# Threshold states and clustering as emerging phenomena

Marek Płoszajczak (GANIL)

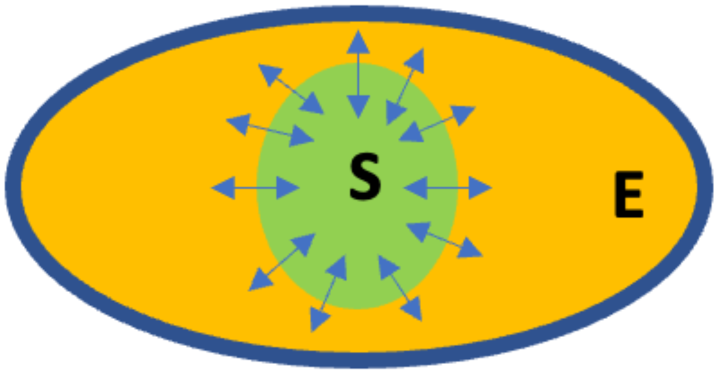
1. Atomic nucleus: open quantum system perspective
2. Shell model for open quantum systems
   - Non-Hermitian QM in Hilbert space
   - Picket fence ($\ell$=0) model
   - GSM – Coupled-channel representation
   - NN interaction in different regimes of binding
   - Configuration mixing
3. Near-threshold states and the origin of clustering
   - Near-threshold collectivization: $\gamma$-transitions
   - Threshold states in nuclear astrophysics
   - Mimicry mechanism in resonances
   - Rise and fall of clustering in $^{7}$Li and $^{8}$Be
4. Message to take

Plenary meeting of the French low energy nuclear physics community
Strasbourg, November 3-7, 2025

GDR RESANET

# What is the open quantum system?

An *open* **quantum system** is a quantum system which is found to be in interaction with an external quantum system, the *environment*. The open quantum system can be viewed as a distinguished part of a larger quantum system.



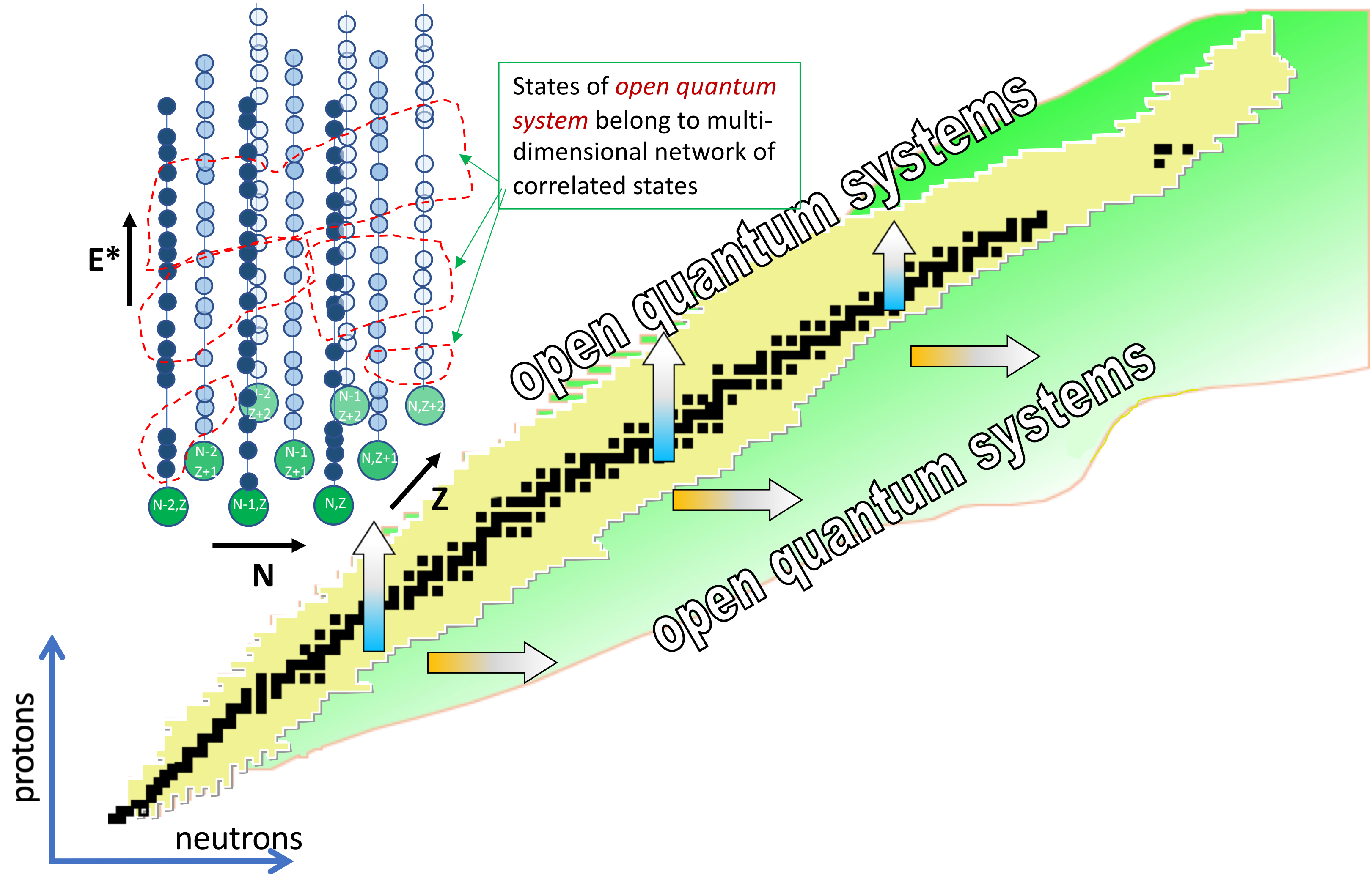

$\rho_S = Tr_E\{\rho_{full}\}$

Standard techniques developed in the context of open quantum systems have proven powerful in fields such as:

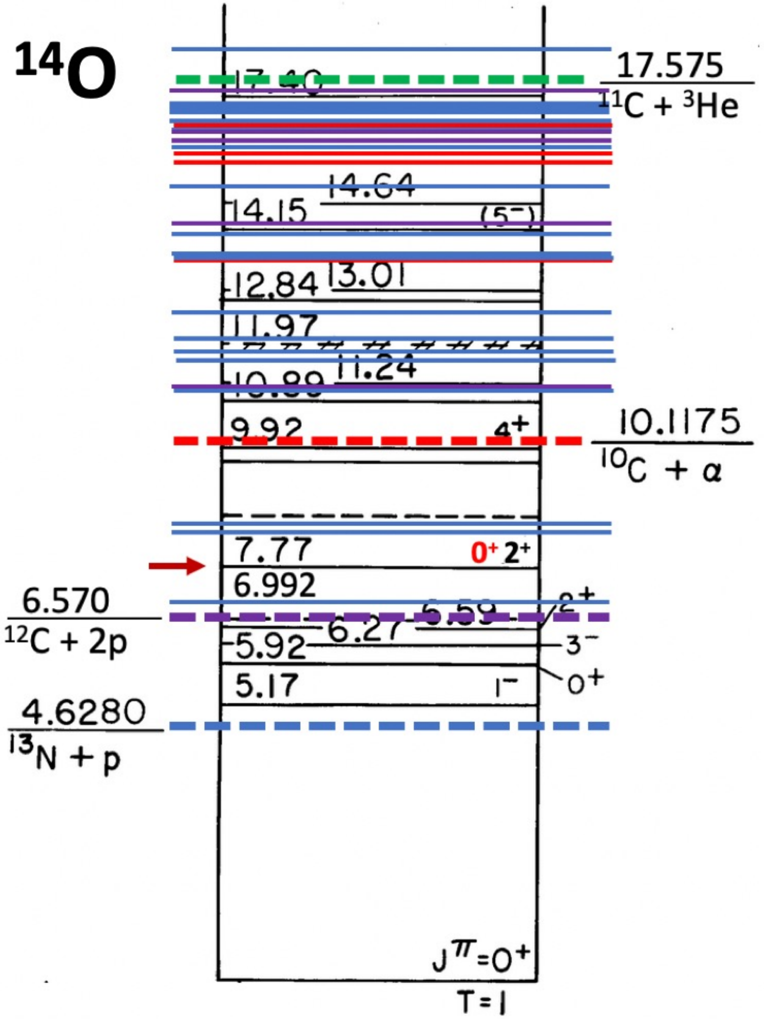
quantum optics, quantum measurement theory, quantum statistical mechanics, quantum information science, quantum cosmology, mesoscopic physics …

Description in terms of the density matrix is not well suited for nuclear physics which deals with the well-defined quantum states → *configuration interaction* formulation

# Open quantum system perspective



# Open quantum system perspective




- Shell model states are *embedded in the continuum*

- Couplings to various particle emission channels are crucial for the properties of near-threshold states

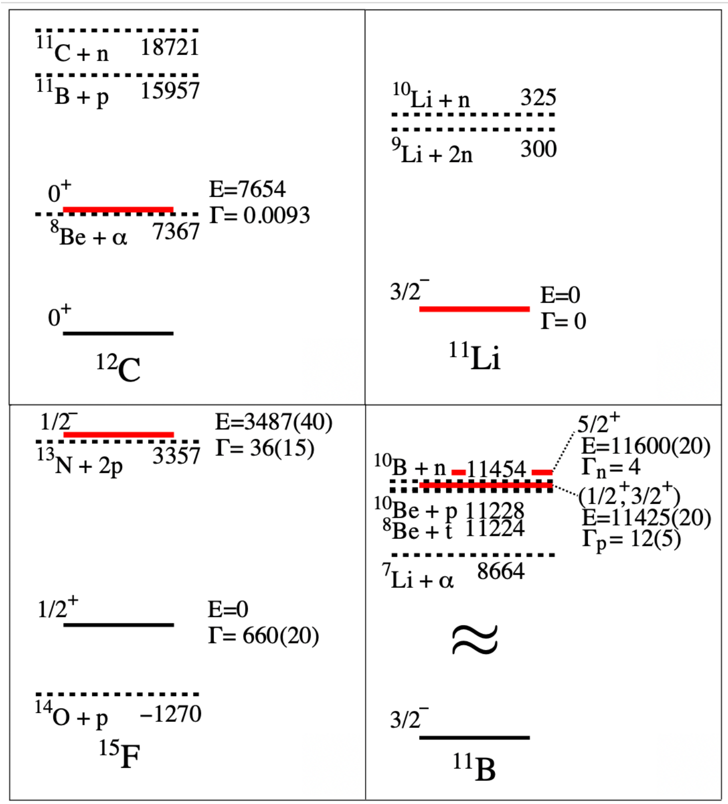
- Thresholds are *branch points*. They cause nonanalytic behavior both in spectroscopic factors and elastic (total) cross sections for production/absorption of (neutral) particles

  E.P. Wigner, PR 73, 1002 (1948)
  N. Michel, W. Nazarewicz., M. Ploszajczak, PRC 75, 031301(R) (2007)

Essential role of *unitarity*!

