Evolution of Transfer-like Reactions from Coulomb to Fermi Energies

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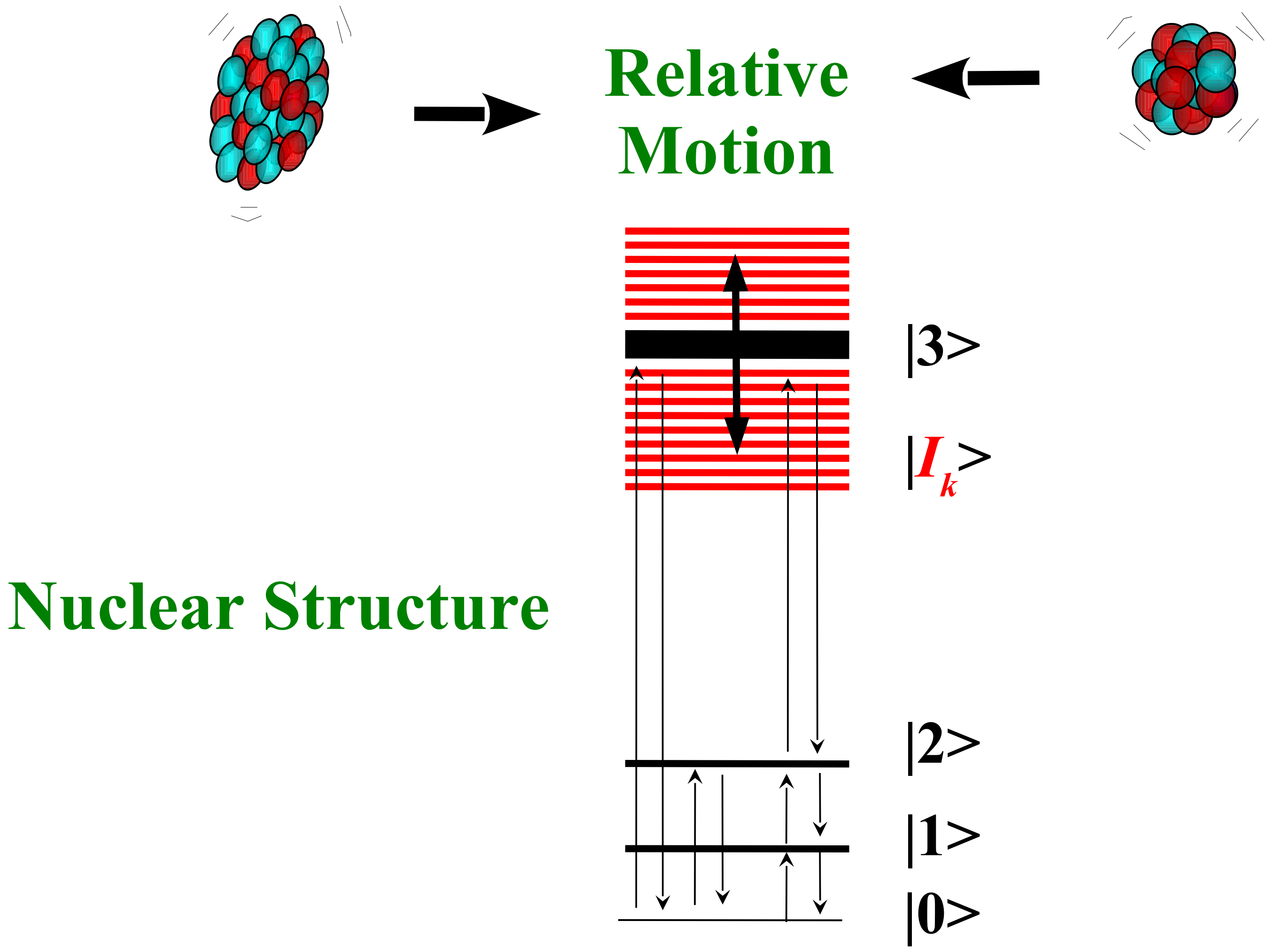
- Two-Centre Shell Model: adiabatic & diabatic states
- Effects of diabaticity on quasi-fission reactions
- Summary & Outlook

