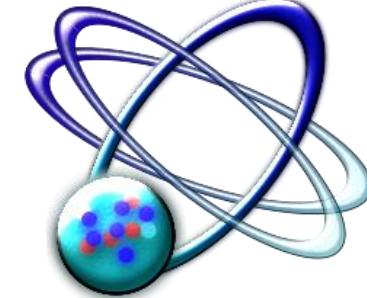




Laboratoire de Physique
des 2 Infinis



Nuclear structure and α radioactivity



PhyNet

Florian MERCIER
IJCLab, Orsay
PhyNet

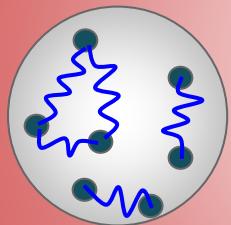
Supervisors :
Elias KHAN
Jean-Paul EBRAN

- I. The nuclear many body problem
- II. Microscopic description of radioactivity
- III. Application to alpha and cluster radioactivity



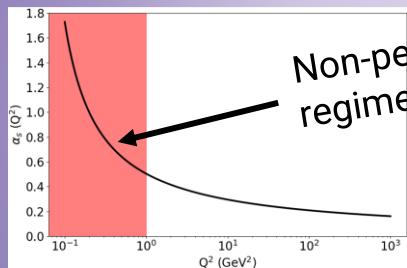
Tackling the nuclear many body problem

Quantum many body interacting problem !



Many (strongly) interacting particles but not enough for statistical approximation
TOOOOO hard to be solved exactly

Interaction coming from (non-perturbative) QCD !



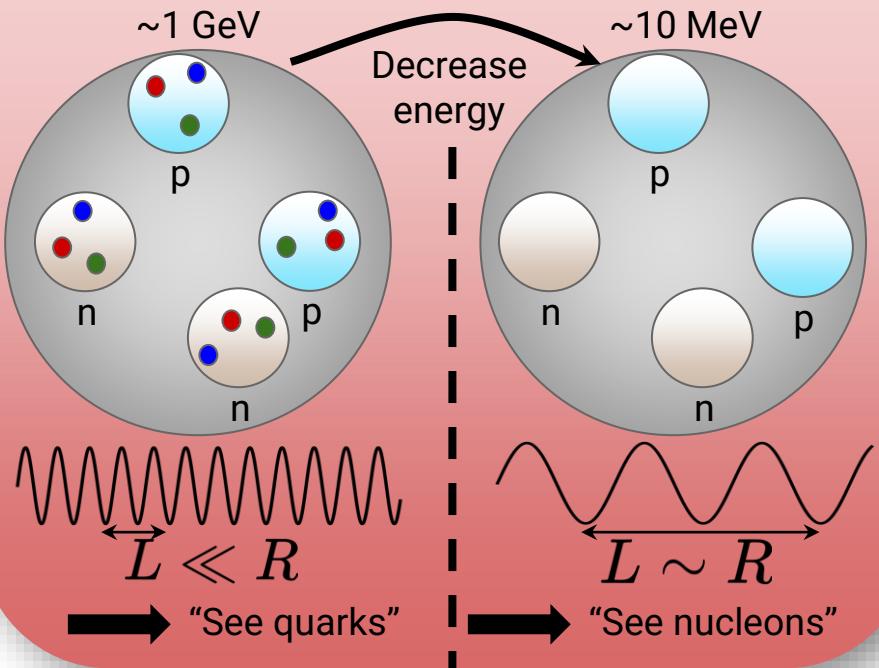
Non-perturbative regime at low energy !
EFT
Relevant degrees of freedom ?
 $2N, 3N, 4N, \dots$ interactions

Huge phenomenology !

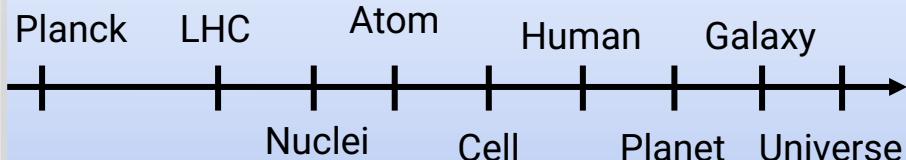
Many emerging properties : deformation, radioactivity, halo, neutron skin, superfluidity, clustering, excitations, ...

Building an interaction : what is the idea ?

Relevant degrees of freedom ?



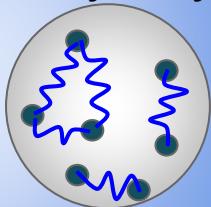
Effective field theory



- Scale separation is the key ingredient
- Zooming out (decreasing energy, increasing scale) leads to different theories !
- Allows a scale by scale study in Science !

Many body interacting problem

Strongly **interacting** many body system



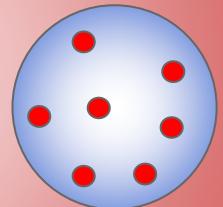
VERY HARD

Mapping



Fermi liquid

One-body problem involving **independent** quasi-particles



Mean-field

Idea :
$$H = \left[\sum_i \frac{p_i^2}{2m} \right] + \left[\sum_{ij} V_{ij} + \sum_{i < j < k} V_{ijk} + \dots \right]$$

$$= \left[\sum_i \frac{p_i^2}{2m} + U_i \right] + \left[\sum_{ij} V_{ij} + \sum_{i < j < k} V_{ijk} + \dots - \sum_i U_i \right]$$

$$= H_0 + \mathcal{V}_{res}$$

Such that

$$|H_0| \gg |\mathcal{V}_{res}|$$

One body term

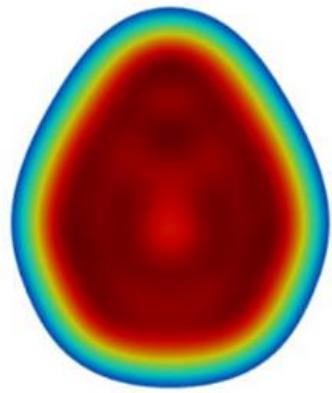


Find the "best" U_i

As much physics
as possible

Justify perturbative
approach

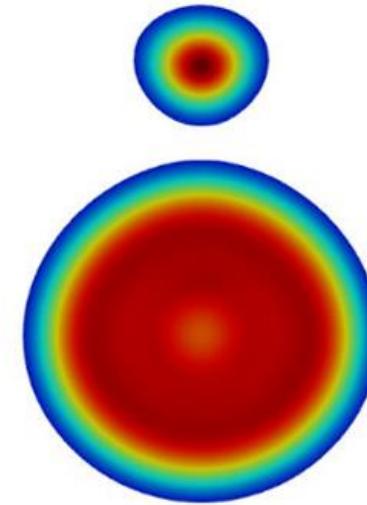
Microscopic description of radioactivity



Initial state



Is it possible to find a continuous transformation between initial and final state ?

