New alpha particle radioactivity

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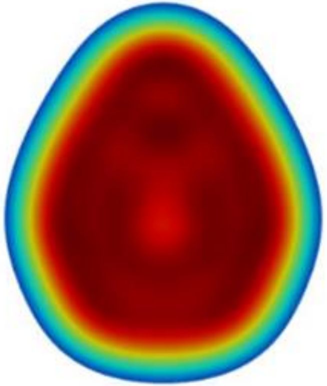
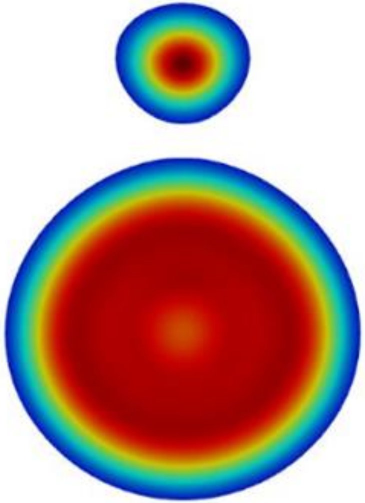
Microscopic description of radioactivity



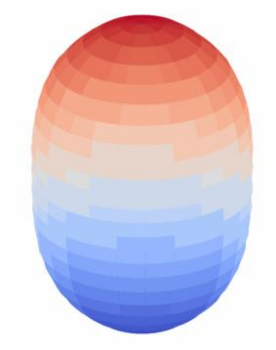
Initial state

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

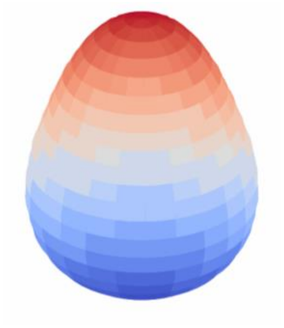


Final state

Microscopic description of radioactivity



Quadrupole β_2

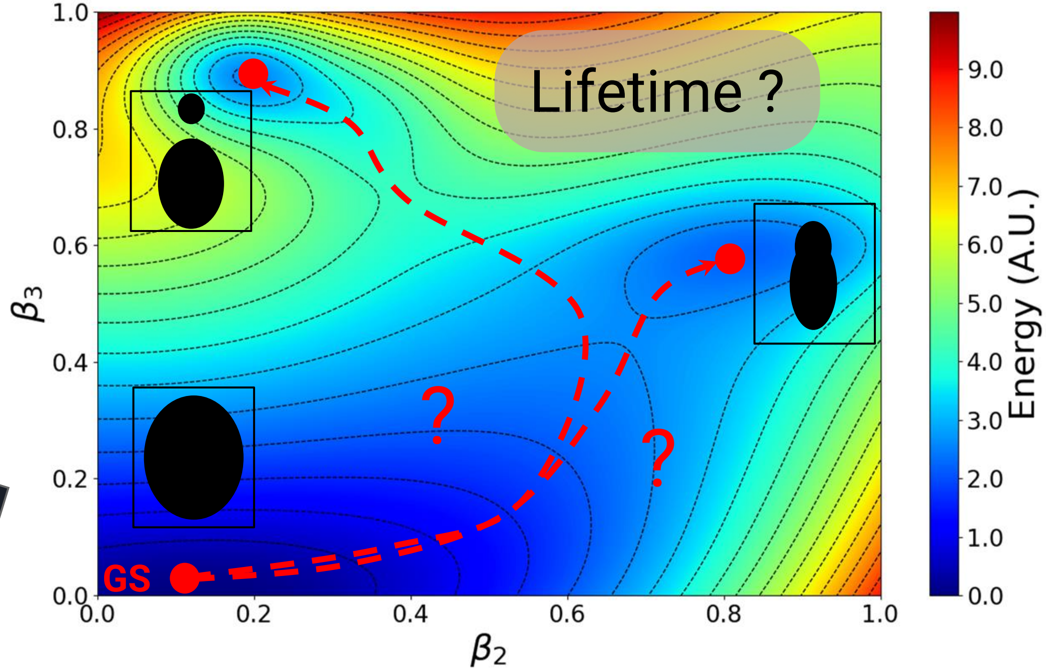


Octupole β_3

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

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

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

PES : information about the energy cost of a certain path. Computed at RHB level with covariant EDF (DD-PC1, DD-ME2 and PC-PK1)

$$\mathcal{M}_{\mathrm{eff}} = \hbar^2 M_{(1)}^{-1} M_{(3)} M_{(1)}^{-1}$$

$$[M_{(k)}]_{ij} = \sum_{\mu\nu} \frac{\langle 0|\hat{Q}_i|\mu\nu\rangle\langle\mu\nu|\hat{Q}_j|0\rangle}{(E_\mu + E_\nu)^k}$$

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

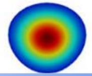
WKB

Lifetime computation

Minimizing the action in two steps :

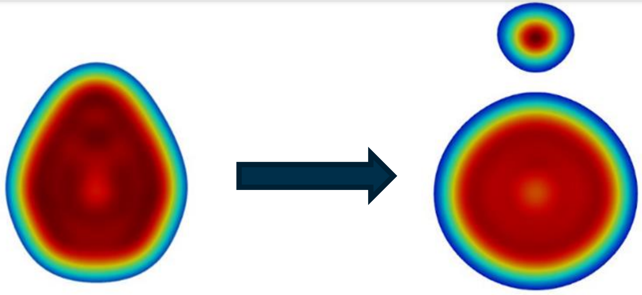
I – From ground state to scission

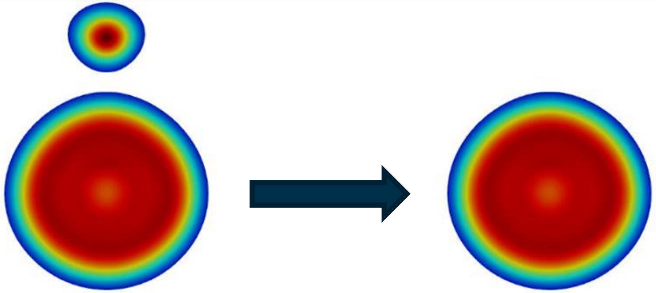
- Computation of the PES with fully self-consistant calculations
- Stop the calculations when the good number of nucleons is reached in the clusters
- Minimize the action w.r.t. β_2 and β_3



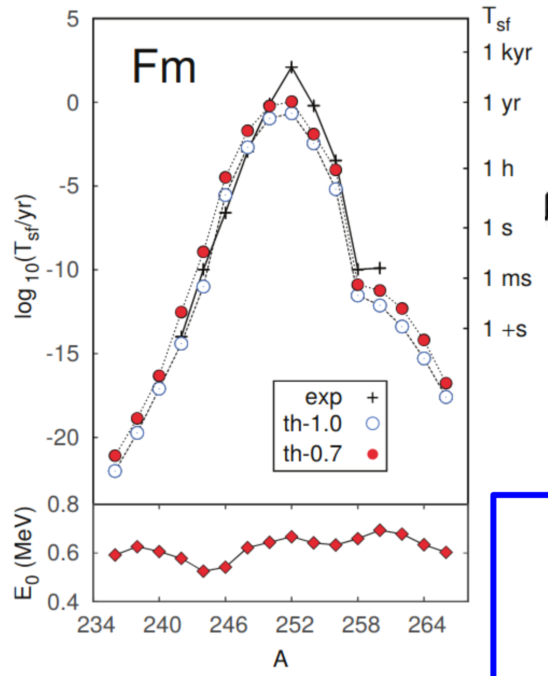
II – Fom scission to emission

- Only Coulomb $V_{eff} = V_C = e^2 \frac{Z_1 Z_2}{R} - Q$
- Classical approximation for inertial mass in terms of R.
- Minimize the action w.r.t. R.

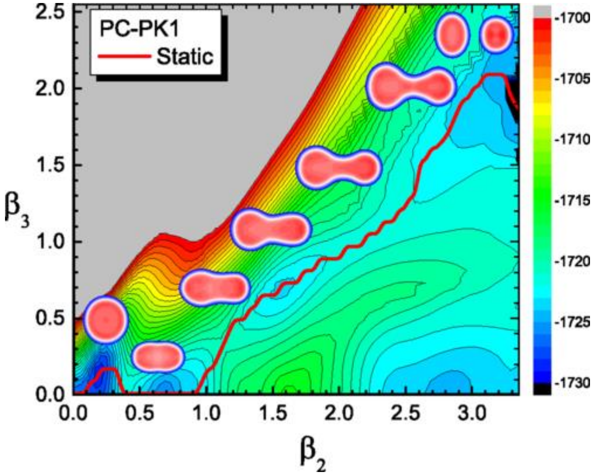




Previous results for cluster emission and fission

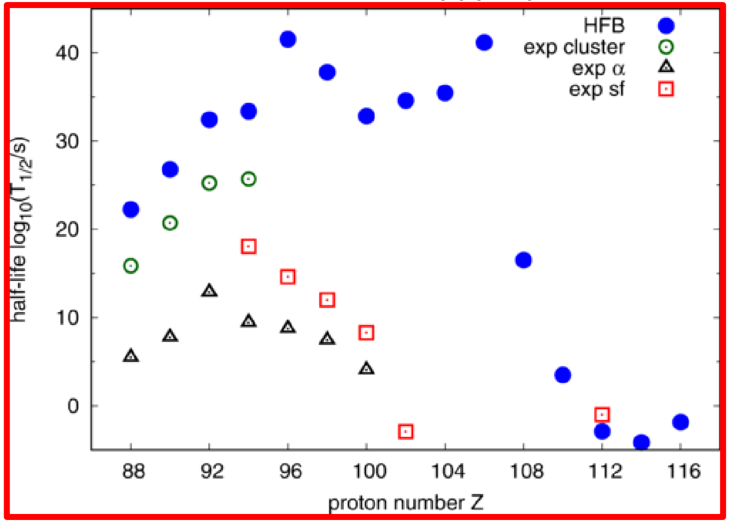


N. Schunck and L M Robledo, Reports on Progress in Physics, Volume 79, Number 11 (2016)



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

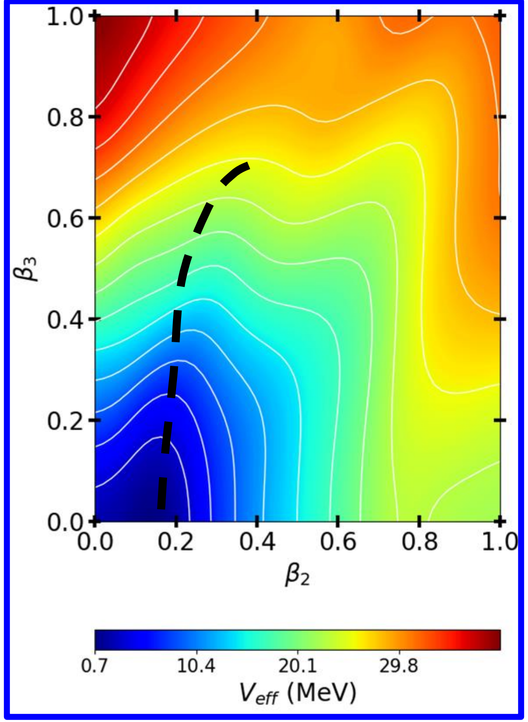
What about α decay ?

