Collective aspects of microscopic mean-field evolution along the fission path

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Y. Tanimura, D. Lacroix, and G. Scamps, Phys. Rev. C**92,** 034601(2015)

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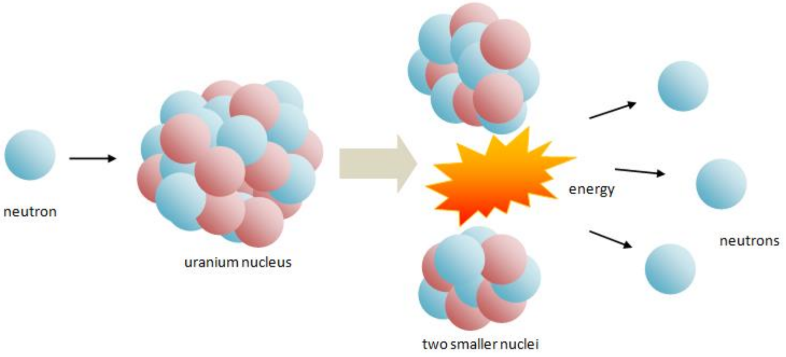
Nuclear fission

- **Importance**
  - Energy production
  - Synthesis of super heavy elements
  - Astrophysical process
  - Production of radioactive isotopes



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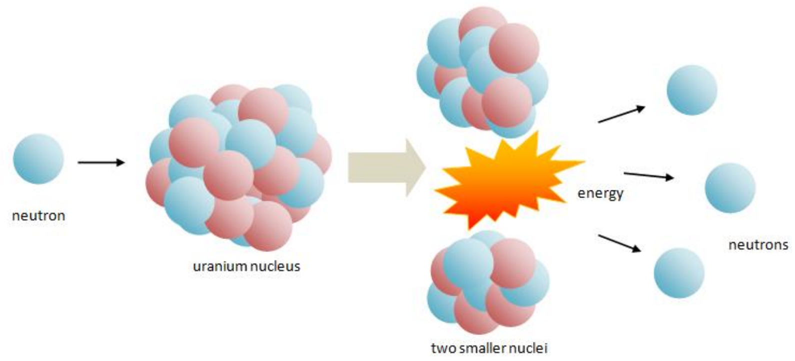
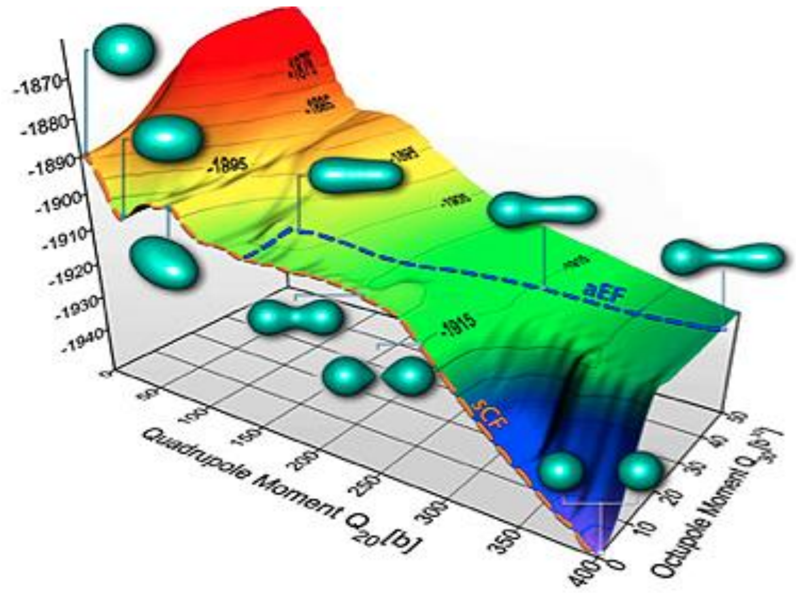


- **Theoretical challenges**
  - Phenomenological models in terms of a few macroscopic degrees of freedom (elongation, mass asymmetry,...) have been developed
  - Successful microscopic models are still under development
  - Complicated dynamical process of quantum many-body system
    - Quantal treatments for both single-particle and collective DOFs
    - Dynamical and non-adiabatic effects
    - Different time scales

Microscopic models for fission

Static approach



- With energy density functional (EDF) theories (Skyrme, Gogny, RMF)
- Fission paths on the **potential energy surface**
- **Adiabatic (no excitation)**
- **Dynamics is poorly treated**

Our motivation:

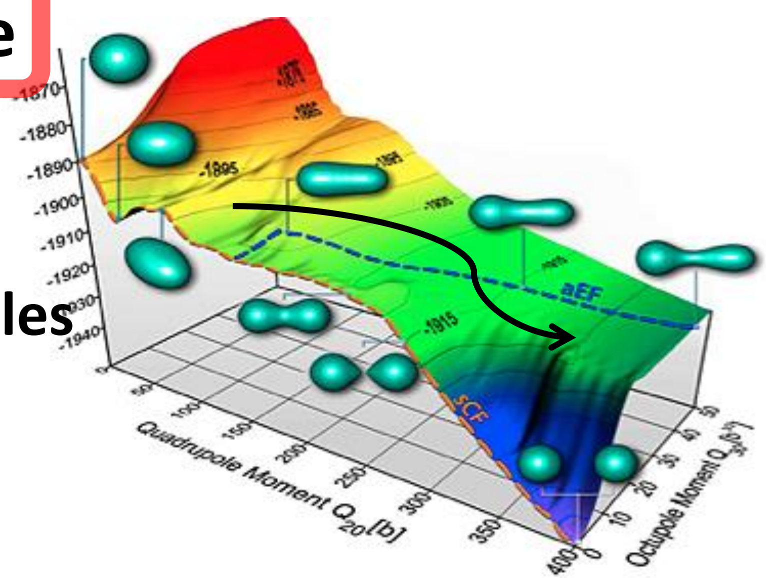
- Dynamical approach to fission based on **time-dependent energy density functional** (TD-EDF) theory
- Mapping TD-EDF trajectory onto a selected set of collective variables

TD-EDF ←→ collective space

✓**Momenta**

✓**Masses**

for a given set of collective variables



To Bridge TD-EDF and collective motion

Collective variable(s): $\hat{Q}_\alpha$
ex: $\hat{Q}_2 = 2z^2 - x^2 - y^2$

⇨ **Mass** and **conjugate momentum** associated with Q_α ?

