Lecture I: Nuclei as (many-body) open quantum systems

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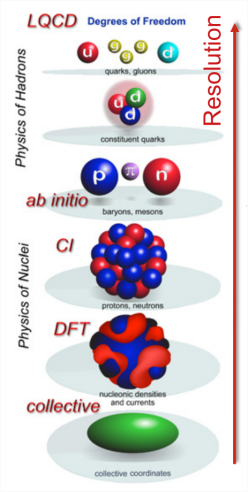
What you will learn in this lecture

How to go from nuclear structure to reactions.

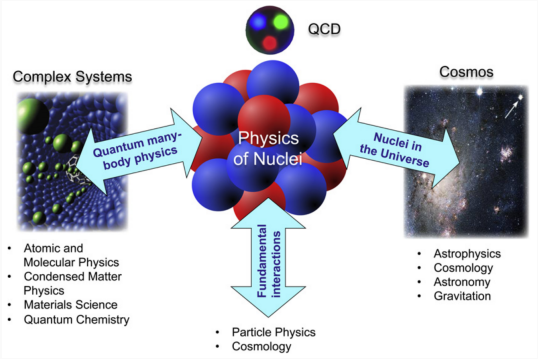
1) The nuclear problem at low energy.
2) The problem of continuum couplings.
3) Nuclei as open quantum systems.
4) Unification of nuclear structure and reactions.
5) Extending quantum many-body methods in the continuum.
6) From many-body structure to reactions observables.

The nuclear problem



- A multi-scale problem.
- At least two kinds of particles involved.
- A residual, but still strong, interaction.
- Emergent properties.

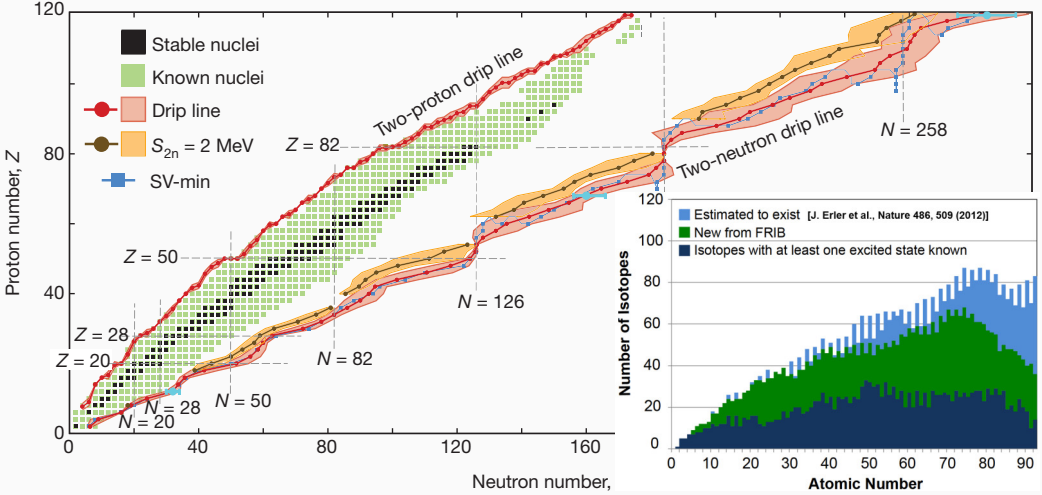
In the middle of the quantum ladder.



From W. Nazarewicz, J. Phys. G **43**, 044002 (2016)

A fundamental problem!

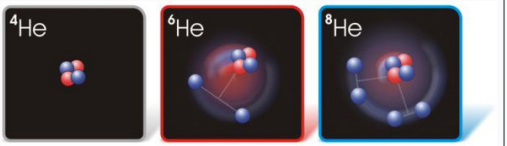
Current situation in nuclear physics



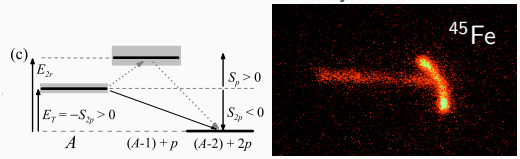
J. Erler *et al.*, Nature **486**, 509 (2012)

Intriguing phenomena at low energy

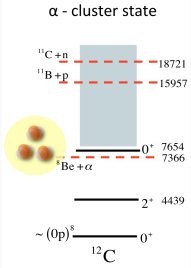
Halos, Borromean systems, neutron skin:



Two-nucleon decay:

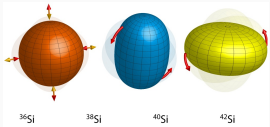


Near-threshold clustering, trapped resonances:

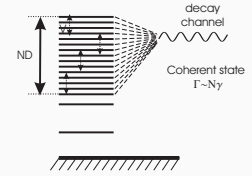


Nuclei as open quantum systems.

