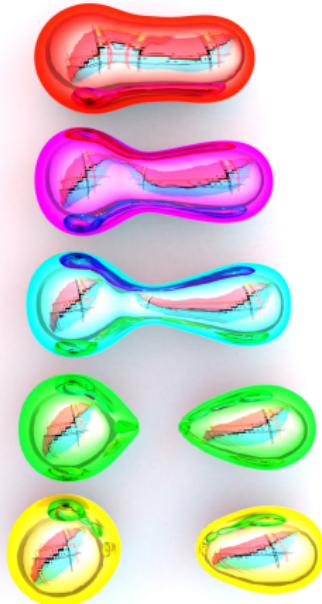


Oct. 24-28, 2022

EuNPC 2022

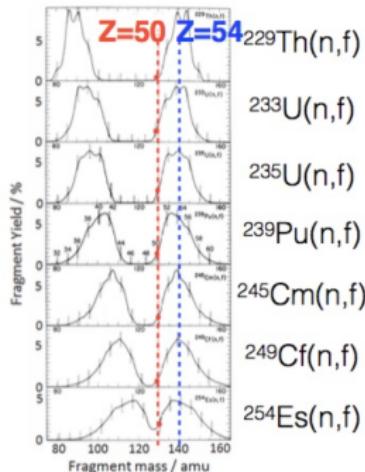


The role of pear shape deformation on the fission of actinides and in the mercury region

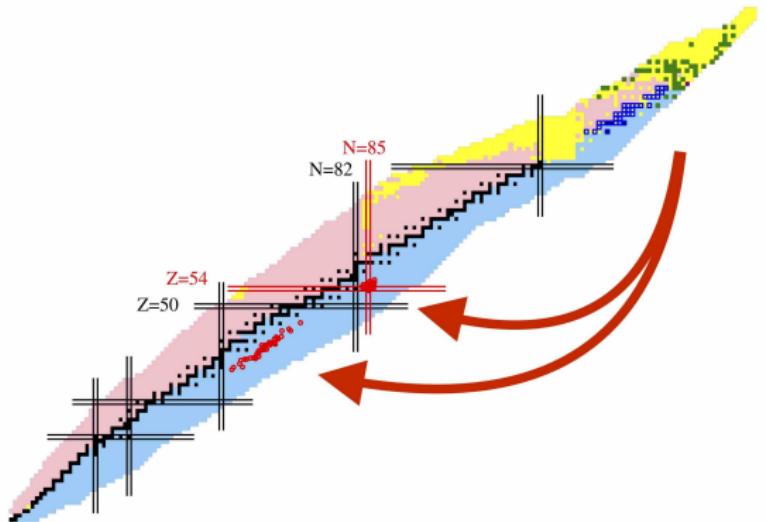
Guillaume SCAMPS

Collaboration : C. Simenel

## Empirical behaviour of actinide nuclei



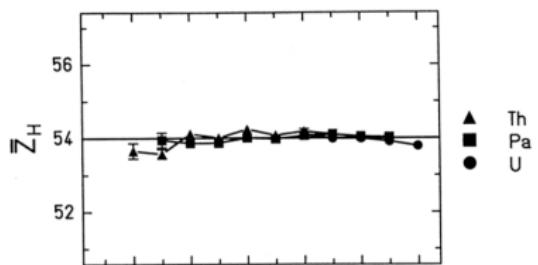
J.P. Unik, J.E. Gindler, J.E. Glendenin et al. : Proc. Phys. and Chem. of Fission IAEA Vienna , Vol II, 20 (1974)



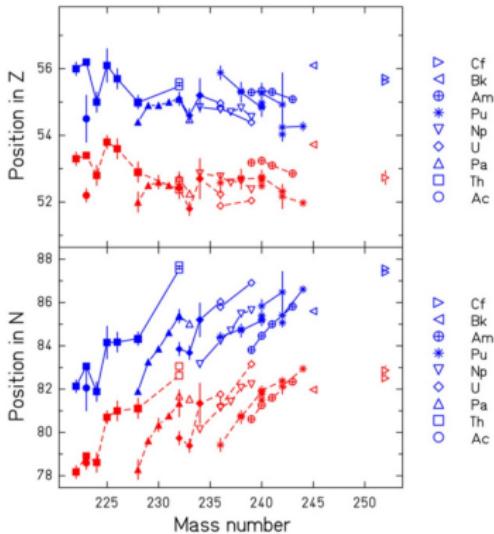
Data from D. A. Brown et al., Endf/b-viii.0, Nucl. Data Sheets 148, 1 (2018), (spontaneous and thermal neutron-capture).

## Empirical behavior of actinide nuclei

C. Böckstiegel et al. / Nuclear Physics A 802 (2008) 12–25



K.-H. Schmidt et al. Nuclear Physics A  
665 (2000)



## Motivation

How can we understand this behavior? The Interplay between structure and reactions?

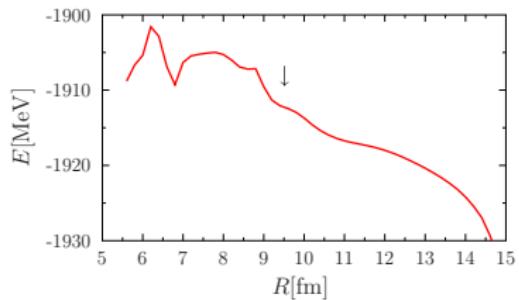
## TDHF+BCS

- Based on TDHFB with the approximation :  $\Delta_{ij} = \delta_{ij}\Delta_i$
- Initialisation from ev8 (HF+BCS)
- Evolution :  
 $i\hbar \frac{d\varphi_i}{dt} = (\hat{h}_{MF} - \epsilon_i)\varphi_i$   
 $i\hbar \frac{dn_i}{dt} = \Delta_i^* \kappa_i - \Delta_i \kappa_i^*$   
 $i\hbar \frac{d\kappa_i}{dt} = \kappa_i(\epsilon_i - \epsilon_{\bar{i}}) + \Delta_i(2n_i - 1)$

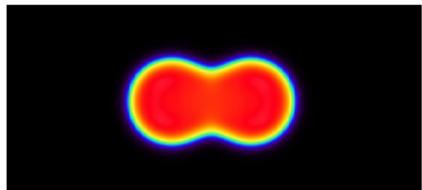
## Details of the calculation

- Skyrme functionnal Sly4d
- Surface pairing interaction
- $\Delta x = 0.8 \text{ fm}$ ;  $\Delta t = 1.5 \times 10^{-24} \text{ s}$
- Lattice :  $L_x \times L_y \times 2L_z = 40 \times 19.2 \times 19.2 \text{ fm}^3$

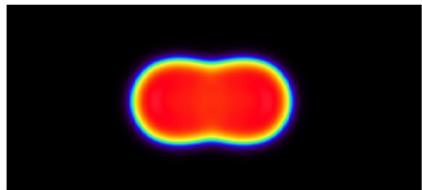
Fission barrier :  $^{258}\text{Fm}$



TDHF



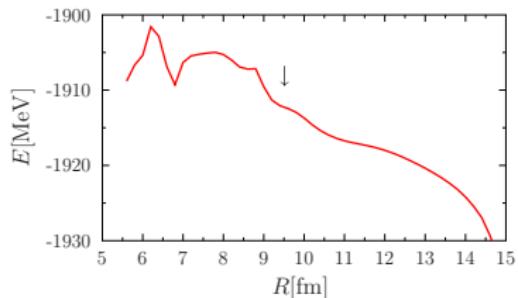
TDHF+BCS



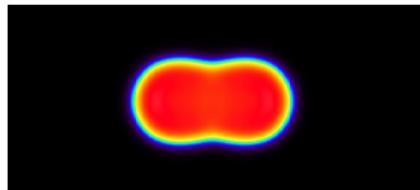
G. Scamps, C. Simenel, D. Lacroix, PRC **92**, 011602(R) (2015).