Results for α decay of ^{108}Xe and ^{104}Te

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

^{104}Te

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



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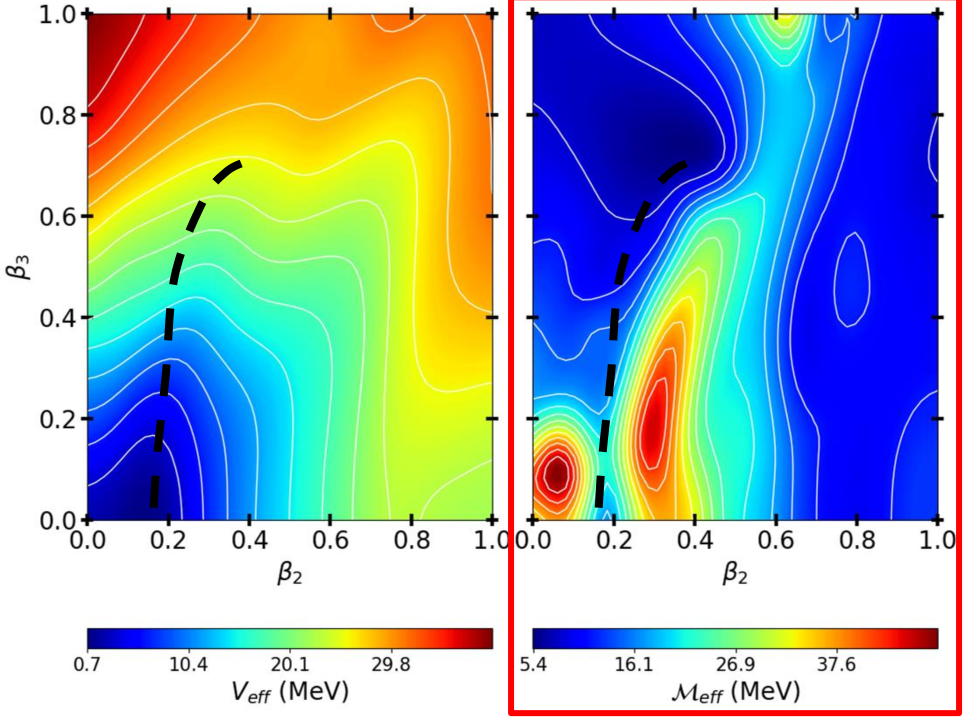

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F. Mercier et al., Phys. Rev. C 102, 011301(R) (2020)

^{104}Te

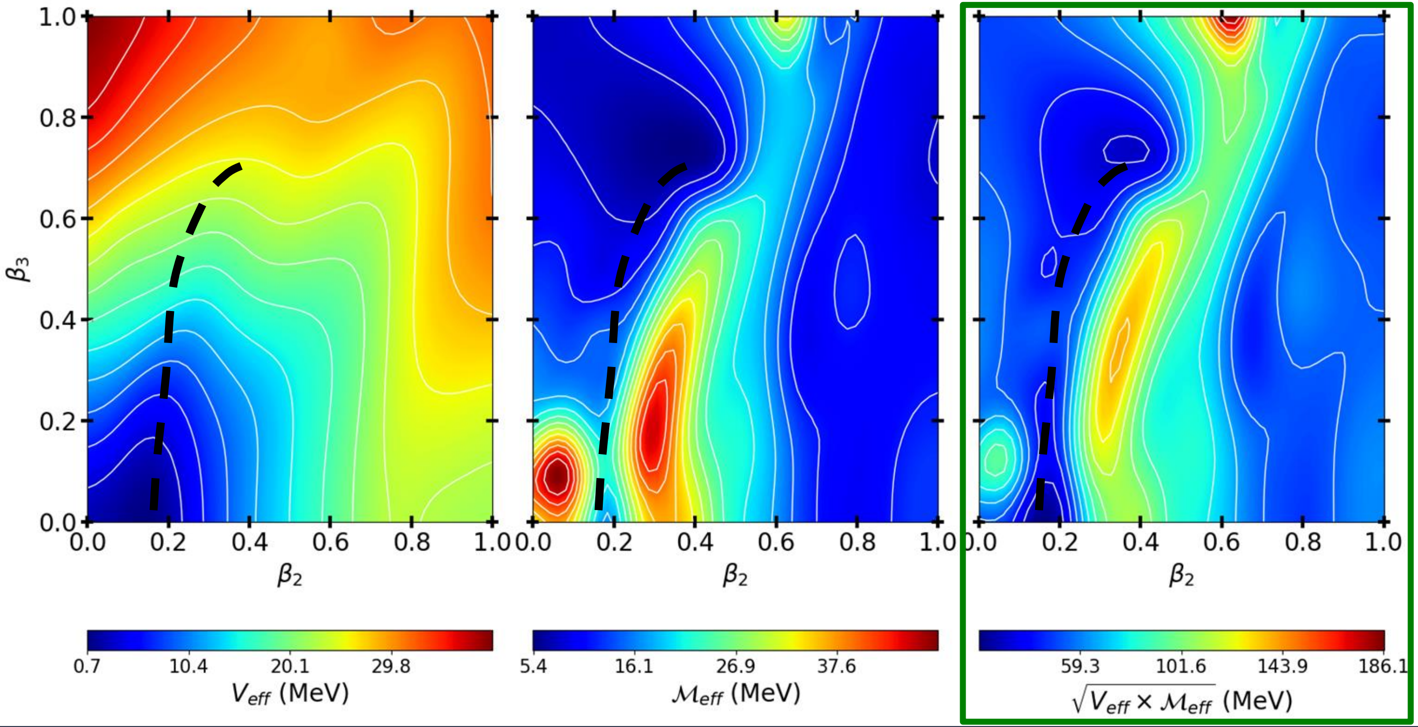
$$S(L) = \int_{s_{in}}^{s_{out}} \frac{1}{\hbar}\sqrt{2\mathcal{M}_{eff}(s)\left[V_{eff}(s) - E_0\right]}ds$$

