A Quick Overview of Some Microscopic Approaches to Nuclear Reactions

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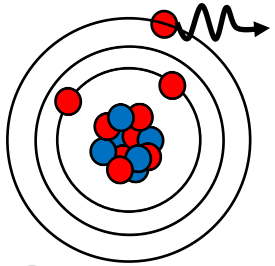
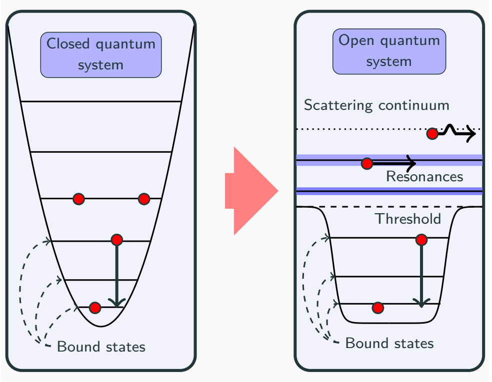
Theoretical Description of Exotic Nuclei

D. Bazin et al., *arXiv:2211.06281*

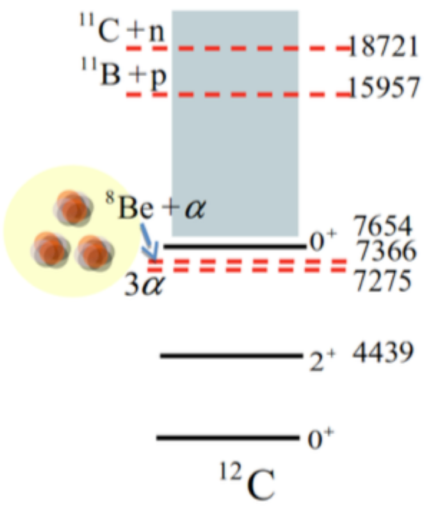
New features:

- Open quantum systems.
- Unstable: short life time, decay through nucleon emission.
- Threshold emissions.
- Loosely bound states.
- Resonances.

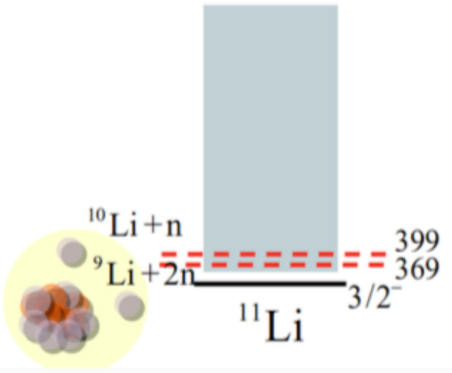


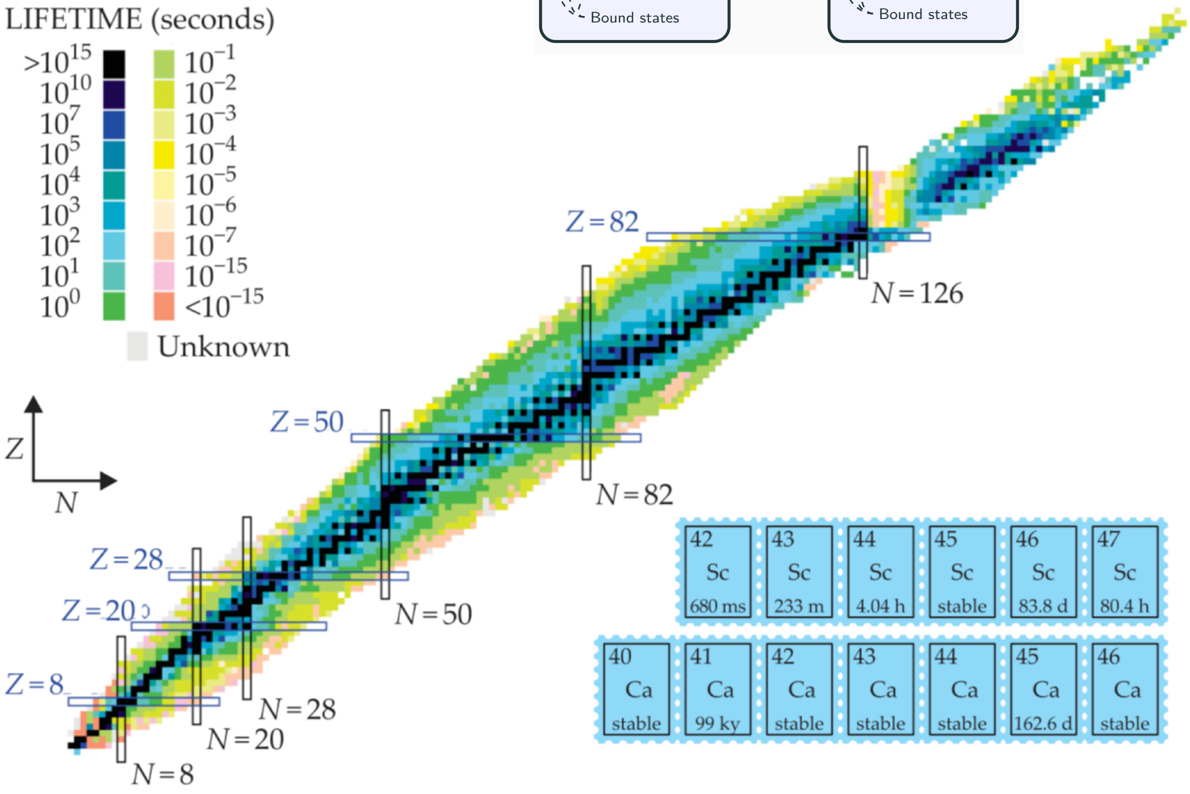


α - cluster state



halo state



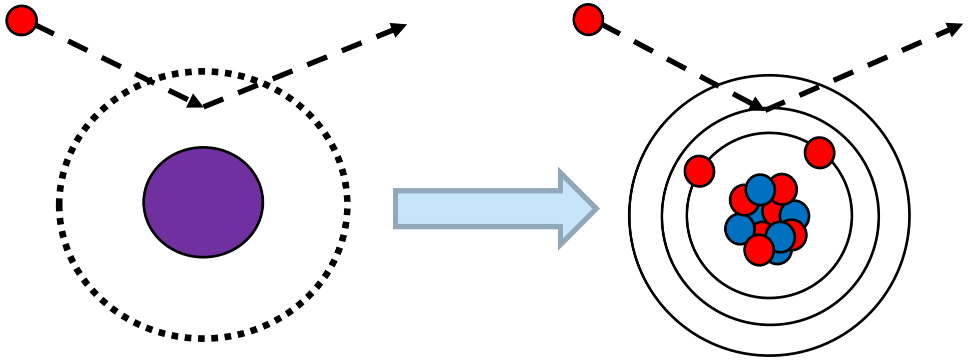


Few-body vs Many-body approaches: Unification of Structure and Reactions

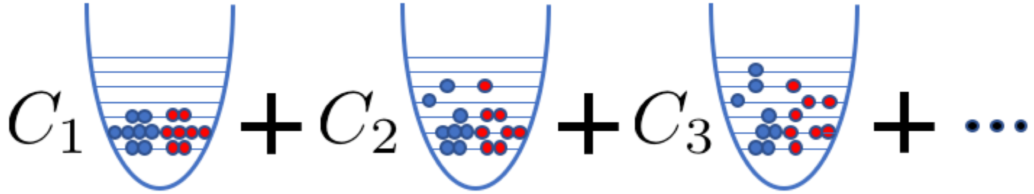
Few-body approach:

- Simpler calculations: two- or three-body generally.
- Optical potentials: imaginary part to mimic the effect of inelastic channels; parameters are fitted on data.
- Allows to study many types of reaction across the nuclear chart.
- Many approaches are now developing optical potentials from microscopic calculations.