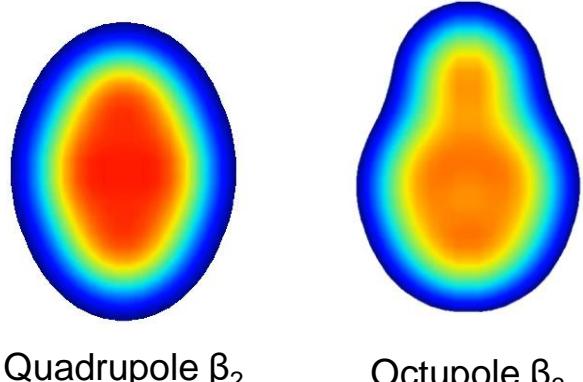


Final state



Impose deformation and compute the energy cost for the system

Microscopic description of radioactivity

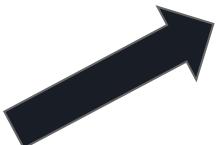


Quadrupole β_2

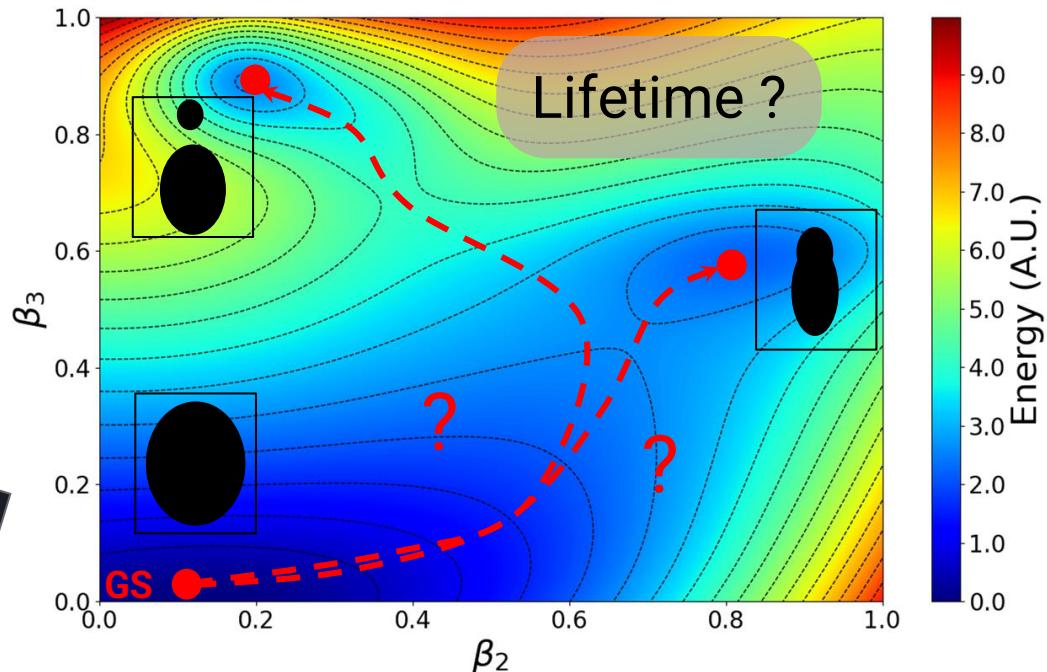
Octupole β_3

Constrain these parameters and compute the associated energy for each of these states

$$E(\beta_2, \beta_3)$$



Example of a Potential Energy Surface (PES)



Lifetime computation

What do we need to minimize to find the “good” path ?

$$\cancel{S(L) = \int_{s_{in}}^{s_{out}} V(s) ds} \quad ?$$

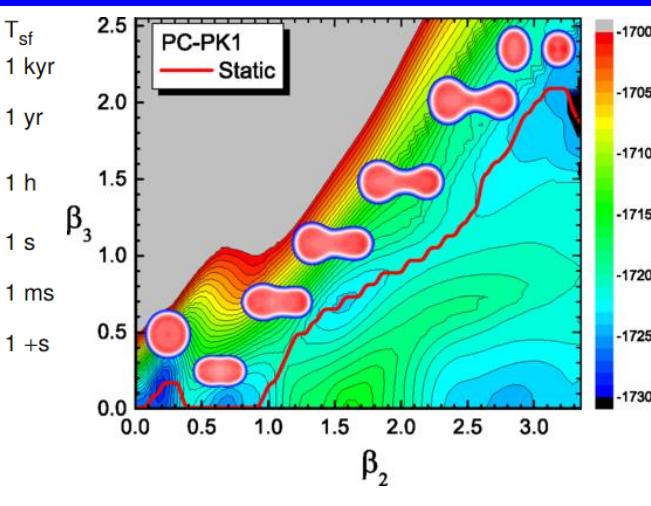
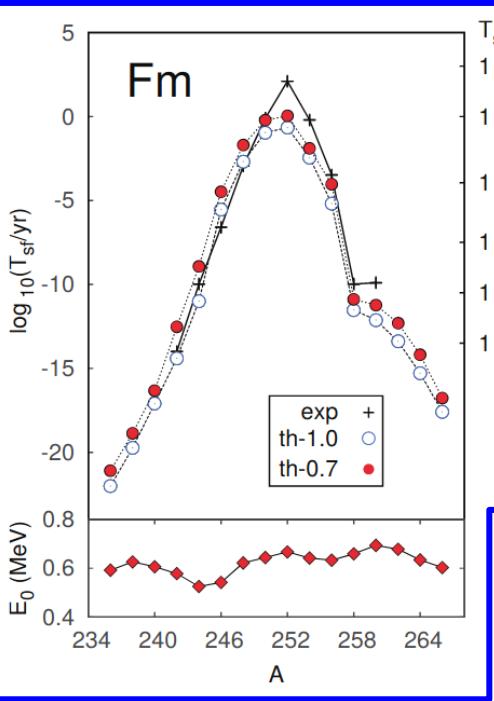
$$S(L) = \int_{s_{in}}^{s_{out}} \frac{1}{\hbar} \sqrt{2\mathcal{M}_{\text{eff}}(s)} [V_{\text{eff}}(s) - E_0] ds$$

Inertial (effective) mass : information about the dynamic.
Computed using Adiabatic Time Dependent Hartree Fock Bogoliubov method (ATDHFB) and perturbative cranking approximation

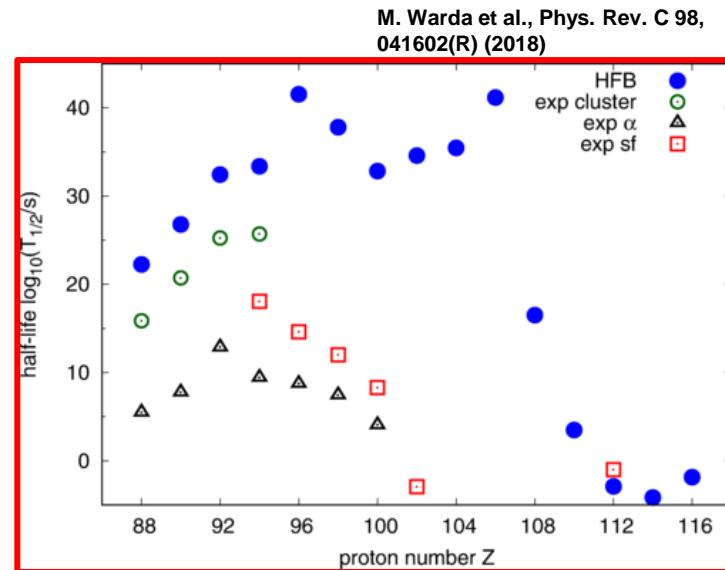
PES : information about the energy cost of a certain path

$$\delta S = 0 \rightarrow \tau \approx A \exp[2S(L)]$$

Previous results for fission and cluster emission



H. Tao, J. Zhao, Z. P. Li, T. Nikšić, and D. Vretenar, Phys. Rev. C 96, 024319 (2017)



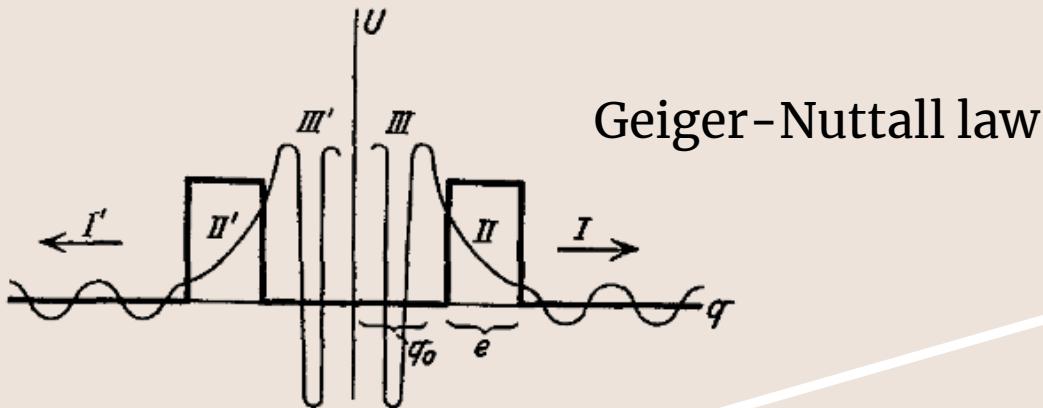
M. Warda et al., Phys. Rev. C 98, 041602(R) (2018)



