Continuum shell model for nuclear structure and reactions

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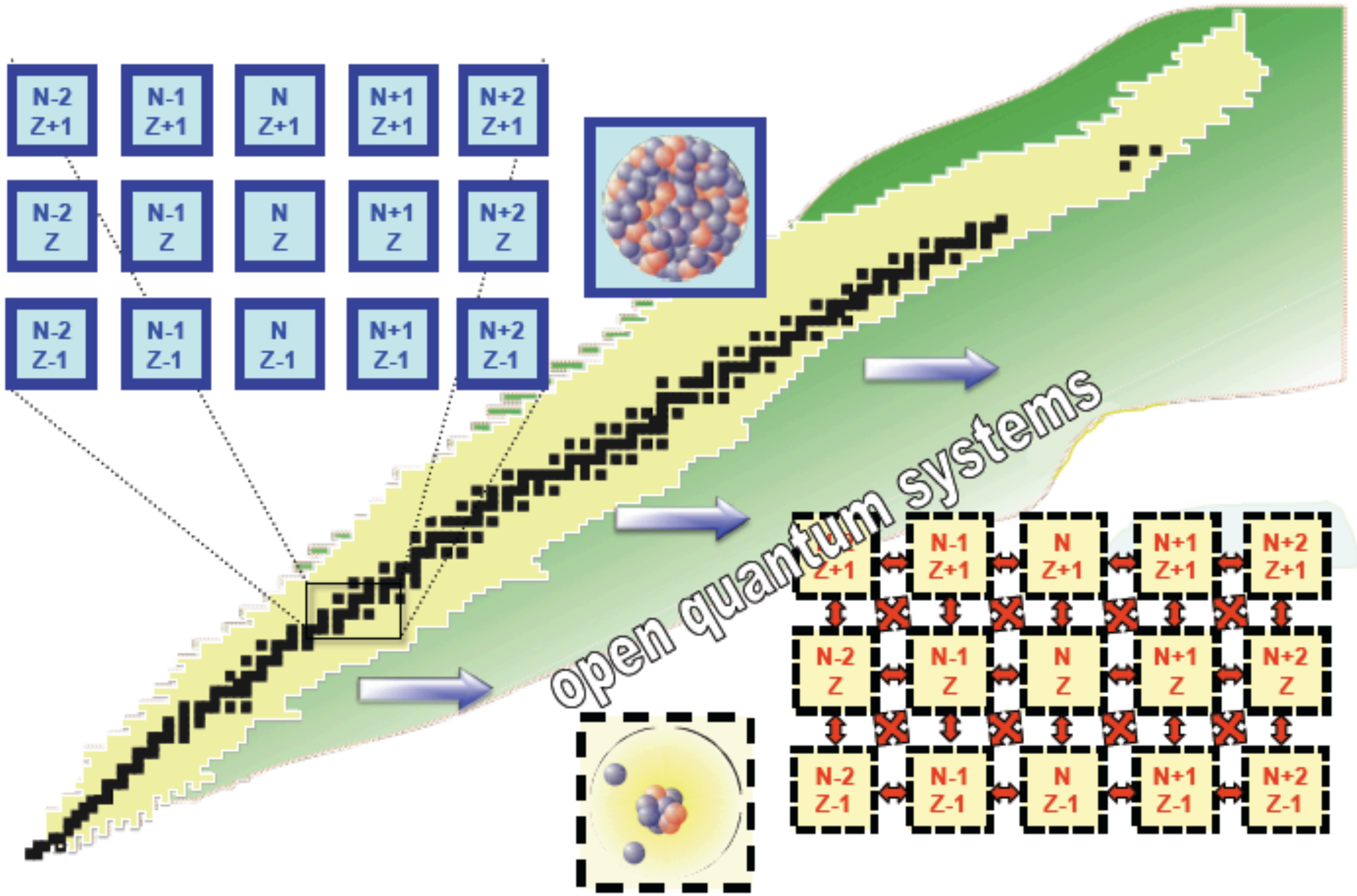
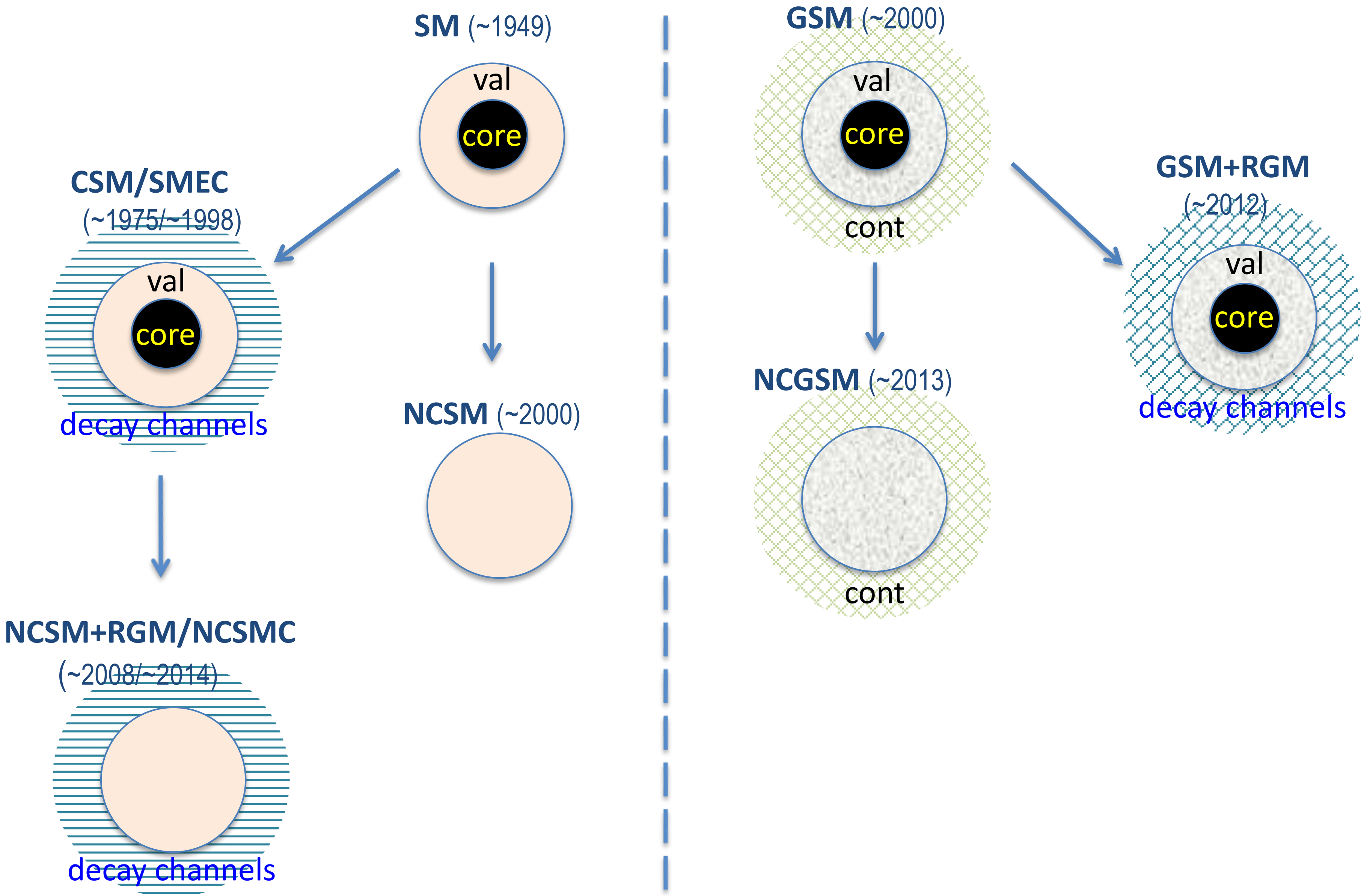


