My Experience as a (Not-So-Young) Post-Doc in Nuclear Theory

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NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

POLSKIE TOWARZYSTWO FIZYCZNE
SOCIETAS PHYSICORUM POLONIAE
Experimento et mente
1920

What makes Nuclear Theory interesting? [A subjective take]

The **Nuclear Interaction** comes from **Quantum Chromodynamics (QCD).**
However, with our current computational capabilities,
we cannot even describe fully all the properties of the proton.

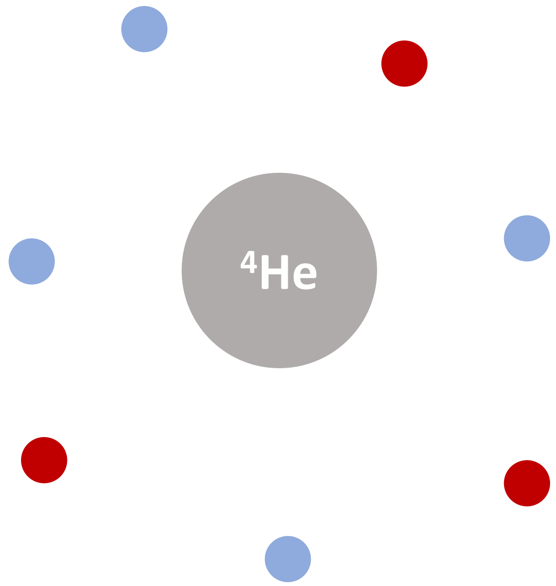
As a result, **all nuclear models are phenomenological** (parameter fitting),
with different levels of phenomenology, leaving the place
to **all different kinds of Physics within Nuclear Theory**.

In this presentation, I will share some of my **personal experience**
with the different aspects of Physics within Nuclear Theory,
highlighting the **diversity of the field.**

Shell Model (embedded in the continuum)

- Model = an **inert core** + **valence nucleons**

$$\mathcal{H} = \sum_{i=1}^{N_{val}} \left[\frac{\vec{p}_i^{\,2}}{2\mu_i} + U(i) \right] + \sum_{i<j=1}^{N_{val}} V_{res}(i,j) + \cdots$$



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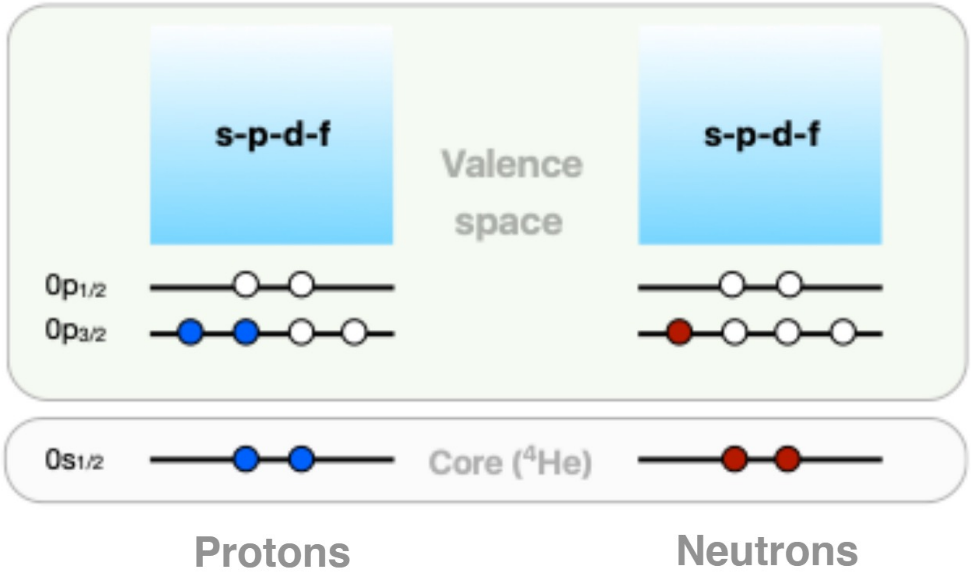
- U generates the **shells [basis]**. U and V_{res} can come from:
  - **First principles** (Ab Initio No Core Shell Model)
  - **Effective forms** (analytical formulas etc.).