TDHF

Fission barrier :  $^{258}\text{Fm}$

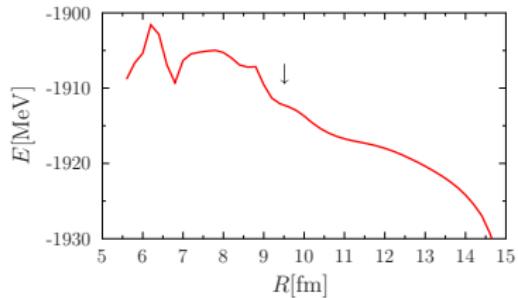


TDHF+BCS

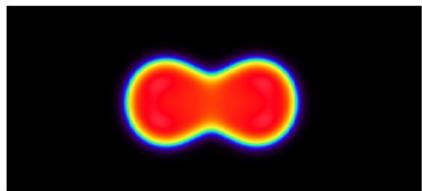


G. Scamps, C. Simenel, D. Lacroix, PRC **92**, 011602(R) (2015).

Fission barrier :  $^{258}\text{Fm}$



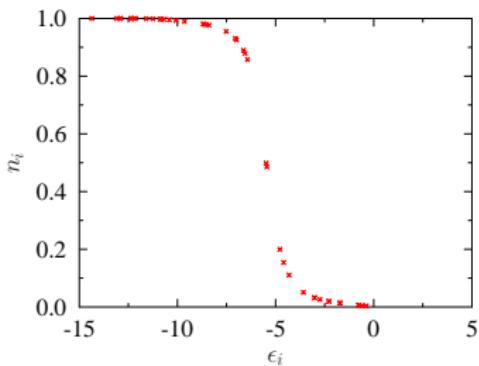
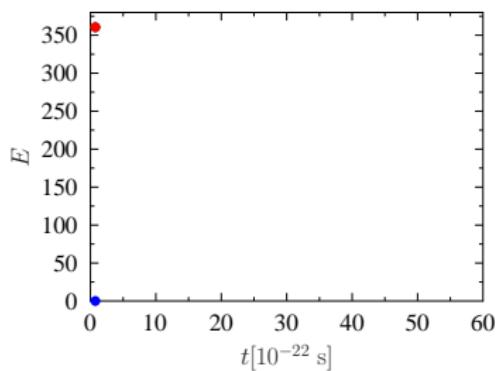
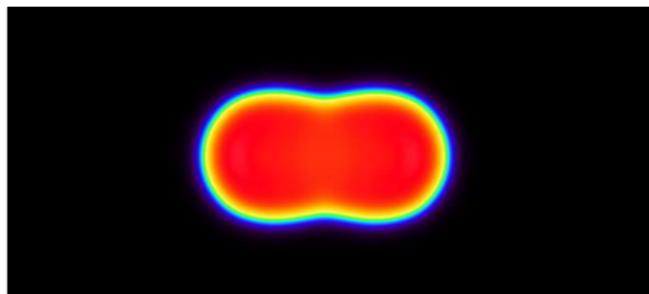
TDHF



TDHF+BCS

G. Scamps, C. Simenel, D. Lacroix, PRC **92**, 011602(R) (2015).

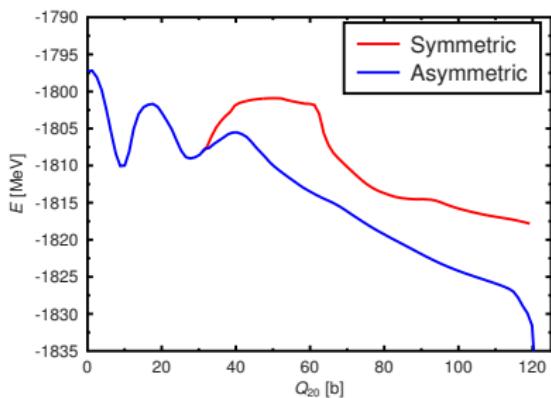
# Influence of pairing on fission process





