# Microscopic Theory of Fission

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# Fission as a grand nuclear-physics challenge

- True quantum many-body problem
- Large-amplitude collective motion ⇒ not perturbative
- Not directly observable experimentally (only products are seen)
- Involves both single-particle and collective d.o.f., and their coupling
- Understanding fission ⇔ understanding a wealth of nuclear phenomena
  - Compound nucleus formation/fusion
  - adiabatic versus non-adiabatic phenomena
  - Transition from single-particle to collective d.o.f.
  - Shape coexistence, shape isomerism…

A 70-year old problem waiting for a solution

# The microscopic method: statics

- Based on highly successful work at BIII
- Main tool: finite-range, constrained Hartree-Fock-Bogoliubov
  - nucleus is built up from individual protons and neutrons
  - only phenomenological input is effective inter-nucleon interaction (Gogny, D1S)
  - finite-range interaction ⇒ mean field and pairing treated on same footing ⇒ truly self-consistent
  - constraints introduce external fields to “mold” nucleus into desired “shape”
    - choose set of “collective” coordinates (e.g., $Q_2$, $Q_3$, $Q_4$)
- LLNL implementation:
  - Finite RANge Constrained Hartree-Fock-Bogoliubov with Rapid Iteration Execution (FRANCHBRIE)

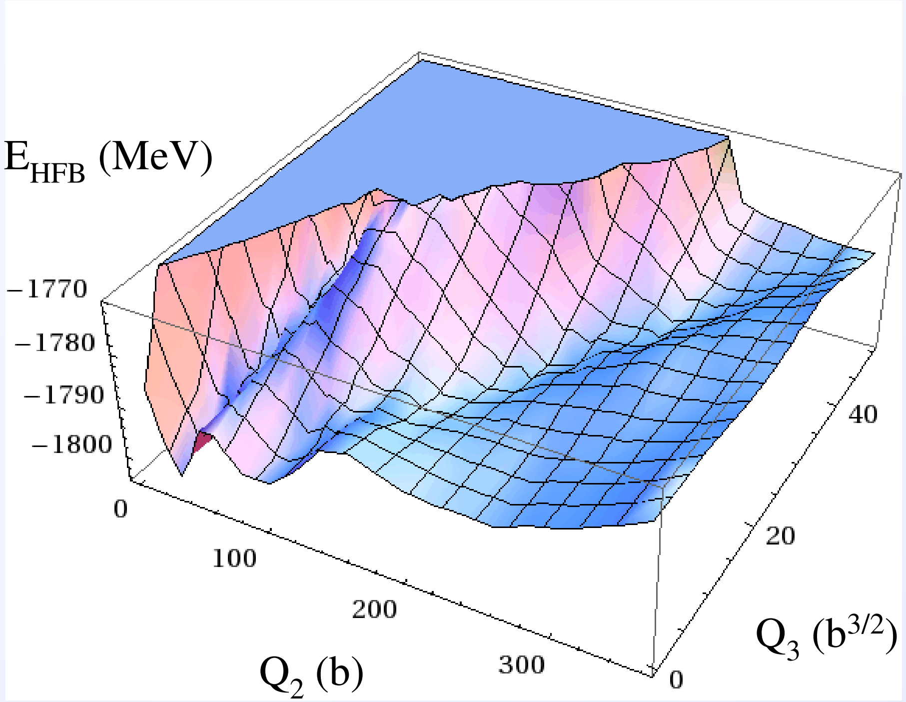
# The microscopic method: dynamics

- Generator-coordinate method + Gaussian-overlap approximation
  - Solve HFB for values of collective coordinates on a mesh
  - Construct wave packet as linear superposition of HFB solutions
    - weights are given by variational procedure that minimizes energy
  - Simplification: assume overlap of HFB solutions is Gaussian function of difference in collective-coordinates ⇒ favor similar “shapes”
- Wave packet is spread over all nuclear configurations
- Wave packet is allowed to evolve naturally out to scission
- Yields <u>Collective Hamiltonian</u> built from single-particle d.o.f.!

