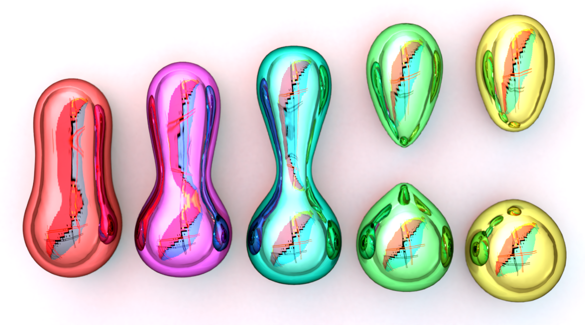
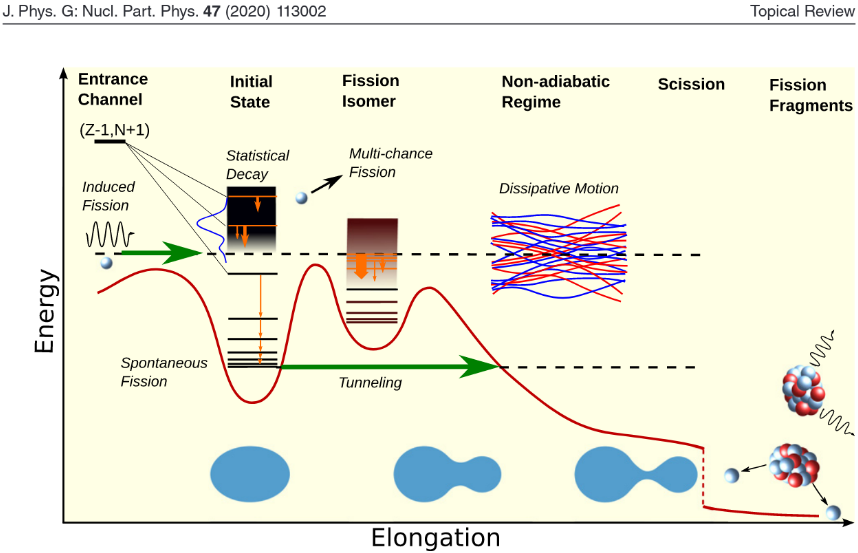
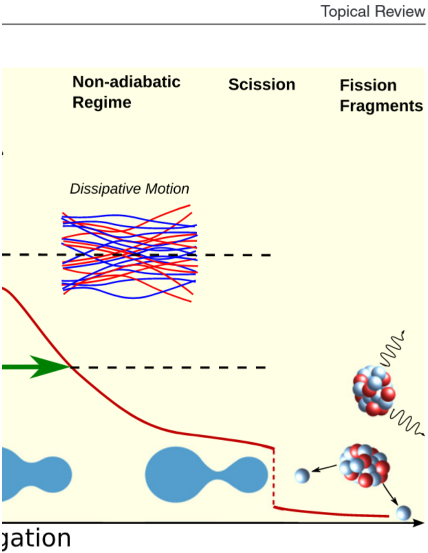
Kickoff meeting of the IRL NPA - Dec. 11 - Dec. 13

Nuclear scructure at scission

Guillaume SCAMPS

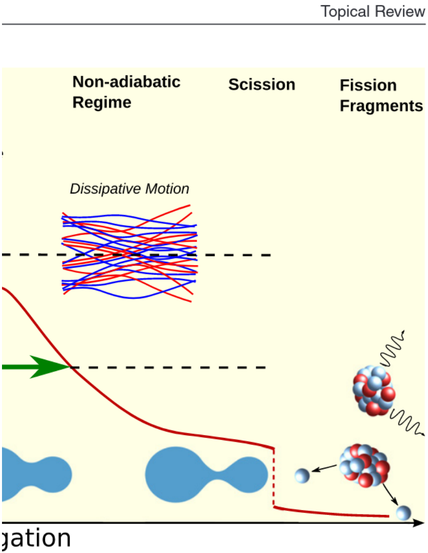



J. Phys. G: Nucl. Part. Phys. 47 (2020) 113002
Topical Review
Entrance Channel
Initial State
Fission Isomer
Non-adiabatic Regime
Scission
Fission Fragments
(Z-1,N+1)
Statistical Decay
Multi-chance Fission
Induced Fission
Dissipative Motion
Spontaneous Fission
Tunneling
Energy
Elongation

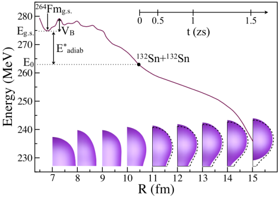

Topical Review
Non-adiabatic Regime
Scission
Fission Fragments
Dissipative Motion
gation

What do we want to understand ?

- Charge and mass distribution
- Connection with structure
- Odd-even effects
- Charge polarization
- Spin of the fragments



