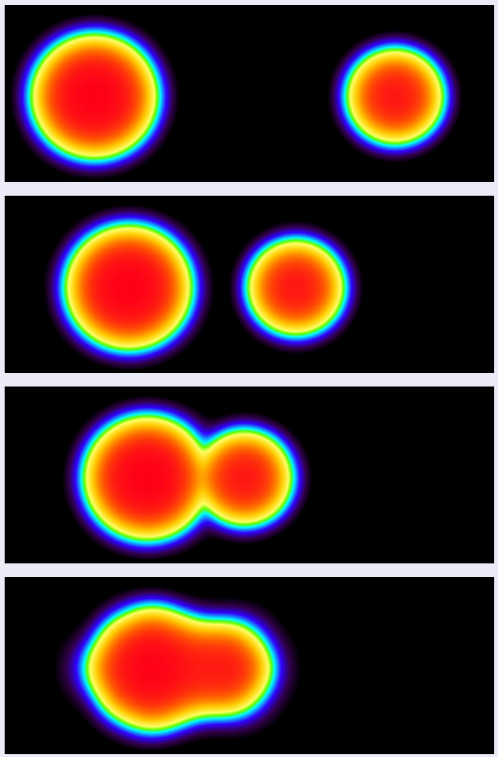


Microscopic description of fission using dynamical theories.

Guillaume SCAMPS

Tohoku University

Collaboration : C. Simenel, D. Lacroix, K. Hagino, Y. Tanimura

Lack of theoretical prediction

Lack of theoretical prediction

- Error of order of magnitudes on the life-time
- Lack of prediction for the charge/mass distribution

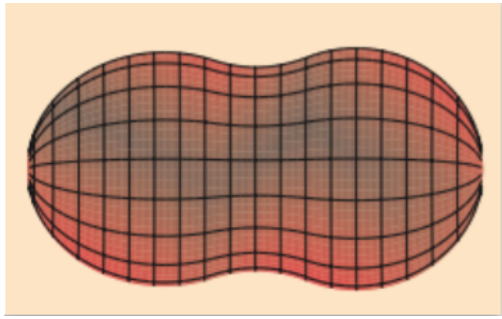
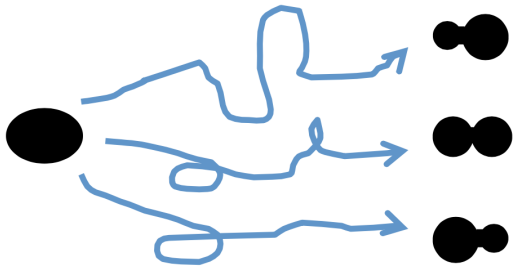
Prediction are necessary for :

- Astrophysics (r-process)
- Industrial applications, production of ions, reactors...

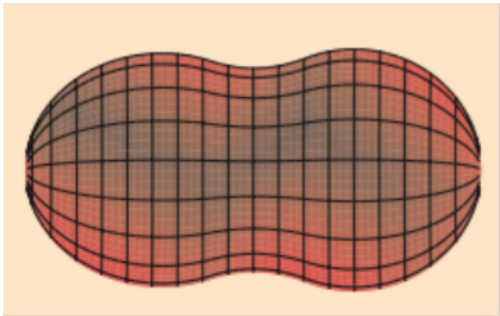
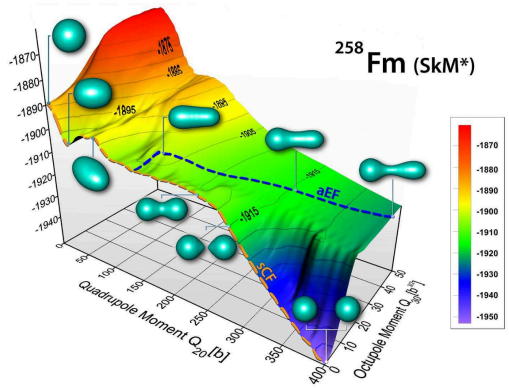
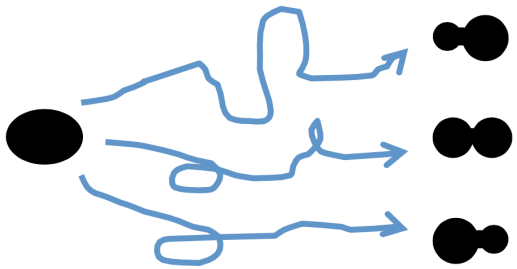
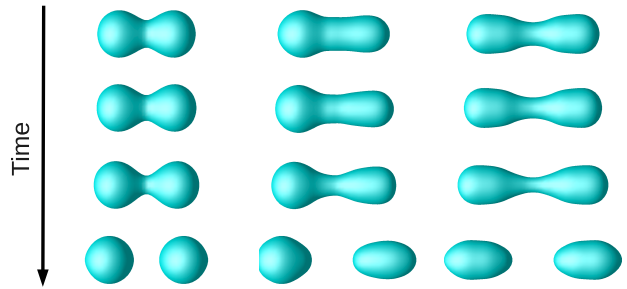
Lots of theoretical questions

- How to define the scission ?
- What are the important degrees of freedom ?
- Shell effects ?
- Effect of pairing ? Odd-even effects ?
- How the energy is split into the fragments ?
- ...

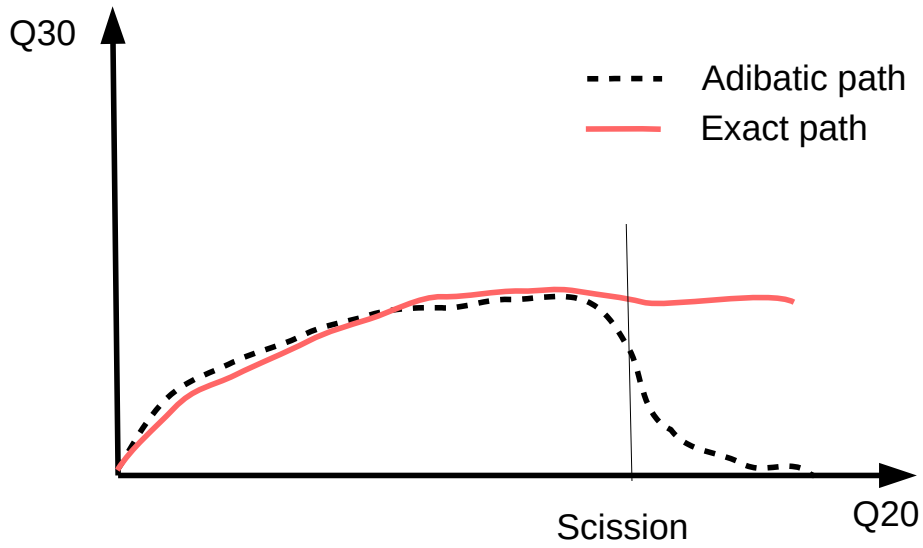
State of the art :

	Macroscopical model
Static	Liquid drop with shell correction  P. Moller, et al., Nature 409 (2001)
Dynamics	Stochastic motion  J. Randrup, PRL 106 (2011)

State of the art :

	Macroscopical model	Microscopical model
Static	Liquid drop with shell correction  P. Moller, et al., Nature 409 (2001)	Mean-field theory with pairing, HF+BCS or HFB  A. Staszczak, et al., PRC 80, (2009)
Dynamics	Stochastic motion  J. Randrup, PRL 106 (2011)	Dynamical mean-field TDHF+BCS  G. Scamps, et al, arXiv :1501.03592

Adiabatic approximation



Adiabatic path

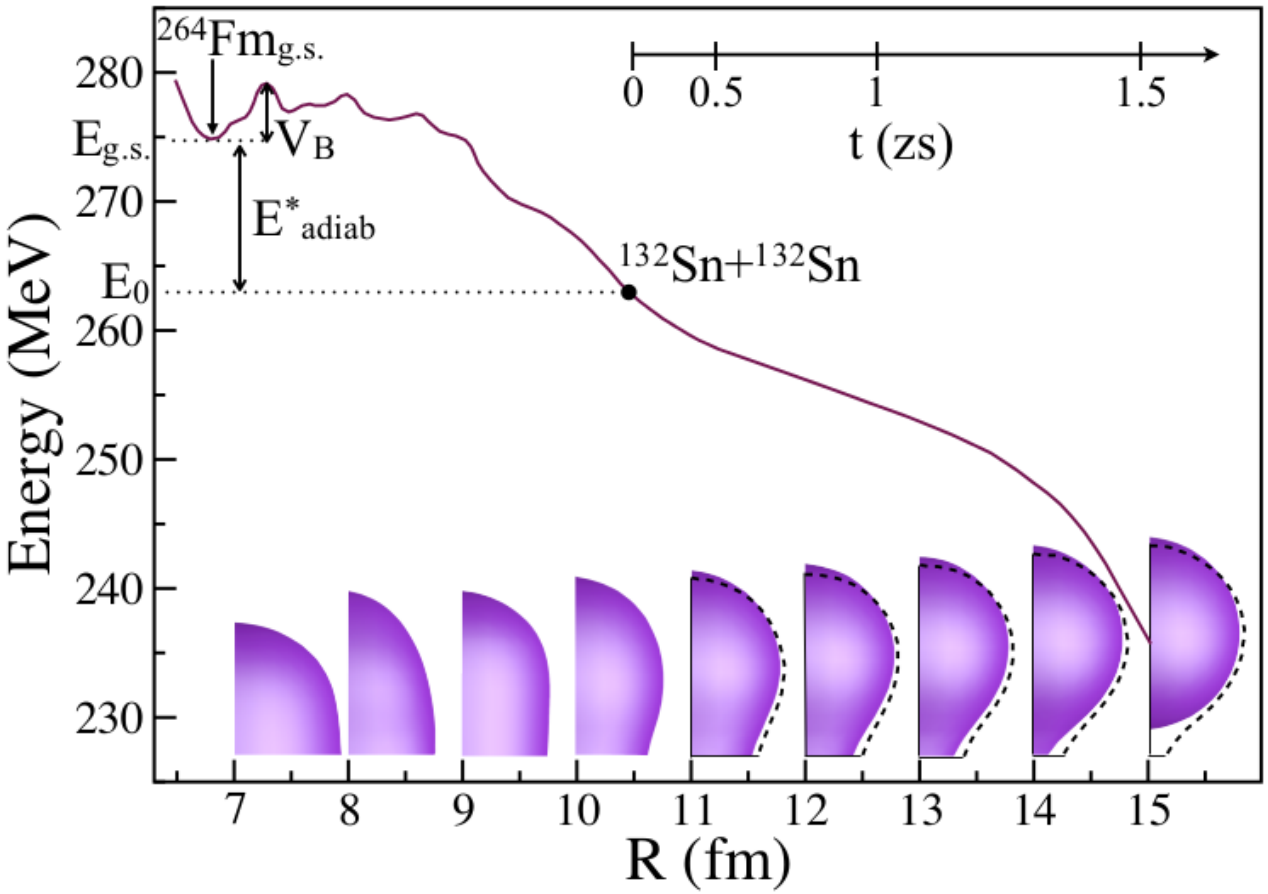
Path that minimize the energy with respect to degrees of freedom orthogonal to the elongation.