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➡ **Mass** and **conjugate momentum** associated with Q_α ?

... We demand that

$$\frac{d\langle \hat{Q}_\alpha \rangle}{dt} = \frac{\langle \hat{P}_\alpha \rangle}{M_\alpha}$$

$$\mathrm{Tr}\big(\rho(t)[\hat{Q}_\alpha, \hat{P}_\alpha]\big) = i\hbar$$

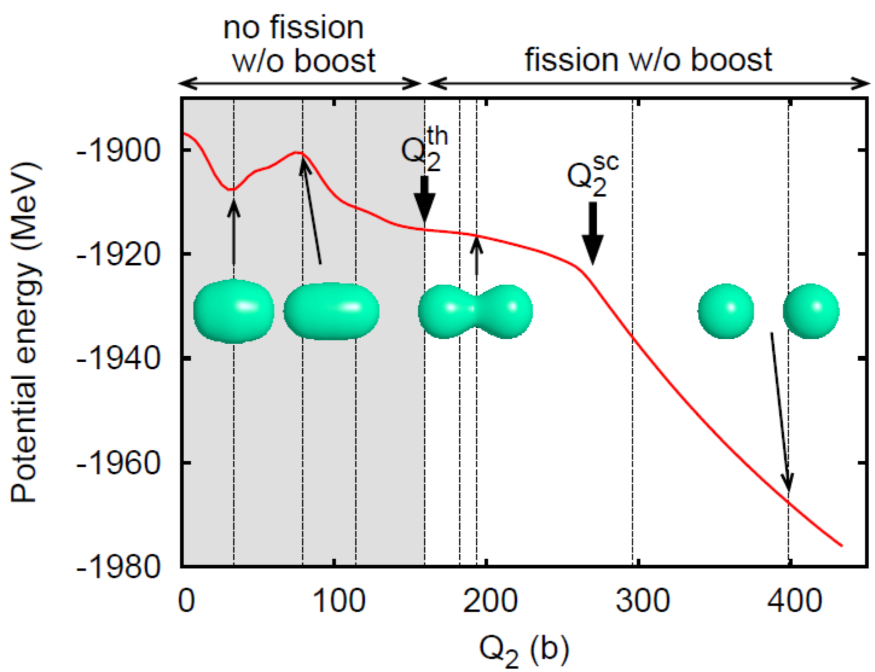
➡

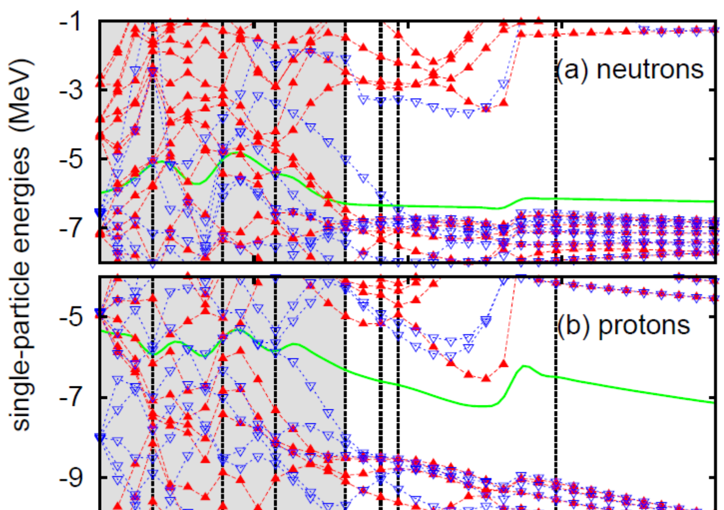
$$\frac{m_N}{M_\alpha} = \mathrm{Tr}[\rho(t)\nabla Q_\alpha \cdot \nabla Q_\alpha]$$

$$P_\alpha = \frac{\hbar}{2i}\frac{M_\alpha}{m_N}[(\nabla Q_\alpha)\cdot\nabla + \nabla\cdot(\nabla Q_\alpha)]$$

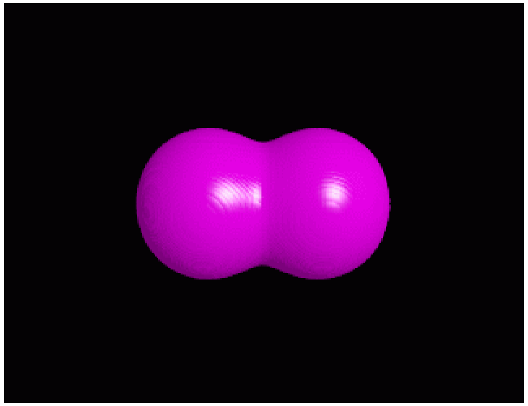
YT, D. Lacroix, and G. Scamps, Phys. Rev. C**92,** 034601(2015)

Application to ^{258}Fm





- TDHF + BCS
  (Sly4d + constant pairing)
- Starting from a point on PEC
- No spontaneous fission for $Q_2(t=0) < 160$ b