C. Hebborn et al., *J. Phys. G: Nucl. Part. Phys.* **50** 060501 (2023)



We eventually want to implement reactants wave functions

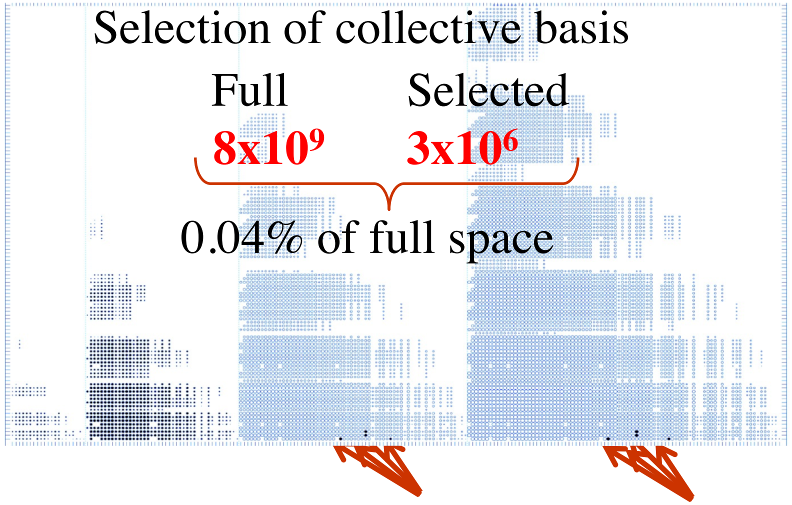


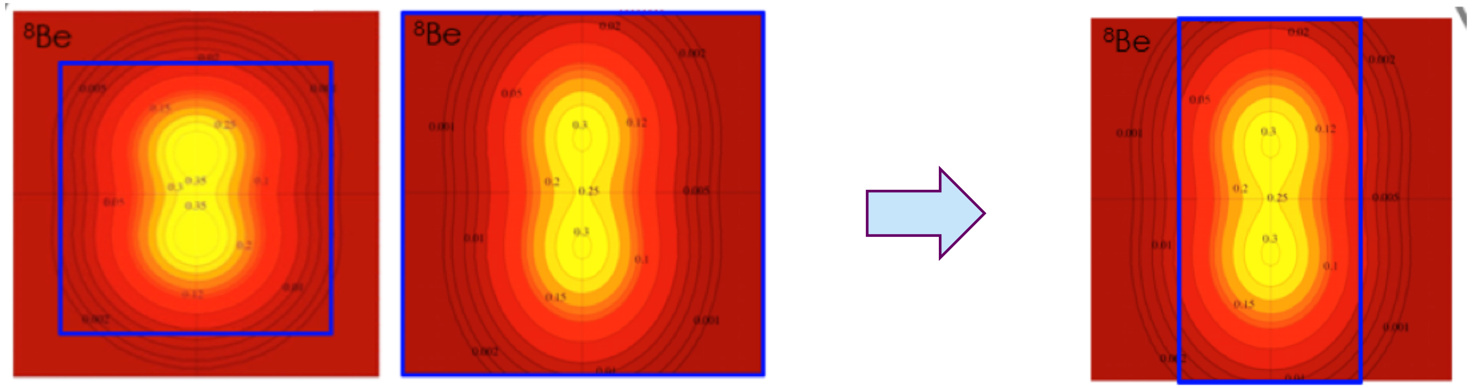
Many-body approach:

- Structure of reactants play an important role.
- Complexity increases fast with light projectile and multi-partition calculations.

Ab Initio Wave Functions for Nuclear Reactions

Symmetry-adapted No-core Shell Model



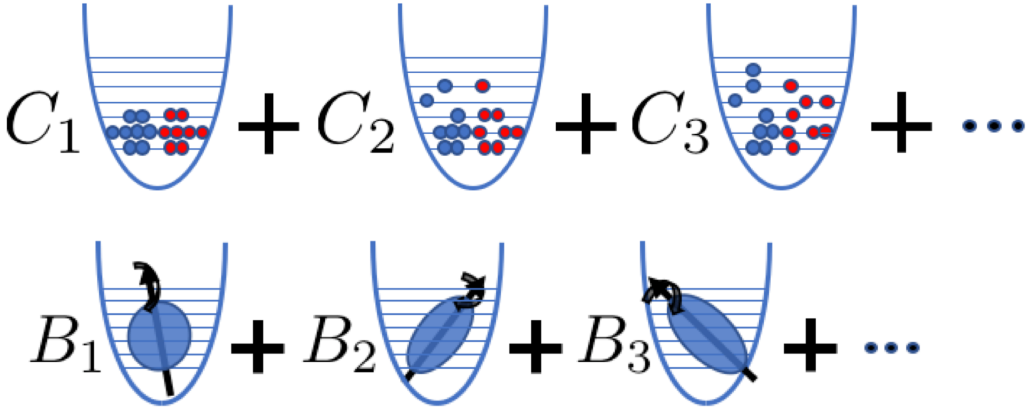


Small model space

Large model space

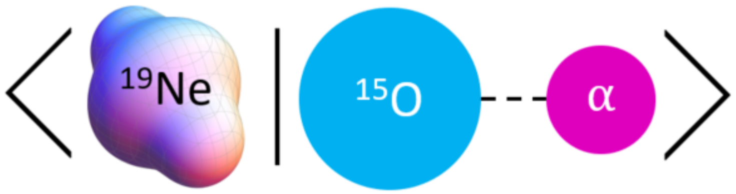
Selected model space

- *Ab initio*: no-core shell model calculations, chiral EFT interactions.
- Physically relevant basis states: better captures collectivity.
- Selection of the most important basis states: capture relevant correlation.
- Manageable model space, can push further the limit of *ab initio* calculations.