Interplay continuum/collectivity:



Isolated vs. Overlapping resonances, superradiance:



- Low-energy virtual states,
- many-body resonances...

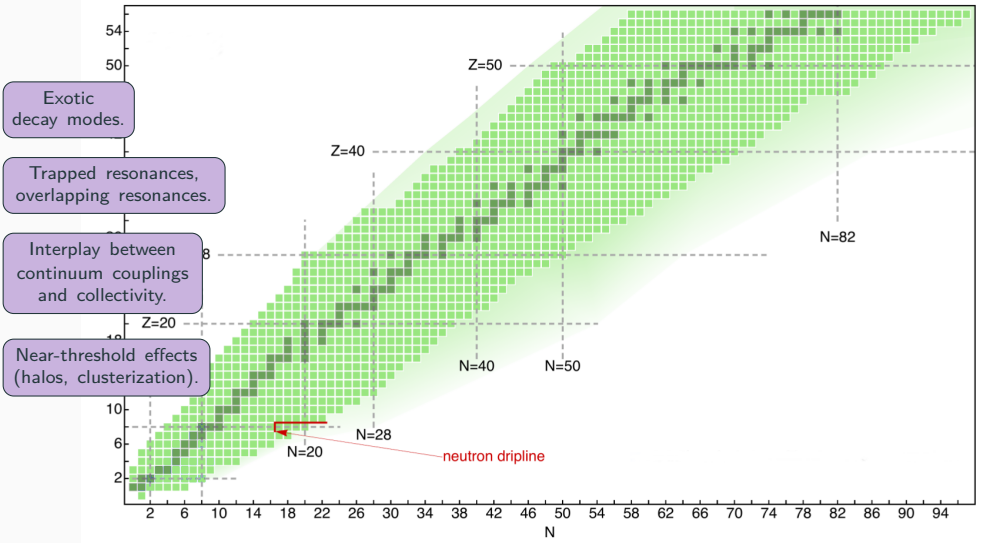
Low-energy nuclear physics: emergence of a new paradigm

Exotic decay modes.

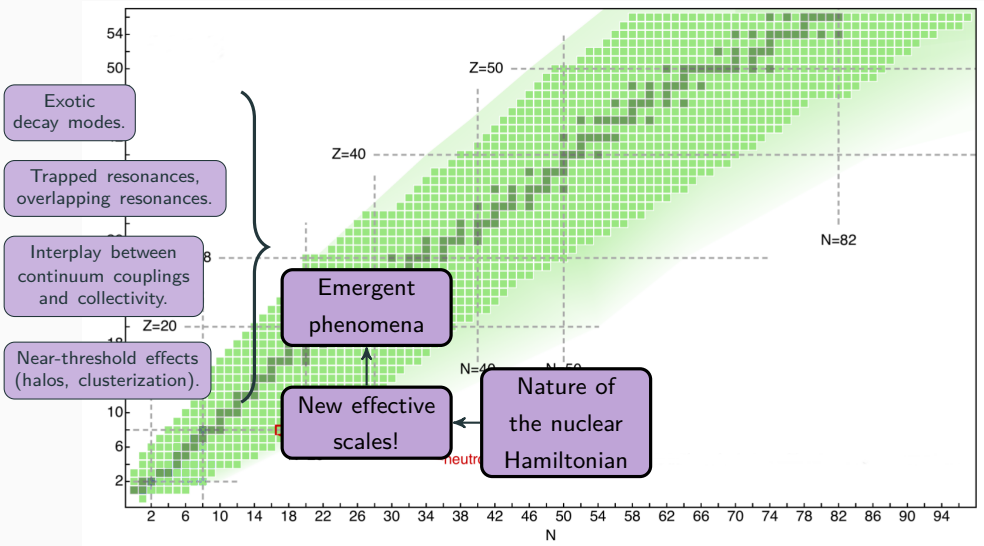
Trapped resonances, overlapping resonances.

Interplay between continuum couplings and collectivity.

