Many-body calculations in the continuum: From four neutrons to ^{28}O

Progress in *ab initio* techniques in nuclear physics

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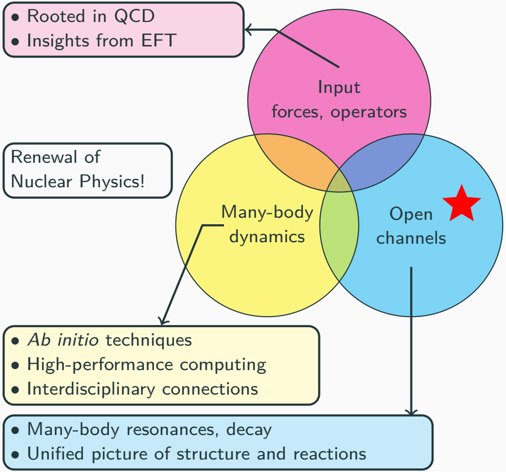
NSCL/MSU

A renewal of nuclear physics

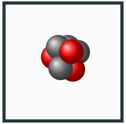
- **Technology:** detectors, electronics, Rare Isotope Beams Facilities (RIBF).
- **Computation:** power, parallelization, algorithms.
- **Theory:**
  → Effective Field Theory,
  → renormalization scheme,
  → *ab initio* methods,
  → couplings to the continuum.

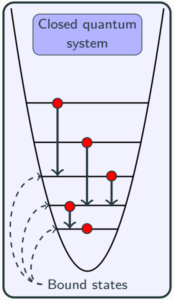
Continuum still challenging.



What is an Open Quantum System?

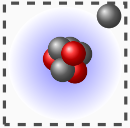
Quantum systems coupled to the environment of scattering states and decay channels.

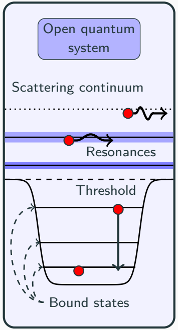




- Structure and reaction channels influence each other.
- Near-threshold effects (halos, clustering).
- Formation of many-body resonances.
- Exotic decay modes.

The continuum is essential
for the description of drip-line nuclei.





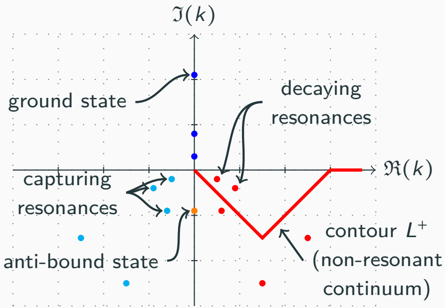
Selected challenges

- Interplay between **collectivity** and couplings to the continuum: Be, Mg chains.
- Unified description of nuclear **structure and reactions**: $^{8}\mathrm{He}(t,p)^{10}\mathrm{He}$.
- ***Ab initio*** calculations in the continuum: $^{7}\mathrm{H}$.
- **Halo** systems + collectivity: $^{11}\mathrm{Be}$, $^{37}\mathrm{Mg}$.
- Many-nucleon **decay**: $^{16}\mathrm{Be}$, $^{26}\mathrm{O}$.

Many problems can now be addressed.

- **Quasi-stationary formalism:**
  $\Phi(E,t) = \phi(t)\Psi(E)$
  + Outgoing boundary conditions.
- **Berggren basis:**

$$\sum_{n\in(b,d)} |u_l(k_n)\rangle\langle\tilde{u}_l(k_n)| + \int_{L^+_{l,j}} dk\, |u_l(k)\rangle\langle\tilde{u}_l(k)| = \hat{\mathbb{1}}.$$



Where we are in nuclear theory

Approaches divided by how the continuum is included/described:

Feshbach projection formalism

CSM, SMEC

Uniform complex-scaling

Fadeev-Yakubowski, many others*

Berggren basis + truncations in correlations

CCT/Berggren

Opportunity: IM-SRG/Berggren

- Light nuclei (*ab initio*).
- Core + about 10 nucleons.
- Closed shell ± 1 or 2 nucleons (*ab initio*).