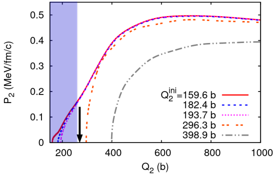
TDHF



C. Simenel and A. S. Umar, Phys. Rev. C 89, 031601(R), 2014

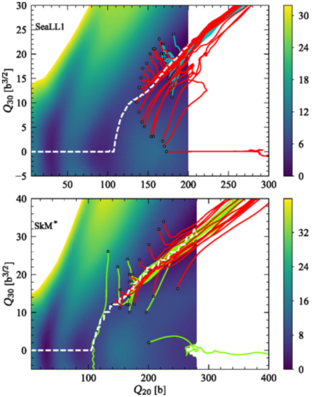
TDHF+BCS

Collective momentum evolution

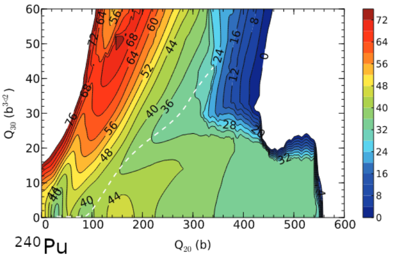


Y. Tanimura, D. Lacroix, and G. Scamps, PRC 92, 034601 (2015)

TDHFB



A. Bulgac, S. Jin, K. J. Roche, N. Schunck, and I. Stetcu Phys. Rev. C 100, 034615, 2019.



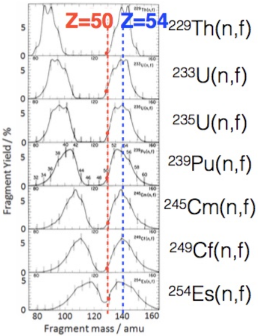
Rep. Prog. Phys. **79** (2016) 116301

Mainly two regimes before and after scission :
1) Overdamped motion, trajectory minimizing the energy
2) Fast separation, the asymmetry of the fission is frozen

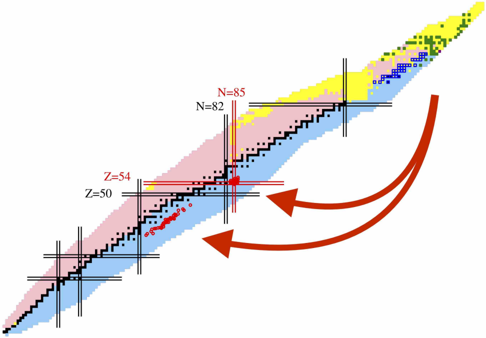
Important

The fission properties are decided at scission

Empirical behaviour of actinide nuclei

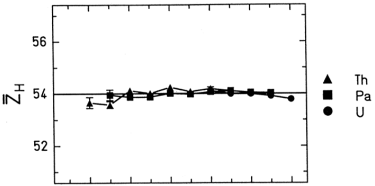


J.P. Unik, J.E. Gindler, J.E. Glendenin et al. : Proc. Phys. and Chem. of Fission IAEA Vienna, Vol II, 20 (1974)



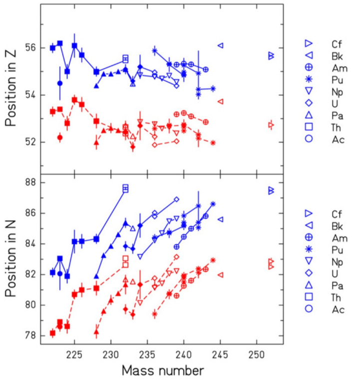
Data from D. A. Brown et al., Endf/b-viii.0, Nucl. Data Sheets 148, 1 (2018), (spontaneous and thermal neutron-capture).

Empirical behavior of actinide nuclei



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

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

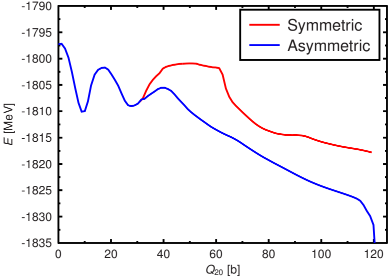


Motivation

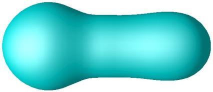
How can we understand this behaviour ? Interplay between structure and reactions ?

First : CHF+BCS

Example : ^{240}Pu



Second : TDHF+BCS



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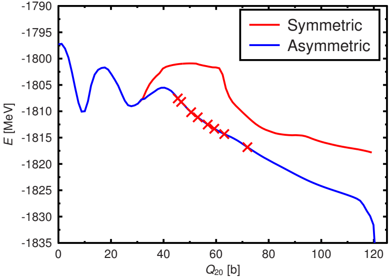
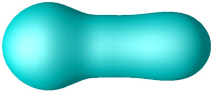


Second : TDHF+BCS



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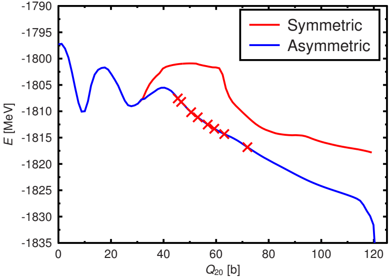

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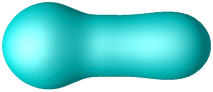
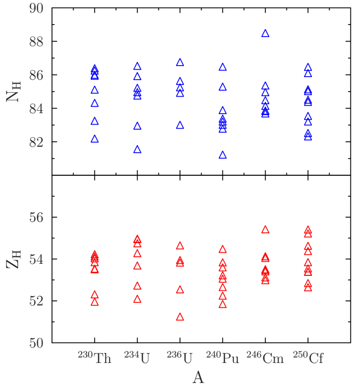
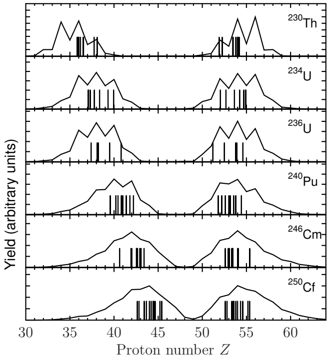