$\tau_{th}^{104Te} = 192\ \mu s$

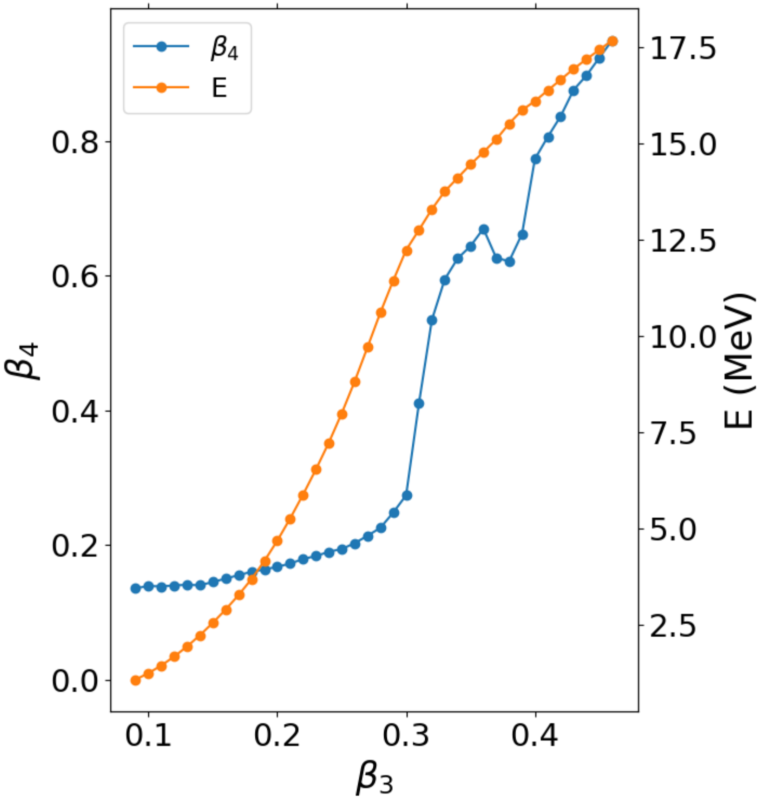
$\tau_{exp}^{104Te} < 18\ \mu s$

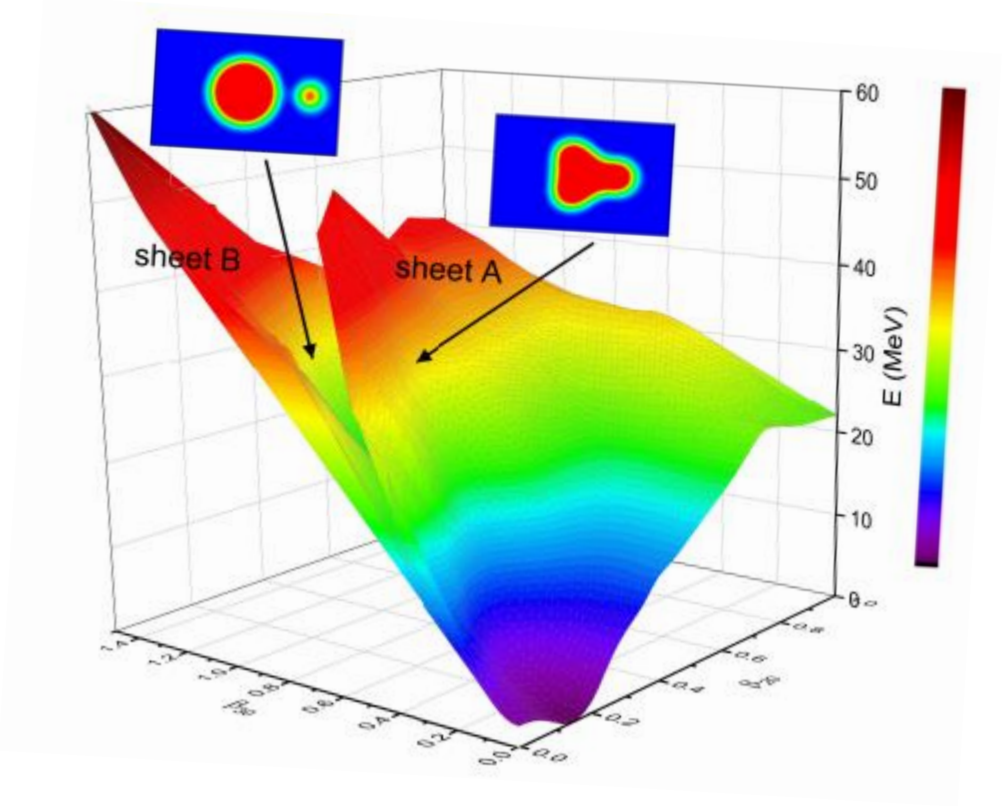
$\tau_{th}^{108Xe} = 50\ \mu s$

$\tau_{exp}^{108Xe} = 58\ \mu s$



Discontinuity in β_4 for ^{104}Te



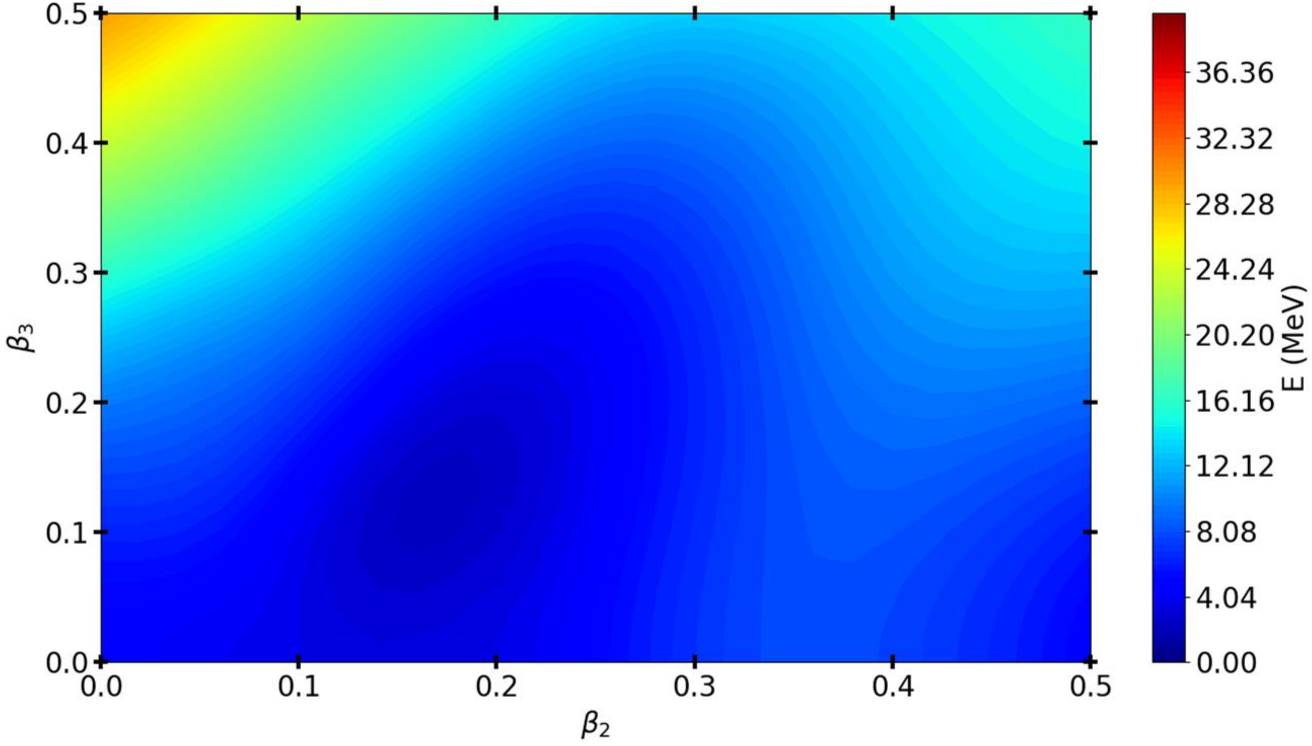


Application to heavier nuclei ...

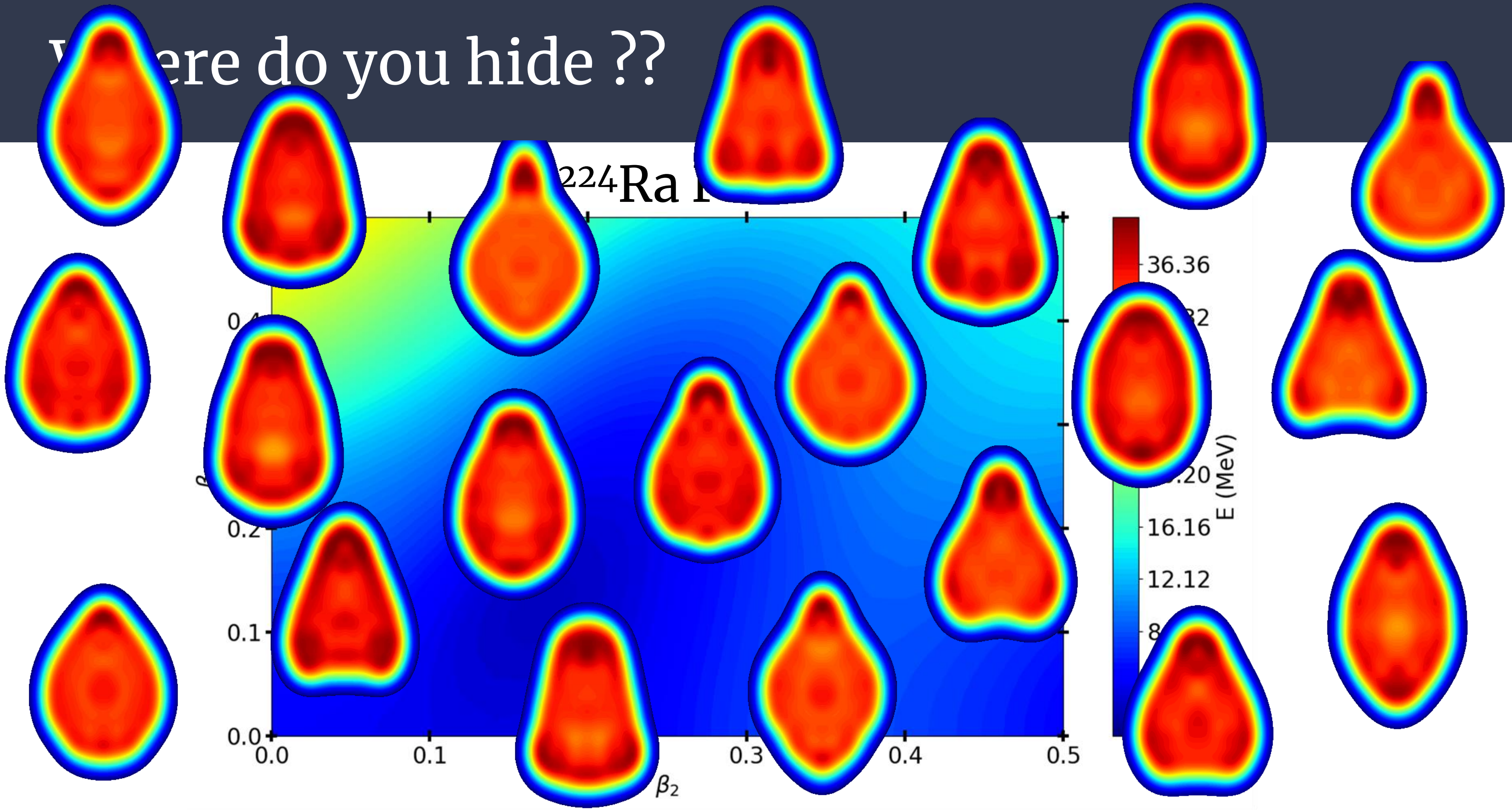
... or the problem of finding an α !

Where do you hide ??

^{224}Ra PES

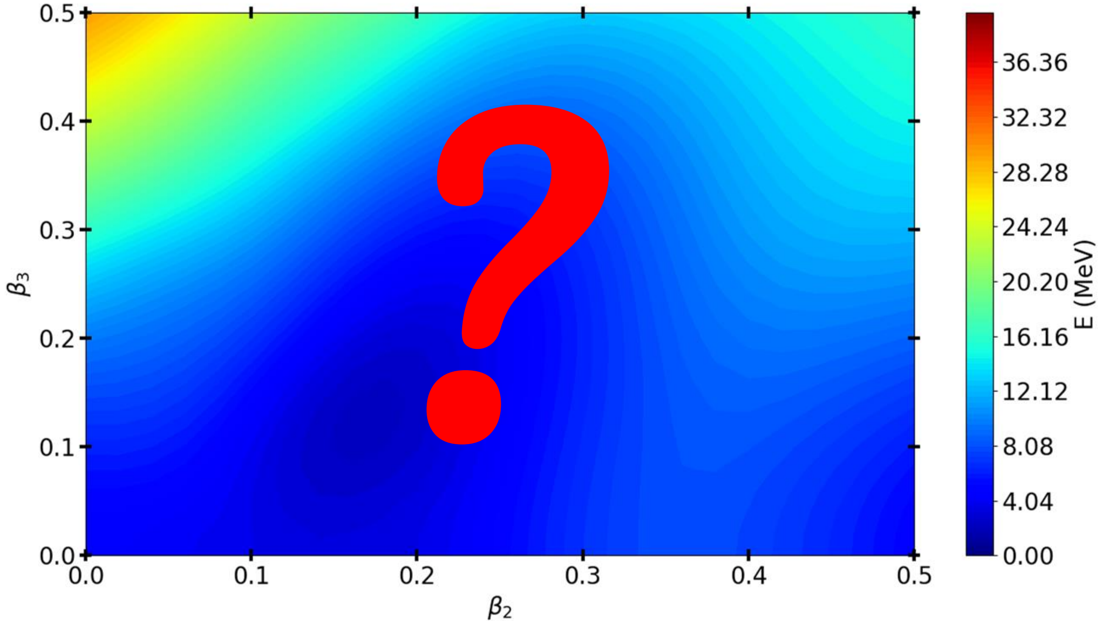


Where do you hide ??



Where do you hide ??

^{224}Ra PES



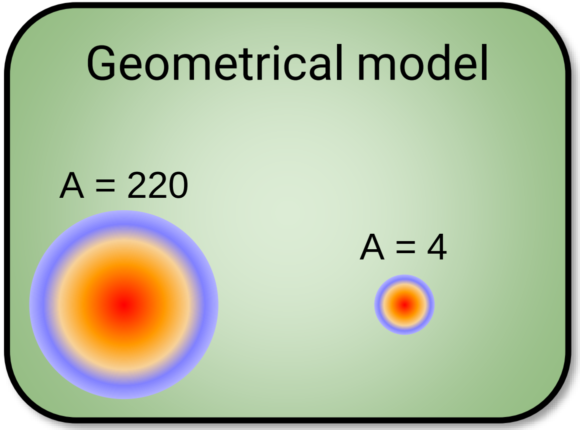
→ Does not mean it does not exist !

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

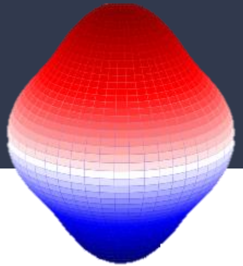
↓

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

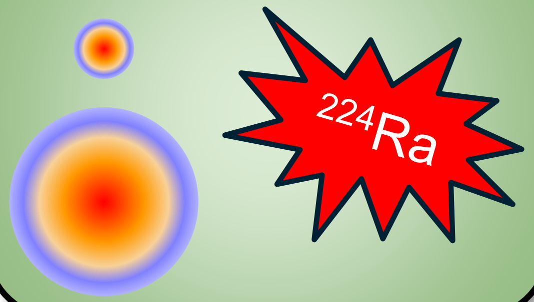
Where do you hide ??



Where do you hide ??