Ab Initio Overlap Functions

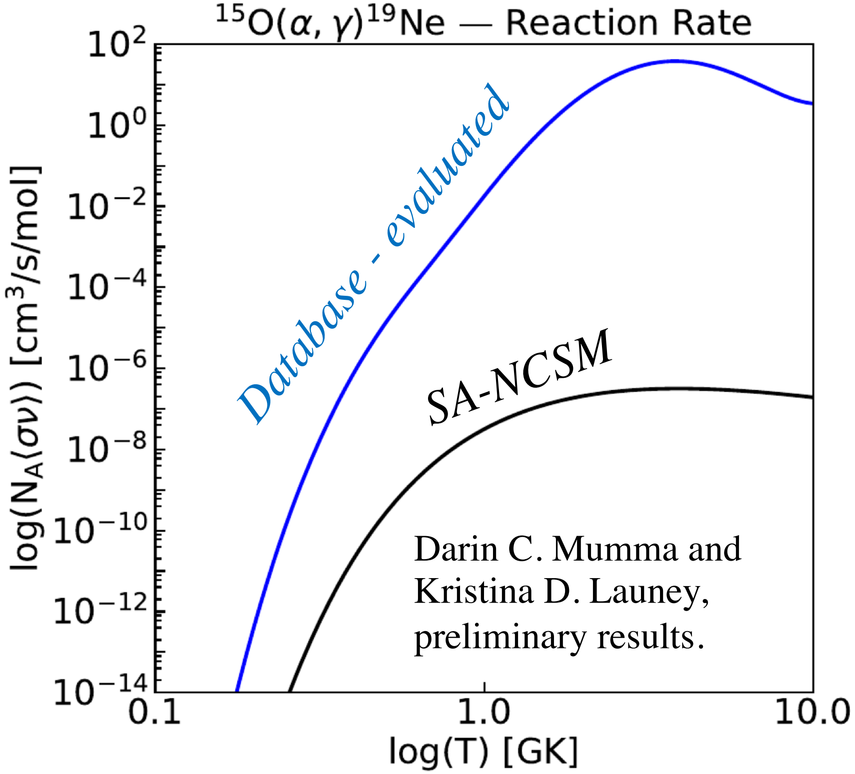
SA-NCSM wave function

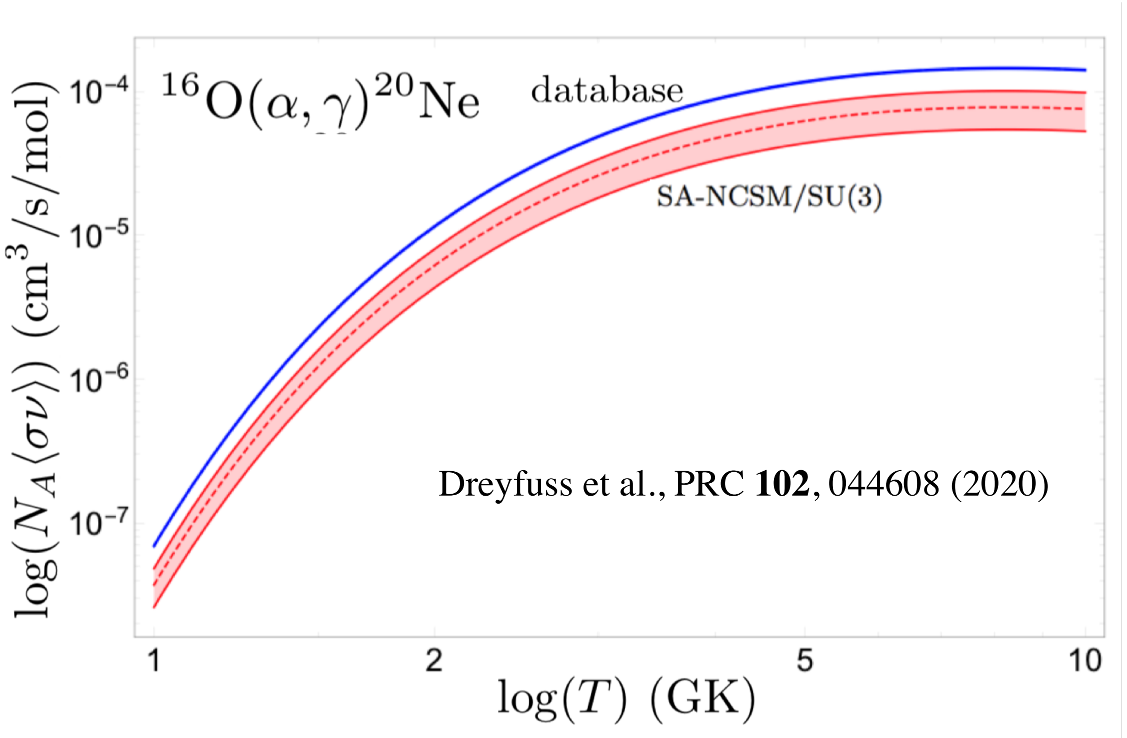


$= u_{\nu l}(r)$

- Rate uses narrow-resonance formula, deduced the matching with asymptotic scattering w.f.
- Calculated rate is a many order of magnitude smaller than evaluated.

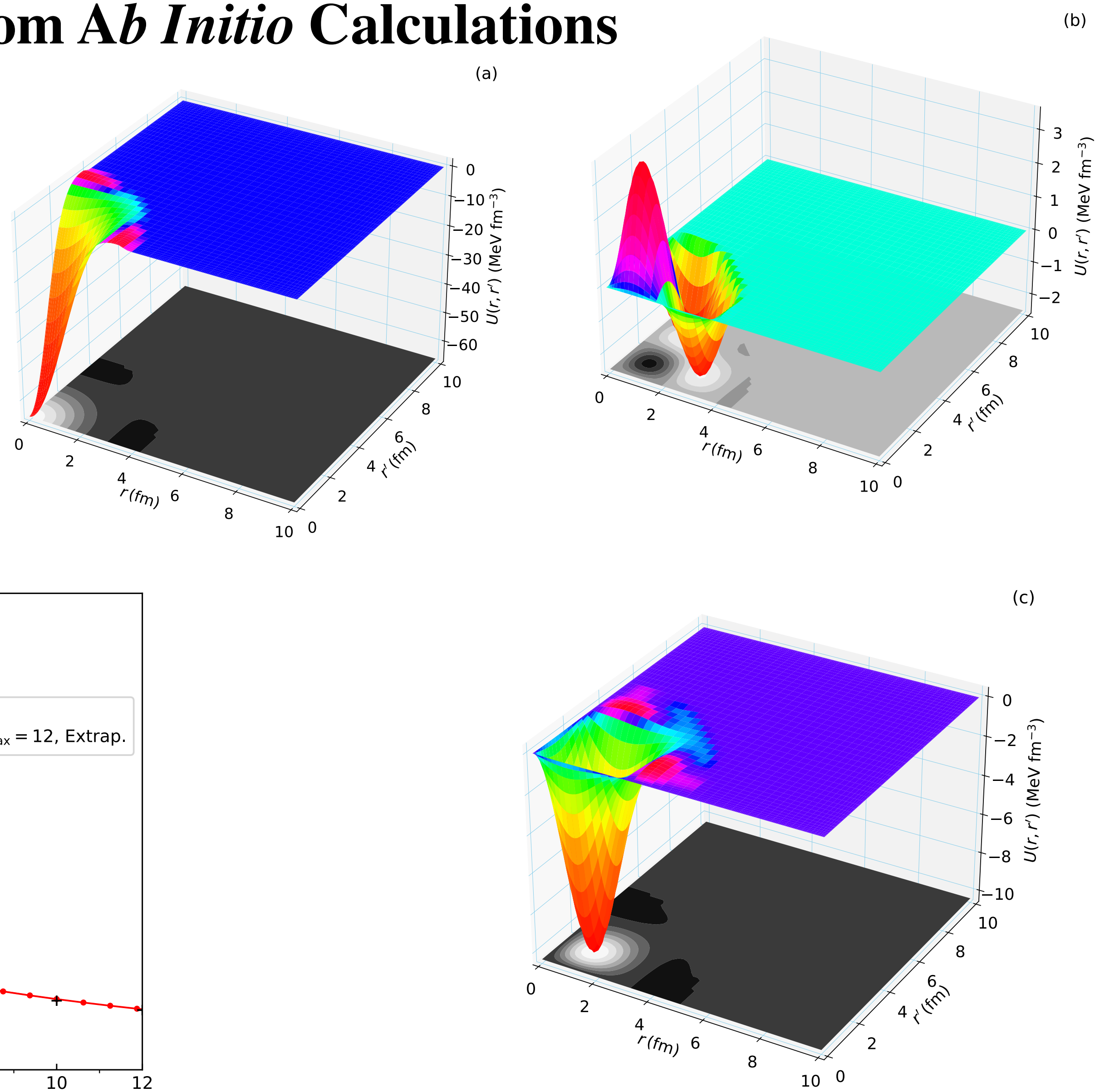
- Relevant for astrophysics: Triggers CNO-cycle breakout.