TDHF+BCS

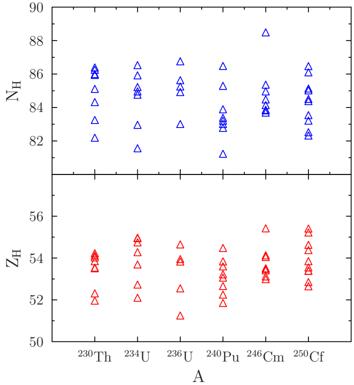


Comparison with experimental data

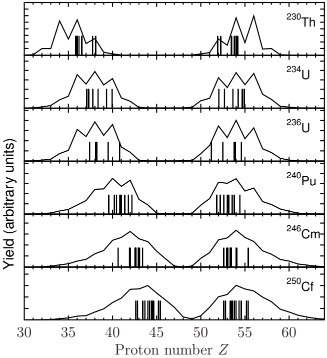


TDHF+BCS systematics results

TDHF+BCS



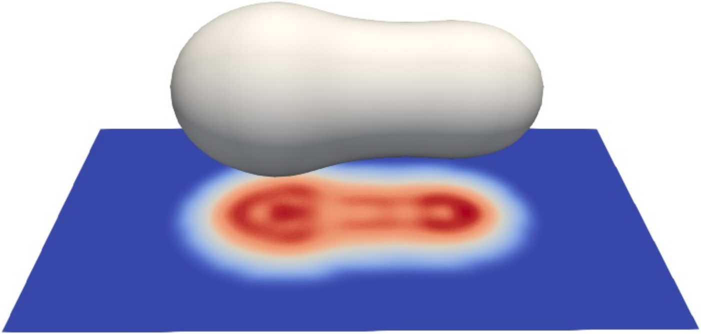
Comparison with experimental data



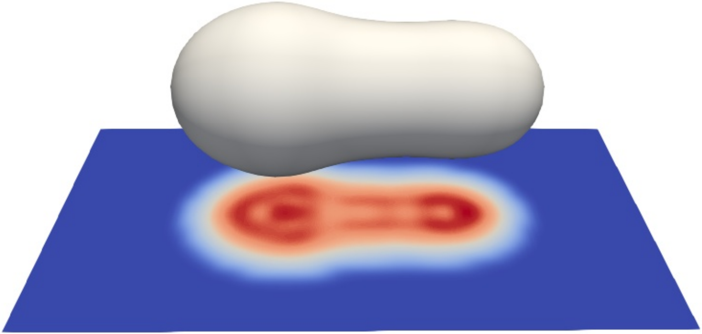
Conclusion :