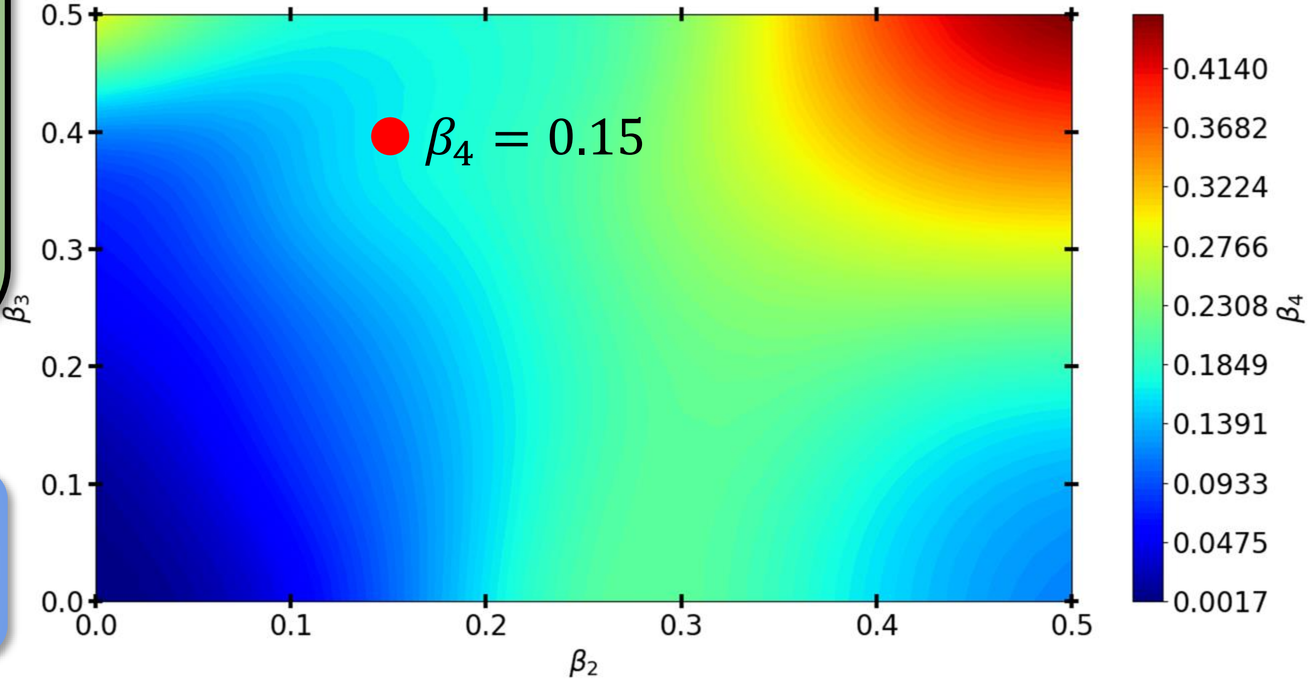


Geometrical model



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

^{224}Ra β_4 values



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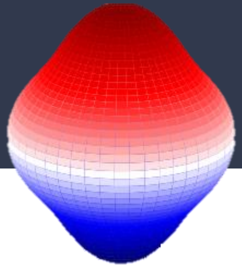
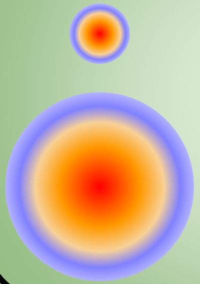


Geometrical model



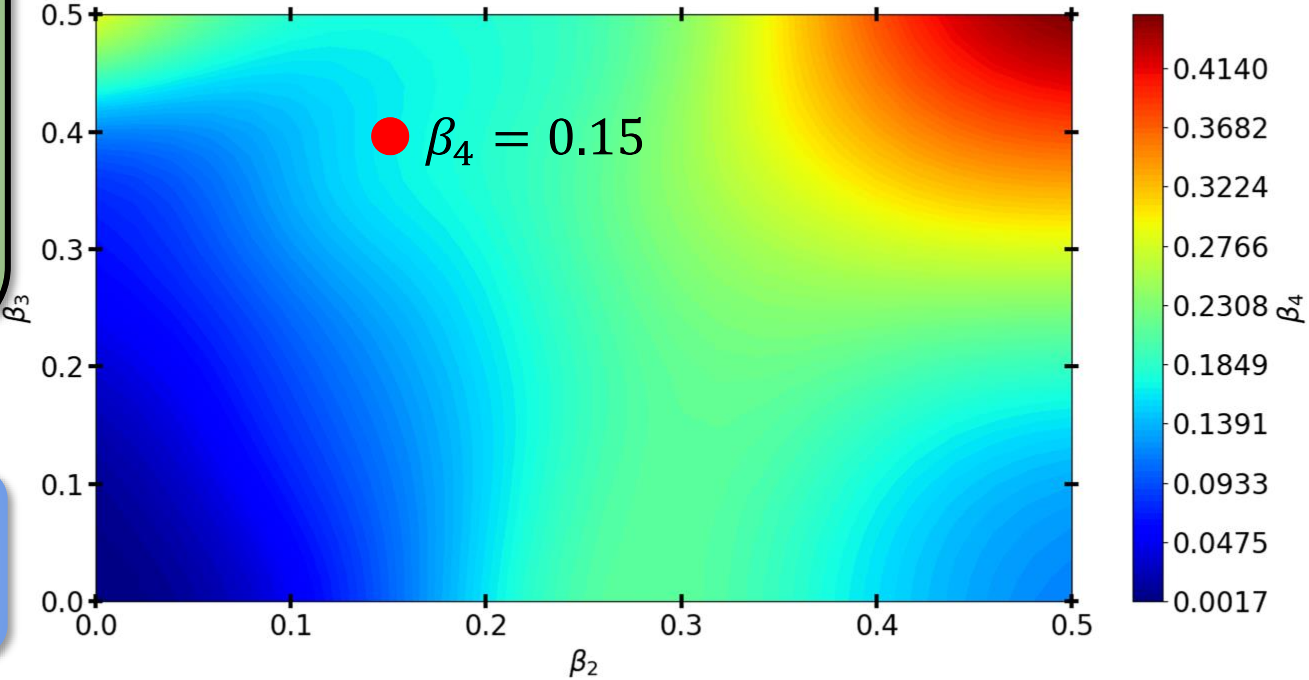
$\beta_2 = 0.15$

$\beta_3 = 0.4$

$\beta_4 = 0.7$

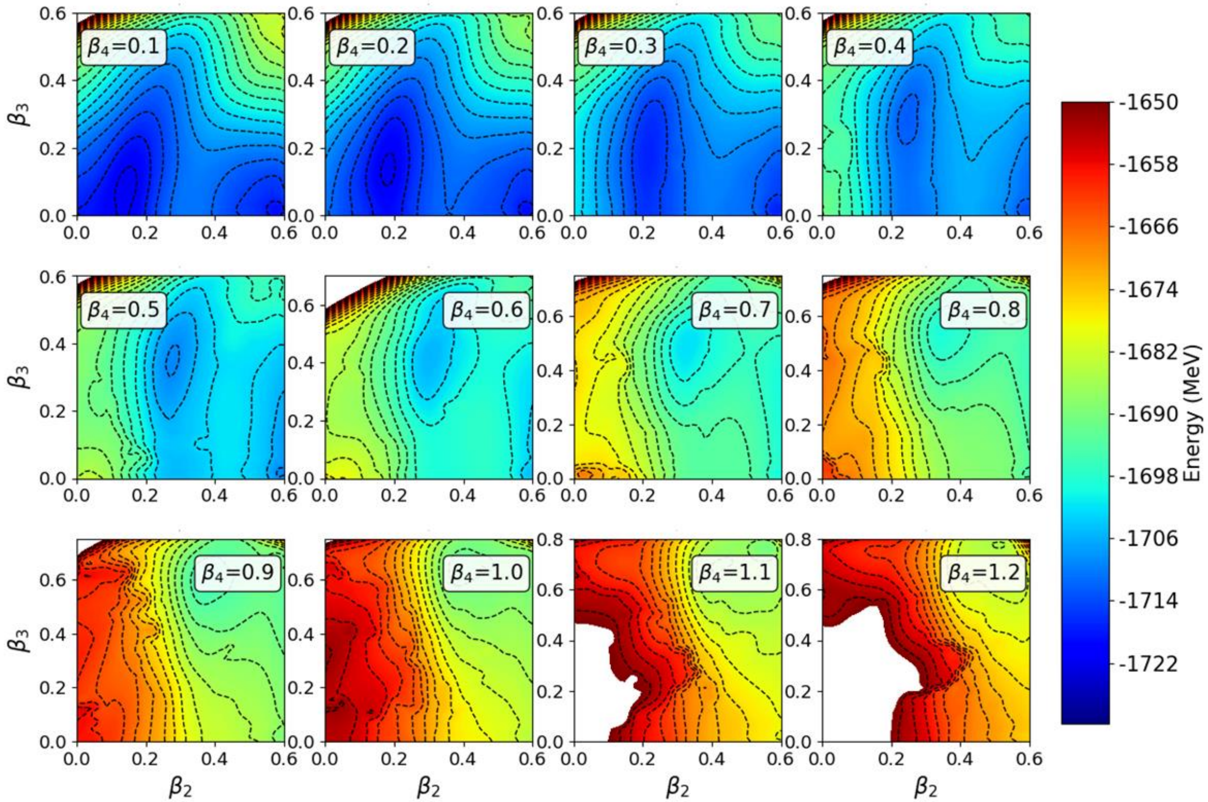
We need to constrain the hexadecapole moment to see an α cluster !

