# Heavy-Ion Fusion/Fission and TDHF

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# Fusion

- No ab-initio many-body theory for sub-barrier fusion exists
- All approaches involve two prongs
  - a) Calculate an ion-ion barrier (usually one-dimensional)
    - Phenomenological (Wood-Saxon, Proximity, Folding, Bass, etc.) using frozen densities.
    - Microscopic, macroscopic-microscopic methods using collective variables (CHF, ATDHF, empirical methods).
  - b) Employ quantum mechanical tunneling methods for the reduced problem (WKB, IWBC)
- Incorporate quantum mechanical processes by hand
  - a) Neutron transfer
  - b) Few excitations of the entrance channel nuclei (CC)

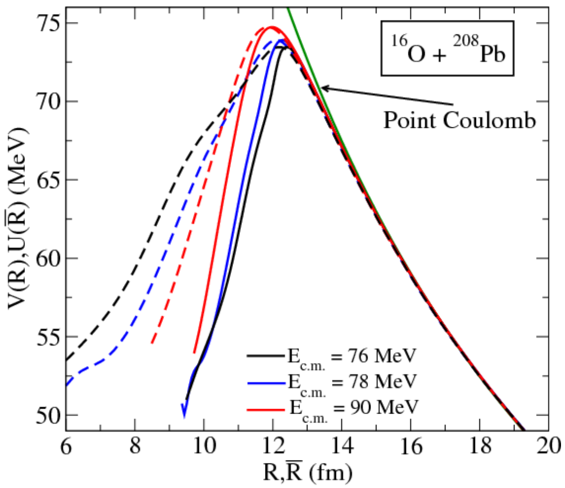
# Observations for Neutron Transfer

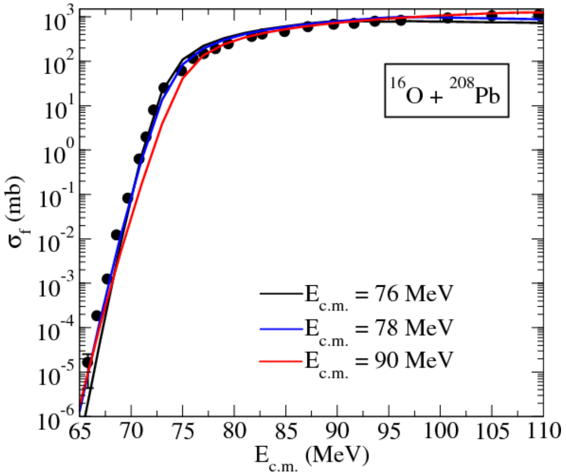
- Recently a quantum mechanical model was developed
  V. I. Zagrebaev, V. V. Samarin, and W. Greiner, Phys. Rev. C 75, 035809 (2007)
- Neutron transfer significantly influences sub-barrier fusion
- Transfer starts to occur when ions are relatively far apart
- Different quantum states see a different barrier
- Dynamical effects cause rearrangement of densities and barriers seen by individual states
- We may be able to study these effects using the TDHF theory

# Density-Constrained TDHF (DC-TDHF)

- Completely microscopic description of ion-ion potentials
- Includes all dynamical entrance channel effects
- Successful in obtaining realistic fusion barriers whenever the two nuclei are well described by Skyrme-HF

Umar & Oberacker, PRC 73, 054607 (2006)
PRC 74, 024606 (2006)
PRC 74, 021601(R) (2006)
PRC 74, 06160 (R) (2006)
PRC 76, 014614 (2007)
PRC 77, 064605 (2008)





EPJA 39, 243 (2009)

- Recent studies show that TDHF description of HI collisions is most accurate for the entrance channel dynamics:

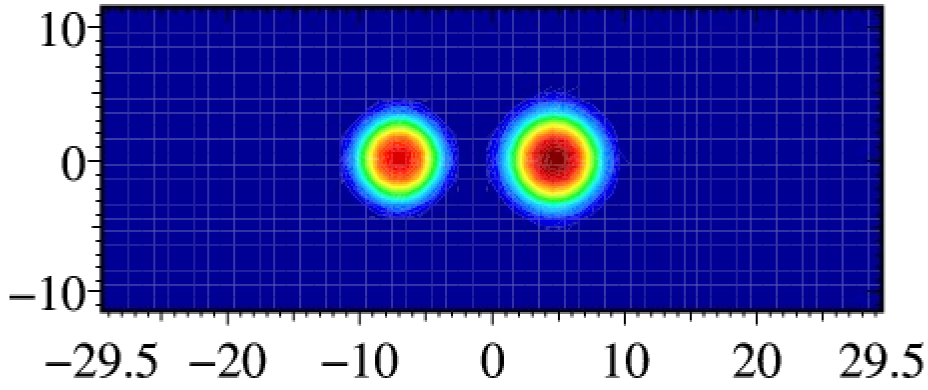
  Umar, Oberacker, J.Phys. G 36, 025101 (2009)
  Guo, Maruhn, Reinhard, Hashimoto, PRC 77, 041301 (2008)

- Recent DD-TDHF studies show good agreement with friction models

# Two Neutron-Rich Systems Above/Below the Barrier

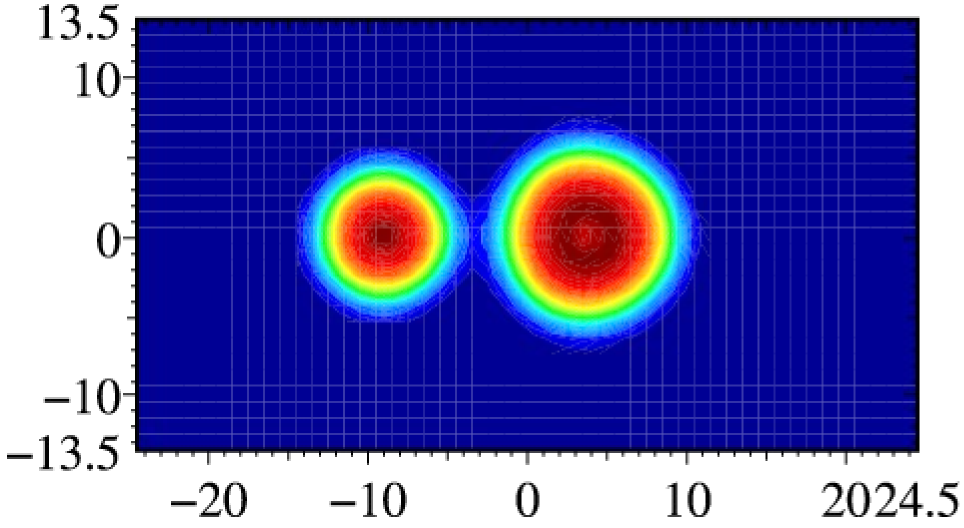
- $^{16}O+^{24}O$ at $E_{cm}$= 8 MeV (below effective barrier)

