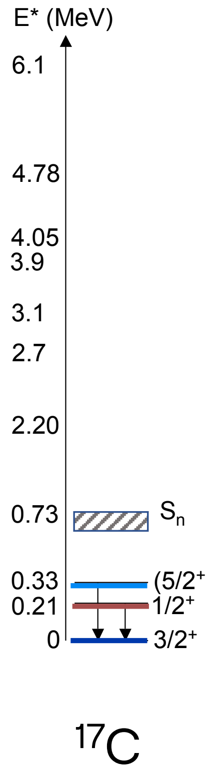
Observables :

- **Prob. particle outside the classic R**
- **Density distribution**

OCS: Neutron Halo in ^{17}C*







- sd-orbitals : N=8-14
- Mid-shell nuclei → deformation core
- Weakly bound S_n=0.734 MeV
- Structure strongly affected by the continuum

→ **sp strength of the $0d_{5/2}$, $1s_{1/2}$ $0d_{3/2}$**

Halo configurations suggested for ^{15}C and ^{19}C in the ground state

Fang et al., Few-body Systems Suppl. 10, (1998)

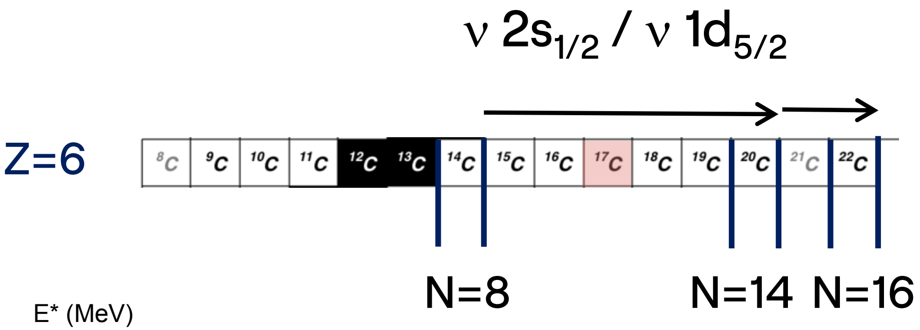
First excited state of ^{17}C : halo configuration suggested by hindered B(M1)

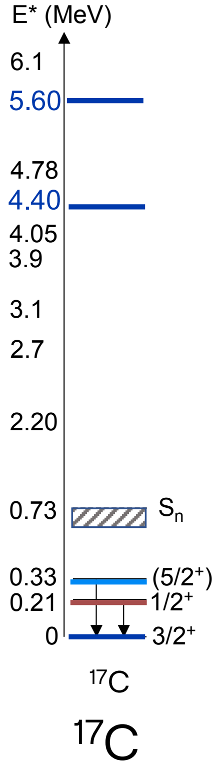
D. Suzuki et al., PLB 666, 222 (2008)

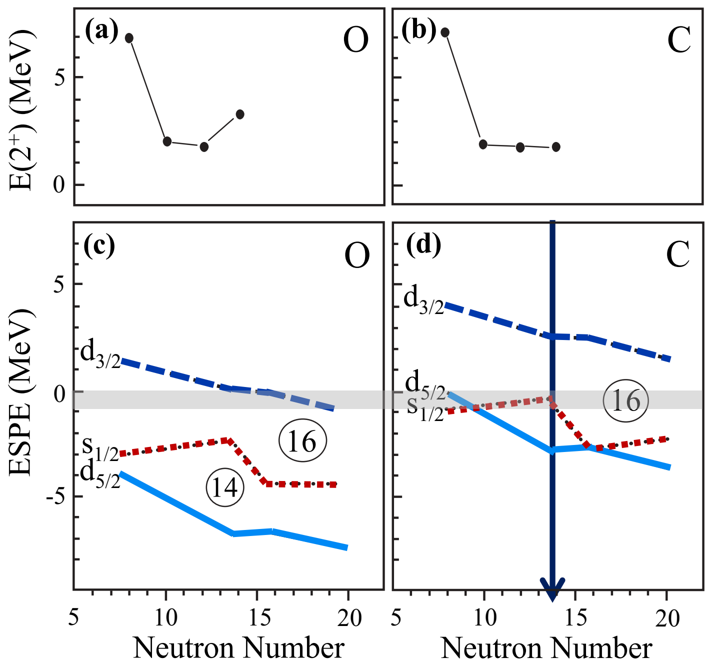
Study of the l=0 configuration in the **first excited state** of ^{17}C

OCS: Shell evolution towards the drip-line

$\nu\ 2s_{1/2}\ /\ \nu\ 1d_{5/2}$







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N=14 disapears in n-rich Carbon isotopes

Low E_x of the 2^+ ^{20}C. M. Stanoiu et al, PRC 69, 034312 (2004)

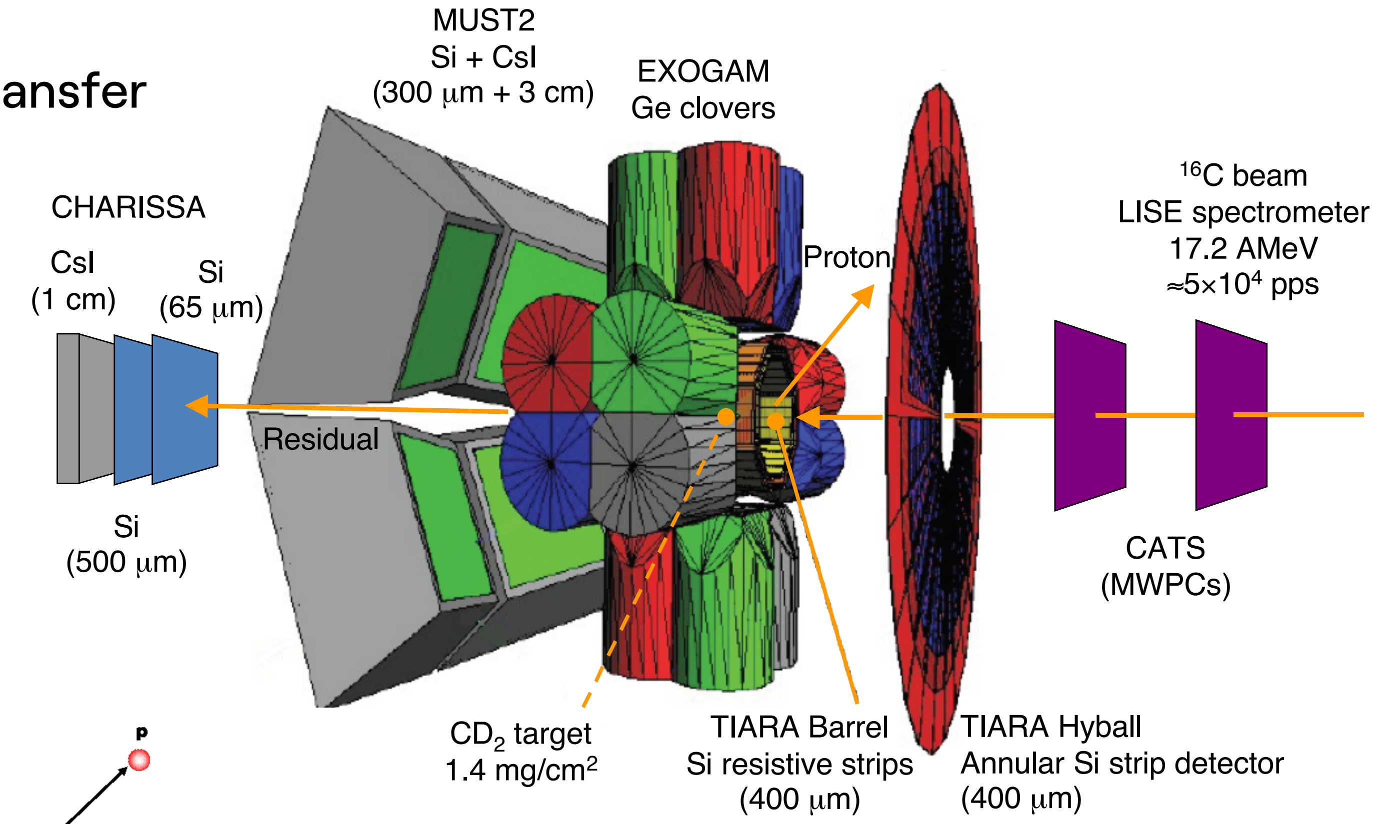
Large B(E2) value. M. Petri et al., PRL 96, 012501 (2011)

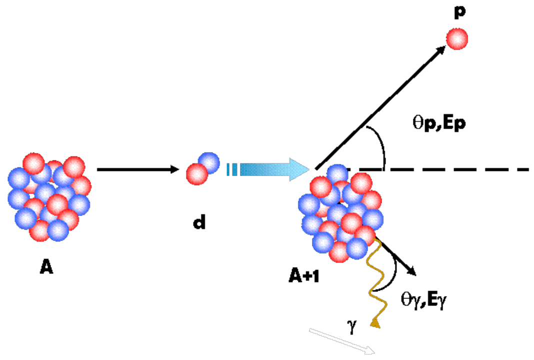
How does the N=16 evolves in n-rich C isotopes ?

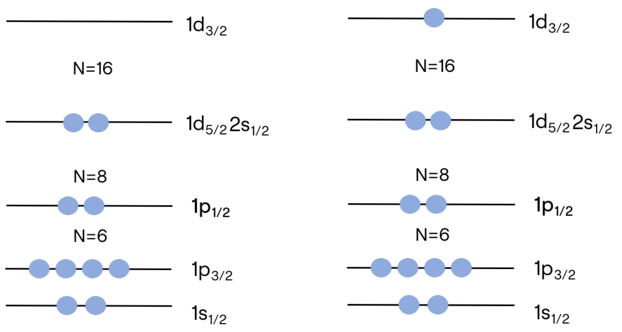
Location of the 3/2+ states in ^{17}C → embedded in the continuum