^{224}Ra β_4 values



3D PES for ^{224}Ra

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



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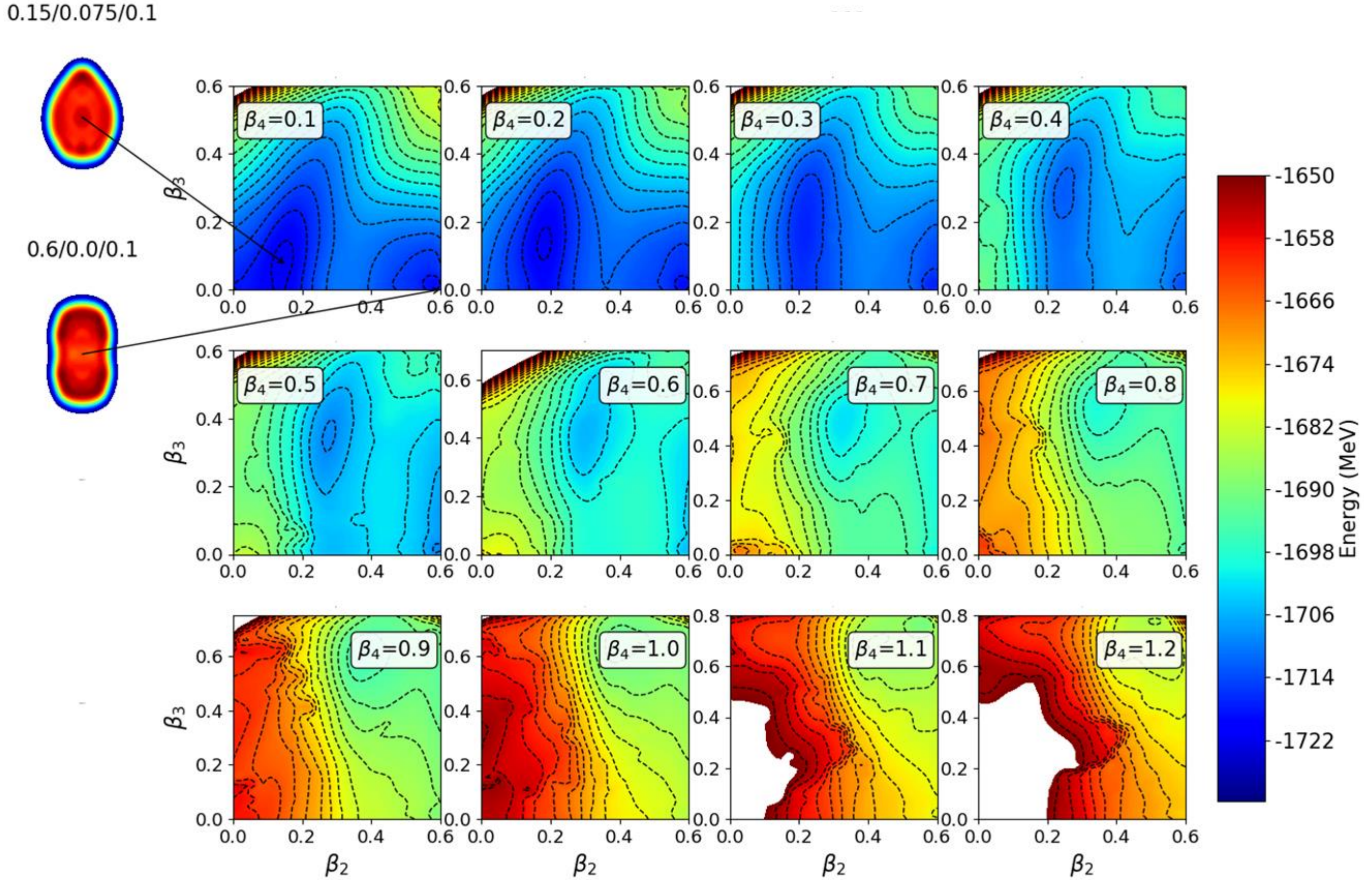

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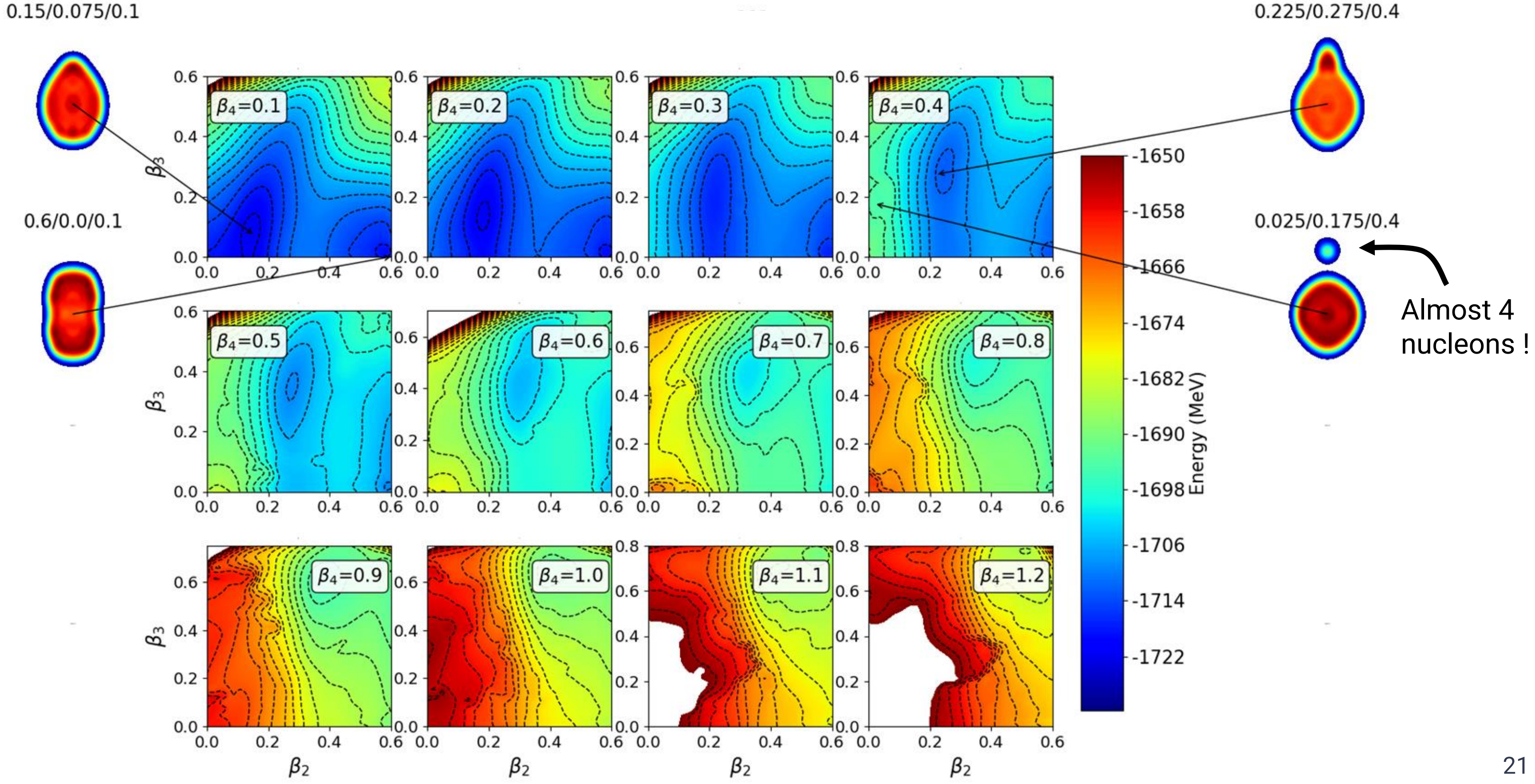

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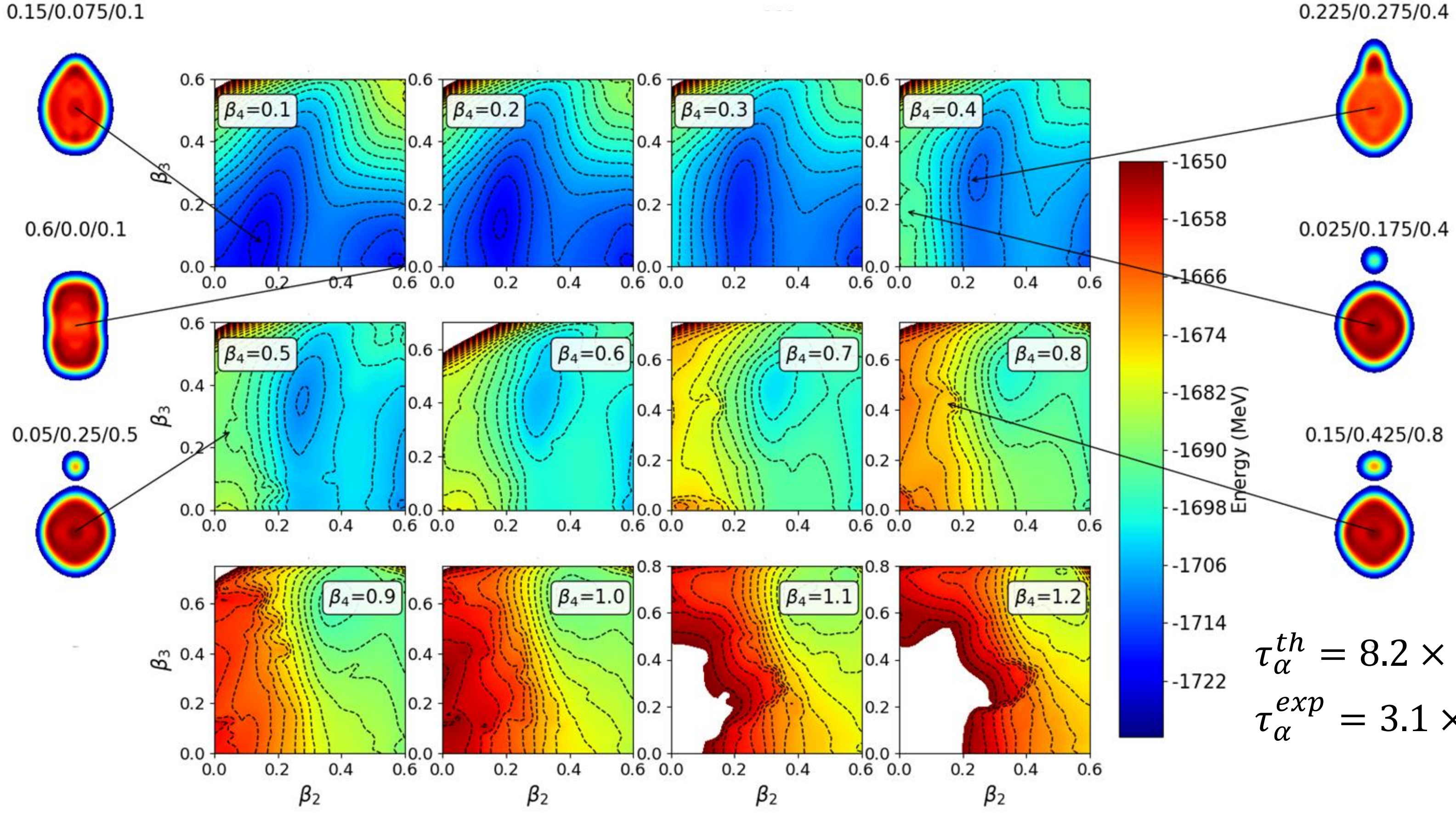

$$\tau_\alpha^{th} = 8.2 \times 10^5 \text{ s}$$
$$\tau_\alpha^{exp} = 3.1 \times 10^5 \text{ s}$$