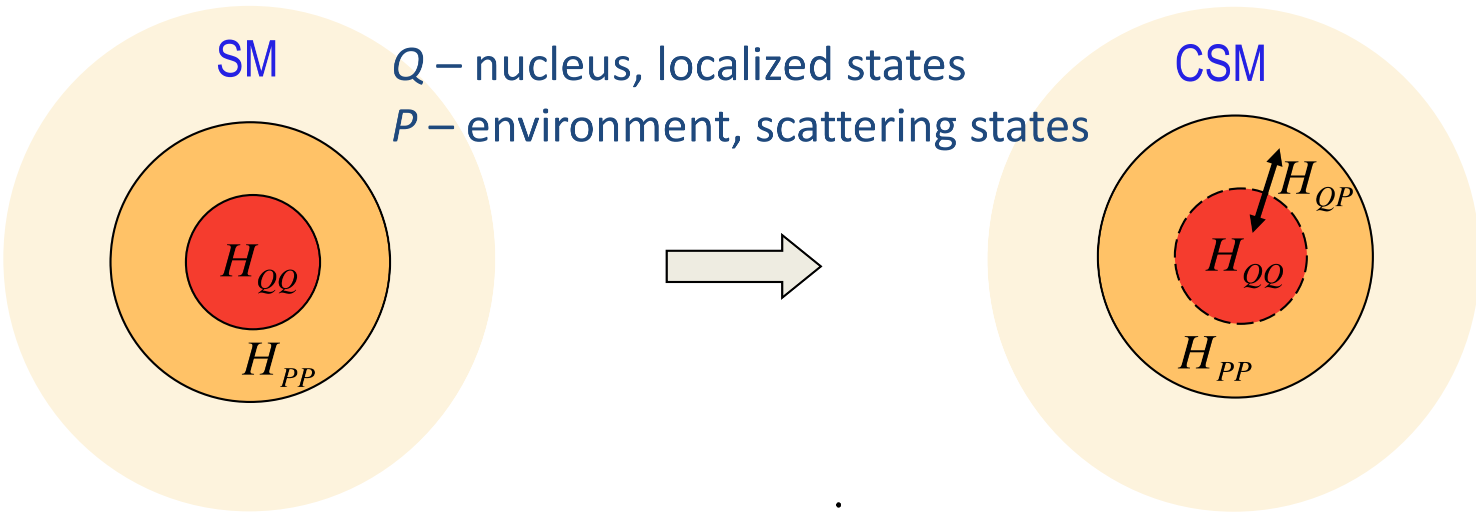
- Network of many-body states coupled via the continuum
- Nuclear structure and reactions merge

How to describe the configuration interaction in open quantum systems?

Evolution of paradigms



Shell Model Embedded in the Continuum (SMEC)



$$H_{QQ} \rightarrow \mathcal{H}_{QQ}^{eff}(E) = H'_{QQ}(E) - \frac{i}{2} V(E) V^{T}(E)$$

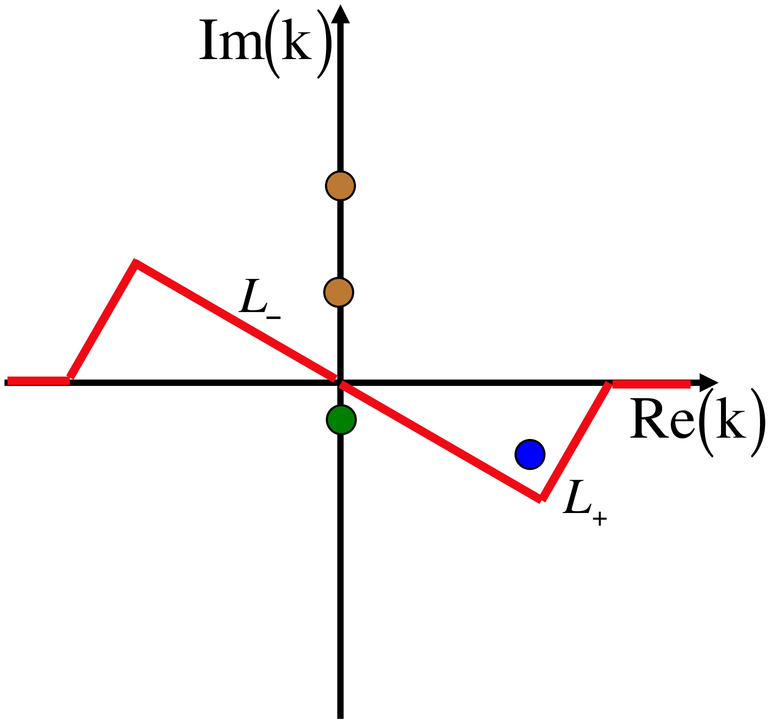
closed quantum system

$$= \underbrace{H_{QQ}^{(SM)} + u_{QQ}(E)}_{\text{hermitian}} - \underbrace{\frac{i}{2} w_{QQ}(E)}_{\text{anti-hermitian}}$$

open quantum system

- Shell model and reaction theory reconciled
- Coupling of 'internal' (in Q) and 'external' (in P) states induces effective A-particle correlations