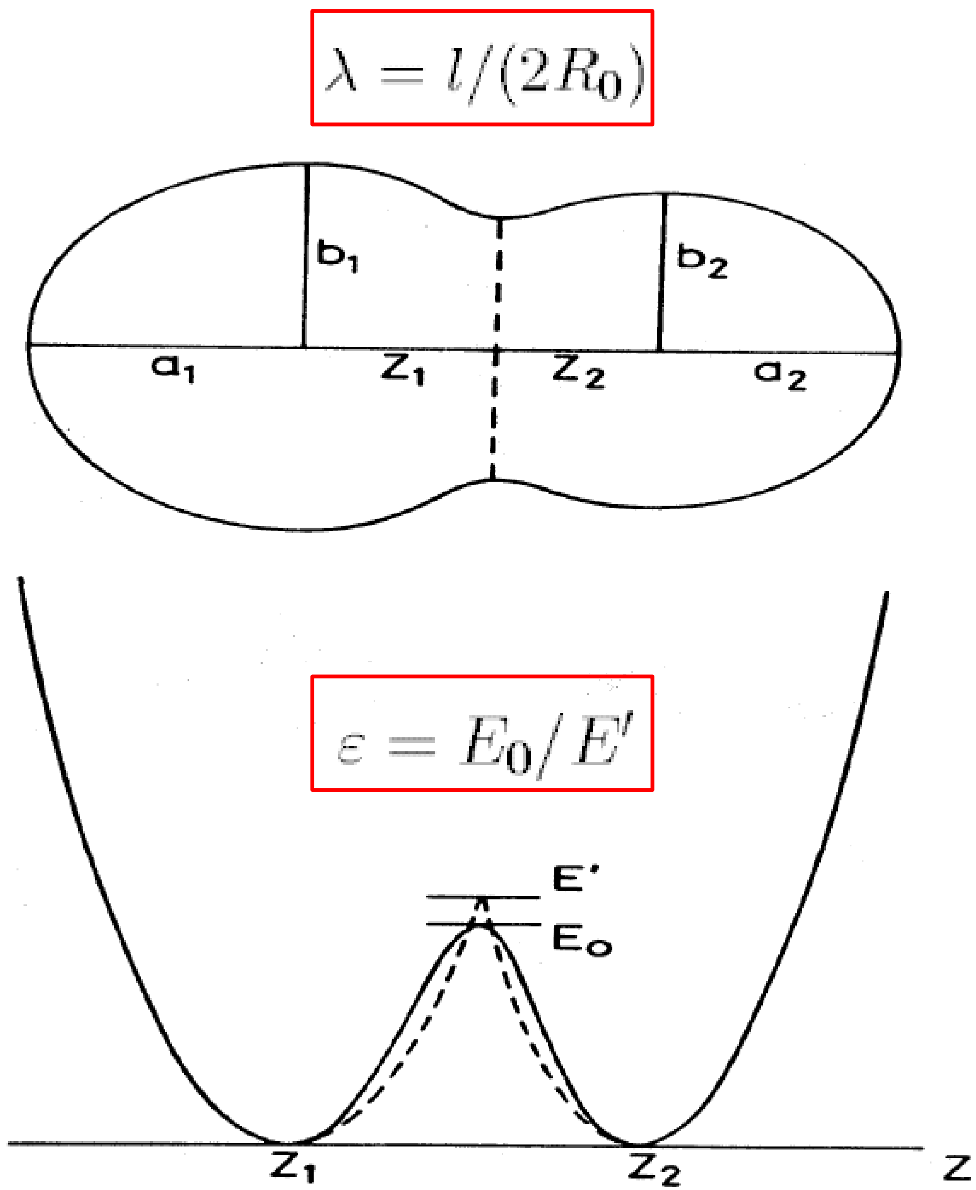
Low-Energy Nuclear Reaction Dynamics

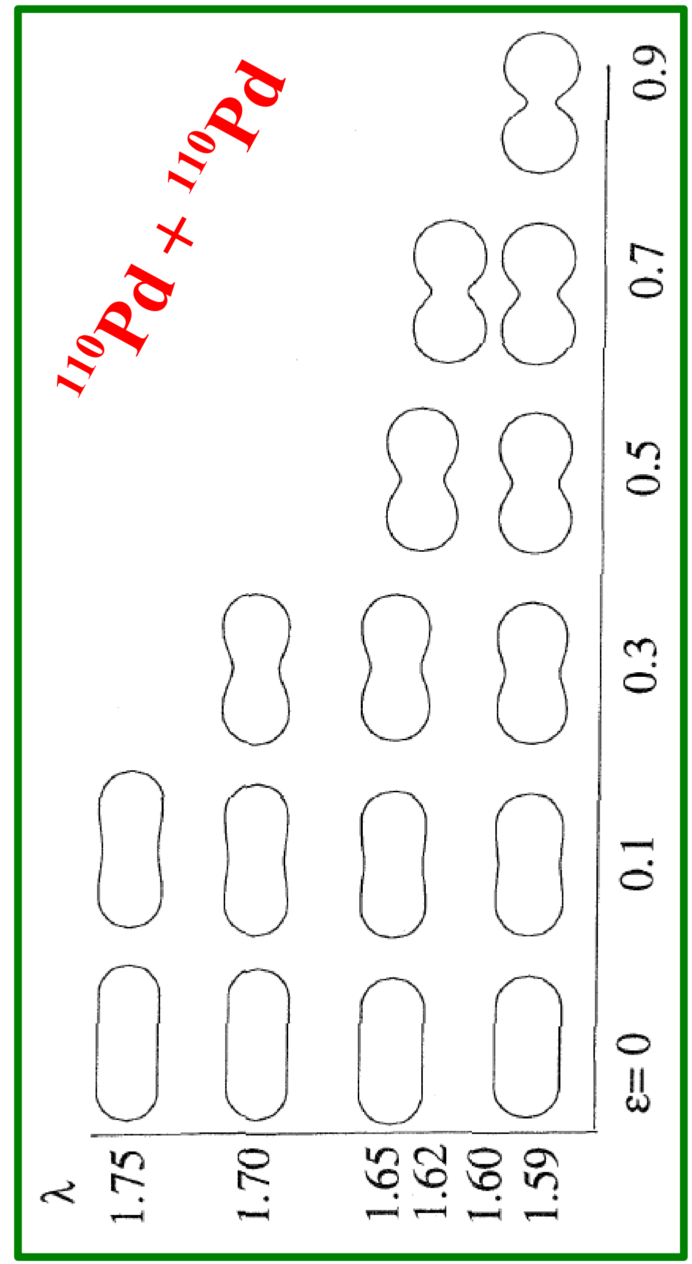


Strong interplay of **nuclear structure** and **reaction dynamics** determines reaction outcomes (**cross sections**)

Two-Centre Shell Model (TCSM)