TDHF or TDHF+BCS

All the degrees of freedom are taken into account

TDHF calculation, fission of ^{264}Fm

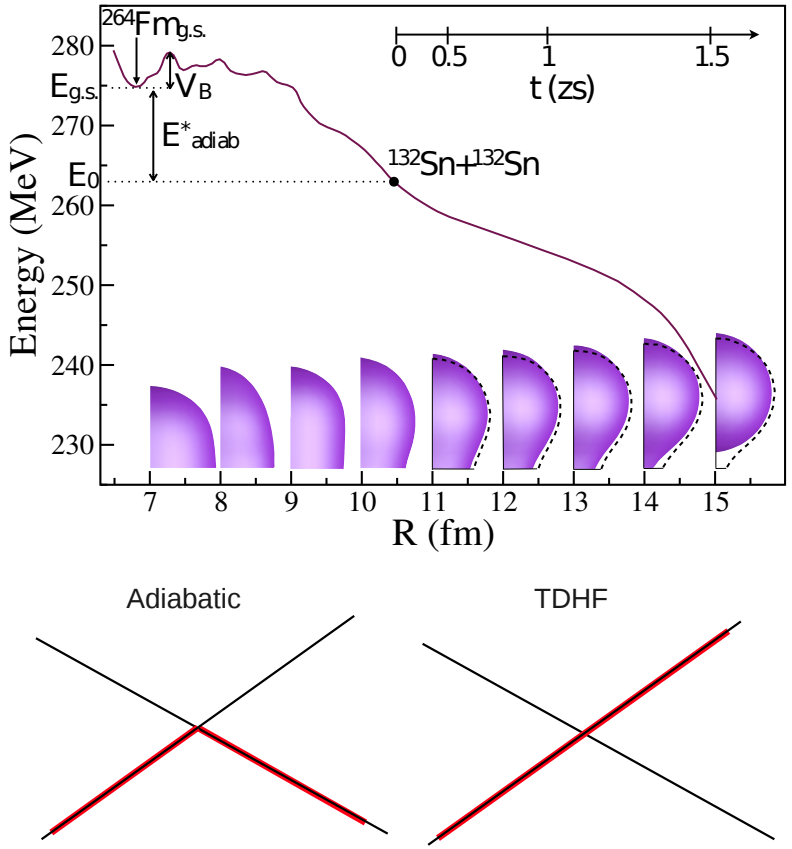
Adiabatique Non adiabatique

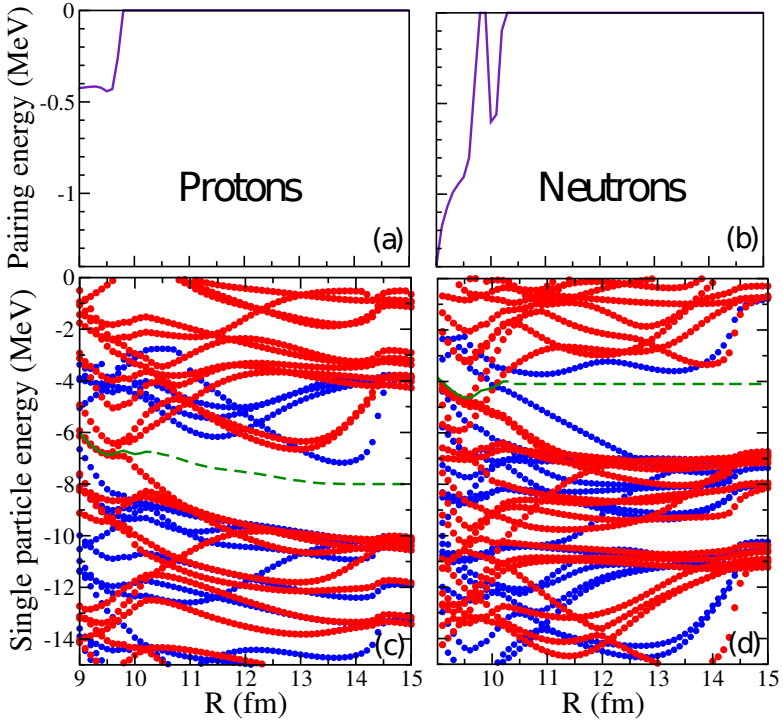


C. Simenel and A. S. Umar, Phys. Rev. C 89, 031601(R), 2014

The adiabaticity approximation is assumed for the barrier crossing but is known to break down before scission.

TDHF calculation, fission of ^{264}Fm

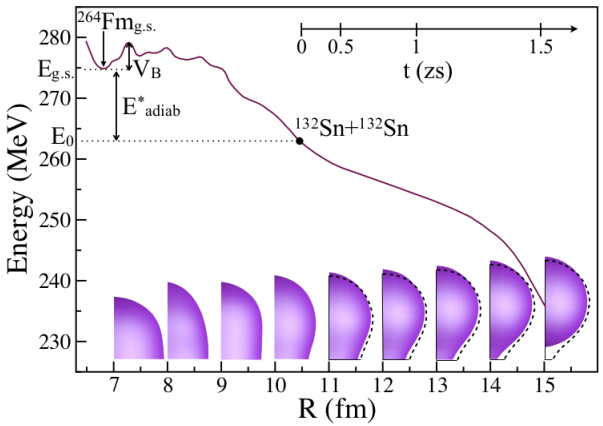


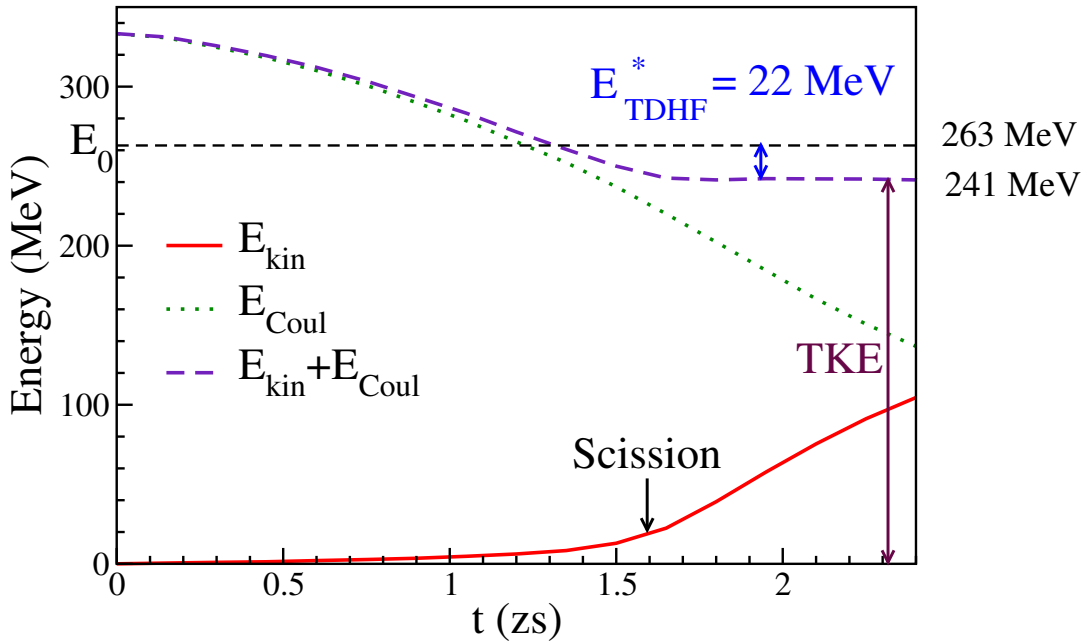


C. Simenel and A. S. Umar, Phys. Rev. C 89, 031601(R), 2014

The adiabaticity is not assume in the TDHF evolution

TDHF calculation, fission of ^{264}Fm





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

Conclusion

Total Kinetic energy = 241 MeV

Excitation energy = $E^*_{\mathrm{adiabatic}} + E^*_{\mathrm{TDHF}} = 34$ MeV

Mean-field theory with pairing

TDHF

- Independent particle
- Initialisation : $\hat{h}_{MF} |\phi_i\rangle = \epsilon_i |\phi_i\rangle$
- Evolution : $i\hbar \frac{d\rho}{dt} = [h_{MF}, \rho]$

TDHFB

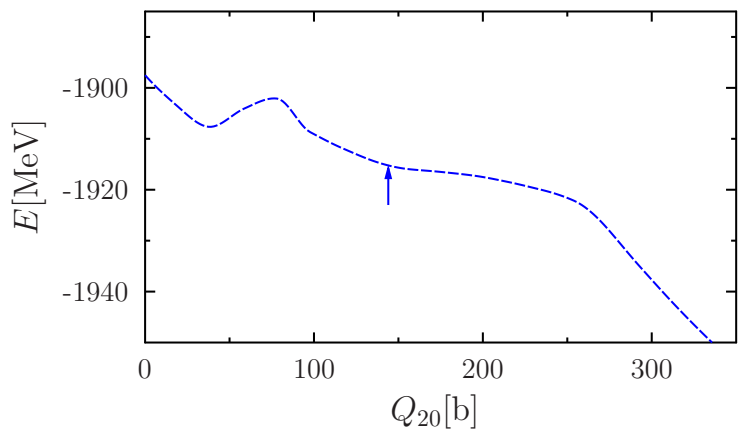
- Pairing correlation
- Quasi-particles : $|\omega_\alpha\rangle = \begin{pmatrix} U_\alpha \\ V_\alpha \end{pmatrix}$
- Evolution : $i\hbar \frac{d|\omega_\alpha\rangle}{dt} = \begin{pmatrix} h & \Delta \\ -\Delta^* & -h^* \end{pmatrix} |\omega_\alpha\rangle$

TDHF+BCS

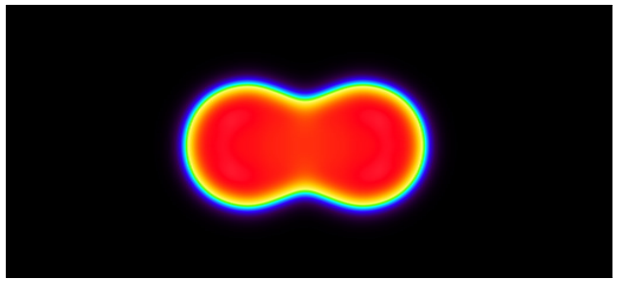
- Based on TDHFB with the approximation : $\Delta_{ij} = \delta_{ij}\Delta_i$
- Evolution :
$$i\hbar \frac{d\phi_i}{dt} = (\hat{h}_{MF} - \epsilon_i)\phi_i$$
$$i\hbar \frac{dn_i}{dt} = \Delta_i^* \kappa_i - \Delta_i \kappa_i^*$$
$$i\hbar \frac{d\kappa_i}{dt} = \kappa_i(\epsilon_i - \epsilon_{\bar{i}})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

Why does we need pairing ?