Gamow Shell Model: First consistent formulation of Shell Model



$$H \to [H]_{ij} = [H]_{ji}$$

Complex-symmetric eigenvalue problem for hermitian Hamiltonian

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

bound states resonances

non-resonant continuum

$$|SD_i\rangle = |u_{i_1} \ldots u_{i_A}\rangle \rightarrow \sum_k |SD_k\rangle\langle\widetilde{SD}_k| \cong 1$$

↓

Gamow Shell Model

N. Michel et al, PRL 89 (2002) 042502
R. Id Betan et al, PRL 89 (2002) 042501
N. Michel et al, PRC 70 (2004) 064311

No identification of reaction channels
→ GSM in this representation is a tool *par excellence* for nuclear structure studies

Coupled channel formulation of the Gamow shell model

$$|\Psi\rangle = \sum_c \int_0^\infty dr \frac{u_c(r)}{r} r^2 \hat{\mathcal{A}} |CS\rangle_c$$

⇓

GSM channel state

Channel basis: $\{c\} = \{A_T, J_T; a_P, \ell_P, J_{\text{int}}, J_P\}$

$$\hat{\mathcal{A}} |CS\rangle_c \equiv |(c,r)\rangle = \hat{\mathcal{A}} \left[|\Psi_T^{J_T}\rangle \otimes |r, \ell_P, J_{\text{int}}, J_P\rangle \right]_{M_A}^{J_A}$$

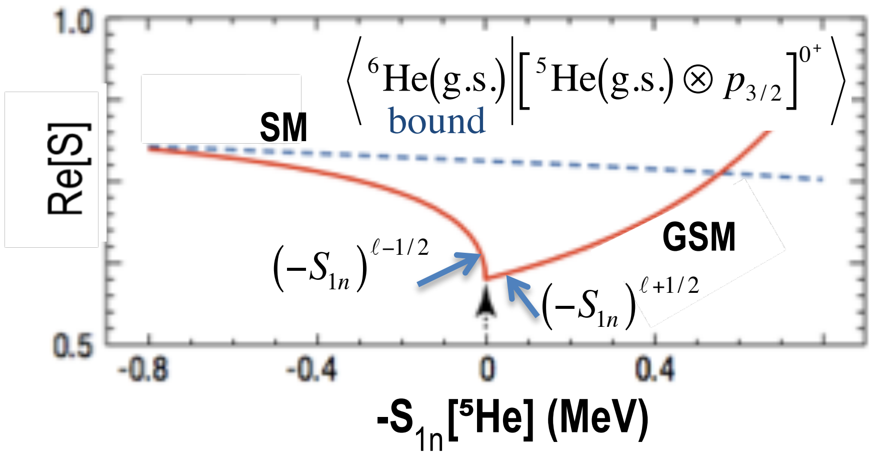
Y. Jaganathen et al, PRC 88, 044318 (2014)
K. Fossez et al., PRC 91, 034609 (2015)

- Entrance and exit reaction channels defined
- Unification of nuclear structure and reactions

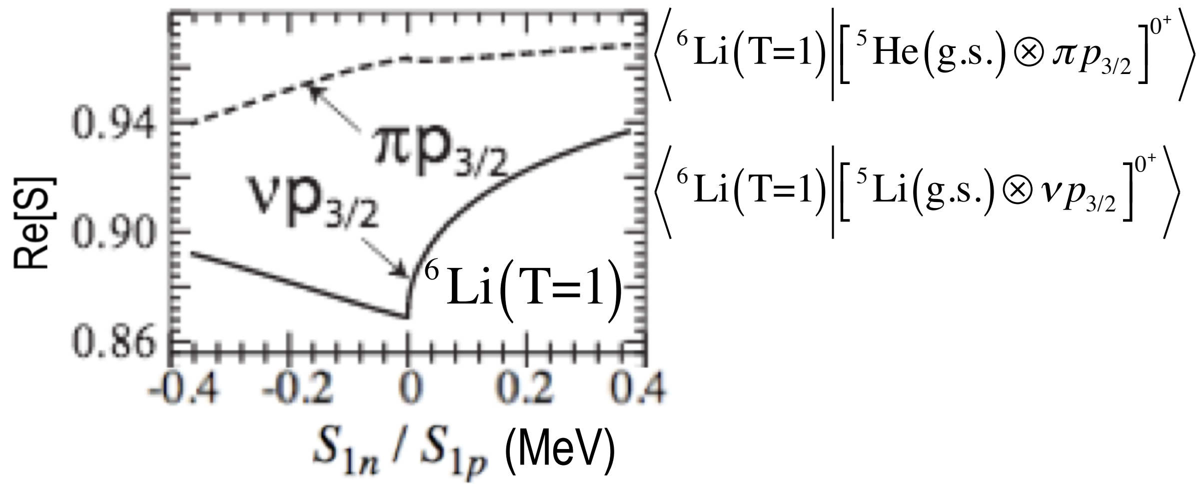
Coupling to the continuum (decay channels) does not reduce to the adjustment of (hermitian) Hamiltonian and leads to new (collective) phenomena

- resonance trapping and super-radiance phenomenon
- modification of spectral fluctuations
- multichannel coupling effects in reaction cross-sections and shell occupancies
- anti-odd-even staggering of separation energies in odd-Z isotopic chains
- clustering
- exceptional points
- violation of orthogonal invariance and channel equivalence
- matter (charge) distribution (pairing anti-halo effect)
- ….