First : CHF+BCS

Example :  $^{240}\text{Pu}$

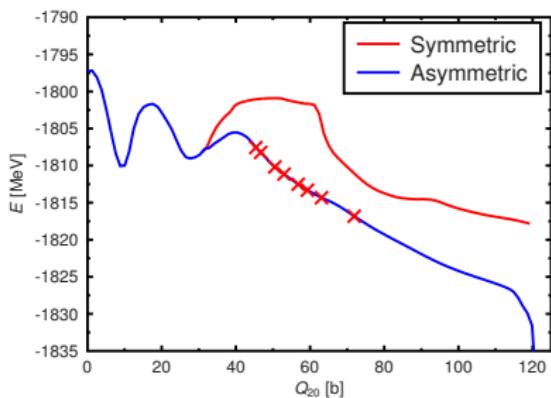


Second : TDHF+BCS



## First : CHF+BCS

Example :  $^{240}\text{Pu}$

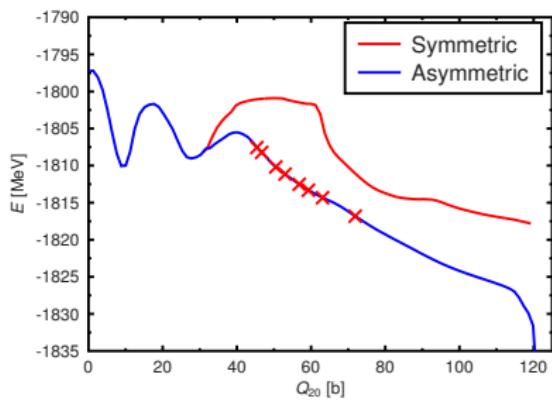


## Second : TDHF+BCS



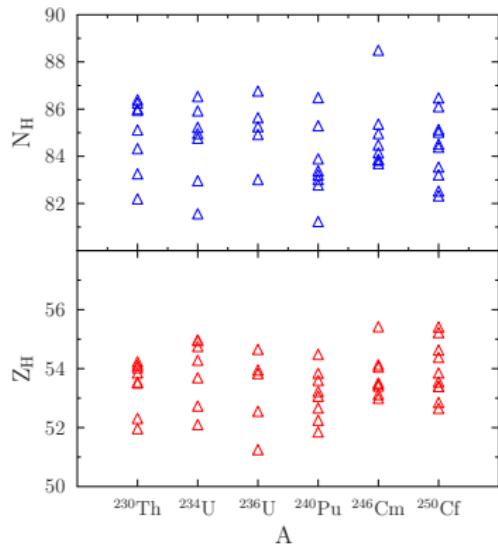
First : CHF+BCS

Example :  $^{240}\text{Pu}$

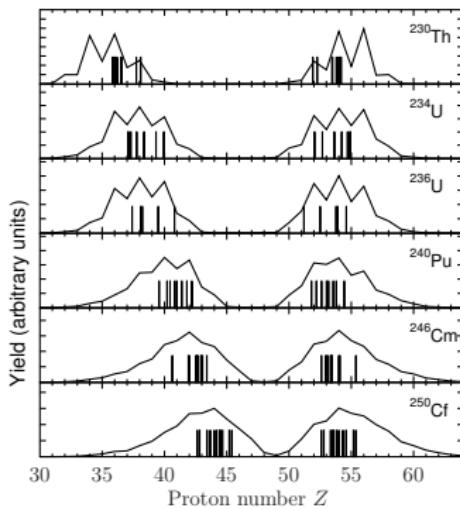


Second : TDHF+BCS

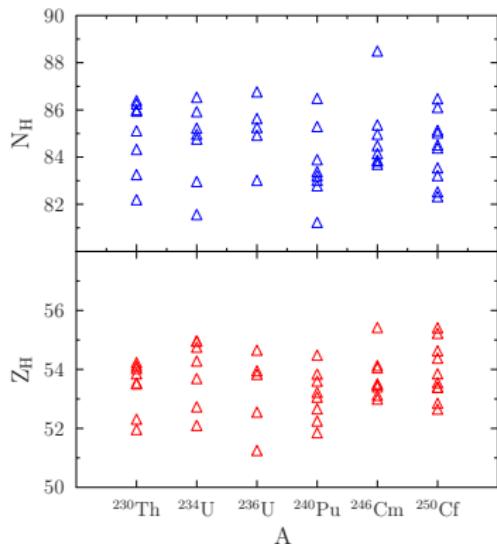
## TDHF+BCS



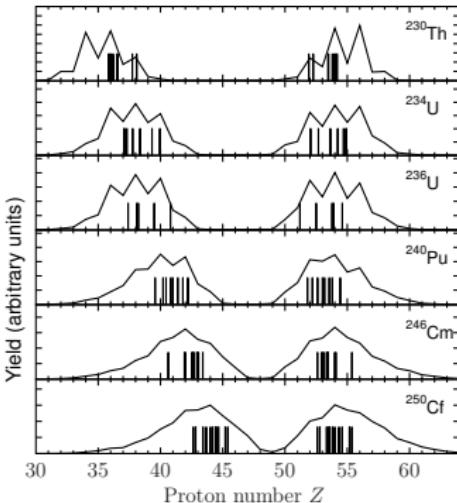
## Comparison with experimental data



## TDHF+BCS



## Comparison with experimental data



## Conclusion :

The TDHF+BCS calculation reproduces well the  $Z=54$  behavior. But why ?

## Fermion localization function

$$\mathcal{C}_{q\sigma}(\mathbf{r}) = \left[ 1 + \left( \frac{\tau_{q\sigma}\rho_{q\sigma} - \frac{1}{4}|\nabla\rho_{q\sigma}|^2 - \mathbf{j}_{q\sigma}^2}{\rho_{q\sigma}\tau_{q\sigma}^{TF}} \right)^2 \right]^{-1}$$

A. D. Becke and K. E. Edgecombe, J. Chem. Phys.  
92, 5397 (1990).

Physical meaning :

$$\mathcal{C} \in [0 : 1]$$

$\mathcal{C}_{q\sigma}(\mathbf{r}) = 1$  Probability to find another particle with  
the same  $q$  and  $\sigma$  very low.

$\mathcal{C}_{q\sigma}(\mathbf{r}) = 0.5$  Limit of uniform-density Fermi gas.

Mask function :

$$\rightarrow \frac{\mathcal{C}_{q\sigma}(\mathbf{r})\rho_{q\sigma}}{\rho_{q\sigma}^{\max}}$$

## Fermion localization function

$$\mathcal{C}_{q\sigma}(\mathbf{r}) = \left[ 1 + \left( \frac{\tau_{q\sigma} \rho_{q\sigma} - \frac{1}{4} |\nabla \rho_{q\sigma}|^2 - \mathbf{j}_{q\sigma}^2}{\rho_{q\sigma} \tau_{q\sigma}^{TF}} \right)^2 \right]^{-1}$$

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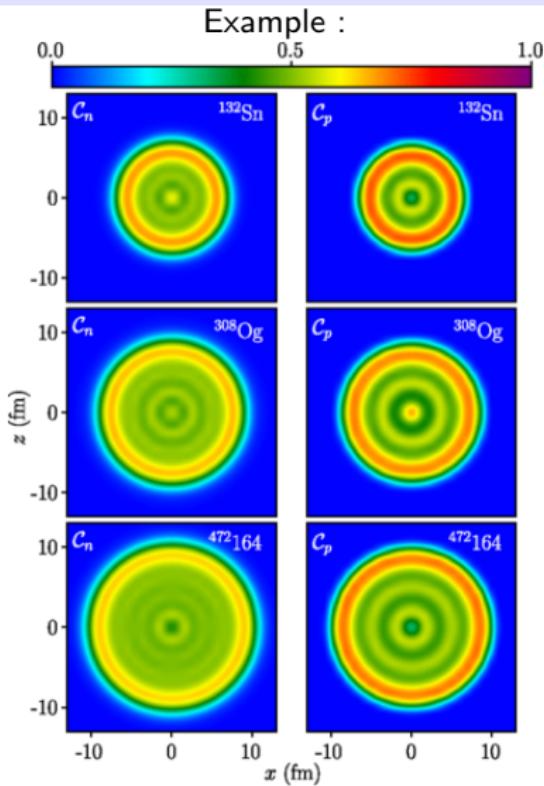
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P. Jerabek, B. Schuetrumpf, P. Schwerdtfeger, and W. Nazarewicz, Phys. Rev. Lett. **120**, 053001 (2018).

## Fermion localization function

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A. D. Becke and K. E. Edgecombe, J. Chem. Phys. 92, 5397 (1990).

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$$\mathcal{C} \in [0 : 1]$$

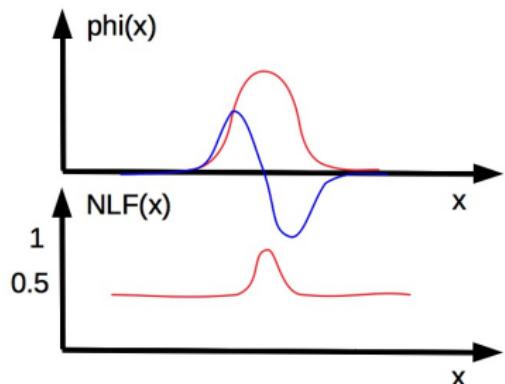
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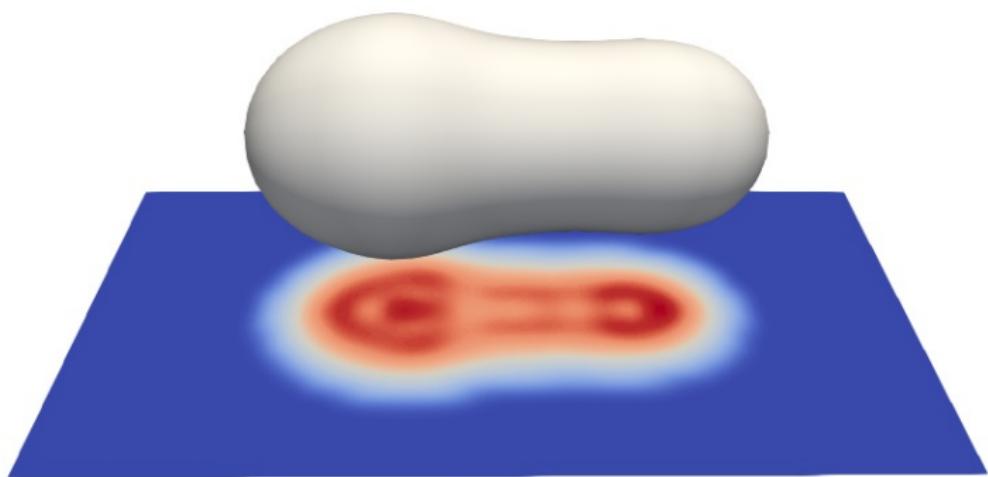
## Schematic system