OCS: Neutron Halo in ^{17}C*

^{16}C(d,p)^{17}C-1n transfer

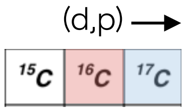






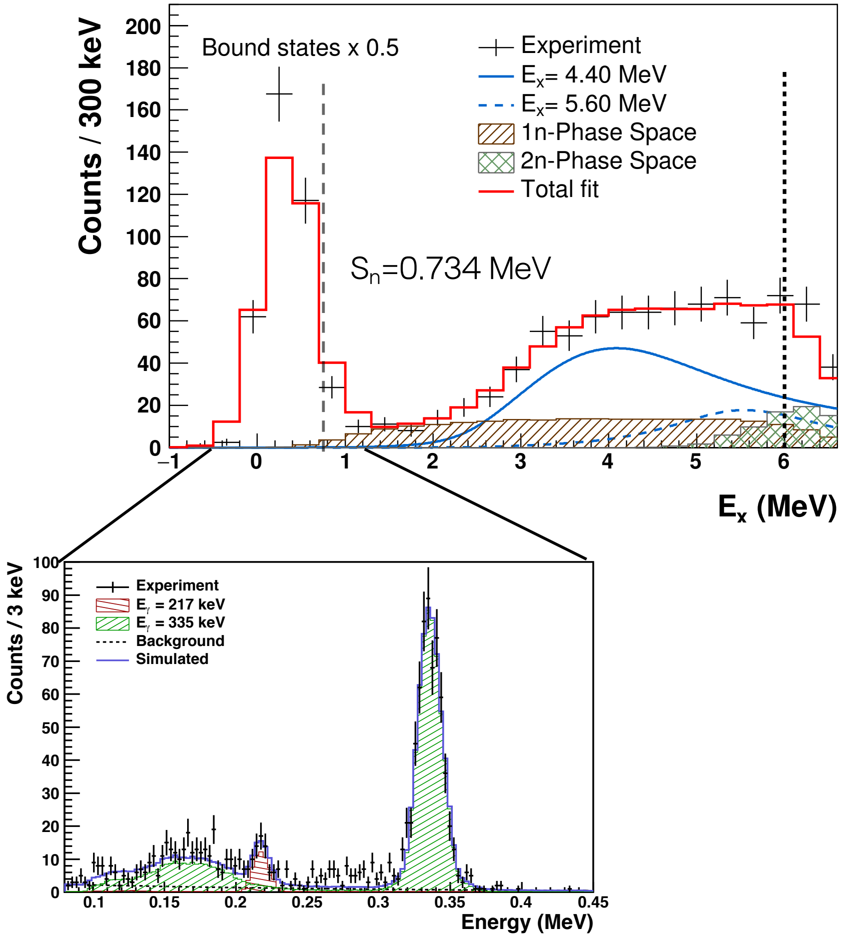
dσ/dΩ → l-orbital , C^{2}S

Ep, Eγ → Ex



OCS: Neutron Halo in ^{17}C*

X. Pereira-López, B. Fernández-Domínguez et al., PLB 811 (2020) 135939

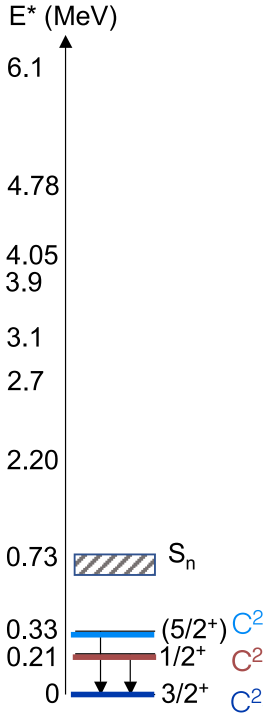


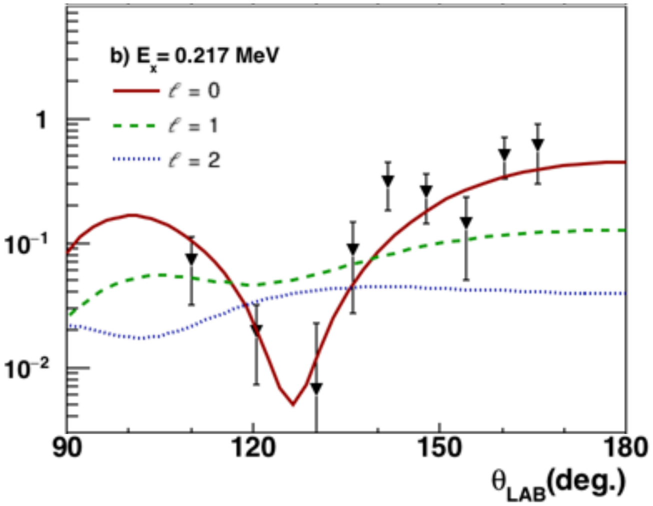
ADWA (JT)

OMP

- Haixia (d+^{16}C)
- CH89/KD (p+^{17}C)

<^{16}C|^{17}C> WS





C^2S=0.62(13) → d −wave

C^2S=0.80(20) → s −wave

C^2S=0.03(−3,+5) → Weak 0d$_{3/2}$ contribution

Asymptotic normalization coefficient ANC :

- S_n (1/2+)=0.518 MeV → ANC = 0.78(8) fm $^{-1/2}$
- S_n (5/2+)=0.400 MeV → ANC = 0.048(4) fm $^{-1/2}$

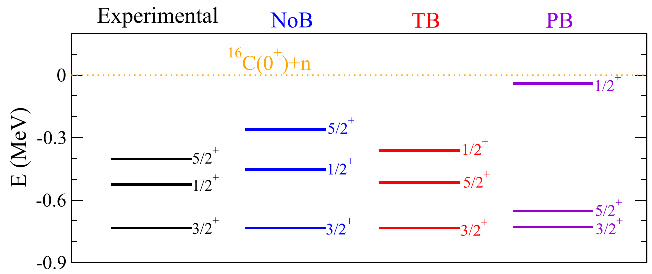
$$\text{ANC} = \sqrt{SF_{lj}} \times b_{lj}$$

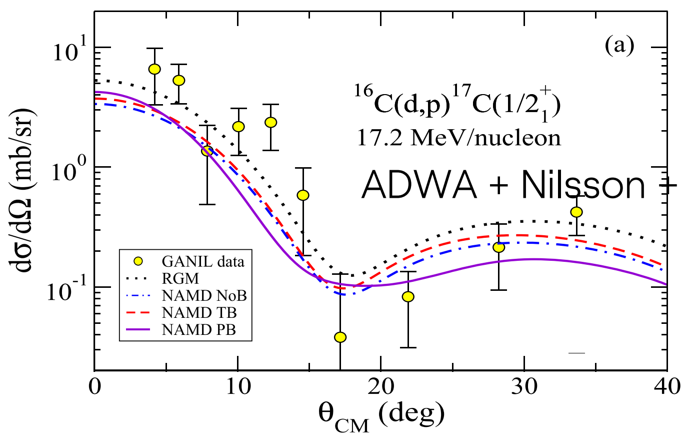
ANC(1/2+) /ANC (5/2+) ~ 20 higher
(r > 15 fm)

OCS: Neutron Halo in ^{17}C*

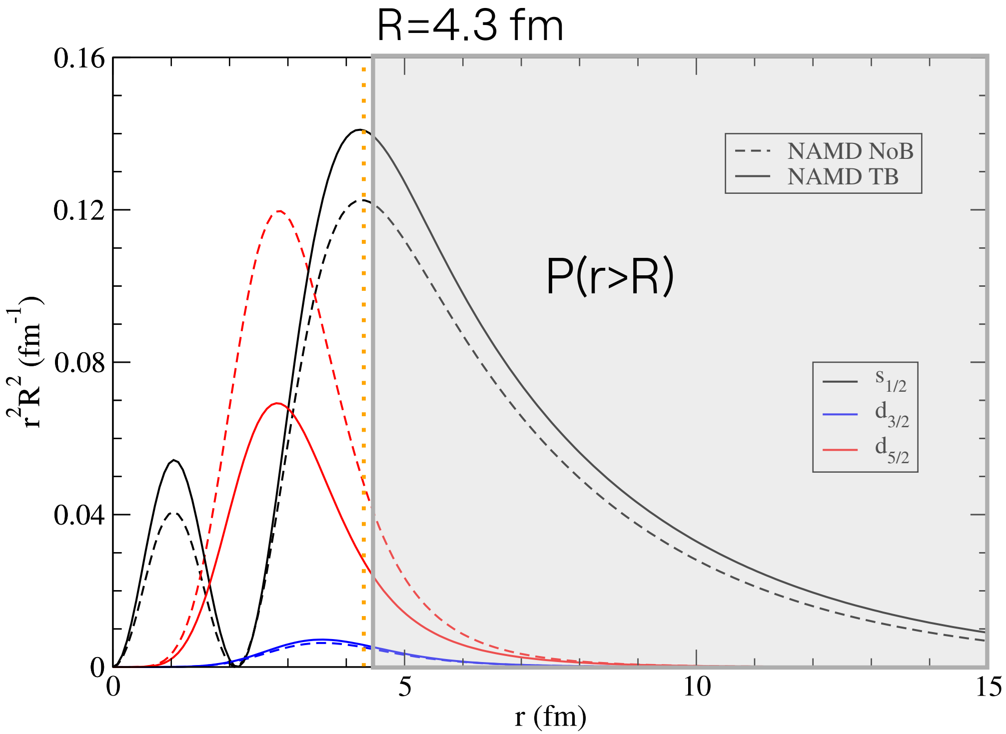
How far the wave function extends ? Nuclear Physics : ^{17}C* (1/2+)

- **Wood - saxon→** rms =7.17 fm -> very large





ADWA + Nilsson + Pauli

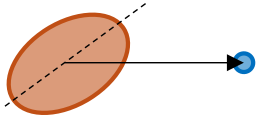


Theoretical methods to calculate transfer reactions including **deformed two-body models**