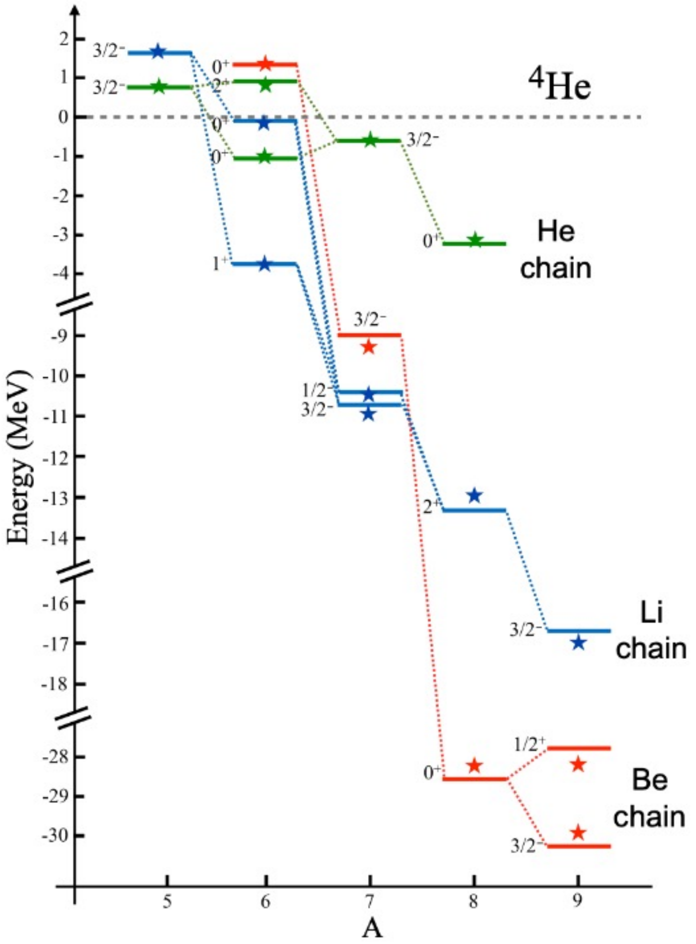
- The **Gamow Shell Model** is an extension of the Shell Model in the **continuum** [particle emission].

- Diagonalization of $\mathcal{H}$ gives the A-body nuclear states.



Shell Model (embedded in the continuum)

- An interaction with **spin-orbit**, **tensor** and **Coulomb** to describe the whole **psd-shell** nuclei (A = 5 - 15). For **bound states and resonances.** With **uncertainty quantification.**