Closest approach →



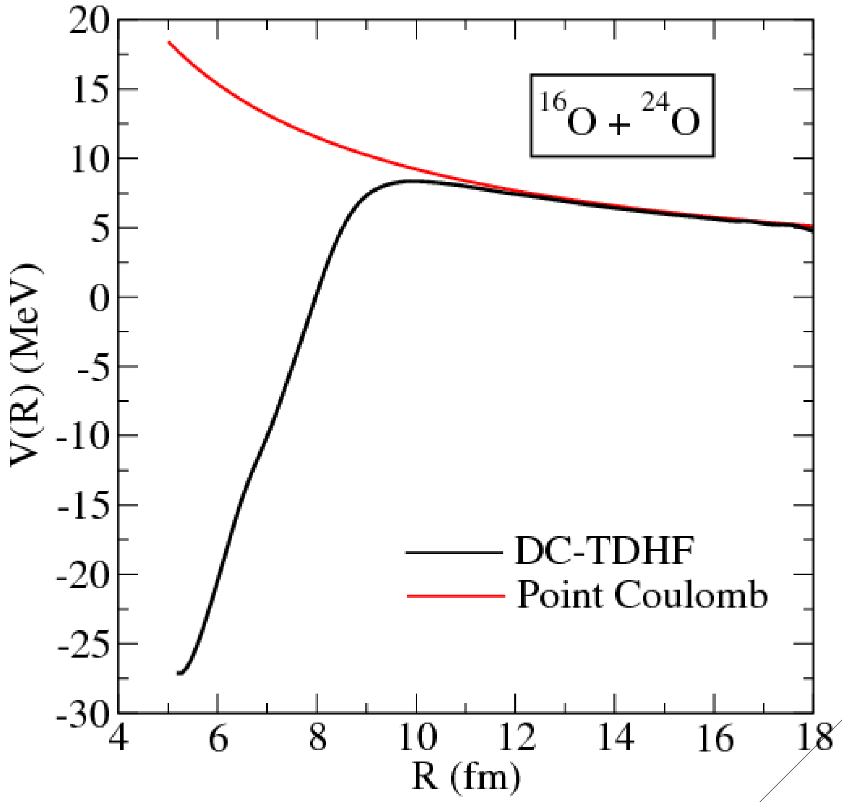
- $^{40}Ca+^{96}Zr$ at $E_{cm}$= 91 MeV (below effective barrier)

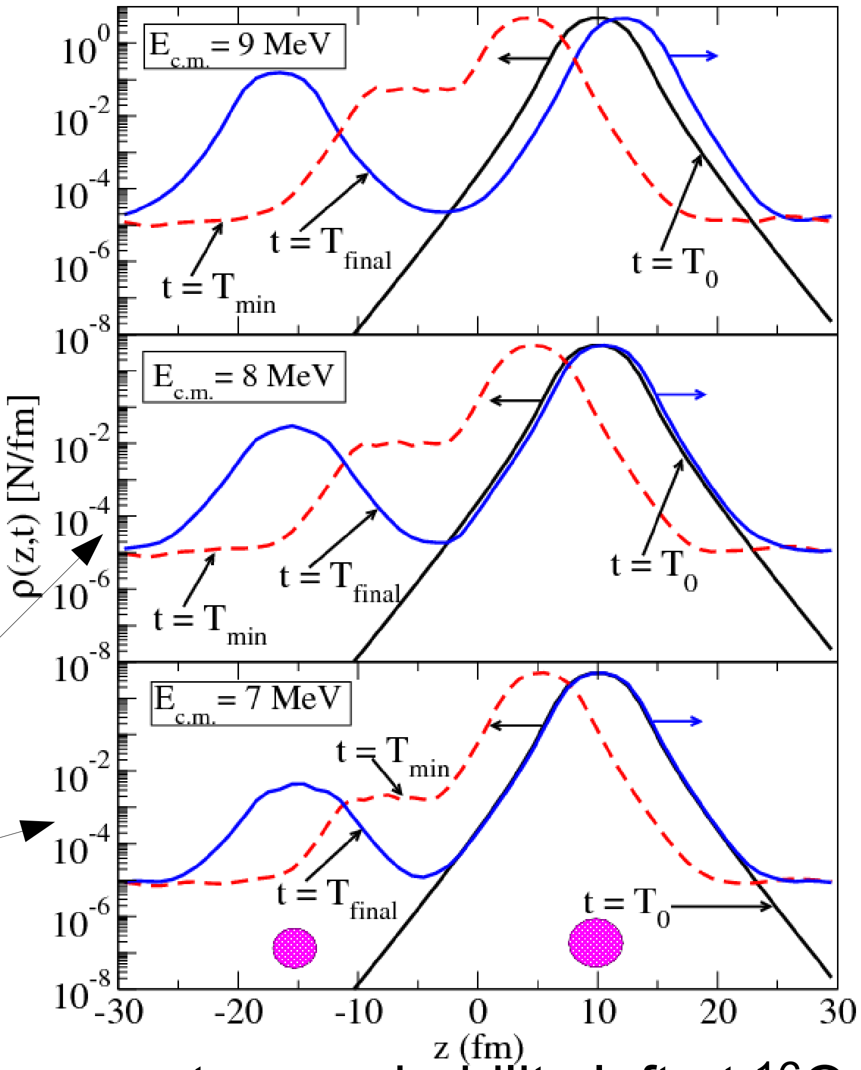
Closest approach →



# Analyze Transfer at Single-Particle Level

Umar, Oberacker, Maruhn, Eur. Phys. J. A 37, 245 (2008)





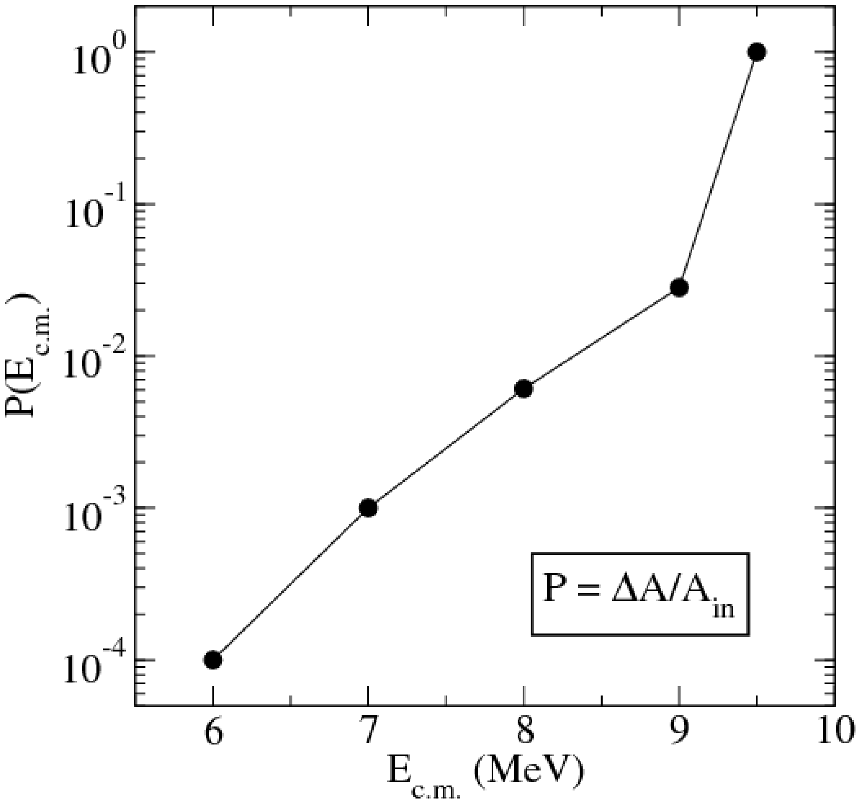
$$\rho(z,t)=\int dx \int dy\, \rho(x,y,z,t)$$