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

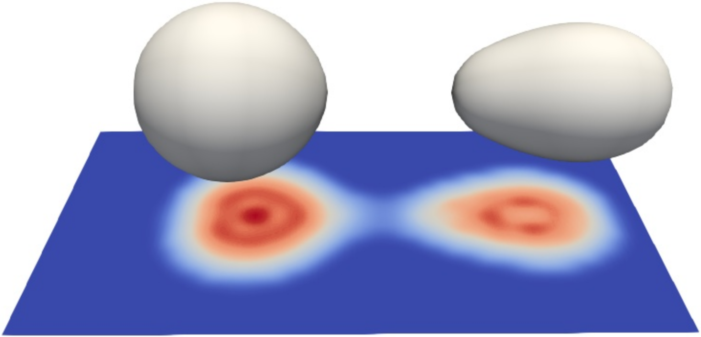
^{240}Pu



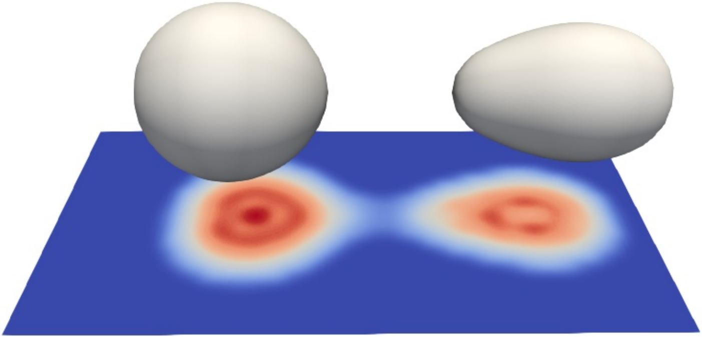
^{240}Pu

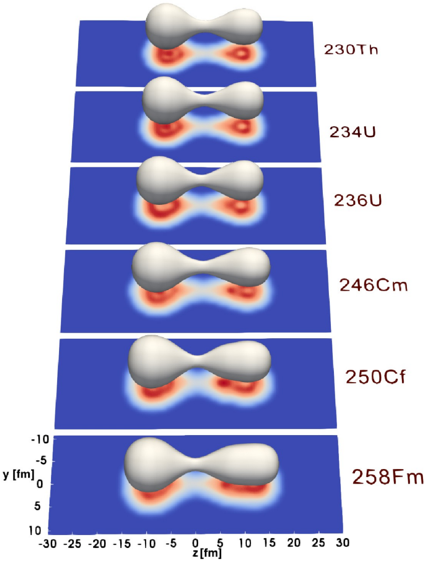


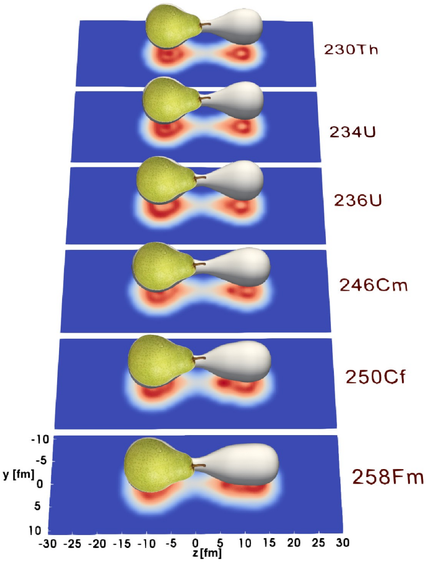
^{240}Pu



^{240}Pu

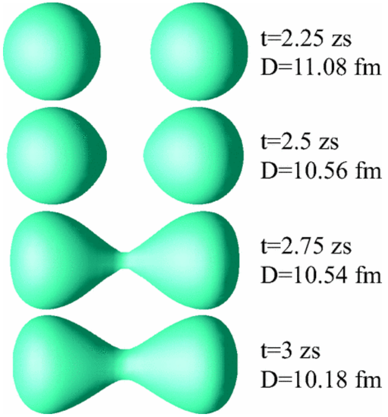



230Th
234U
236U
246Cm
250Cf
258Fm
y [fm]
-10
-5
0
5
10
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30
z [fm]

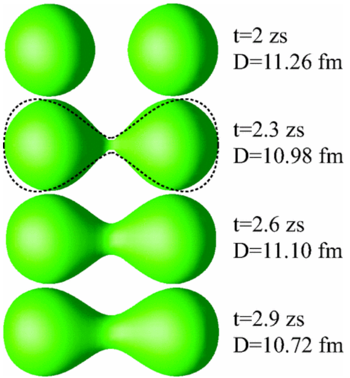

230Th
234U
236U
246Cm
250Cf
258Fm
y [fm]
-10
-5
0
5
10
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30
z [fm]

Similar effect on fusion reaction :

^{40}Ca+^{40}Ca, $E3^- = 3.7$ MeV



^{56}Ni+^{56}Ni, $E3^- = 7.5$ MeV



C. Simenel, M. Dasgupta, D. J. Hinde, and E. Williams, Phys. Rev. C 88, 064604 (2013).

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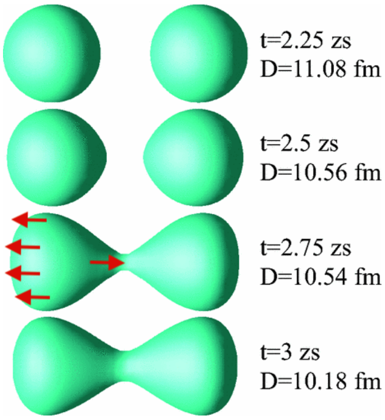

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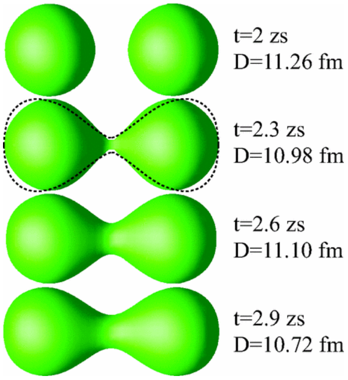
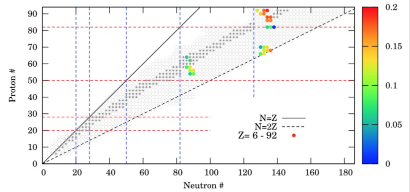


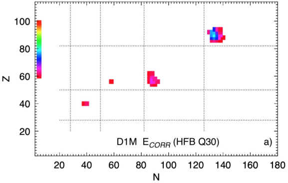
C. Simenel, M. Dasgupta, D. J. Hinde, and E. Williams, Phys. Rev. C 88, 064604 (2013).

Skyrme Skm*.



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

Gogny D1S



LM Robledo - J. phys. G : Nucl. and Part. Phys. (2015)

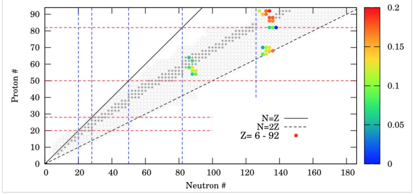
Results from systematic calculation

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

Experimental results

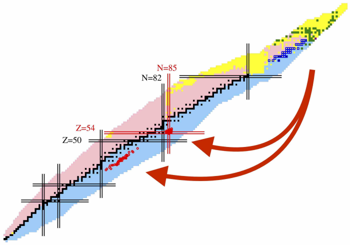
^{144}Ba is found to be octupole in its ground state. Burcher et al. PRL 116 (2016).

Skyrme Skm*.



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

Fission data



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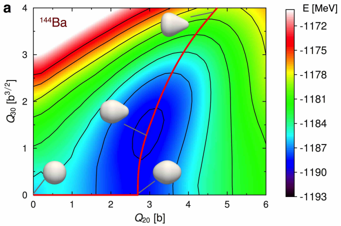
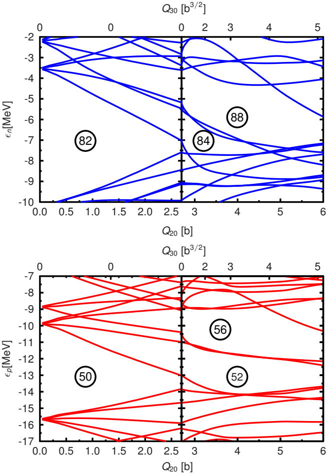
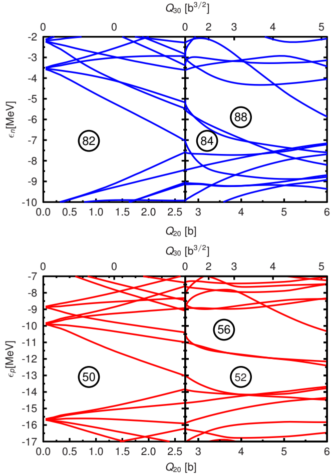
Q_2 - Q_3 potential energy surface