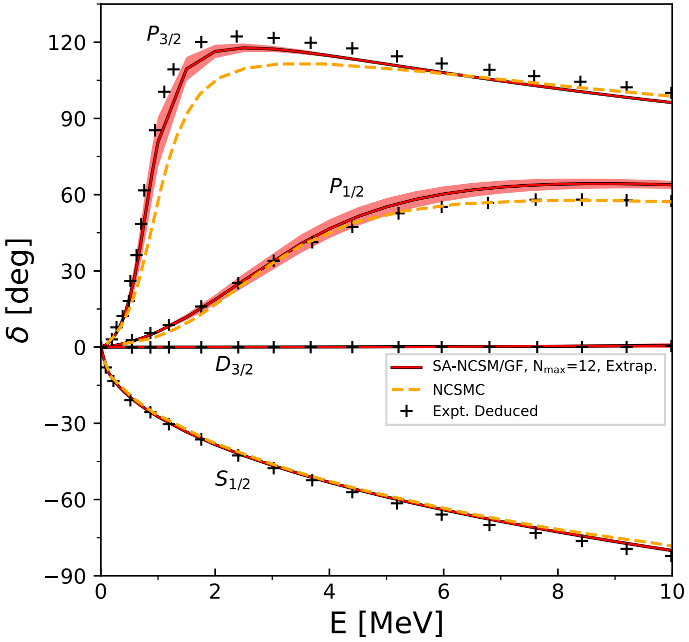


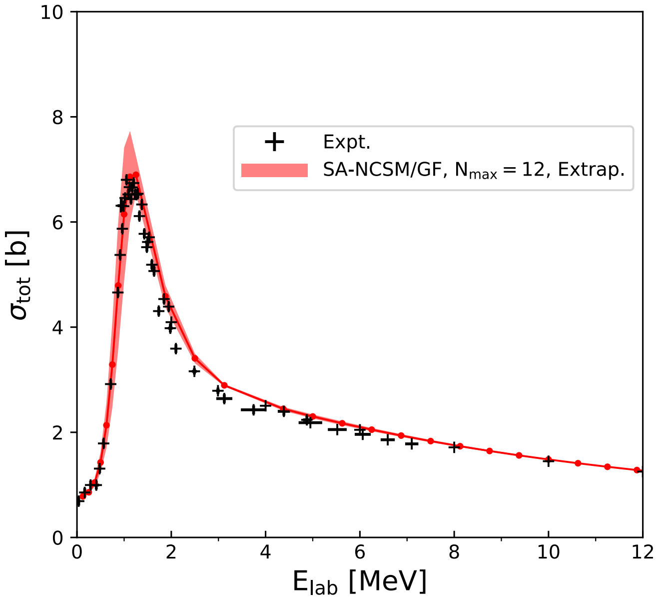
Optical Potential Derived from A*b Initio* Calculations

- ^{4}He wave function calculated with SA-NCSM.
- Optical potential describing neutron scattering on ^{4}He constructed with Green's function method.



Matthew Burrows and Kristina Launey, preliminary results





Coupled-channels Framework for Nuclear Reactions

Everything starts here:

$$(T_c - (E - E_c))u_c(r) + \sum_{c'=1}^{N_c} \int dr' V_{cc'}(r', r) u_{c'}(r') = 0$$

Solution

Kinetic part

Scattering energy

Threshold energy

Coupling potential

Can be solved with calculable R-matrix.

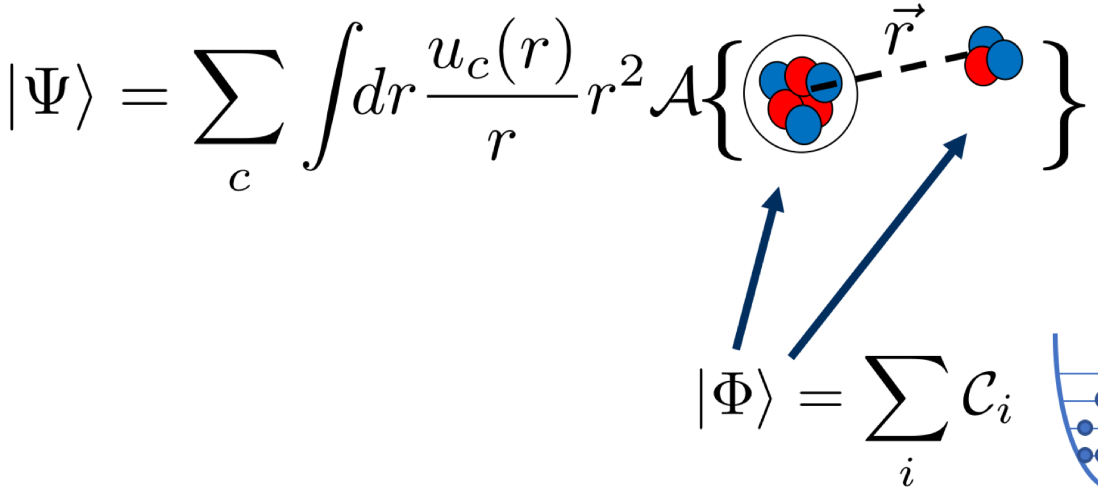
a.k.a optical potential, inter-cluster interaction, nucleon-nucleus potential …etc

A basis for reactions: channel index gathers partitions, quantum numbers of projectile and target, total angular momentum of composite …etc

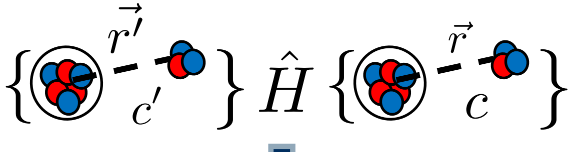
$$c = \{A\ I_T; a\ I_p; n\ell j; J\}$$

Low Energy Reactions With the Resonating Group Method (RGM)

- $u_c(r)$ describes the relative motion between the two clusters.
- Asymptotic of $u_c(r)$ gives cross section for specific channel.
- Requires internal wave functions and NN interaction.
- Microscopic: full antisymmetrization + cluster correlations.
- Can be generalized to any number of clusters.

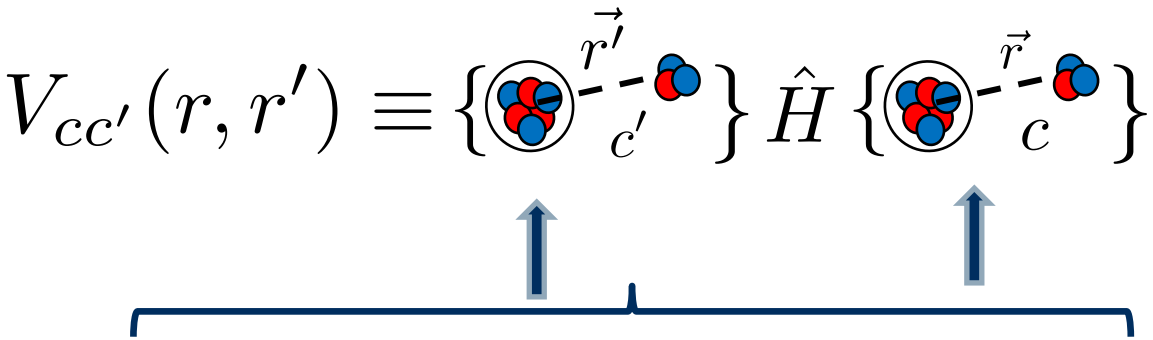


$$\boxed{c = \{A\ I_T; a\ I_p; n\ell j; J\}}$$



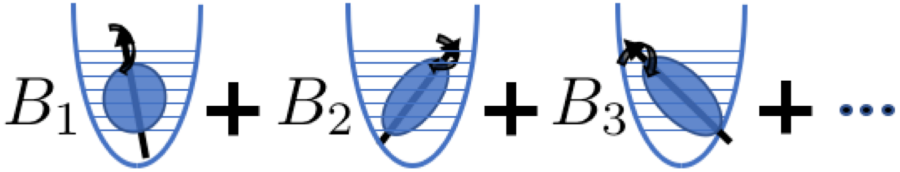
$$(T_c - (E - E_c))u_c(r) + \sum_{c'=1}^{N_c} \int dr' V_{cc'}(r', r) u_{c'}(r') = 0$$

Implementing Shell-model Wave Functions into Reactions



Symmetry-adapted No-core Shell-model

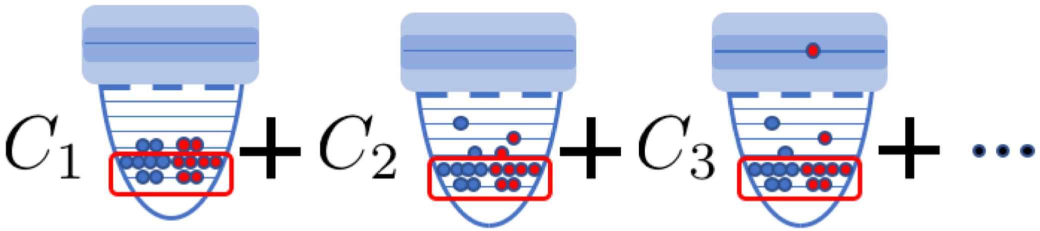
- All nucleons are active.
- Chiral EFT interaction.