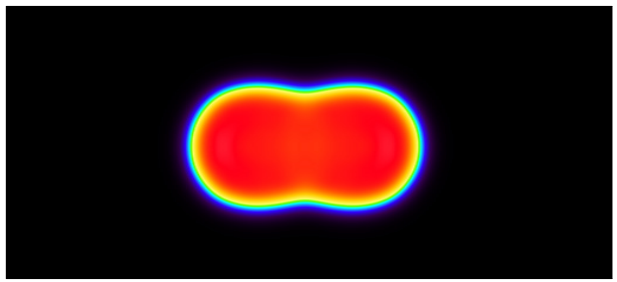
Fission barrier : ^{258}Fm



TDHF



TDHF+BCS



G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

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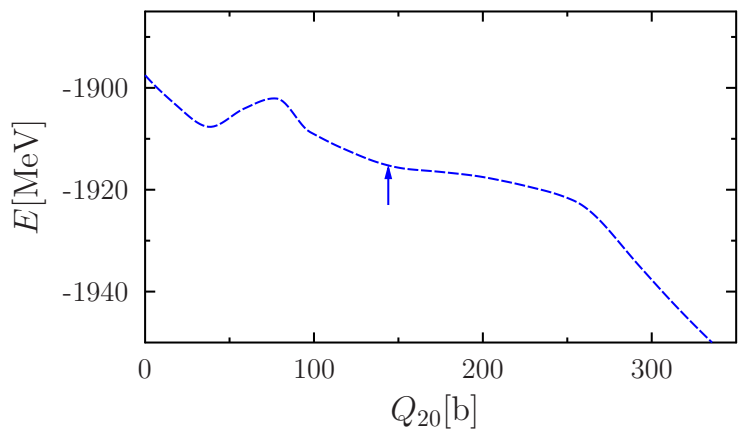
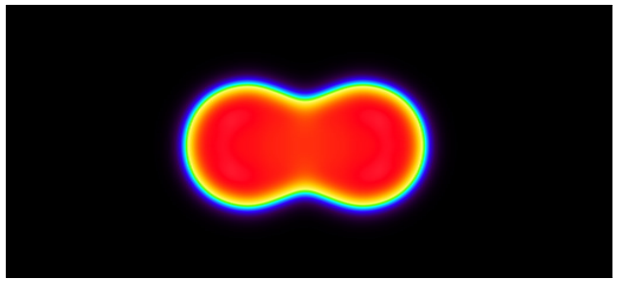
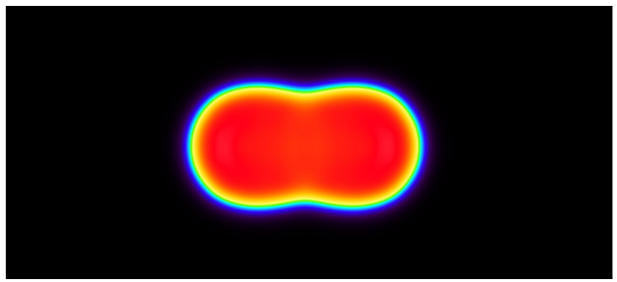


TDHF



TDHF+BCS



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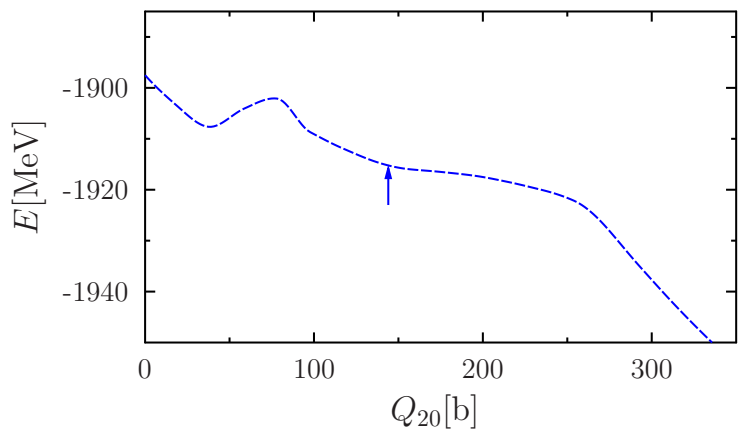
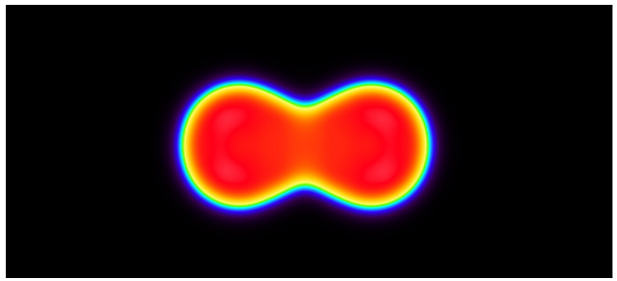
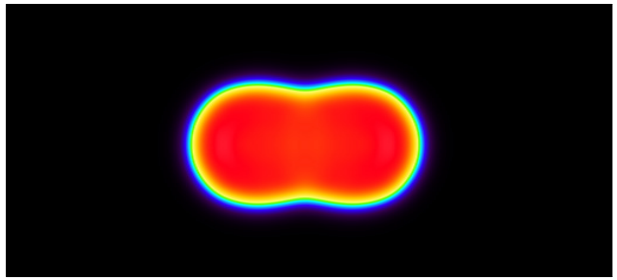