J.A. Maruhn & W. Greiner, Z. Phys. **251** (1972) 431

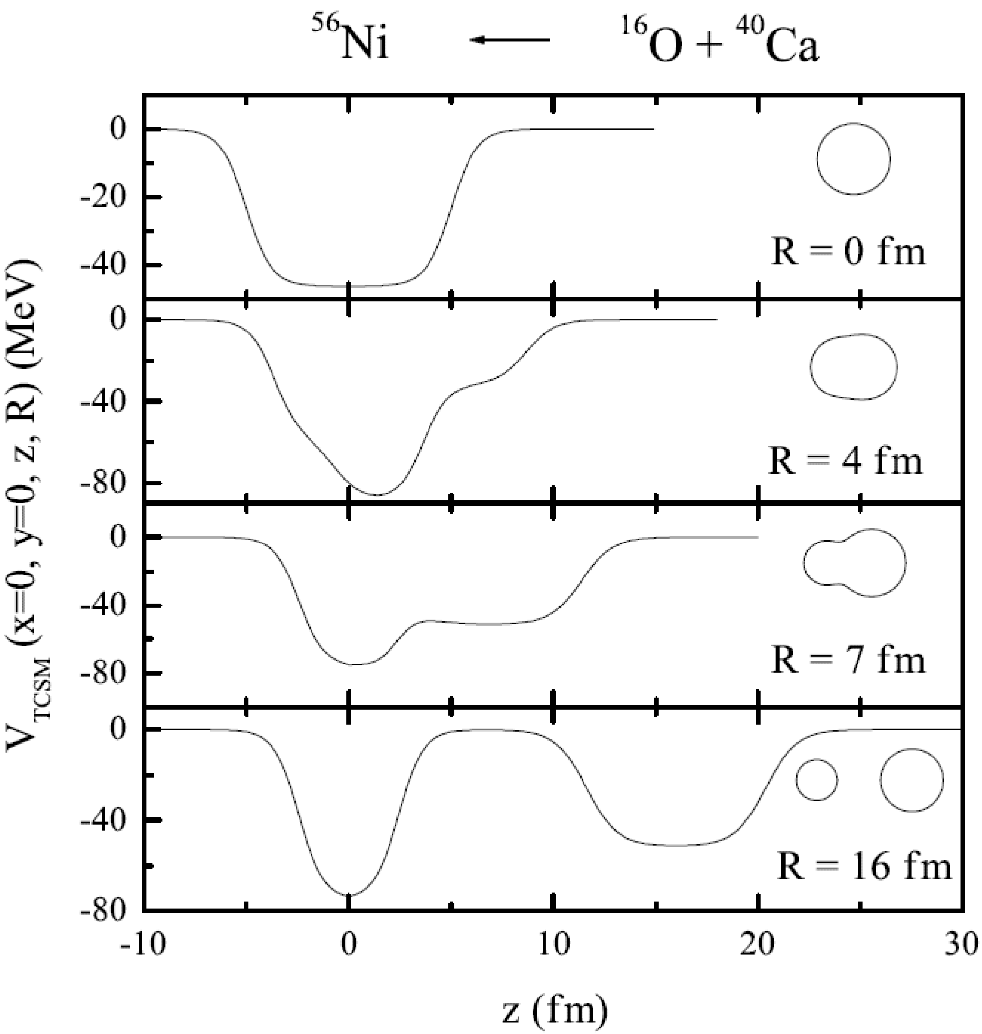


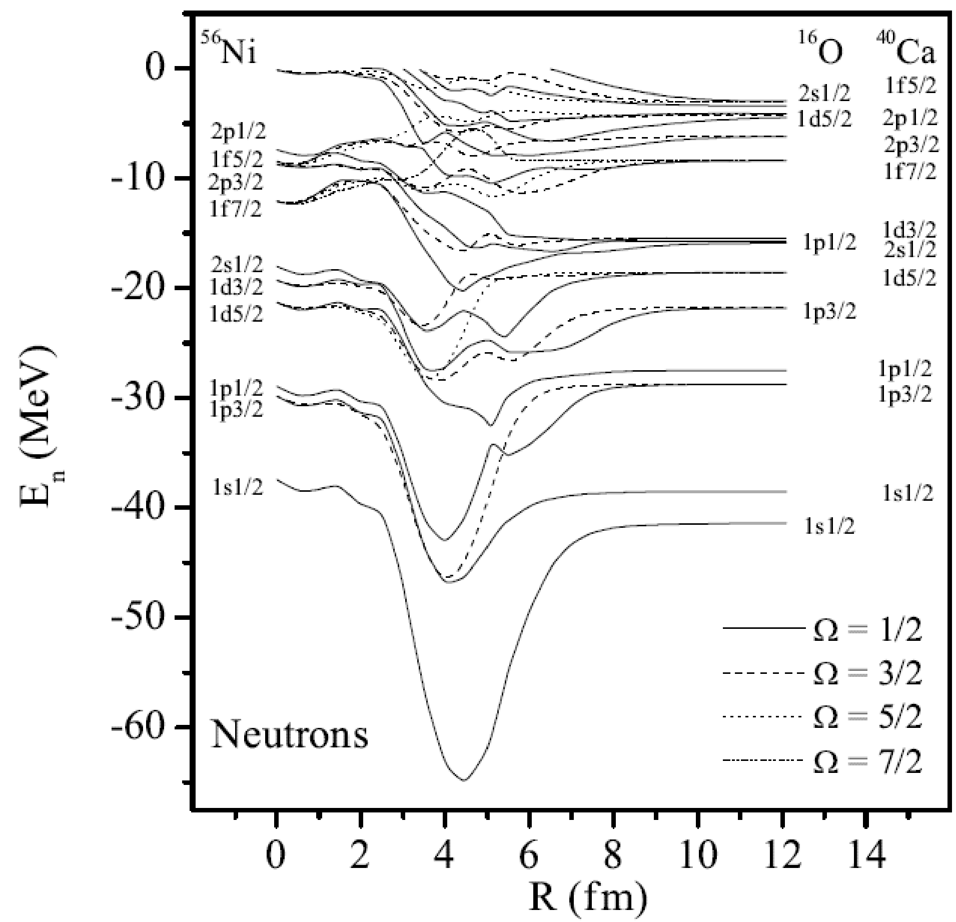


TCSM with Woods-Saxon Potentials

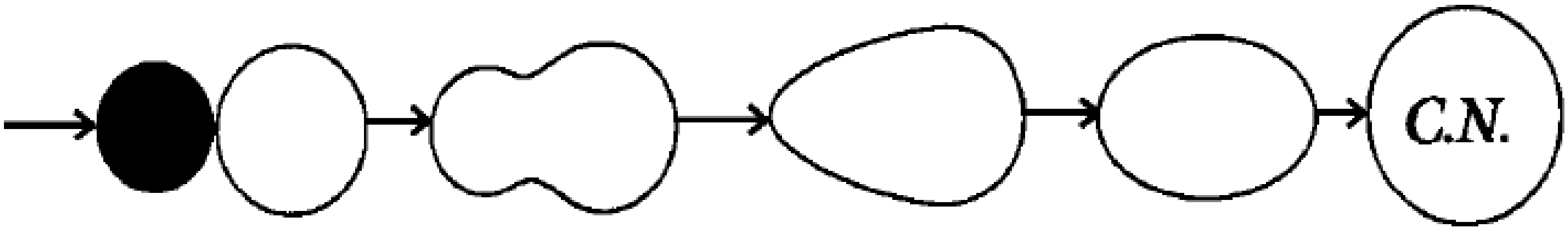
AD-T & W. Scheid, Nucl. Phys. A **757** (2005) 373