Symmetric fission of ^{258}Fm with TDHF + BCS

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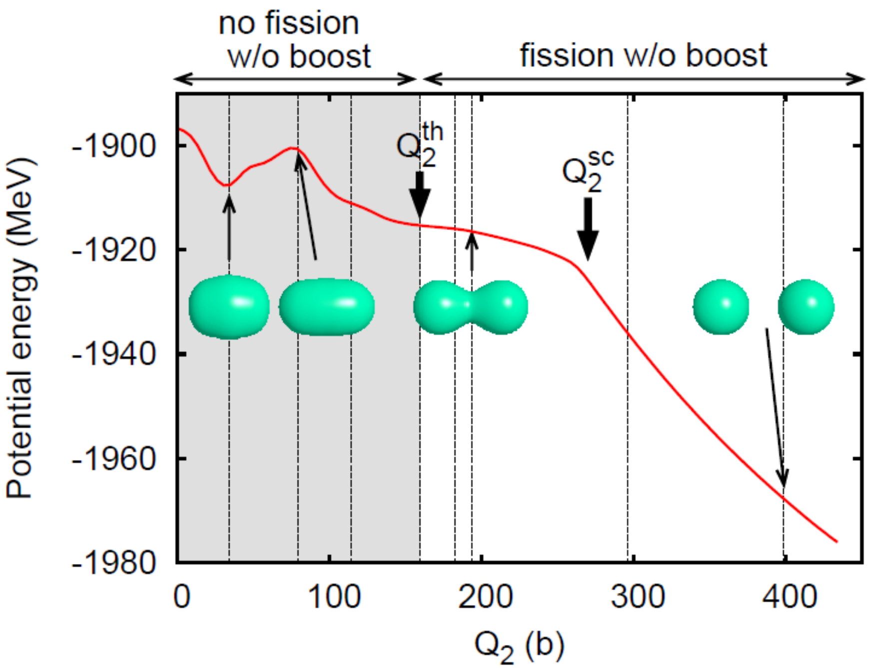

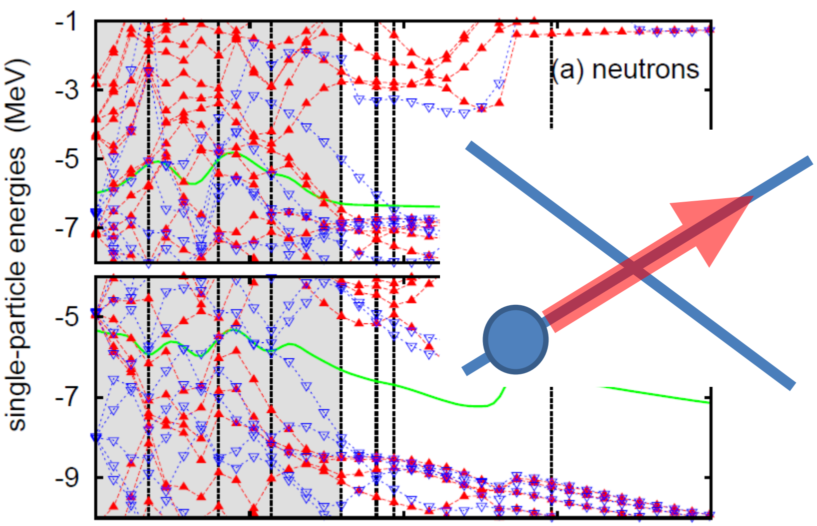

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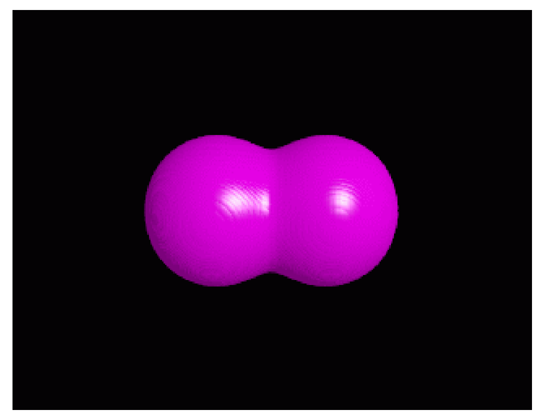
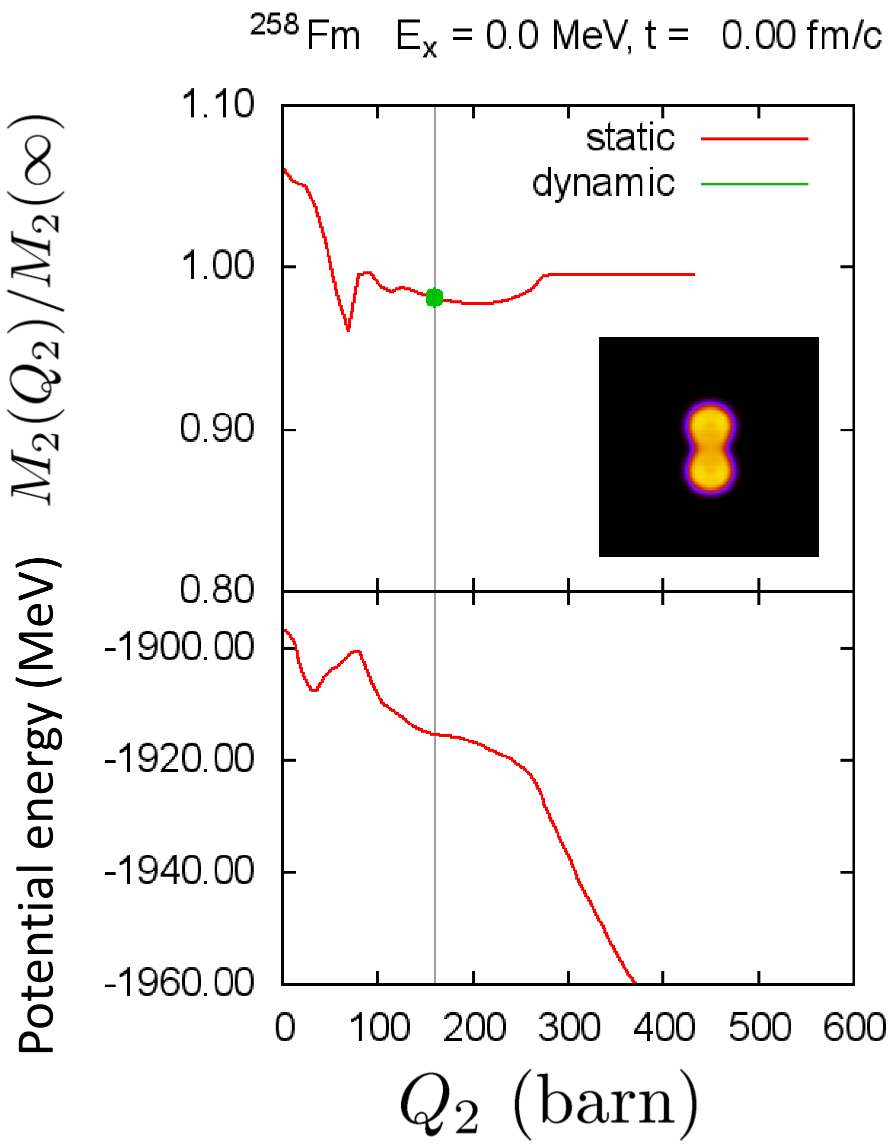