Successful application to fission and
cluster radioactivity

N. Schunck and L M Robledo,
Reports on Progress in Physics,
Volume 79, Number 11 (2016)

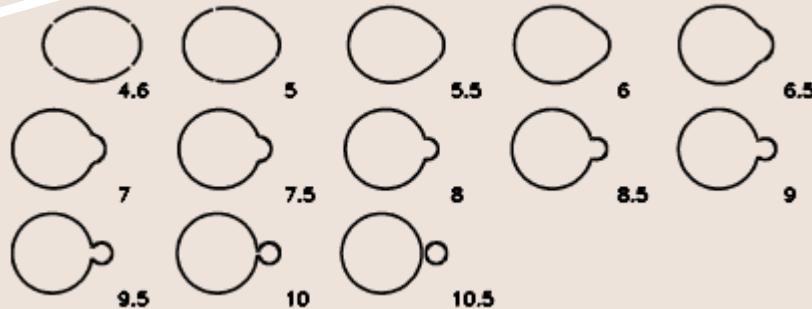
What about α decay ?



G. Gamow, Eur. Phys. J. A
51, 204 (1928)

WKB model

Geiger-Nuttall law



Microscopic-macroscopic
approaches

M. Mirea, R. Budaca, and A. Sandulescu,
Ann. Phys. (NY) 380, 154 (2017).

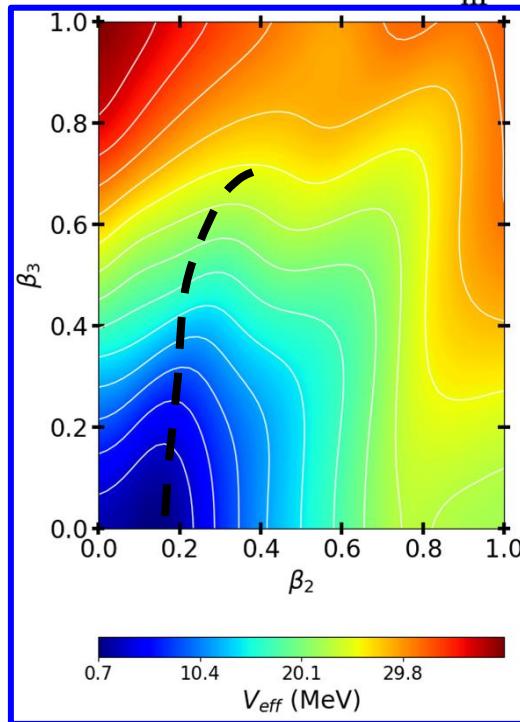
α preformation factor

Results for α decay of ^{104}Te

F. Mercier et al., Phys. Rev. C 102, 011301(R) (2020)

^{104}Te

$$S(L) = \int_{s_{\text{in}}}^{s_{\text{out}}} \frac{1}{\hbar} \sqrt{2\mathcal{M}_{\text{eff}}(s)} [V_{\text{eff}}(s) - E_0] ds$$

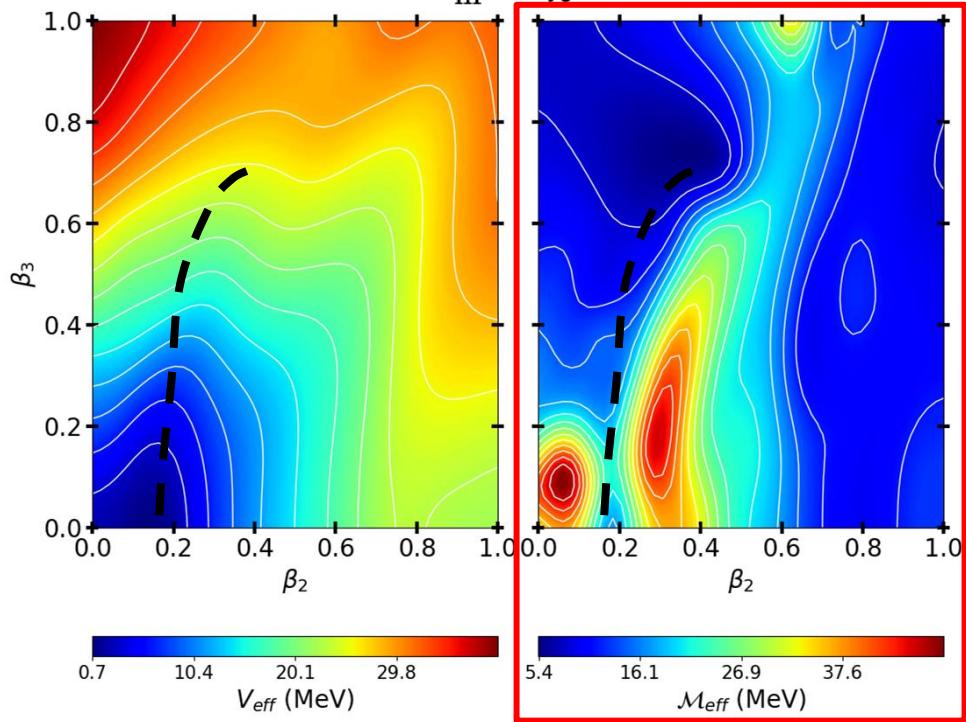


Results for α decay of ^{104}Te

F. Mercier et al., Phys. Rev. C 102, 011301(R) (2020)

^{104}Te

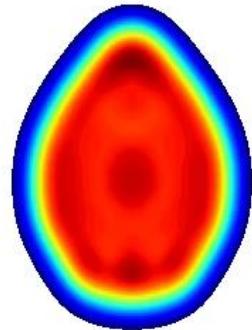
$$S(L) = \int_{s_{\text{in}}}^{s_{\text{out}}} \frac{1}{\hbar} \sqrt{2\mathcal{M}_{\text{eff}}(s)} [V_{\text{eff}}(s) - E_0] ds$$