Nilsson Hamiltonian constructed with AMD calculations of ^{16}C

- Total Pauli Blocking (TB) rms =7.08 fm
  → P(r>R) = 61% TB

- no Pauli Blocking (NoB) rms=6.50 fm
  → P(r>R) = 55% NoB

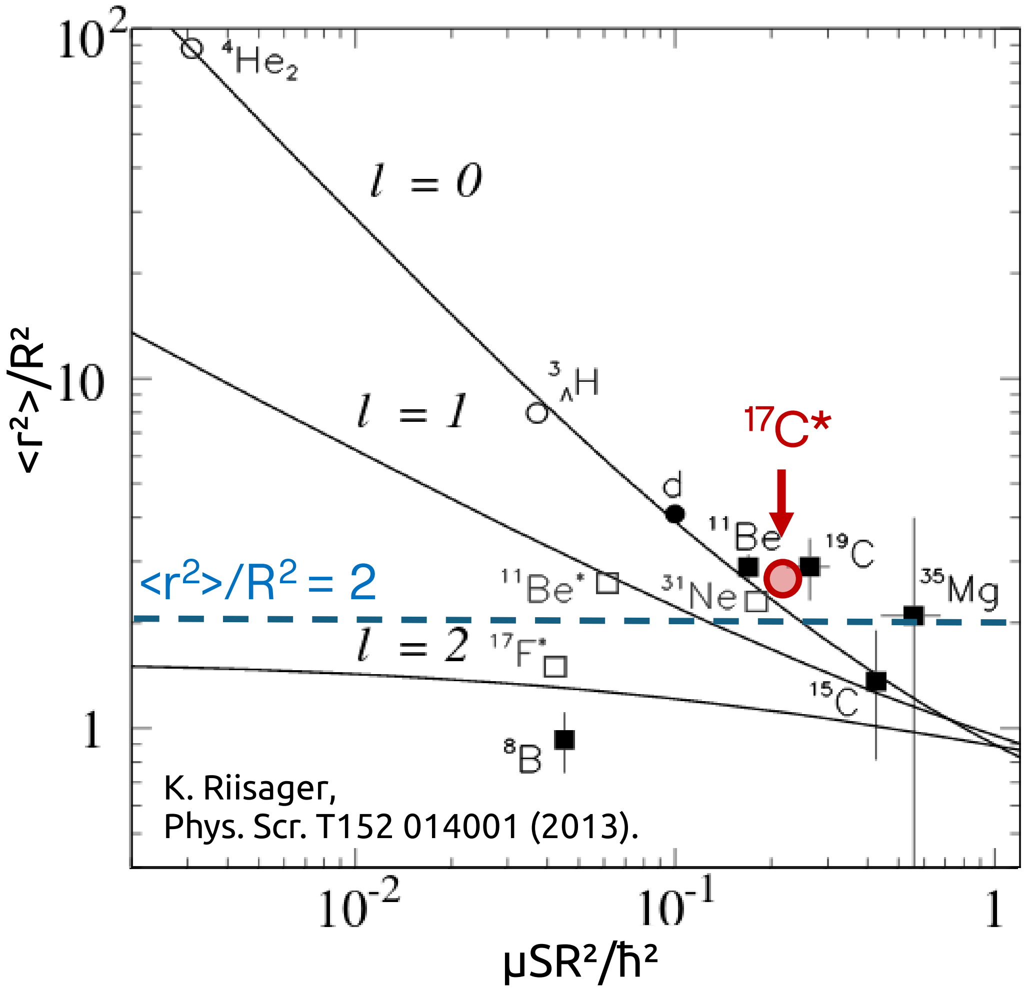


P. Punta , J.A. Lay, A. Moro, PRC 108 (2023) 024613

P. Punta , J.A. Lay, A. Moro, G. Coló PRC 111 (2025) 064614

OCS: Neutron Halo in $^{17}C^*$

Universal scaling law for two-body halo nuclei



K. Riisager,
Phys. Scr. T152 014001 (2013).

$^{17}C^*(1/2\ +)$ → halo candidate:

- Small $S_n^{eff} = S_n - E_x = 0.517\ (18)$
- l=0 configuration
- Large SF: 0.80(20) s-wave large

$$R^2 = \frac{5}{3}\left(\left\langle r^2 \right\rangle_{^{16}C} + 4\,fm^2\right) = 4.3\ fm$$

$$\left\langle r^2 \right\rangle_{^{16}C} = 2.7\,fm$$

A. Ozawa et al., NPA 691, 599 (2001)

Model	$<r^2>^{½}$ (fm)	$<r^2>/R^2$
WS	7.17	2.78
NAMD TB	7.08	2.71
NAMD NoB	6.50	2.28

^{17}C (1/2+) at 217 keV well-developed halo

odd-mass n-rich C isotopes
→ 1-neutron halo in the s1/2 orbital

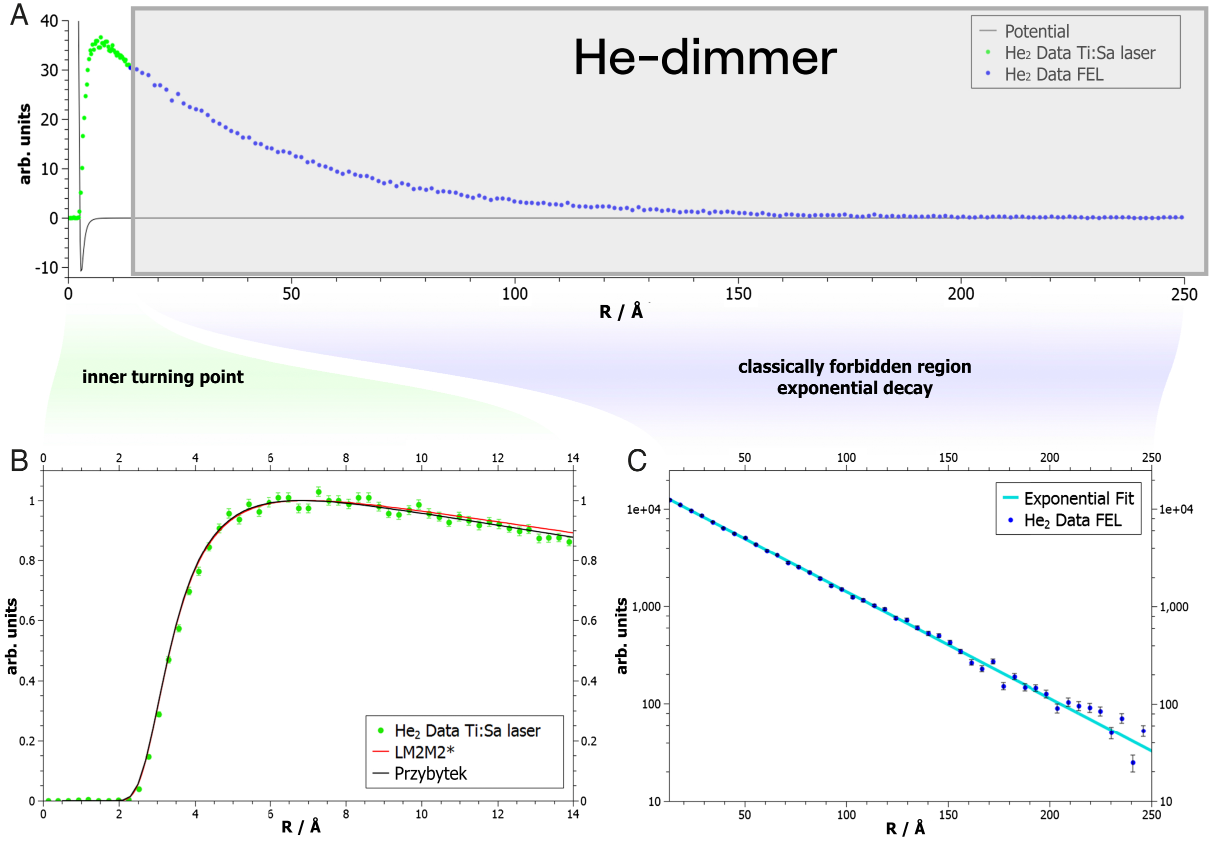
P. Punta , J.A. Lay, A. Moro, G. Coló PRC 111 (2025) 064614

X. Pereira-López, B. Fernández-Domínguez et al., PLB 811 (2020) 135939

OCS: Neutron Halo

How far the wave function extends ? Molecular physics : He dimmer

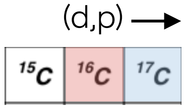
S. Zeller et al., PNAS 113 (2016) 14651



He-dimmer shows a gigantic halo

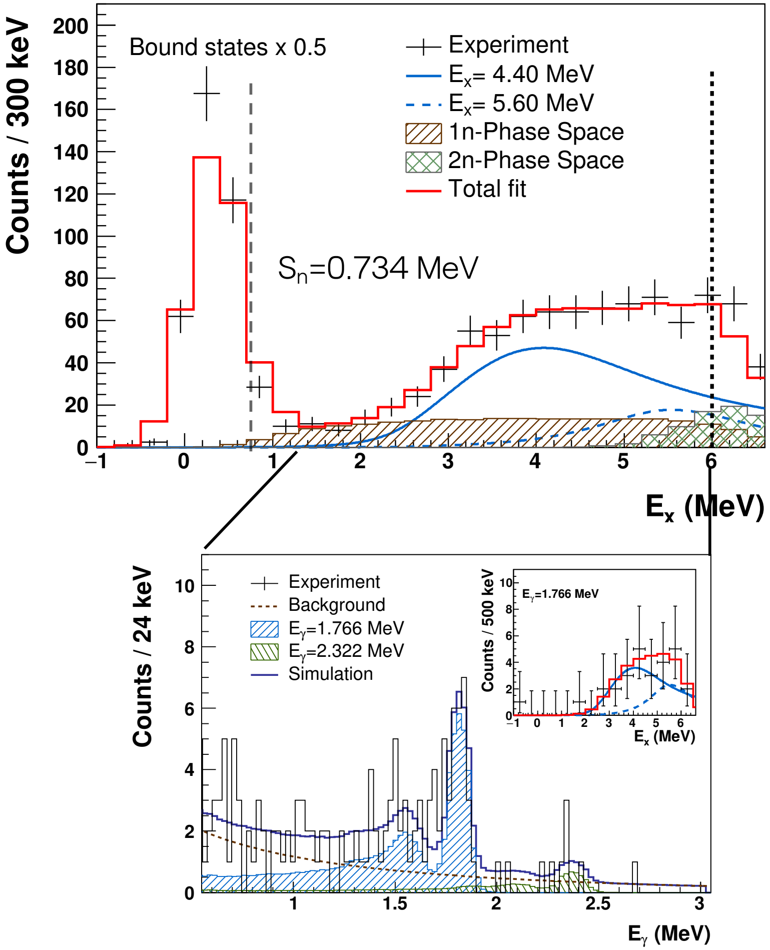
P(r>R) = 80% of being outside R~15 Amstrong

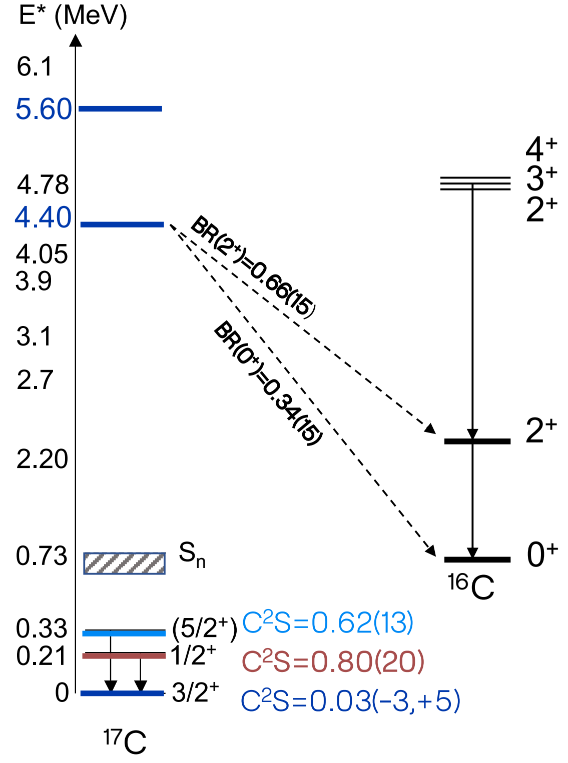
Impressive measure of the spatial probability density !!