Resonating Group Method + outgoing boundary conditions

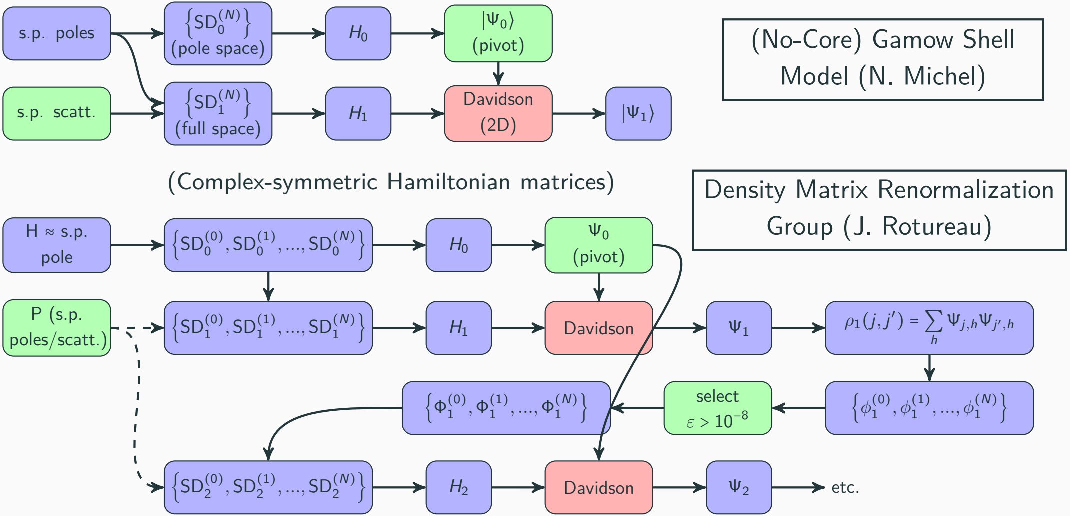
NCSM/RGM, NCSM/SS-HORSE, NCSMC, GSM/CC

Berggren basis + Configuration Interaction

GSM, NCGSM, DMRG, GSM/CC

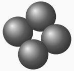
Many ongoing developments: algorithm, uncertainties, natural orbitals...

(NC)GSM vs DMRG



Can four neutrons form a nucleus?

Bound state:



- Exp. claim: ${}^{14}\mathrm{Be}^* \rightarrow {}^{10}\mathrm{Be} + {}^{4}\mathrm{n}$.

  F. M. Marqués *et al.*, PRC **65**, 044006 (2002)

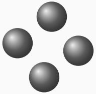
- Physics with a hammer: *ab initio* results.

  S. C. Pieper, PRL **25**, 252501 (2003)

$\rightarrow$ Bound four-neutron system ruled out.

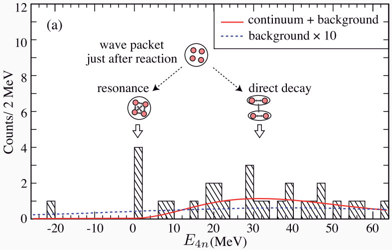
Subtle interplay between the many-body components of the nuclear interaction, the Pauli principle and the coupling to the neutron continuum.

Resonance:



- Exp. claim: ${}^{4}\mathrm{He}({}^{8}\mathrm{He}, {}^{8}\mathrm{Be})$.

  K. Kisamori *et al.*, PRL **116**, 052501 (2016)

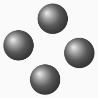


$E = 0.83 \pm 0.65$ (stat) $\pm$ 1.25 (syst) MeV

$\Gamma^{(\mathrm{max})} = 2.6$ MeV

Can four neutrons form a nucleus?

Theoretical investigations:



- Fadeev-Yakubowski + unif. cx-scaling: Resonant ^{4}n unlikely.