SA-NCSM+RGM = SA-RGM

Gamow Shell Model

- Core + valence nucleons.
- Schematic interaction.

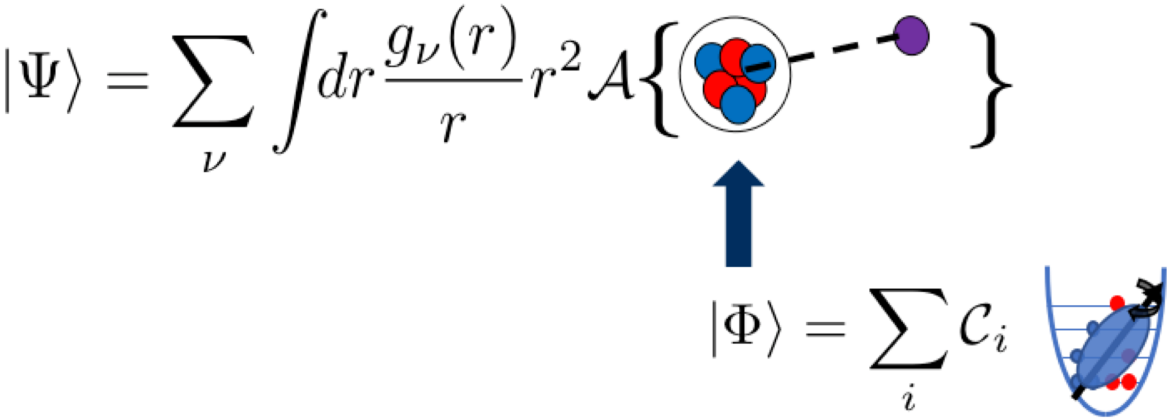


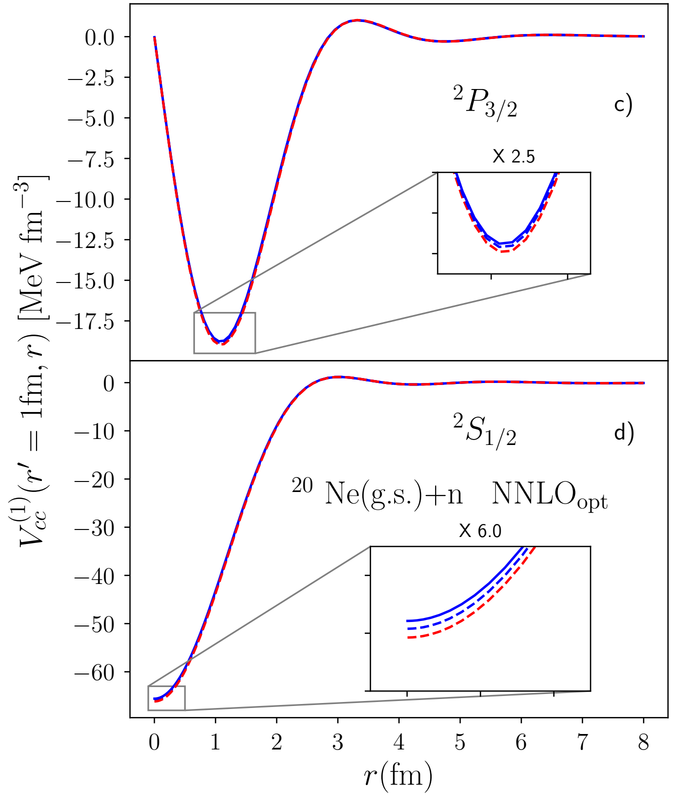
GSM+RGM = GSM-CC

Ab Initio Nuclear Reactions with Nuclei Up to Medium-mass Region

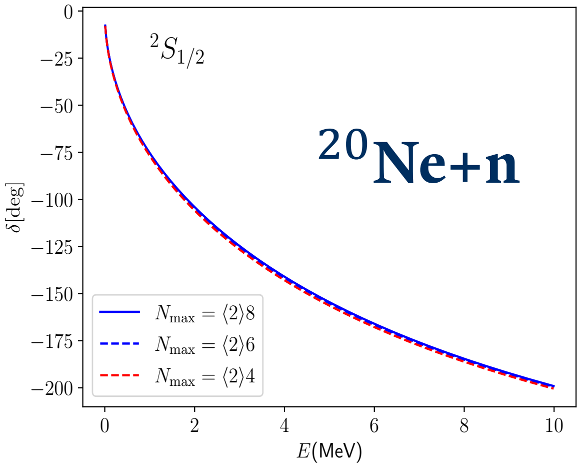
Symmetry-adapted RGM:

- *Ab initio* single-nucleon projectile reactions in a coupled-channel framework.
- First results studied the influence of selected model space on non-local potentials.

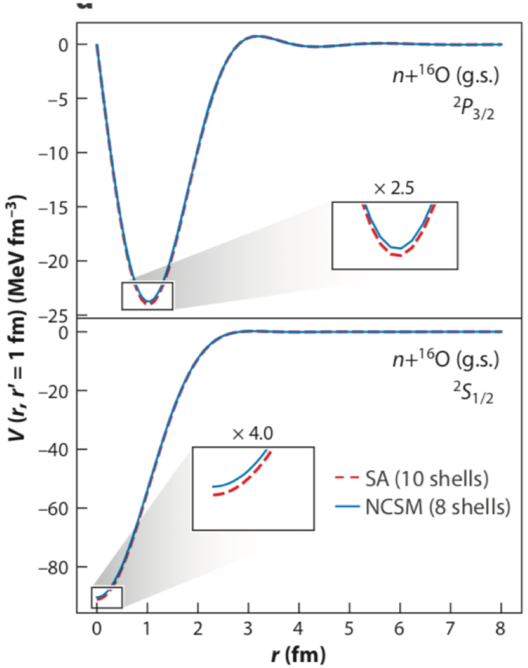


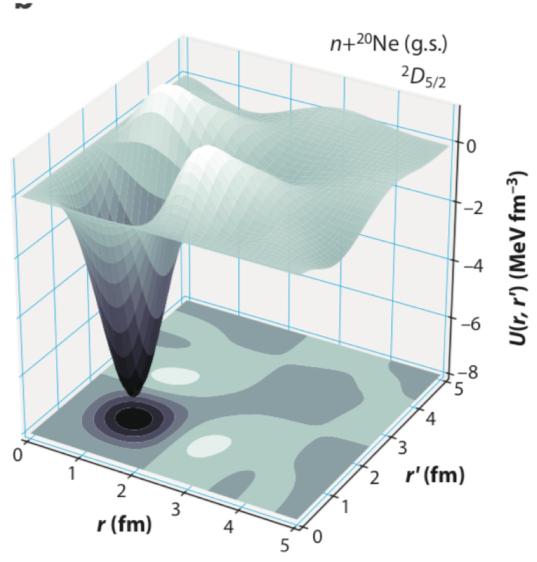


- More to come …



Mercenne, Launey, Dytrych, Escher, Quaglioni, Sargsyan, Draayer Comput. Phys. Comm. ***280****, 108476 (2022)*