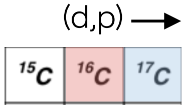


OCS: Shell evolution towards drip-line

J. L. Fuentes, B. Fernández-Domínguez et al., PLB 867 (2025) 139600







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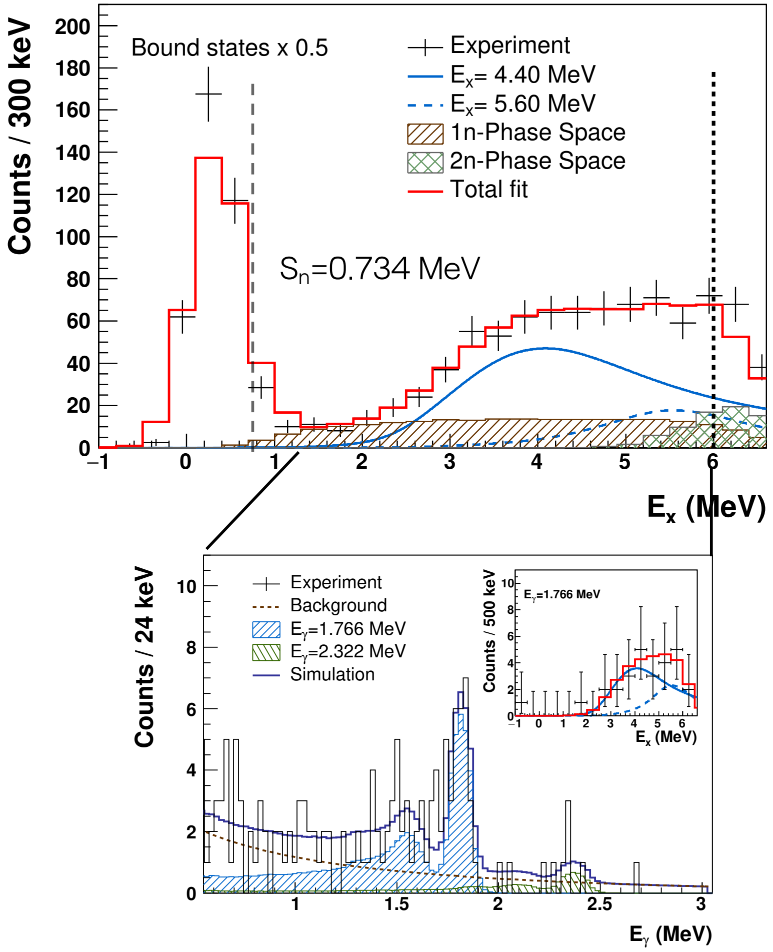
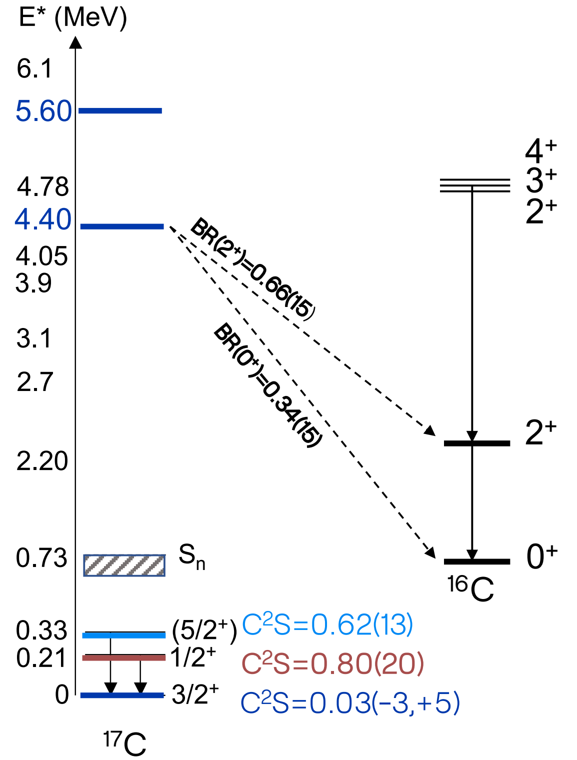




$$\sigma_r(E_x, E_0) \propto \frac{\Gamma^{tot}(E_x)}{(E_x - E_0)^2 + (\Gamma^{tot}(E_x)/2)^2}$$

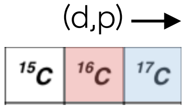
$$\Gamma^{tot}(E_x, E_0) = \Gamma_\ell(0_1^+) + \Gamma_\ell(2_1^+)$$

→ 1st Res

$\Gamma(0^+) = C^2S(0^+) \times \Gamma^{l}_{sp}(E_x)$

$C^2S(0^+) = 0.45(_{+0.32,}{}^{-0.22})$ $0d_{3/2}$

$C^2S(0^+) = 1.58(_{+5.08,}{}^{-0.71})$ $0f_{7/2}$



OCS: Shell evolution towards drip-line

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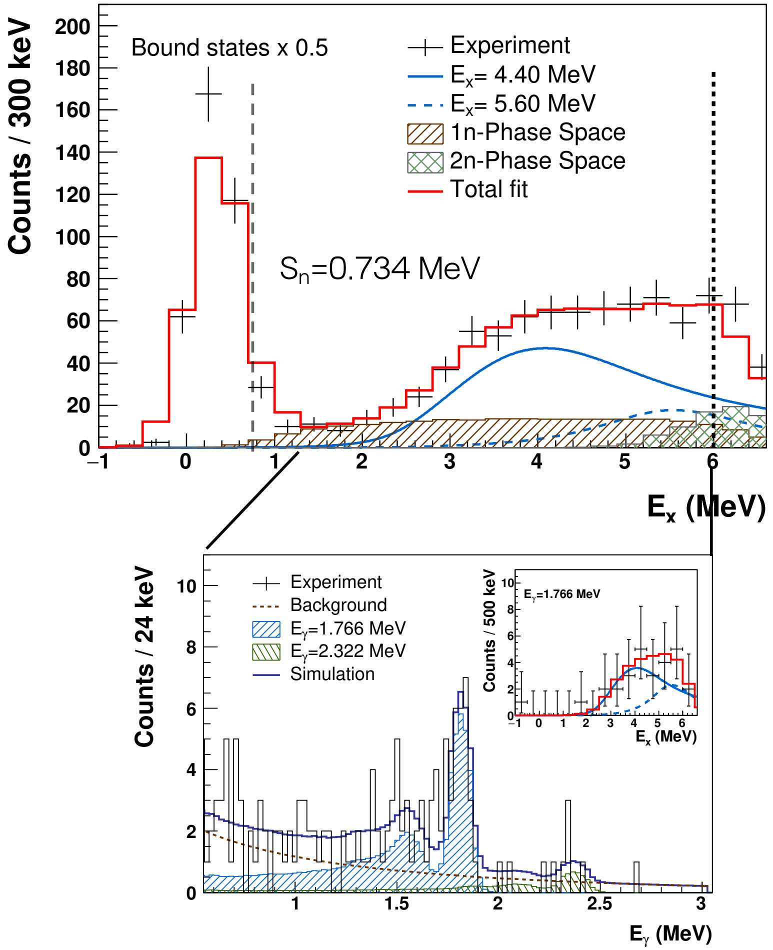
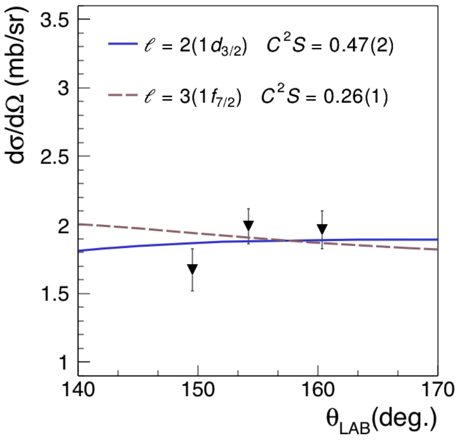
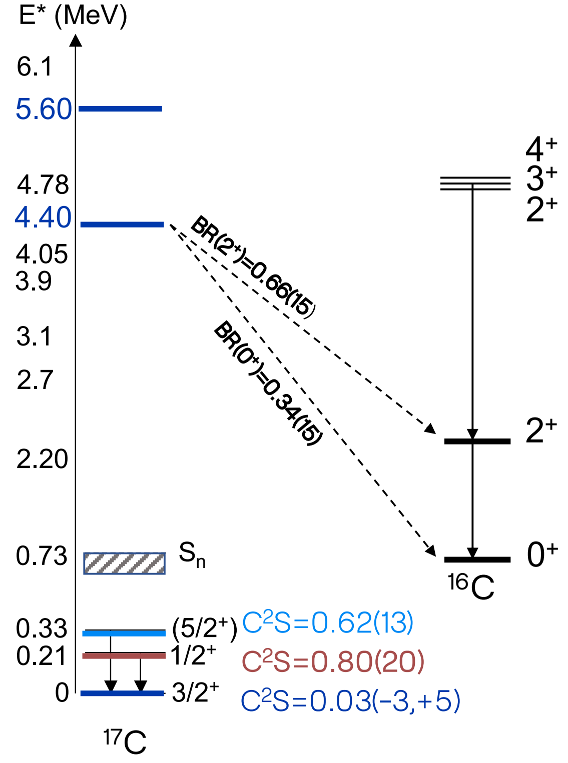


Found unbound $0d_{3/2}$ strength !