TDHF

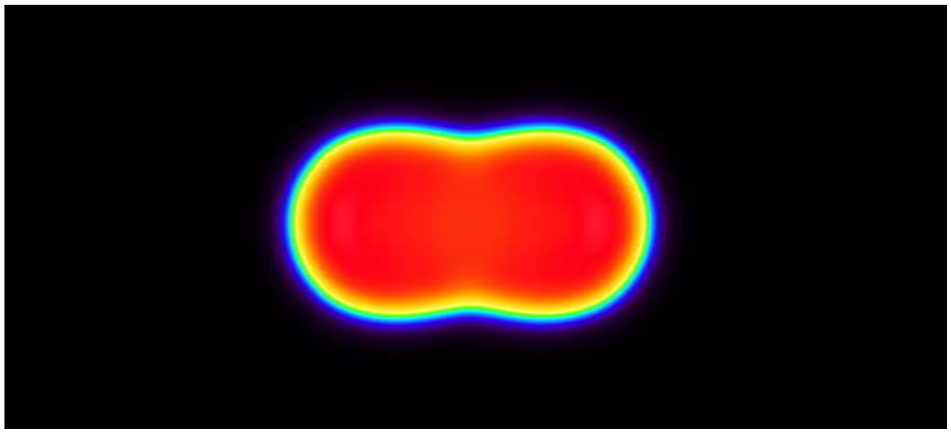


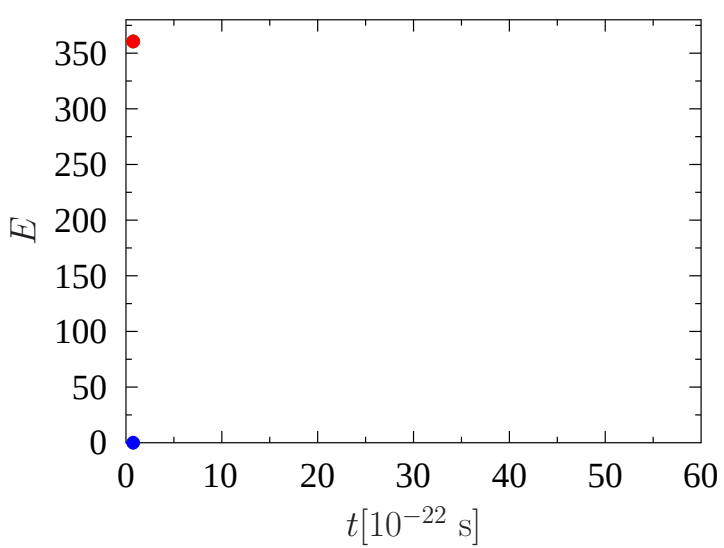
TDHF+BCS

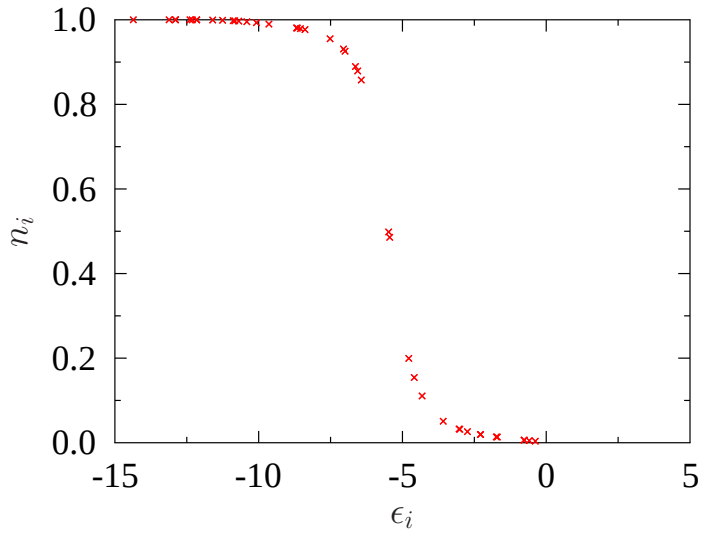


G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

Influence of pairing on fission process







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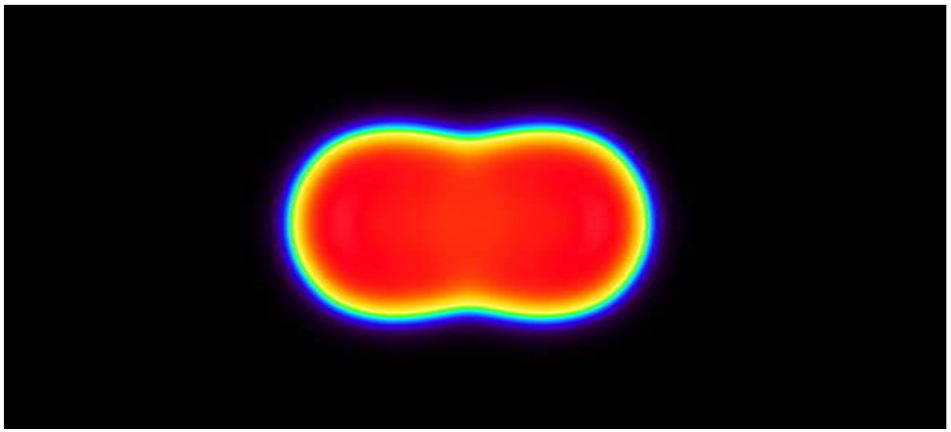
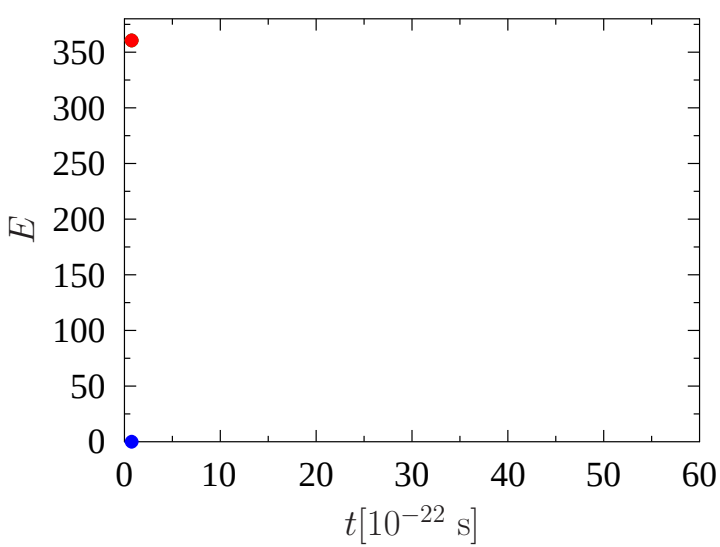
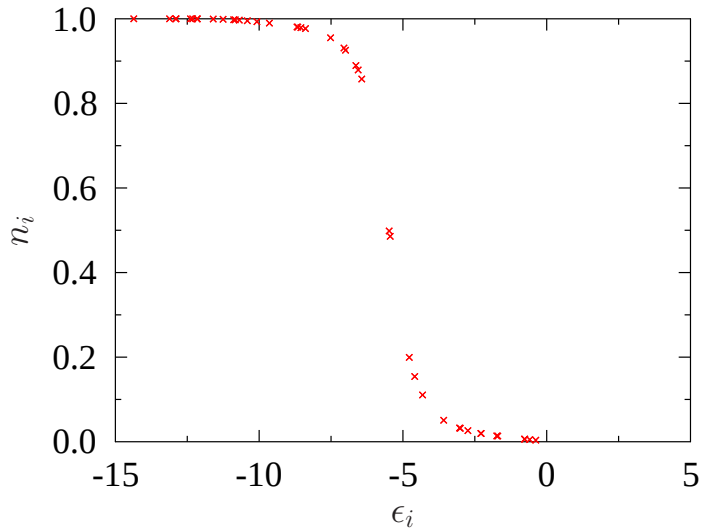
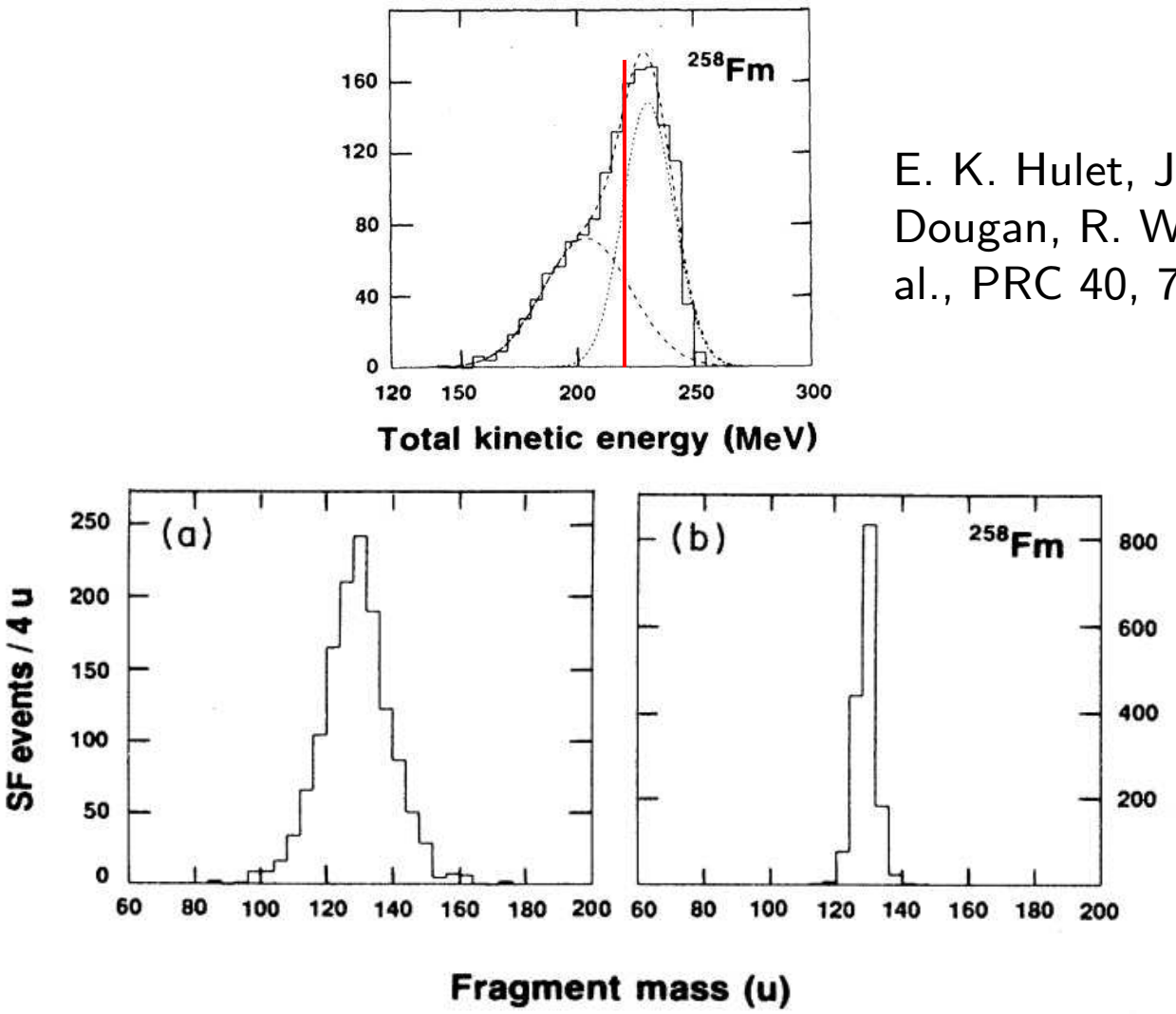






^{258}Fm : Experimental results



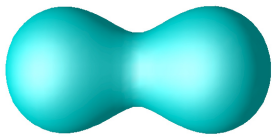
E. K. Hulet, J. F. Wild, R. J. Dougan, R. W. Lougheed,et al., PRC 40, 770 (1989)

FIG. 8. Mass distributions obtained by sorting fission events according to their total kinetic energies: (a) for events with TKE's <220 MeV and (b) for those with TKE's ≥ 220 MeV.

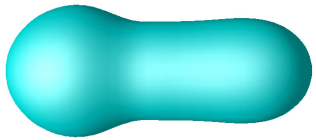
^{258}Fm : Bimodal or trimodal fission ?

3 possible modes

- Symmetric compact fragment



- Asymmetric elongated fragment



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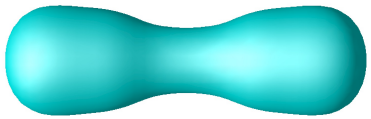
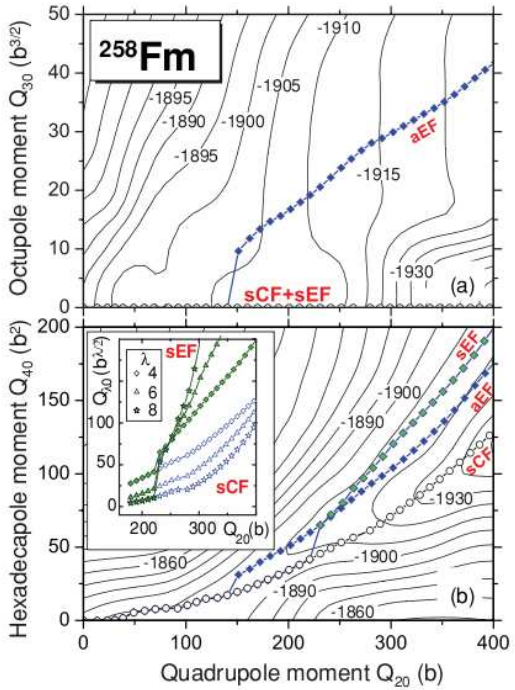
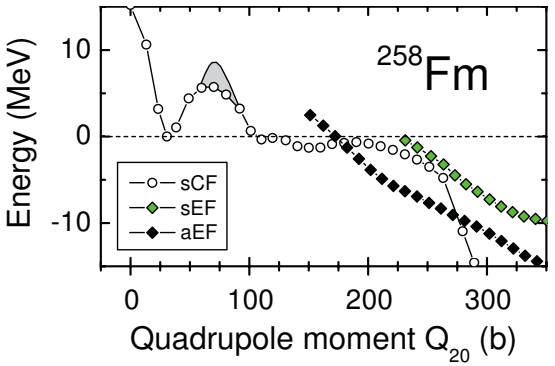


Constraint HF+BCS calculations (Skm*)



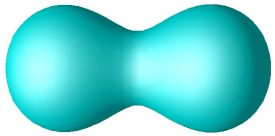


A. Staszczak, A. Baran, J. Dobaczewski, and W. Nazarewicz, PRC 80, 014309 (2009)

^{258}Fm : TDHF+BCS results

3 possible modes

- Symmetric compact fragment



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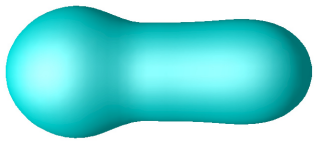

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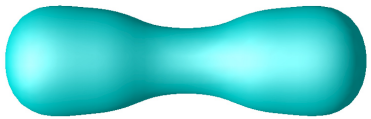
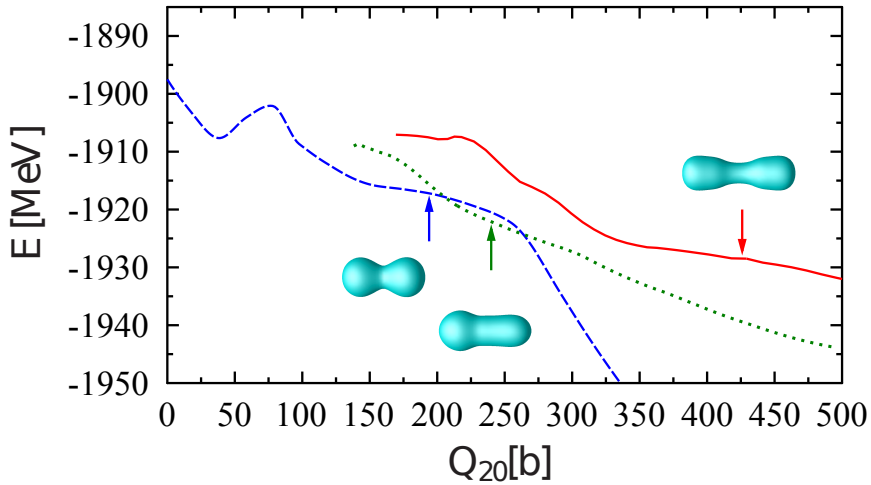
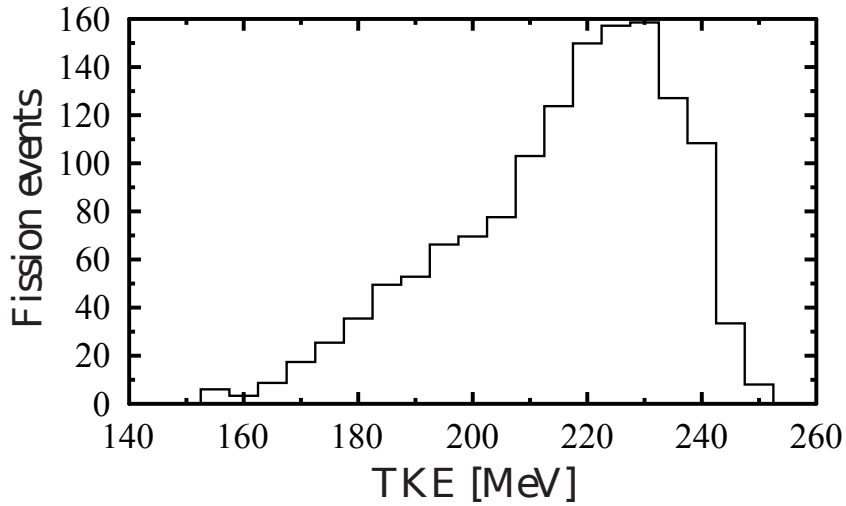