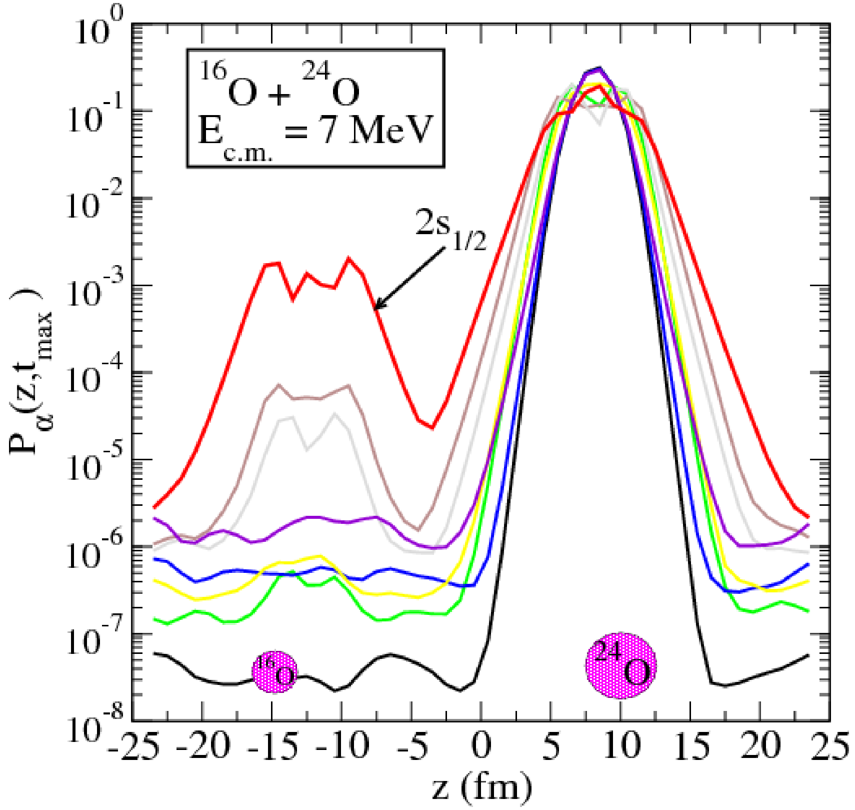
Below the barrier!

- Long after recoil we have non-zero neutron probability left at $^{16}O$

# Transfer Probability Below the Effective Barrier

Umar, Oberacker, Maruhn, Eur. Phys. J. A 37, 245 (2008)

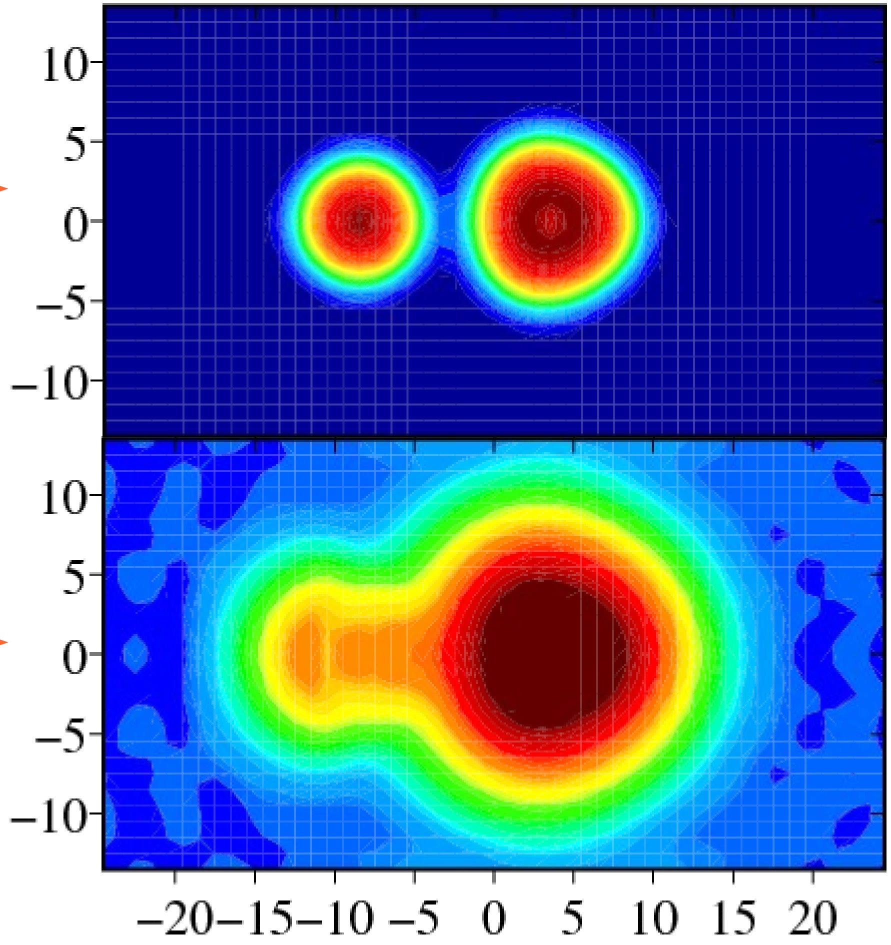




- Different single-particle states see different barriers!