Configuration mixing in weakly bound/unbound states



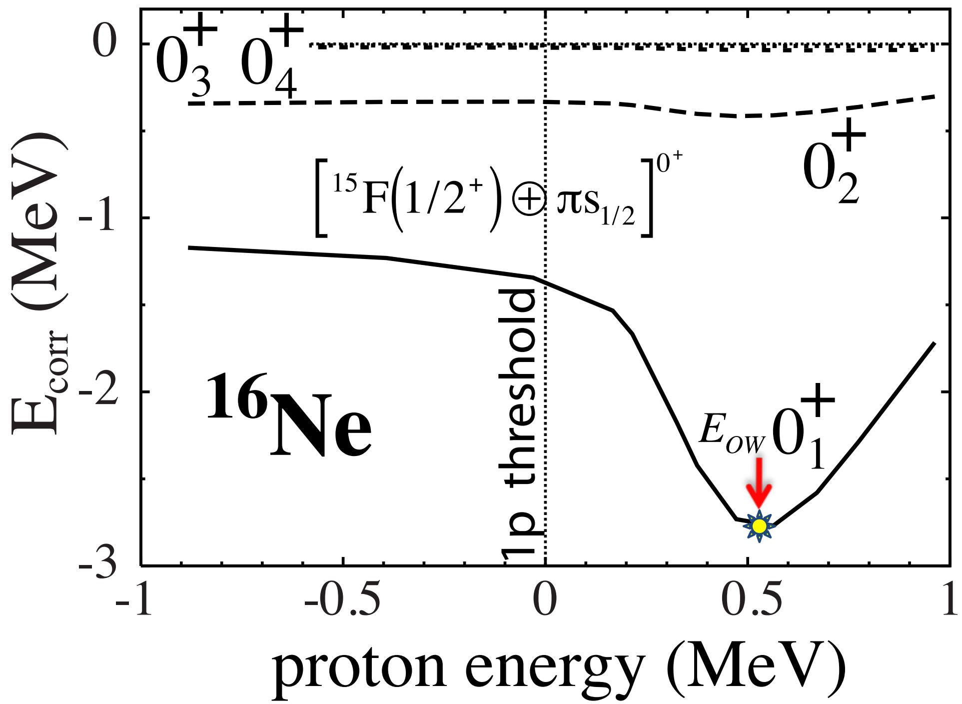
- Analogy with the Wigner threshold phenomenon for reaction cross-sections
- The interference phenomenon between resonant states and non-resonant continuum in the vicinity of the particle emission threshold



Near-threshold configuration mixing acts differently at the proton and neutron drip lines

Continuum coupling correlation energy

$$E_{corr;i}^{(\ell)}(E) = \langle \Phi_i^A | \mathcal{H}_{QQ}^{eff}(E) - H_{QQ} | \Phi_i^A \rangle$$

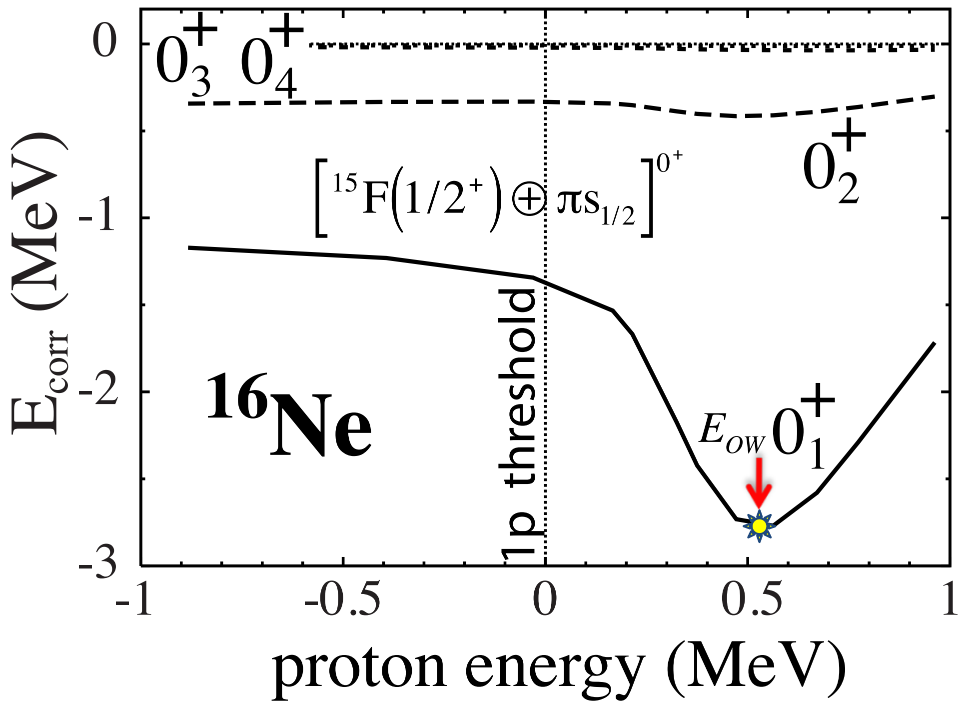


Okolowicz et al., Prog. Theor. Phys. Suppl. 196 (2012) 230
Fortschr. Phys. 61 (2013) 66

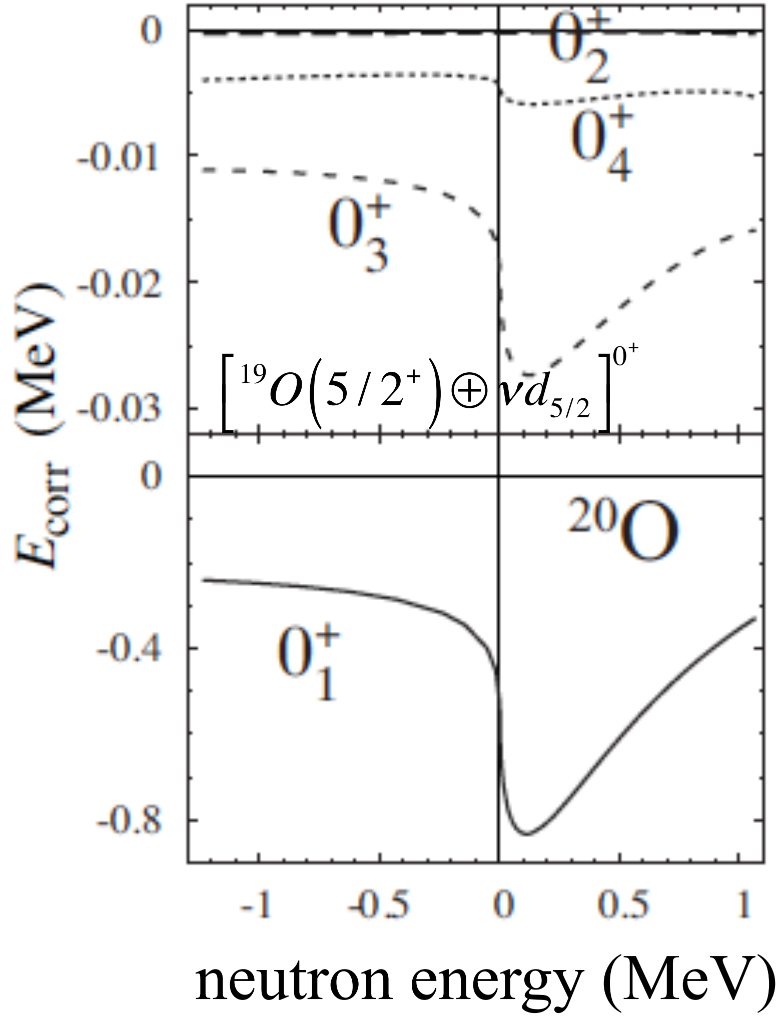
- Interaction through the continuum leads to the formation of the collective eigenstate ('aligned state') which couples strongly to the decay channel and carries many of its characteristics
- Aligned state is a superposition of SM eigenstates having the same quantum numbers