Single particle energy

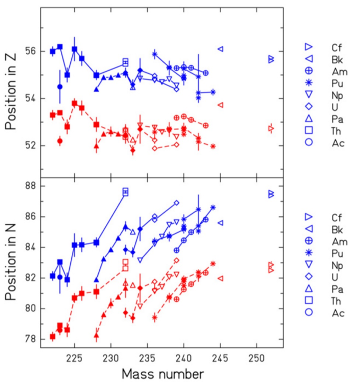


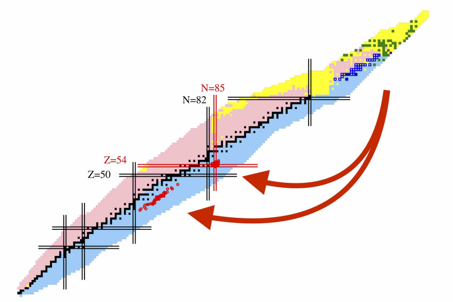
Single particle energies



Experimental results

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

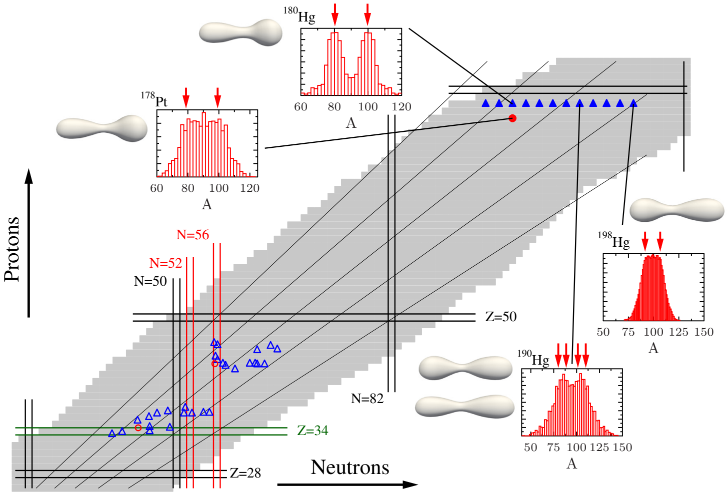




Mechanism

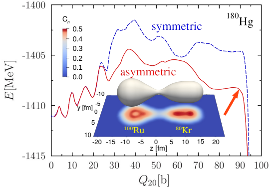
- The Nucleus-Nucleus interaction at the scission configuration favors the octupole shapes
- Shell structure favors octupole shape in the region Z $\simeq$ 52-56, N $\simeq$ 84-88
- Actinide fission fragments are driven in the region Z $\simeq$ 54, N $\simeq$ 86

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

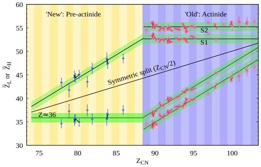


G. Scamps and C. Simenel, PRC 100, 041602(R) (2019)

Fission of light nuclei

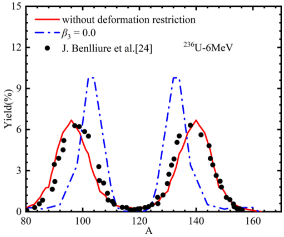


G. Scamps C. Simenel, PRC 100, 041602(R) (2019)



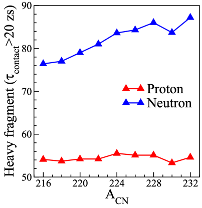
K. Mahata, C. Schmitt, S. Gupta, A. Shrivastava, G. Scamps, K.-H. Schmidt, PLB 825, 136859 (2022)

Scission point model



Dong-ying Huo, Zheng Wei, et al., PRC108, 024608(2023)

Quasi-fission ; Ex. $^{40-56}$Ca+^{176}Yb



C. Simenel, et al, J.P. CS 2586(2023).

What generates the fragments' spin ?

Literature

- Thermal excitations
- Quantum fluctuations
- Coulomb force

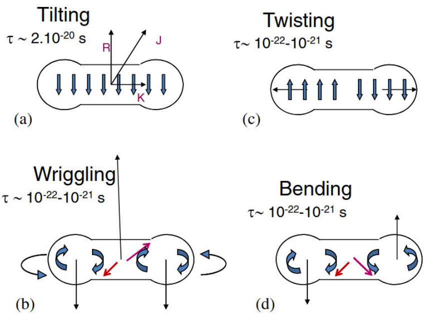
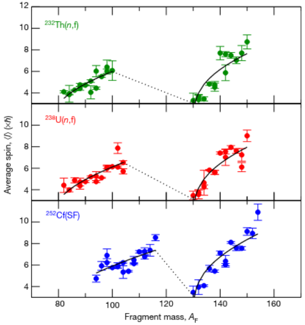


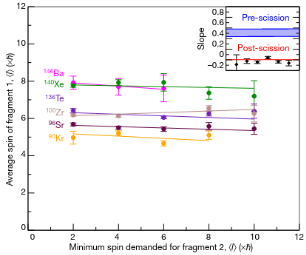
Illustration from B. John, J. Phys., 85, 2, (2015).