AD-T, Phys. Rev. Lett. **101** (2008) 122501

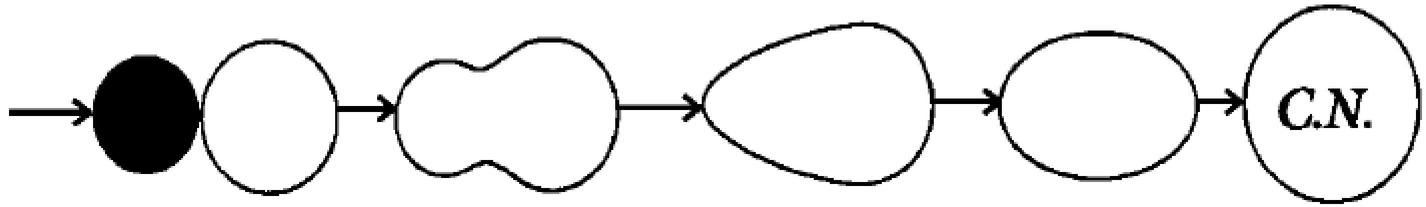


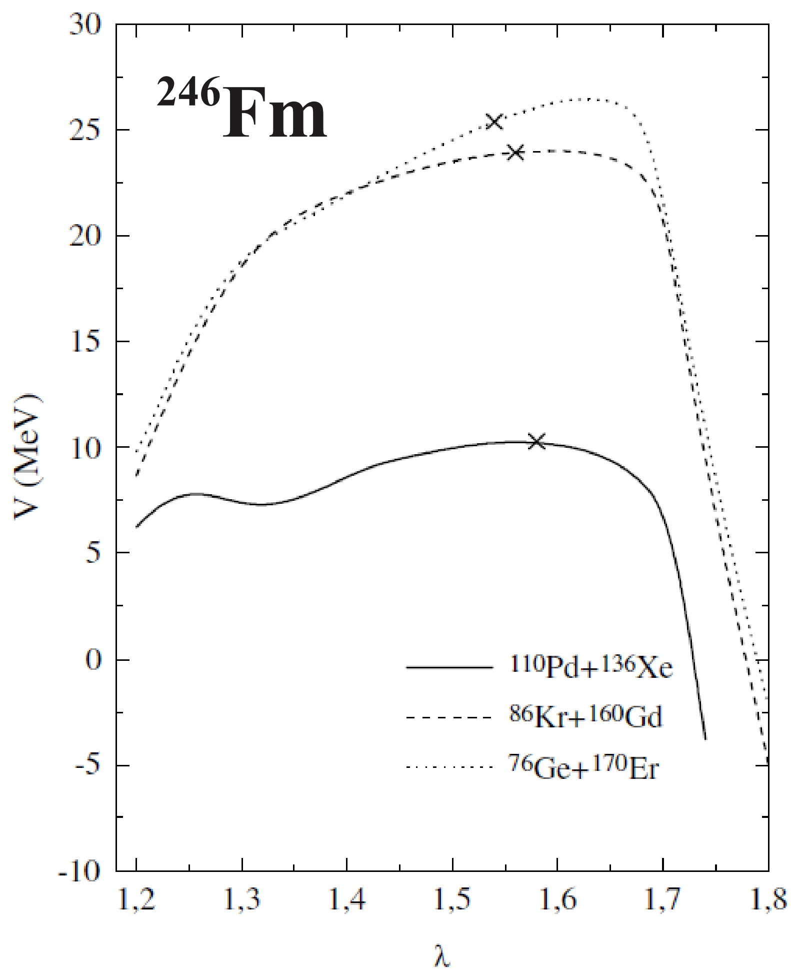


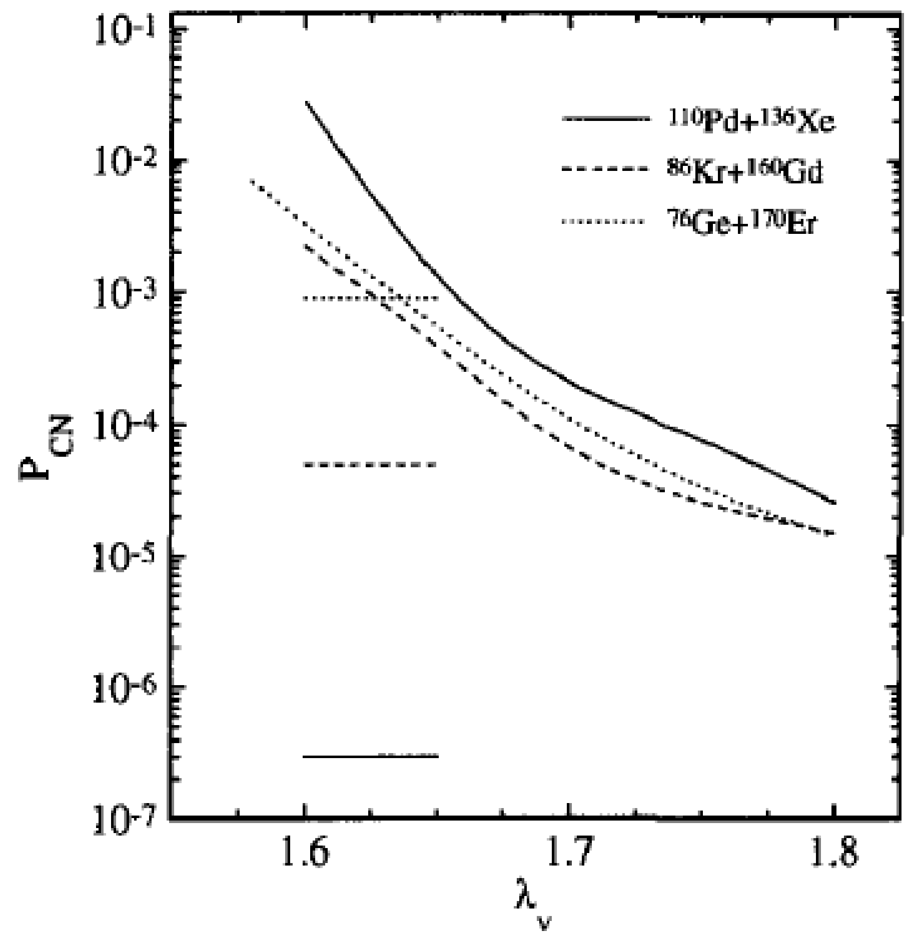
The Adiabatic Picture of Fusion



Some Problems with the Adiabatic Picture of Fusion





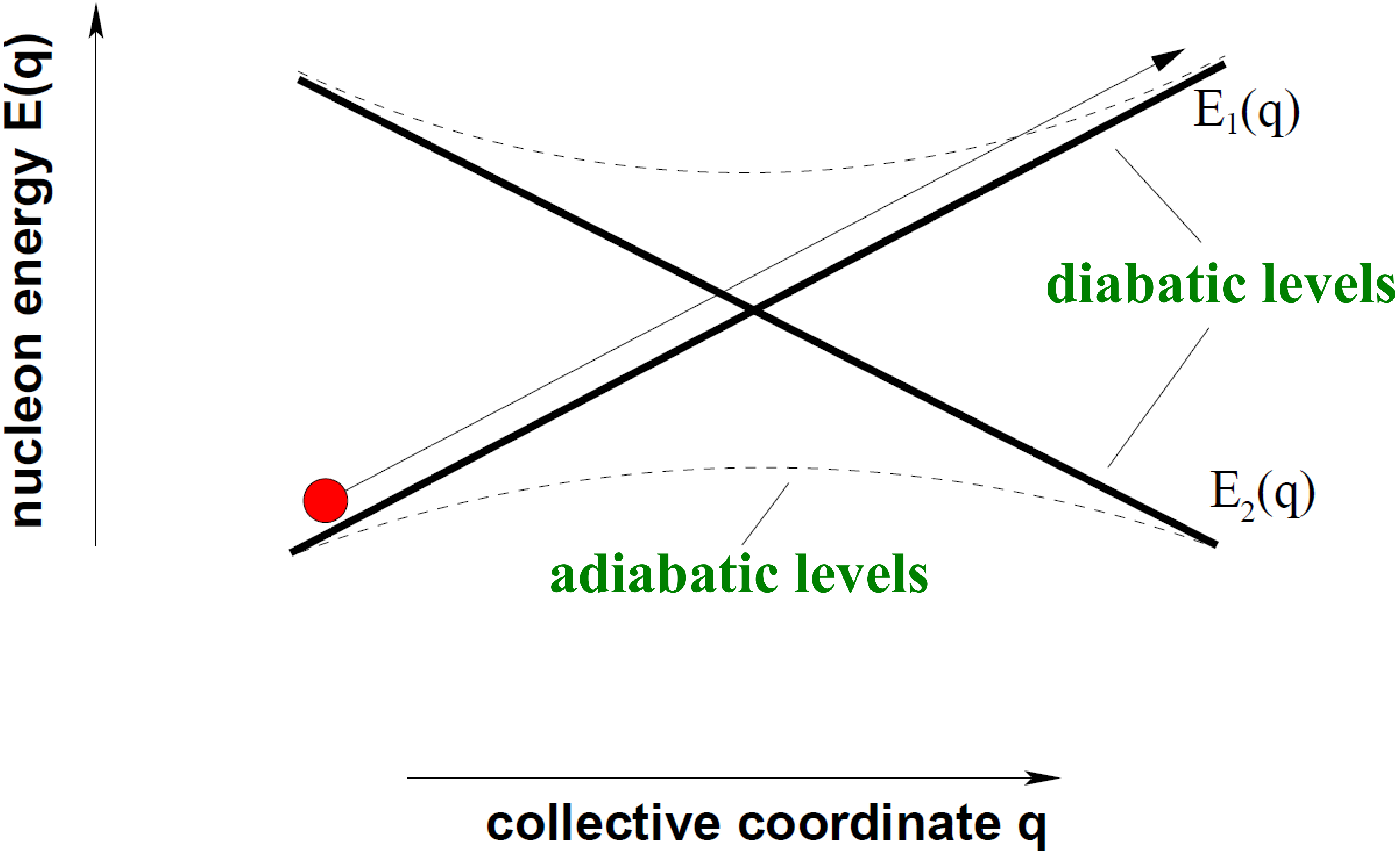


Adamian, Antonenko, Ivanova & Scheid, Nucl. Phys. A **646** (1999) 29

Adiabatic and Diabatic Single-Particle Motion

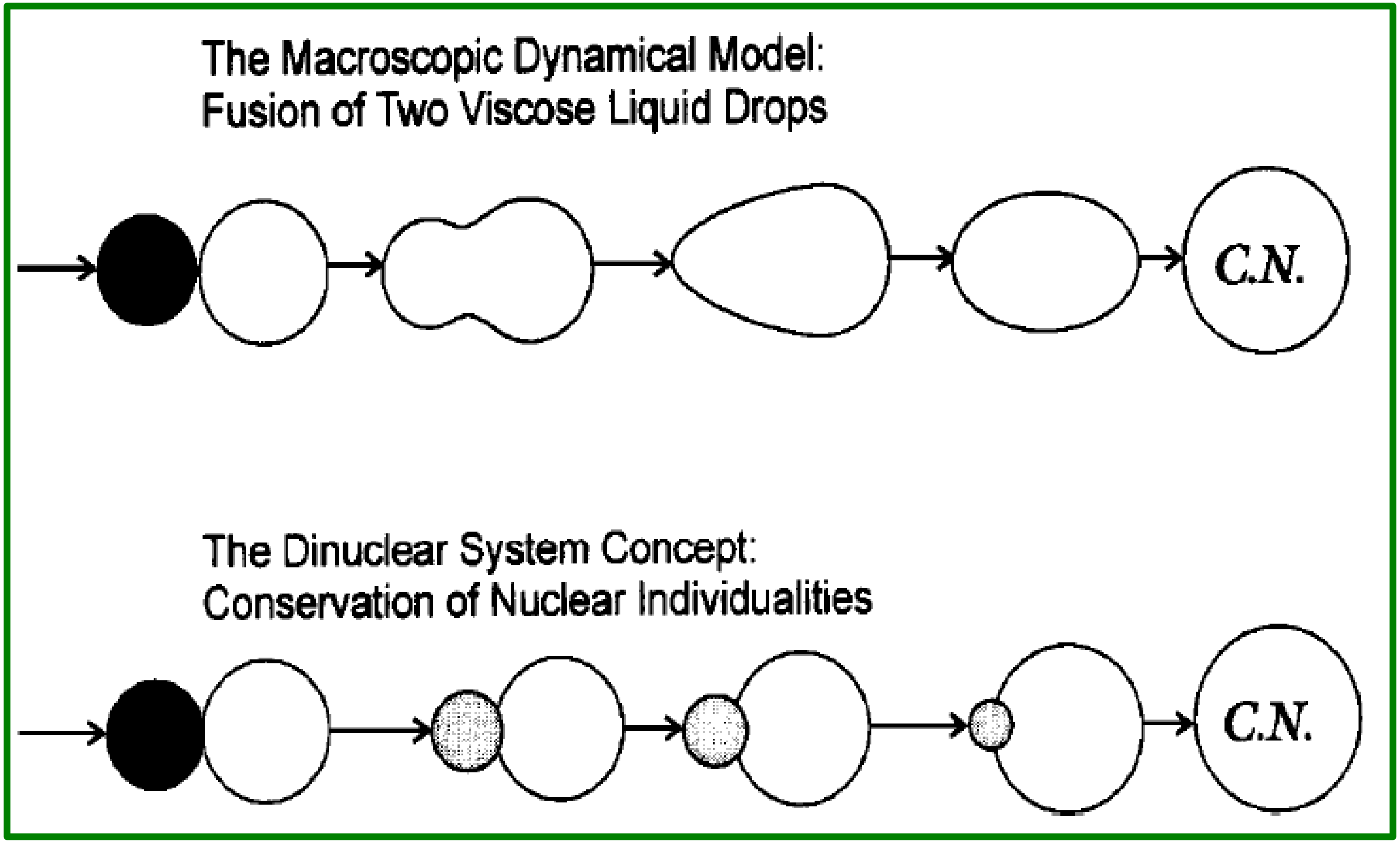
W. Noerenberg, Phys. Lett. B **104** (1981) 107

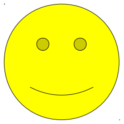
AD-T & W. Scheid, Nucl. Phys. A **757** (2005) 373



Fusion of Heavy Nuclei

The **diabatic picture** supports the dinuclear system model for complete fusion of heavy nuclei at Coulomb energies.





AD-T, Adamian, Antonenko & Scheid, Phys. Lett. B **481** (2000) 228

Effects of diabaticity on quasi-fission reactions

- Dynamical collective potential-energy landscape plays a crucial role in determining the reaction outcomes.

- Elasto-plasticity should be important as energy increases from Coulomb to Fermi energies.