Symmetric fission of ^{258}Fm
with TDHF + BCS

1. Collective mass and momentum



← **Q_2 mass on dynamical path**

- **Deviation from static one around scission**
- **Scission happens more smoothly**

$$\frac{m_N}{M_\alpha} = \mathrm{Tr}[\rho \nabla Q_\alpha \cdot \nabla Q_\alpha]$$

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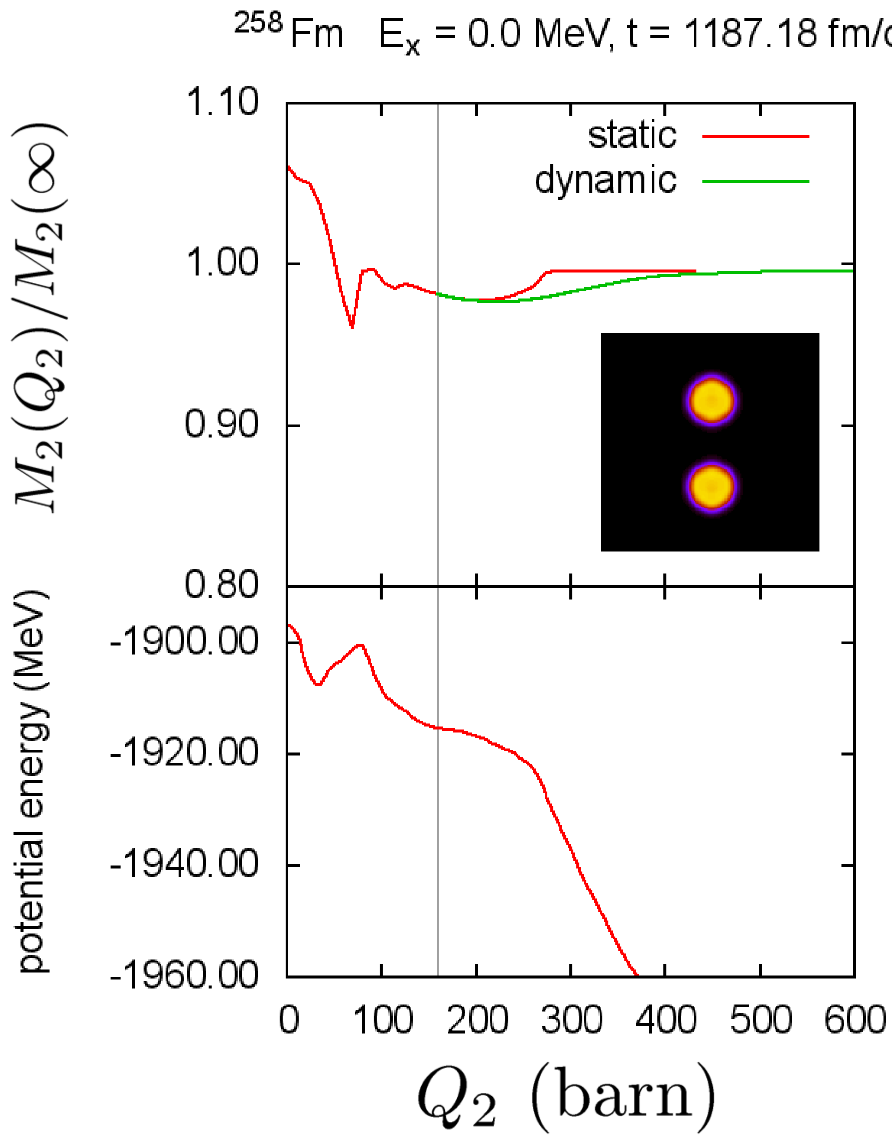