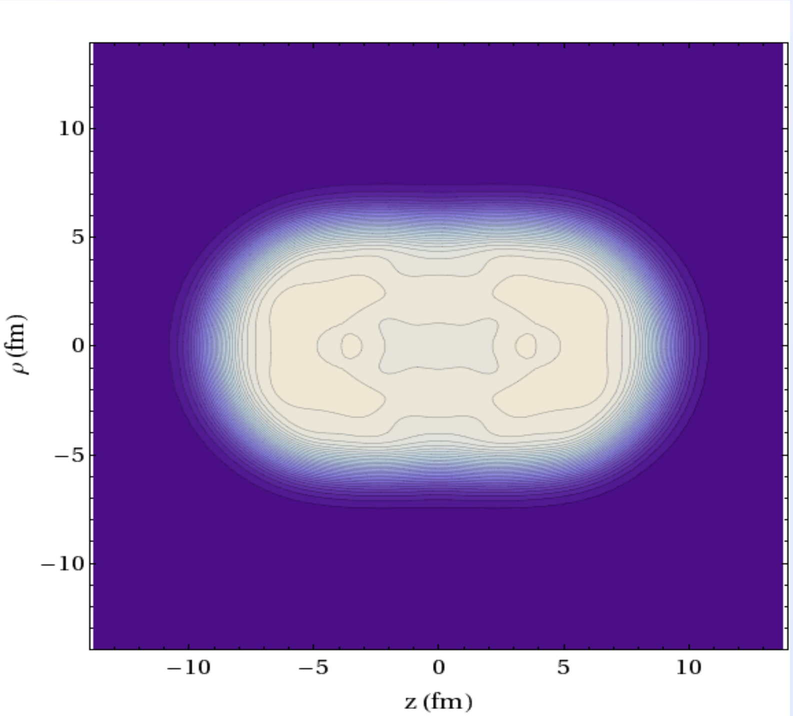
Fully quantum-mechanical approach

# Energy surface: elongation & asymmetry

**$^{240}$Pu**



**Densities along most likely path**

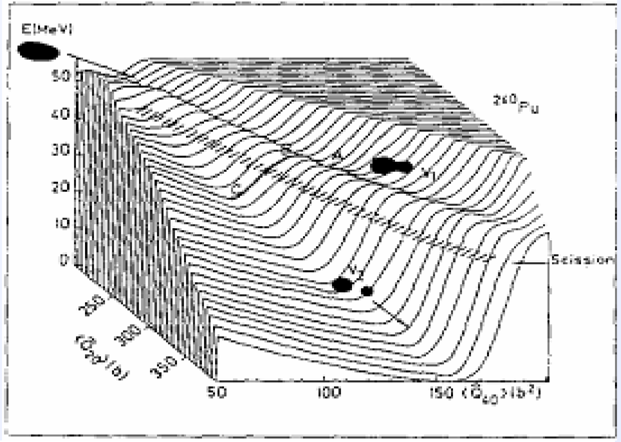


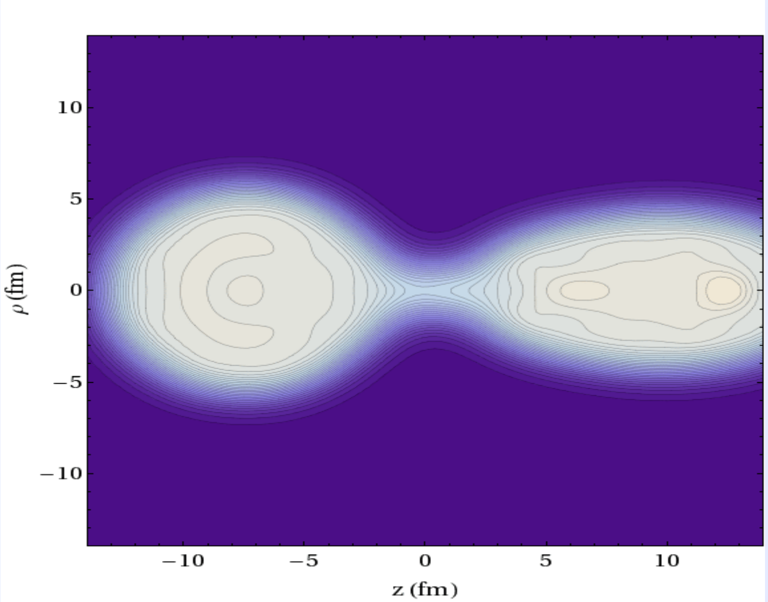
Reflection symmetry is spontaneously broken
⇒ asymmetric fission ($Q_3 \neq 0$)