AD-T, Phys. Rev. C **69** (2004) 021603(R)

AD-T, Phys. Rev. C **74** (2006) 064601

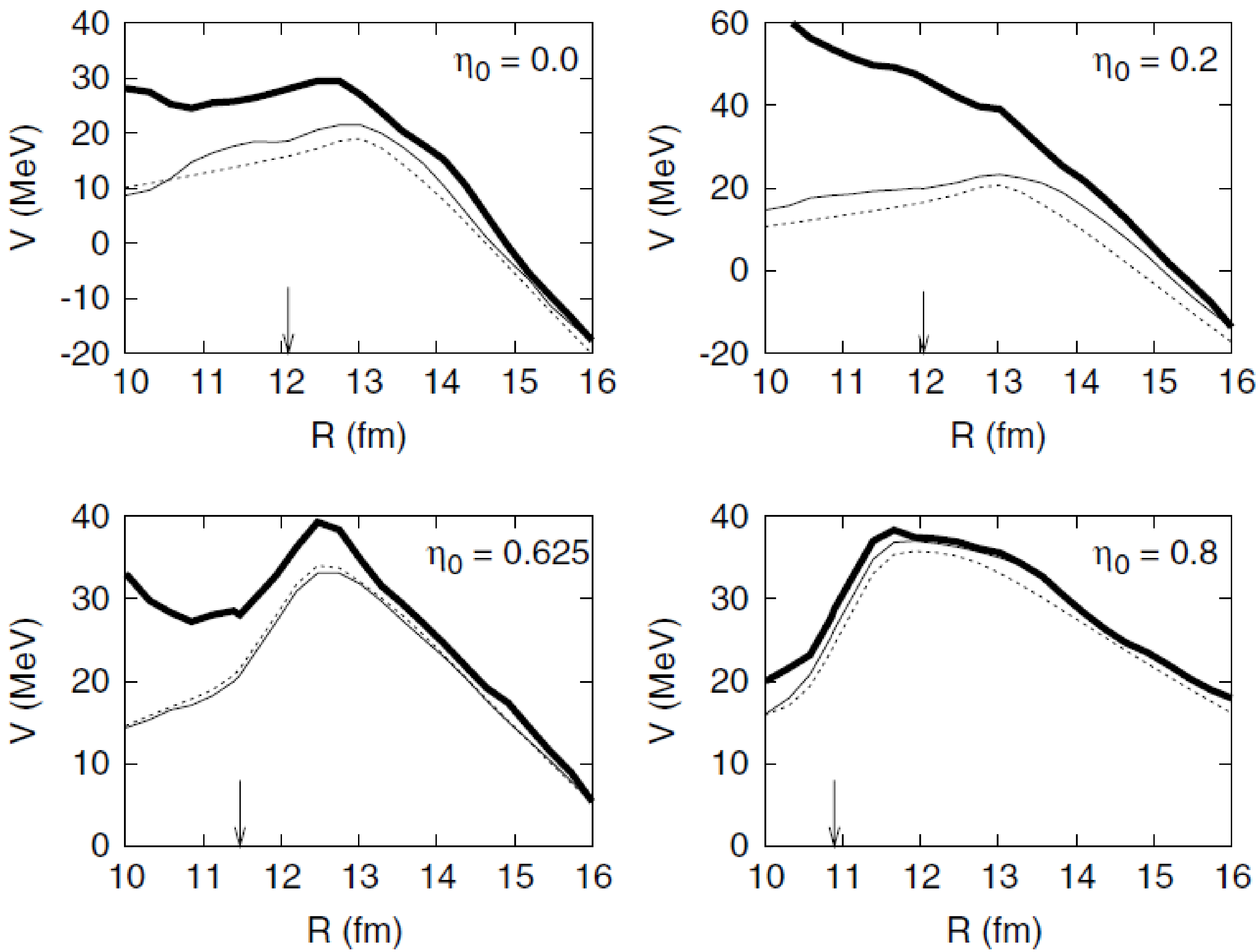
AD-T, Phys. Rev. C **82** (2010) 054617

Diabatic Contribution to the Collective PES

AD-T, Phys. Rev. C **74** (2006) 064601

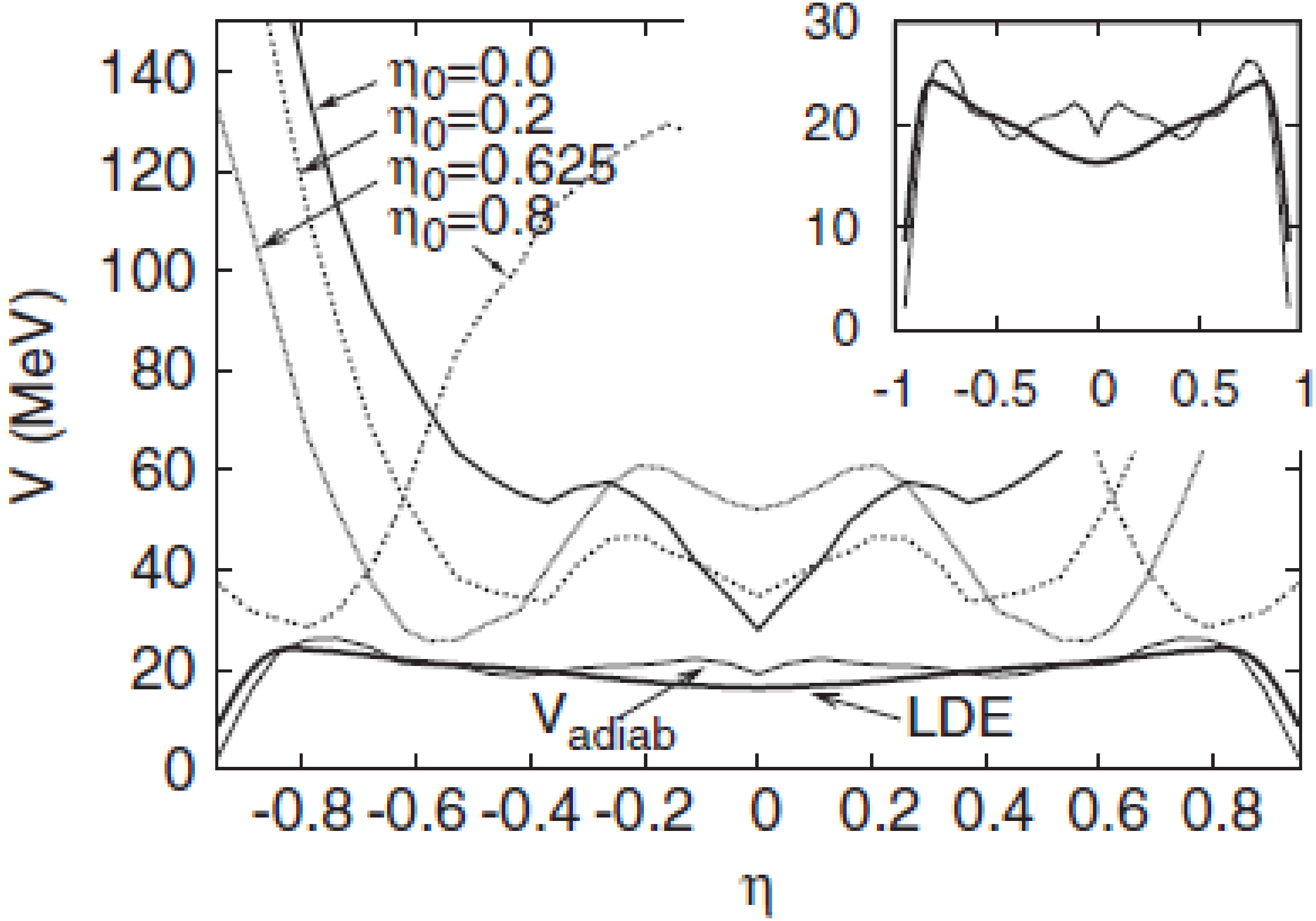
$$\Delta V_{diab}(q) \approx \sum_{\alpha} E_{\alpha}^{diab}(q)\,(n_{\alpha}^{diab} - n_{\alpha}^{adiab})$$