Y. J. *et al.*, Phys. Rev. C 96, 054316 (2017)

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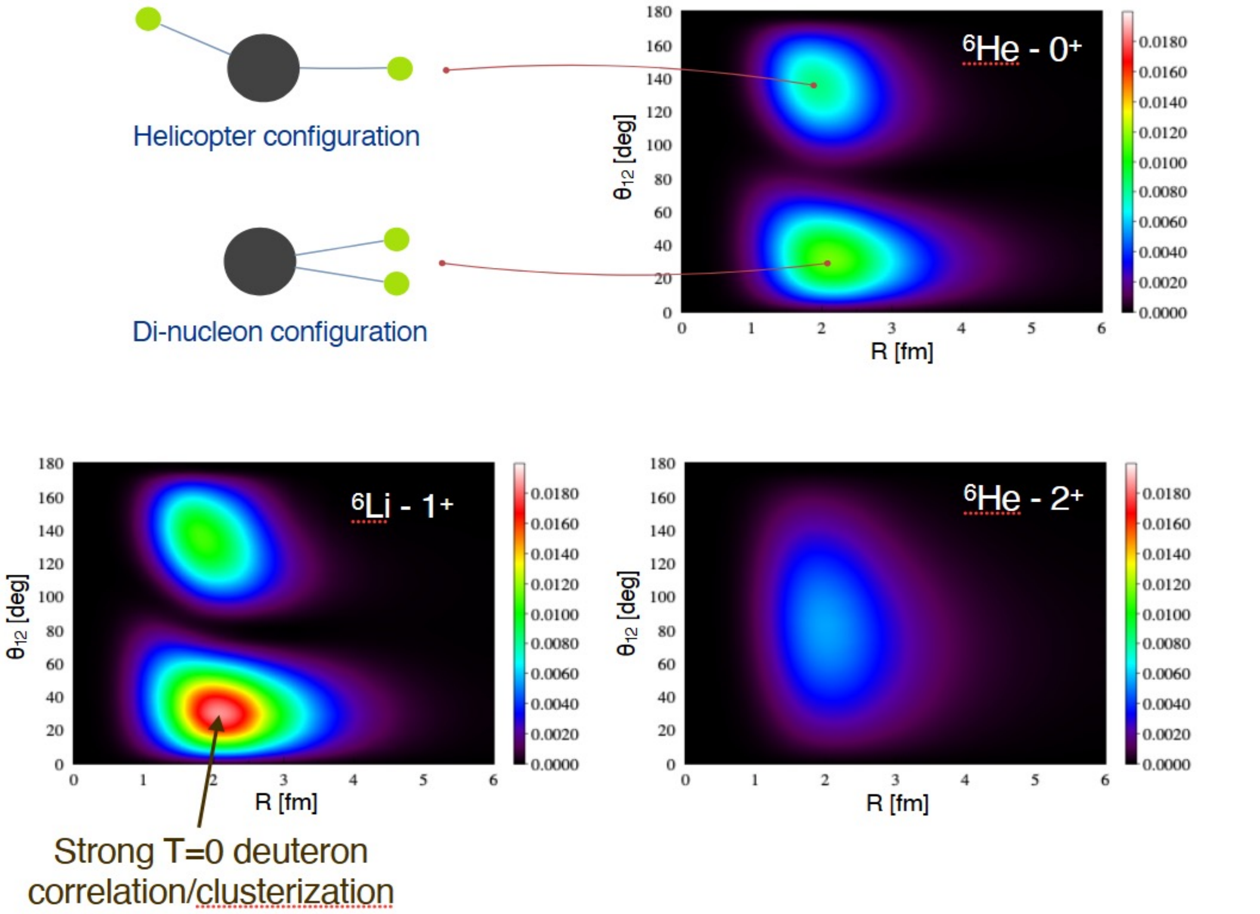
- Description of exotic phenomena:
  - **Halo states**
  - **Helicopter/di-nucleon configuration**
  - **Deuteron clusterization…**



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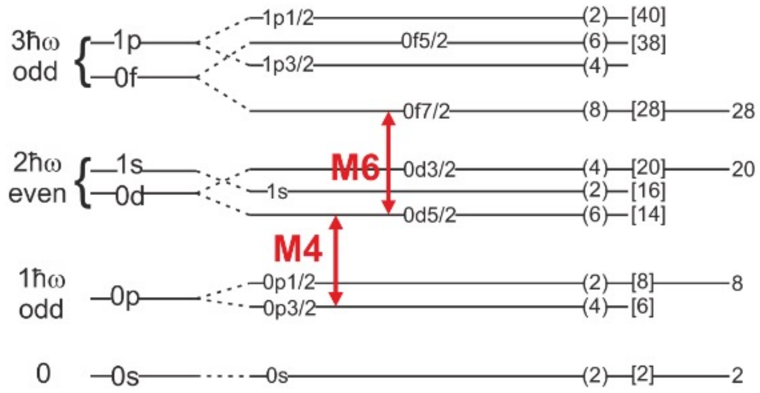
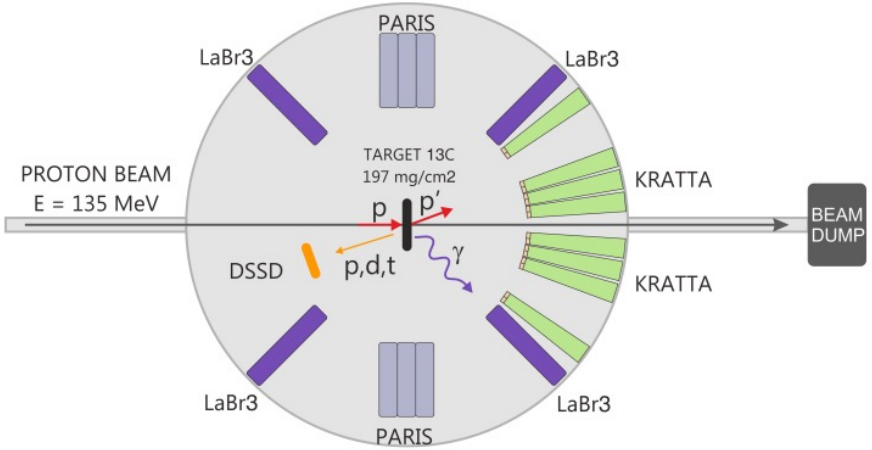
Super-stretched states (direct collaboration with experimentalists)

- Existence of a **M4 super-stretched** state in ^{13}C.
  (Almost) **pure neutron excitation from $0p_{3/2}$ to $0d_{5/2}$**
  Gives precise information on the nuclear interaction.