## Example of $^{240}\text{Pu}$

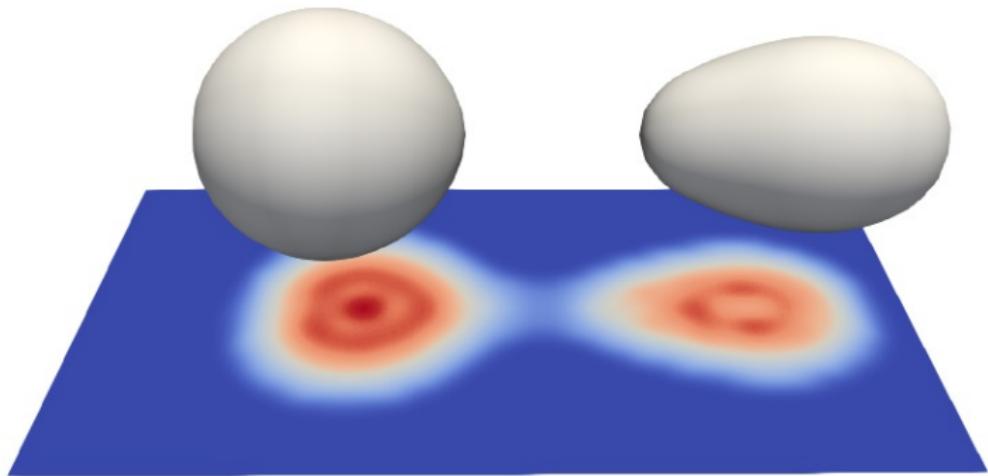
10

$^{240}\text{Pu}$

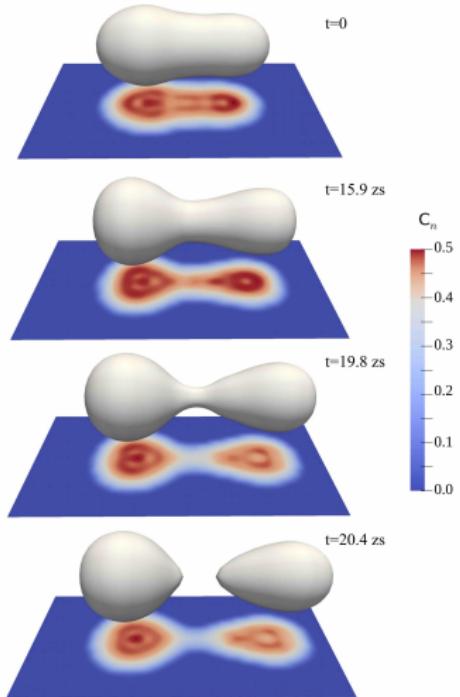


$^{240}\text{Pu}$

$^{240}\text{Pu}$

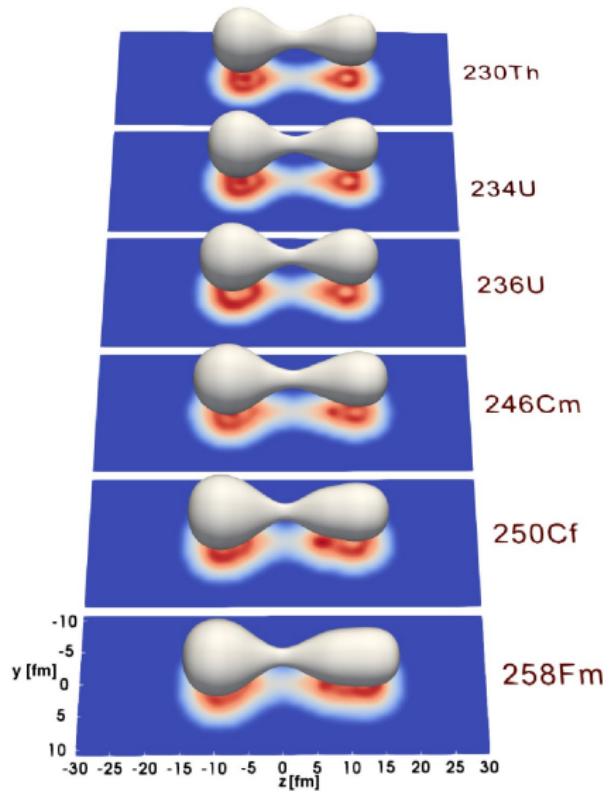


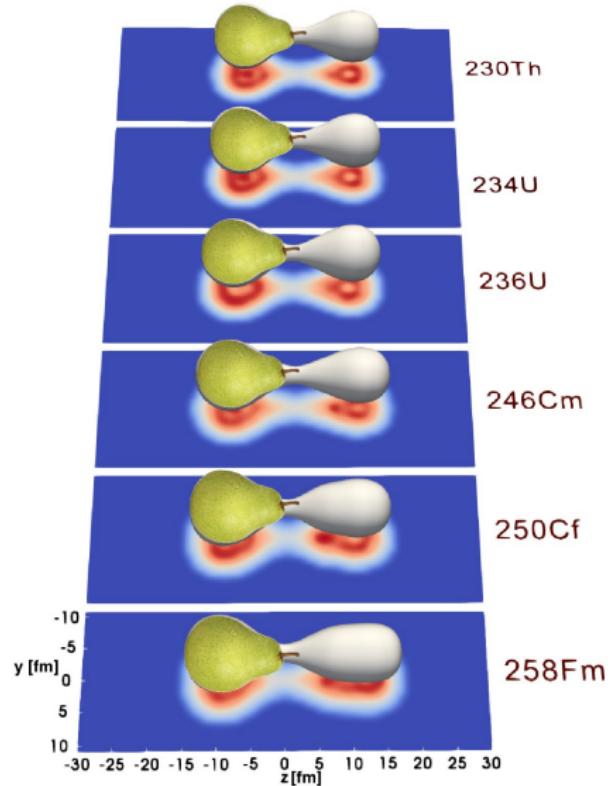
$^{240}\text{Pu}$



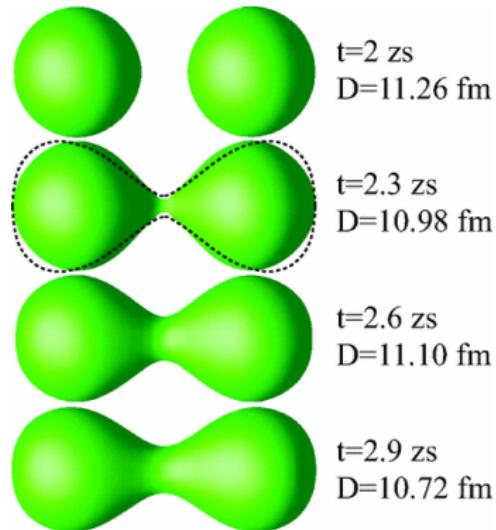
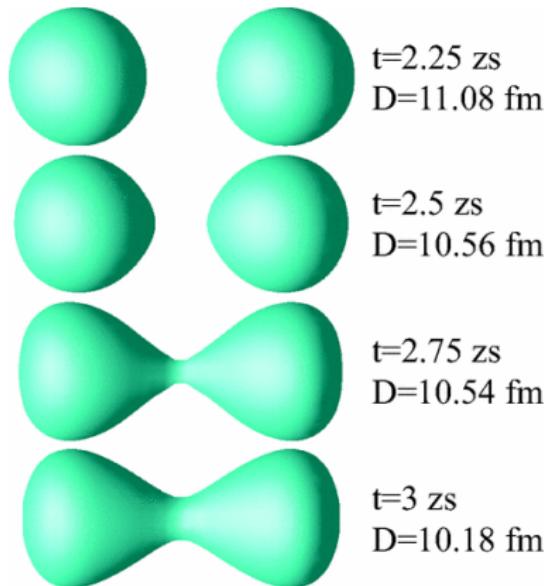
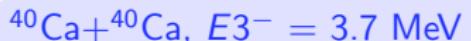
### Hypothesis