# $^{40}$Ca+$^{96}$Zr System at $E_{cm}$ = 91 MeV

Umar, Oberacker, Maruhn, Eur. Phys. J. A 37, 245 (2008)

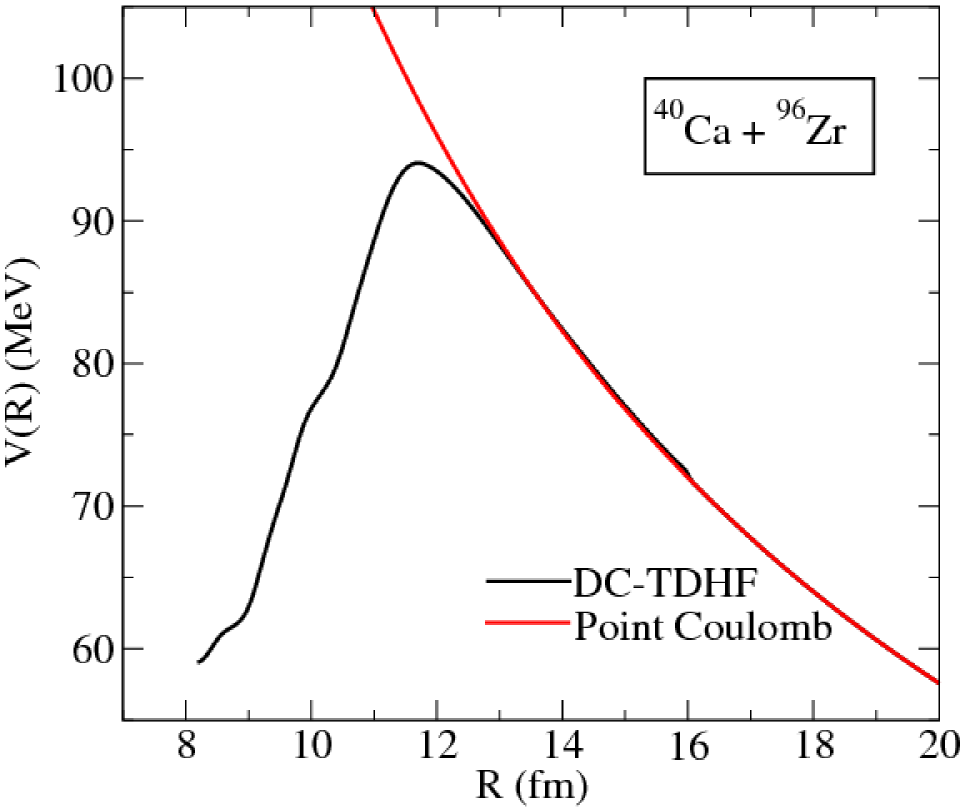


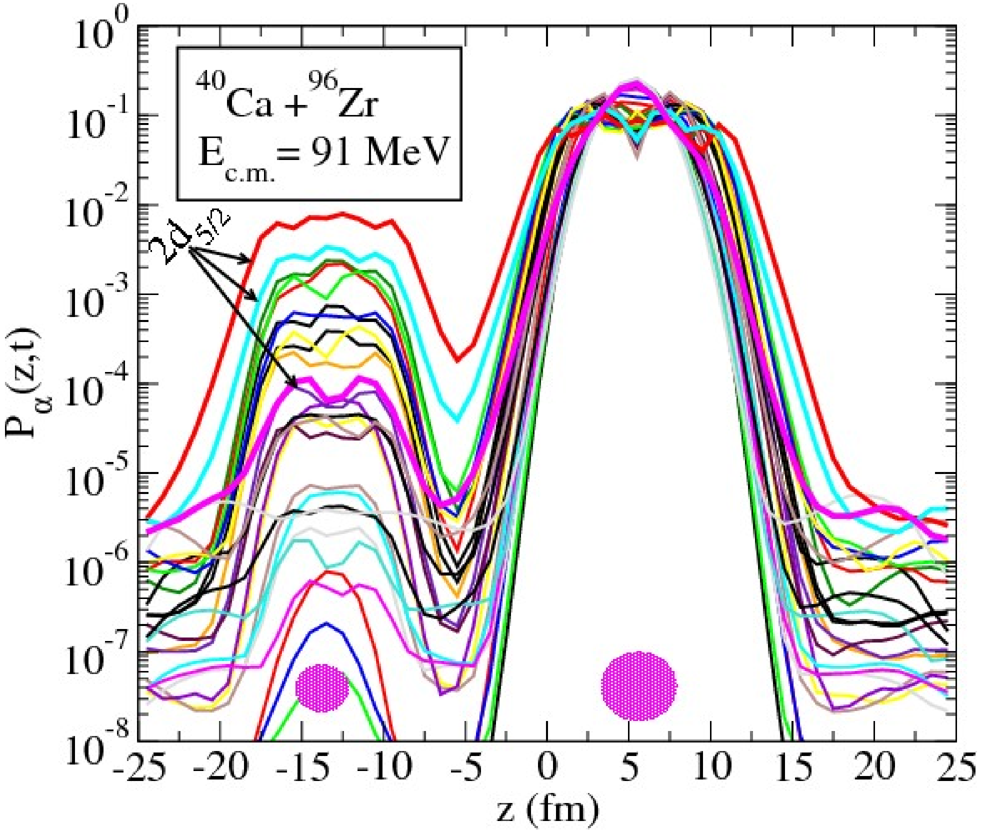
Closest approach
(normal plot)

Closest approach
(log plot, only $^{96}$Zr)

# Transfer Probability Below the Effective Barrier

Umar, Oberacker, Maruhn, Eur. Phys. J. A 37, 245 (2008)





- Sub-states of $2d_{5/2}$ dominate the transfer
- Our results in agreement with quantum mechanical model:

V. I. Zagrebaev, V. V. Samarin, and W. Greiner, Phys. Rev. C 75, 035809 (2007)

# Conclusions - Implications

- Effective potential barrier description of fusion is obviously an oversimplification
- In a many-body system different states will see different barriers – TDHF can simulate some aspects of this physics
- This should also be true for many-body fission in addition to virtual quantum mechanical excitations
- What is the dynamics of fission?
- Can we study these effects using the TDHF theory?

# Fission – Microscopic Static Adibatic Methods

- Barriers calculated via self-consistent methods in terms of collective coordinates
- Include configuration mixing, various projections, etc.