- In **collaboration with experimentalists** from Kraków
  Experience performed at the **Cyclotron Centre Bronowice**
  at IFJ-PAN Kraków





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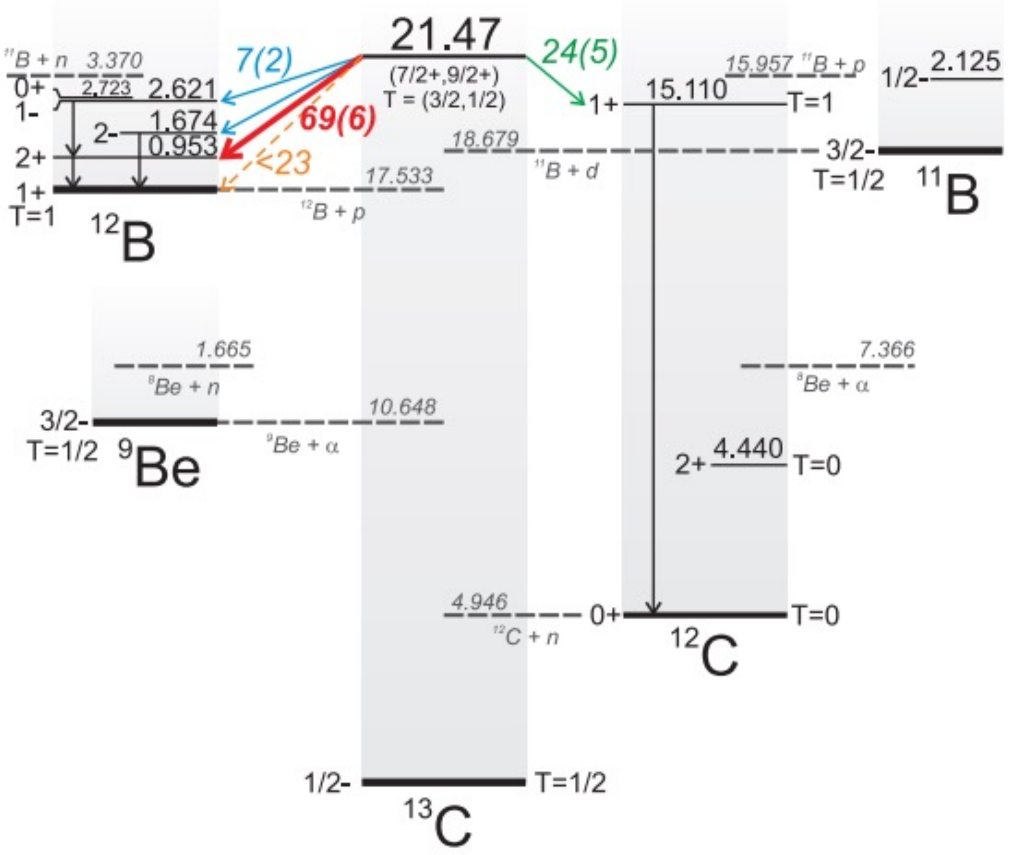