Results for α decay of ^{104}Te

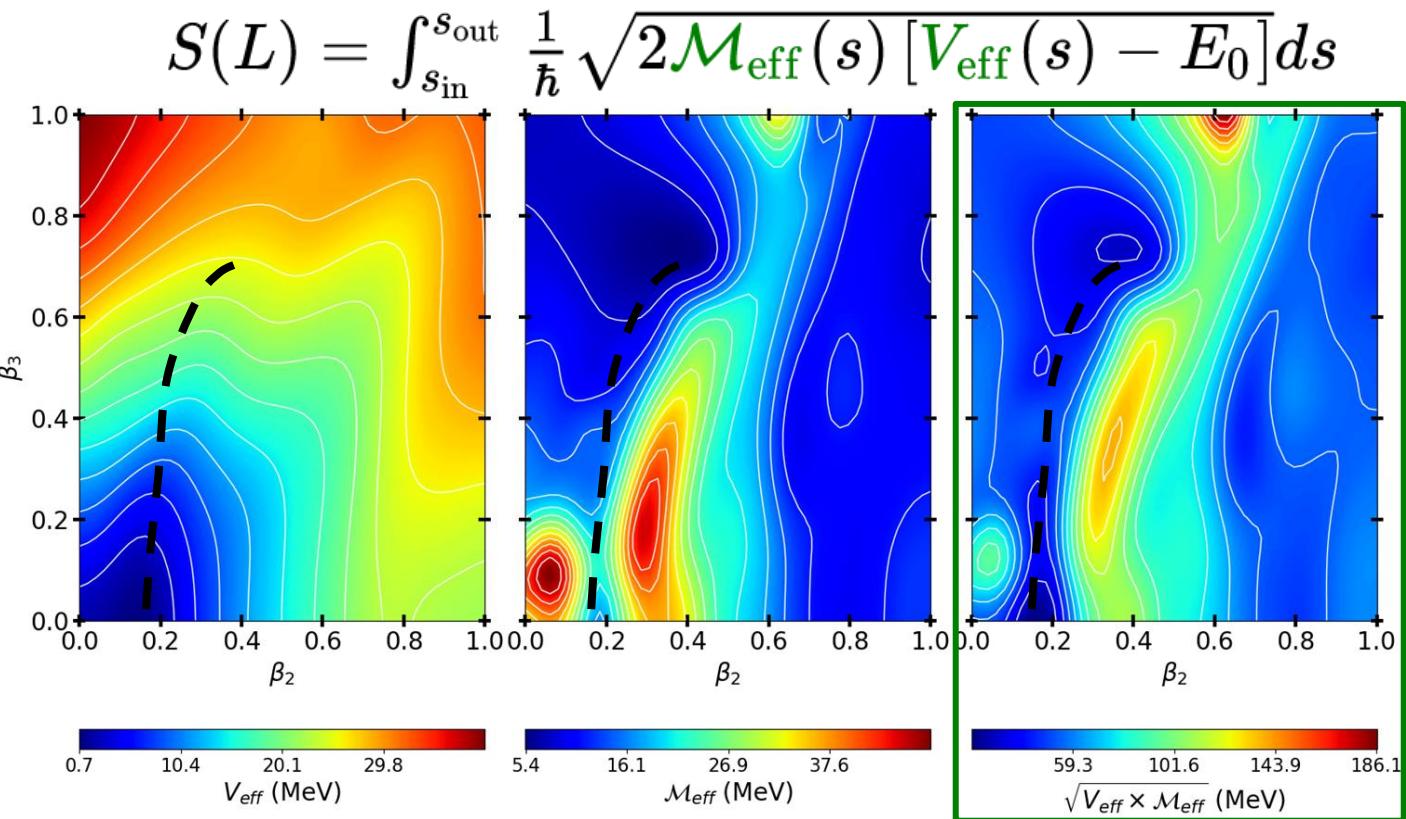
F. Mercier et al., Phys. Rev. C 102, 011301(R) (2020)

^{104}Te

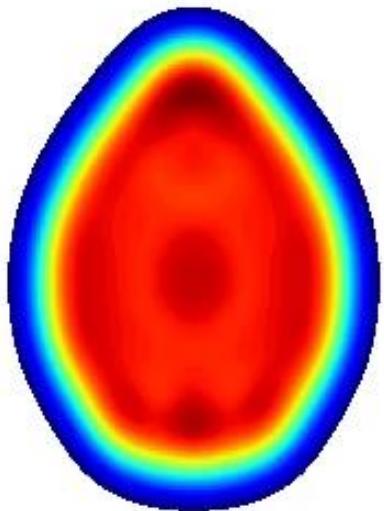


$$\tau_{\text{th}} = 192 \mu\text{s}$$

$$\tau_{\text{exp}} < 18 \mu\text{s}$$



A disturbing similarity ...



$$\tau_\alpha \approx 2.0 \times 10^{-7} \text{ s}$$



$$\tau_{pearl} \approx 5 \times 10^8 \text{ s}$$

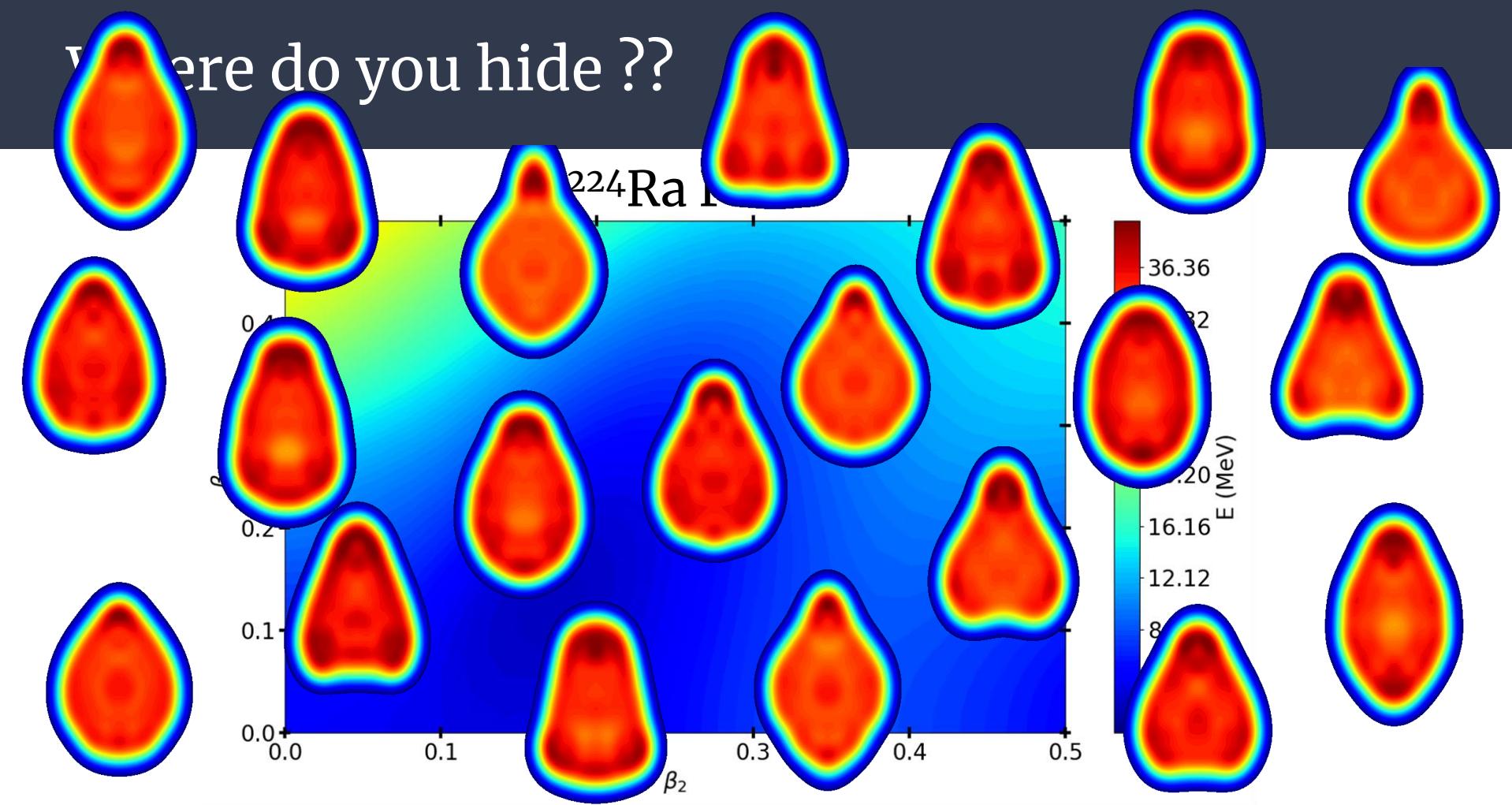


A small discrepancy but very promising results !

Application to heavier nuclei ...