Continuum coupling correlation energy

$$E^{(\ell)}_{corr;i}(E) = \left\langle \Phi^A_i \middle| \mathcal{H}^{eff}_{QQ}(E) - H_{QQ} \middle| \Phi^A_i \right\rangle$$



Okolowicz et al., Prog. Theor. Phys. Suppl. 196 (2012) 230
Fortschr. Phys. 61 (2013) 66

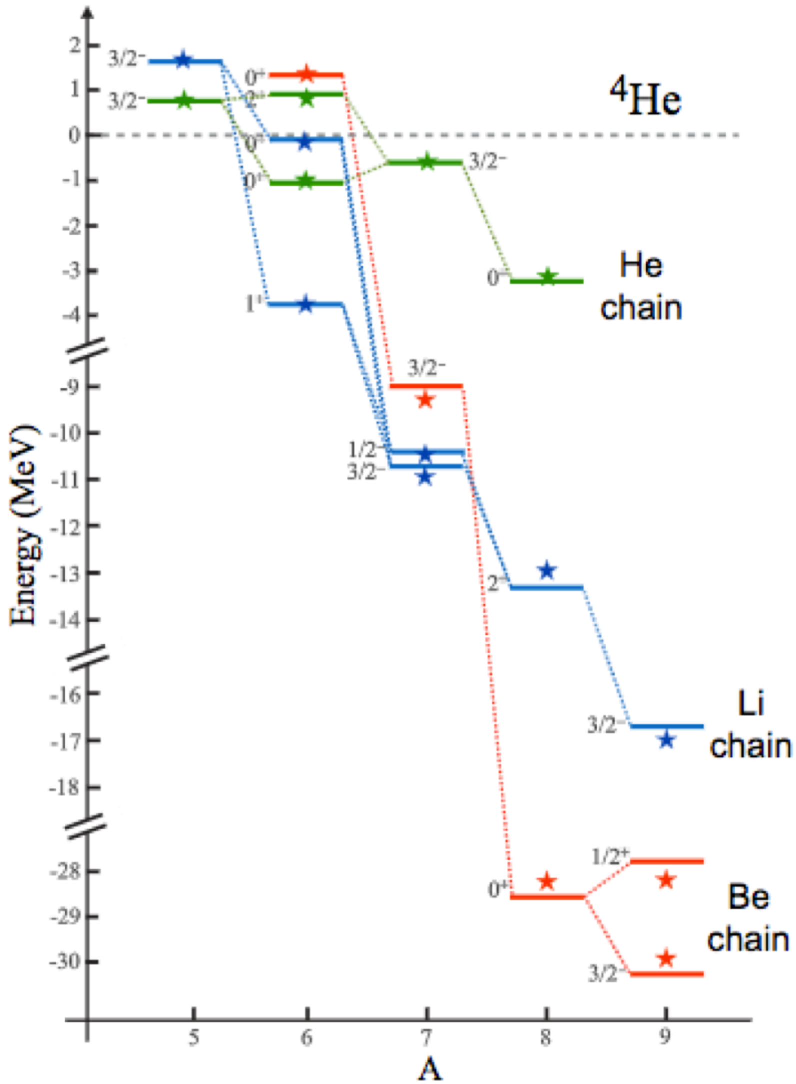


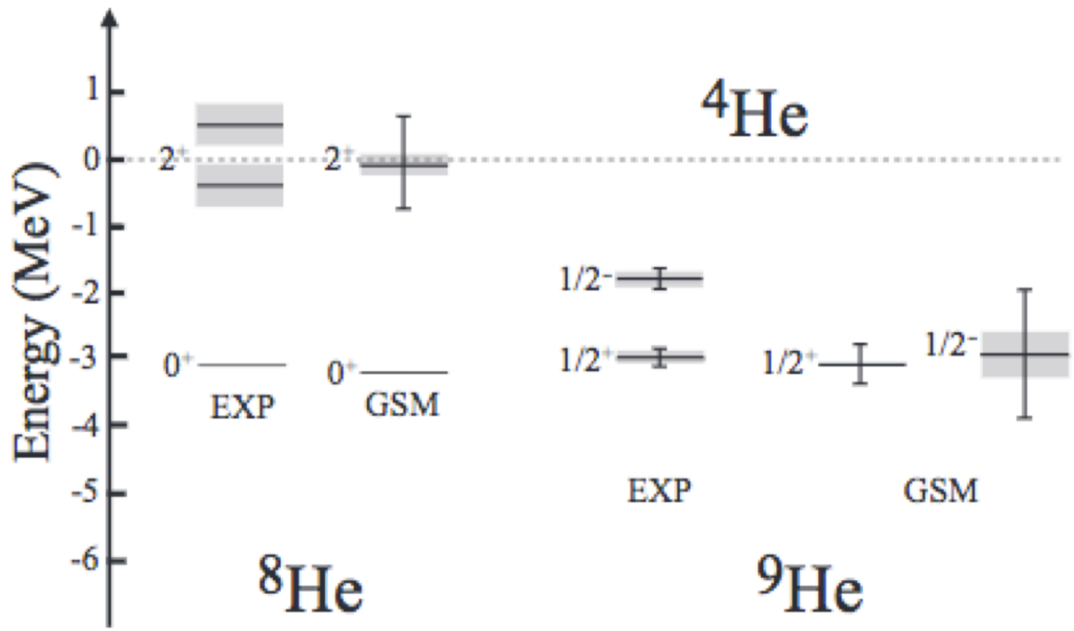
→ Emergence of new energy scale related to the external configuration mixing via decay channel(s)

→ This generic phenomenon in open quantum systems explains why so many states, both on and off the nucleosynthesis path, exist 'fortuitously' close to open channels