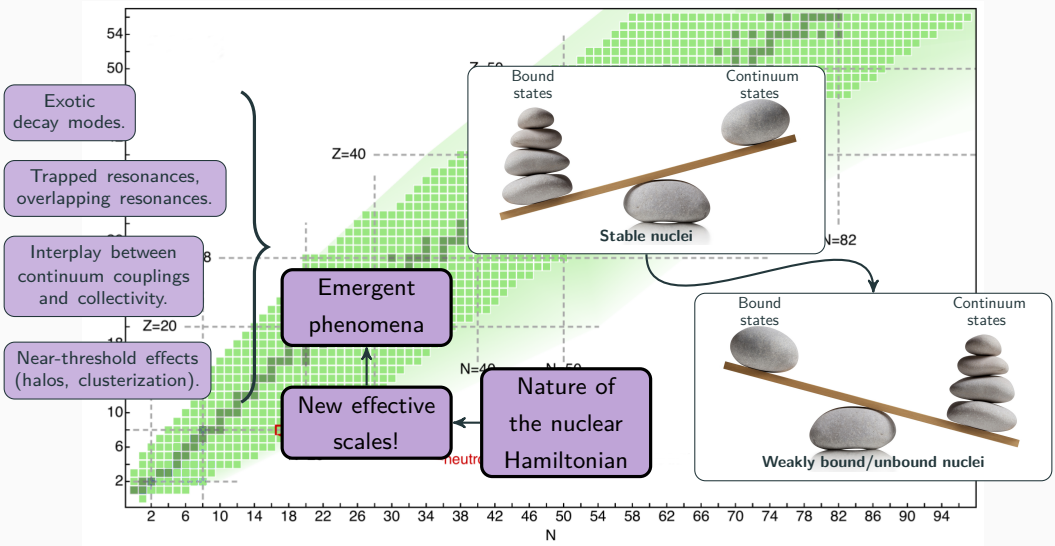
Near-threshold effects (halos, clusterization).



Low-energy nuclear physics: emergence of a new paradigm



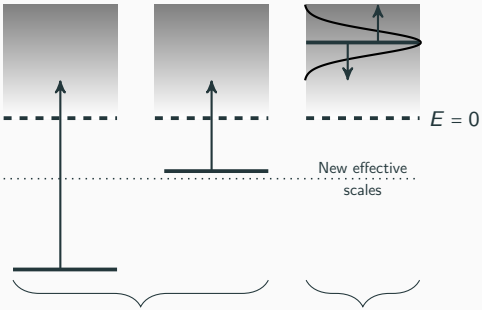
Low-energy nuclear physics: emergence of a new paradigm



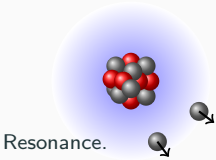
Continuum couplings: a general problem

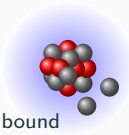
Physics close to the threshold:

- The Hamiltonian couples bound states with continuum states.



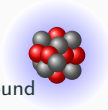
- Quantum systems can break apart.
- Notion of open quantum system.



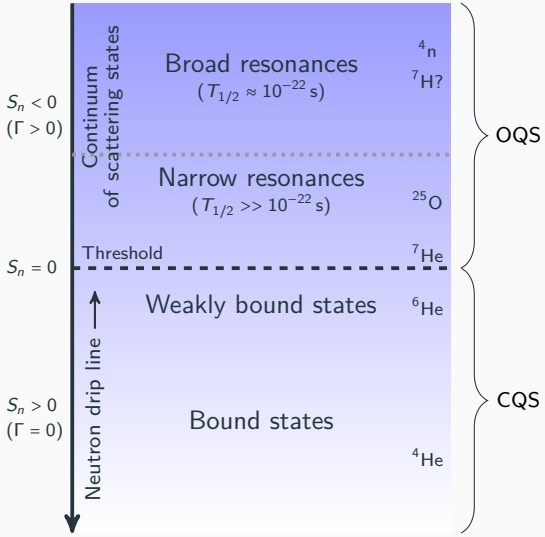


- Energy: E
- Width: Γ

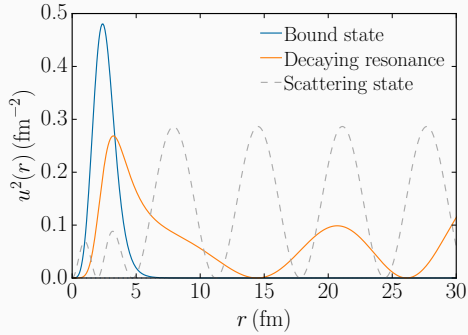
$\Rightarrow T_{1/2} = \hbar \ln(2)/\Gamma$



Consequences in nuclear physics



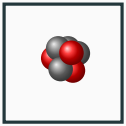
Nuclei as open quantum systems.

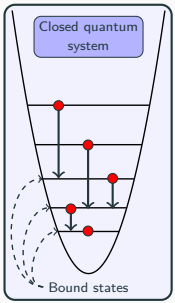


- Wave function with outgoing asymptotics (particle or cluster leaving).
- When can we talk about a nuclear state?