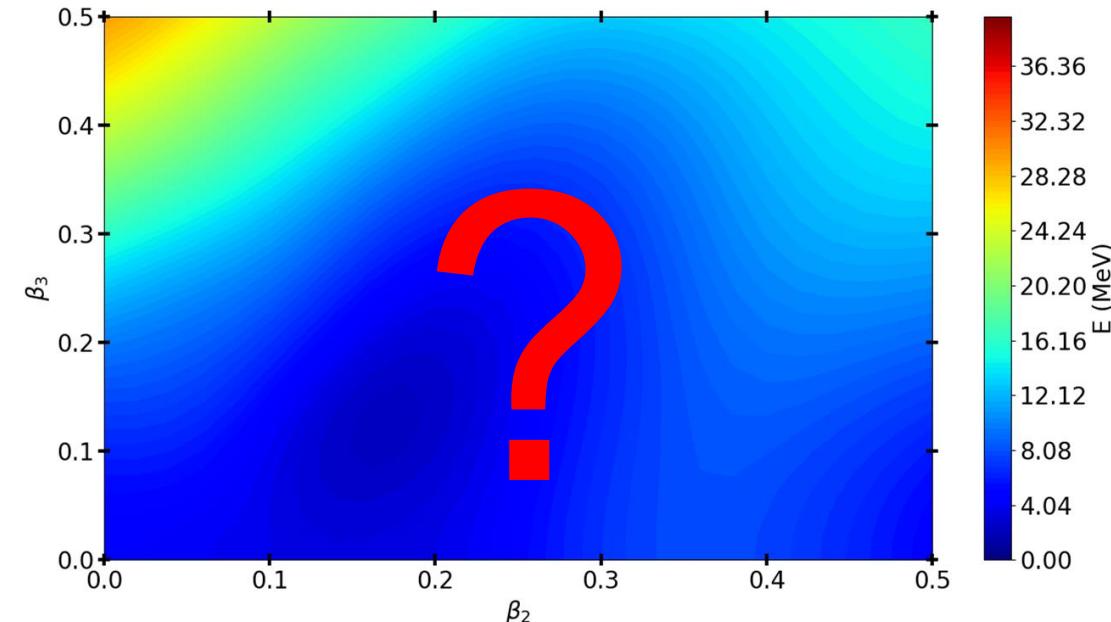
... or the problem of finding an α !

Where do you hide ??



Where do you hide ??

^{224}Ra PES



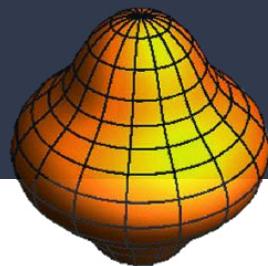
Does not mean it does not exist !

We need to understand what it means to preform and emit an alpha from the deformation point of view !

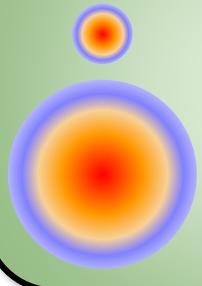


Simply put two spheres on top of each others and compute the deformation parameters

Where do you hide ??



Geometrical model



$$\beta_2 = 0.15$$

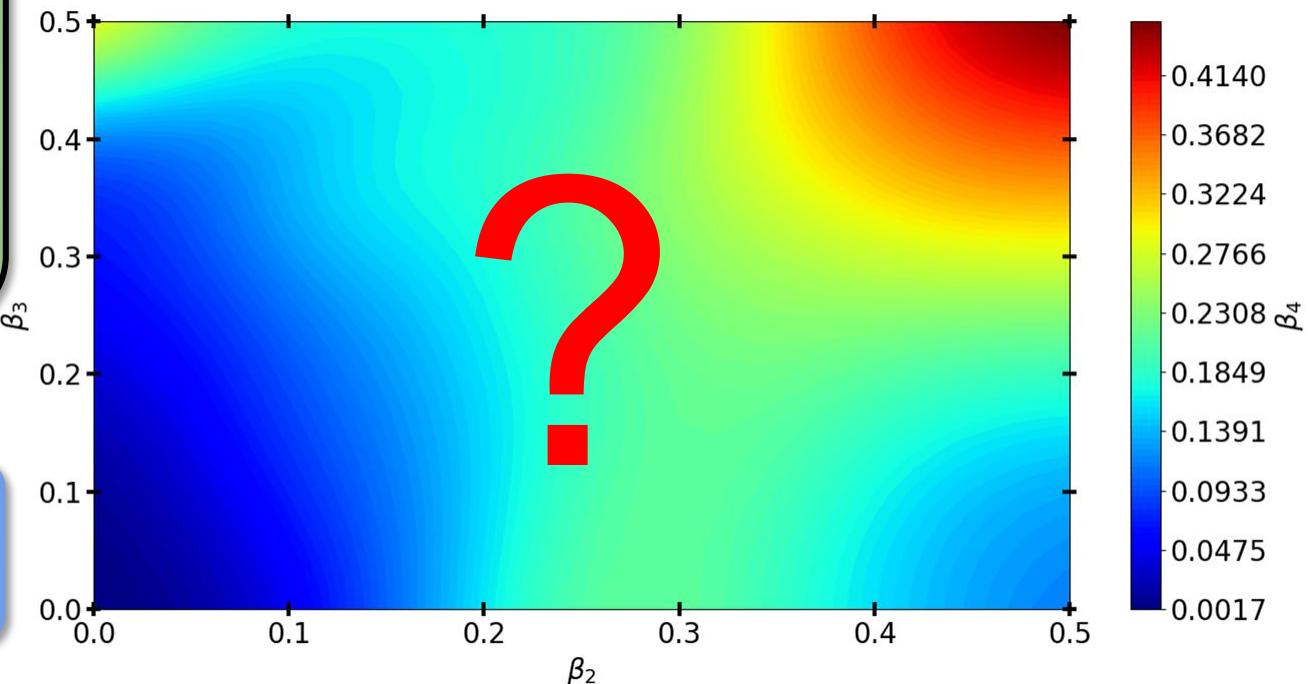
$$\beta_3 = 0.4$$

$$\beta_4 = 0.7$$



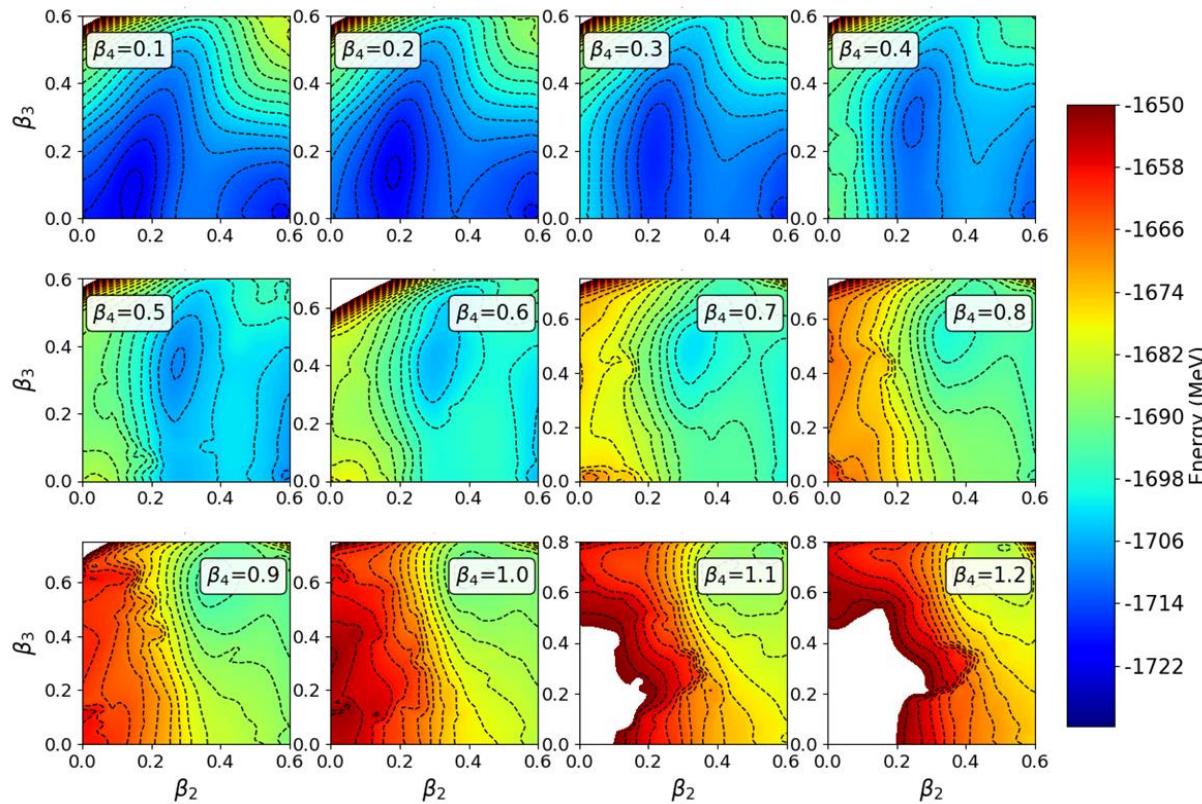
We need to constrain the hexadecapole moment to see an α particle !!