C^2S=0.62(13)

C^2S=0.80(20)

C^2S=0.03(-3,+5)

ADWA

OMP

- KD (d/p+^{16}C)

<^{16}C|^{17}C>

- Vincent & Fortune

$$\sigma_r(E_x, E_0) \propto \frac{\Gamma^{tot}(E_x)}{(E_x - E_0)^2 + (\Gamma^{tot}(E_x)/2)^2}$$

$$\Gamma^{tot}(E_x, E_0) = \Gamma_\ell(0_1^+) + \Gamma_\ell(2_1^+)$$

→ 1st Res

$\Gamma(0^+)=C^2S(0^+) \times \Gamma^l_{sp}(E_x)$

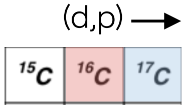
$C^2S(0^+)$ =0.45($_{+0.32,}{}^{-0.22}$) $0d_{3/2}$

$C^2S(0^+)$ =1.58($_{+5.08,}{}^{-0.71}$) $0f_{7/2}$

ADWA

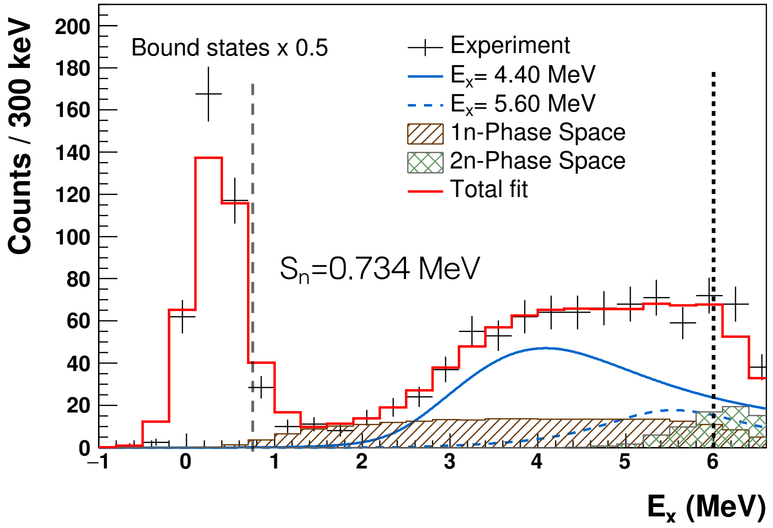
$C^2S(0^+)$ =0.47(2) $0d_{3/2}$

$C^2S(0^+)$ =0.26(1) $0f_{7/2}$

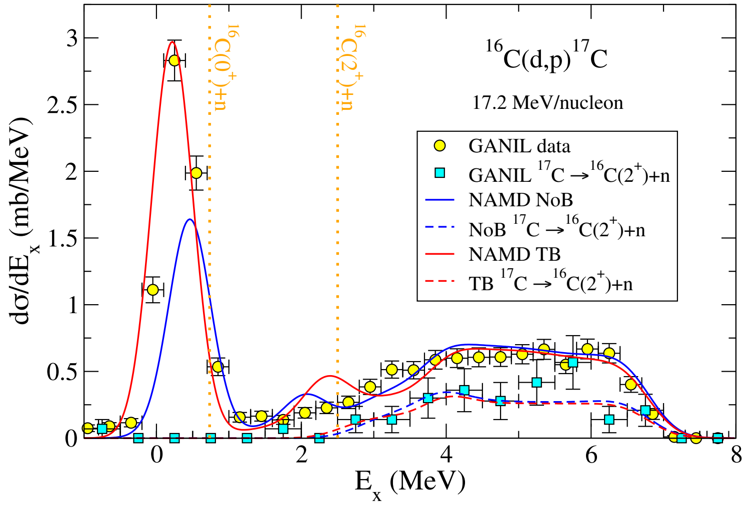


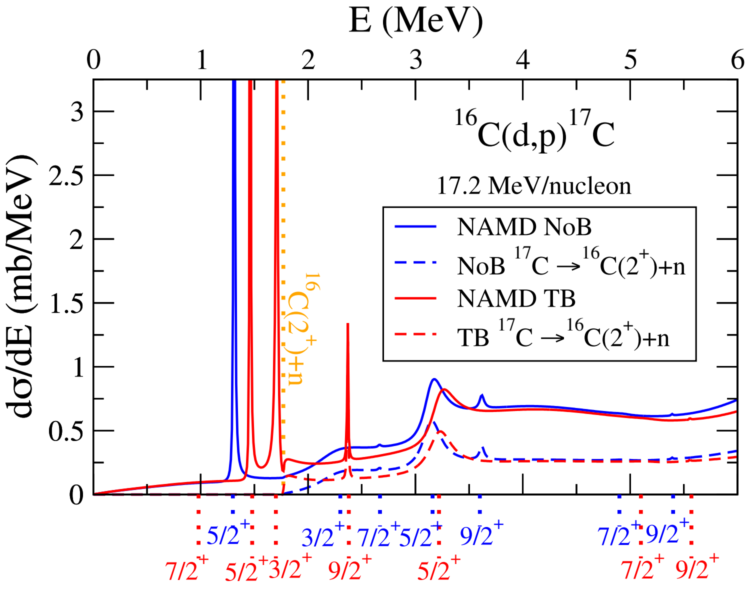
OCS: Shell evolution towards drip-line

J. L. Fuentes, B. Fernández-Domínguez et al., PLB 867 (2025) 139600



P. Punta et al., submitted PLB

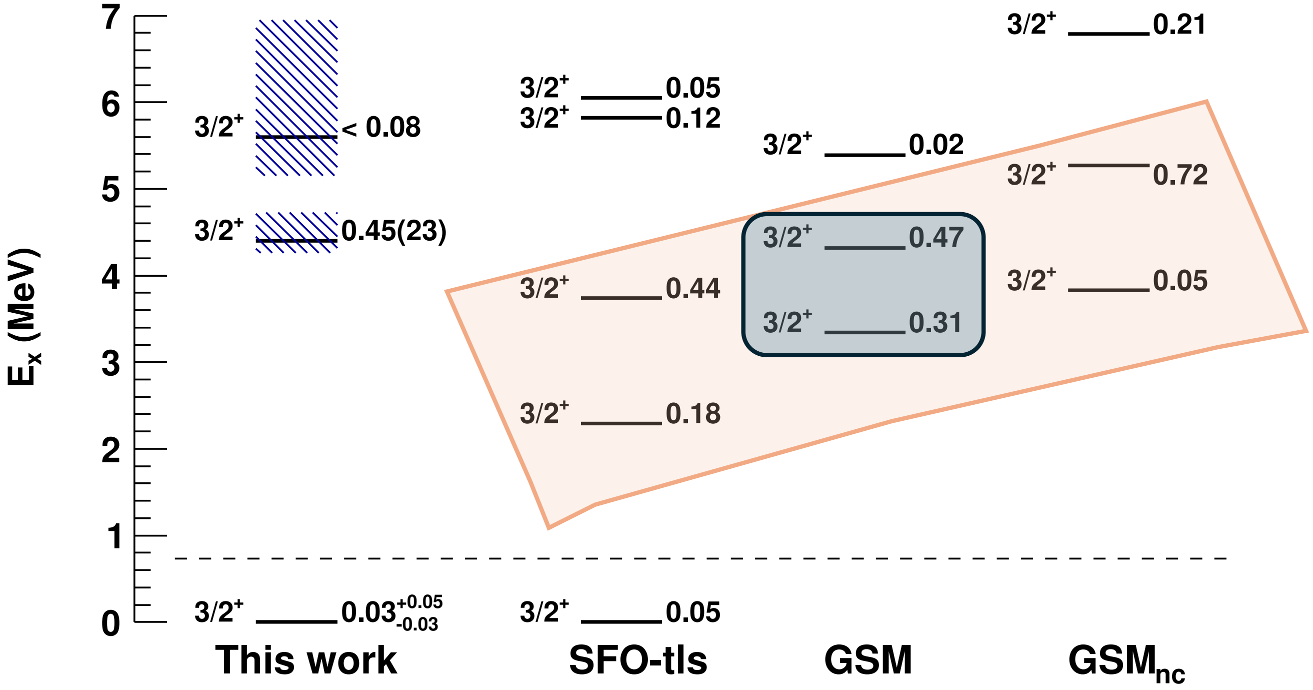




- Theoretical ADWA +NAMD= Nilsson Hamiltonian + AMD +TB reproduce the E_x of ^{17}C
- Confirm our results on the position of the main strength of $0d_{3/2}$ orbital.

https://arxiv.org/pdf/2604.14423

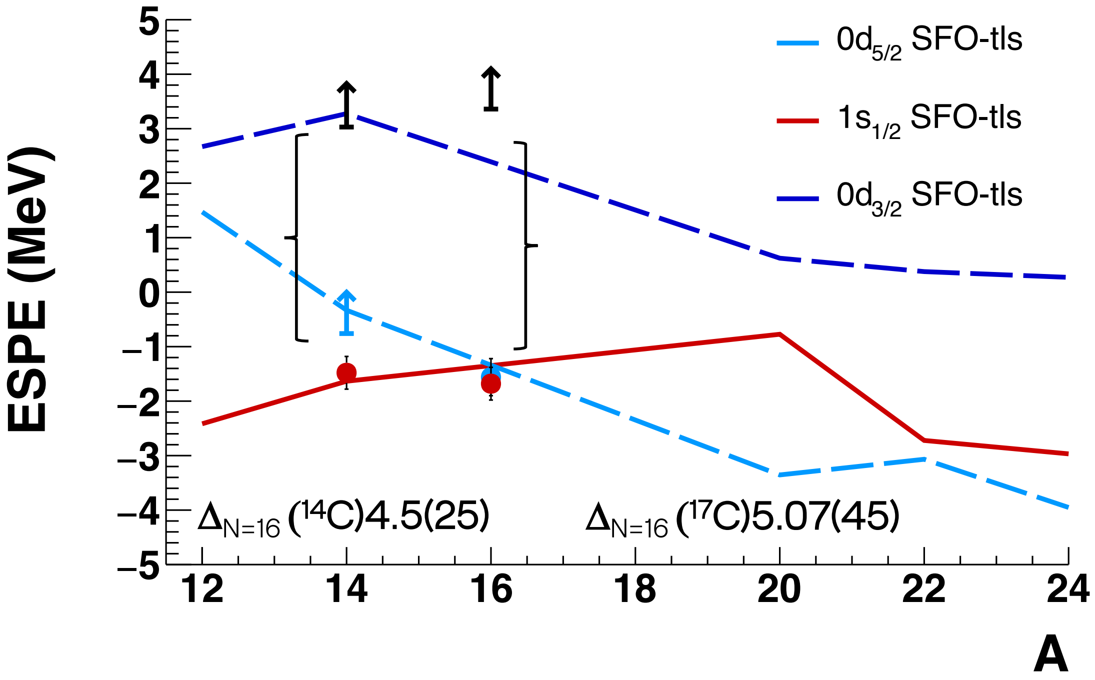
OCS: Shell evolution towards drip-line



- Experimentally the strength is located at 4.40 and 5.60 MeV
- Continuum effects tend to lower the E_x & shares the strength equally
- SFO-tls and GSM predict the major part of the 0d3/2 strength concentrated in 2-4 MeV

IGFAE

OCS: Shell evolution towards drip-line



ESPE from (d,p) & (d,t)

$\varepsilon 1s_{1/2}$

$\varepsilon 0d_{5/2}$

$\varepsilon 0d_{3/2}$

$\Delta(N=16)= \varepsilon 0d_{3/2} - \varepsilon 1s_{1/2}$

M. Baranger et al. NPA 149, 225 (1970)

- $\Delta(N=16)=5.07(45)$ MeV **survival of the N=16** in ^{17}C
- SFO-tls predicts the $0d_{3/2}$ ESPE ~ 1.3 MeV lower → **continuum effects or 3NF ?**
- Important implications for the N=16 Shell gap in ^{22}C