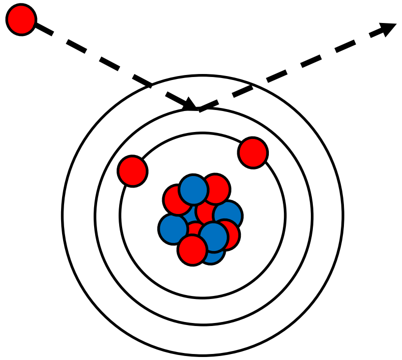


Launey, Mercenne, Dytrych Ann. Rev. Nucl. Part. Sci. ***71****, 253 (2021)*

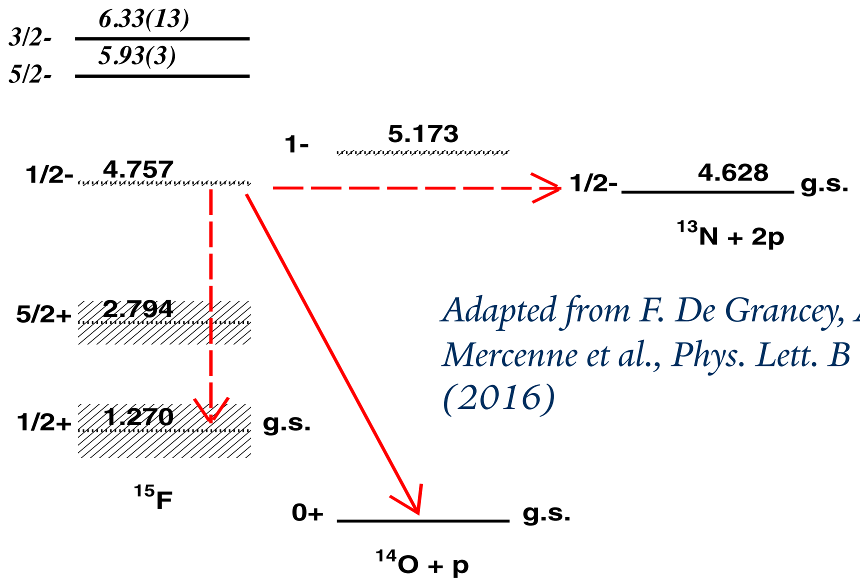
Exotic ^{15}F Studied Through p+ ^{14}O With Gamow Shell Model Coupled Channel

Goal : Study the structure of ^{15}F through the elastic cross section p+ ^{14}O

Motivation: ^{15}F is unbound, several measured narrow resonances located well above the Coulomb plus centrifugal barrier.



- Core ^{12}C, 3 valence protons.
- Many channels: 8 states of ^{14}O



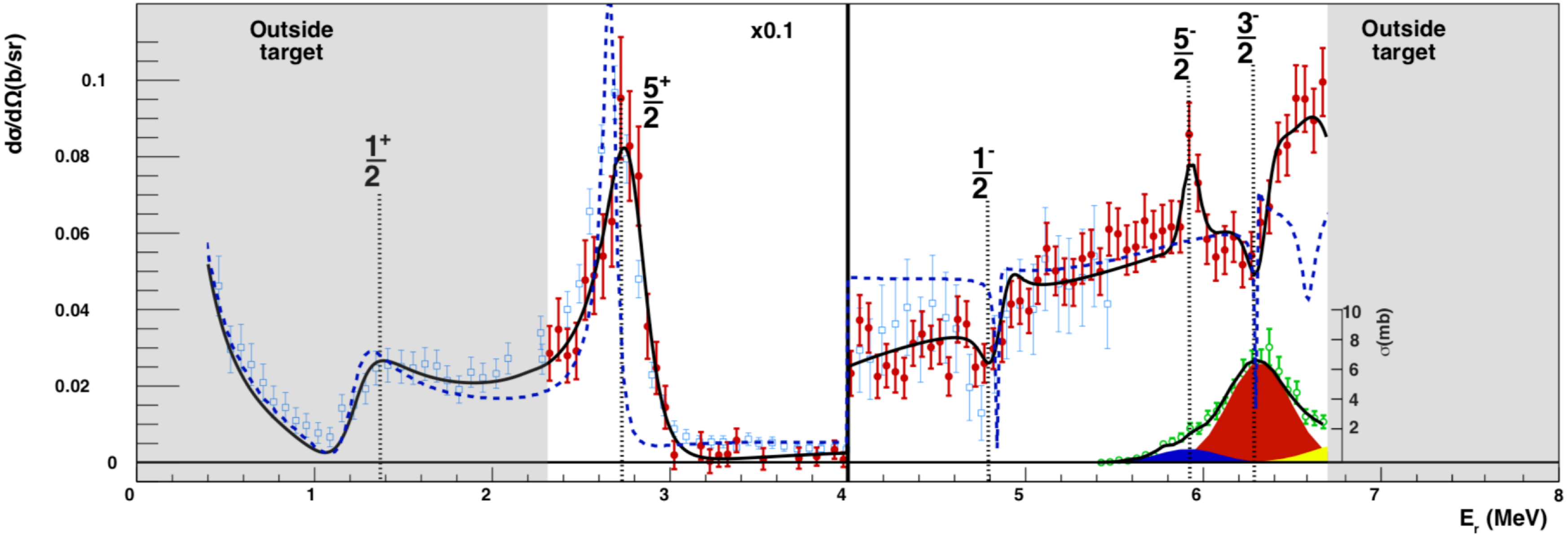
Adapted from F. De Grancey, A. Mercenne et al., Phys. Lett. B ***758****, 26 (2016)*

Schematic interaction (FHT) is fitted using GSM to reproduce the low lying states of ^{14}O and ^{15}F

Astrophysics: Properties of ^{15}F, and proton riche systems in general, play an important role in rp-process .

Exotic ^{15}F Studied Through p+ ^{14}O With Gamow Shell Model Coupled Channel

*V. Girard-Alcindor, A. Mercenne et al., PRC **105**, L051301 (2022)*



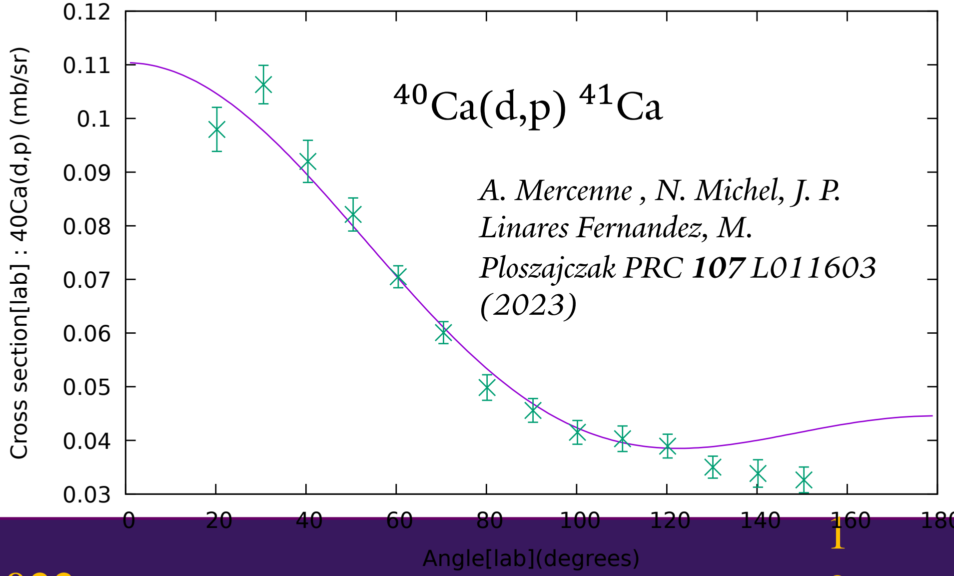
- Collaboration with different experimental team to analyze their results: spin-parity assignment.
- More to come … Higher resonances detected in another experiments (B. Charity, L. Sobotka et al.)

Manifestation of continuum couplings effect.

Shell-model framework tells us about competition between two decay modes.