Nuclei as open quantum system

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

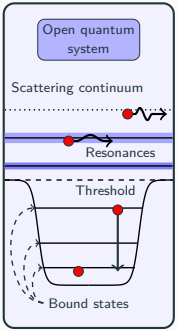




Nuclei can capture and emit nucleons or clusters in the open quantum system framework.

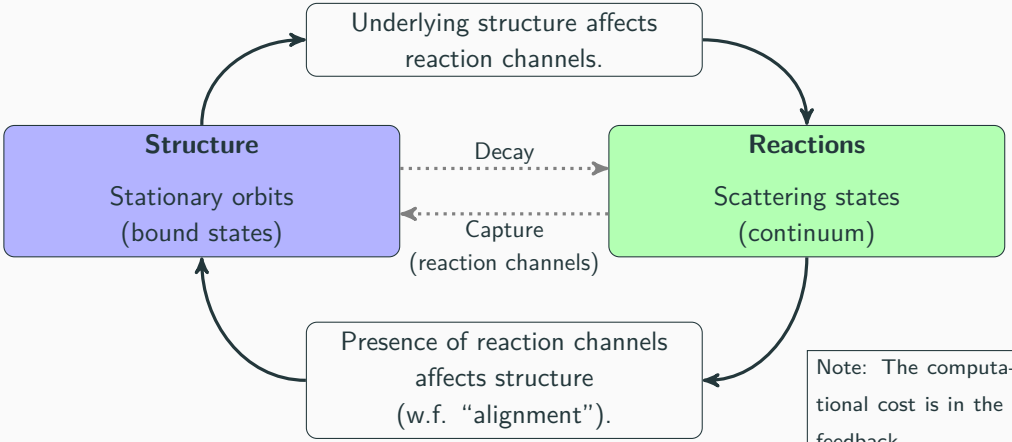
Structure and reaction channels influence each other.

Unification of nuclear structure and reactions



Unification of nuclear structure and reactions

A question of feedback:



Quantum description of nuclei

Basic approximations in nuclear physics:

Fundamental approximations:

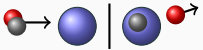
Phenomenological interactions
(no clear improvement scheme)

Bound state approximation
(no continuum couplings)

Reactions approximations:

Static optical
potentials

Statistical models for quasi-
continuum of bound states



Structure approximations:

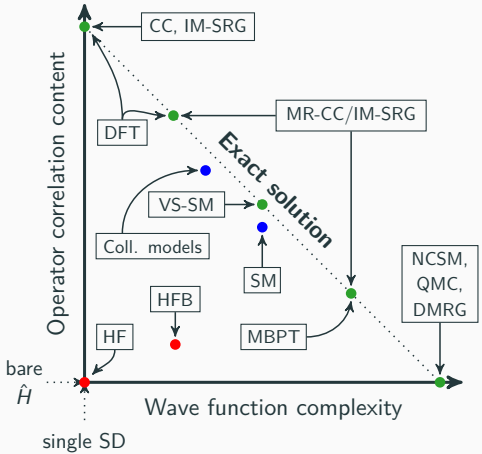
Mean-field
approximation

Inert core
plus valence space

Collective
degrees of freedom

→ Separated treatments of nuclear structure and reactions. Invalid paradigm at low energy.

Strategies to solve the nuclear problem: Schrödinger *vs.* Heisenberg



Unitary transformation: $\hat{U}^\dagger \hat{U} = \hat{1}$.

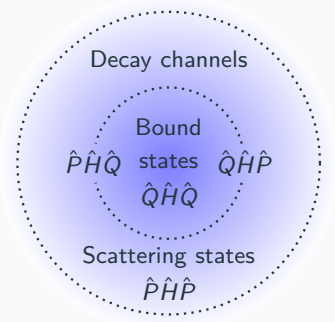
$$
\begin{aligned}
E_{\text{exact}} &= \langle \Psi | \hat{H}_{\text{bare}} | \Psi \rangle \\
&= \langle \Psi | (\hat{U}^\dagger \hat{U}) \hat{H}_{\text{bare}} (\hat{U}^\dagger \hat{U}) | \Psi \rangle \\
&= \langle \Psi \hat{U}^\dagger | \hat{U} \hat{H}_{\text{bare}} \hat{U}^\dagger | \hat{U} \Psi \rangle \\
&= \langle \text{SD} | \hat{H}_{\text{dressed}} | \text{SD} \rangle
\end{aligned}
$$

→ One can either find $|\Psi\rangle$, or an operator $\hat{U}$ that maps the noninteracting system of "dressed" particles with the interacting system of "bare" particles.