Sly4d





G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

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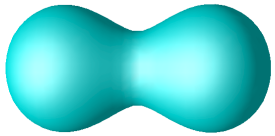

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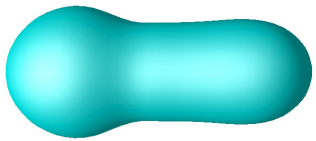

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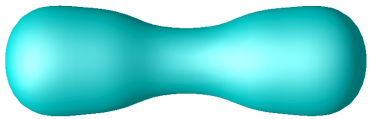
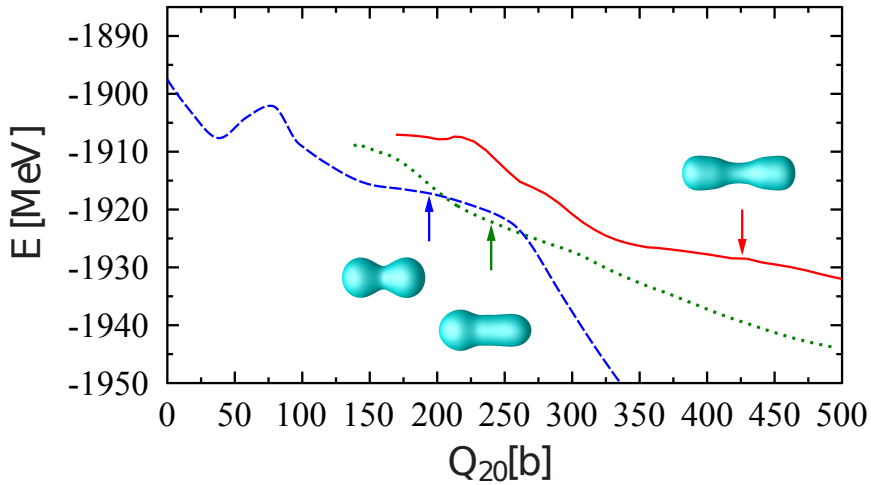
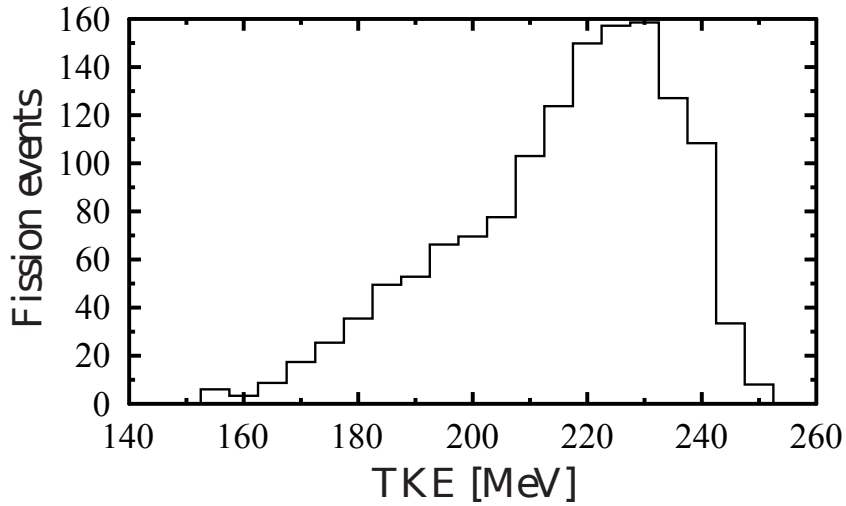


Sly4d





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^{258}Fm : TDHF+BCS results

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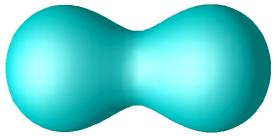

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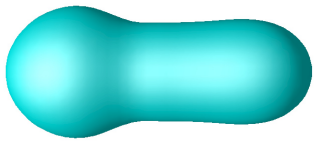

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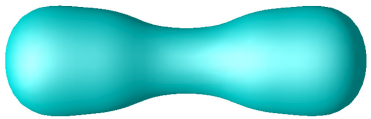
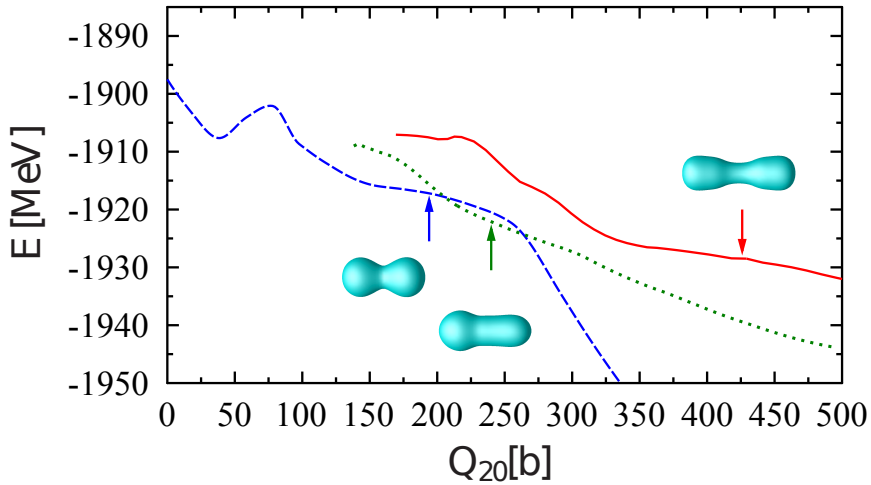
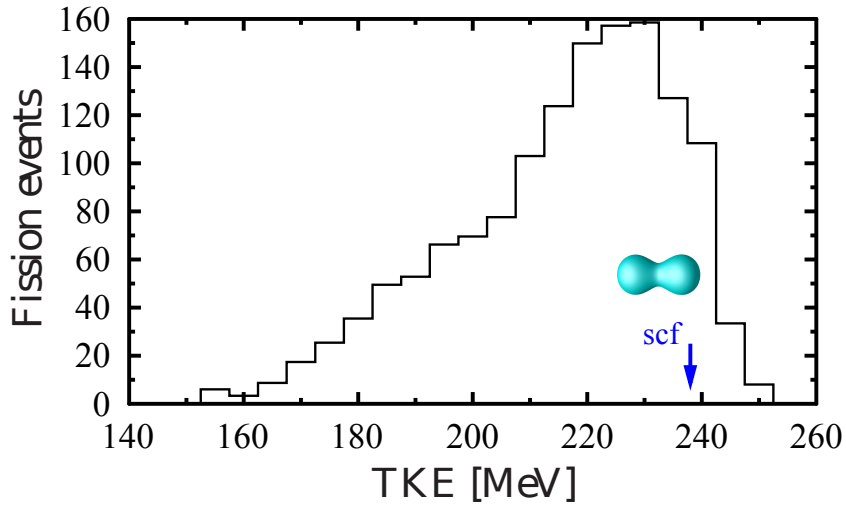


Sly4d





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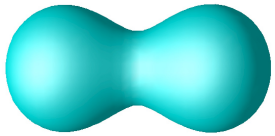
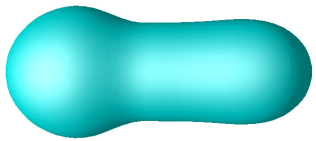
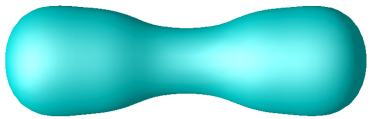