# Energy surface: elongation & necking

- Barrier separates fission (V1) and fusion (V2) valleys
- Barrier disappears at high elongations ⇒ “hot” fission
- $Q_4$ controls thickness of neck
- Introduction of $Q_4$ leads to new physics: hot vs cold fission
  - fission at low $Q_2$ ⇒ fragments are close ⇒ TKE ↑ ⇒ $E_x$ ↓
  - fission at high $Q_2$ ⇒ fragments are far ⇒ TKE ↓ ⇒ $E_x$ ↑

Berger et al., NPA 502, 85 (1989)



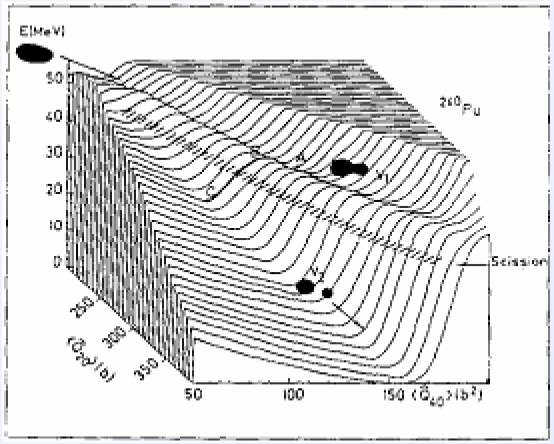


# Hot vs. cold fission

## The cold-fission mechanism:

- $Q_{20}$-$Q_{40}$ coupling from two sources

$$H_{\text{coll}} = \frac{\partial}{\partial q_2}\frac{-\hbar^2}{2M(q_2,q_4)}\frac{\partial}{\partial q_2} + \frac{\partial}{\partial q_4}\frac{-\hbar^2}{2M(q_2,q_4)}\frac{\partial}{\partial q_4} + \frac{\partial}{\partial q_2}\frac{-\hbar^2}{2M(q_2,q_4)}\frac{\partial}{\partial q_4} + \frac{\partial}{\partial q_4}\frac{-\hbar^2}{2M(q_2,q_4)}\frac{\partial}{\partial q_2} + V(q_2,q_4)$$