N. Cieplicka, Y. J. *et al.*, Phys. Lett. B 834, 137398 (2022)

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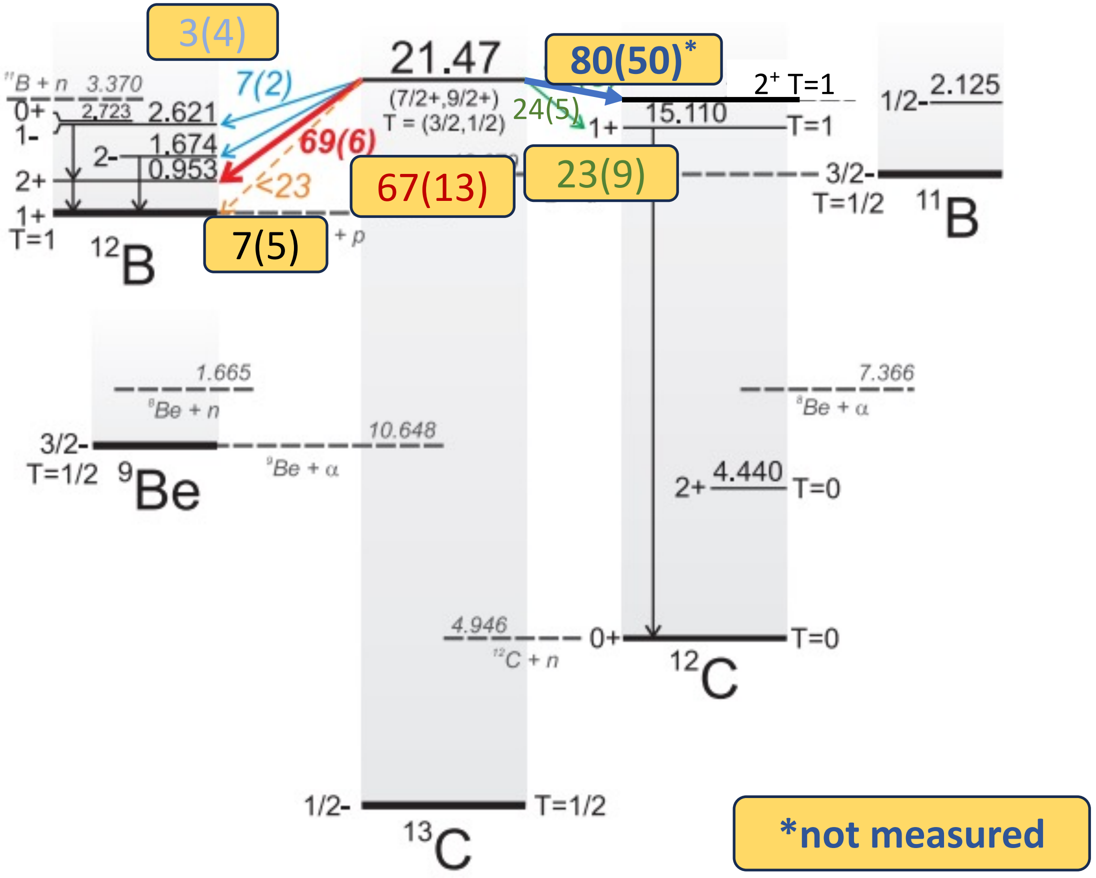
- **Fine-tuning** of the previous interaction to the neighboring states/nuclei.
- **High phenomenology is often required to describe experimental data** with an acceptable precision.



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Self-consistent calculations / Genuine ternary fission

- In the **Hartree-Fock + BCS method**, the nuclear states are obtained by minimizing the Routhian:

$$\delta\left(\left\langle \phi \,\middle|\, \hat{H} - \sum_i \lambda_i \hat{Q}_i - \lambda_N \hat{N} - \lambda_Z \hat{Z} \,\middle|\, \phi \right\rangle\right) = 0$$

with the **constraints** $\langle\phi|\hat{Q}|\phi\rangle = Q_{constr}$ (**quadrupole moment etc.**)

- One obtains the **ground states** and **some excited states**.
- **Possibilities to go beyond mean-field to compute the whole spectrum.**