# Open quantum system perspective

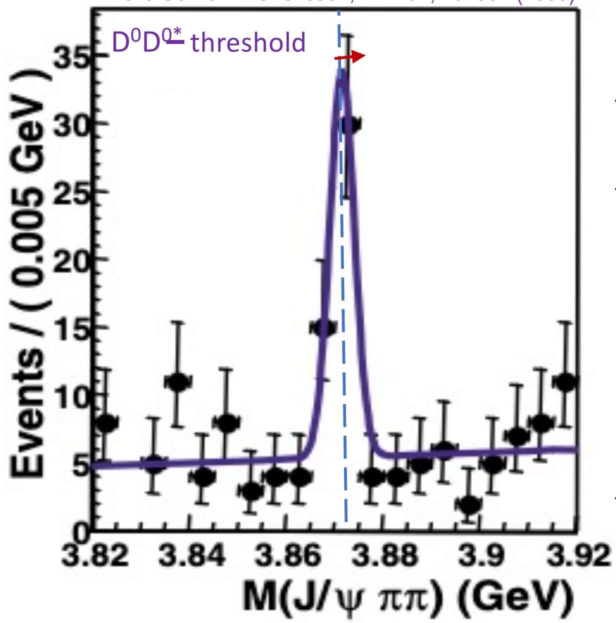
## Near-threshold correlations and clustering




- Other cases: $^{6}$He, $^{6}$Li, $^{7}$Be, $^{7}$Li, $^{11}$O, $^{11}$C, $^{17}$O, $^{20}$Ne, $^{26}$O,…
- Various clusterings: 2p, 2n, $^{3}$He, $^{3}$H, …

### Threshold effects in multiquark systems

Belle Coll. J.-K. Choi et al., PRL 91, 262001 (2003)




$$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$$

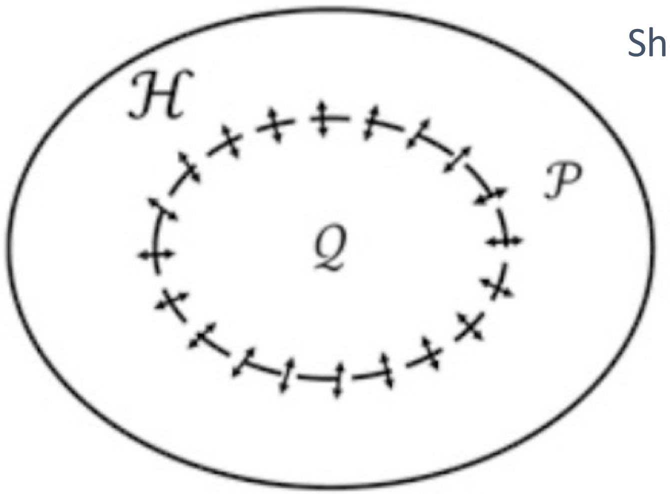
$M_X$ = 3872 +/- 0.6 (stat) +/- 0.5 (syst) MeV

$(M_{D^0} + M_{D^{*0}})$ = 3871.1 +/- 1 MeV

- Emergence of *new energy scale(s)*
- Correlated (clustered) states near the reaction channel thresholds are a consequence of the *rearrangement* of wave functions caused by mutual coupling through the continuum
- This is the generic emergent phenomenon in the **OQS**s

# Shell model for open quantum systems

## Non-Hermitian QM in Hilbert space




### Shell model embedded in the continuum (SMEC)

$$H^{(SM)} \rightarrow \mathcal{H}^{eff}(E) = H'(E) - (i/2)V(E)V^T(E)$$

[N×N] [N×N] [N×N] [N×k] [k×N]

$$= H^{(SM)} + u(E) - (i/2)w(E)$$

Hermitian anti-Hermitian

Coupling to the environment of scattering states and decay channels *cannot be reduced* to refitting parameters of the **CQS**

### Open QS solution in Q

$$\mathcal{H}_{QQ}^{eff}|\Psi_\alpha\rangle = \mathcal{E}_\alpha(E)|\Psi_\alpha\rangle$$

$$\langle\Psi_{\tilde{\alpha}}|\mathcal{H}_{QQ}^{eff} = \mathcal{E}_\alpha^*(E)\langle\Psi_{\tilde{\alpha}}|$$

$\Leftarrow$ $\langle\Psi_{\tilde{\alpha}}|\Psi_\beta\rangle = \delta_{\alpha\beta}$

For bound states: $\mathcal{E}_\alpha(E)$ is real

$$\Psi_\alpha = \sum_i b_{\alpha i}\Phi_i^{(SM)} \Rightarrow \Psi_E^c \sim \sum_\alpha c_\alpha \Psi_\alpha$$

Physical resonances $\equiv$ poles of the scattering matrix

Entrance and exit reaction channels defined

⬇

Shell model and reaction theory reconciled

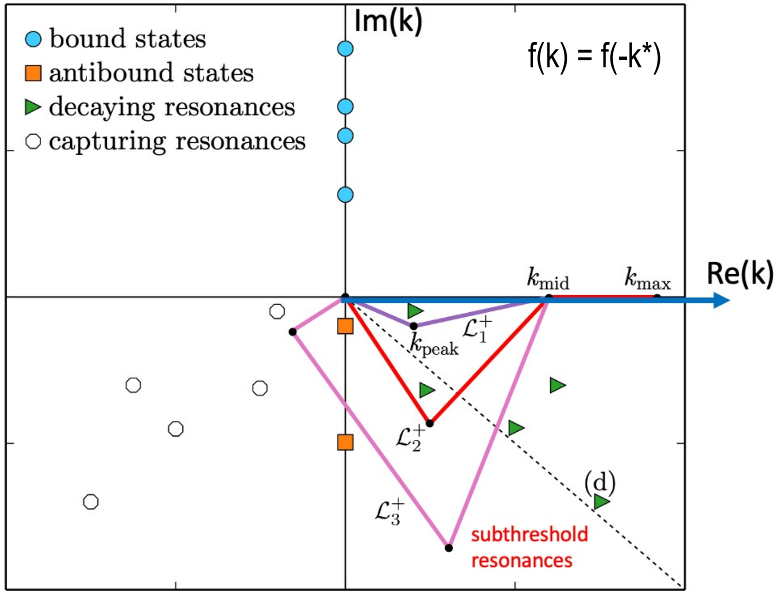

C. Mahaux, H.A. Weidenmüller,
« *Shell Model Approach to Nuclear Reactions* »
(North-Holland Publishing Company, 1969)

J. Okołowicz, M. Ploszajczak, I. Rotter,
Physics Reports 374, 271 (2003)

N. Moiseyev
« *Non-Hermitian Quantum Mechanics*»
(Cambridge University Press, 2011)

# Shell model for open quantum systems

## GSM – Coupled-channel representation




$$\sum_n |u_n\rangle\langle\tilde{u}_n| + \int_{L_+} |u_k\rangle\langle\tilde{u}_k| dk = 1 \; ; \; \langle u_i|\tilde{u}_j\rangle = \delta_{ij}$$

T. Berggren, Nucl. Phys. A 109, 265 (1968)

$$|SD_i\rangle = |u_{i_1} \ldots u_{i_A}\rangle \Rightarrow \sum_k |SD_k\rangle\langle SD_k| \cong 1$$

N. Michel, et al, J. Phys. G37, 064042 (2010)

- *Unitary formulation* of the nuclear Shell Model
- *Complex-symmetric* eigenvalue problem for *hermitian* Hamiltonian
- No identification of reaction channels

$$|\Psi_M^J\rangle = \sum_c \int_0^{+\infty} |(c,r)_M^J\rangle \frac{u_c^{JM}(r)}{r} r^2 \, dr$$

$$|(c,r)\rangle = \hat{\mathcal{A}}[|\Psi_T^{J_T}; N_T, Z_T\rangle \otimes |r \; L_{\mathrm{CM}} \; J_{\mathrm{int}} \; J_P; n, z\rangle]_M^J$$

$$H\,|\Psi_M^J\rangle = E\,|\Psi_M^J\rangle \Rightarrow \sum_c \int_0^{\infty} r^2 \left(H_{cc'}(r,r') - E N_{cc'}(r,r')\right) \frac{u_c(r)}{r} = 0$$

$$H_{cc'}(r,r') = \langle (c,r)|\,\hat{H}\,|(c',r')\rangle$$

$$N_{cc'}(r,r') = \langle (c,r)|(c',r')\rangle$$

- Entrance and exit reaction channels defined
  - ⇒ Unification of nuclear structure and reactions
- Calculation in relative coordinates of core cluster orbital SM coordinates
  - Center-of-mass handled by recoil term in the Hamiltonian
- Reaction channels with different (binary) mass partitions
- Core is arbitrary

Y. Jaganathen et al, PRC 88, 044318 (2014)
K. Fossez et al., PRC 91, 034609 (2015)
A. Mercenne et al., PRC 99, 044606 (2019)

N. Michel, M.Płoszajczak,
*«Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions »*
Lecture Notes in Physics, Vol. 983, (Springer Verlag, 2021