  E. Hiyama *et al.*, PRC **93**, 044004 (2016)

- NCSM/SS-HORSE: $E \approx 0.8$ MeV and $\Gamma \approx 1.4$ MeV

  A. M. Shirokov *et al.*, PRL **117**, 182502 (2016)

$E = 0.83 \pm 0.65$ (stat) $\pm$ 1.25 (syst) MeV

$\Gamma^{(max)} = 2.6$ MeV

- Monte Carlo calculations: $E \approx 1.8$ MeV and $\Gamma \approx 0.3$ MeV

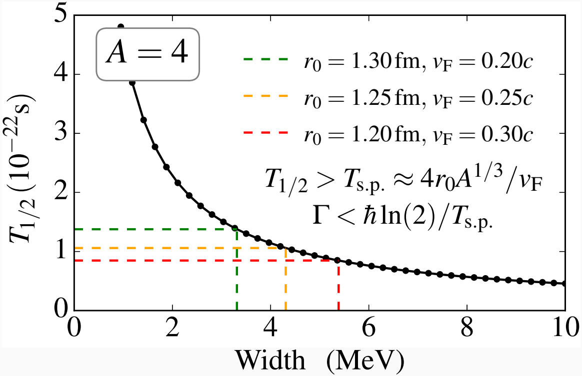
  S. Gandolfi *et al.*, arXiv:1612.01502

⇒ No influence of 3-body forces.

→ Most suitable approach for this problem in E. Hiyama *et al.*, suggests a very large width ($\Gamma \approx 6$ MeV), but no EFT interaction.

Need for a full continuum approach with EFT interactions.

Nucleus *vs.* reaction process:



How much times does a nucleon need to start from one side of the nucleus, go to the other side and come back?

- One must have: $T_{1/2} > T_{s.p.}$ to have a nucleus.
- $\Gamma = (\hbar \ln(2))/T_{1/2}$ is convexe, small variations on $T_{1/2}$ gives large variations on Γ.

→ No clear limit, but $\Gamma < 3\,\mathrm{MeV}$ is rather safe (for $A = 4$, using a crude argument).

Methods:

- NCGSM (N. Michel), DMRG (J. Rotureau).
- 2-body forces, continuum, *ab initio*.
- Natural orbitals.
- Broad resonance "tracing".

Model space:

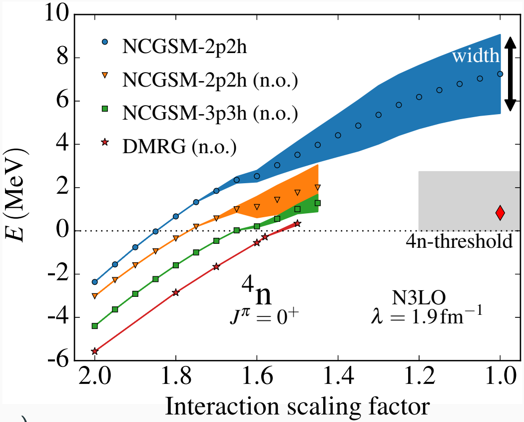
- Two poles: $0s_{1/2}$ and $0p_{3/2}$ (WS).
- Continua for s and p waves (45-45-30 states)
- HO states for d, f and g waves (7, $b = 2\,\text{fm}$).
- Several contours and basis tested.

→ Results independent of the interaction.

→ Rapid grow of the width ($\Gamma \approx 6\,\text{MeV}$ at 2p2h...).

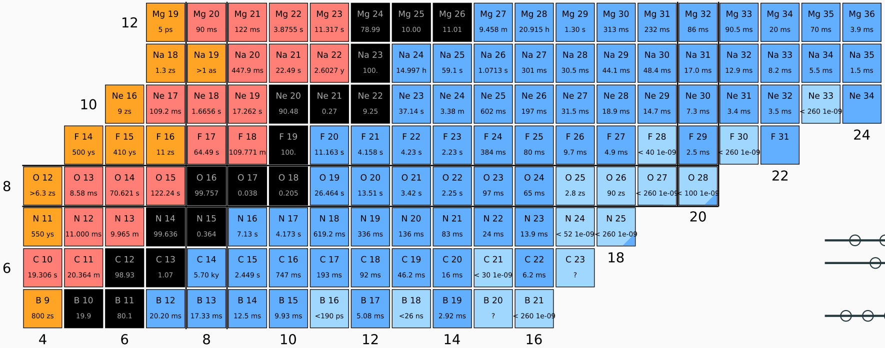
→ Energy mismatch with Exp.?