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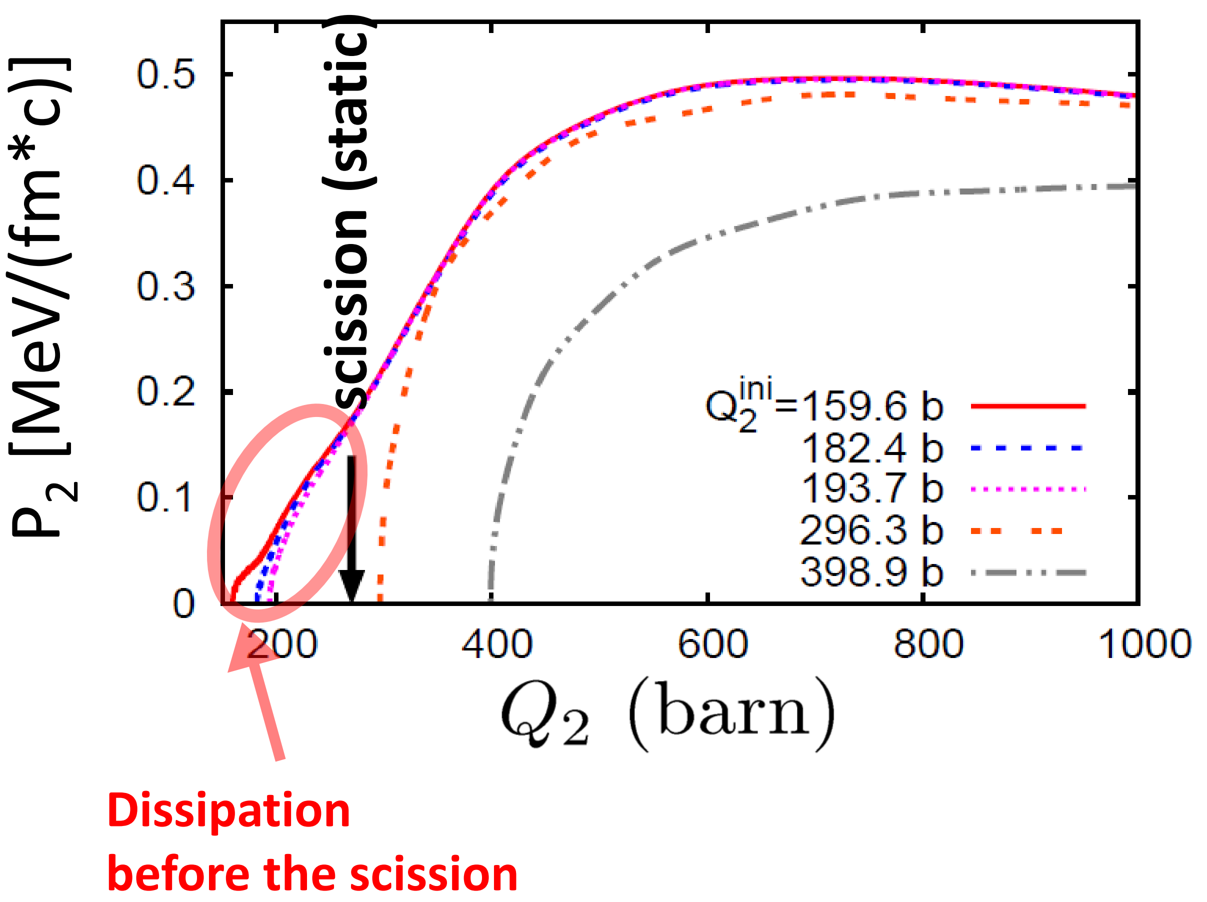
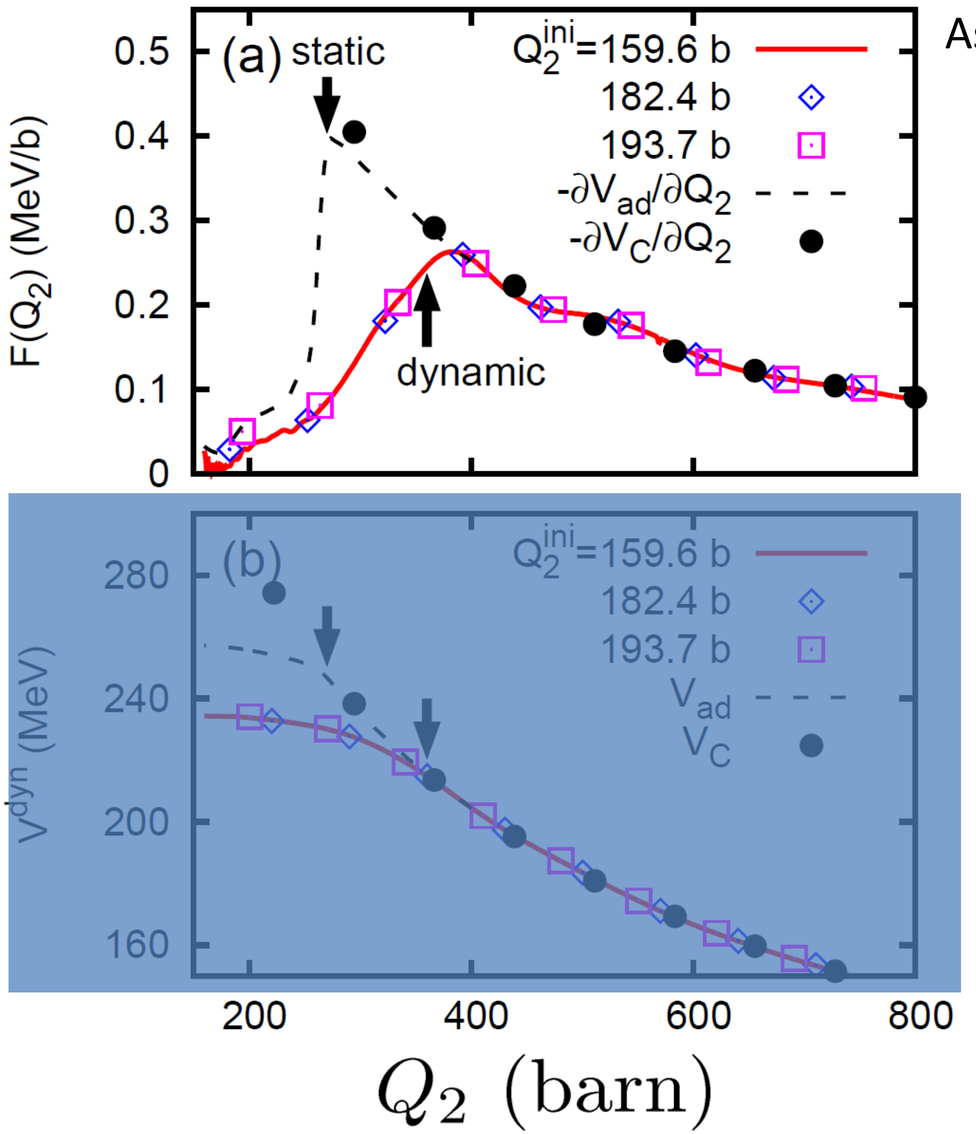
1. Collective mass and momentum

$$P_2 = M_2(dQ_2/dt)$$



2. More analysis of the motion in Q_2 space



Assume a classical motion with dissipative force

cf. K. Washiyama and D. Lacroix, PRC78, 024610 ('08)

$$\dot{Q}_2 = \frac{P_2}{M_2}$$

$$\dot{P}_2 = -\frac{\partial V_{coll}}{\partial Q_2} + \frac{1}{2}\frac{\partial M_2}{\partial Q_2}\dot{Q}_2^2 + \gamma(Q_2)\dot{Q}_2$$