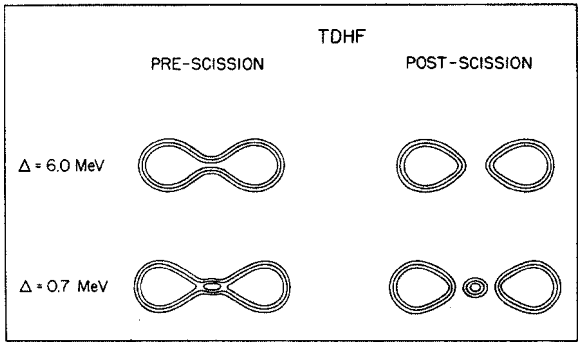
Baran, Staszczak, Dobaczewski, Nazarewicz, J. Mod. Phys. E16, 443 (2007)
(HF+BCS, GCM+GOA+Cranking)
Pei, Nazarewicz, Sheikh, Kerman (http://arxiv.org/0901.0901)
(Finite-temperature DFT or HFB)
Burvenich, Bender, Maruhn, Reinhard, PRC 69, 014307 (2004)
(RMF + Skyrme HF systematics)
Bender, Heenen, Bonche, PRC 70, 054304 (2004)
(HF+BCS, angular momentum projection)
Dobrowolski, Goutte, Berger, J. Mod. Phys. E17, 81 (2008)
(HFB with Gogny + GCM)

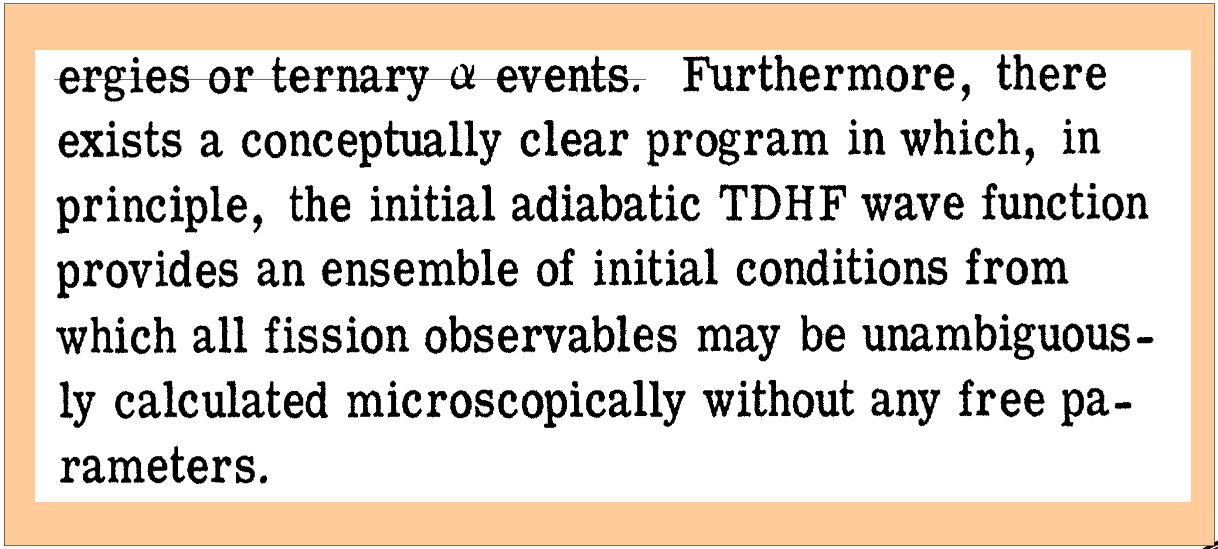
# Fission – TDHF - History

- Most well known attempt to study fission via TDHF:

  **Dynamics of Induced Fission**, Negele, Koonin, Möller, Nix, Sierk, PRC 17, 1098 (1978)

  - Nucleus is initialized via quadrupole constraint with energy 1 MeV below and beyond the saddle point (alternately one can give small initial kinetic energy).
  - Crude numerical methods, axial symmetry, reflection symmetry, no spin-orbit, BKN force.
  - To break symmetries and couple angular momenta time-dependent BCS was coupled to TDHF calculations.
  - Results depend strongly on gap parameter.




ergies or ternary α events. Furthermore, there exists a conceptually clear program in which, in principle, the initial adiabatic TDHF wave function provides an ensemble of initial conditions from which all fission observables may be unambiguously calculated microscopically without any free parameters.

# Fission – TDHF - History

- Very few other fission studies using TDHF:

**Dietrich, Nemeth, Z. Phys. A300, 183 (1981)**

- Fission studied with TDHF for slabs by giving a collective boost to the initial HF state

**1**. Fission was not seen when using small velocity field for boost but higher fields resulted in fission.

**2.** Instead, the initial states were constructed by exciting single particle states into higher unoccupied states. Easier to induce fission from these configurations.

**Okolowicz, Irvine, Nemeth, J. Phys. G 9, 1385 (1983)**

- Nucleus is initialized inside and just outside of the barrier and given a **quadrupole boost**
- Two different method used to create the initial HF states:

**1.** A single center regular HF state – no fission achieved for different initializations.

**2.** A spherical two-center initial HF state leads to fission almost always.

**Jung, Cassing, Mosel, Cusson. NP A477, 256(1988)**

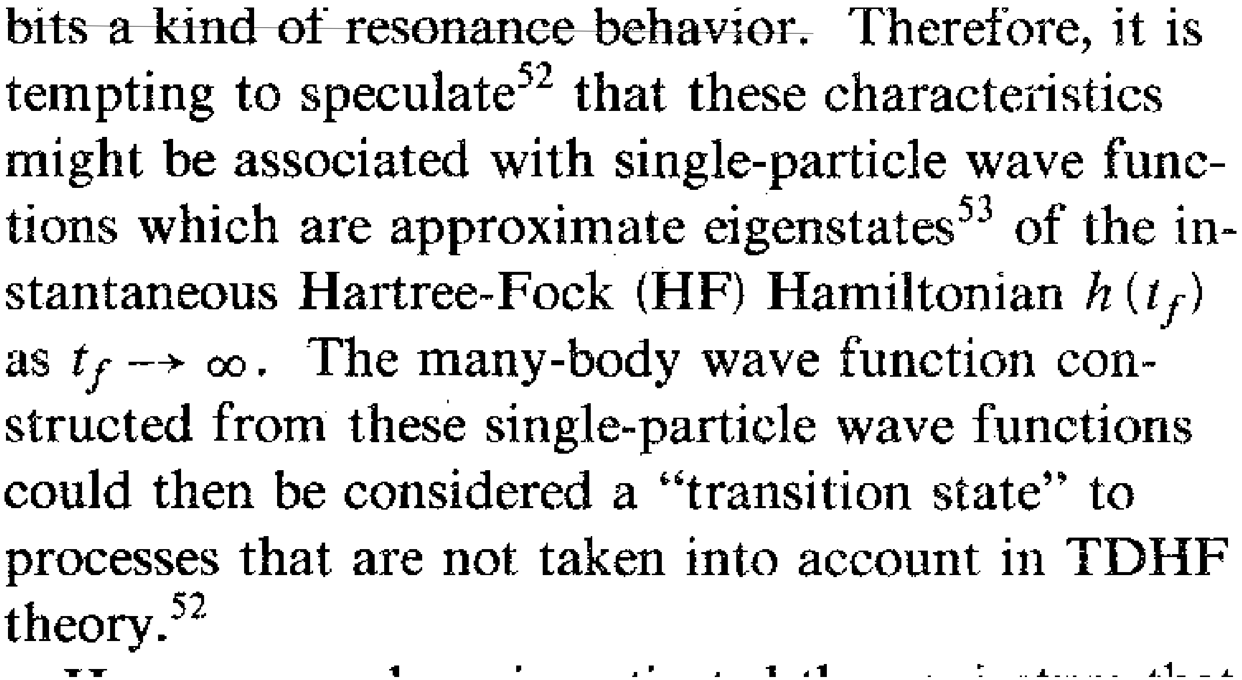
- Studied multi-fragmentation anf fission using TDHF (very adhoc).