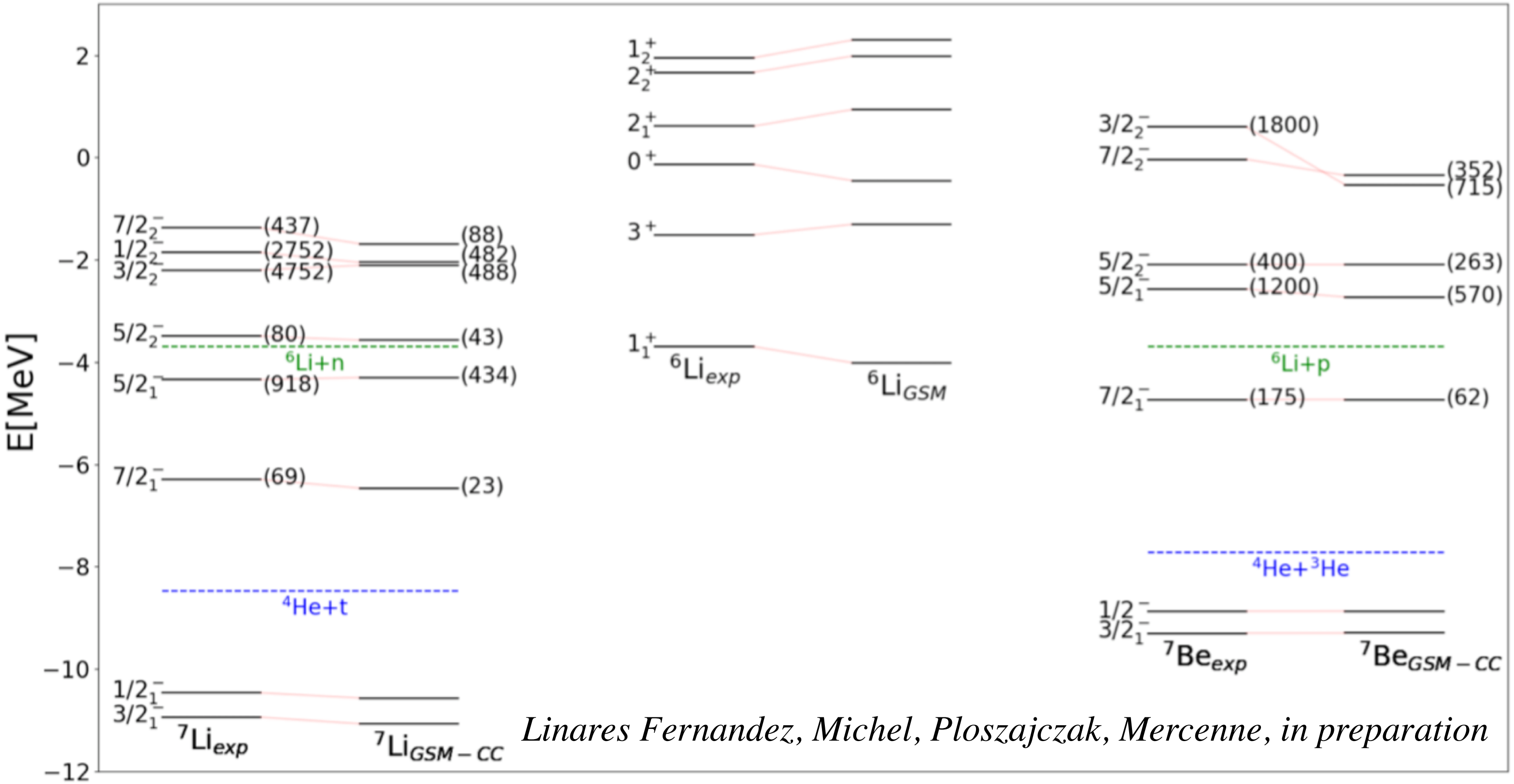
Beyond single-nucleon projectile:

- Generalization of the formalism to complex projectile (deuteron, alpha …etc) *Mercenne, Michel, Ploszajczak, PRC **99**, 0044606(2019)*



Multi-partition Reactions for ^{7}Li, ^{7}Be and ^{8}Be With GSM-CC

^{4}He core + valence particles. Same Hamiltonian to describe ^{7}Be and ^{7}Li. Performed GSM (Slater determinant basis) and GSM-CC (channel basis) calculations. Schematic interaction fitted to reproduced low-lying spectra of reactants.



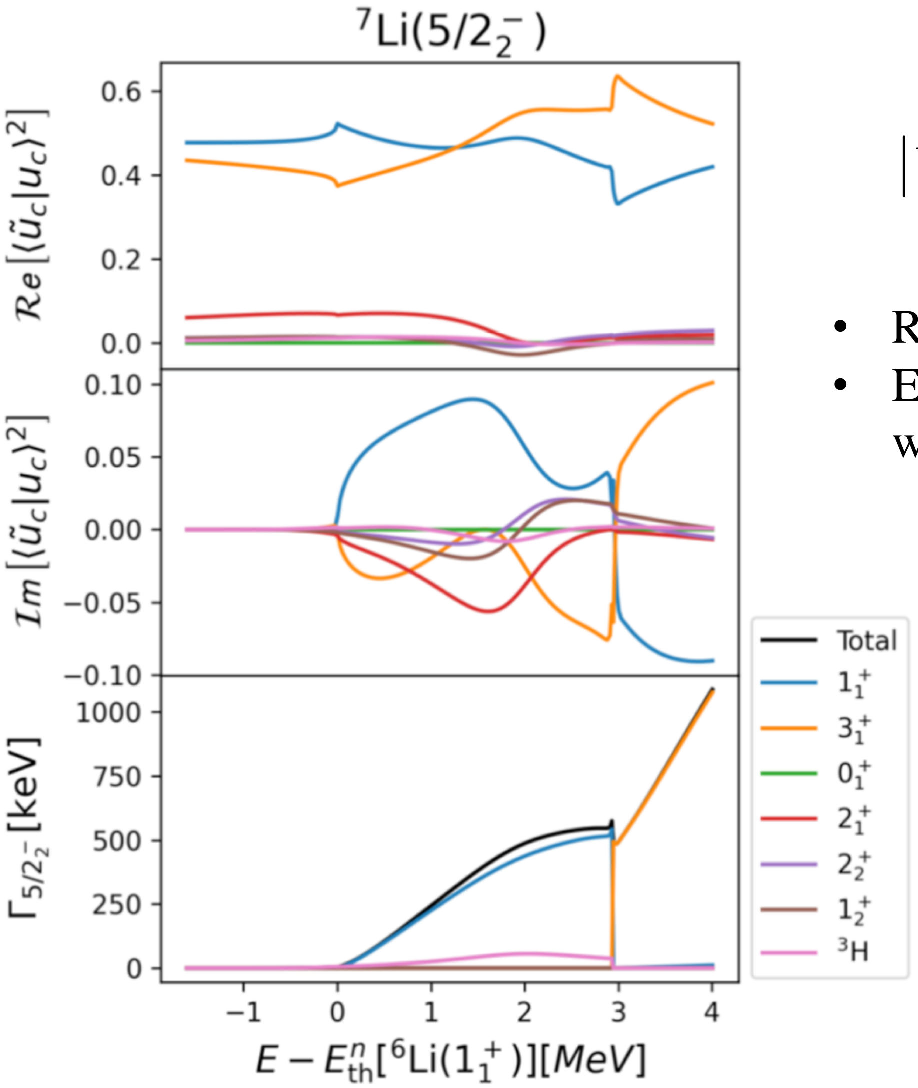
Linares Fernandez, Michel, Ploszajczak, Mercenne, in preparation

^{7}Li
- **^{6}Li*+n**
- **^{4}He(0^+)+ ^{3}H**

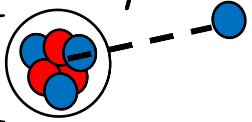
^{7}Be
- **^{6}Li*+p**
- **^{4}He(0^+)+ ^{3}He**