The octupole shell effects are important in the fission fragment

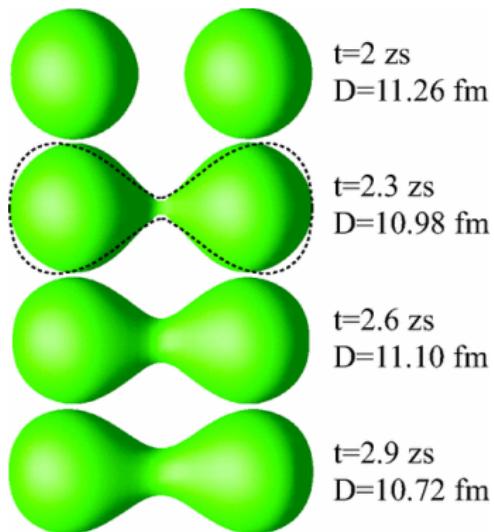
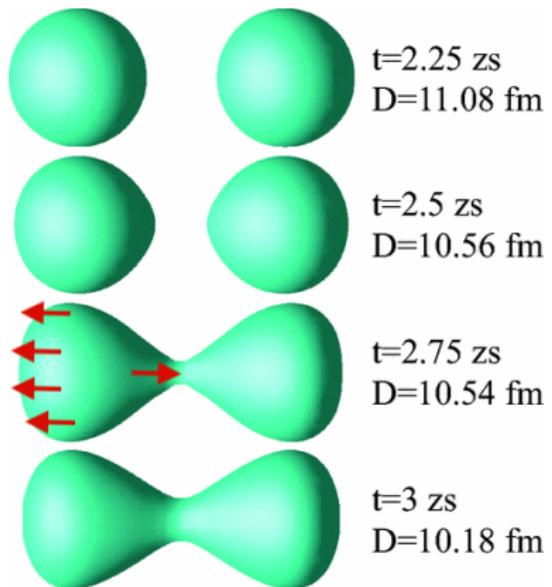
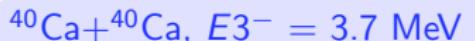




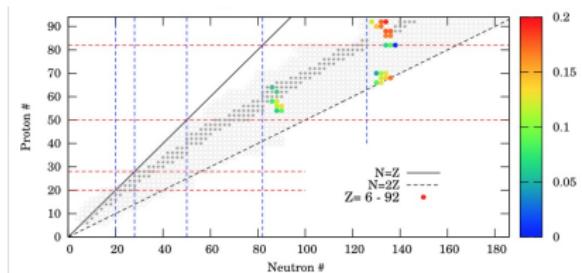
Similar effect on fusion reaction



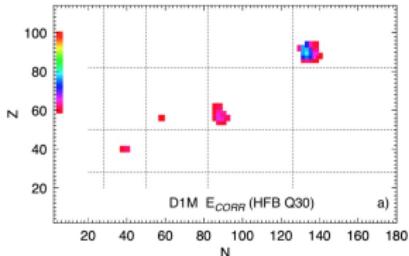
Similar effect on fusion reaction



Skyrme Skm\*.



Gogny D1S



S. Ebata, and T. Nakatsukasa, Phys. Scr. 92 (2017) 064005

LM Robledo - J. phys. G : Nucl. and Particle Physics, 2015

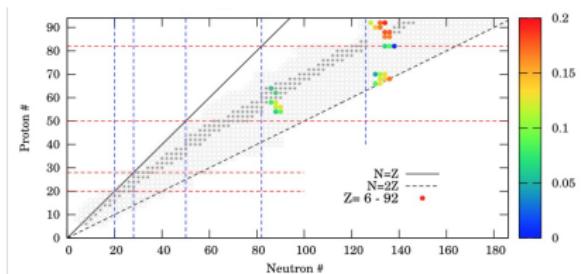
### Results from systematic calculation

In both calculations, the region  $Z \simeq 56$ ,  $N \simeq 88$  is favorable for octupole deformation .

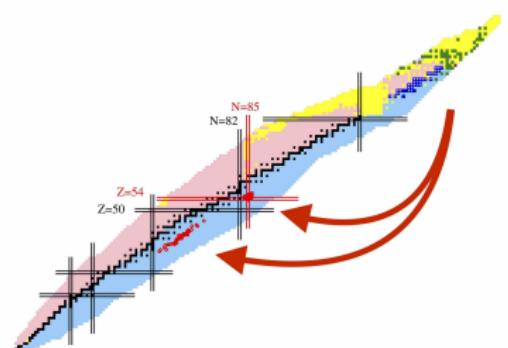
### Experimental results

$^{144}\text{Ba}$  is found to be octupole in its ground state. Burcher et al. PRL 116 (2016).

Skyrme Skm\*.



Fission data



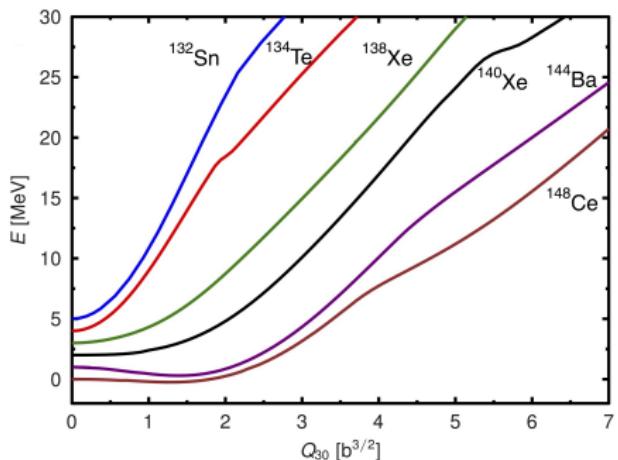
S. Ebata, and T. Nakatsukasa, Phys. Scr.  
92 (2017) 064005

### Results from systematic calculation

In both calculations, the region  $Z \approx 56$ ,  $N \approx 88$  is favorable for octupole deformation .

### Experimental results

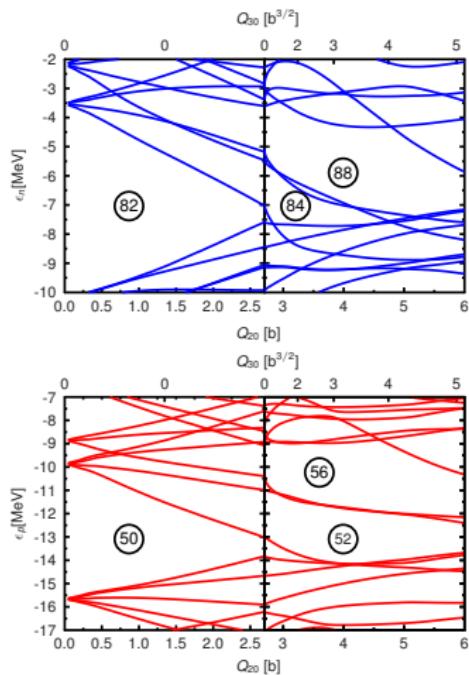
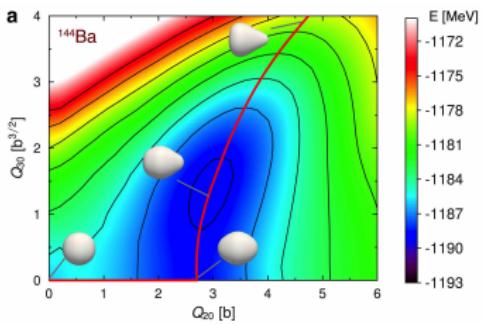
$^{144}\text{Ba}$  is found to be octupole in its ground state. Burcher et al. PRL 116 (2016).