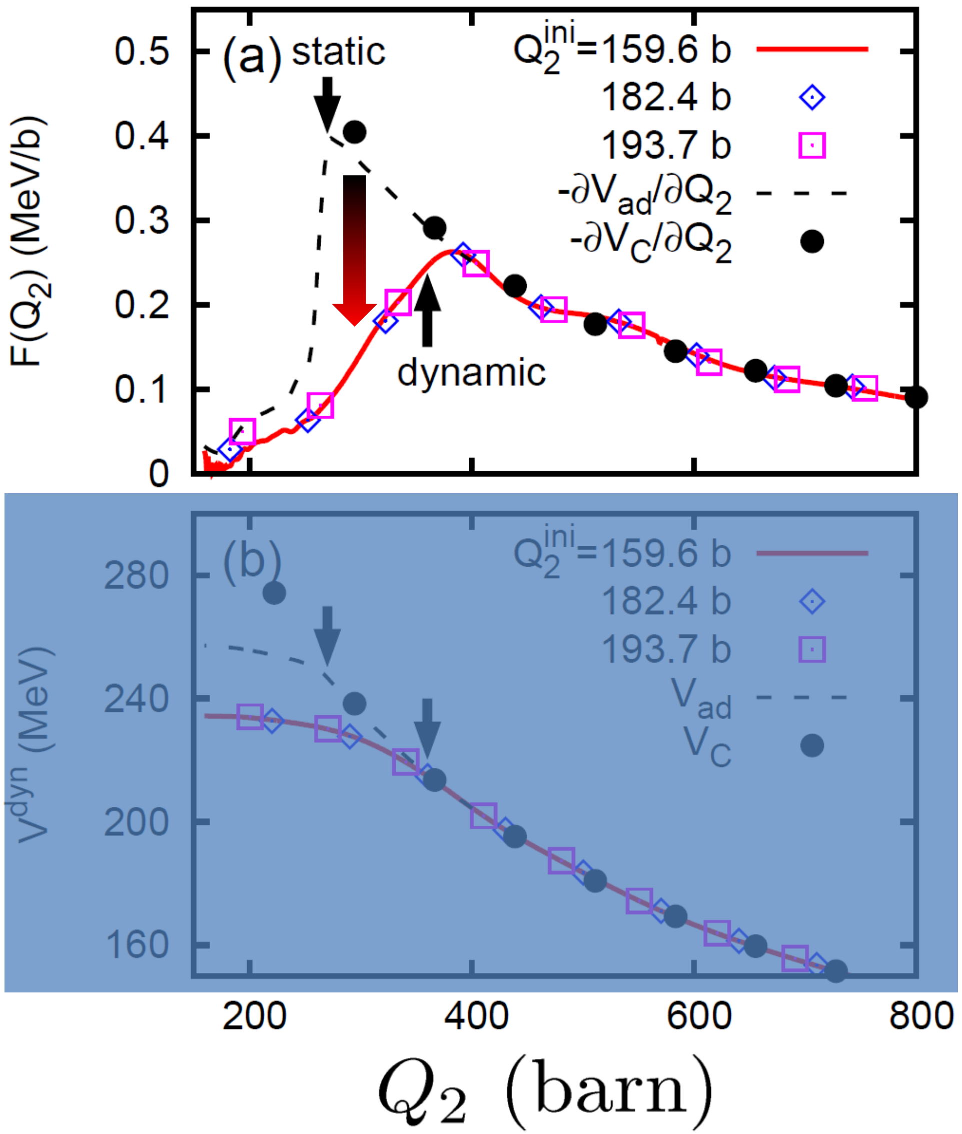
$$\underbrace{\dot{P}_2 - \frac{1}{2}\frac{\partial M_2}{\partial Q_2}\dot{Q}_2^2}_{} = -\frac{\partial V_{coll}}{\partial Q_2} + \gamma(Q_2)\dot{Q}_2$$