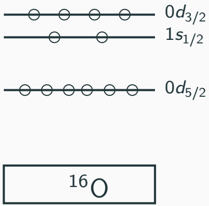
Preliminary results:



Neutron-rich oxygen isotopes

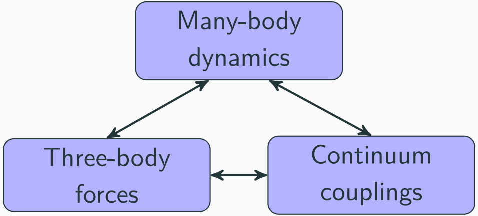
Is ^{28}O bound or unbound?



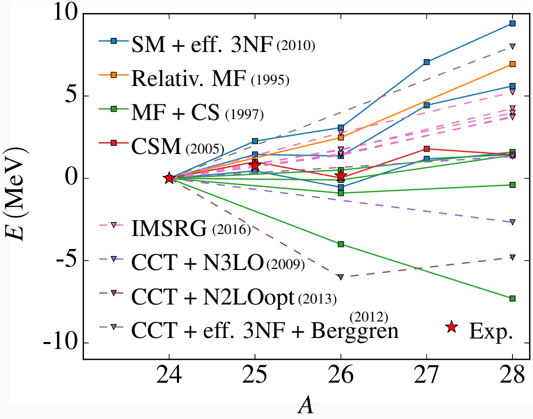


- ^{24}O bound, ^{25}O unbound and ^{26}O barely unbound.
- A bound ^{28}O nucleus is excluded from previous experiments, but no direct observation.

What theory says on neutron-rich oxygen isotopes: Everything.



- *Ab initio* results not better than models for these systems.
- Need for an approach with a better balance between the main ingredients.



→ Core + two-body interaction locally fitted + GSM.

Description of neutron-rich oxygen isotopes

Shell model approaches have known limitations.

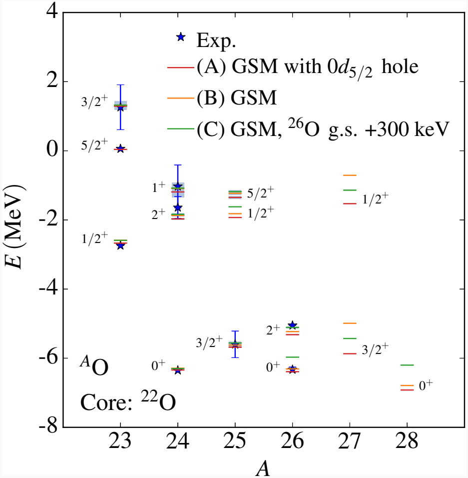
- How the choice of the core affects results?
- How reasonnable are the truncations?
- How good is the interaction?

- Introducing one hole in $0d_{5/2}$ (core):

$$\hat{H} - \hat{H}_{\text{core}} = \sum_{i=1}^{N_{\text{val}}} (\hat{t}_i + \hat{U}_i) + \sum_{i<k}^{N_{\text{val}}} \left(\hat{V}_{ik} + \frac{\hat{p}_i.\hat{p}_k}{M_{\text{core}}} \right)$$

→ Set $\hat{V}_{ik} = 0$ on $0d_{5/2}$ and remove the double-counting with $\hat{W}_i = \sum_p \hat{V}_{ip}, p \in 0d_{5/2}$:

$$\hat{H} - \hat{H}_{\text{core}} = \sum_{i=1}^{N_{\text{val}}+1} (\hat{t}_i + \hat{U}_i - \hat{W}_i) + \sum_{i<k}^{N_{\text{val}}+1} \left(\hat{V}_{ik} + \frac{\hat{p}_i.\hat{p}_k}{M_{\text{core}}} \right)$$



Description of neutron-rich oxygen isotopes

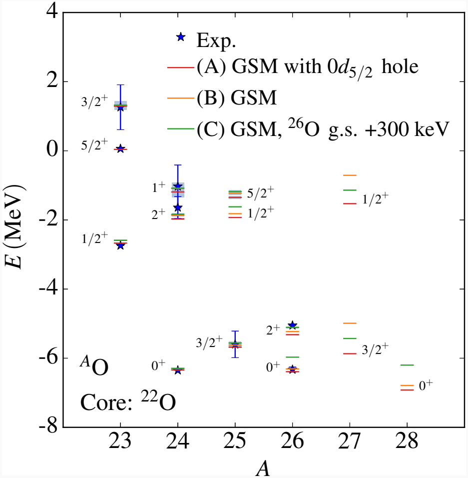
Shell model approaches have known limitations.