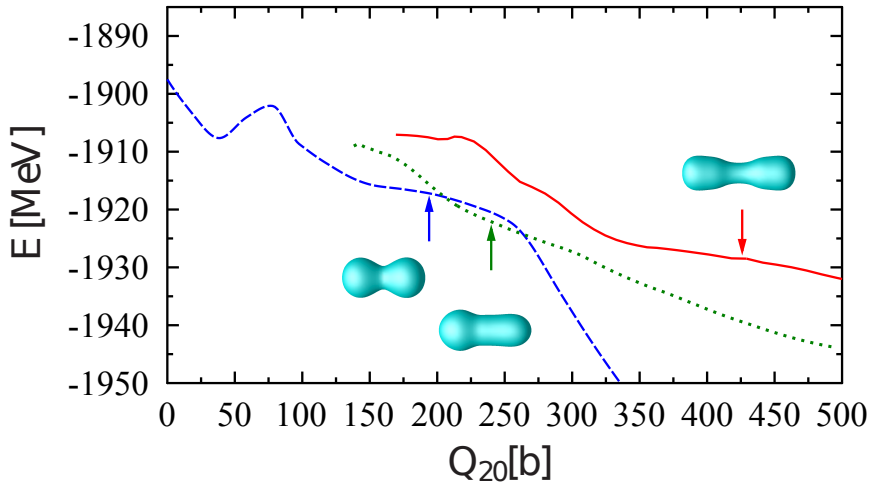
- Asymmetric elongated fragment

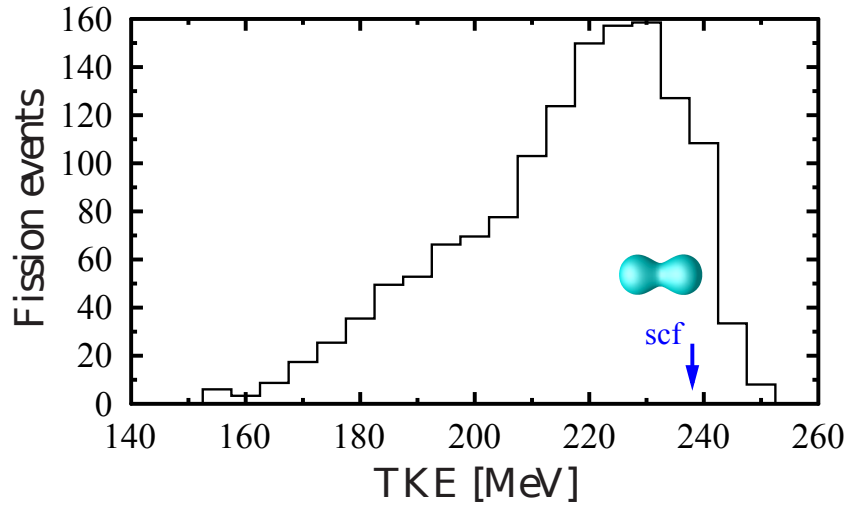


- Symmetric elongated fragment



Sly4d



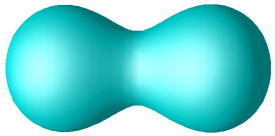


G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

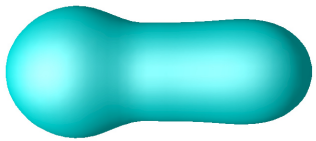
^{258}Fm : TDHF+BCS results

3 possible modes

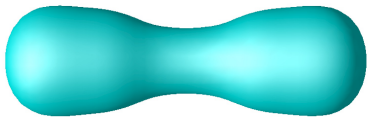
- Symmetric compact fragment



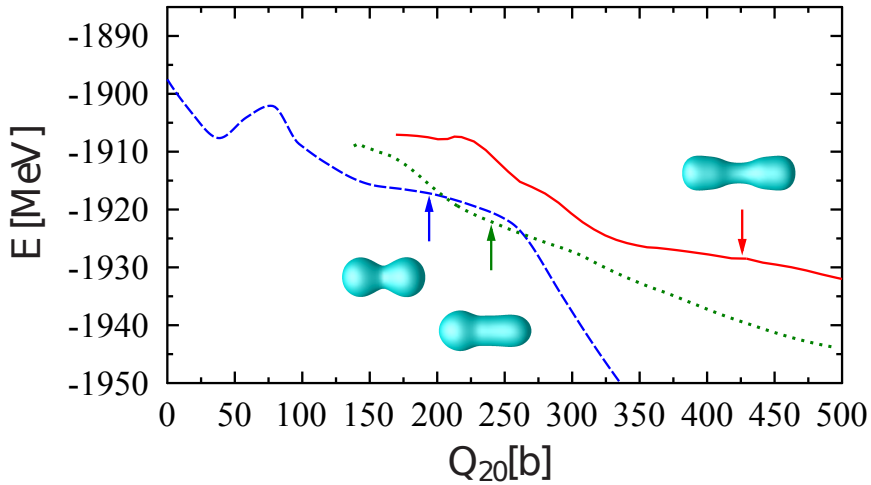
- Asymmetric elongated fragment

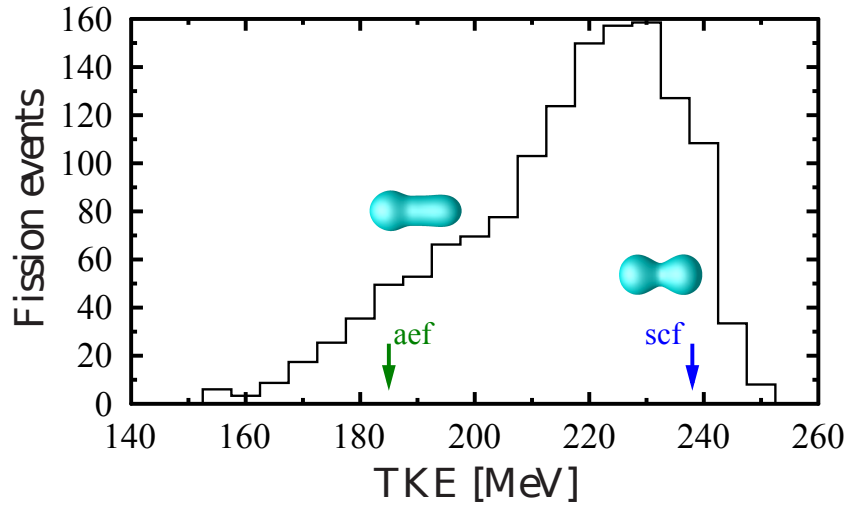


- Symmetric elongated fragment



Sly4d



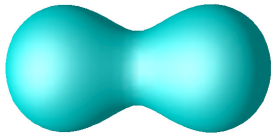


G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

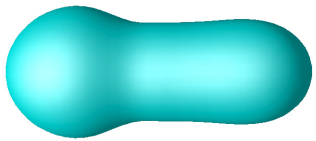
^{258}Fm : TDHF+BCS results

3 possible modes

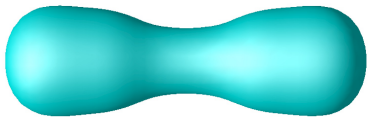
- Symmetric compact fragment



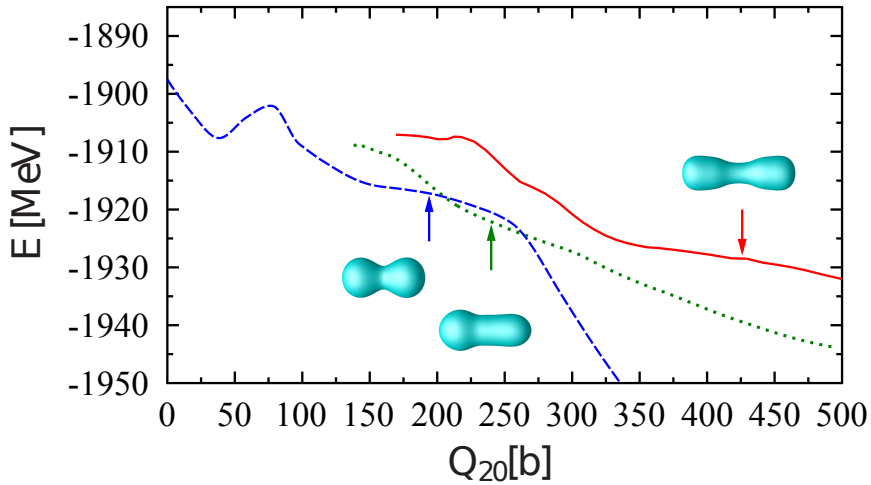
- Asymmetric elongated fragment

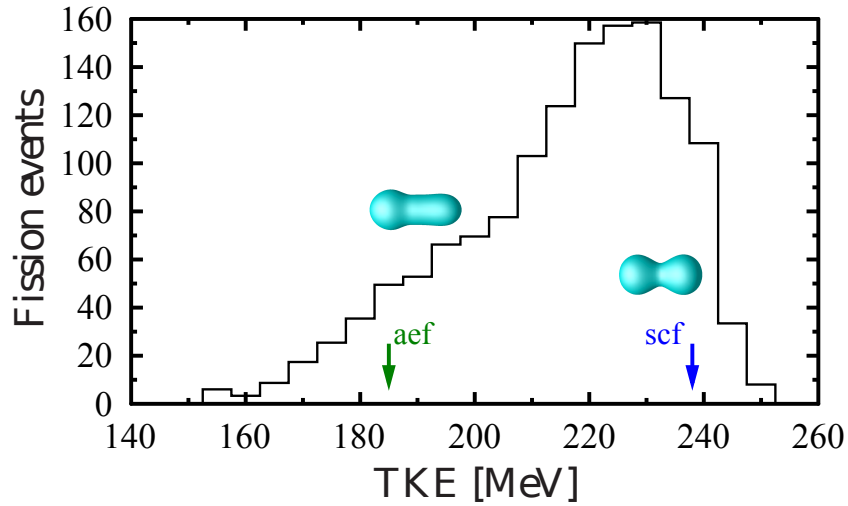


- Symmetric elongated fragment



Sly4d



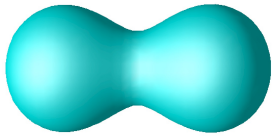


G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

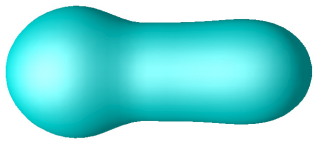
^{258}Fm : TDHF+BCS results

3 possible modes

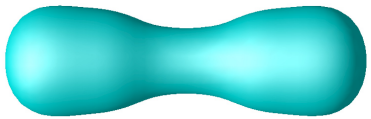
- Symmetric compact fragment



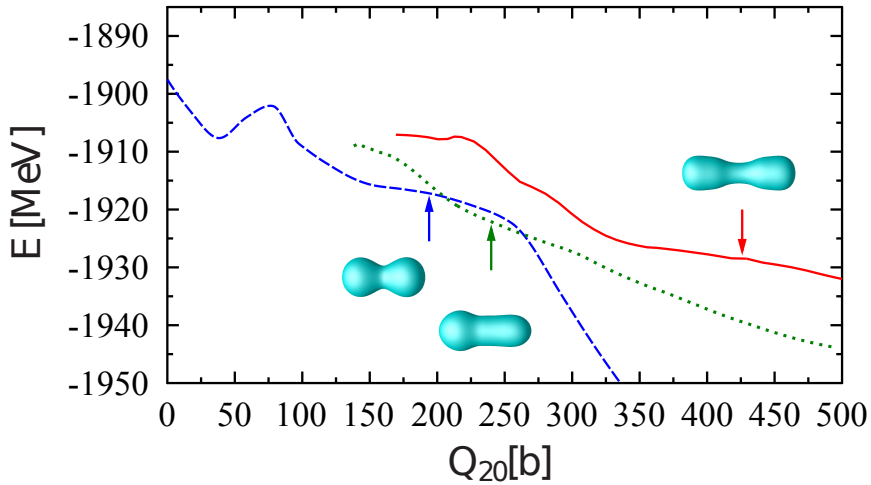
- Asymmetric elongated fragment

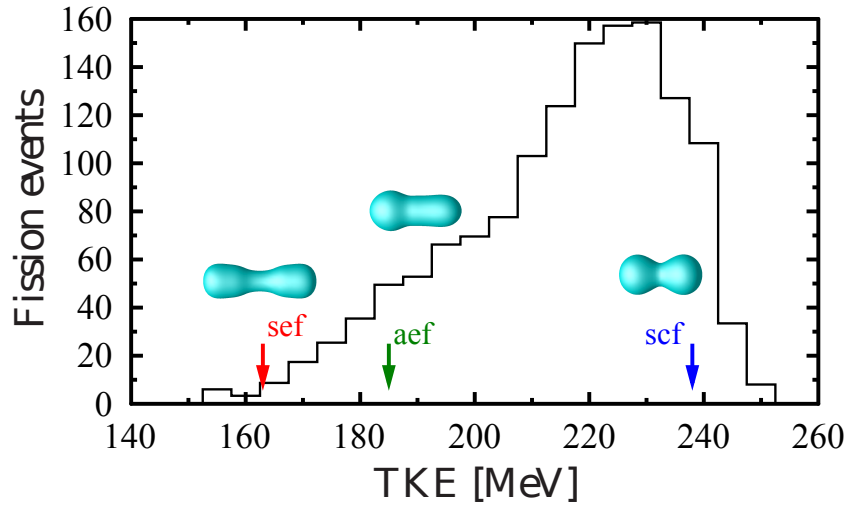


- Symmetric elongated fragment



Sly4d

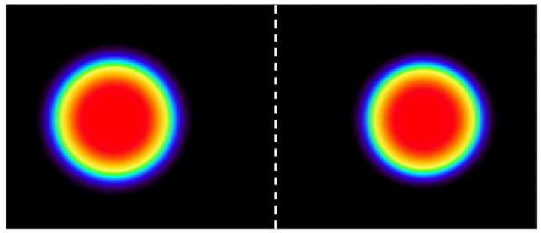




G. Scamps, C. Simenel, D. Lacroix, arXiv :1501.03592 [nucl-th]

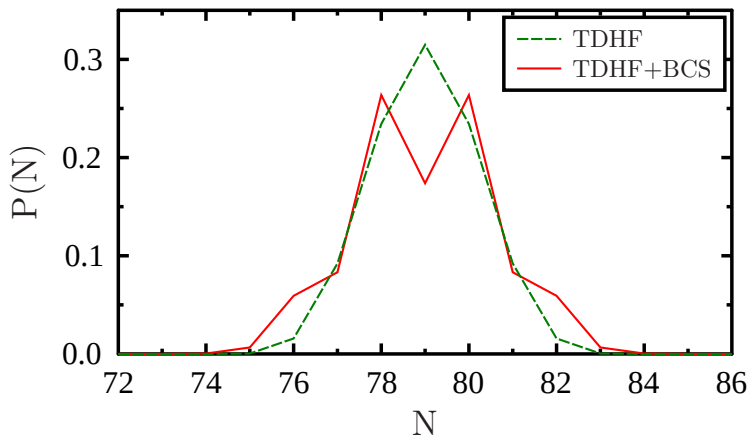
Distribution of number of particles

Projection technique



Proba (N part. on the left)= $\langle \Psi | \hat{P}_{left}(N) | \Psi \rangle$
TDHF : C. Simenel, PRL 105 (2010)
TDHF+BCS : G. Scamps and D. Lacroix, PRC 87, 014605 (2013)