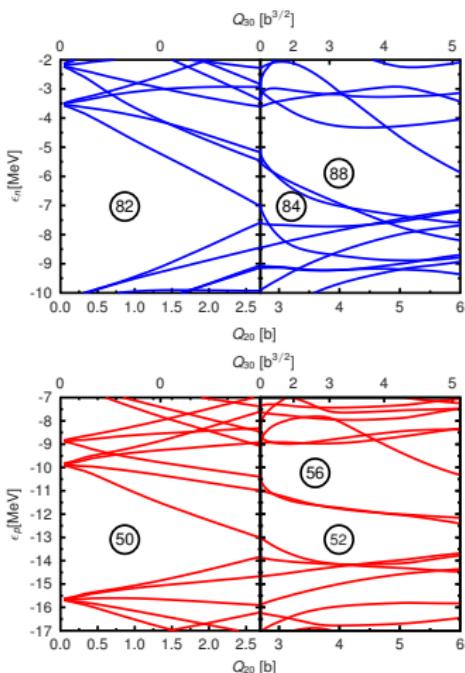
Result from constraint calculation of the heavy fragment

The gain in energy due to the octupole softness drives the fission to the  $Z \approx 54$

## Single particle energy

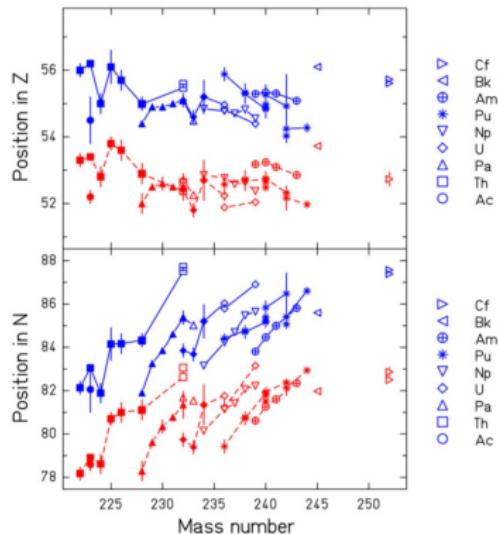
 $Q_2 - Q_3$  potential energy surface

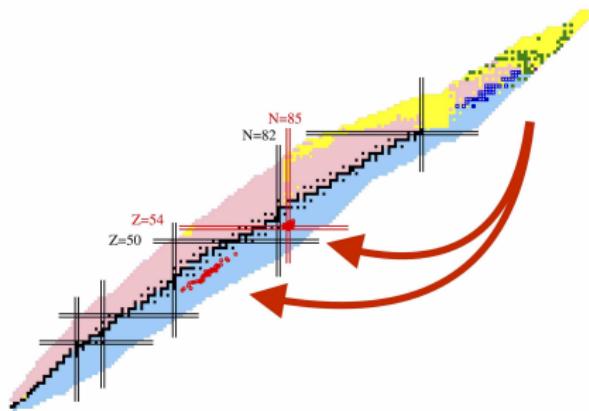
## Single particle energies



## Experimental results

C. Böckstiegel et al. / Nuclear Physics A 802 (2008) 12–25





### Mechanism

- The Nucleus-Nucleus interaction at the scission configuration favors the octupole shapes
- Shell structure favors octupole shape in the region  $Z \simeq 52-56$ ,  $N \simeq 84-88$
- Actinide fission fragments are driven in the region  $Z \simeq 54$ ,  $N \simeq 86$

G. Scamps, C. Simenel, Nature 564, 382 (2018).

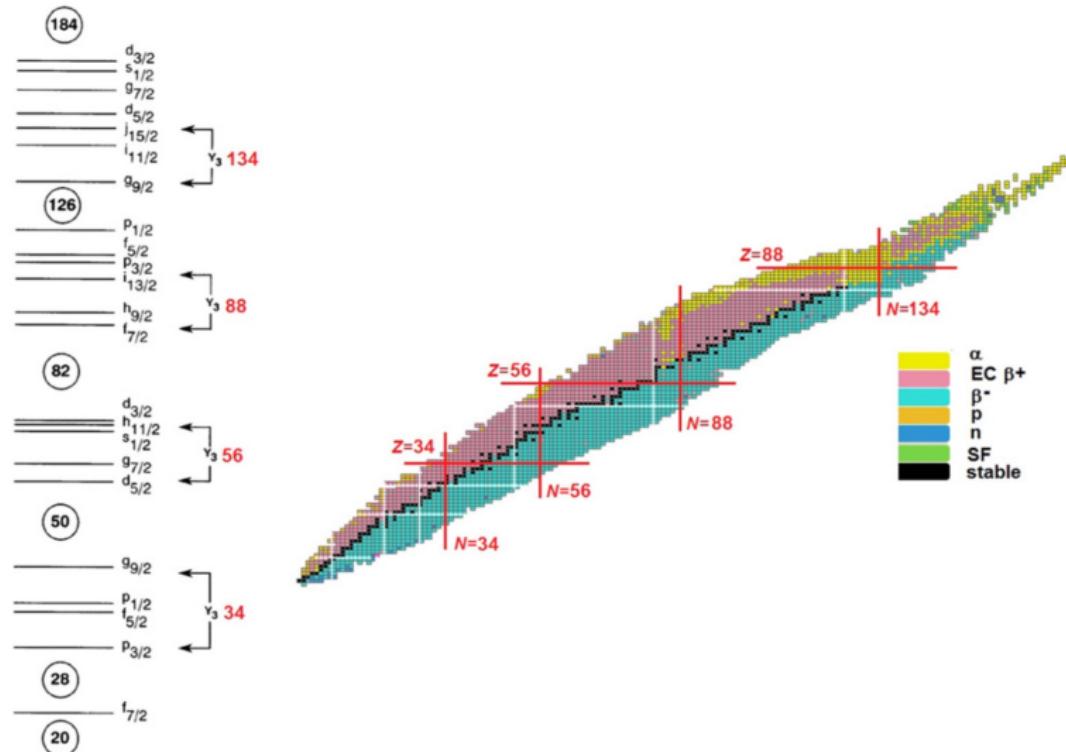
# Similar effect for other systems?