3D PES for ^{224}Ra

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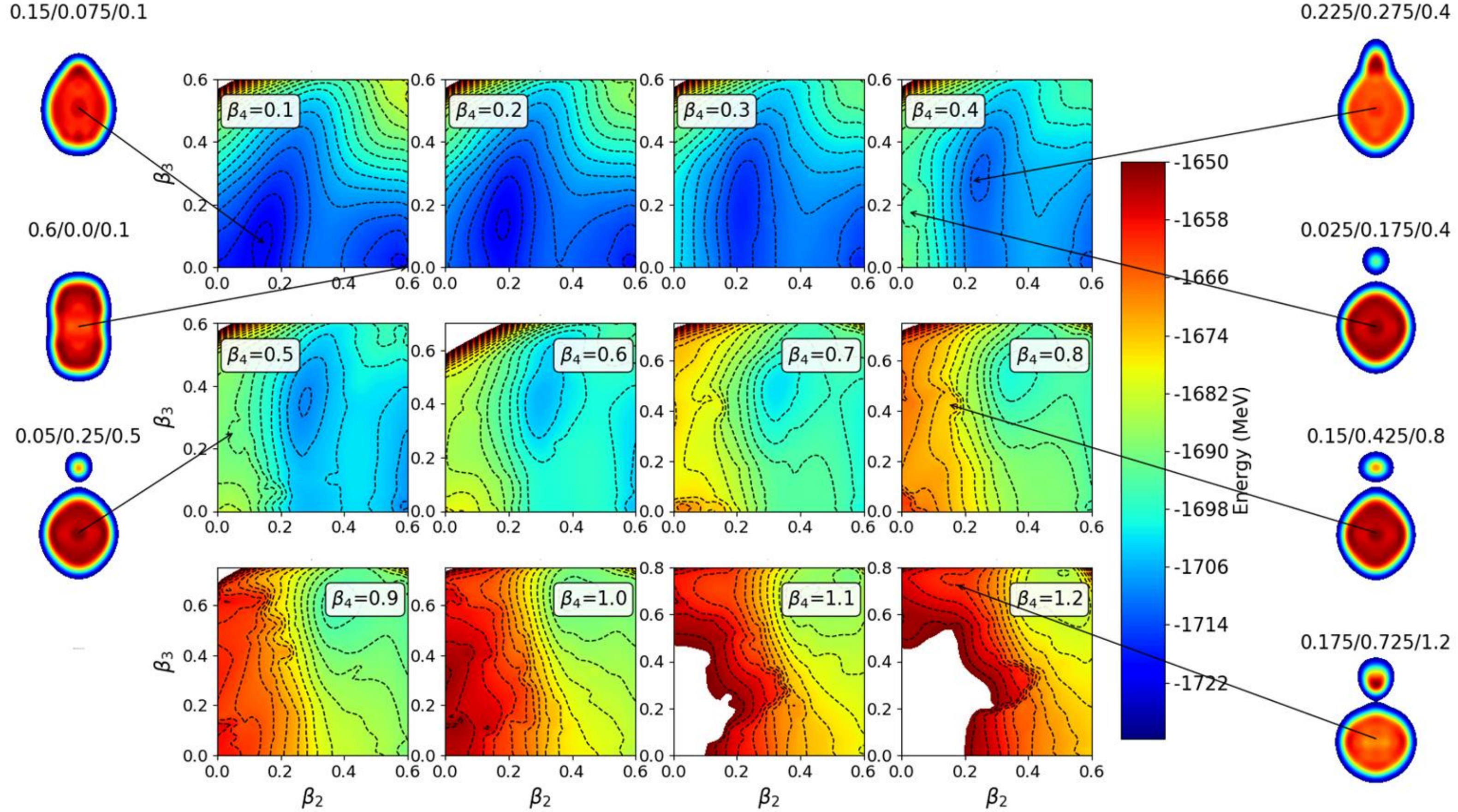

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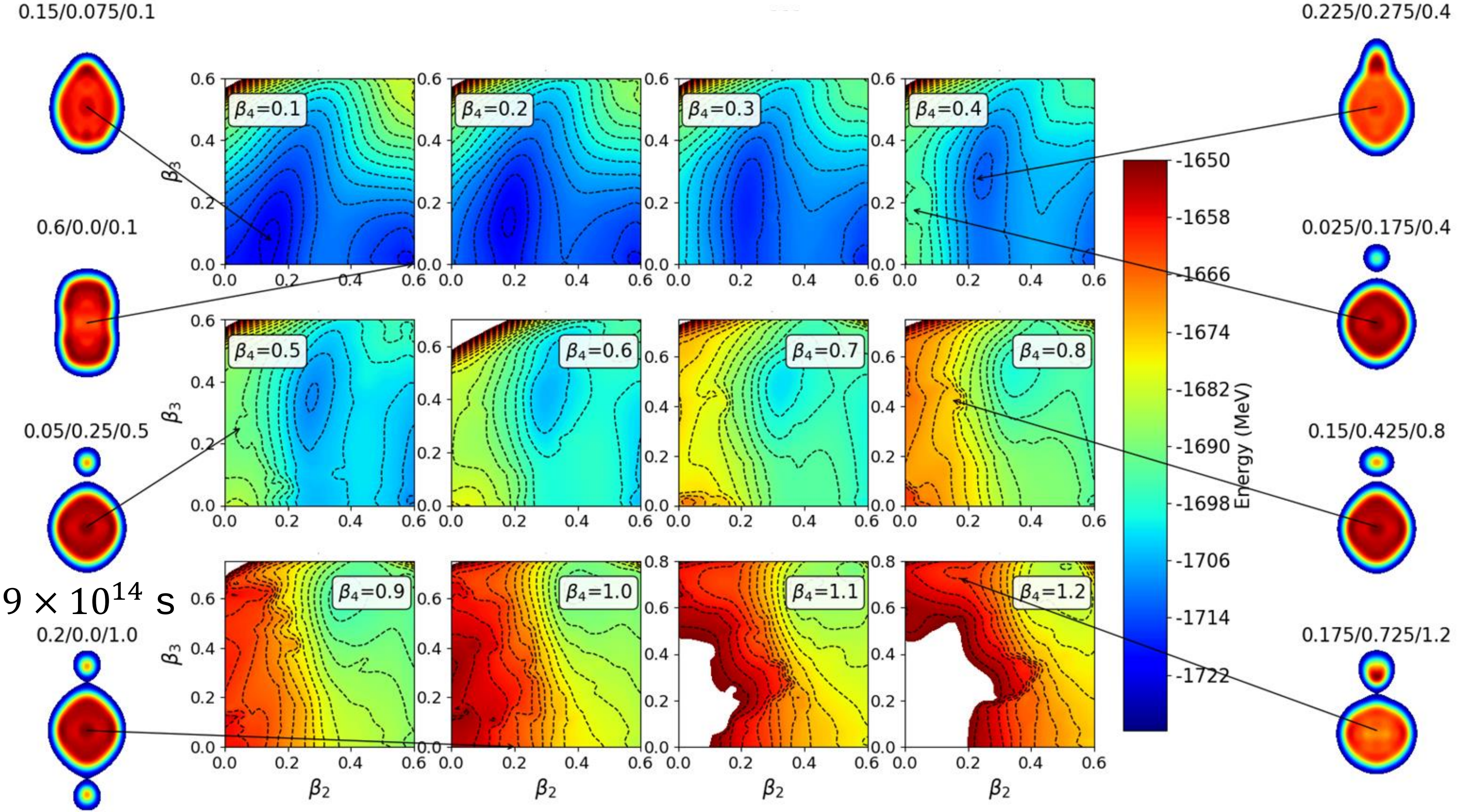


$$\tau_{2\alpha}^{th} = 2.9 \times 10^{14} \text{ s}$$

Details on 2α decay of ^{224}Ra : pairing et parametrization

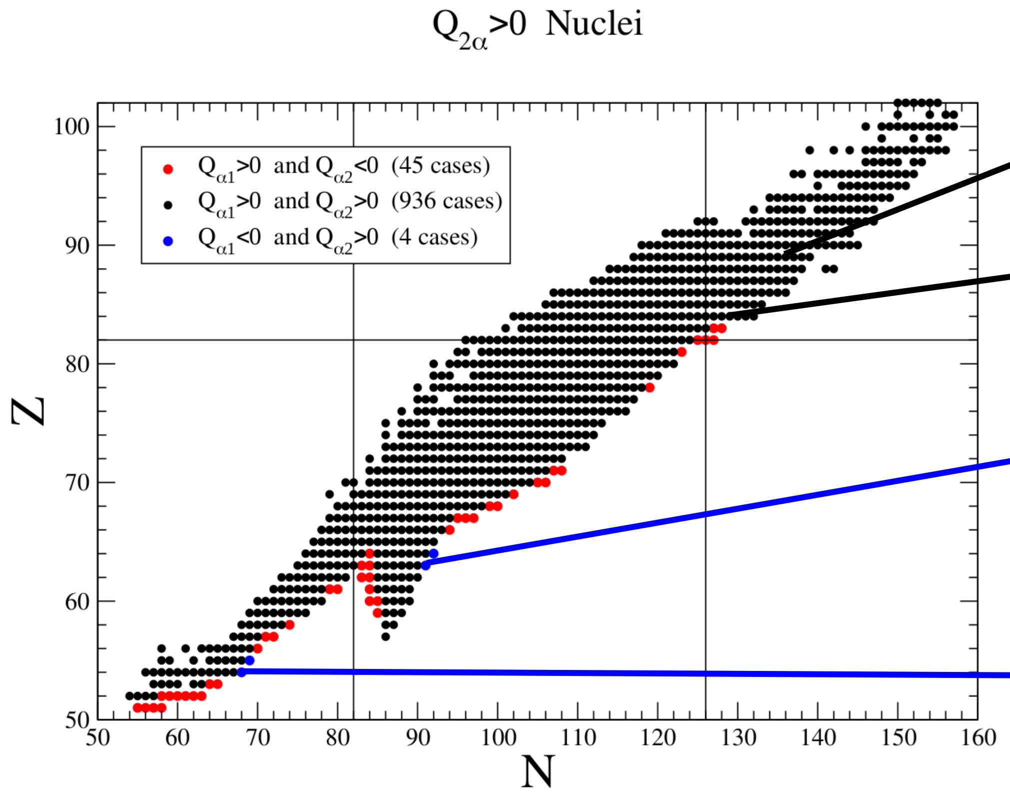
Interaction	Pairing parameters	Action from GS to scission	Coulomb action	Lifetime (s)
DD-PC1	(1.0,1.0)	18.5	23.9	$\sim 10^{16.27}$
DD-PC1	(1.09,1.12)	16.2	23.9	$\sim 10^{14.24}$
DD-ME2	(1.09,1.12)	15.3	23.9	$\sim 10^{13.47}$
PC-PK1	(1.09,1.12)	15.0	23.9	$\sim 10^{13.25}$

Pairing adjusted to reproduce pairing gap of Gogny D1S interaction

Pairing adjusted on pairing gap of ^{224}Ra

What about 2α emission in other nuclei ?