- How the choice of the core affects results?
- How reasonnable are the truncations?
- How good is the interaction?

- Only 3 neutrons at most in the continuum.

→ No truncations in DMRG.

Nucleus	J^π	E_{GSM}	E_{DMRG}
^{26}O	0^+	-6.31 (0)	-6.30 (0)
^{26}O	2^+	-5.23 (0.027)	-5.22 (0.01)
^{27}O	$3/2^+$	-5.76 (0.014)	-5.76 (<10 keV)
^{27}O	$1/2^+$	-1.42 (0.017)	-1.43 (<10 keV)
^{28}O	0^+	-6.79	-6.74



Description of neutron-rich oxygen isotopes

Shell model approaches have known limitations.

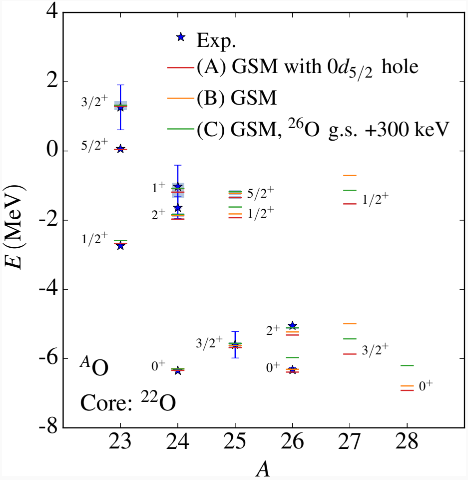
- How the choice of the core affects results?
- How reasonnable are the truncations?
- How good is the interaction?

- We have the g.s. of ^{26}O slightly bound in the original fits.

→ New fit (C) with the g.s. of ^{26}O 300 keV higher to seen the effect on ^{28}O.

→ The g.s. of ^{28}O is now slightly unbound, but still below the g.s. of ^{26}O.

→ Something is missing: 3-body forces?

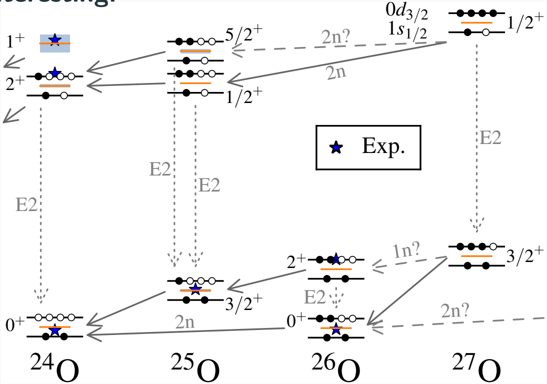


Predictions on neutron-rich oxygen isotopes

After all, ^{28}O may not be the only one interesting.

- Narrow resonances in ^{25,27}O.
- Particle-emission decay through $d_{3/2}$ waves ($\Gamma \sim 10$keV).

- M1 transitions are inexistent.
- E2 transitions ($e^n_{\mathrm{eff}} = 0.5$) are weak with B(E2) between 1.65 and 2.3 W.u. ($\Gamma \sim$ eV).

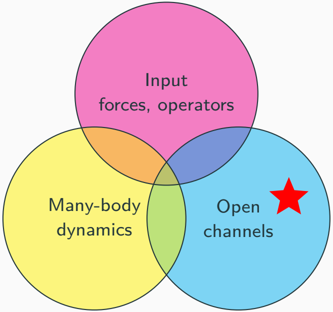


→ Many challenges for experimental studies, uncertain theoretical predictions.

Conclusion

Couplings to the continuum are an important ingredients for the description of exotic nuclei.

- The four-neutron system seems unlikely to be a genuine nucleus (from the GSM perspective), but the problem is still open.
- The g.s. of ^{28}O is expected to be a narrow resonance.



Emergence of new phenomena when couplings to the continuum are present.

Features generic to all open quantum systems, cross-fertilization with other fields.

Thank you for your attention!