Results

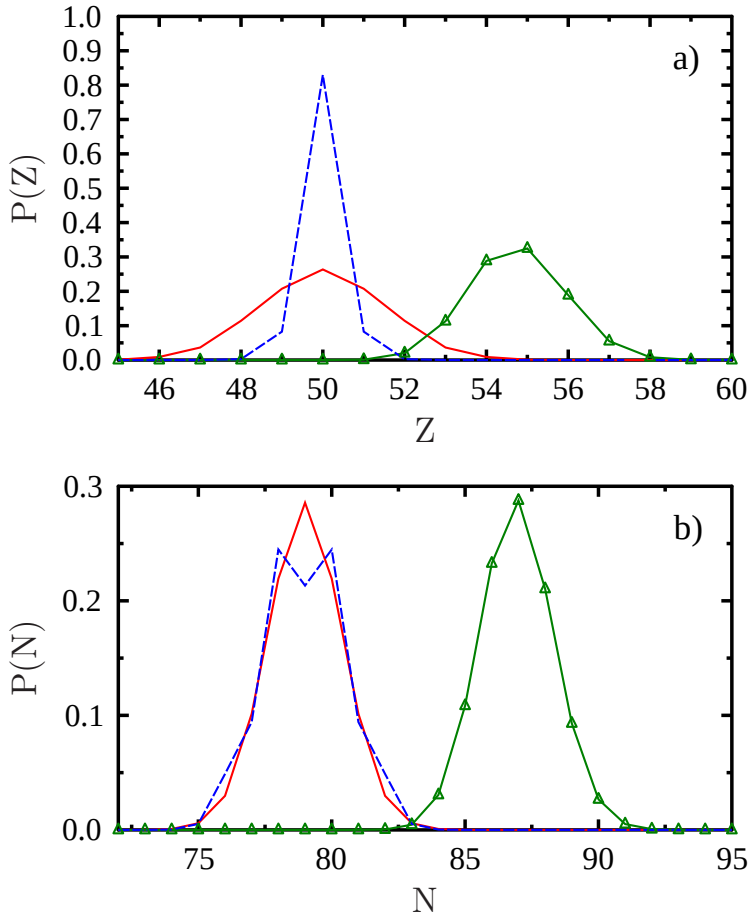


Conclusion

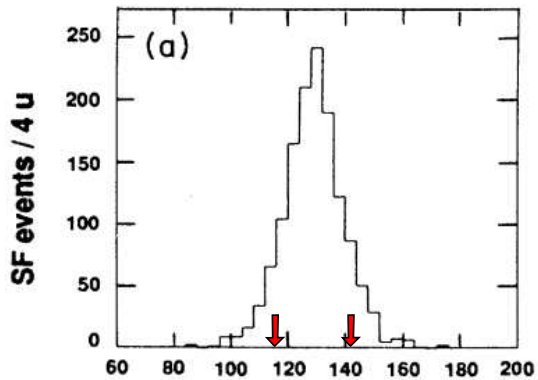
Reproduction of the odd-even effect with TDHF+BCS

Distribution of number of particles

Results



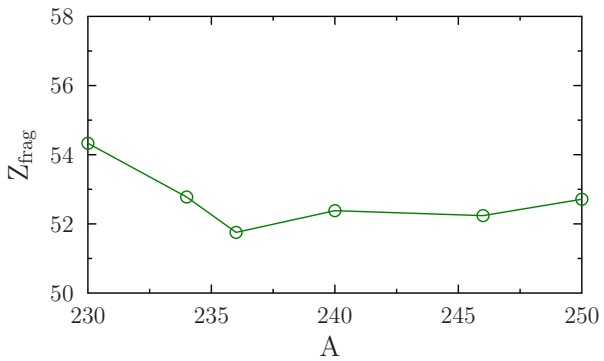
Experimental data



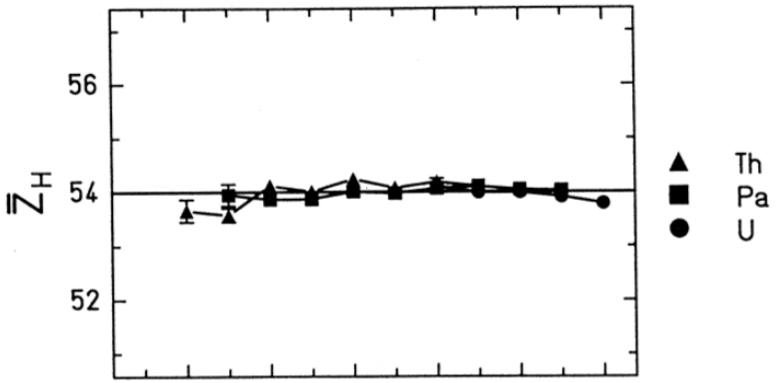
Systematic comparison for actinide

Comparison with experimental data

TDHF+BCS results for ^{230}Th, ^{234}U, ^{236}U, ^{240}Pu, ^{246}Cm, ^{250}Cf



Experimental data

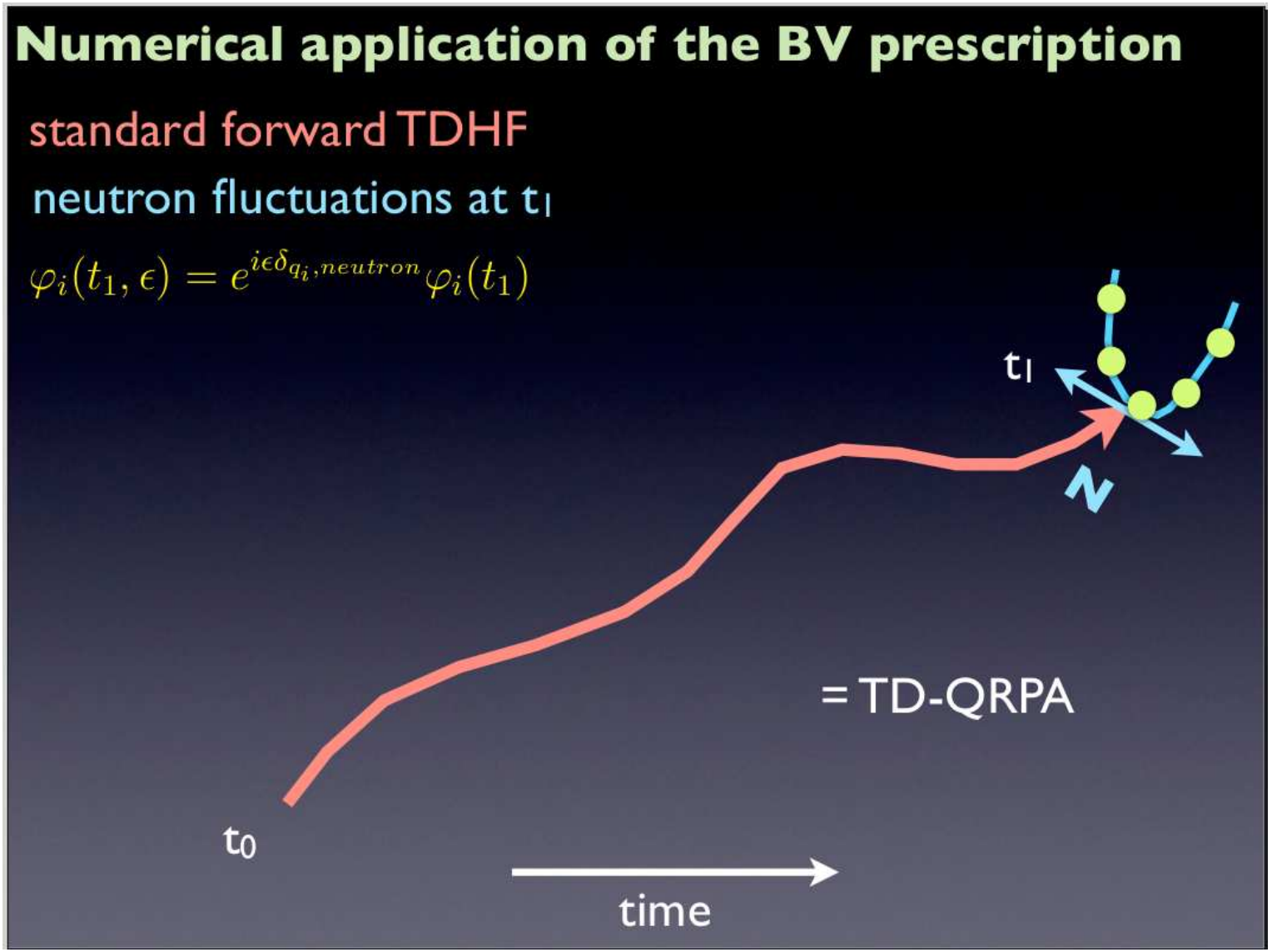


K.-H. Schmidt et al. Nuclear Physics A 665 (2000)