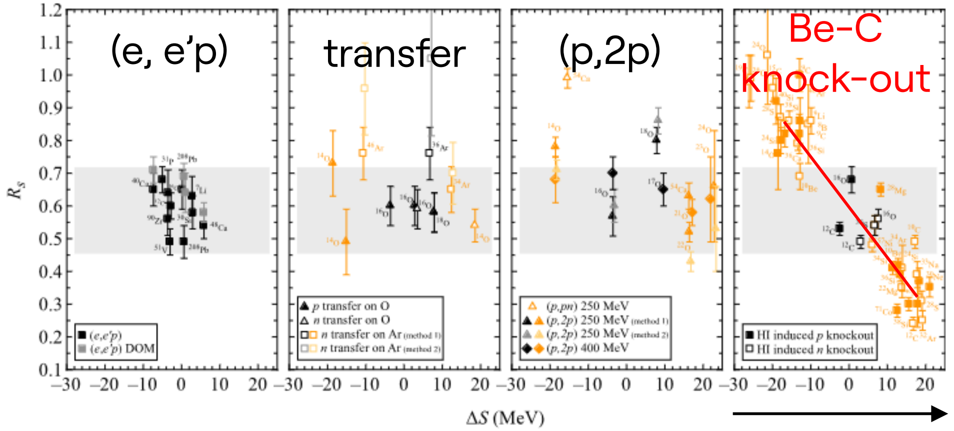
OCS: Quenching of SF in halo systems

Quenching of single-particle strength : R_s

$$R_s = \frac{C^2S_{exp}}{C^2S_{theo}}$$

- Short range correlations (SRC)
- Long range correlations (LRC)

→ Disagreement among probes



T. Aumann et al. Prog. Part. Nucl. Phys. 118 (2021)

Strongly bound

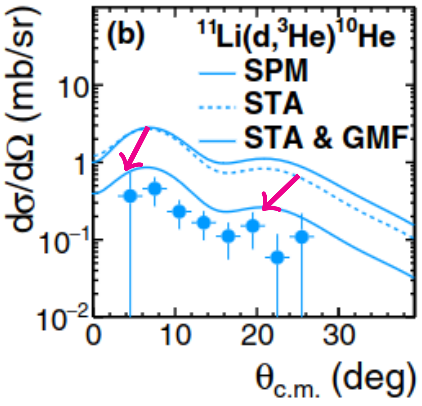
In reactions involving weakly bound/halo nuclei ?

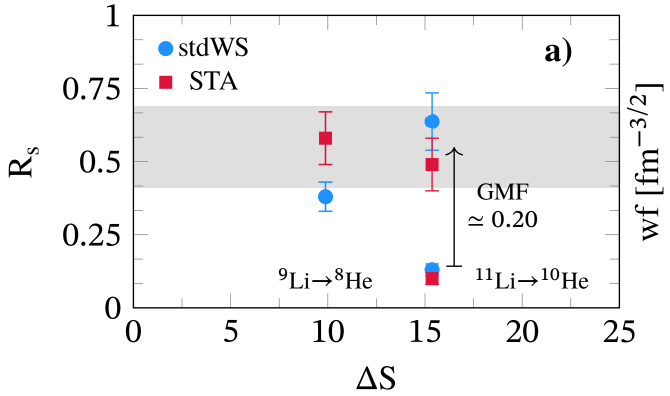
→ **Extreme quenching in proton pickup**

A. Matta et al. PRC 92, (2015) 041302

M. Lozano-González (Ph.D. Univ. Santiago de Compostela 2026)

Geometrical mismatch factor : **GMF <^{11}Li|^{10}He> = 0.20**

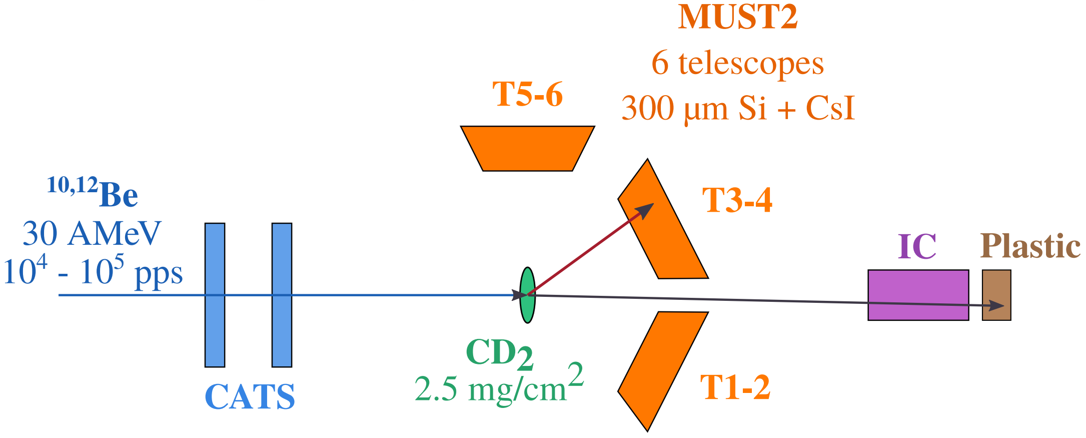




OCS: Quenching of SF in halo systems

Quenching of single-particle strength : R_s

M. Lozano-González (Ph.D. Univ. Santiago de Compostela 2026)



(d,t) and (d,^{3}He)

DWBA

OMP

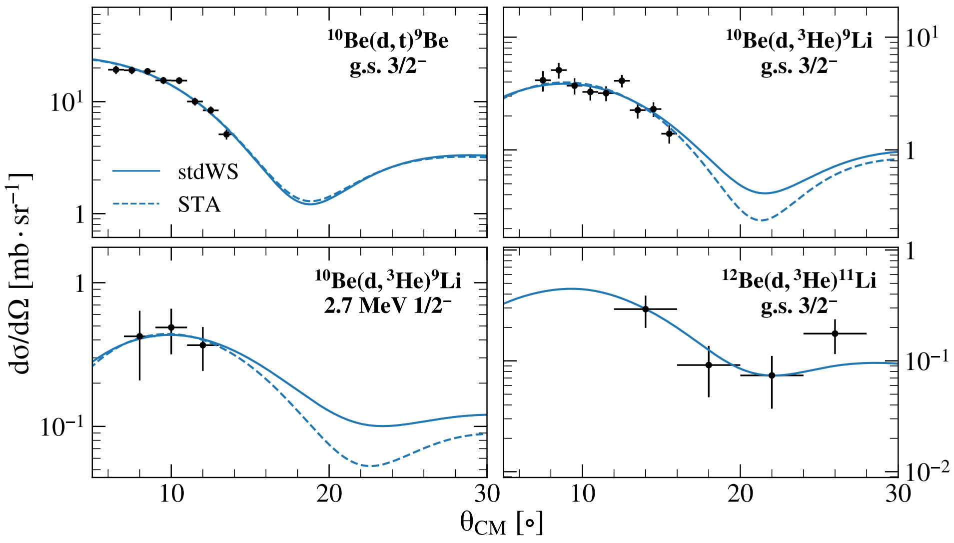
- Pang/HTp1

<d|^{3}He>

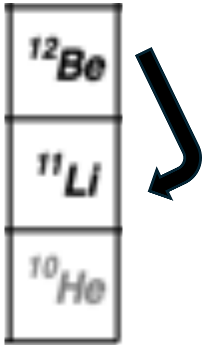
- GFMC

<^{A}Be|^{A}Li>

- WS
- STA



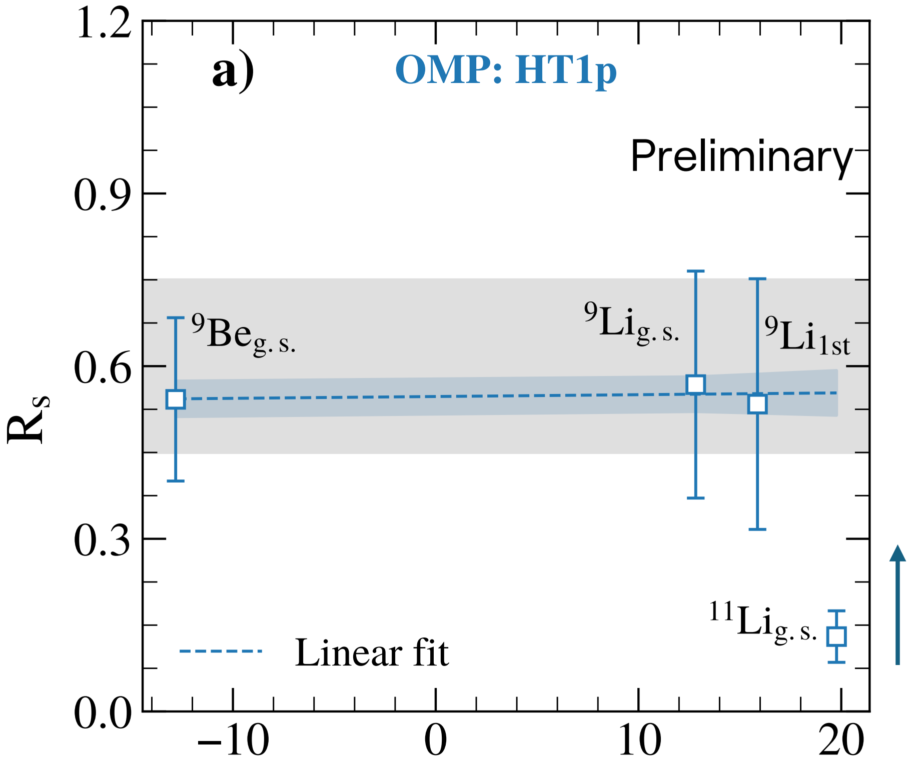
^{12}Be(d,^{3}He)^{11}Li



OCS: Quenching of SF in halo systems

Quenching of single-particle strength : R_s

M. Lozano-González (Ph.D. Univ. Santiago de Compostela 2026)
PELIMINARY

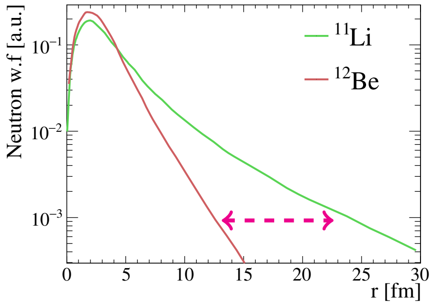


$$\begin{aligned}\langle {}^{12}\mathrm{Be}|{}^{11}\mathrm{Li}\rangle = \alpha\alpha'\langle {}^{10}\mathrm{Be}\otimes \mathrm{s}^2|{}^{9}\mathrm{Li}\otimes \mathrm{s}^2\rangle &+ \\ \beta\beta'\langle {}^{10}\mathrm{Be}\otimes \mathrm{p}^2|{}^{9}\mathrm{Li}\otimes \mathrm{p}^2\rangle &+ \\ \gamma\gamma'\langle {}^{10}\mathrm{Be}\otimes \mathrm{d}^2|{}^{9}\mathrm{Li}\otimes \mathrm{d}^2\rangle&.\end{aligned}$$

GMF = 0.8

FRESCO
single-particle wave functions
WS- potential ($r0$ = 1.25 fm and a = 0.65 fm).