J. N. Wilson, Nature, 590, 566 (2021)

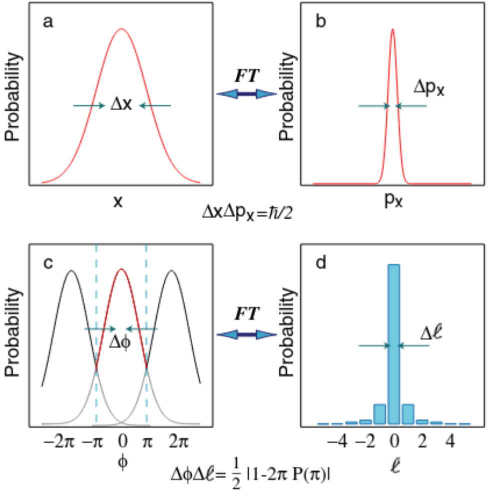
Spin of the fragments



Correlations

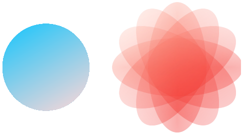


- The average spin follows a sawtooth shape
- No correlations between the spins of the fragments

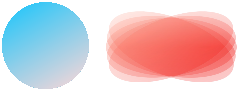


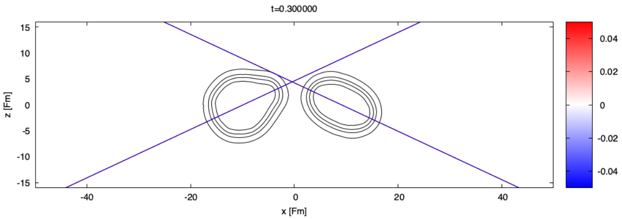
S. Franke-Arnold, et al. New Journal of Physics 6, 103 (2004)

Isotropic potential at scission

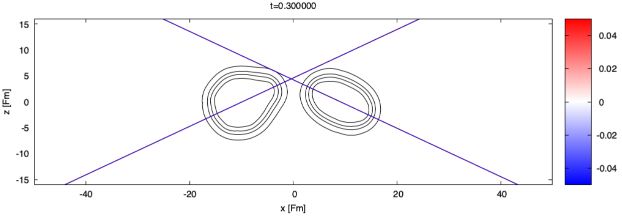


Confining potential at scission

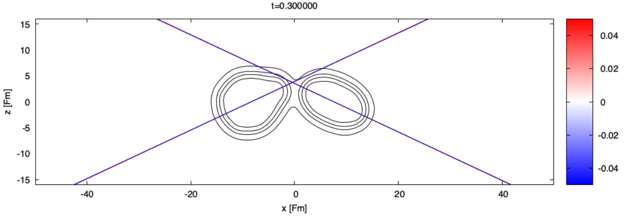




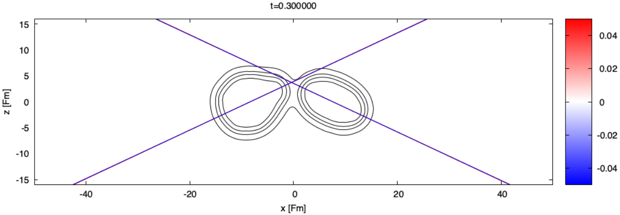
G. Scamps, PRC 106, 054614 (2022).



G. Scamps, PRC 106, 054614 (2022).

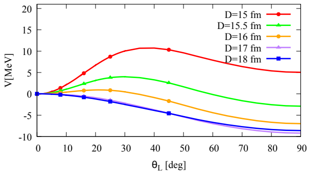


G. Scamps, PRC 106, 054614 (2022).



G. Scamps, PRC 106, 054614 (2022).

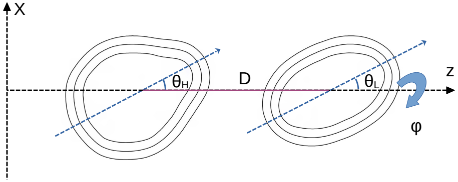
Frozen Hartree-Fock potential



Two torques :

- attractive nucleus-nucleus torque
- repulsive Coulomb torque

4 degrees of freedom



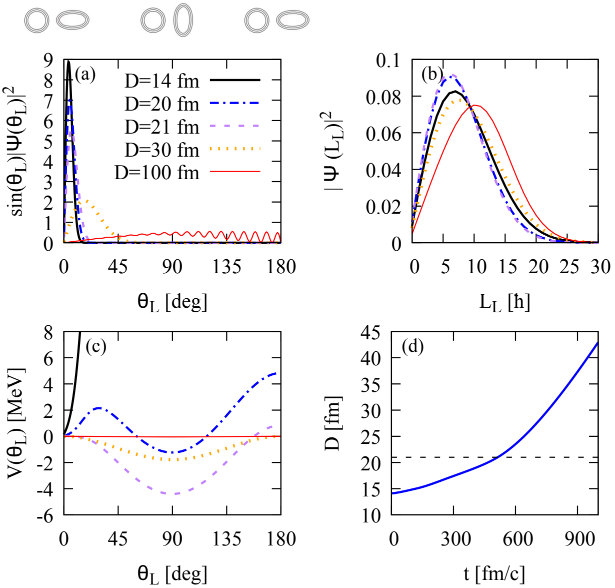
Hamiltonian

$$\hat{H}(D) = \frac{\hbar^2}{2I_H}\hat{L}_H^2 + \frac{\hbar^2}{2I_L}\hat{L}_L^2 + \frac{\hbar^2}{2I_\Lambda(D)}\hat{\Lambda}^2 + \hat{V}(D)$$

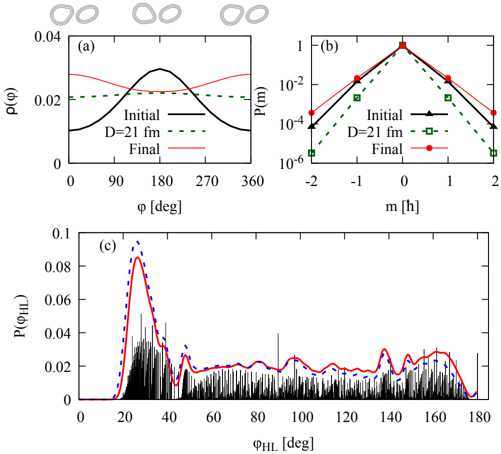
Solved in basis $|L_H, m, L_L, -m\rangle$

G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616(2023).