$F(Q_2)$ ~ force coming from

dynamical potential

and friction

2. More analysis of motion in Q_2 space



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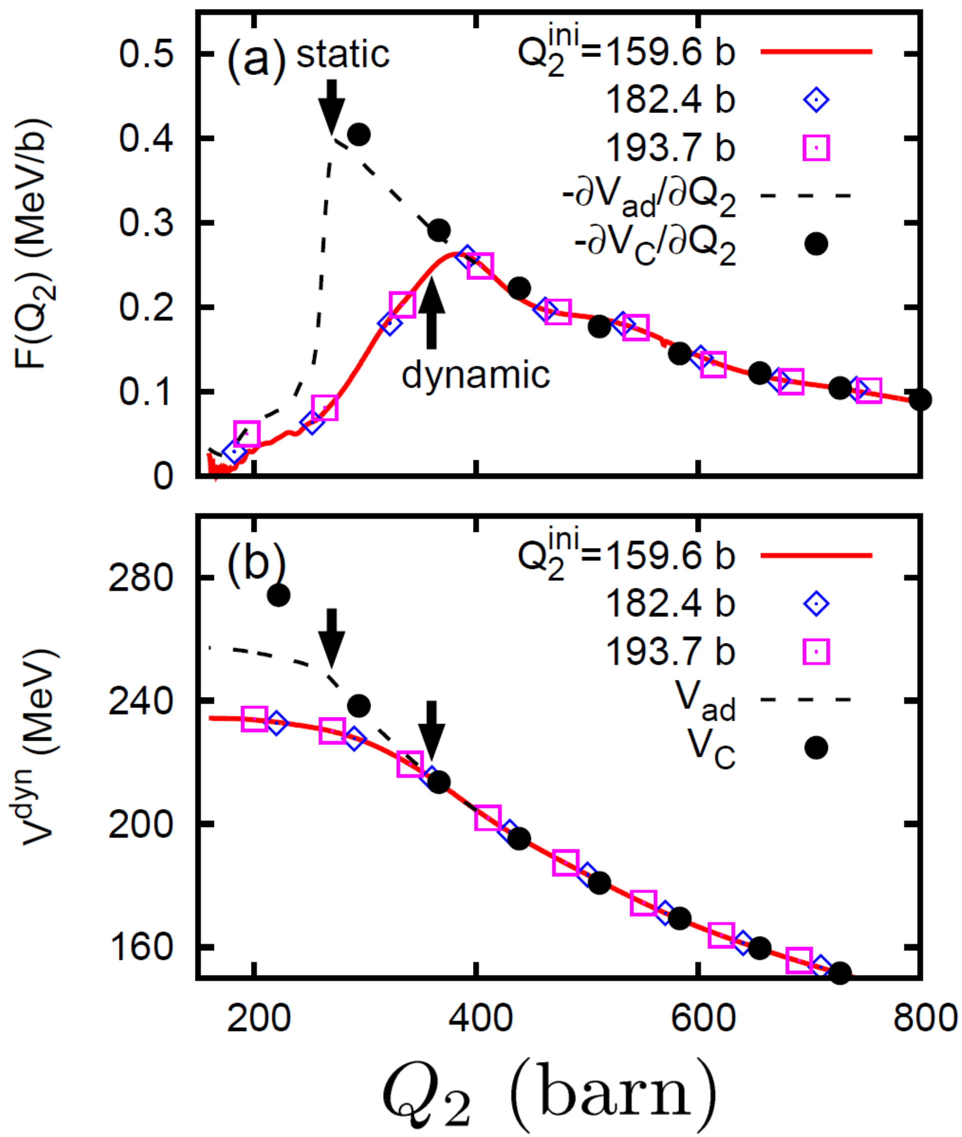
$F(Q_2)$ ~ force coming from dynamical potential and friction

- **Reduction of outward force compared to the static path**
  - ✓ **fragments stick together more**
    and/or
  - ✓ **friction against separation (dissipation)**
- **Dissipation occurs before scission**

2. More analysis of motion in Q_2 space



Define
"dynamical potential"
(work done by F on Q_2)

$$V^{\rm dyn}(Q_2) \equiv V_C(Q_2^{\rm max}) + \int_{Q_2}^{Q_2^{\rm max}} dQ_2' \; F(Q_2')$$

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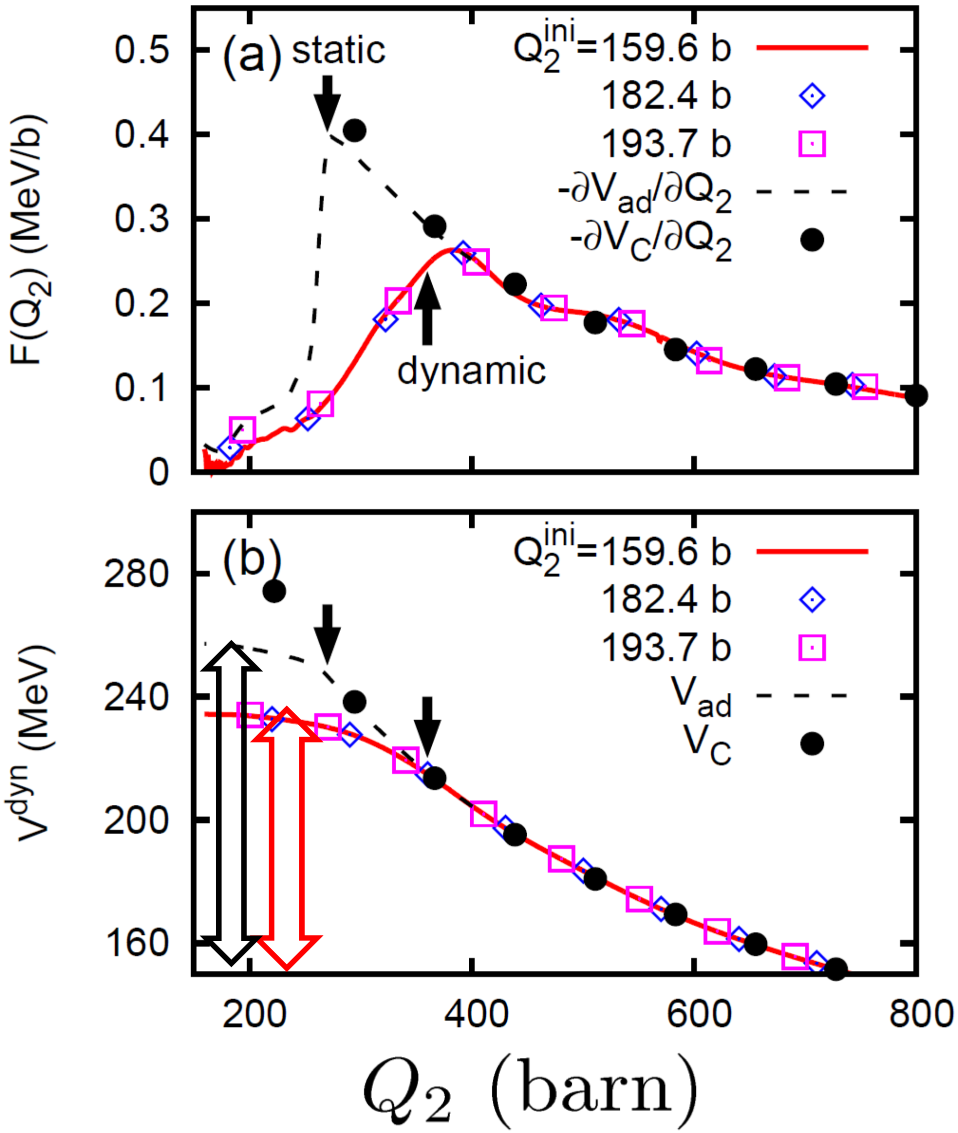