# Shell model for open quantum systems

## NN interaction in different regimes of binding

★ B(ja,jb)=-10 MeV
★ B(ja,jb)= -1 MeV
★ B(ja,jb)=+1 MeV

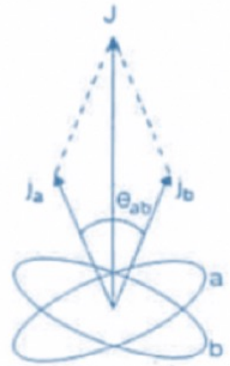
$\ell$=p,d,f,g,h
Minnesota interaction

$\Re(V_{12})=E_n/\langle E_n\rangle$ ; $E_n=E-e_a-e_b$

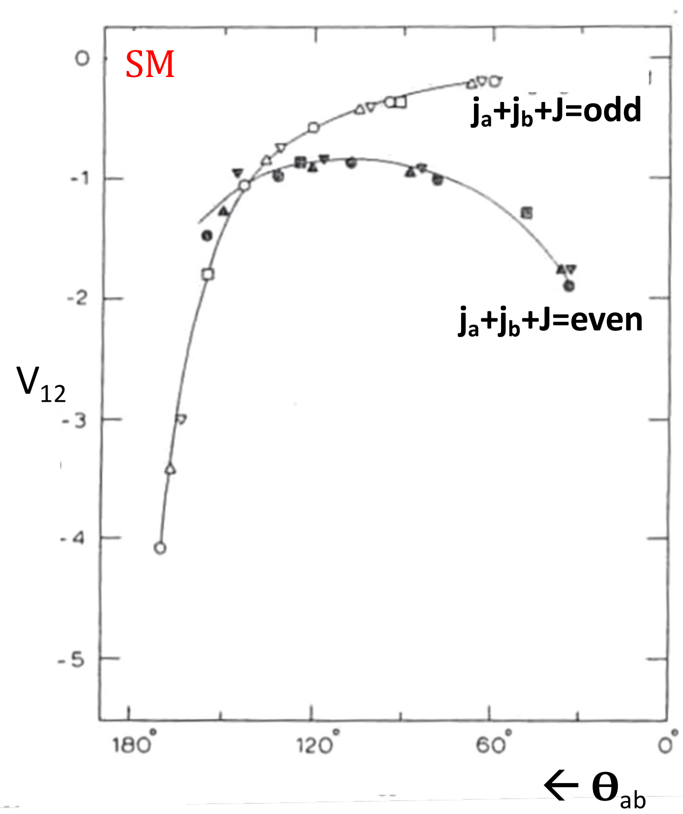
$\langle E_n\rangle=|\Sigma_J(2J+1)(E-e_a-e_b)/\Sigma_J(2J+1)|$

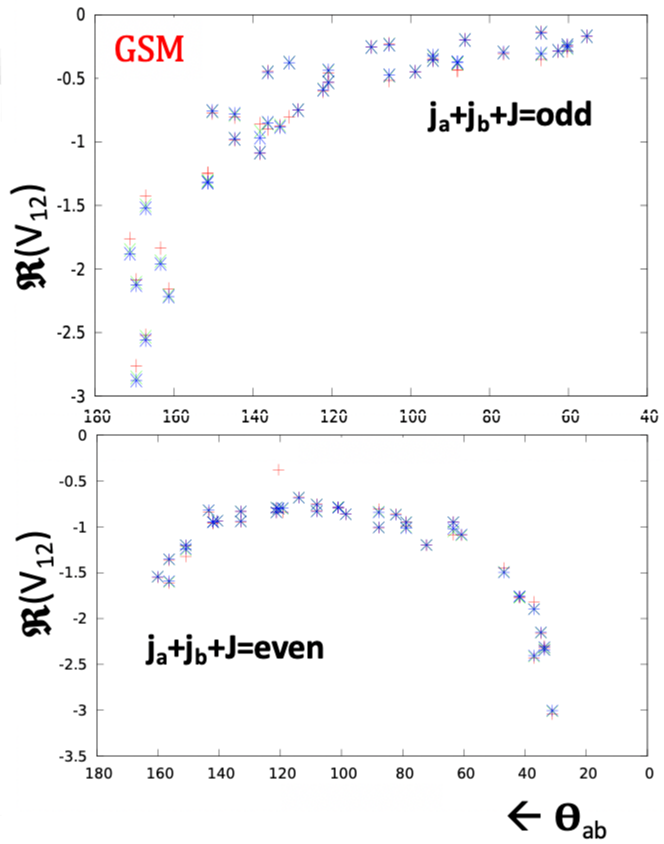
$\Im(V_{12})=\Gamma_n/\langle\Gamma_n\rangle$ ; $\Gamma_n=\Gamma-\gamma_a-\gamma_b$

$\langle\Gamma_n\rangle=|\Sigma_J(2J+1)(\Gamma-\gamma_a-\gamma_b)/\Sigma_J(2J+1)|$




$$\cos(\theta)=\frac{J(J+1)-j_a(j_a+1)-j_b(j_b+1)}{2\sqrt{j_a(j_a+1)j_b(j_b+1)}}$$




- Similar qualitative dependence of the TBMEs on angle $\Theta_{ab}$ in SM and GSM
- TBMEs are *complex* in weakly bound/unbound nuclei

# Shell model for open quantum systems

## Dependence of $V_{nn}/V_{pp}$ on $S_n - S_p$ asymmetry

| $\ell_j$ | $J^\pi$ | $S_p$[MeV] | $S_n$[MeV] | $V_{nn}/V_{pp}$ |
|---|---|---|---|---|
| $p_{1/2}$ | $2^{+}$ | 10 | -1 | 0.39 |
| | | 1 | -1 | 0.58 |
| $d_{5/2}$ | $2^{+}$ | 10 | -1 | 0.83 |
| | | 1 | -1 | 0.835 |
| | $4^{+}$ | 10 | -1 | 0.75 |
| | | 1 | -1 | 0.84 |

- Strong asymmetry of $V_{nn}$ and $V_{pp}$ for large $|S_n - S_p|$ and low $\ell_j$

N. Michel, M.Ploszajczak, «*Gamow Shell Model: The Unified Theory of Nuclear Structure and Reactions* »
Lecture Notes in Physics, Vol. 983, (Springer Verlag, 2021)

## Dependence of spectroscopic factors on $S_n - S_p$ asymmetry

Spectroscopic factors for the knockout of a $p_{3/2}$ nucleon from the 3/2- g.s. of $^9C$ and $^9Li$ to the g.s. of $^8B$, $^8He$, $^8B$, and $^8Li$

| Model | $N_{cont}$ | $^9C \to {}^8C$ 14.22 | $^9Li \to {}^8He$ 13.94 | $^9C \to {}^8B$ 1.30 | $^9Li \to {}^8Li$ 4.06 |
|---|---|---|---|---|---|
| HO-SM | 0 | 0.86 | 0.85 | 0.95 | 0.96 |
| GSM-*ps* | 3 | 0.67 | 0.67 | 0.98 | 0.98 |
| GSM-*psd* | 3 | 0.60 | 0.67 | 0.89 | 0.88 |
| GSM-*psd* | 4 | 0.48 | 0.65 | 0.89 | 0.88 |
| GSM-$psd_{res}$ | 4 | 0.48 | 0.64 | 0.84 | 0.85 |

- If $S_n \gg S_p$ ($S_p \gg S_n$) , then neutron (proton) spectroscopic factor is reduced with respect to the SM prediction

J. Wylie, J. Okolowicz et al, Phys. Rev. C 104, L061301 (2021)

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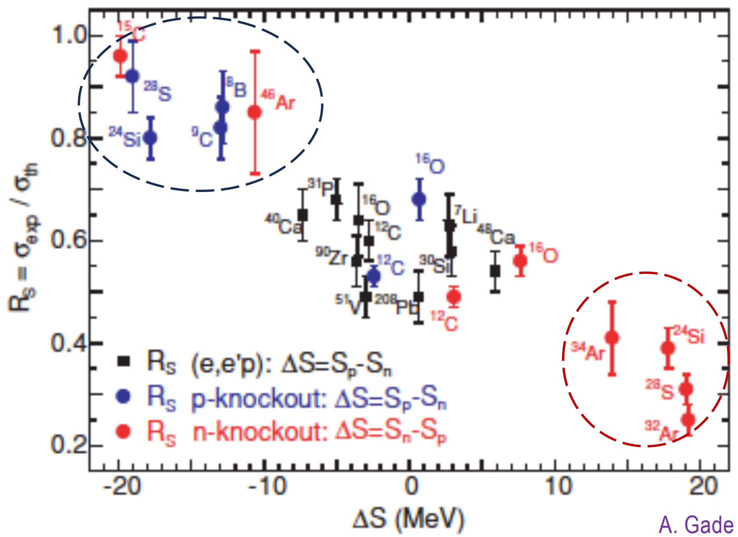


A. Gade et al, PRL 93, 042501

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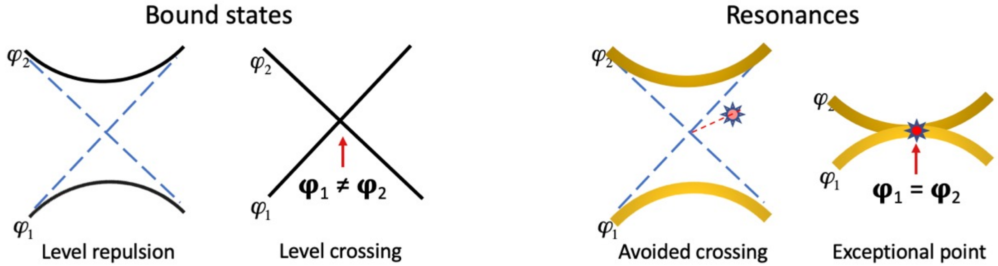
- Near and beyond the drip lines, different reactions that lead to the same nucleus/final state may give inconsistent results due to the different *environment* of the continuum states (*spectroscopic factors*) in these reactions

knockout reactions ⟷ transfer reactions
fusion reactions ⟷ THM
charge exchange ⟷ peripheral transfer

could be unsafe in certain regimes (broad resonances, large asymmetry of the separation energies, …)