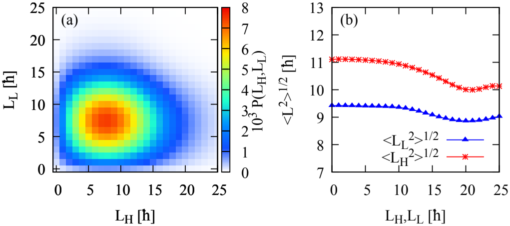
Evolution of a one-angle wave packet



G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616(2023).



G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616(2023).



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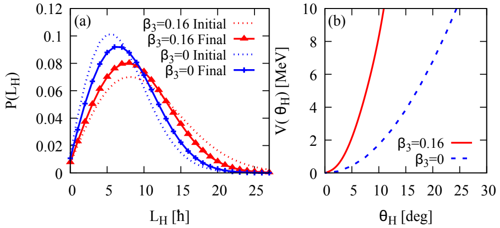
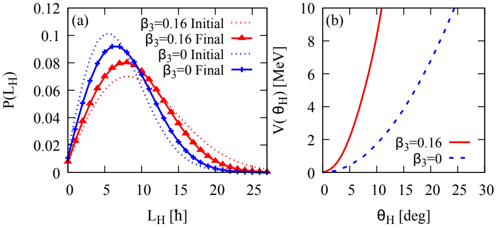


G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616(2023).



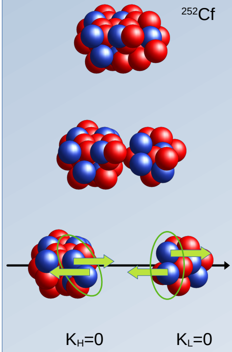
Conclusion

- No strong correlation of the magnitude and direction of the spins
- Both spins are oriented in the plane perpendicular to the fission axis.
- The Coulomb interaction induces an increase of the angular momentum by 1 to 3 $\hbar$
- The octupole deformation increases the angular momentum generated at scision

G. Scamps, G. Bertsch, Phys. Rev. C 108, 034616(2023).

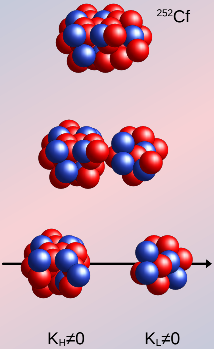
Pair breaking mechanism ?

Assuming Cold fission



Fully paired fragments
Only even-even fragments

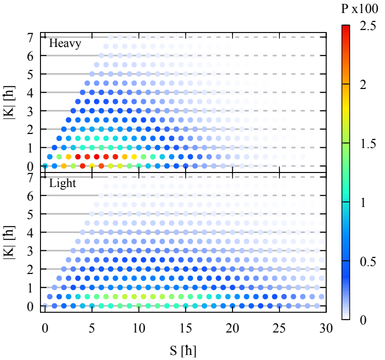
Realistic case



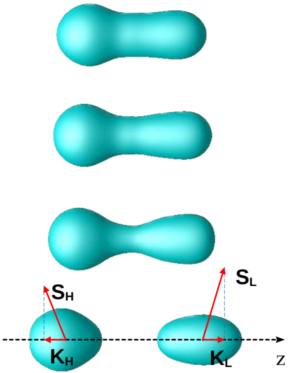
Pairs are broken
Every outcome are possible

Spin distribution in the fragments

Obtained using 3-angle projection operator

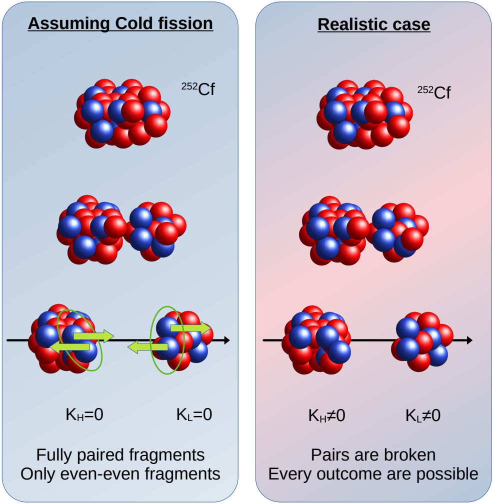


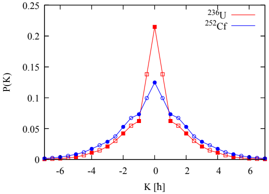
Geometry of the reaction

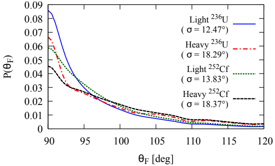


G.scamps, I. Abdurrahman, M. Kafker, A. Bulgac, and I. Stetcu, arXiv :2307.14455.

Pair breaking mechanism ?