^{256}No ←



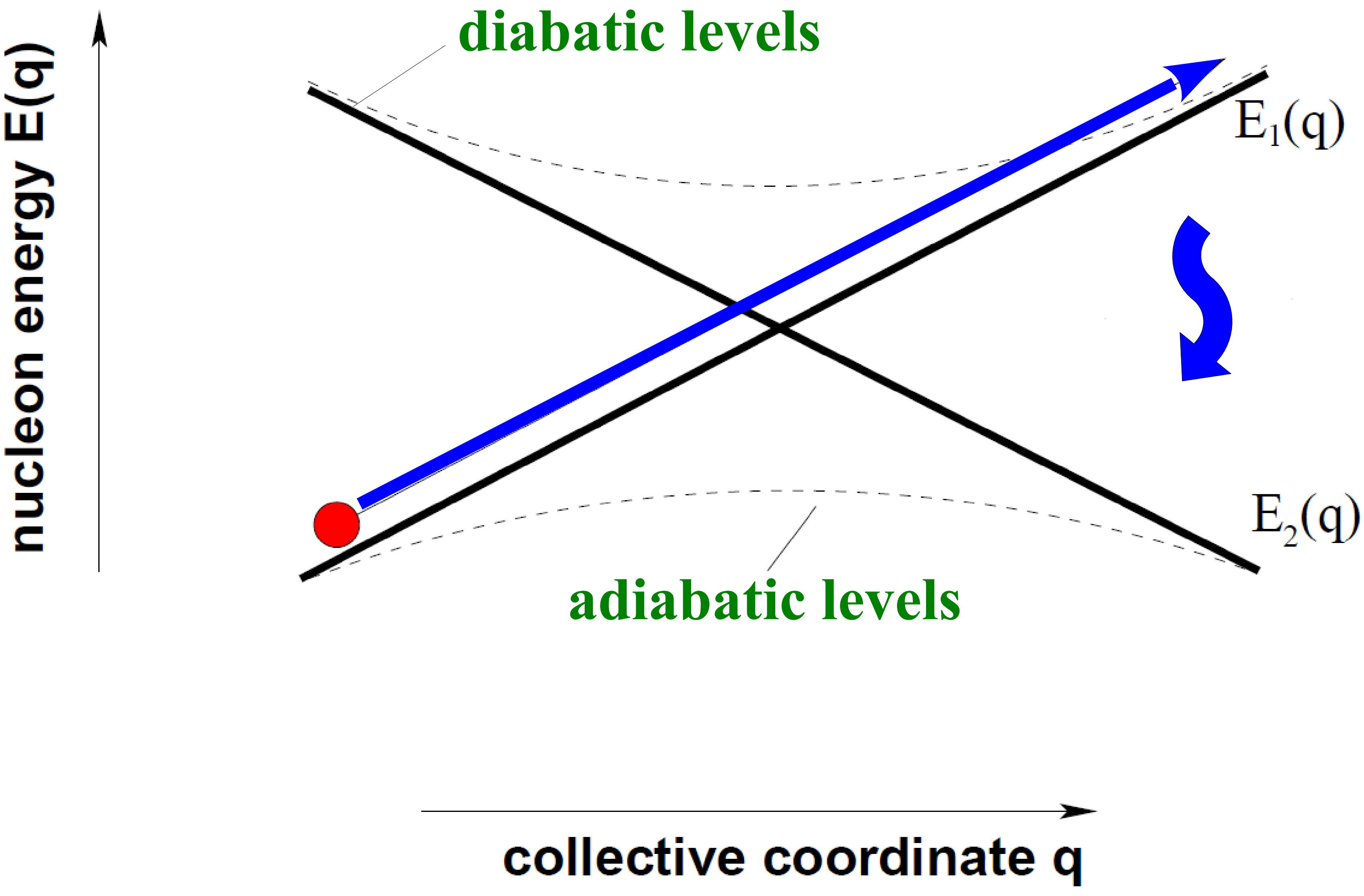
Driving Potential

AD-T, Phys. Rev. C **74** (2006) 064601

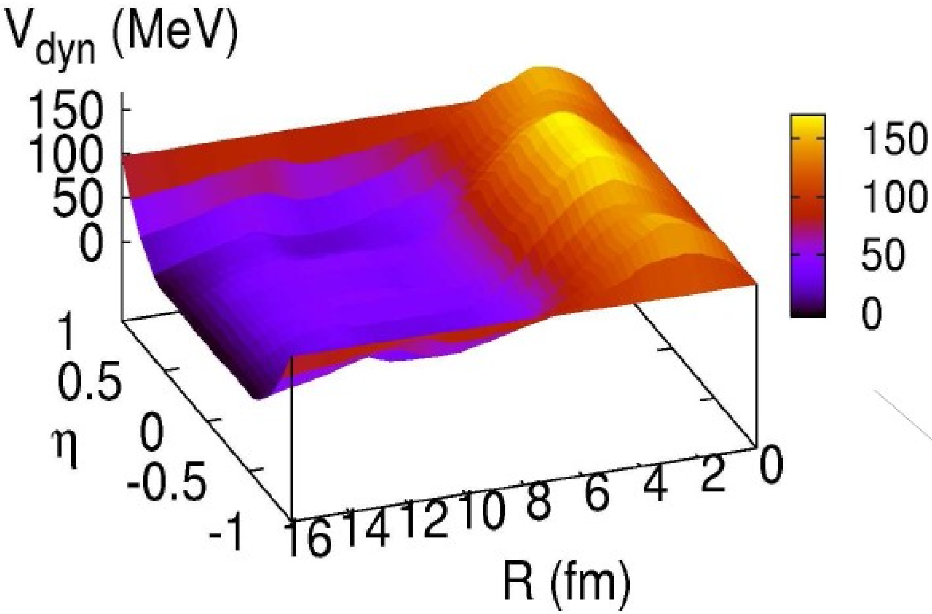


Diabatic Dissipative Dynamics

W. Noerenberg, Phys. Lett. B **104** (1981) 107

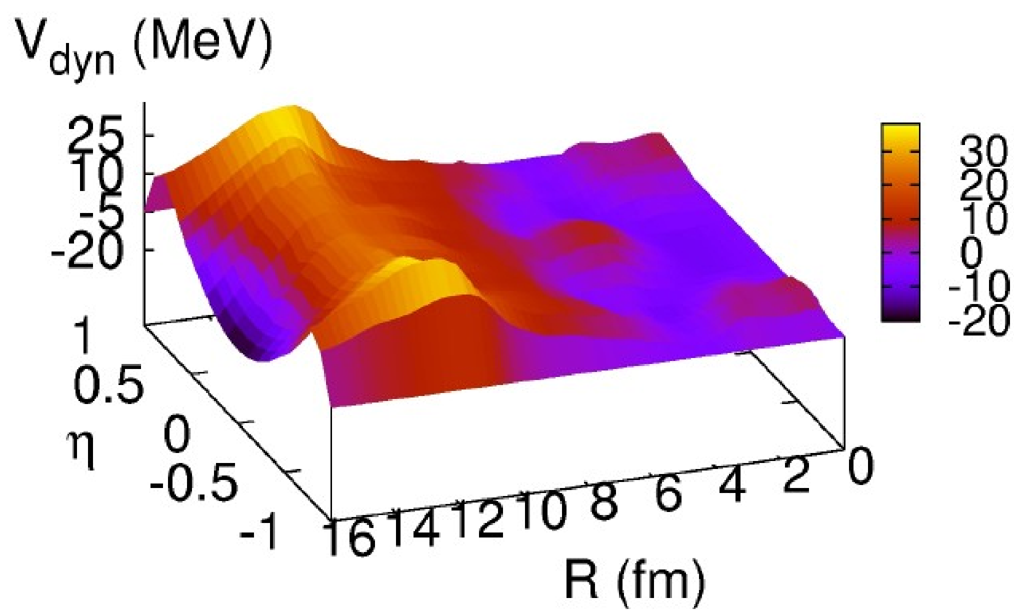


Time = 5×10^{-23} s



TIME

Time = 2×10^{-21} s



Dynamical Landscape !