# Shell model for open quantum systems

## Configuration mixing



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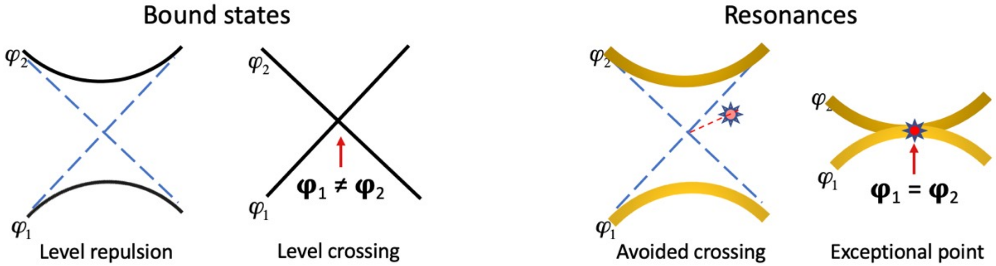
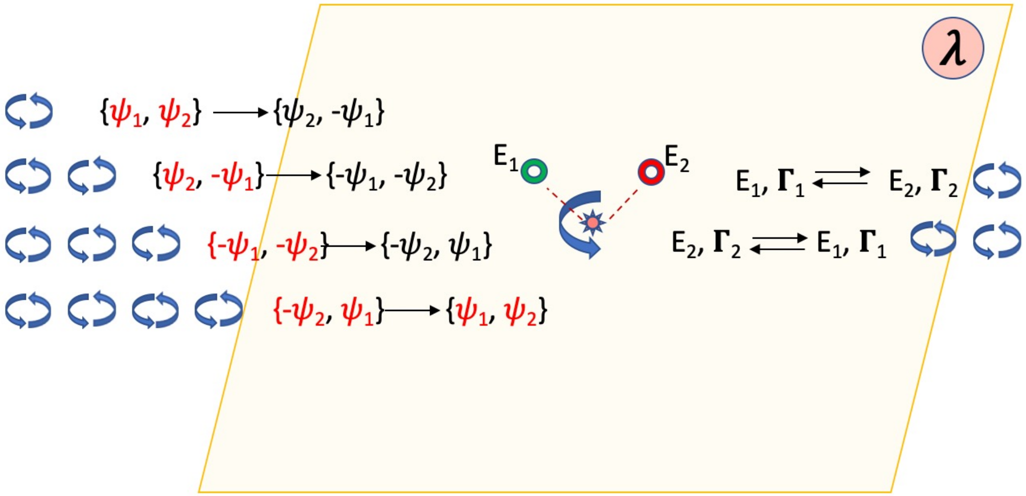



## Topological features of the exceptional points (Berry phase)




- Bose-Einstein condensation of gases with attractive 1/r – interaction
- Microwave cavity experiments
- Atoms coupled to radiation field
- Atom – cavity quantum composite
- Optical lattices
- Atomic nuclei

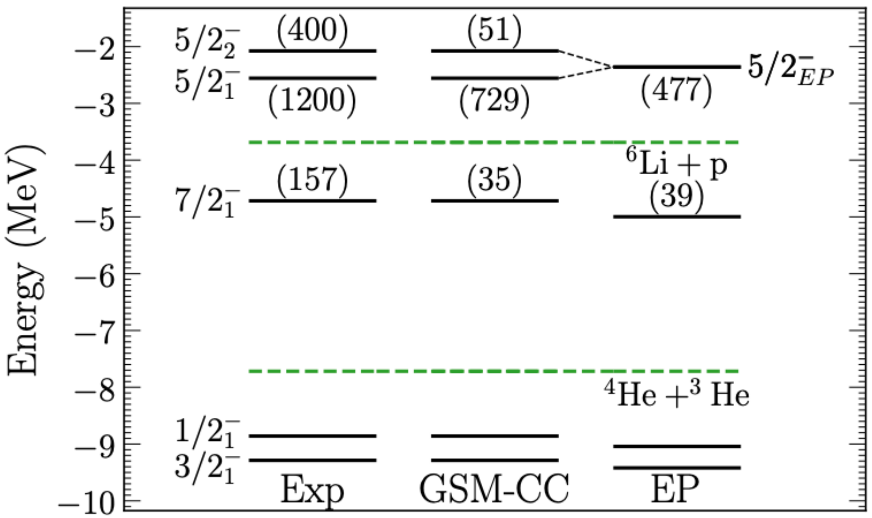
M.R. Zirnbauer et al., Nucl. Phys. A411 (1983) 161
C. Dembowski et al., PRL 86 (2001) 787; PRL 90 (2003) 034101
J. Okołowicz, M. Ploszajczak PRC 80 (2009) 034619

- Orientation of a loop in the parameter space determines which wave function will pick a sign during encircling of the EP ⟶ *chirality*

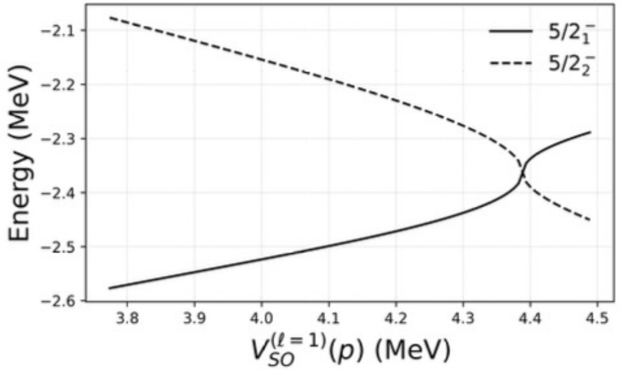
# Shell model for open quantum systems

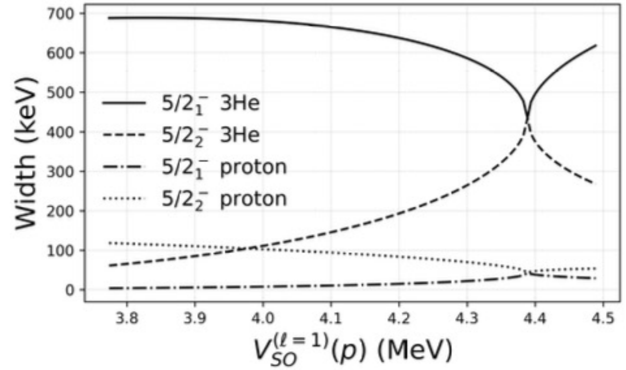
## Configuration mixing

**$^7$Be**




[|$^4$He⟩ ⊗ |$^3$He⟩], [| $^6$Li ⟩ ⊗ |p⟩]



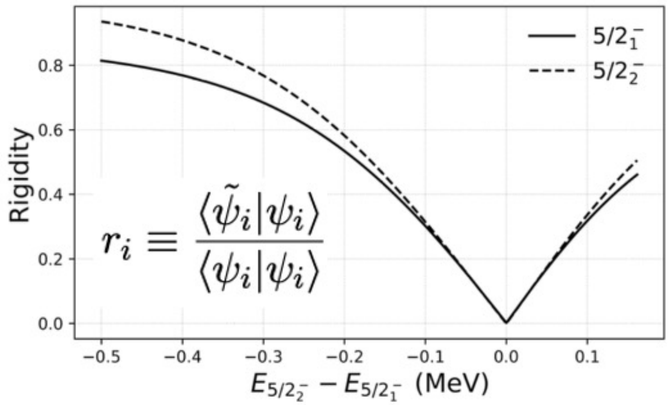

- Hamiltonian: 1-body potential, 2-body FHT interaction

  H. Furutani et al, Prog. Theor. Phys. 62, 981 (1979)

  $^3$He wave functions calculated using N$^3$LO$_{(2\text{-body})}$ interaction

- Channels: $^6$Li($K^\pi$): $K^\pi$=$1_1^+$, $1_2^+$, $3_1^+$, $0_1^+$, $2_1^+$, $2_2^+$
  n: $\ell_j$ = $s_{1/2}$, $p_{1/2}$, $p_{3/2}$, $d_{3/2}$, $d_{5/2}$, $f_{5/2}$, $f_{7/2}$
  $^3$He(L): L ≡ $^{2Jint+1}[L_{CM}]_{JP}$ = $^2S_{1/2}$, $^2P_{1/2}$, $^2P_{3/2}$, $^2D_{3/2}$, $^2D_{5/2}$, $^2F_{5/2}$, $^2F_{7/2}$

- 2D-search for EPs in the plane $\boldsymbol{\nu}V_{so}$ - $\boldsymbol{\pi}V_{so}$ for l=1

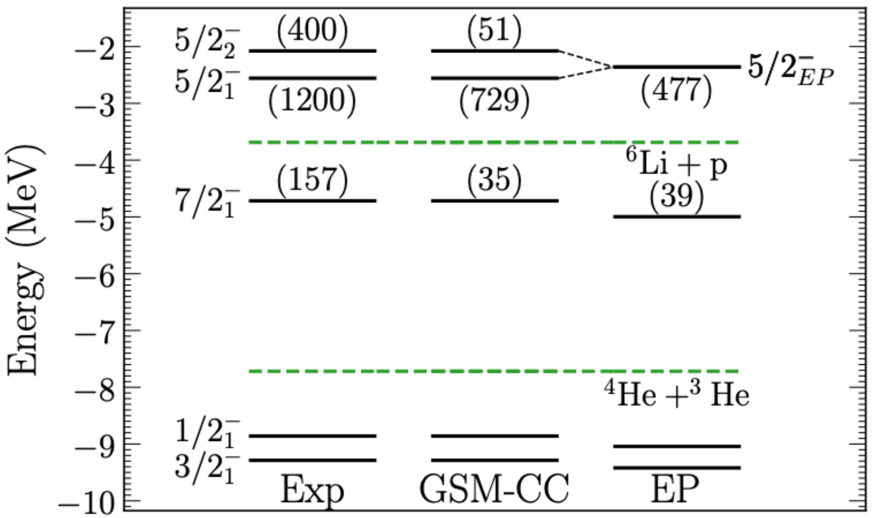



D. Cardona Ochoa et al., arXiv:2510.27293

# Shell model for open quantum systems

## Configuration mixing

### $^7$Be




$[|^4\text{He}\rangle \otimes |^3\text{He}\rangle]$, $[|^6\text{Li}\rangle \otimes |\text{p}\rangle]$