Strategies to include continuum couplings I

Feshbach projection formalism:

$\hat{Q} + \hat{P} = \hat{1}$.



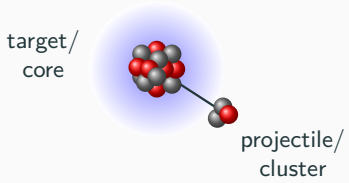
$\hat{Q}$: reference space.

$\hat{P}$: medium or environment.

Resonating group method:

$|\Psi\rangle = \sum_c |\Psi_c\rangle$.

Coordinate space description.



$|\Psi\rangle = \sum_{c=(i_c,j_c)} |\Psi_{\text{target}}\rangle_{i_c} \otimes |\Psi_{\text{cluster}}\rangle_{j_c}$.

Explicit asymptotics.

Momentum space representation:

$|\Psi\rangle = \int dk\ |k\rangle \langle k|\Psi\rangle$.

$|k\rangle$: plane waves, directly into the continuum.

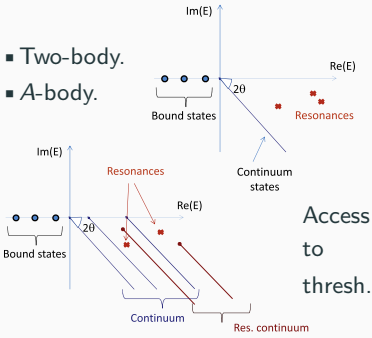
Example:
AGS-Faddeev (-Yakubowski) Eqs.

Strategies to include continuum couplings II

Uniform complex-scaling:

$$\hat{U}(\theta)\Psi(\vec{r}) = e^{i\frac{3}{2}\theta}\Psi(e^{i\theta}\vec{r}).$$
$$\hat{H}(\theta) = \hat{U}(\theta)\hat{H}\hat{U}^{-1}(\theta).$$

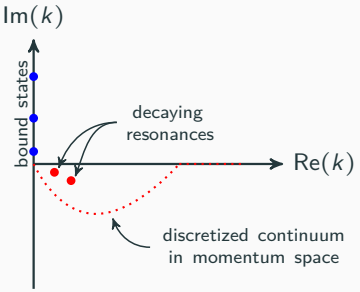
- Two-body.
- A-body.



Access to thresh.

Berggren basis:

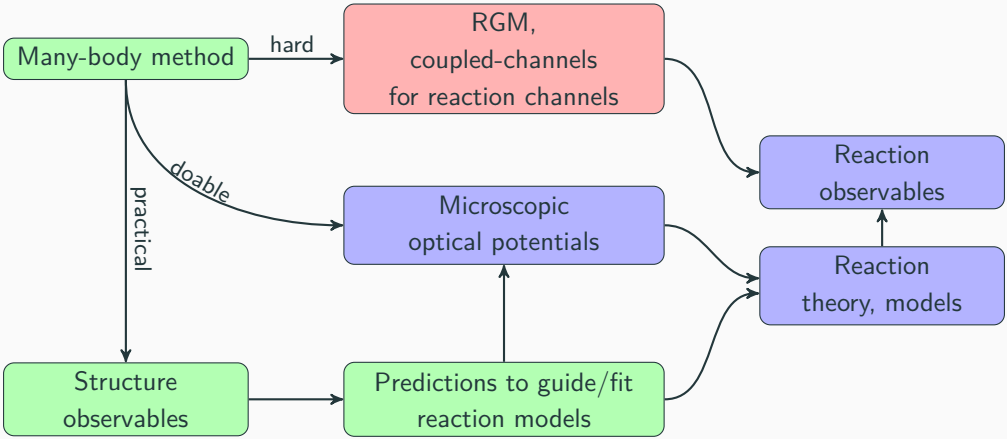
$$\sum_{n\in(b,d)} |u_\ell(k_n)\rangle \langle\tilde{u}_\ell(k_n)| + \int_{\mathcal{L}^+} dk\, |u_\ell(k)\rangle \langle\tilde{u}_\ell(k)| = \hat{\mathbb{1}}_{\ell,j}.$$



Basis expansion technique, versatile.

Figures from J. Carbonnel *et al.*, Prog. Part. Nucl. Phys. **74**, 55 (2014)

From nuclear structure to reactions



Summary

At low energy:

Emergent exotic phenomena due to continuum couplings. Nuclei as open quantum systems.

From structure to reactions:

Feedback between structure and reactions, unified description. Real *vs.* complex energy methods, importance of reaction channels.

→ Knowing particularities of many-body methods is critical to revisit them in the continuum.

Thank you for your attention!