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Potential *along adiabatic path*

Work by *F* *along dynamic path*

Difference = Dissipated Energy

3. Generalization to several DOFs

Diagonalize the inertia tensor:

$$\frac{m_N}{M_{\alpha\beta}} = \mathrm{Tr}[\rho \nabla Q_\alpha \nabla Q_\beta]$$

$$\begin{aligned} \frac{1}{M} &\rightarrow \frac{1}{M'} = W \frac{1}{M} W^T \\ \boldsymbol{Q}' &\rightarrow W\boldsymbol{Q} \\ (\boldsymbol{P}/\boldsymbol{M})' &\rightarrow W(\boldsymbol{P}/\boldsymbol{M}) \end{aligned}$$

$$\Rightarrow \langle [Q'_\alpha, P'_\beta] \rangle = \delta_{\alpha\beta} i\hbar$$

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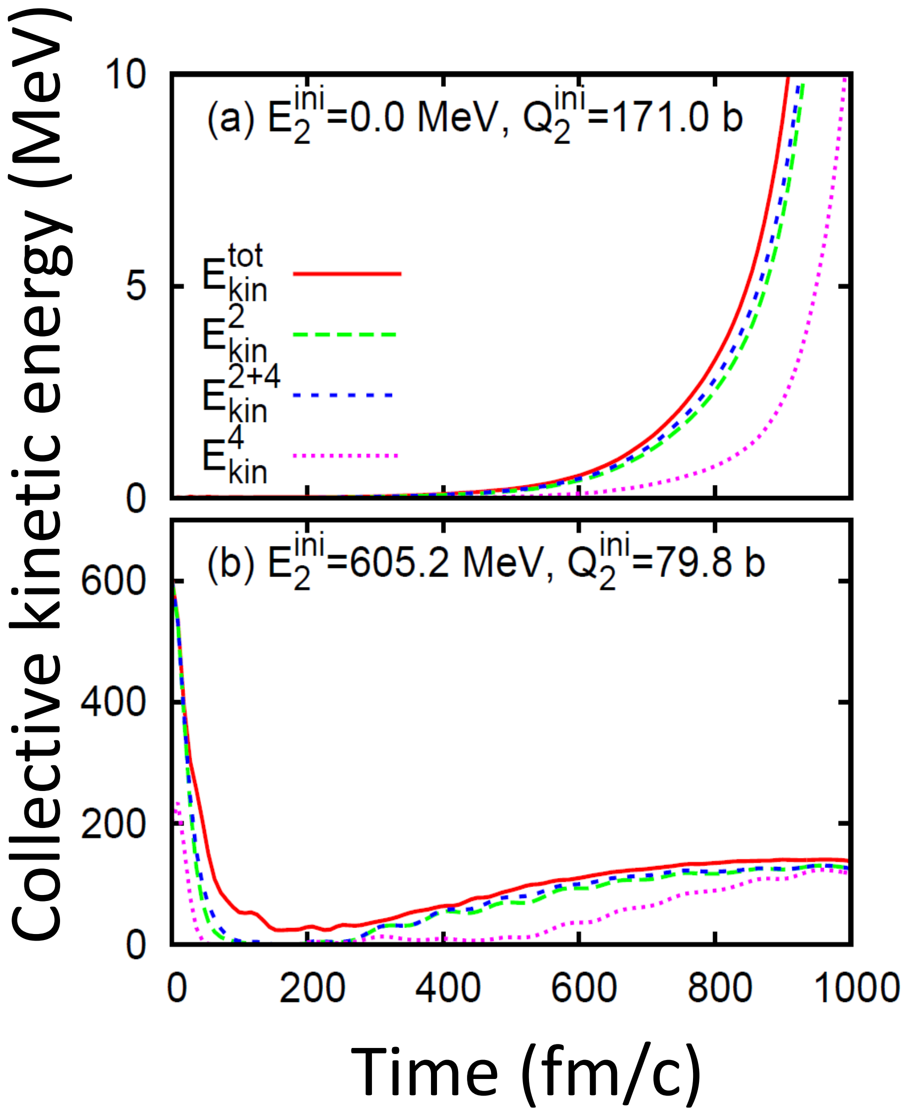

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$$\boldsymbol{Q}' \rightarrow W\boldsymbol{Q}$$

$$(\boldsymbol{P}/\boldsymbol{M})' \rightarrow W(\boldsymbol{P}/\boldsymbol{M})$$

Collective kinetic energy

$$E_{\mathrm{kin}}^{\{\alpha\}} = \sum_\alpha \frac{P_\alpha'^2}{2M_\alpha'} \quad \text{selected set}$$

$$E_{\mathrm{kin}}^{\mathrm{tot}} = \int d^3r \, \frac{\boldsymbol{j}^2}{\rho} \quad \text{total}$$

Summary and perspectives

- **We have developed a method to extract information in collective space from TD-EDF theory**
- **Our goal: unified microscopic approach for fission**
- **Next steps**
  - beyond-mean-field effects with configuration mixing
    - mapping onto $\{Q_\alpha, P_\alpha\}$ space
    - quantum/thermal fluctuation of collective DOFs
  - obtain physical observables
    - ✓ fragment mass/charge distribution
    - ✓ kinetic energy of fragments
    - ✓ ...
  - compare them with data
    and other theoretical approaches