^{224}Ra β_4 values



3D PES for ^{224}Ra

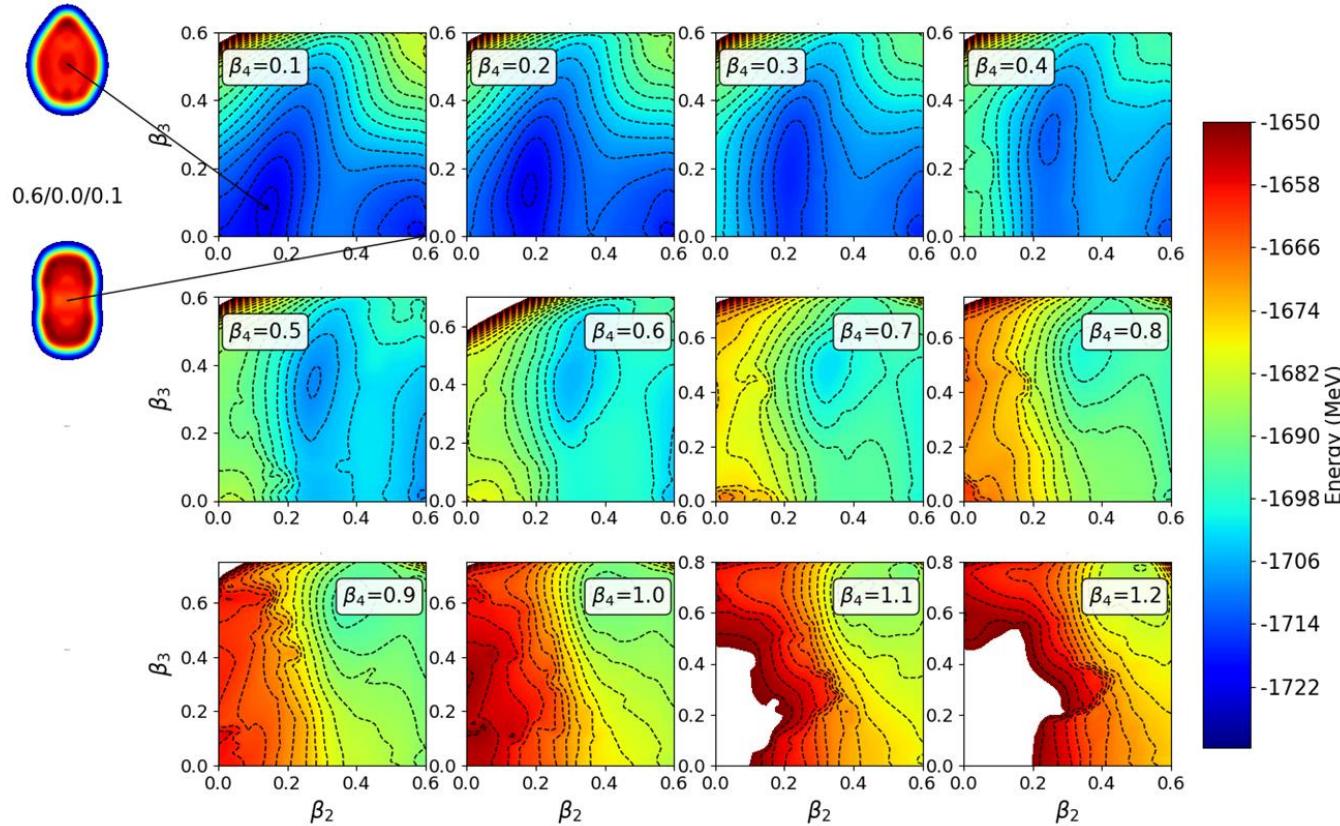
F. Mercier et al., Phys. Rev. Lett. 127, 012501 (2021)



3D PES for ^{224}Ra

F. Mercier et al., Phys. Rev. Lett. 127, 012501 (2021)

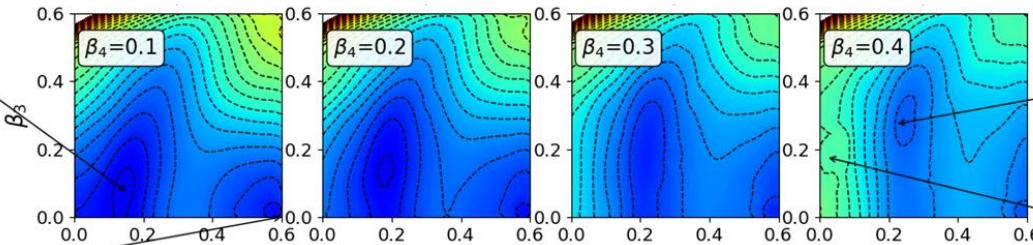
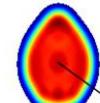
0.15/0.075/0.1



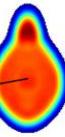
3D PES for ^{224}Ra

F. Mercier et al., Phys. Rev. Lett. 127, 012501 (2021)

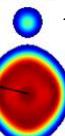
0.15/0.075/0.1



0.225/0.275/0.4

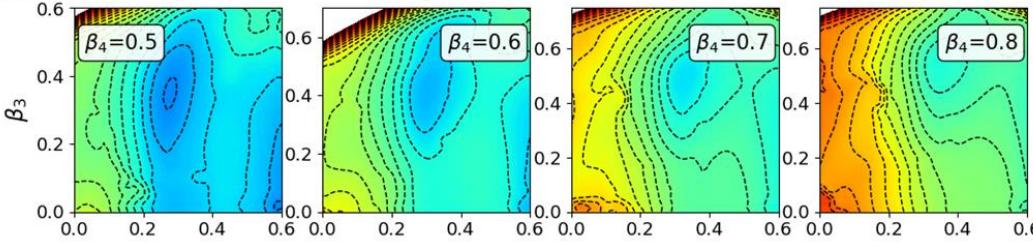


0.025/0.175/0.4



Almost 4 nucleons !

0.6/0.0/0.1



-1650

-1658

-1666

-1674

-1682

-1690

-1698

-1706

-1714

-1722

Energy (MeV)