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



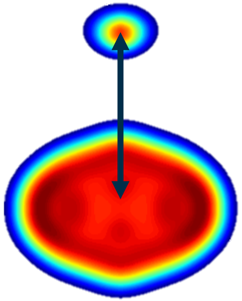
$^{224}\text{Ra} \quad \tau_{2\alpha} \approx 10^{14.24}\,\text{s}$

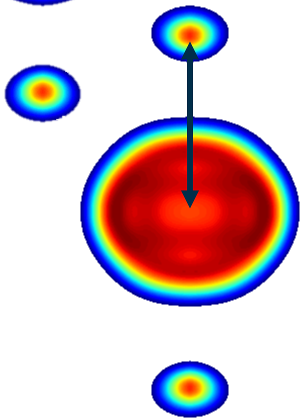
$^{212}\text{Po} \quad \tau_{2\alpha} \approx 10^{18.36}\,\text{s}$

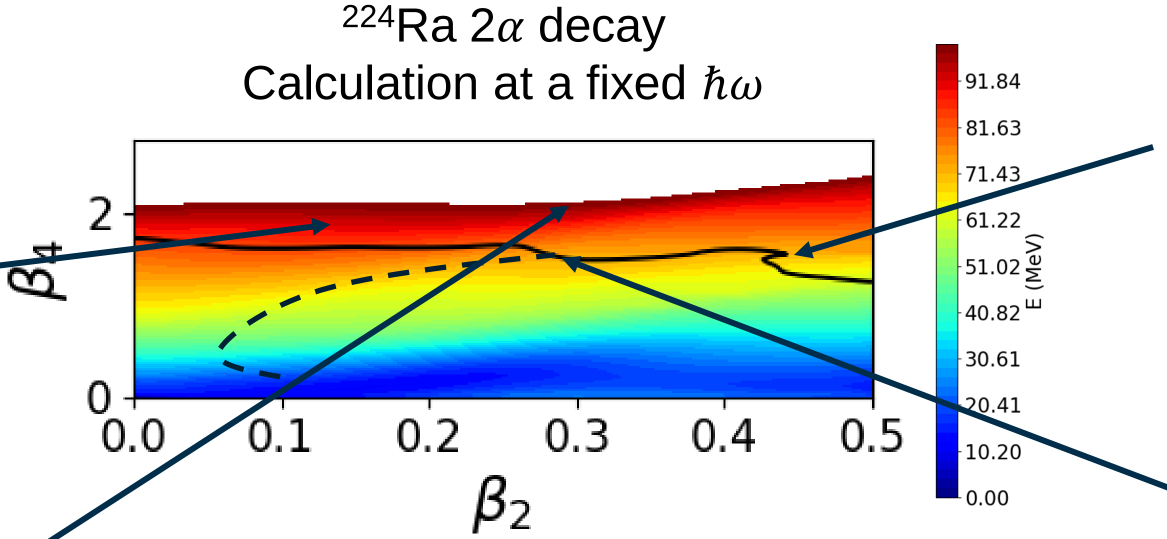
$^{156}\text{Gd} \quad \tau_{2\alpha} \approx 10^{102.62}\,\text{s}$

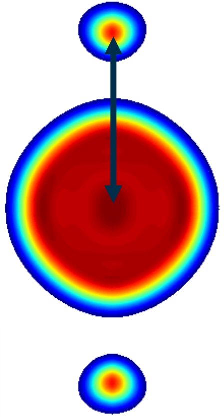
$^{122}\text{Xe} \quad \tau_{2\alpha} \approx 10^{67.46}\,\text{s}$

« Nuclear many body dynamics through **barrier** »



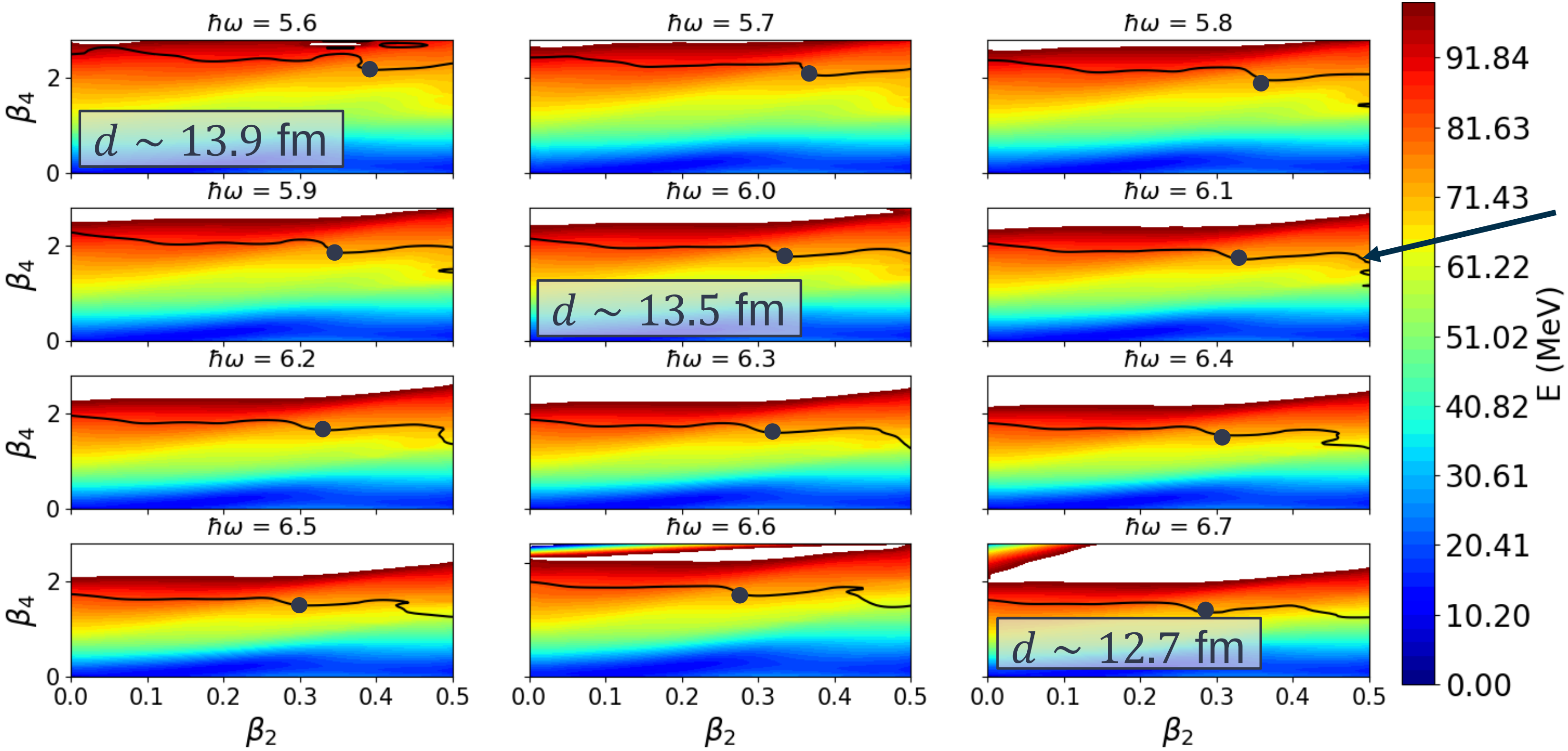






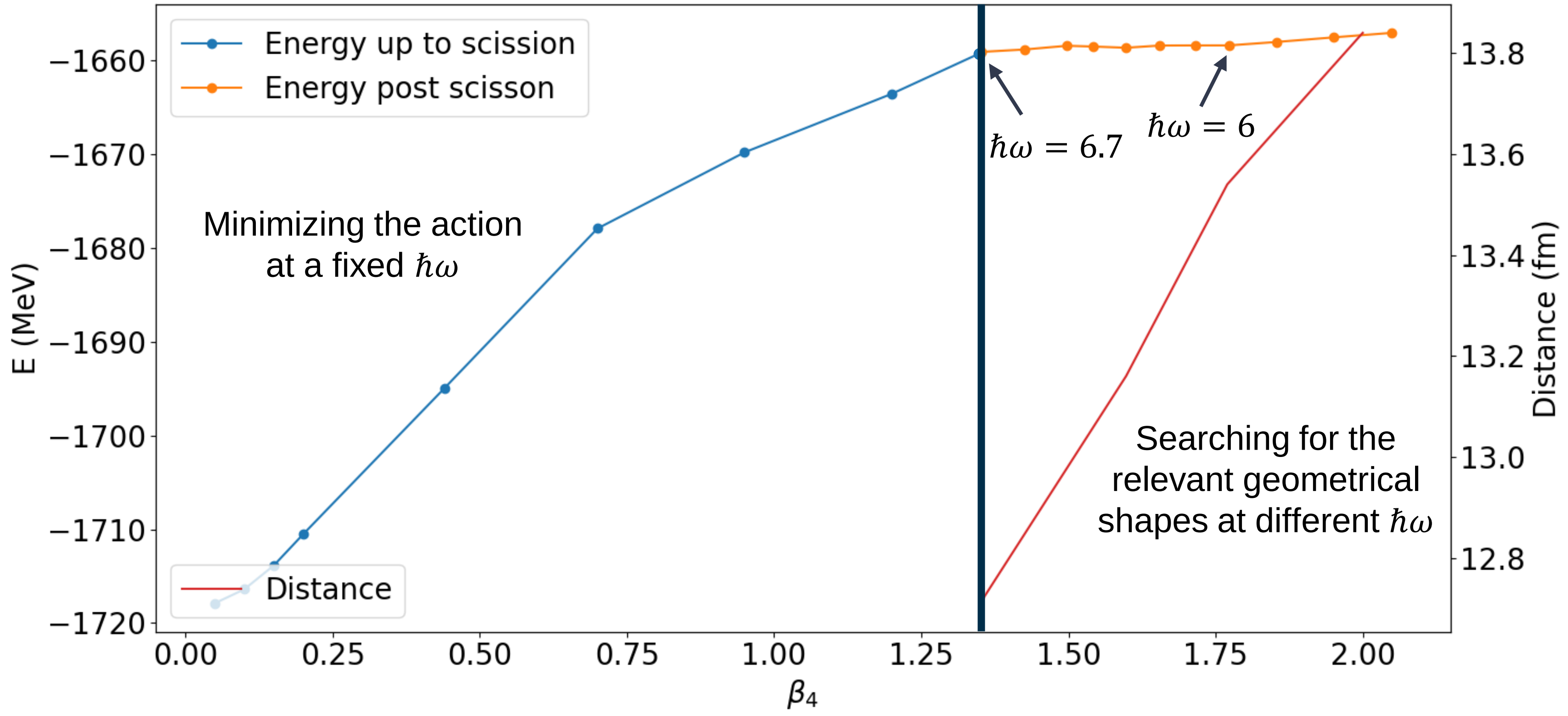
At a fixed $\hbar\omega$, the distance between cluster and daughter nucleus is fixed, regardless of the deformation parameters. Only the shape and number on nucleons in each clusters change.