Equations of Motion

$$\frac{dP_\nu(t)}{dt} = \sum_{\mu\neq\nu}[\Lambda_{\nu\mu}(t)P_\mu(t) - \Lambda_{\mu\nu}(t)P_\nu(t)], \tag{1}$$

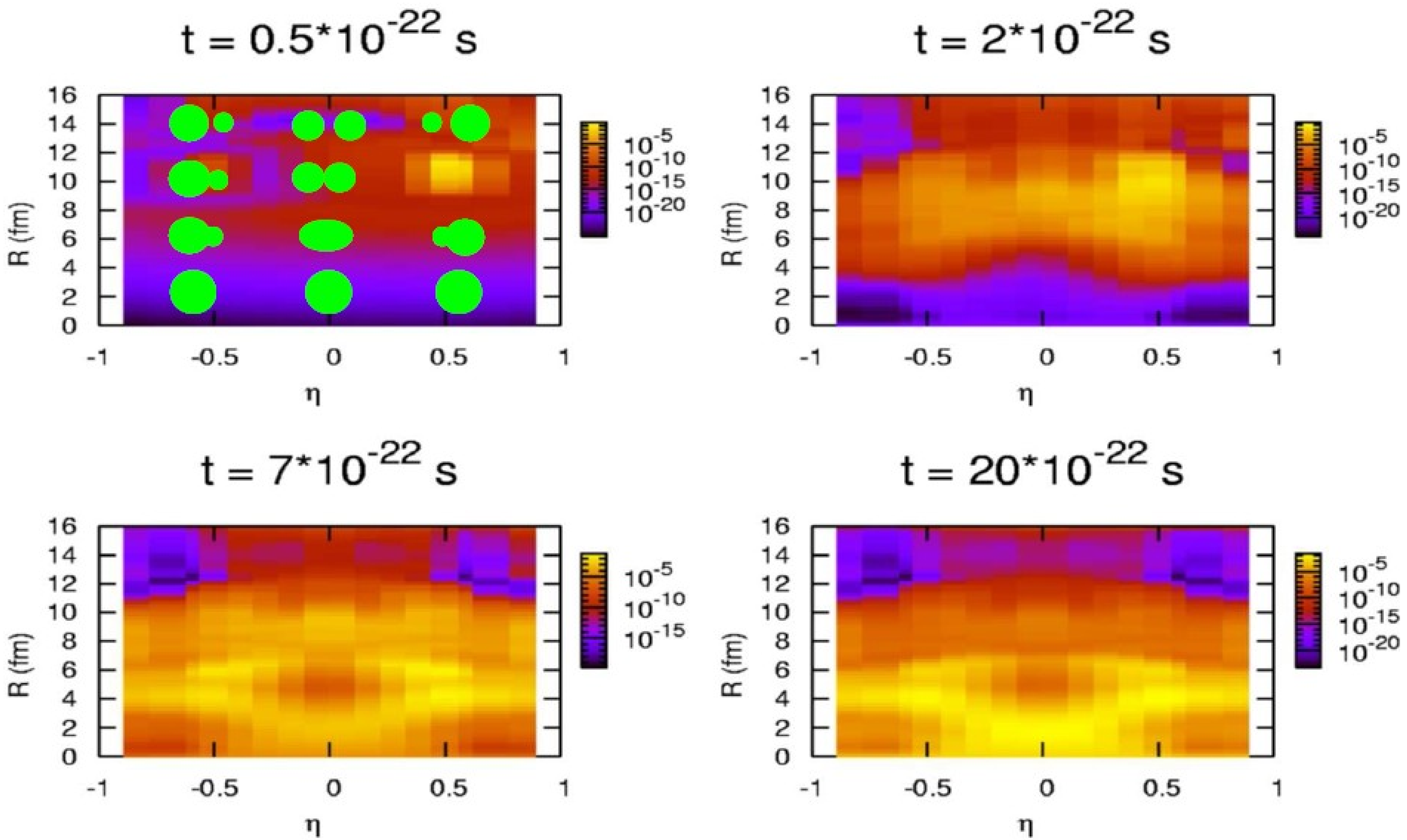
$$\Lambda_{\nu\mu}(t) = \lambda_0^{\nu\mu}(t)\exp[\sqrt{aE_\nu^*(t)} - \sqrt{aE_\mu^*(t)}], \tag{2}$$

$$\lambda_0^{\nu\mu}(t) \approx \kappa_0^{\nu\mu}(t)\exp\left\{-\frac{(\mathbf{q}_\mu - \mathbf{q}_\nu)^2}{\tilde{\sigma}_\nu^2}\right\}, \tag{3}$$

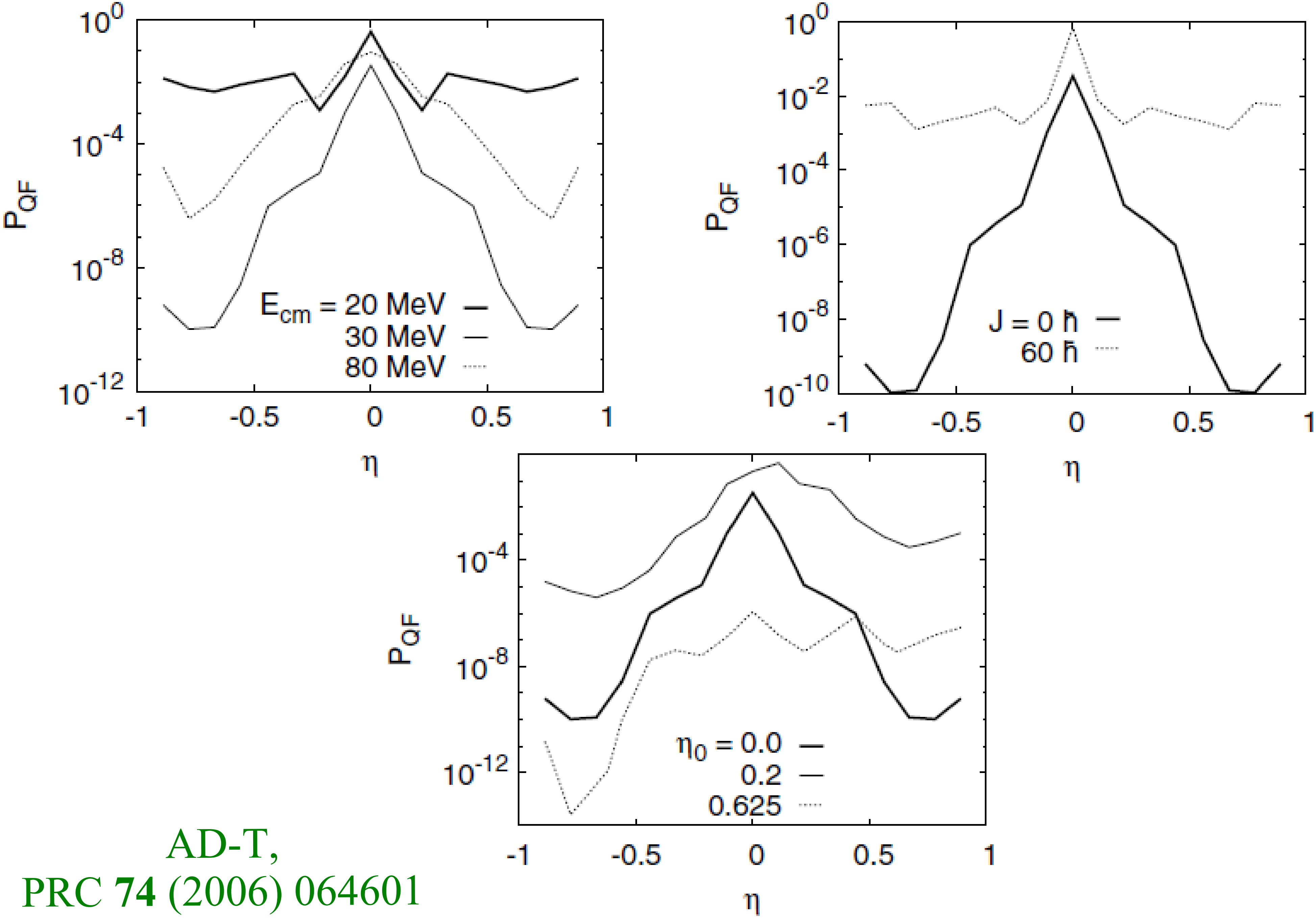
$$E_\nu^*(t) = \text{Maximum}\left[\epsilon_\nu^*(t),\, E_{\text{c.m.}} - \frac{\hbar^2 J(J+1)}{2\Theta_\nu} - V_{\text{dyn}}^\nu(t)\right], \tag{4}$$

$$V_{\text{dyn}}^\nu(t) = V_{\text{adiab}}^\nu[\epsilon_\nu^*(t)] + \Delta V_{\text{diab}}^\nu(t), \tag{5}$$

Probability distribution of the nuclear shapes:
$^{48}Ca + ^{208}Pb \longrightarrow ^{256}No$