Nuclear structure calculations using quantified effective interaction

Optimized finite-range 2-body interaction: $V=V_c+V_{LS}+V_T+V_{Coul}$ with quantified uncertainties



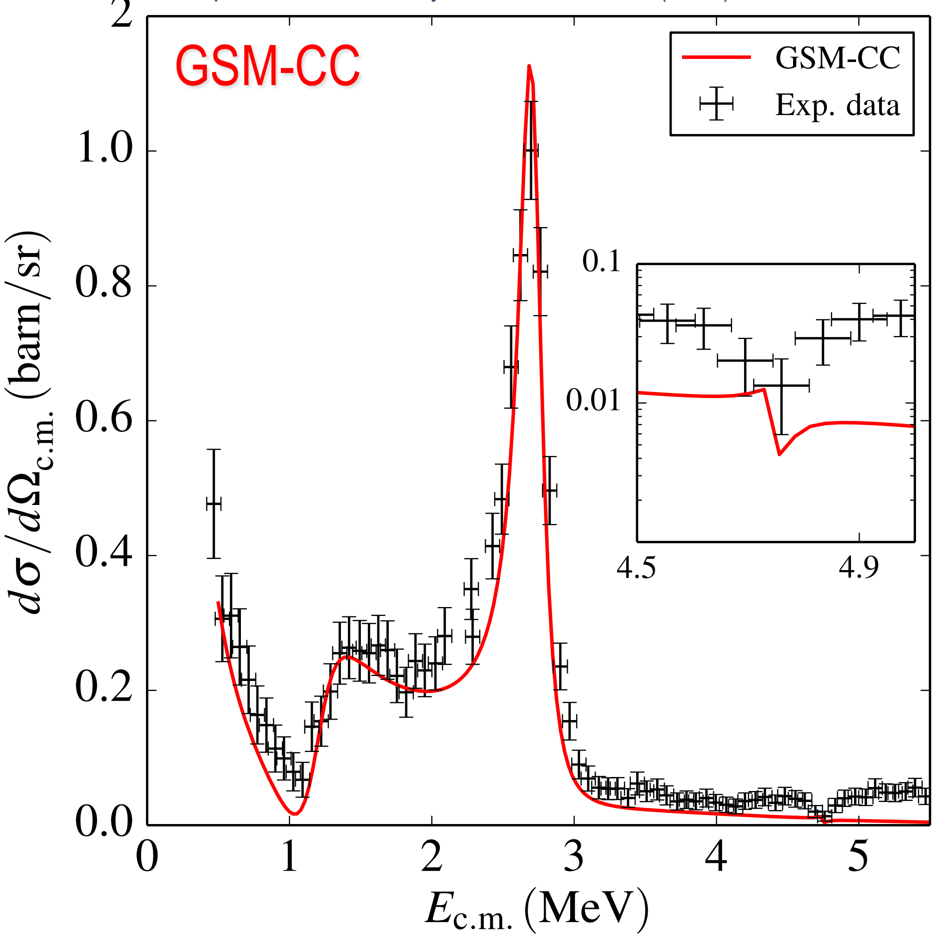


Y. Jaganathen et al., PRC 96, 054316 (2017)

Unified desciption of nuclear structure and reactions

p+^{14}O excitation function and spectroscopy of ^{15}F

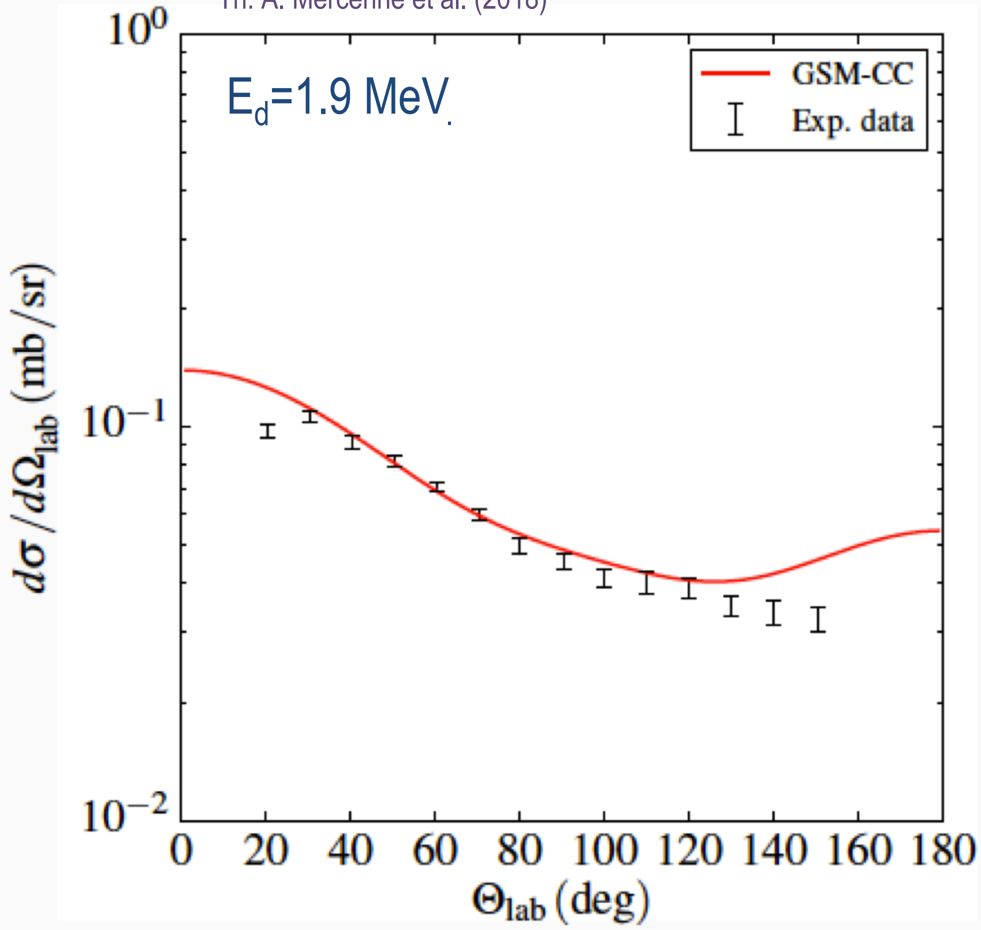
Exp/Th: F. De Grancey et al, PLB 758, 26 (2016)