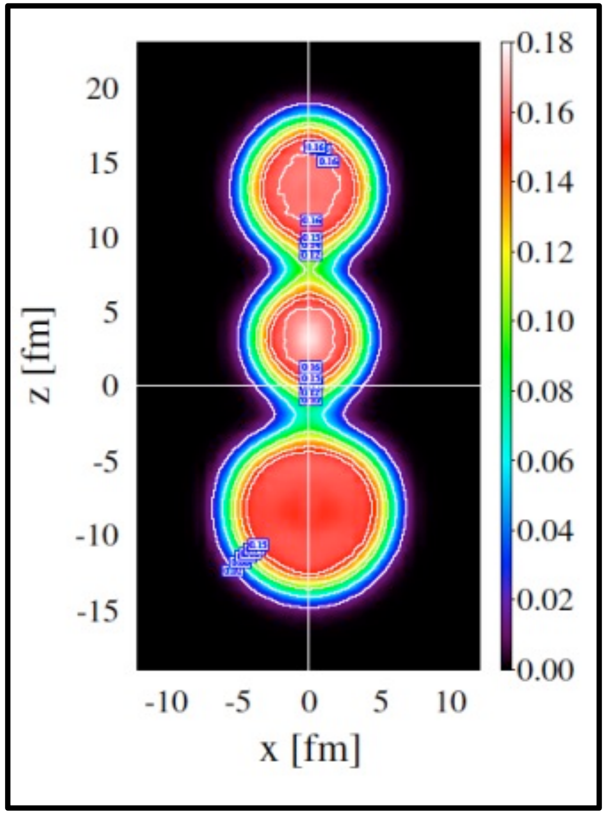
Self-consistent calculations / Genuine ternary fission

- A **question out of curiosity…**

- **Genuine ternary fission** is **an extremely rare process**.
- Generally, the additional fragment is an α-particle.
- The existence of genuine **ternary fission with a heavier fragment is still an open question**.

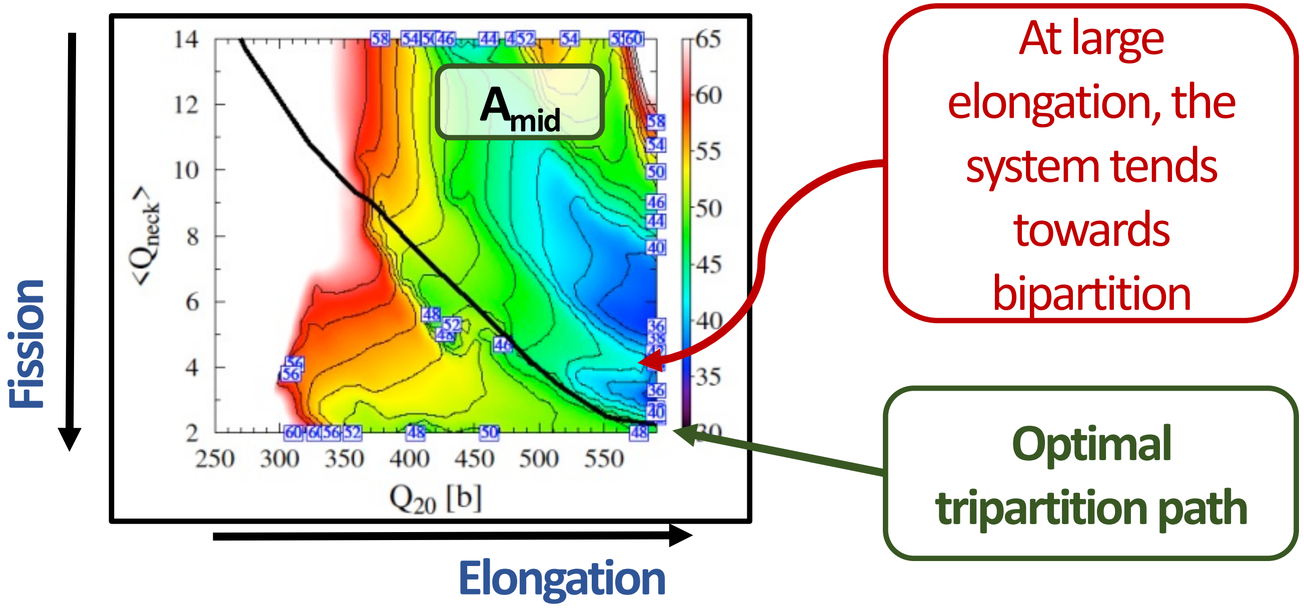
- Actinides: $^{252}_{98}\mathrm{Cf} \rightarrow {}^{132}_{50}\mathrm{Sn}_{82} + {}^{48}_{20}\mathrm{Ca}_{28} + {}^{72}_{28}\mathrm{Ni}_{44}$
- **Experimental hints** to a colinear tripartition fission.