^{12}Be ($S_{2n}/2$)= 1.84 MeV
^{11}Li ($S_{2n}/2$)= 0.18 MeV



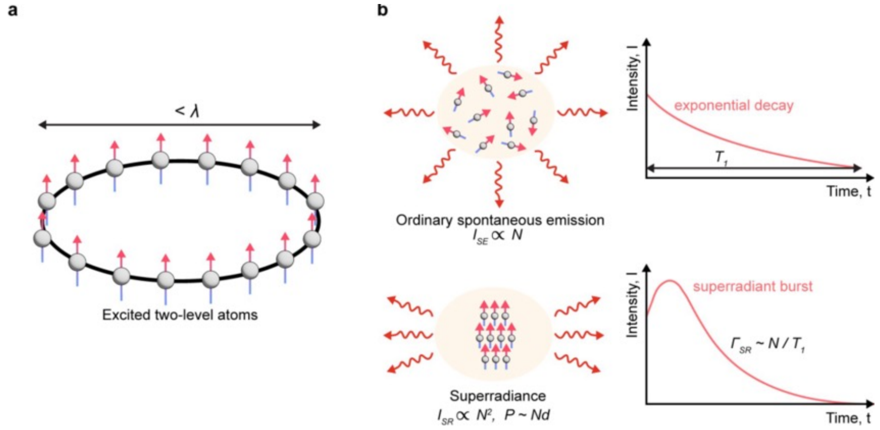
N. K. Timofeyuk, private communication (in E748 proposal)

GMF = 0.2 is needed → continuum effects ?
→ GSM for theory ?

Superradiant – Trapped systems

Atomic physics

R. H. Dicke Phys. Rev. 93, 99 (1954)



N-Identical excited emitters interact via **same** field

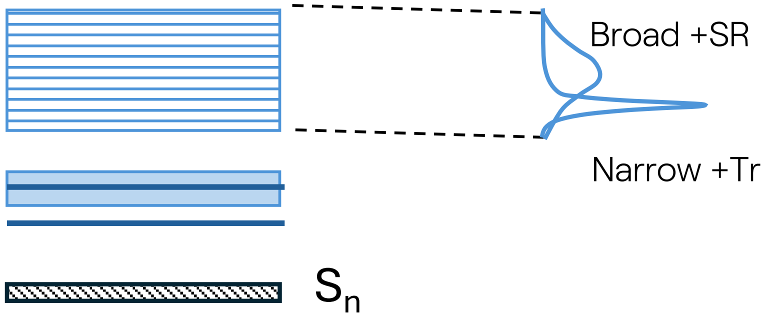
→ Emit short, high intense pulse of radiation N^2

→ Coherence lifetime competes with decay

- Spontaneous emission : *I* →N, t → exponential
- Superradiance : decay collectively : I → N^2 , t→ burst (delay)

Nuclear physics

N. Auerbach and V. Zelevinsky (2011) Rep. Prog. Phys. 74 106301
K. Kravvaris, A. Voyla AIP conf proc 1912 (2017) 020010



Above threshold excited configurations with identical **|nlj>** can all decay to the **same** reaction channel : ${}^{A}X \rightarrow {}^{A-1}X+n$

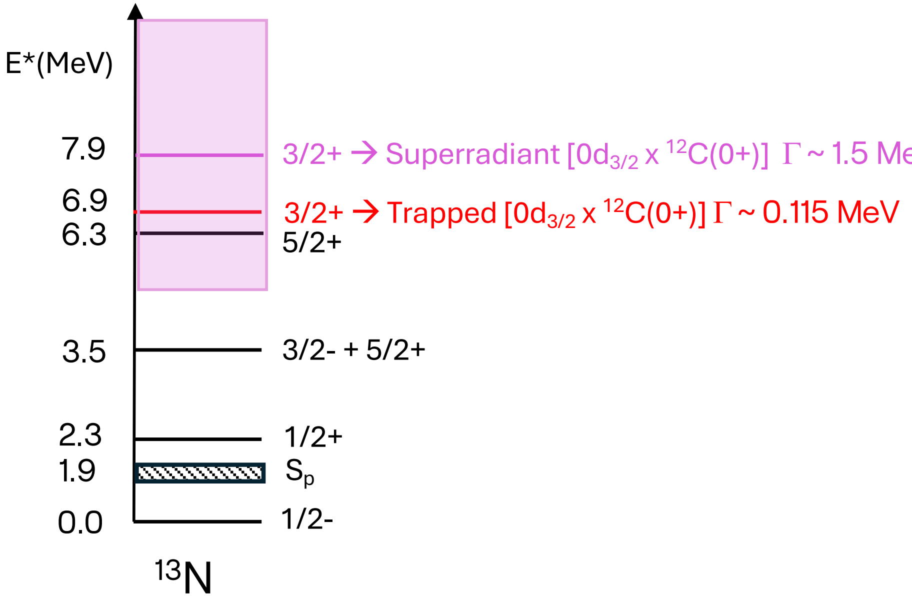
→ Broad superradiant state + narrow trapped resonance

→ Reorganisation of structure : one aligns with open quantum channel, and the other decouples

OCS: Superradiant-trapped resonances

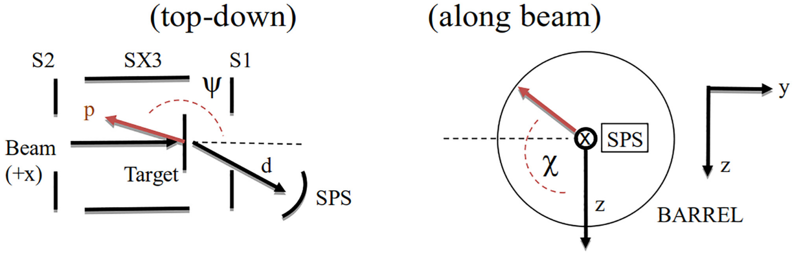
Superradiant – Trapped resonances in ^{13}N

K. Hanselman, I. Wiedenhöver et al. PRC 112 (2025) 034312



Experiment at FSU : SE-SPS + SABRE

$^{12}C(^3He,d)^{13}N$ → p, ^{12}C

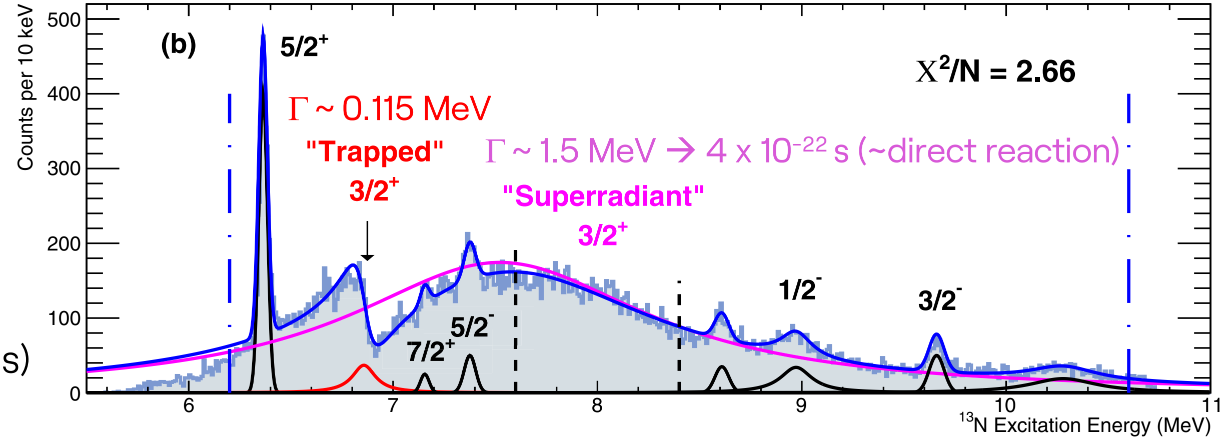


K. Hanselman, I. Wiedenhöver et al. PRC 112 (2025) 034312

CSM + FSU interaction

- Without continuum coupling
  Γt ~ Γsr
- With continuum
  Γt << Γsr

Superradiant ~ 7.6 – 8.4 MeV
(avoid mixture with other resonances)



OCS: Superradiant-trapped resonances

Superradiant – Trapped resonances in ^{13}N

K. Hanselman, I. Wiedenhöver et al. PRC 112 (2025) 034312

Superradiant is 1.5 MeV broad and well above S_p
→ Beyond single-step DWBA + CDCC (unbound)

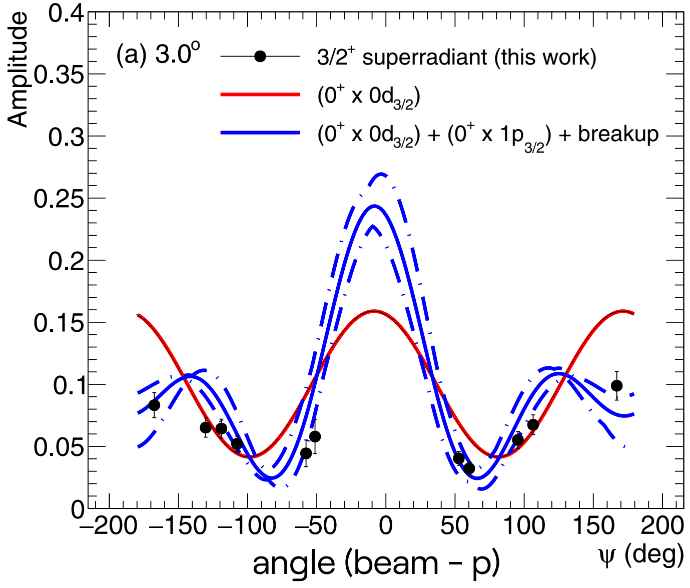
New observables : angular correlations
→ Extend formalism to OQ studies

CoSMo : Only 0^+ contributes, 2^+ omitted

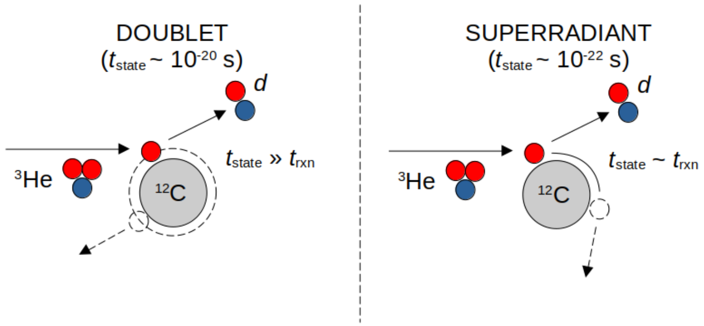
- Main configuration CSM not enough (0^+ x $0d_{3/2}$)
  → region free from non-3/2+ contaminant
- Asymmetries come from interference of opposite-parity partial waves → $1p_{3/2}$ (same Ex)