^{40}Ca(d,p)^{41}Ca$_{g.s.}$ transfer cross-section and spectroscopy of ^{41}Ca and ^{41}Sc

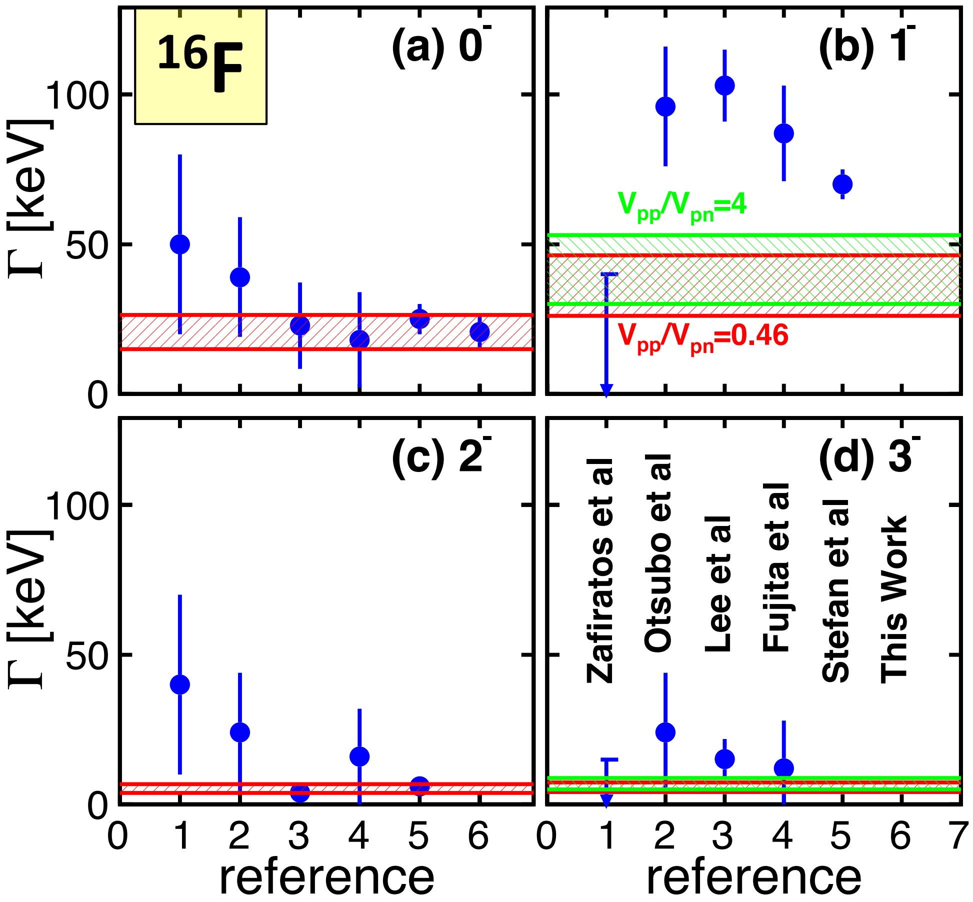
Exp: I. Fodor et al., Nucl. Phys.. 73, 155 (1965)

Th: A. Mercenne et al. (2018)



Effective interactions near drip line

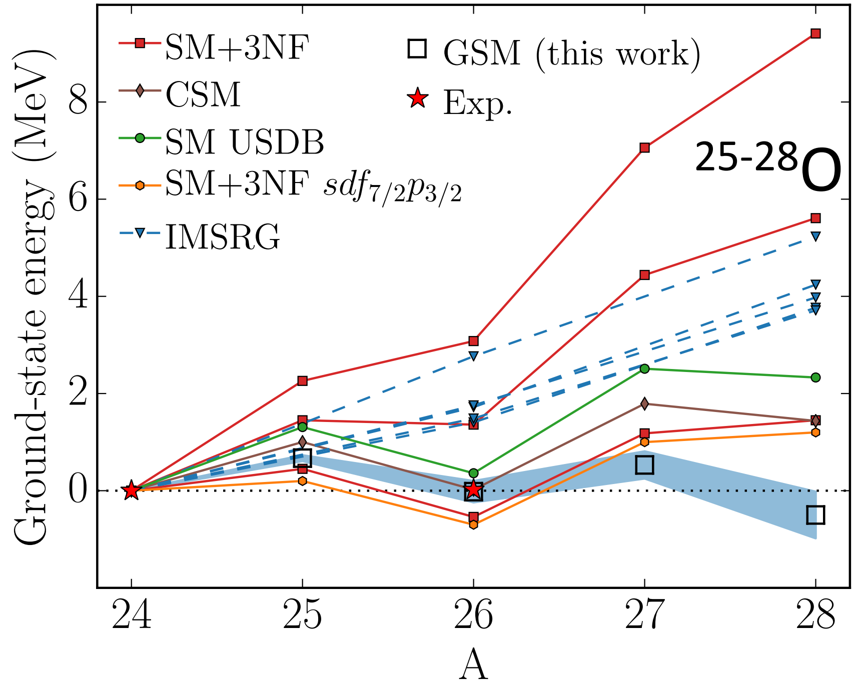
Exp/Th: R.J. Charity et al., PRC 97, 054318 (2018)
Exp: I. Stefan et al., PRC 90, 014307 (2014)



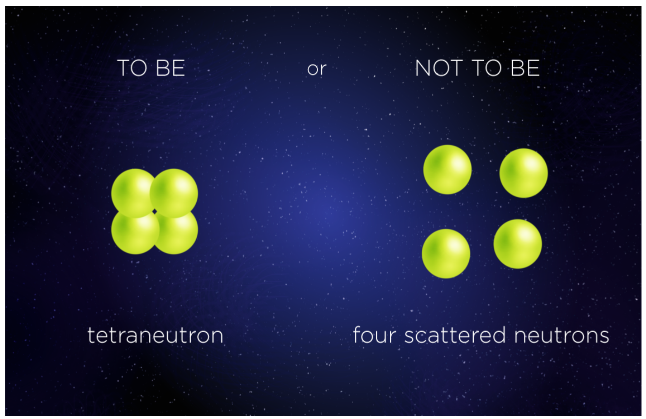
Width of resonances 0-,1-, determines the ratio V_{pp}/V_{np} in a vicinity of the proton drip line

Nuclei beyond neutron drip line

Th: K. Fossez et al., PRC 96, 024308 (2017)
Exp/Th: M.D. Jones et al., PRC 96, 054322 (2017)