^{8}Be
- **^{7}Li*+p**
- **^{7}Be*+n**
- **^{4}He(0^+)+^{4}He**

Multi-partition Reactions for ^{7}Li, ^{7}Be and ^{8}Be With GSM-CC



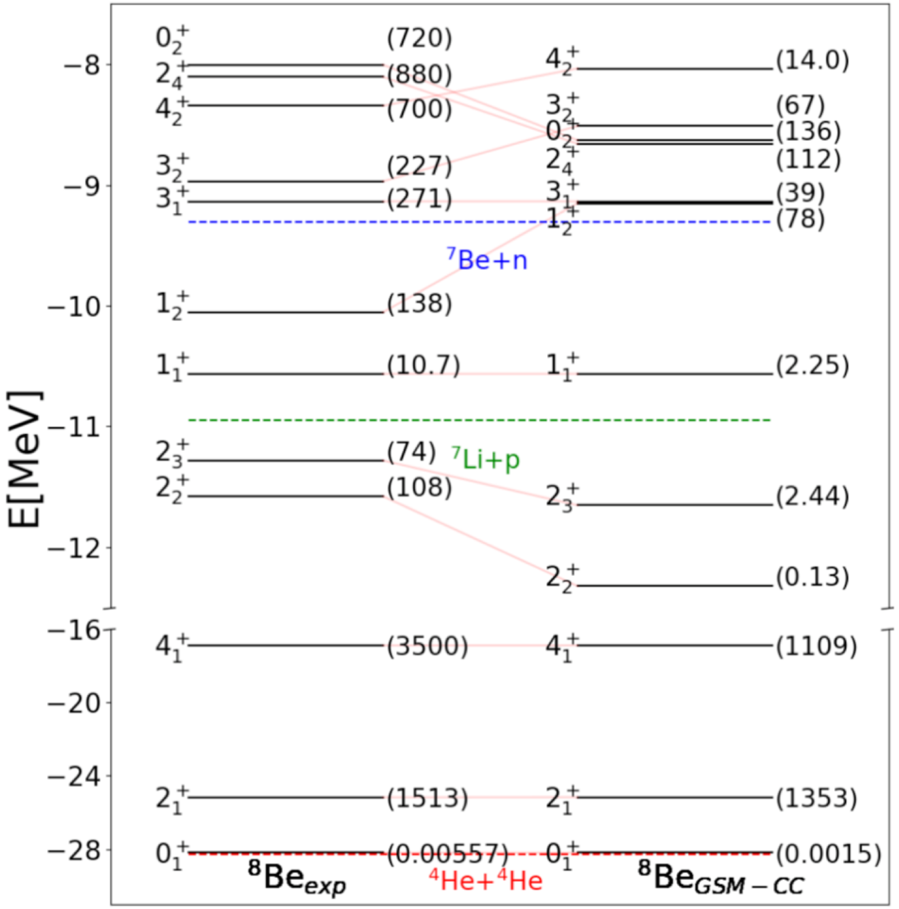
$$|\Psi\rangle = \sum_c \int dr \frac{u_c(r)}{r} r^2 \mathcal{A}\{ \quad \vec{r} \quad \}$$

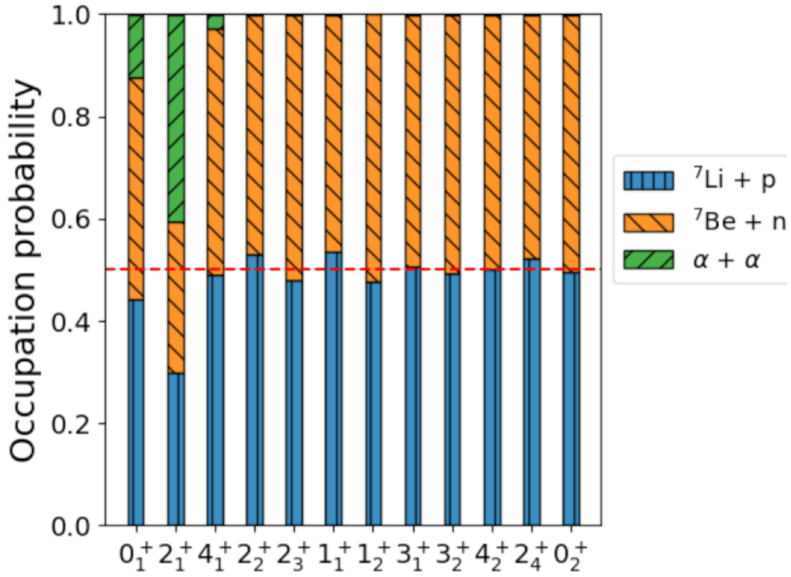


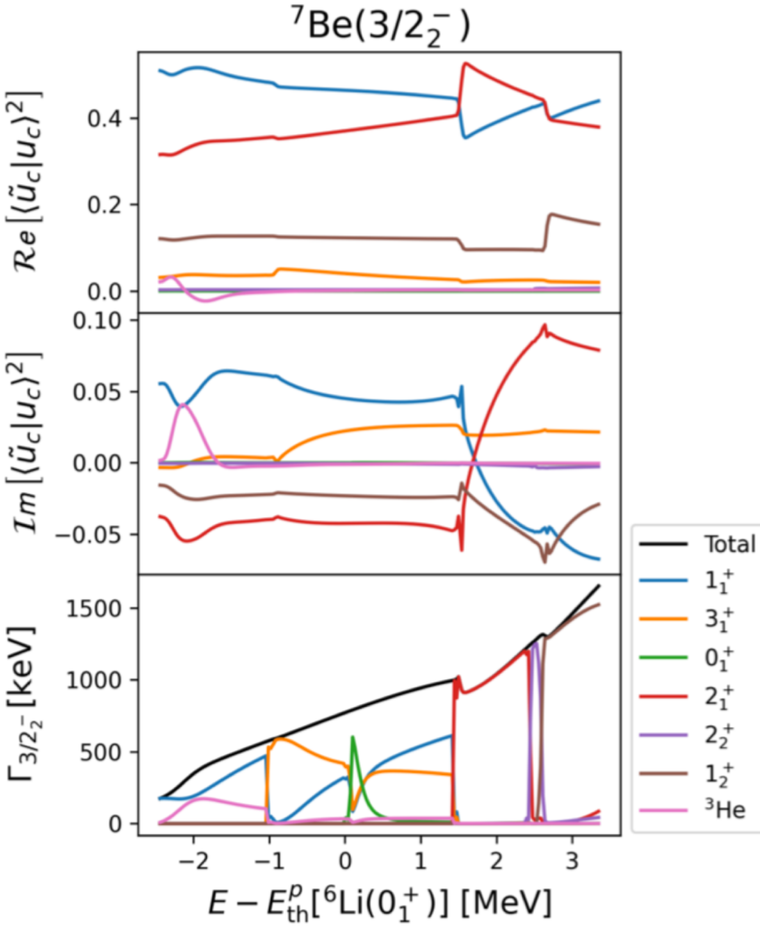
- RGM can tell us more than cross sections.
- Enhancement of the scattering cross section at the threshold energies where new channels open: Wigner cusps.

Linares Fernandez, Michel, Ploszajczak, Mercenne, in preparation

Multi-partition Reactions for ^{7}Li, ^{7}Be and ^{8}Be With GSM-CC







Linares Fernandez, Michel, Ploszajczak, Mercenne, in preparation

Summary

- You can already do “reactions” with a structure approach: overlap function can help to calculate reaction rates.

- Structure wave functions are becoming a necessary ingredient for low energy nuclear reactions:
  - To construct optical potentials (i.e. with Green’s function method)
  - For RGM-based approach to coupled-channel calculations.

- Cross sections are the observables that will have the most impact for advancing the science in connection with these theoretical methods.

- Future advances:
  - Uncertainty quantification, especially on models that depend upon fitting an interaction.
  - Pushing further *ab initio* reactions with multi-partition calculations.