β_3

β_3

β_3

β_3

β_3

β_2

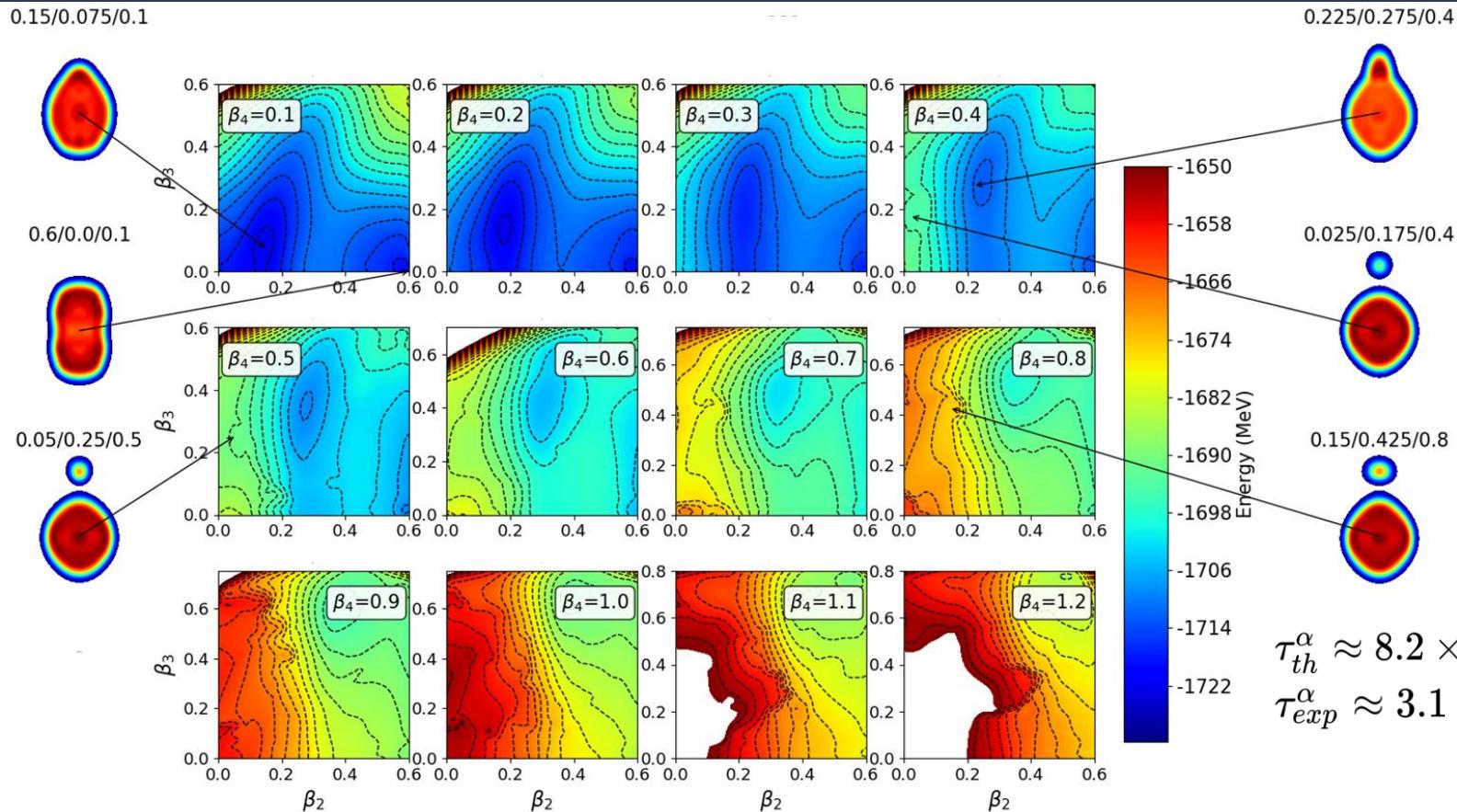
β_2

β_2

β_2

3D PES for ^{224}Ra

F. Mercier et al., Phys. Rev. Lett. 127, 012501 (2021)

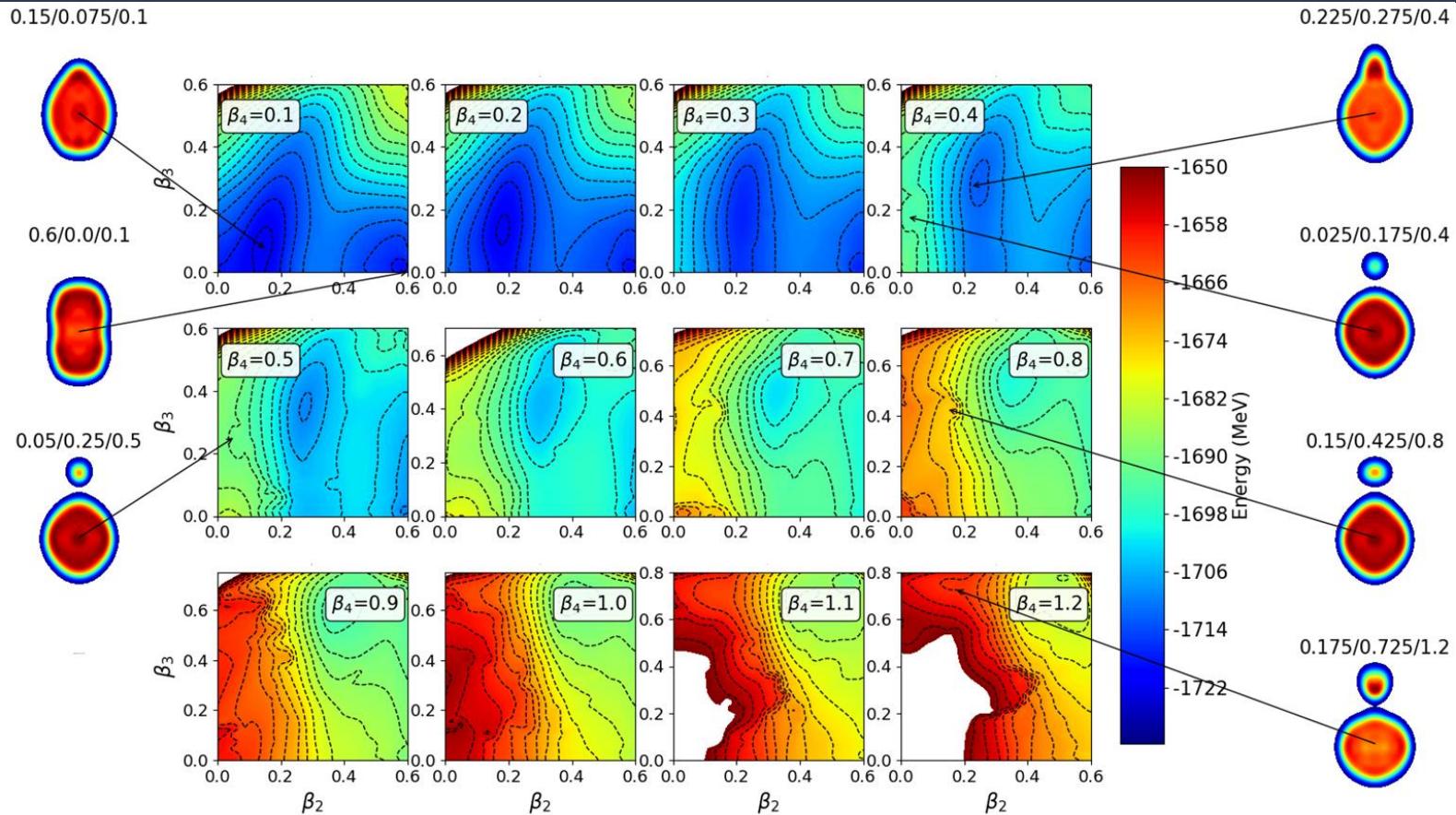


$$\tau_{th}^\alpha \approx 8.2 \times 10^5 \text{ s}$$

$$\tau_{exp}^\alpha \approx 3.1 \times 10^5 \text{ s}$$

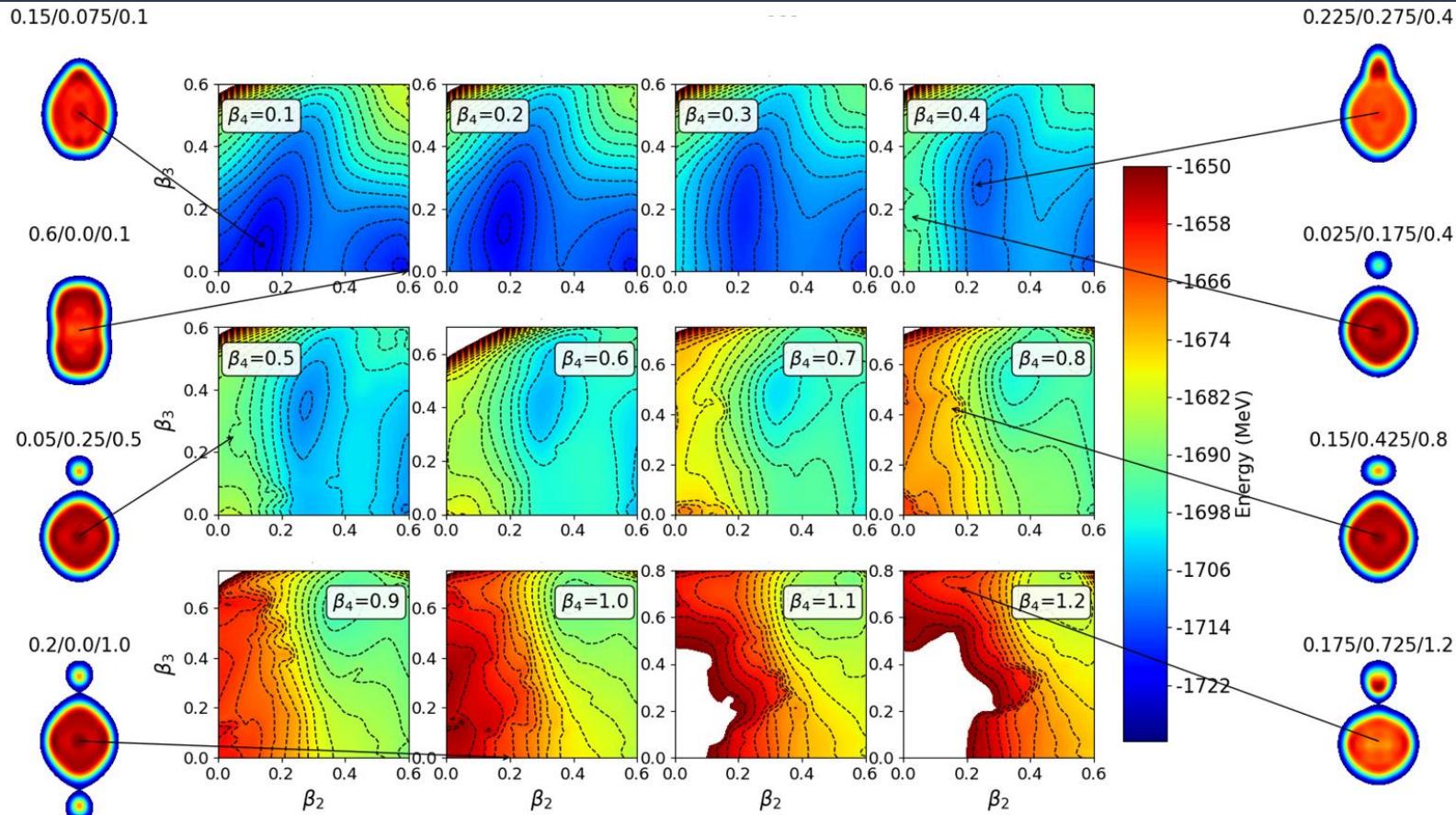
3D PES for ^{224}Ra

F. Mercier et al., Phys. Rev. Lett. 127, 012501 (2021)

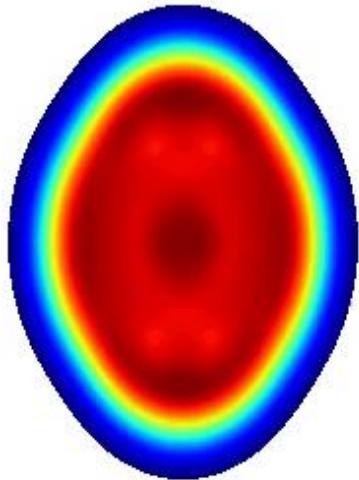


3D PES for ^{224}Ra

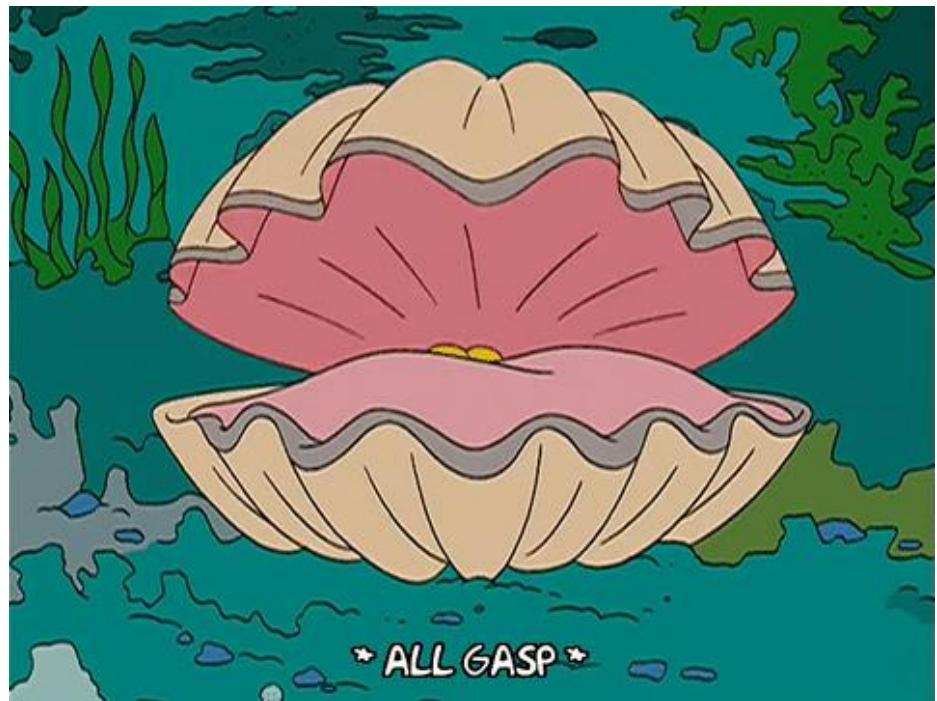
F. Mercier et al., Phys. Rev. Lett. 127, 012501 (2021)



About the relevance of such a prediction



$$\tau_{2\alpha} \approx 1.7 \times 10^{14} \text{ s}$$

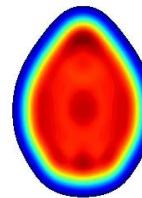


$$\tau_{2 \text{ pearls}} \approx 5.0 \times 10^{13} \text{ s}$$

Conclusion : a single framework for ...

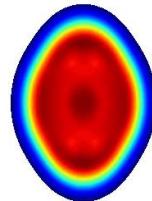
Alpha decay

Nucleus	Theoretical Lifetime	Experimental Lifetime
^{104}Te	$2.0 \times 10^{-7} \text{ s}$	$< 2 \times 10^{-8} \text{ s}$
^{108}Xe	$5.0 \times 10^{-6} \text{ s}$	$5.8 \times 10^{-6} \text{ s}$
^{212}Po	$6 \times 10^{-7} \text{ s}$	$3 \times 10^{-7} \text{ s}$