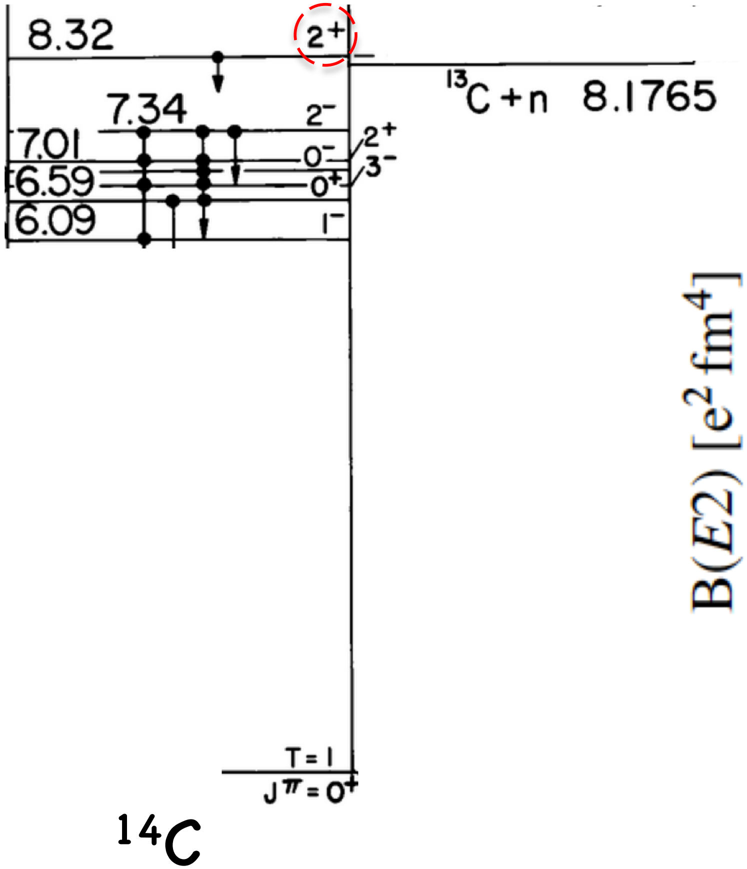


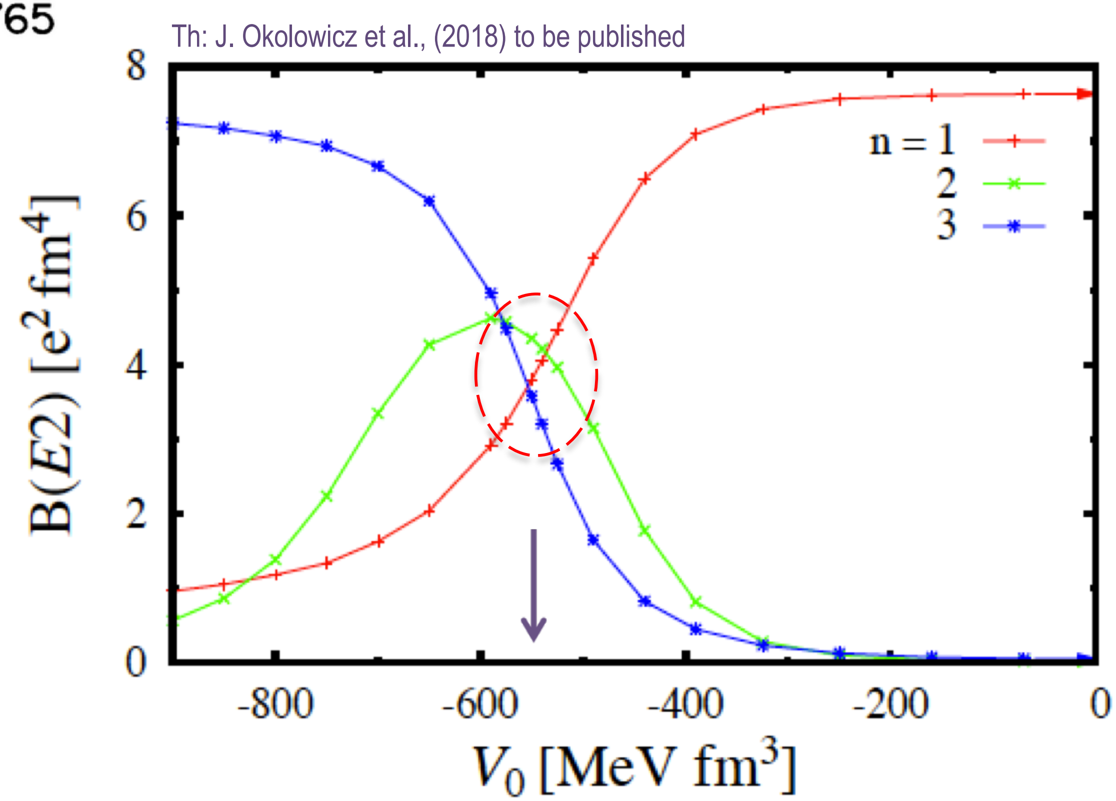
Th: K. Fossez et al., PRL 119, 032501 (2017)



http://physicsworld.com/cws/article/news/2017/jul/24/can-four-neutrons-form-a-stable-nucleus

Collectivization of electromagnetic transtions





- Strong collectivization of the B(E2) in ^{14}C from the near-threshold resonance 2^+_2 to the ground state 0^+_1
- Another example: strong collective B(E1) transition between halo state $1/2^-_1$ (S_n=181 keV) and the ground state $1/2^+_1$ in ^{11}Be

Takeaway message

- GSM and SMEC became now standard tools of analysis of weakly-bound and unbound nuclei studied experimentally worldwide

- Shell model treatment of weakly bound/unbound states → unification of nuclear structure and reactions

- Future challenges:
  - effective NN interaction in weakly-bound/unbound states
  - γ-selection rules for in- and out- band transitions in the resonance bands
  - coupling of rotational/vibrational and intrinsic motion in the continuum
  - near-threshold phenomena in γ and particle decay
  - new kinds of multi-nucleon correlations and clustering in the vicinity of particle emission thresholds
  - effects of exceptional points in nuclear spectroscopy and reactions
  - quantifiable effective interactions for sd-fp, … nuclei
  - development of GSM-CC for (α,γ) reactions of astrophysical interest
  - … …