**1.** Initialize by multiplying density with some r-dependent function c(**r**).

**2.** Boost by exp(i**k.r**) but with **k** having different sign for different parts of the nucleus.

# Fission – TDHF – Suggestion!

- In studying fusion with TDHF we sometimes see states that are coalesced and show kind of a resonance behavior.
- For light nuclei these have been associated with shape-isomers and nuclear molecular resonances.
- In heavy systems they may: **K.T.R. Davies et al. PRC 24, 2576 (1981)**

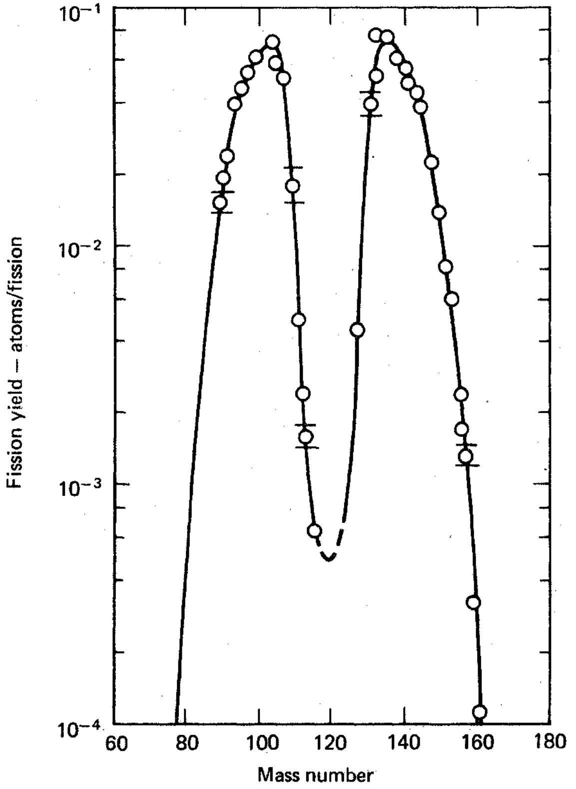


~~bits a kind of resonance behavior.~~ Therefore, it is tempting to speculate[52] that these characteristics might be associated with single-particle wave functions which are approximate eigenstates[53] of the instantaneous Hartree-Fock (HF) Hamiltonian $h(t_f)$ as $t_f \to \infty$. The many-body wave function constructed from these single-particle wave functions could then be considered a "transition state" to processes that are not taken into account in TDHF theory.[52]

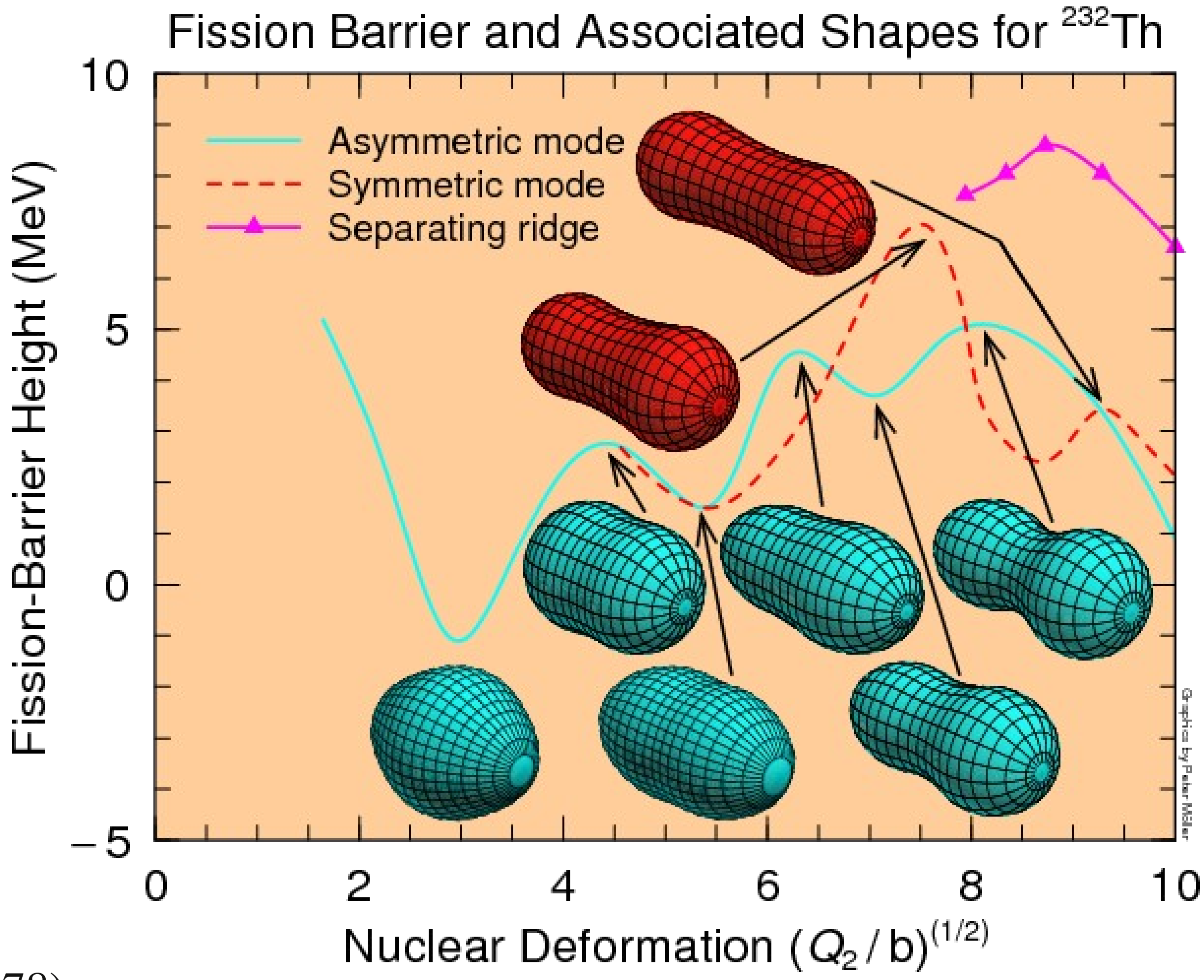
[52] Private comm. A.K. Kerman

# Characterizing Fission

$^{240}$Pu



Myers et al. PRC 18, 1700 (1978)