19

P. A. Butler.

J. Phys. G: Nucl. Part. Phys. **43** (2016) 073002

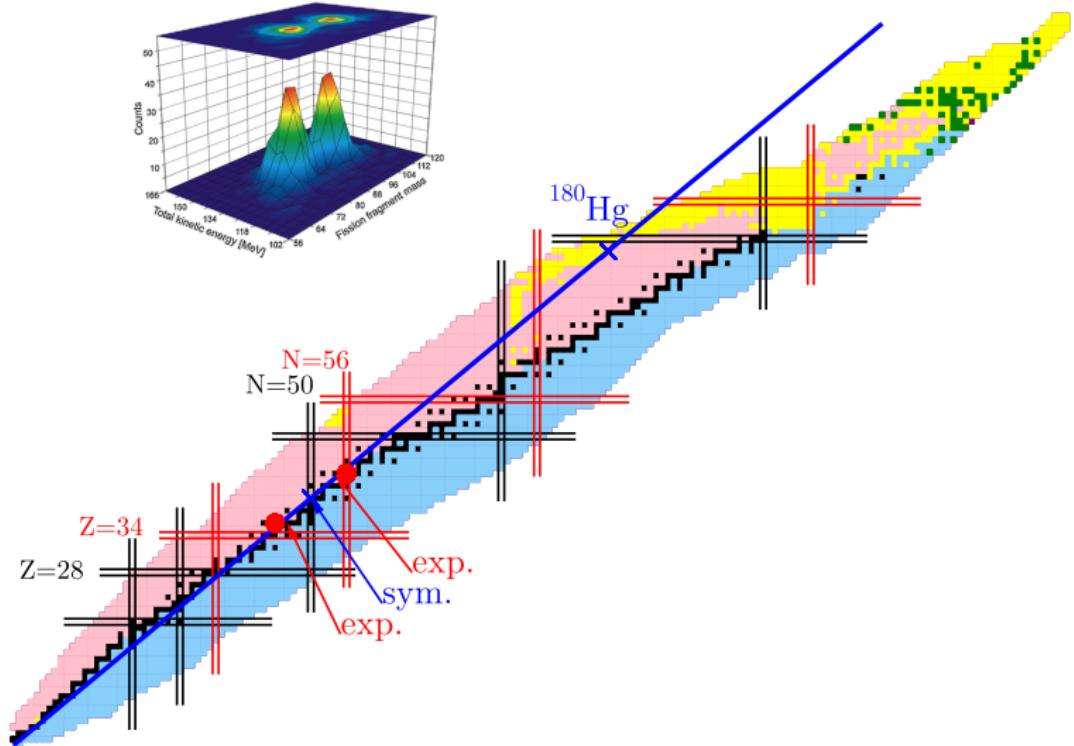
Topical Review



# Experimental data of $^{180}\text{Hg}$

20

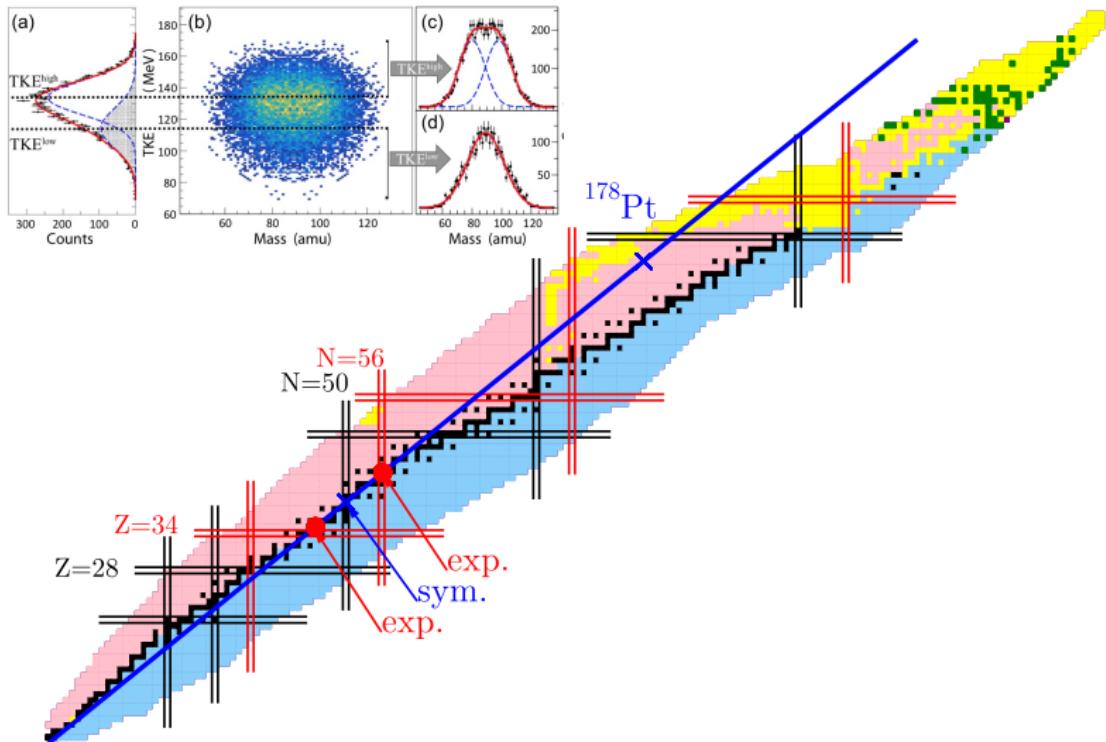
A. N. Andreyev, et al., PRL 105, 252502 (2010)

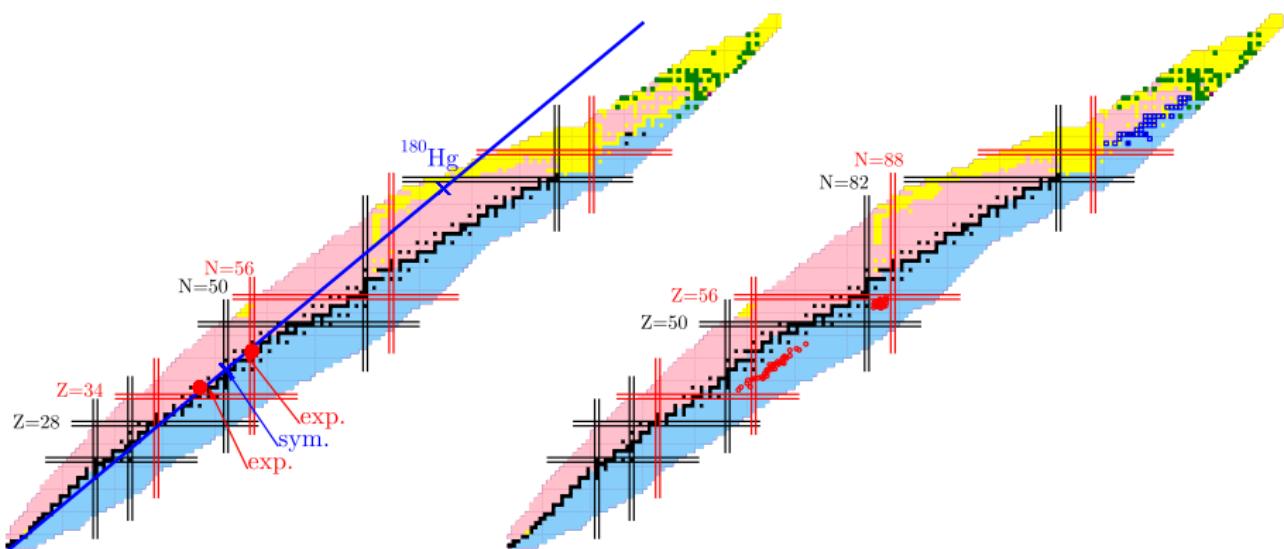


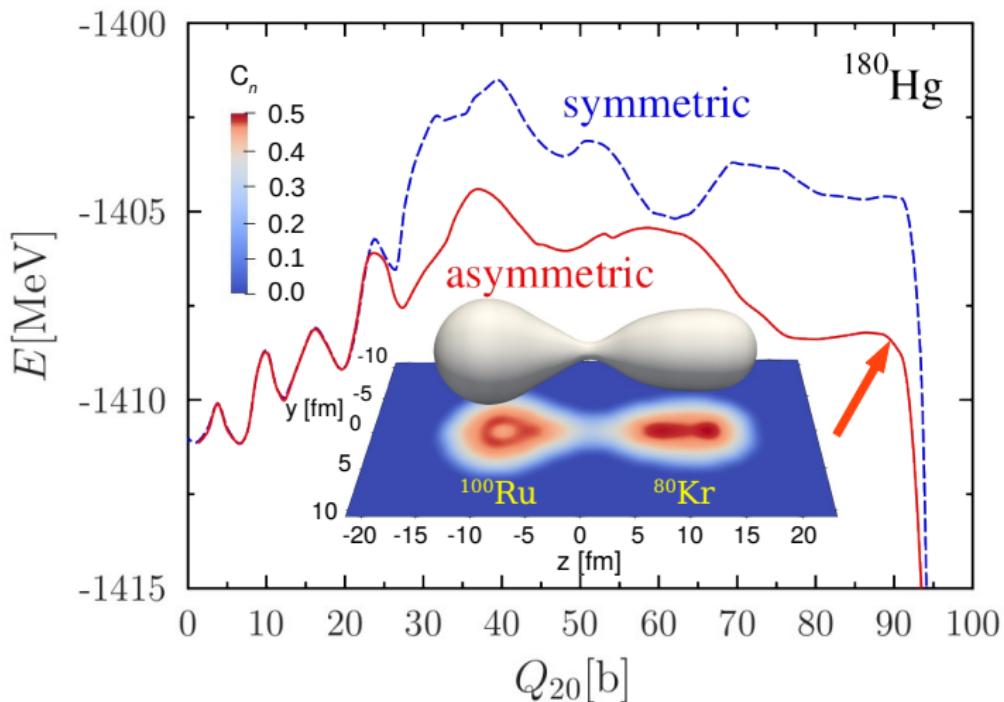
# Experimental data of $^{178}\text{Pt}$