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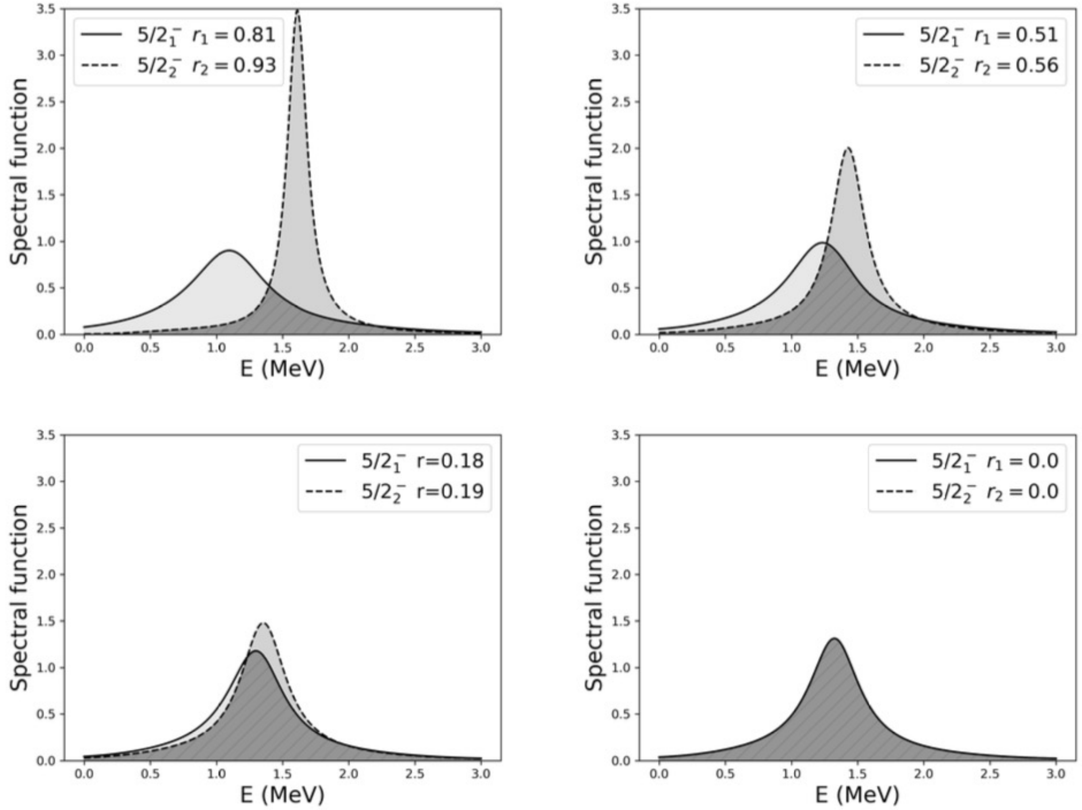
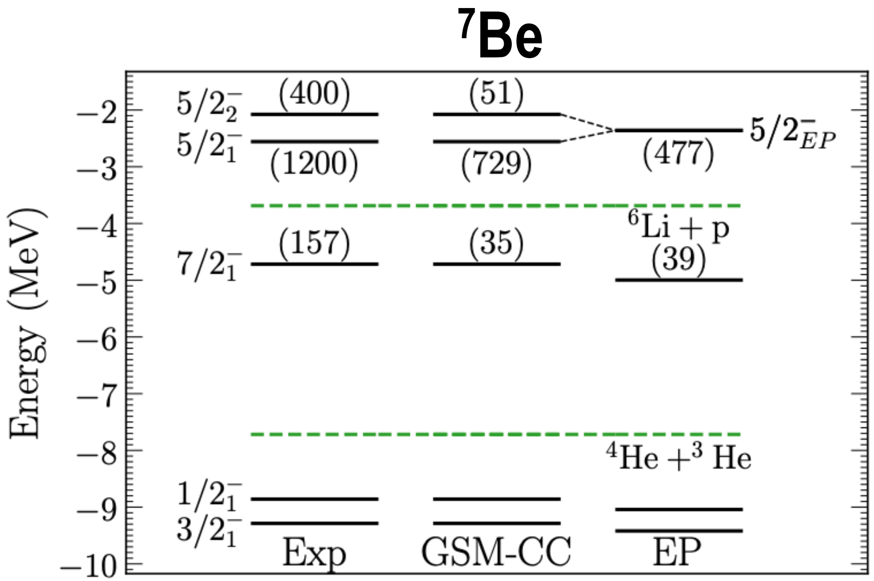



$$\rho(E) = \sum_n |\langle \Psi_{E;c_n} | \Psi \rangle|^2$$

D. Cardona Ochoa et al., arXiv:2510.27293

# Shell model for open quantum systems

## Configuration mixing

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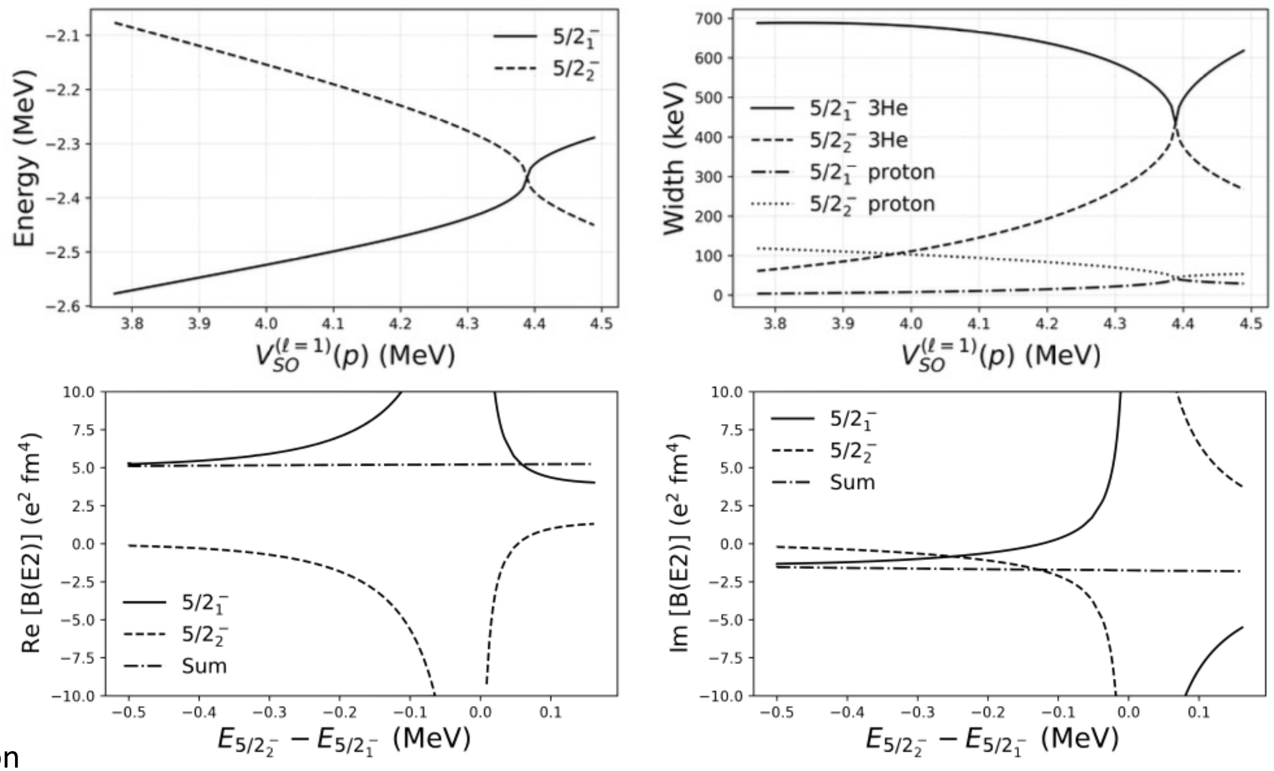


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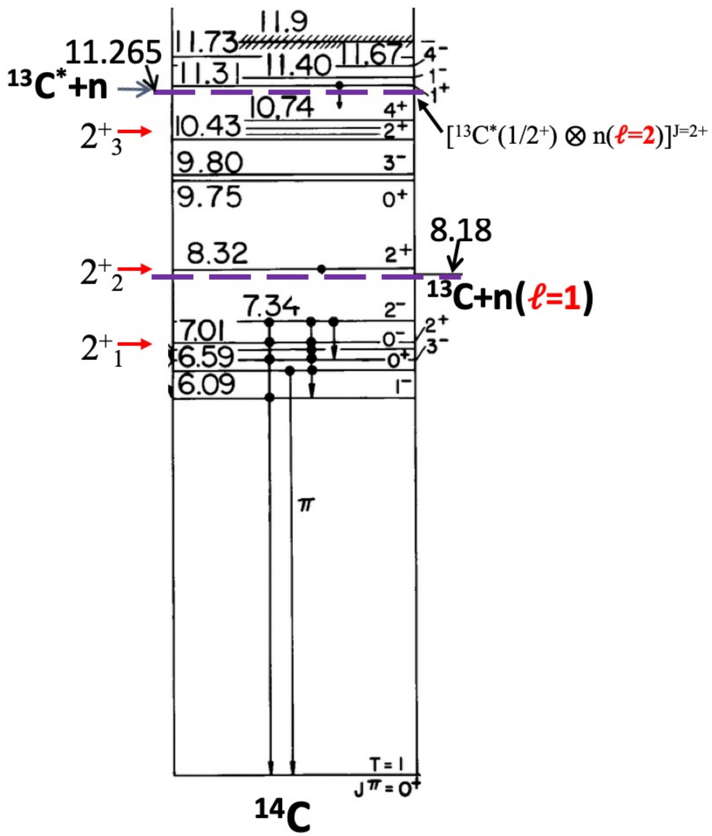
- 2D-search for EPs in the plane $\boldsymbol{\nu}V_{so}$ - $\boldsymbol{\pi}V_{so}$ for l=1