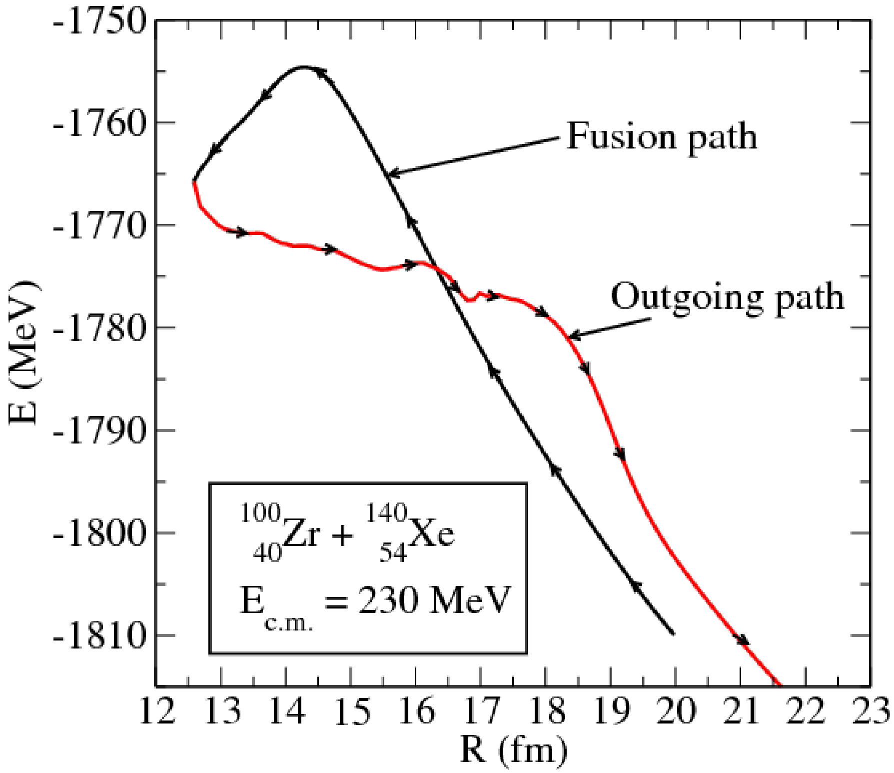


Möller, Sierk, Iwamoto, PRL 92, 072501 (2004)

# Fusion of $^{100}$Zr + $^{140}$Xe

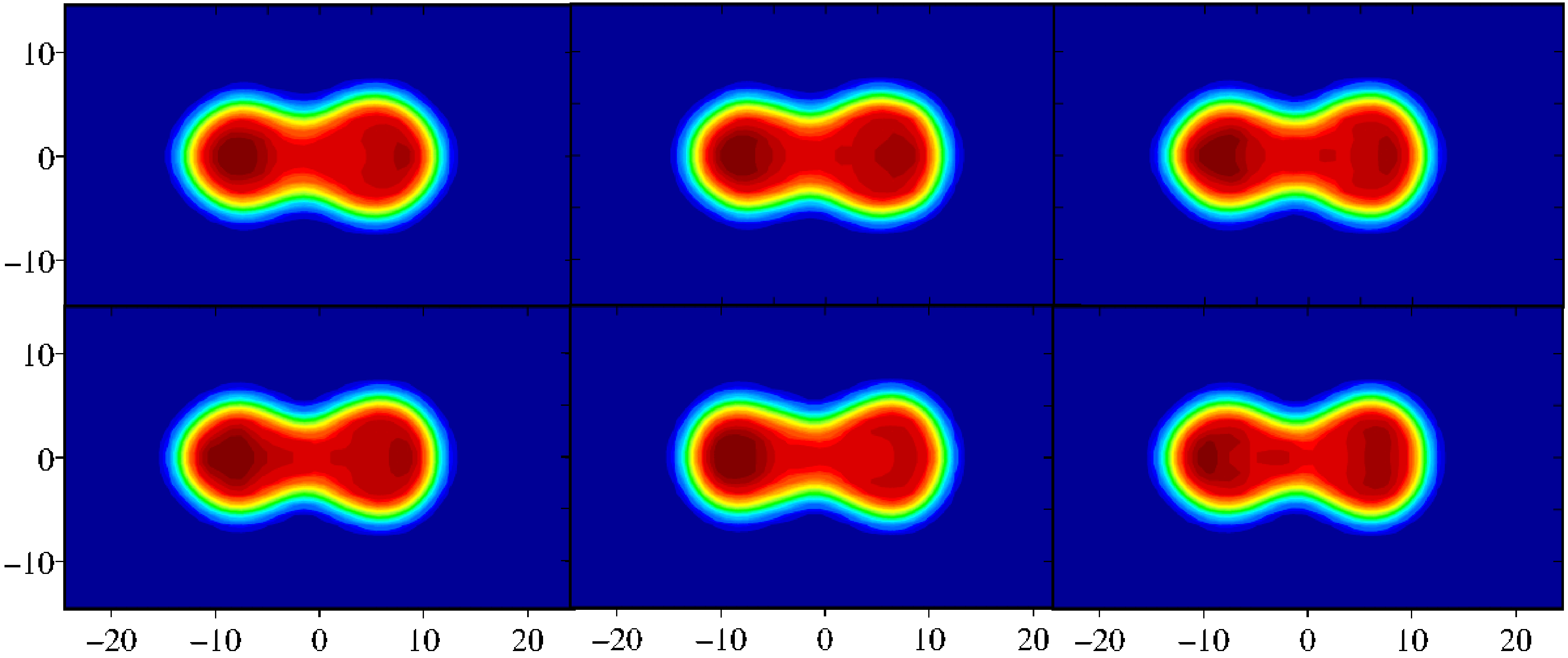
- We have studied fusion of $^{100}$Zr+$^{140}$Xe at c.m. energies of 230, 250, and 280 MeV.

- We find no fusion at 230 MeV, long-time structure at 250 MeV, and complete fusion at 280 MeV.