« Nuclear many body dynamics through **barrier** »



Scission line (4 nucleons in each clusters)

« Nuclear many body dynamics through **barrier** »



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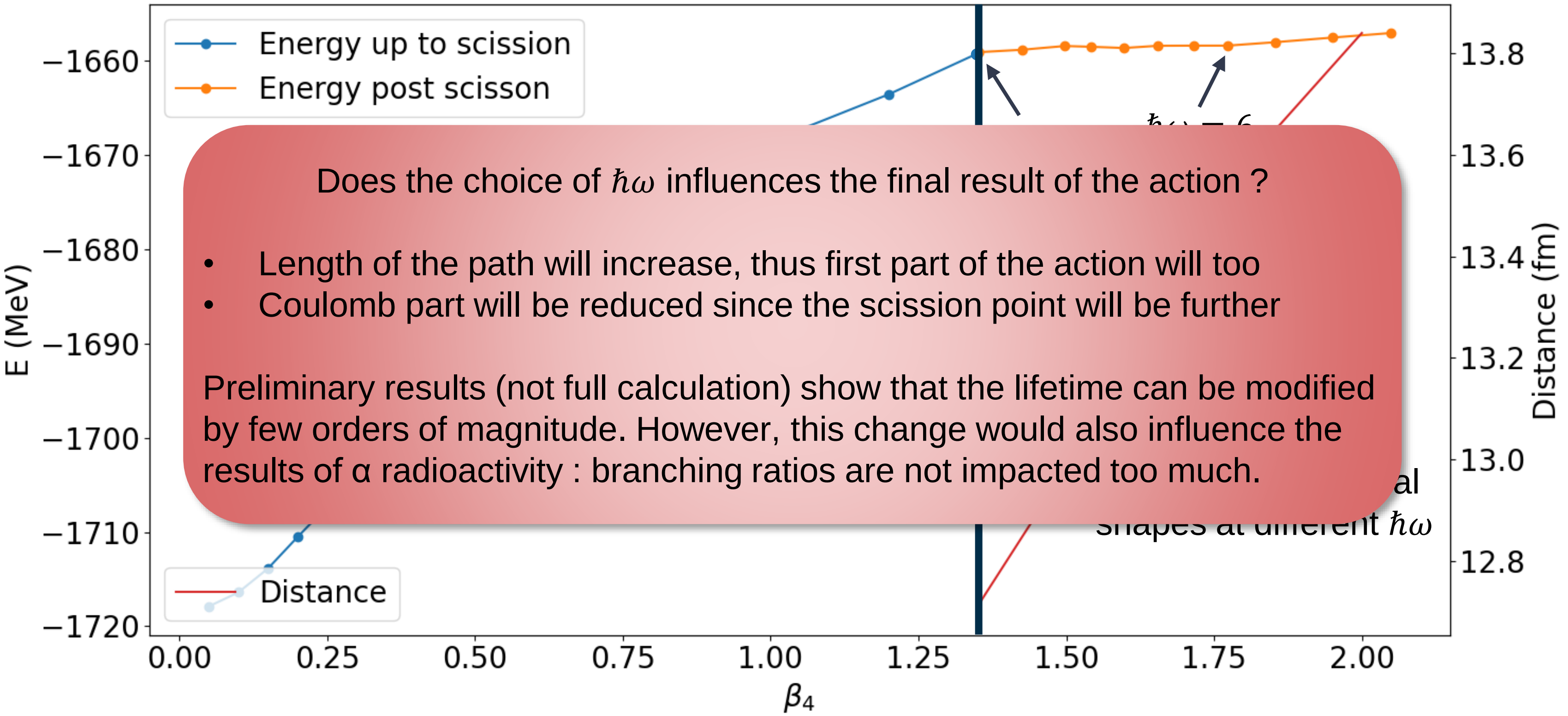
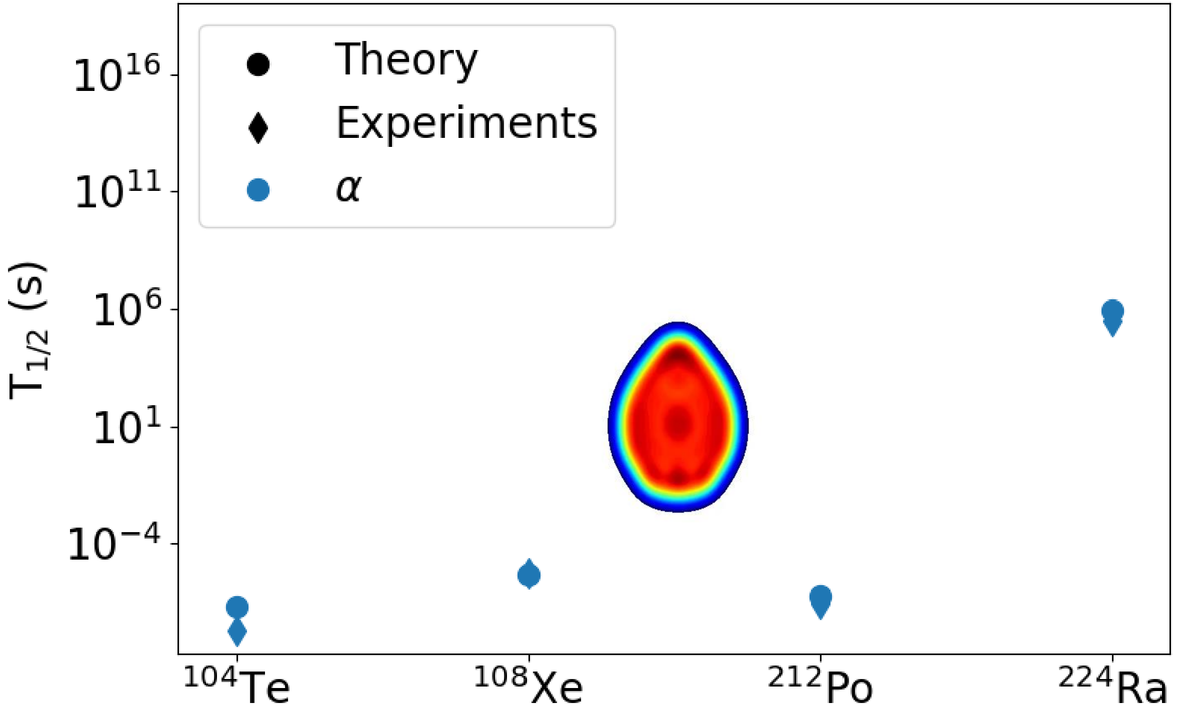


Does the choice of $\hbar\omega$ influences the final result of the action ?

- Length of the path will increase, thus first part of the action will too
- Coulomb part will be reduced since the scission point will be further

Preliminary results (not full calculation) show that the lifetime can be modified by few orders of magnitude. However, this change would also influence the results of α radioactivity : branching ratios are not impacted too much.

A single framework to describe ...



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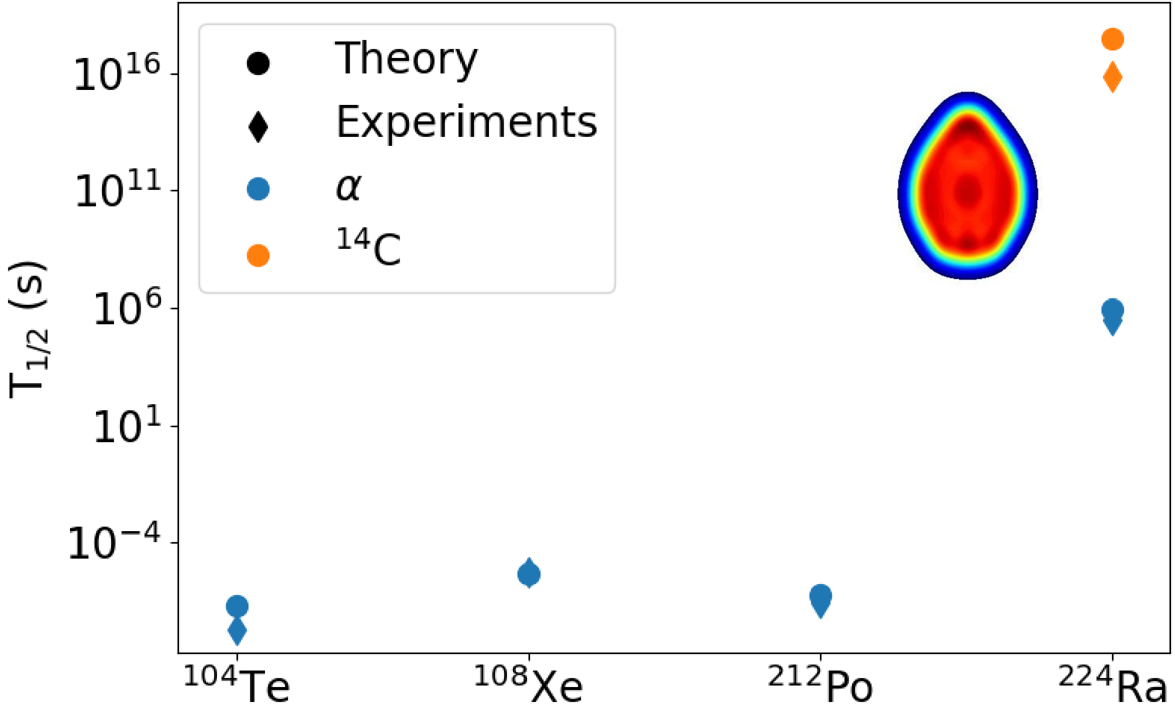

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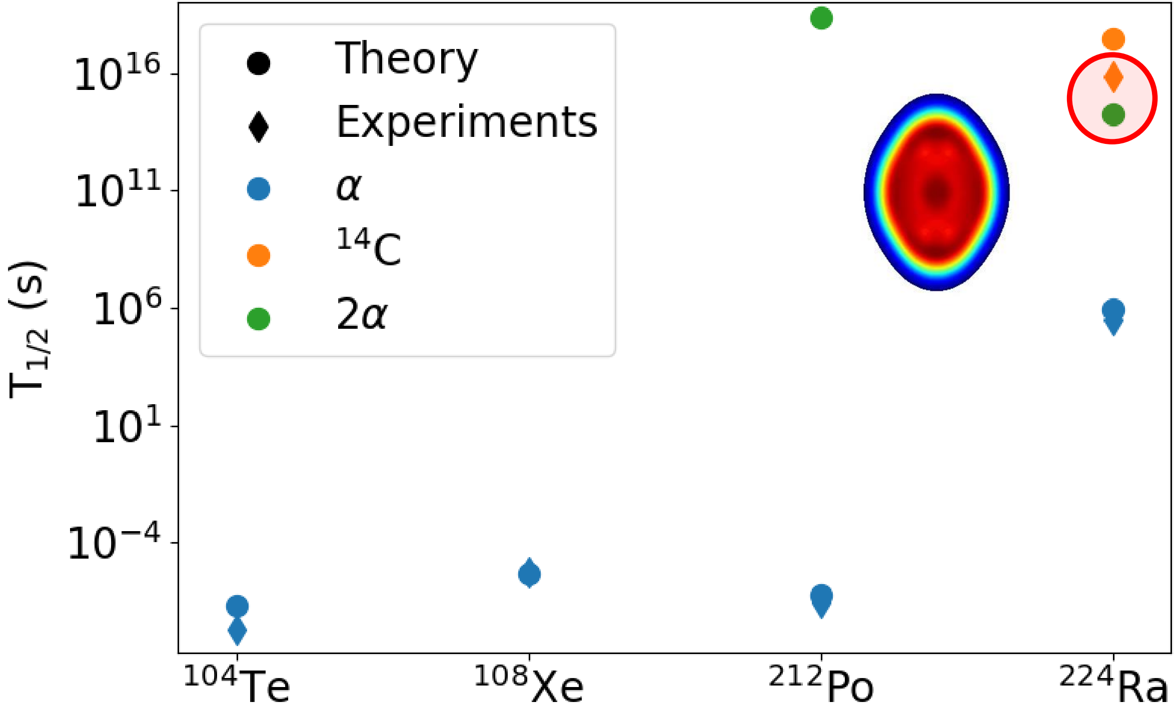

Experimental cluster decay lifetime and theoretical 2α decay lifetime are quite close !

Ongoing experiment at GSI

Hopefully upcoming experiment at ISOLDE