- Contrary to microwave or atomic physics experiments, the EPs in nuclear physics cannot be found but their influence on observables can be studied experimentally

D. Cardona Ochoa et al., arXiv:2510.27293

# Near-threshold states and origin of clustering

Near-threshold collectivization: $\gamma$-transitions in $^{14}C$

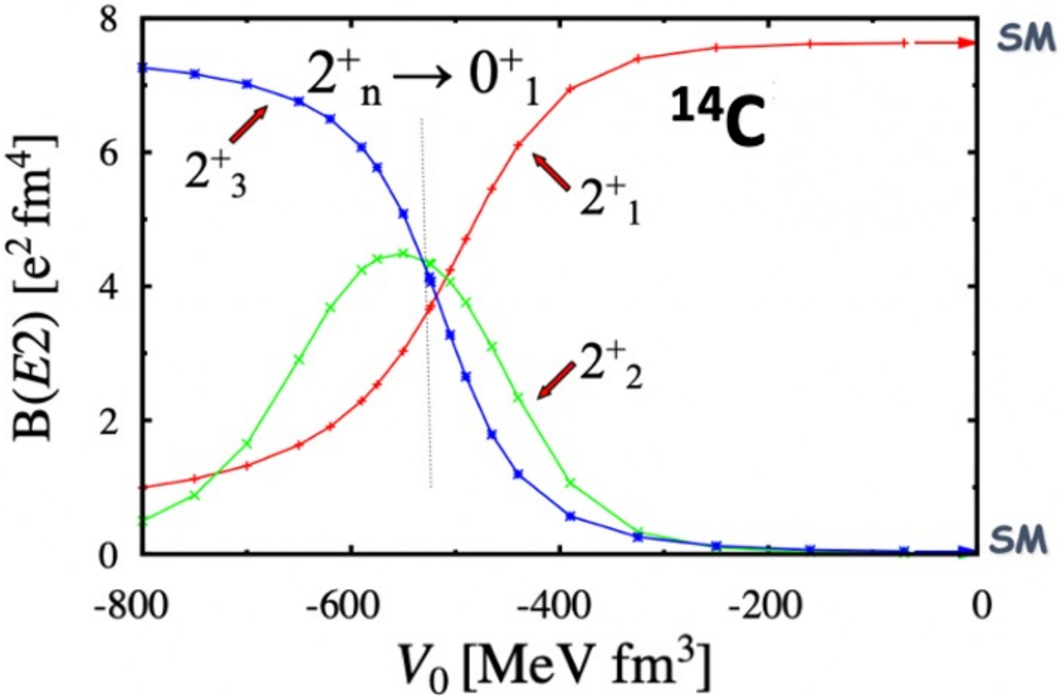



$[^{13}C(1/2^-) \otimes n(\ell=1)]^{J=2+}$

$[^{13}C(K^\pi) \otimes n(\ell_j)]^J$

$K^\pi=1/2^+_1, 3/2^-_1, 5/2^+_1, 5/2^+_2, 3/2^+_1, 7/2^+_1, 5/2^-_1, 3/2$

M. Płoszajczak and J. Okołowicz, J. Phys.Conf. Ser. 1643, 012156 (2020)

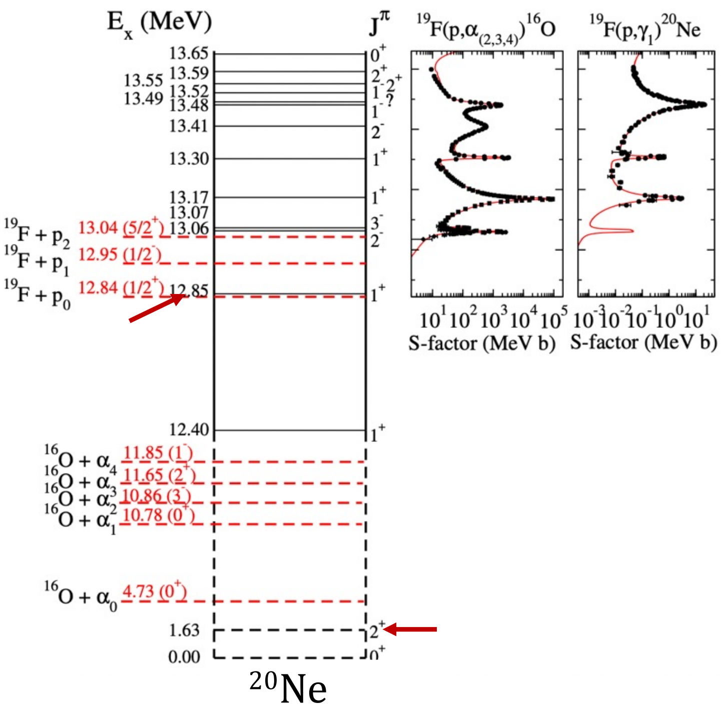


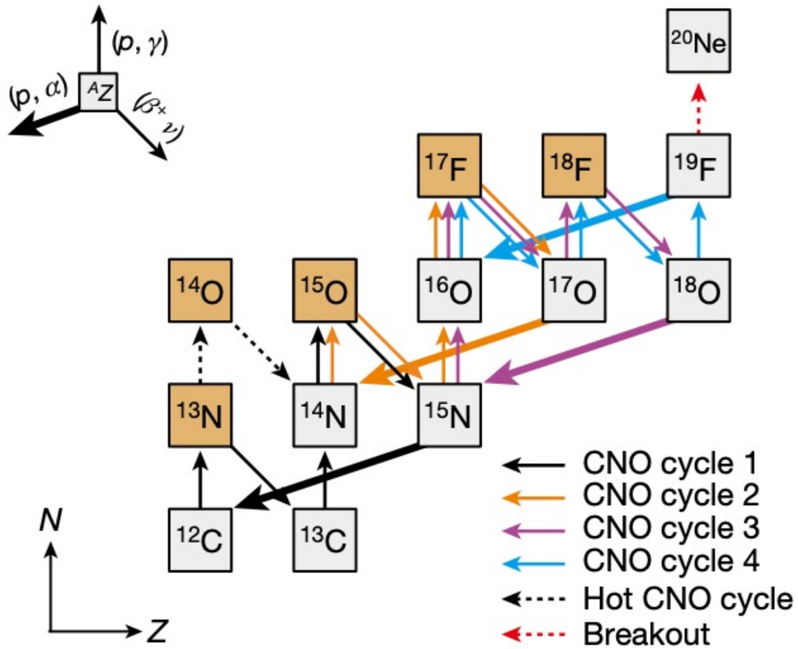

Strong collectivization of B(E2)[$0^+_1 \rightarrow 2^+_2$]
due to the nearby exceptional point

# Near-threshold states and origin of clustering

## Threshold states in nuclear astrophysics

R.J. DeBoer et al, Nature 610, 656 (2022)



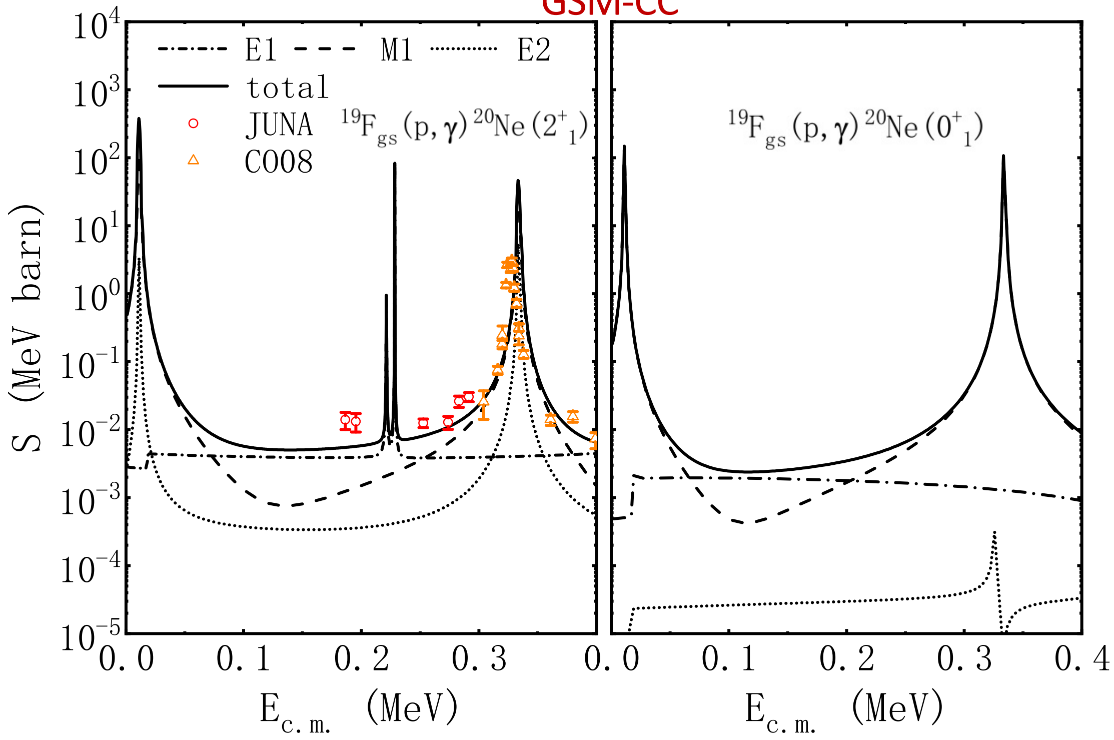

Liyong Zhang et al., Nature 610, 656 (2022)

What is the effect of $1^+$ resonance at ~10 keV above the proton emission threshold on the S-factor?