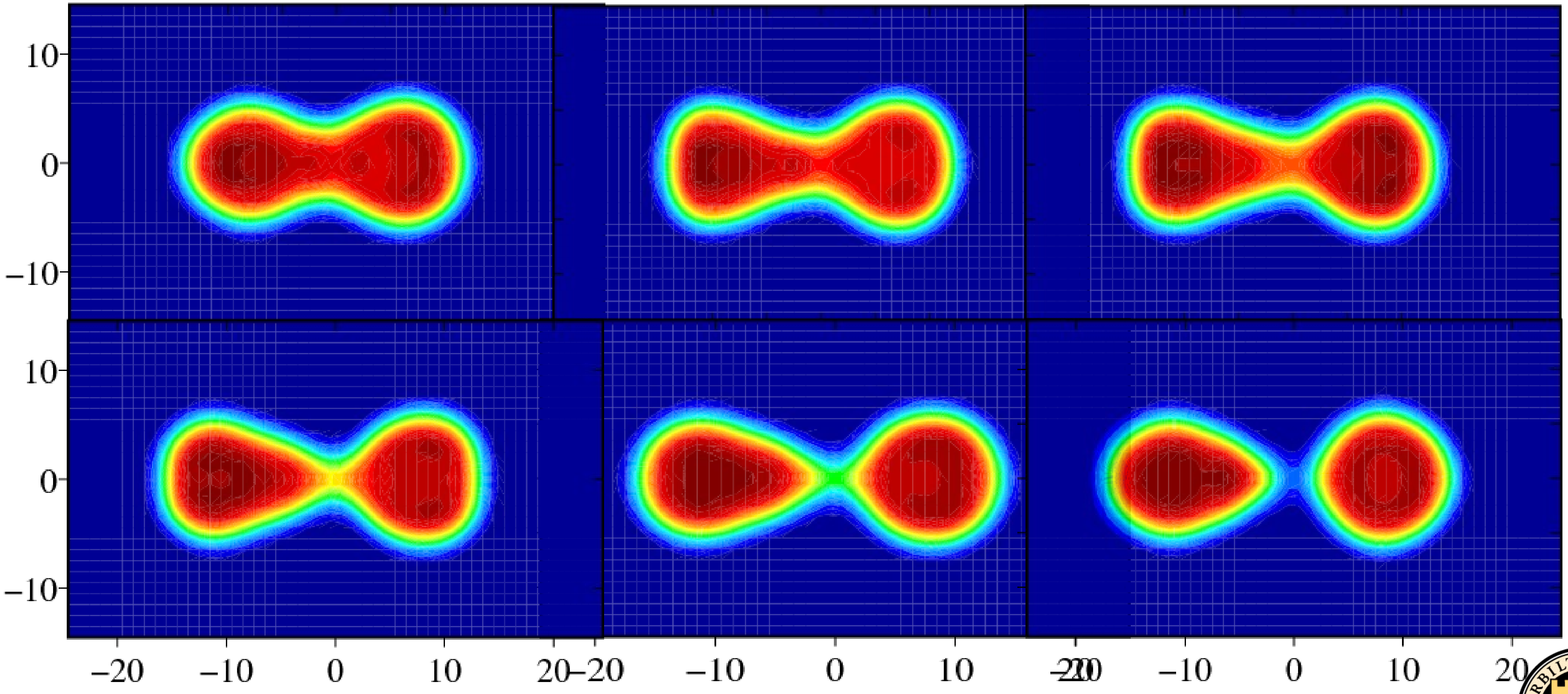
# Fusion of $^{100}$Zr + $^{140}$Xe at $E_{cm}$ = 250 MeV

- Long-time oscillatory behavior, followed up to 2600 fm/c



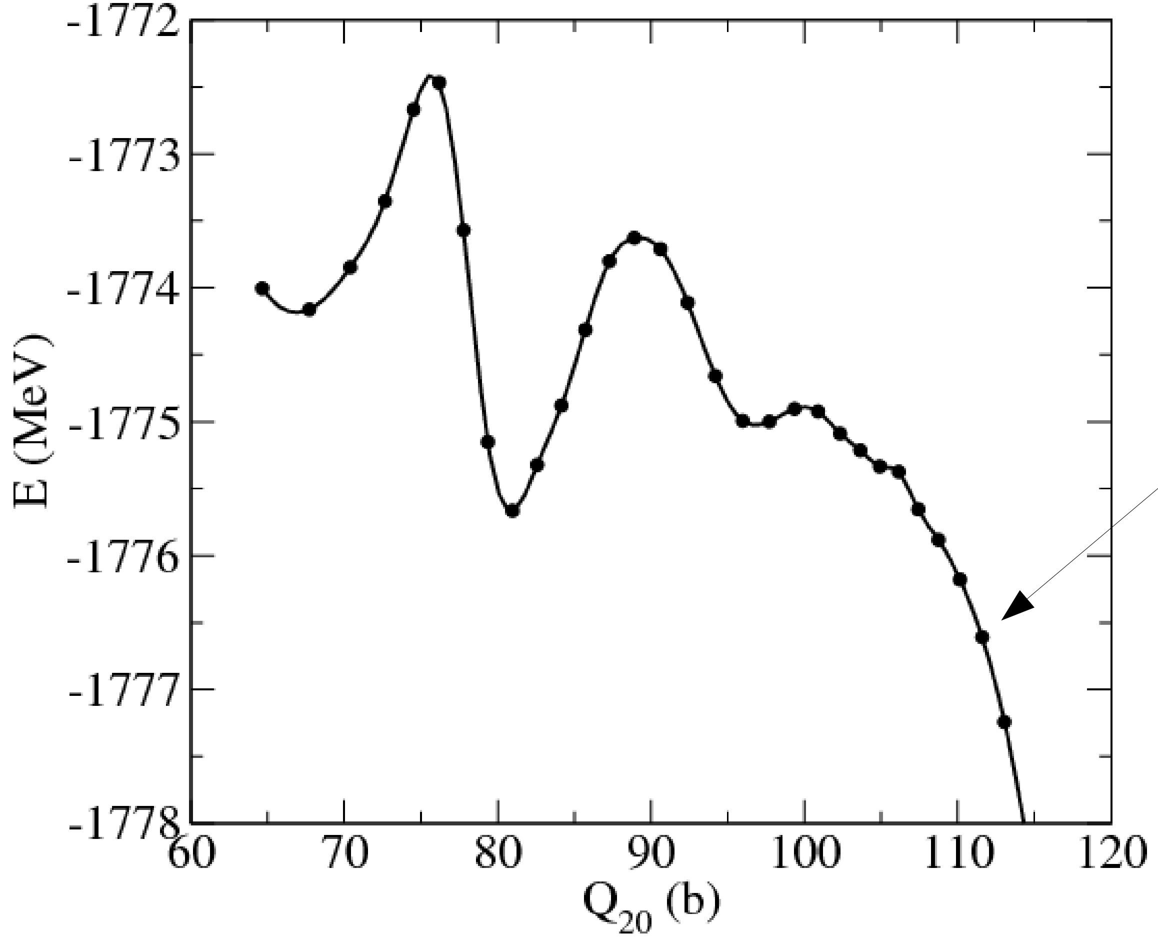
# Initiation of Fission

- Start from TDHF fusion state and minimize energy by density constraint
- Boost this state by a unitary collective boost operator $e^{ip\,q_{20}(\boldsymbol{r})}$ where for p = 0.005 we get 10-20 MeV excitation



# Tracing of the PES

- Density constraint along fission path for one initial/final state



$A_1 = 107$

$A_2 = 133$

# How do we make progress?

- Issues with initialization must be better understood
- Fusion states versus excited states
- Too many variables in the problem, collective boost operator, Boost strength, different final states, ...
- Will try unconstrained minimization