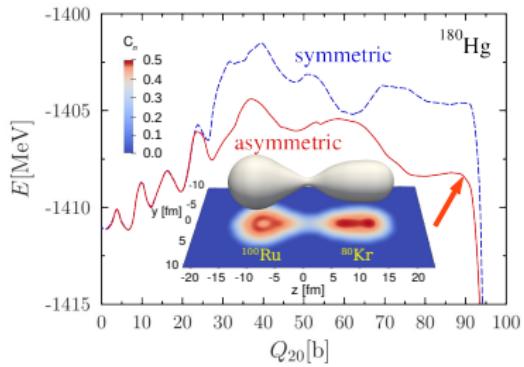
21

I. Tsekhanovich, et al. PLB 790 (2019).







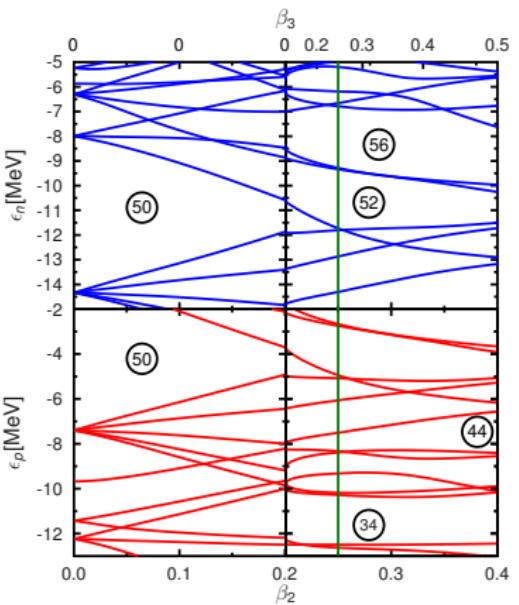
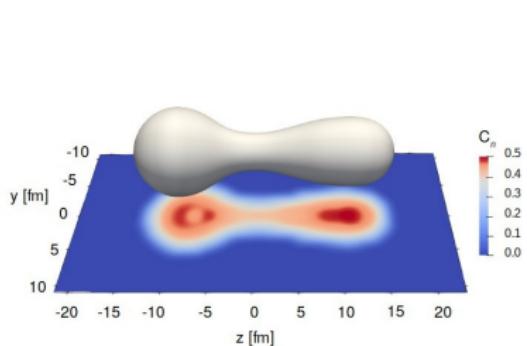


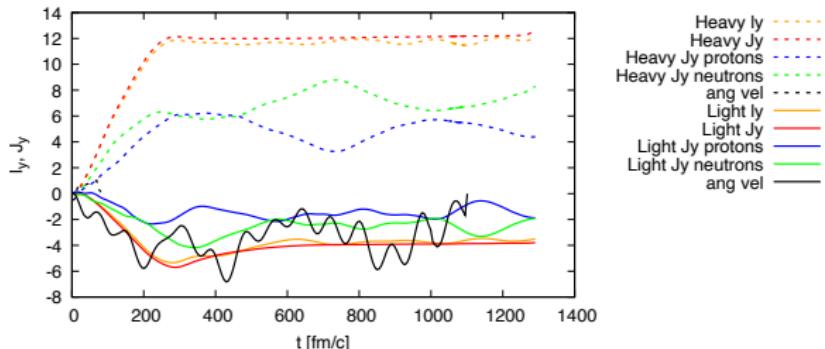
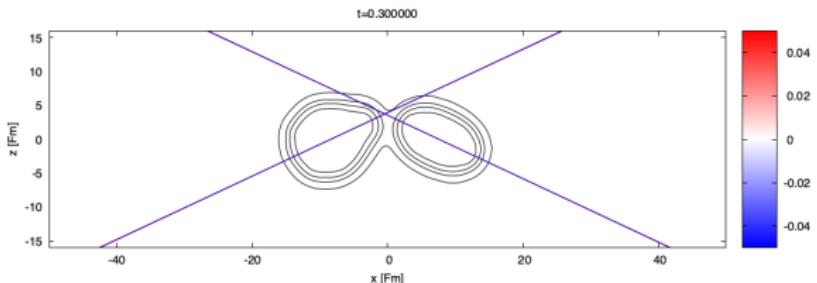
G. Scamps and C. Simenel, PRC 100, 041602(R) (2019).

**Experimental article : A. N. Andreyev, et al. Phys. Rev. Lett. 105, 252502 (2010).**

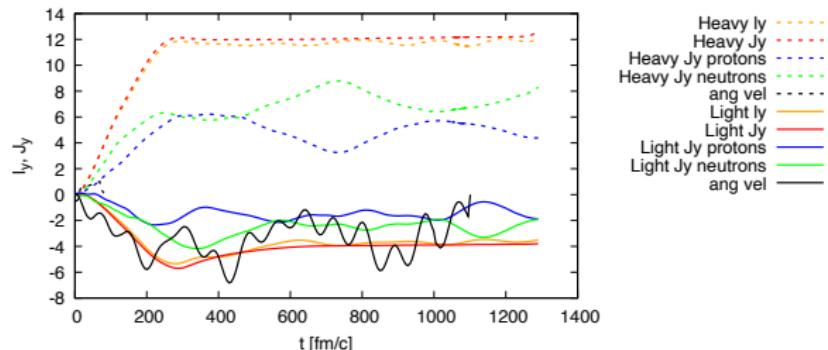
and the fission-fragment mass is shown in Fig. 4. The mass distribution is clearly asymmetric, with the most probable heavy and light masses of  $A_H = 100(1)$  and  $A_L = 80(1)$ , having a width of sigma = 4.0(3) amu. The most probable

$Z$  values of the heavy and light fission fragments are deduced to be  $Z_H = 44(2)$  and  $Z_L = 36(2)$ , respectively, assuming that the  $N/Z$  ratio of the parent nucleus  $^{180}\text{Hg}$  is preserved in the fission fragments. Thus, the most abundantly produced fission fragments are  $^{100}\text{Ru}$  and  $^{80}\text{Kr}$  and their neighbors. Although 75% of the fission events are

Structure of  $^{100}\text{Ru}$  ( $Z=44$  and  $N=56$ )

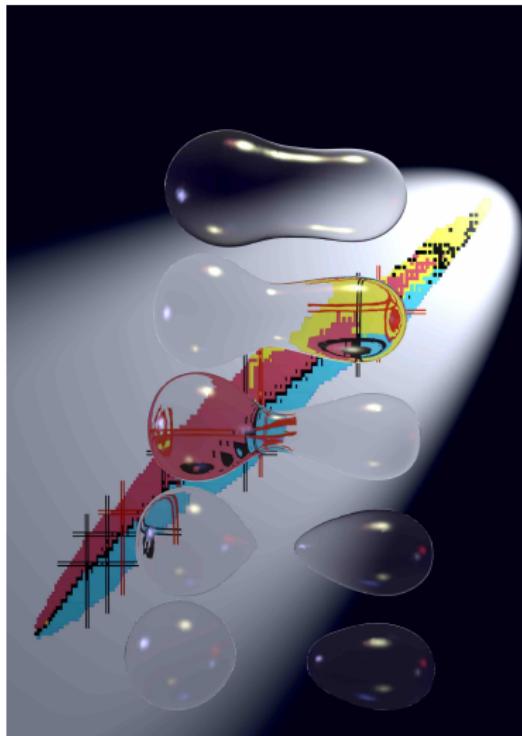


G. Scamps, Microscopic description of the torque acting on fission fragments, arXiv :2209.10759  
 See also poster.



G. Scamps, Microscopic description of the torque acting on fission fragments, arXiv :2209.10759  
See also poster.

The fission process magnifies the octupole shell structure



Thank you