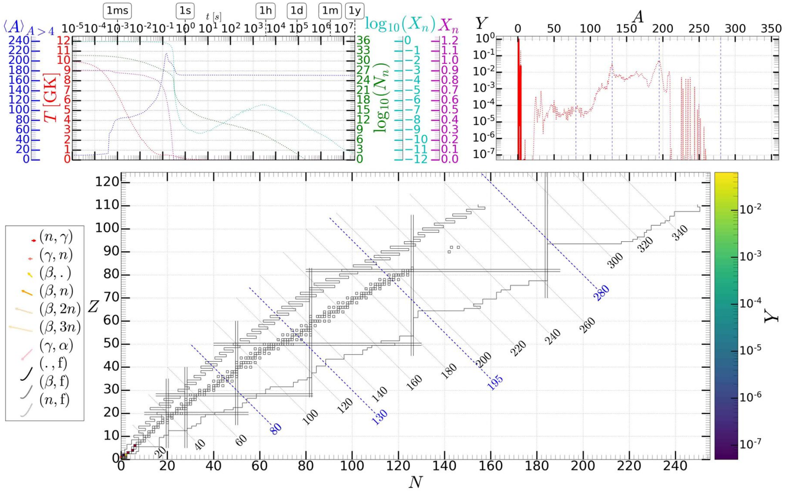


$$\cos\theta_F = \frac{K_F}{\sqrt{S_F(S_F+1)}}$$

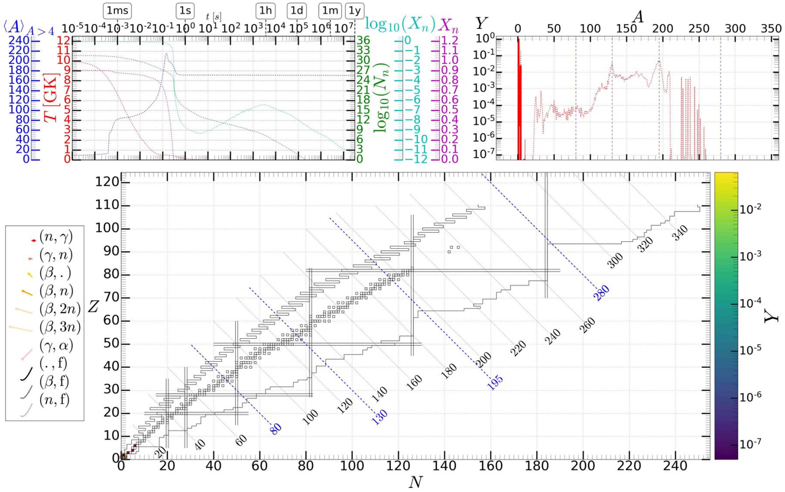
G.scamps, I. Abdurrahman, M. Kafker, A. Bulgac, and I. Stetcu, arXiv :2307.14455.

Main points

- Orientation-pumping (uncertainty principle) mechanism at scission
- Additional effect of the Coulomb torque
- Internal excitation (breaking of pairs)
- Spin are mainly perpendicular to the fission axis
- Uncorrelated magnitude and orientation of the spins
- Dependence of the mechanism with the deformation (quadrupole and octupole)



J.-F. Lemaître, S. Goriely, A. Bauswein, and H.-T. Janka, PRC 103, 025806 (2021)



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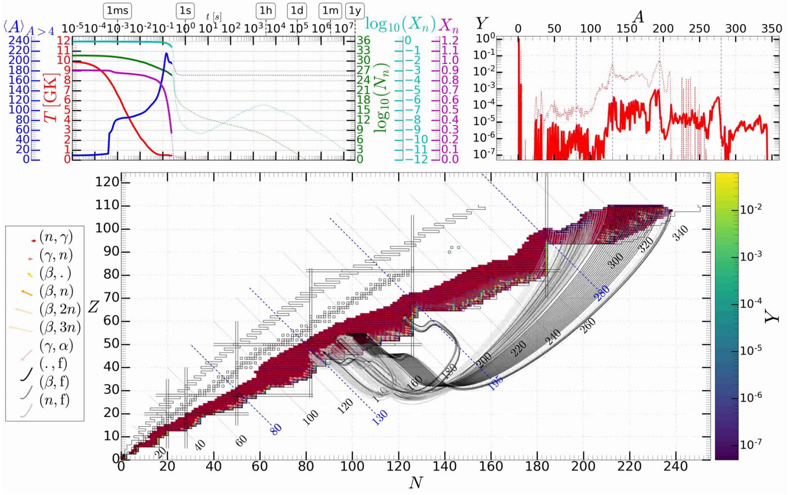
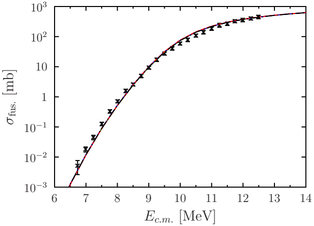


J.-F. Lemaître, S. Goriely, A. Bauswein, and H.-T. Janka, PRC 103, 025806 (2021)

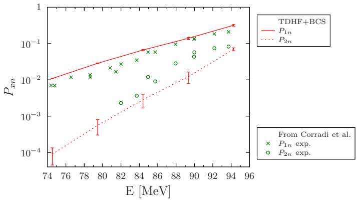
TDDFT codes

- TDHF ; TdBCS ; TDHFB
- Gogny - Skyrme
- Fusion, Transfert, Fission, Giant-resonances

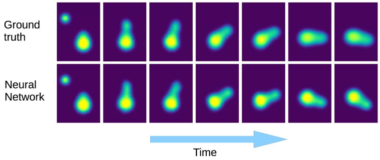
DCTDHFB Ex : $^{16}O+^{16}O$



Projection method for transfer reaction



Machine learning



Thank you

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- Denis Lacroix
- Cedric Simenel
- George Bertsch
- Aurel Bulgac
- Ibrahim Abdurrahman
- Ionel Stetcu
- Matthew Kafker

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