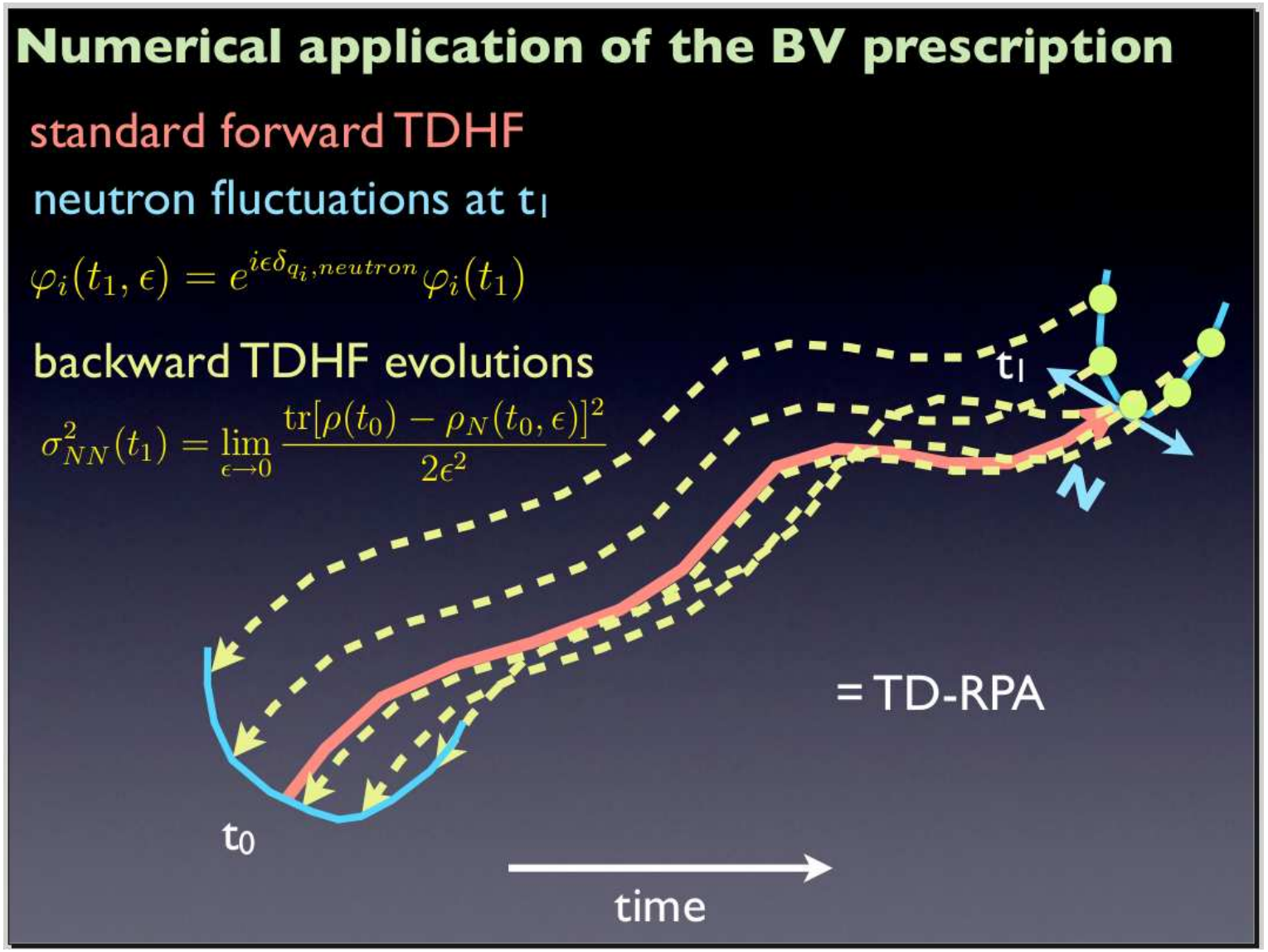
Conclusion

→ Good reproduction of the Z≃54 "magic" number

TDHF with Balian-Véneroni variational principle

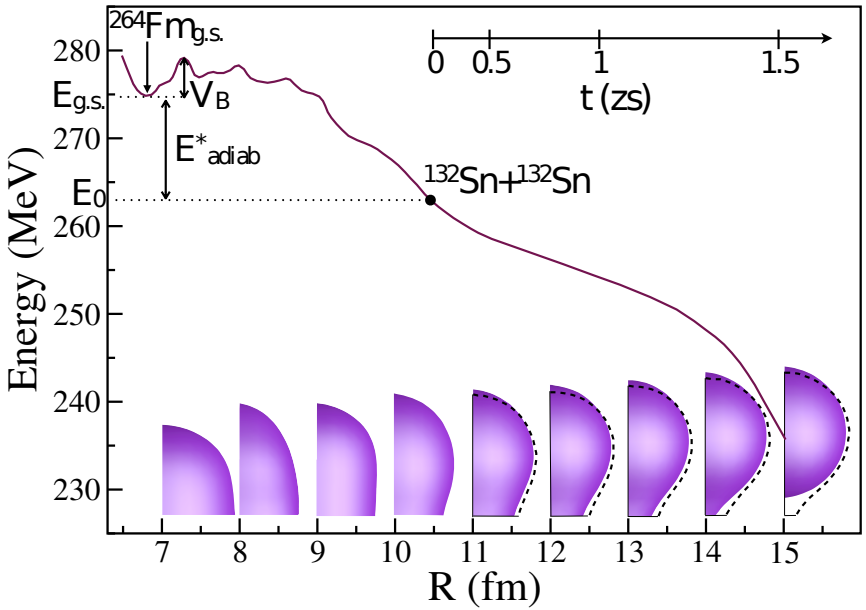


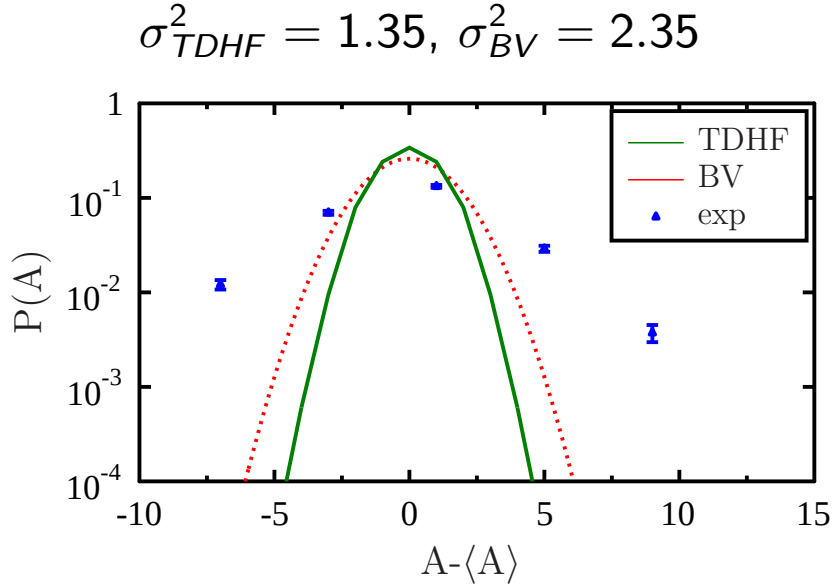
TDHF with Balian-Vénéroni variational principle



TDHF with Balian-Vénéroni variational principle

Results





Conclusion

BV provides the fluctuations for the scission process
Need initial fluctuations (second part of the talk)

Conclusion TDHF+BCS

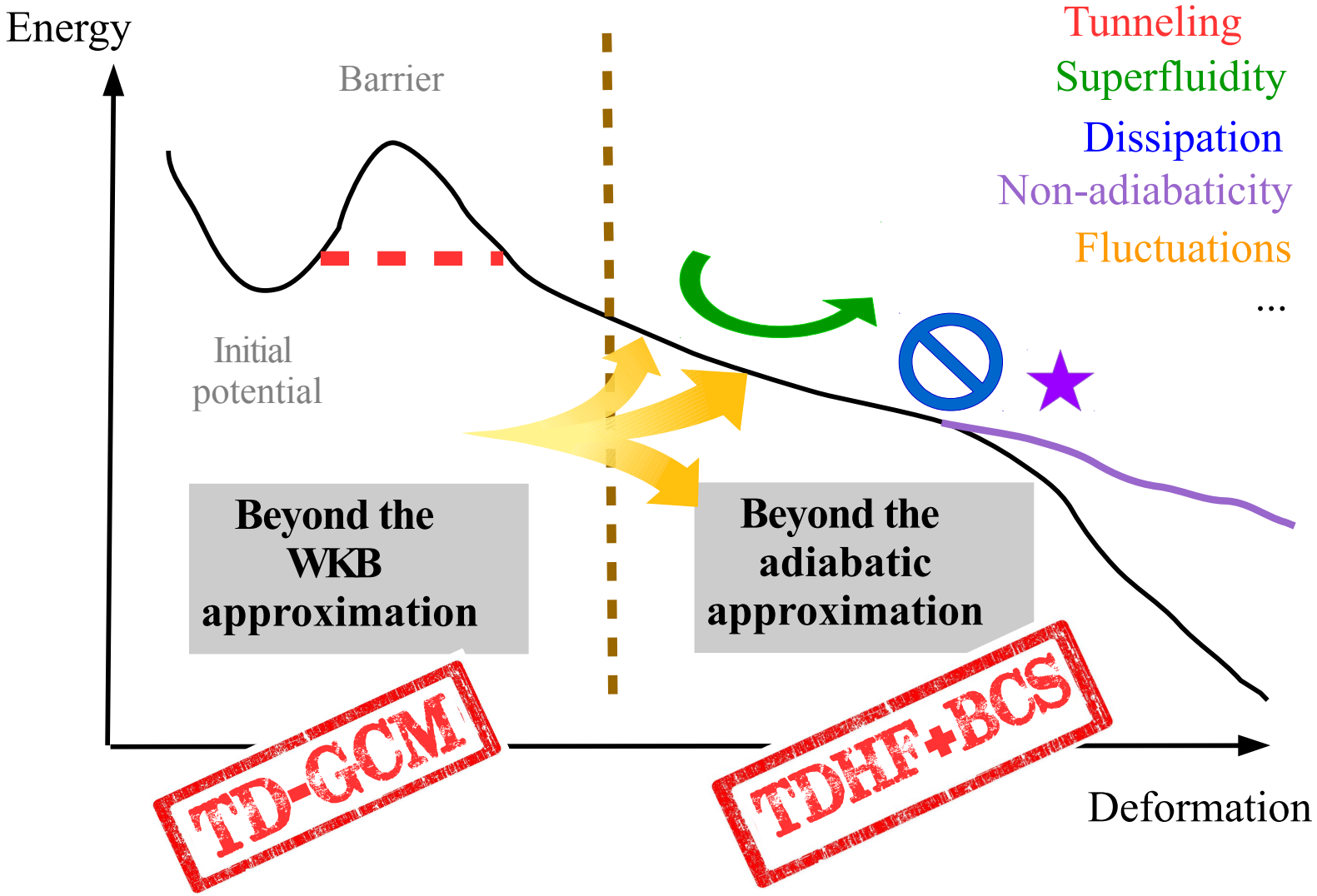
Conclusion

- Good reproduction of the total kinetic energy
- Important effect of pairing on fission process (J. W. Negele, et al. (1978))
- Reproduction of the even-odd effects
- Reproduction of the Z$\simeq$54 behavior
- Fluctuation obtained with Balian-Véneroni method (for TDHF)

Prospects

- Finite temperature calculation
- Description of the evaporation
- Study of the collective excitation after the scission

Outlooks


Energy
Barrier
Initial
potential
Tunneling
Superfluidity
Dissipation
Non-adiabaticity
Fluctuations
...
Beyond the
WKB
approximation
Beyond the
adiabatic
approximation
TD-GCM
TDHF+BCS
Deformation

Thank you