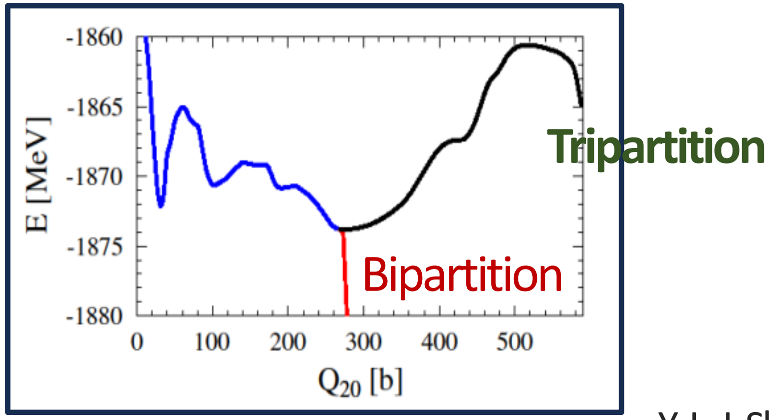
- HF + BCS calculations with **neck constraints.**



Self-consistent calculations / Genuine ternary fission

- With neck constraints properly chosen for ^{48}**Ca** as the middle fragment, one sees a **potential path to tripartition**.
- **Tripartition possible with a barrier of ~13MeV**.
- Impossible paths for other partitions (^{40}S).





Y. J., J. Skalski, in preparation

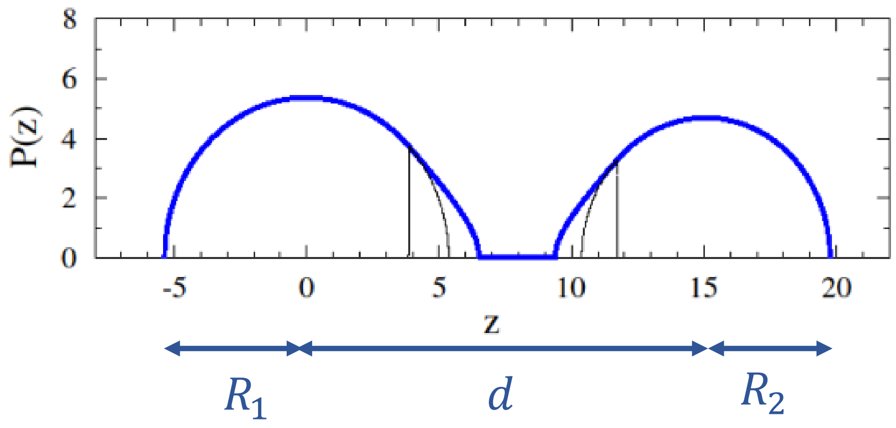
Dissipative dynamics / Fusion in the Langevin formalism

$^{92}Zr + ^{64}Ni$

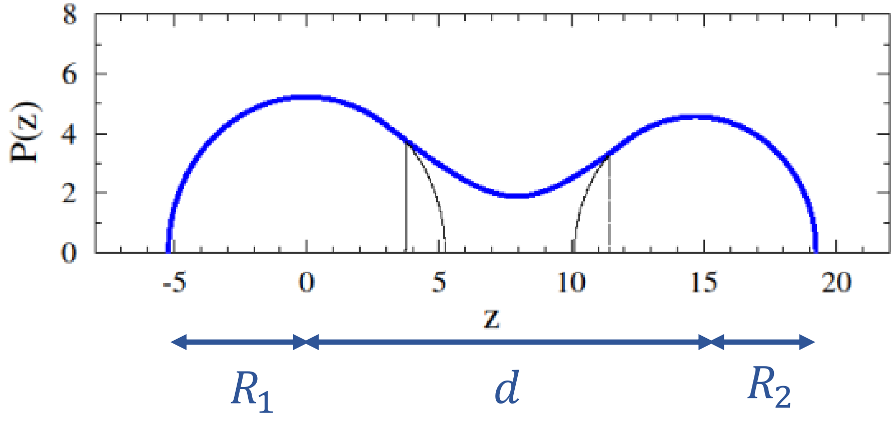
- Axially symmetric **parameterized** shapes.
- **Spherical** cups connected by quadratic surfaces[1]

- **Three shape variables**:
  - **Distance/elongation ρ**
  - **Neck/deformation λ**
  - **Asymmetry Δ**