Angular-correlations

DWBA + CDCC : CSM amplitudes



Time scale → super radiant

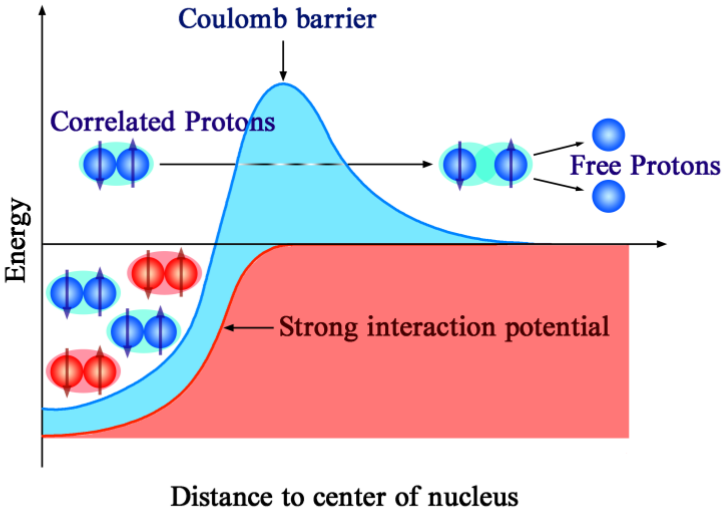


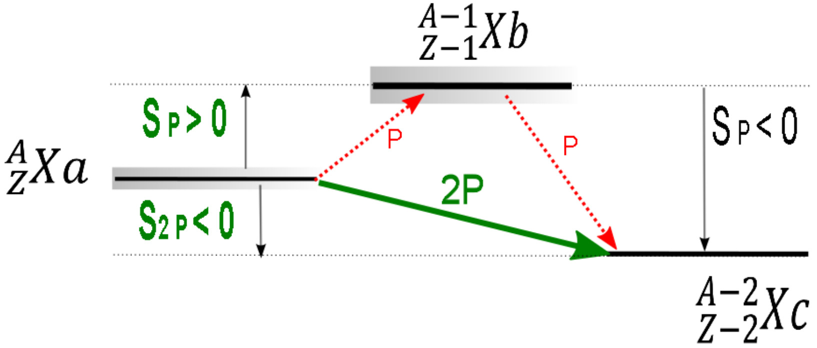
- Γ ~ 1.5 MeV → 4 x 10^{-22} s (~direct reaction) → not enough time to project into a single l (ang. mom)
- Multiple partial waves contribute
- → Time dependent model : reaction+ decay

OCS: 2p-decay

Two-proton radioactivity

V. I. **Goldansky** , Nuc. Phys. 19, (1960) 482





Effects from continuum :

- Nature of near-threshold
- Structure of many-body continuum near 2p-thresholds
- Modification of decay lifetimes : non-exponential decay

Observables :

- 2p decay half-life: $T_{1/2.}$ ~ ps-ms
- Q_{2p} : energy released
- Properties of emitted protons: angular and energy correlations

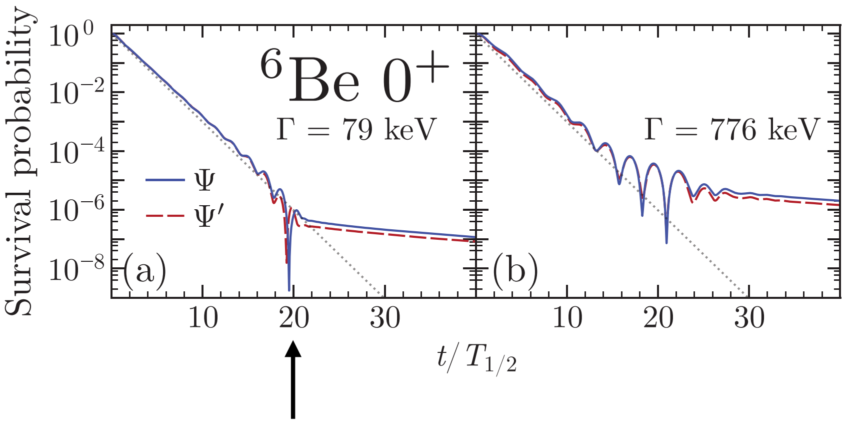
→ Improve precision in energy (100 keV) , angular measurements (< 1 deg), decay time (ms)

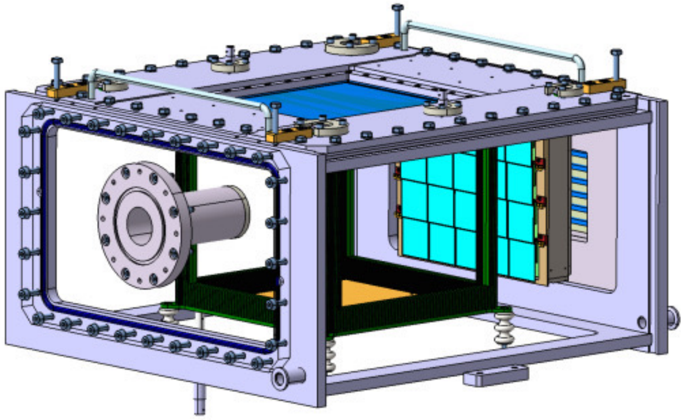
Two-proton radioactivity

S. M. Wang, W. Nazarewicz, A. Volya and Y.G. Ma, Phys Rev. Res. 5 (2023) 023183

Modification of decay lifetimes : non-exponential decay at long times

- At short times : exponential law → P(t) ~ $e^{-\Gamma t}$
- At long times : post-exponential regime → P(t) ~ $t^{-\nu}$





- Transition from exp to decay **t~20$T_{1/2}$**

- Large statistics
- Integrate over 20 half-lives ...

→ Not possible to be measured with current devices

OCS: Conclusions

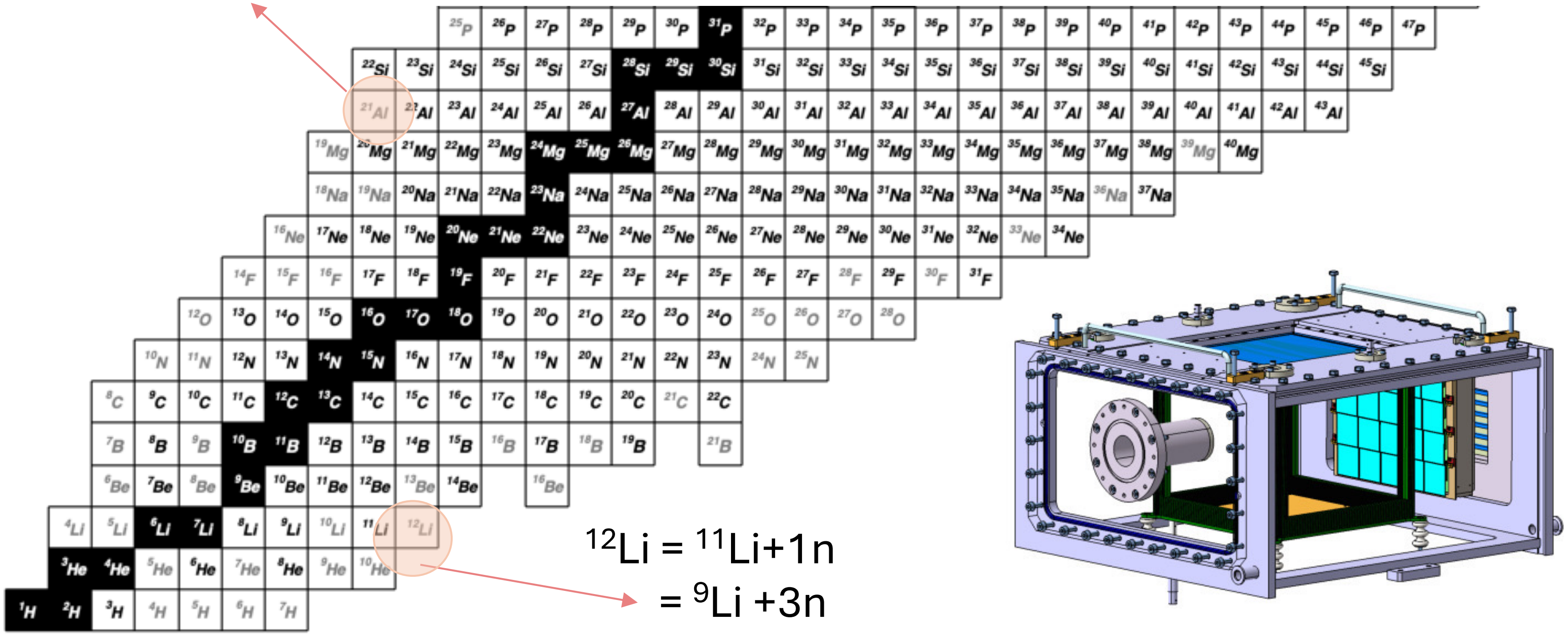
- Weakly (un)bound nuclei are interesting laboratories to explore open quantum effects
- Current tools and experimental methods are at the limit of what can be explored

- Improve setups for combine measurement of reaction & decay: angular correlations (measuring decaying particles), time measurements.
- Reaction model adapted to narrow and broad resonances (DWBA+ CDCC) that include non resonance continuum with different partial waves
- Time dependent methods
- Other types of observables

OQS: Future perspectives

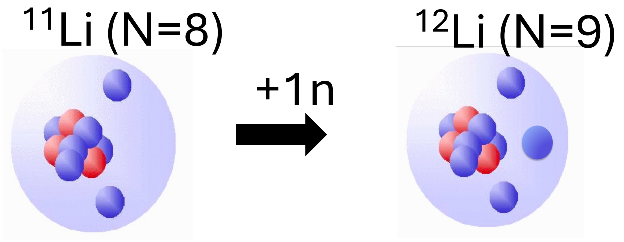
Study of OQS with active targets : beyond drip-line

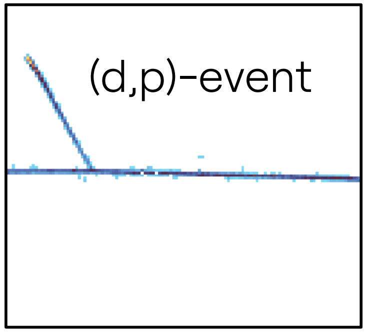
^{20}Mg+p→^{21}Al



^{12}Li = ^{11}Li+1n
= ^{9}Li +3n

I. Blanco Calviño (Ph.D. analysis)





Thanks for your attention !