^{224}Ra	$8.2 \times 10^5 \text{ s}$	$3.1 \times 10^5 \text{ s}$



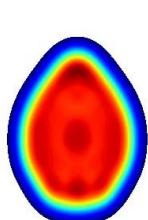
Double Alpha decay

Nucleus	Theoretical Lifetime
^{212}Po	$2.3 \times 10^{18} \text{ s}$
^{224}Ra	$1.7 \times 10^{14} \text{ s}$



Cluster decay

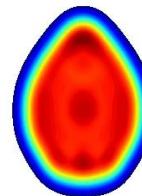
Nucleus	Theoretical Lifetime	Experimental Lifetime
^{222}Ra	$2.8 \times 10^{15} \text{ s}$	$1.0 \times 10^{12} \text{ s}$
^{224}Ra	$2.9 \times 10^{17} \text{ s}$	$7.2 \times 10^{15} \text{ s}$



Conclusion : a single framework for ...

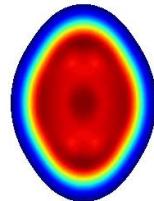
Alpha decay

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^{224}Ra	$8.2 \times 10^5 \text{ s}$	$3.1 \times 10^5 \text{ s}$

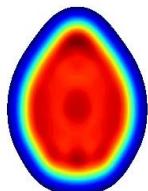


Double Alpha decay

Nucleus	Theoretical Lifetime
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Cluster decay		
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^{224}Ra	$2.9 \times 10^{17} \text{ s}$	$7.2 \times 10^{15} \text{ s}$



Double alpha decay lifetime comparable
with cluster decay



Ongoing experiment : GSI
Upcoming experiment : ISOLDE