# Near-threshold states and origin of clustering

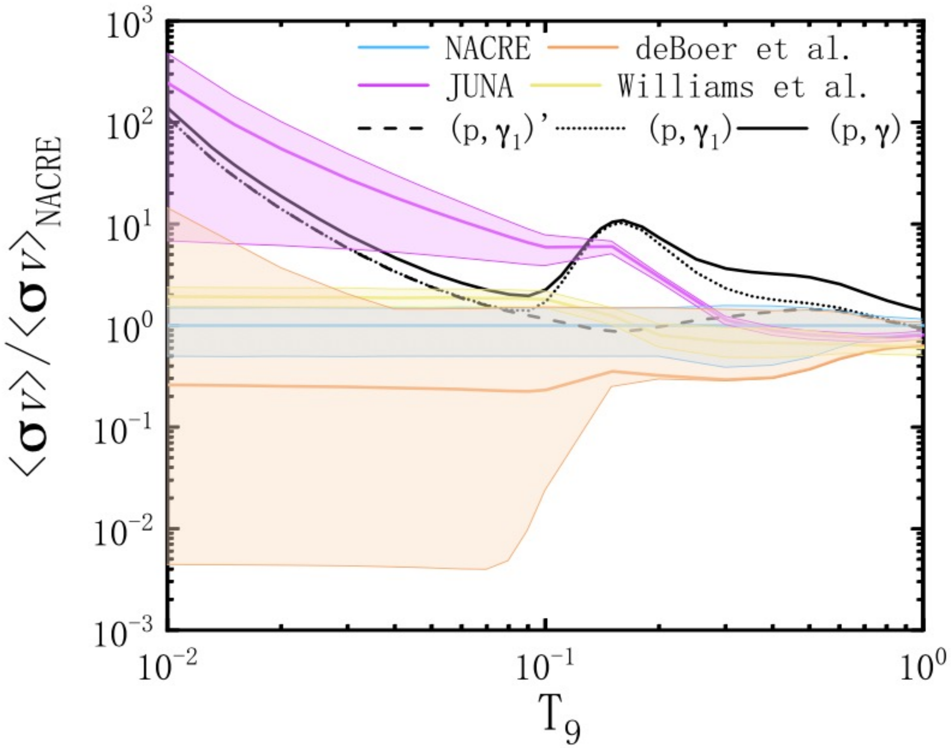
## Threshold states in nuclear astrophysics

GSM-CC




Exp: Liyong Zhang et al., Nature 610, 656 (2022)

Exp: Liyong Zhang et al., Nature 610, 656 (2022)



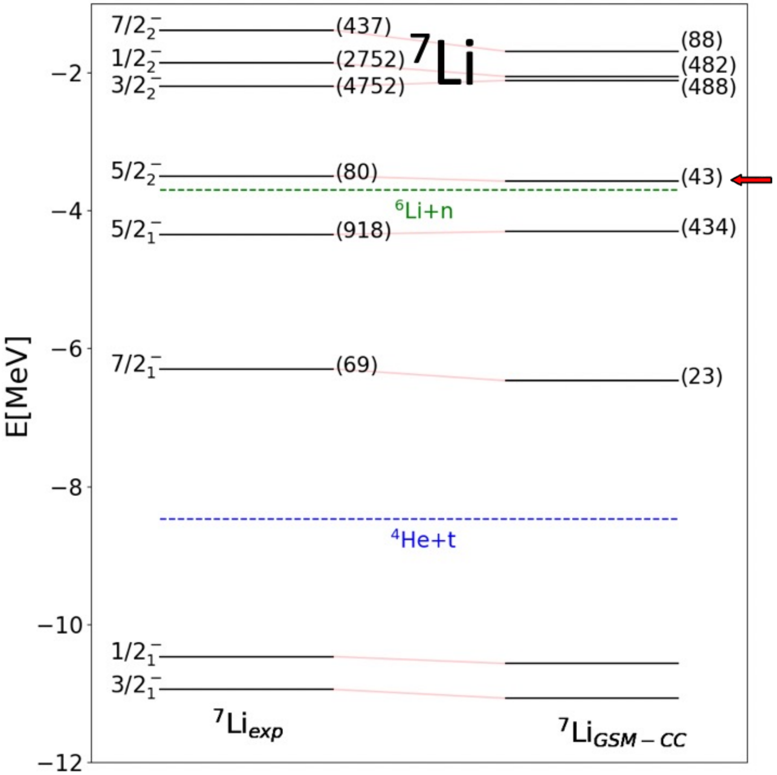

- The decay to the 2+ first excited state in $^{20}$Ne dominates

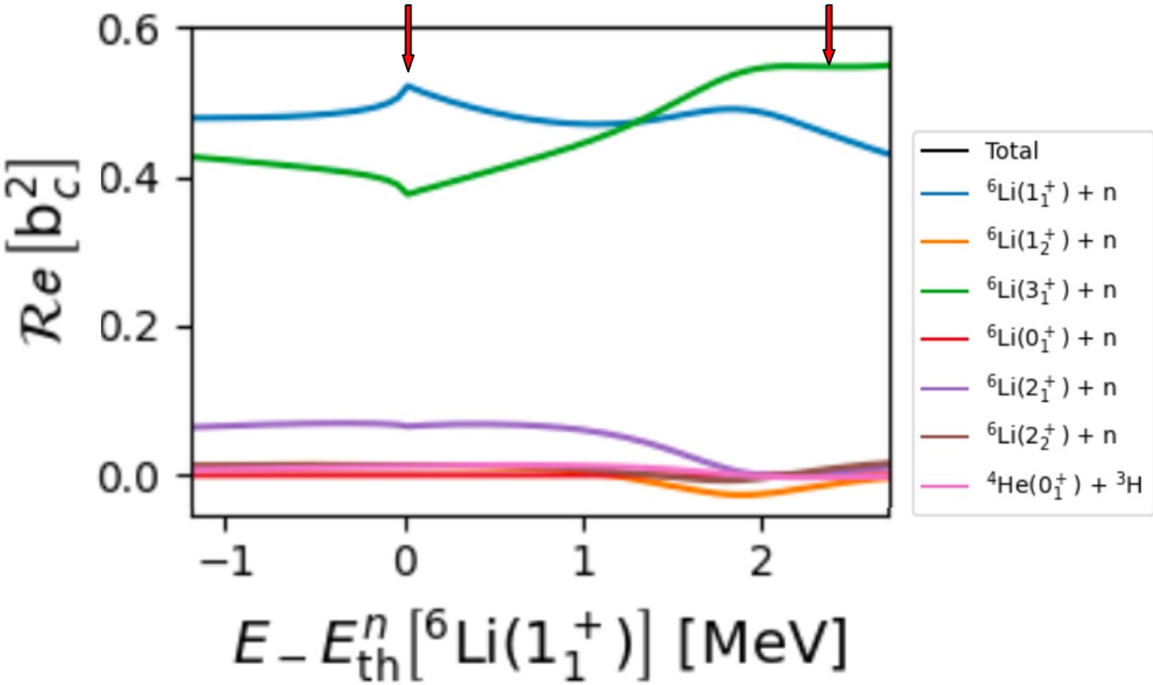
X.B. Wang, et al, Phys. Rev. C 110, L061601 (2024)

- GSM-CC reaction rate is significantly larger than that given in NACRE database and close to that of JUNA data

# Near-threshold states and origin of clustering

Mimicry mechanism in resonances




$[|^4\mathrm{He}\rangle \otimes |^3\mathrm{H}\rangle], [|^6\mathrm{Li}\rangle \otimes |n\rangle]$

- Hamiltonian: 1-body potential, 2-body FHT interaction
  $^3$H wave functions calculated using N$^3$LO$_{(2\text{-body})}$ interaction

- Structure of the resonance w.f. changes with changing energy as a result of the alignment (*mimicry*) with the nearby reaction channel

J.P. Linares Fernandez, et al, Phys. Rev. C 108, 044616 (2023)

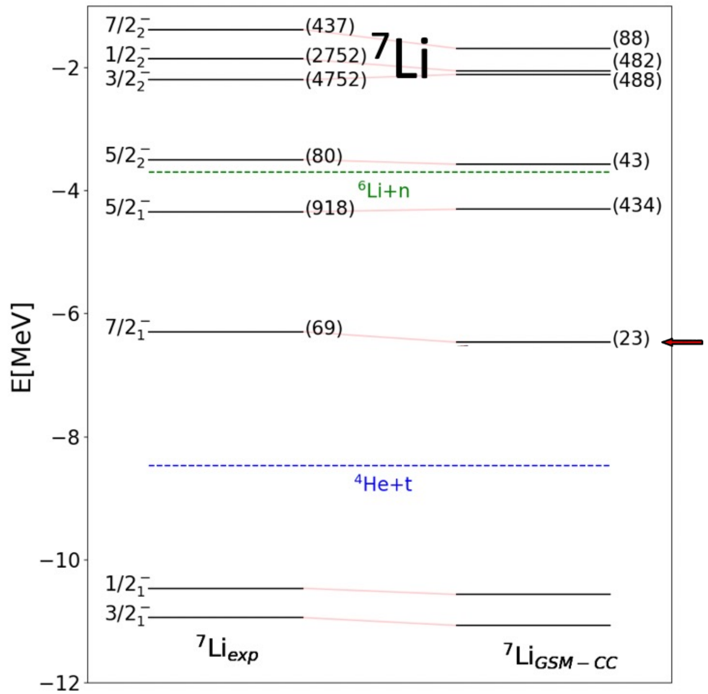
# Near-threshold states and origin of clustering