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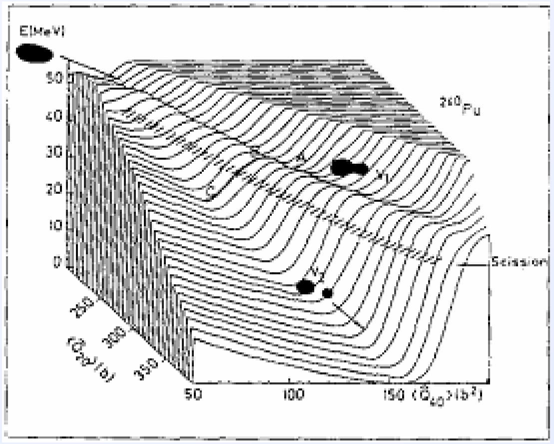
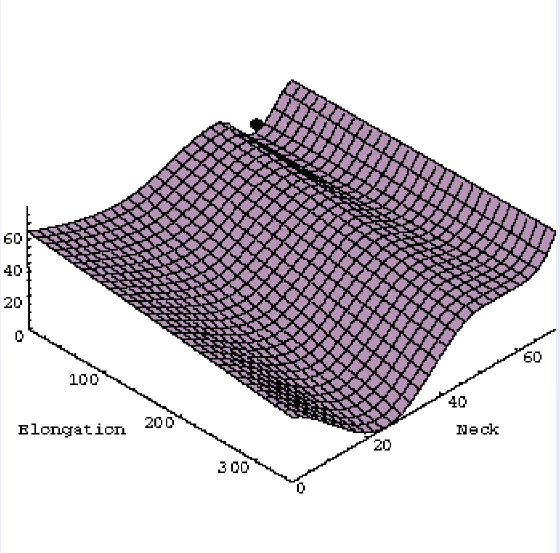
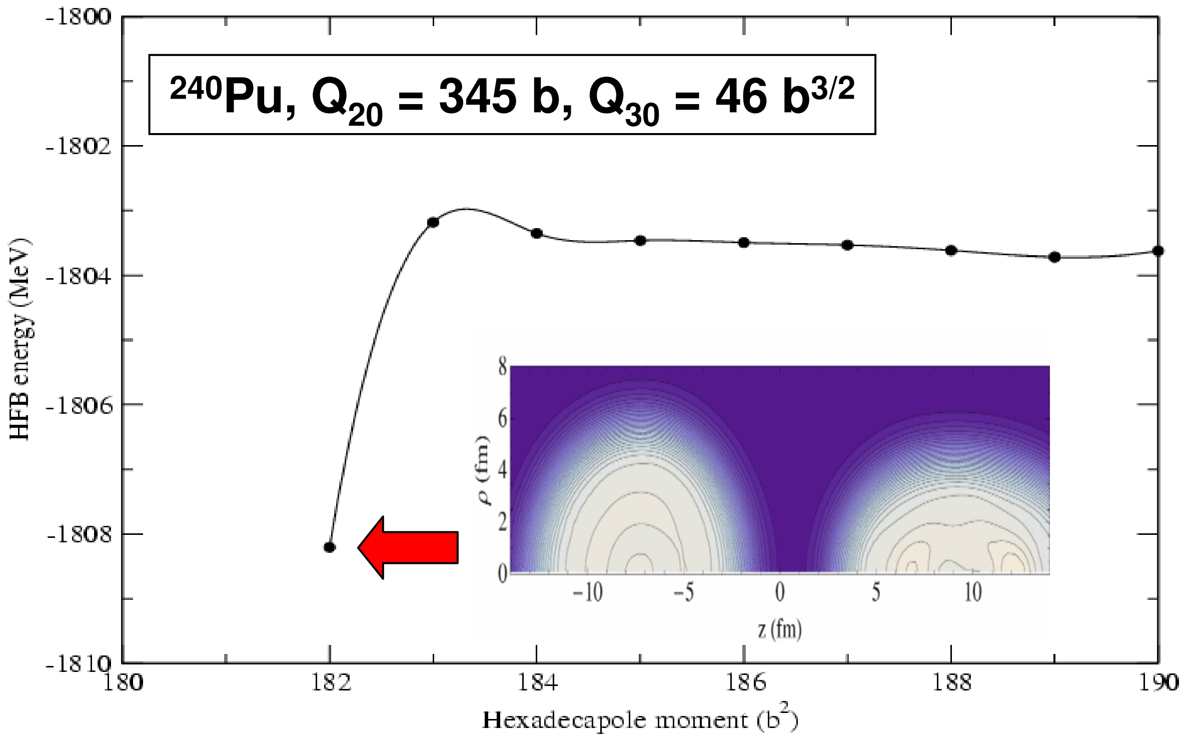
- **Transverse motion**
  - ☐ **excitation above barrier**
  - ☐ **slowing-down along longitudinal dir.**
- **effect mimicked by ad-hoc dissipation term in semiclassical models**

**Naturally built into the microscopic approach**





# Fragment excitation and kinetic energies



**Integrate densities separately:**

- $^{135}$I/$^{105}$Nb
- d = 16.9 fm
- TKE = 185.5 MeV
- TXE = 18.9 MeV
- $E_x(^{135}I)$ = 10.2 MeV
- $\Rightarrow \langle\nu\rangle(^{135}I) \approx 1.04$
- $E_x(^{105}Nb)$ = 8.7 MeV
- $\Rightarrow \langle\nu\rangle(^{105}Nb) \approx 1.00$

**Calculation can be repeated for any mass split/any exit point**

# Conclusion

- Microscopic fission-theory program at LLNL (Younes/Gogny)
  - Based on BIII 30-year effort
  - Homegrown code essential for adaptability to needs, new phys.
  - Adapted to LLNL computational resources
- Microscopic approach is incredibly powerful and rich
  - Explains wealth of phenomena without ad-hoc modifications
- Calculations of $^{240}$Pu fission-fragment properties have begun
  - Extracted TKE, TXE, $E_x$ for most likely (hot) fragmentation
- Next:
  - Large-scale computations of fragment properties
  - Investigation of formal criteria for scission
  - Investigation of best collective coordinates, esp. at scission
  - Dynamics
  - …