- Three angular variables:
  - For a correct description of angular momentum



Bipartite
$\rho = 1.5$
$\lambda = 0.3$
$\Delta = \Delta_0$



Monopartite
$\rho = 1.5$
$\lambda = 0.4$
$\Delta = \Delta_0$

[1] J. Błocki, H. Feldmeier and W. J. Świątecki, Nucl. Phys. A 459 (1986) 145

Dissipative dynamics / Fusion in the Langevin formalism

- The **collective variables** $q_i(t)$ and their **associated moments** $p_i(t)$ follow the **Langevin equations**:

$$\dot{q}_i(t) = \sum_k (\mathcal{M}^{-1})_{ik}\, p_k \qquad \leftrightarrow (P = MV)$$

$$\dot{p}_i(t) = -\frac{\partial H}{\partial q_i} - \sum_k \gamma_{ik}\, \dot{q}_k + \sum_k g_{ik}\, \xi_k(t) \qquad \leftrightarrow \left(\frac{dP}{dt} = \sum F\right)$$

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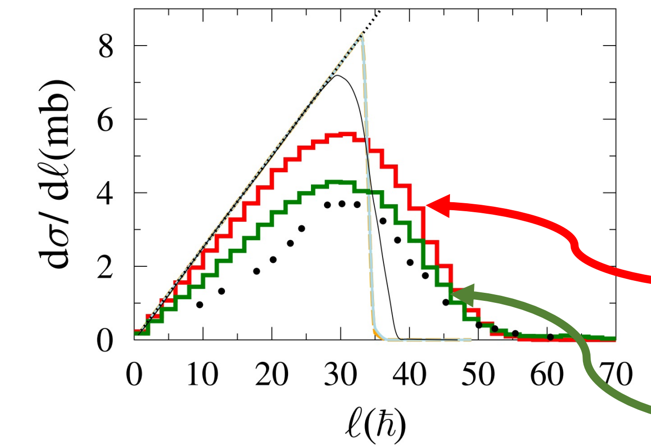
Conservative forces
$H = T + V$, V **can be macroscopic or microscopic (shell corrections)**

Langevin/random forces
(quantum origin)

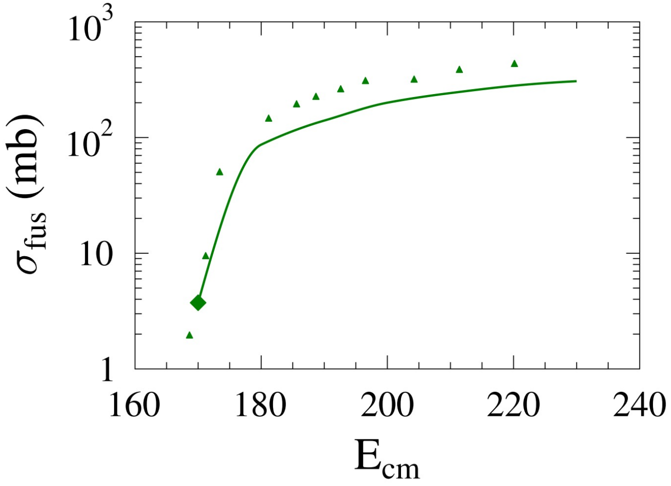
→ A **comprehensive understanding of the dynamics process.**

Dissipative dynamics / Fusion in the Langevin formalism

- Experimental data are **well reproduced with a simple Yukawa-plus-exponential folding potential + Coulomb macroscopic potential.**
- **No parameters adjusted to our calculations!**
- Upcoming calculations involving heavier systems (^{50}Ti, ^{54}Cr) to study the **hindrance mechanism**, which **prevents the formation of super-heavy nuclei.**



Spin distribution of ^{64}Ni + ^{92}Zr → ^{156}Er at E_{cm} = 138.8 MeV



Excitation function of ^{48}Ca + ^{208}Pb ⟶ ^{256}No

Y. J., M. Kowal *et al.* in preparation

Conclusions and perspectives

- **Nuclear Theory** is an **extremely diverse field**, encompassing different types of Physics.
- **All nuclear models are phenomenological**, with the level of phenomenology depending on the Physics they are aiming to explain.
- Many open problems persist in Nuclear Theory, with **potential solutions increasingly attainable thanks to advances in supercomputing.**

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Dziękuję za państwa uwagę!