## Rise and fall of clustering in $^7$Li

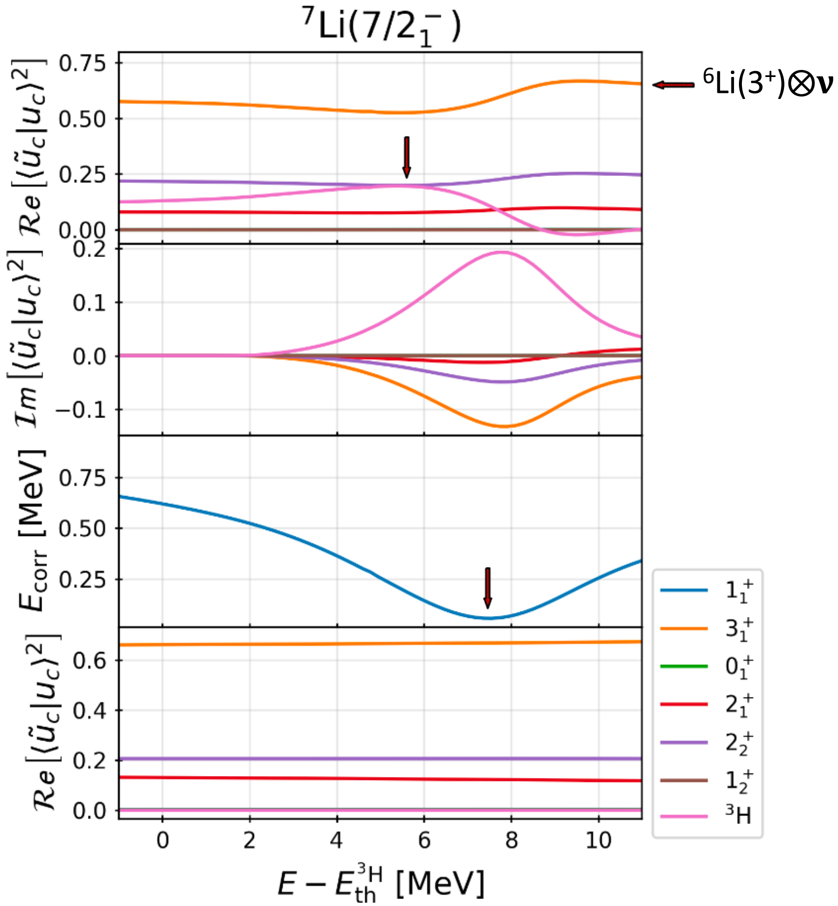
Continuum coupling correlation energy

$$E^{(\mathrm{corr})}_{J^\pi,M} = \langle \tilde{\Psi}^J_M | H | \Psi^J_M \rangle - \langle \tilde{\Phi}^{J;(\alpha)}_M | H | \Phi^{J;(\alpha)}_M \rangle \equiv \mathcal{E}_{J^\pi,M} - \mathcal{E}^{(\alpha)}_{J^\pi,M}$$

$$|\Phi^{J;(\alpha)}_M\rangle = \sum_{\mathrm{c;c}\neq\alpha} \int_0^{+\infty} |(\mathrm{c},r)^J_M\rangle \, \frac{\bar{u}^{JM}_{\mathrm{c}}(r)}{r} r^2 \, dr$$




$[|^4\mathrm{He}\rangle \otimes |^3\mathrm{H}\rangle], [|^6\mathrm{Li}\rangle \otimes |\mathrm{n}\rangle]$




- Strong influence of the *centrifugal barrier ($\ell$=3)* on alignment and on $^3$H-clusterization

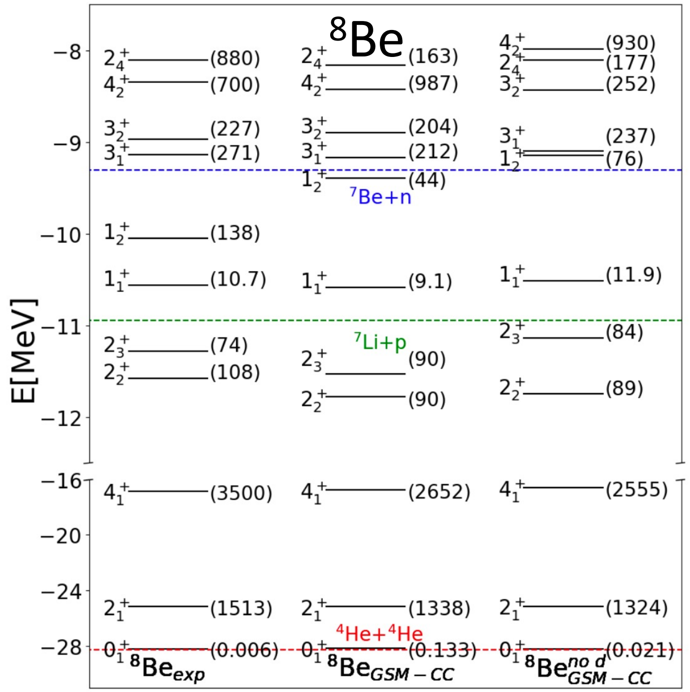
# Near-threshold states and origin of clustering

## Rise and fall of α-clustering in $^8$Be

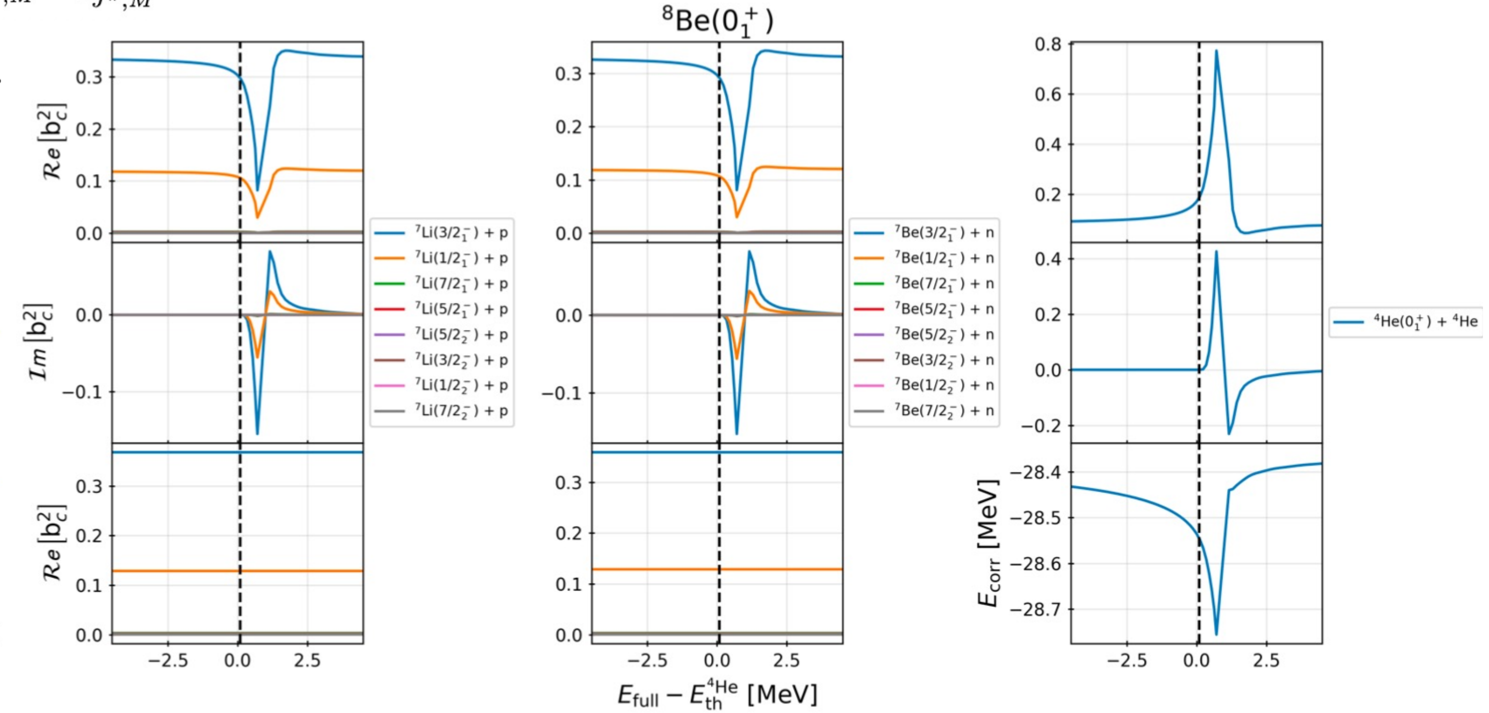
Continuum coupling correlation energy

$$E^{(\mathrm{corr})}_{J^\pi,M} = \langle \tilde{\Psi}^J_M | H | \Psi^J_M \rangle - \langle \tilde{\Phi}^{J;(\alpha)}_M | H | \Phi^{J;(\alpha)}_M \rangle \equiv \mathcal{E}_{J^\pi,M} - \mathcal{E}^{(\alpha)}_{J^\pi,M}$$

$$|\Phi^{J;(\alpha)}_M\rangle = \sum_{\mathrm{c;c}\neq\alpha} \int_0^{+\infty} |(\mathrm{c},r)^J_M\rangle \frac{\bar{u}^{JM}_{\mathrm{c}}(r)}{r} r^2 \, dr$$




$[|^4\mathrm{He}\rangle \otimes |^4\mathrm{He}\rangle]$, $[|^7\mathrm{Li}\rangle \otimes |\mathrm{p}\rangle]$, $[|^7\mathrm{Be}\rangle \otimes |\mathrm{n}\rangle]$, $[|^6\mathrm{Li}\rangle \otimes |\mathrm{d}\rangle]$




Near-threshold clustering is the *emergent phenomenon* in SM for open quantum systems

J.P. Linares Fernandez, et al, Phys. Rev. C 108, 044616 (2023)

# Message to take

- Near-threshold eigenstates of open quantum systems have unique properties which distinguish them from eigenstates of well-bound closed quantum systems

  The richness of nuclear interaction and the existence of nucleons in two distinct states (proton/neutron) make studies on the near-threshold phenomena in atomic nucleus unique

- Near-threshold phenomena are *terra incognita* of nuclear physics:
  - Collectivization of wave functions due to the coupling to decay channel(s)
  - $\gamma$-selection rules for in- and out-band transitions in resonance bands
  - Coupling of collective and single-particle motion in the continuum
  - Violation of mirror symmetry/isospin symmetry
  - Formation of clusters/correlations which carry an imprint of nearby decay channel(s) : $^{2}$H, $^{3}$H, $^{3}$He, $^{3}$n, $^{4}$n, …
  - NN interaction/spectroscopic factors
  - Effects of coalescing resonances in nuclear spectroscopy and reactions
  - … …

  Essential role of *unitarity* !

- Deeper understanding of near-threshold phenomena will help to define new territory of nuclear spectroscopy studies

Special thanks:

| | | |
|---|---|---|
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Thank You