Quasi-fission Mass Distributions



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PRC **74** (2006) 064601

Quantum Decoherence in Nuclear Collisions

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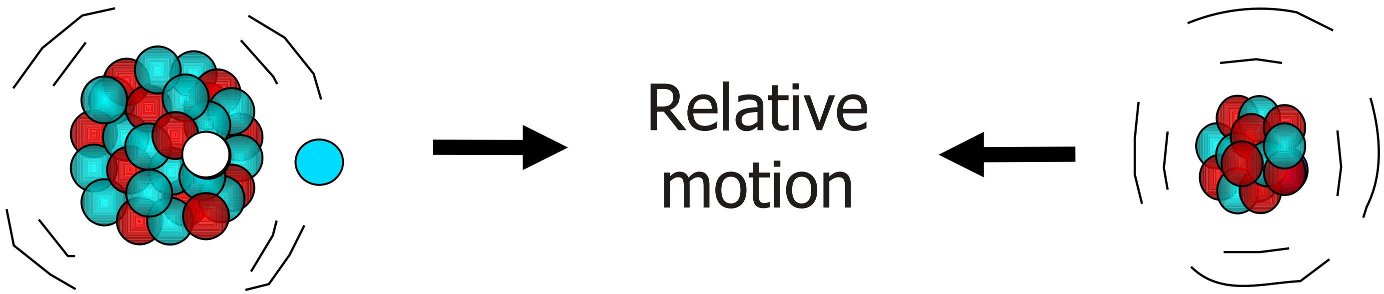
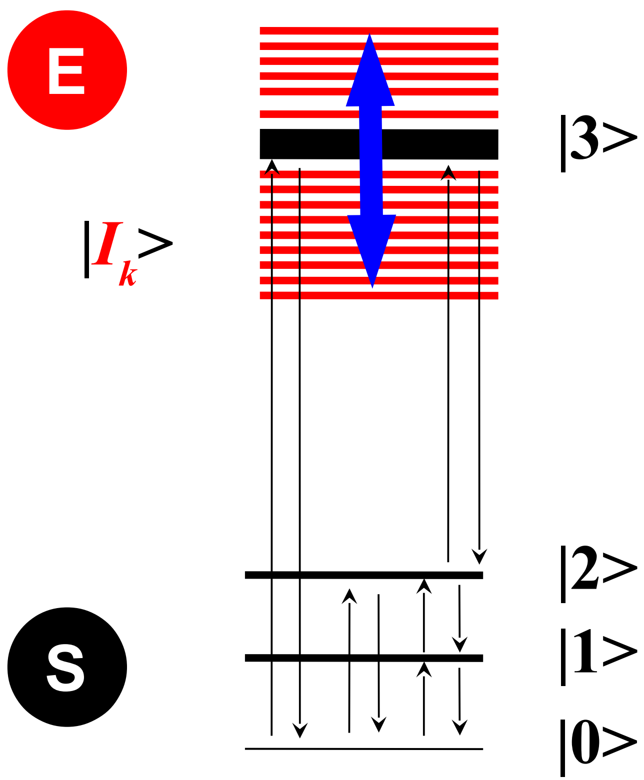
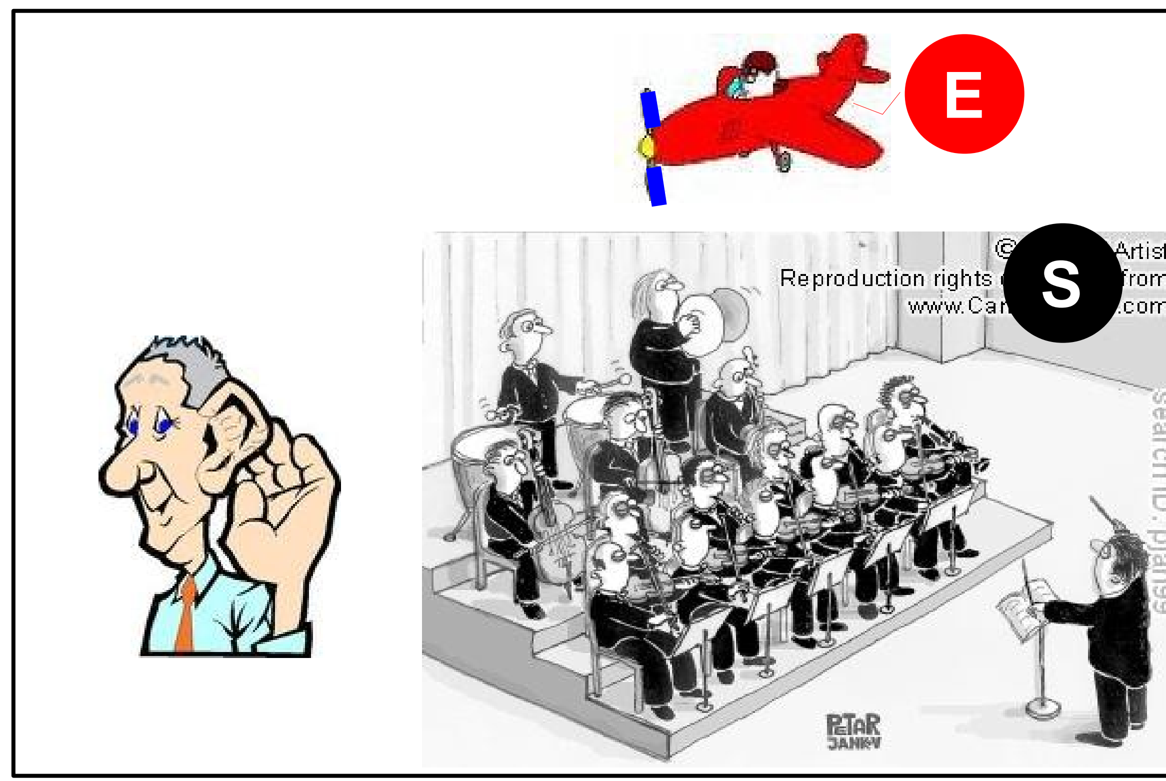




Intrinsic quantum states



Can decoherence & dissipation be quantified?

Coupled-Channels Density-Matrix Framework

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Hamiltonian Dynamics

$$i\hbar \frac{\partial \rho^{rs}_{\alpha\alpha'}}{\partial t} = \sum_t (T^{rt} \rho^{ts}_{\alpha\alpha'} - \rho^{rt}_{\alpha\alpha'} T^{ts})$$

$$+ [U_\alpha(r) - U_{\alpha'}(s)] \rho^{rs}_{\alpha\alpha'}$$

$$+ \sum_\beta [V_{\alpha\beta}(r) \rho^{rs}_{\beta\alpha'} - \rho^{rs}_{\alpha\beta} V_{\beta\alpha'}(s)]$$

$$+ (\varepsilon_\alpha - \varepsilon_{\alpha'}) \rho^{rs}_{\alpha\alpha'}$$

Decoherence & Dissipation

$$+ i\hbar \{ \delta_{\alpha\alpha'} \sum_\mu \sqrt{\Gamma^{rr}_{\alpha\mu}} \rho^{rs}_{\mu\mu} \sqrt{\Gamma^{ss}_{\alpha\mu}}$$

$$- \frac{1}{2} \sum_\mu (\Gamma^{rr}_{\mu\alpha} + \Gamma^{ss}_{\mu\alpha'}) \rho^{rs}_{\alpha\alpha'} \}$$

Expectation value of an observable: $< \hat{\mathcal{O}}(t) > = \mathrm{Tr}[\hat{\mathcal{O}} \, \hat{\rho}(t)]$

What do I expect as energy increases?

- There is **experimental** evidence of **elasto-plastic** behaviour.

  See e.g., M. Rhein *et al.*, Phys. Rev. Lett. **69** (1992) 1340

  ^{208}Pb + ^{208}Pb @ 12 MeV/nucleon

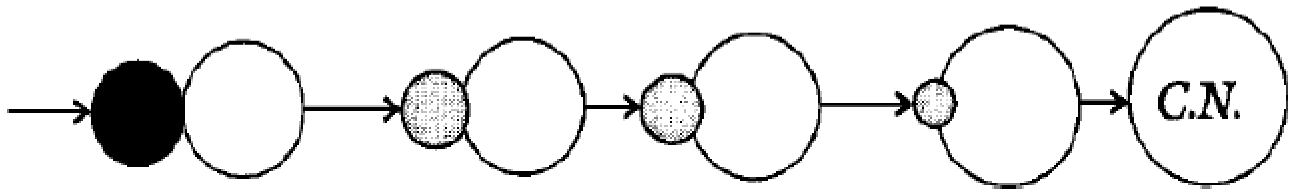
  δ-electron spectra → Fast stopping & Long contact times

- **Elasto-plasticity** seems **not** to be included in current models of collisions at **Fermi** energies.
  - DIT model [e.g., Tassan-Got & Stephan, NPA **524** (1991) 121]
  - DNS model [e.g., Adamian *et al.*, PRC **78** (2008) 024613]
  - CoMD model [e.g., Papa, Bonasera *et al.*, PRC **64** (2001) 024612]

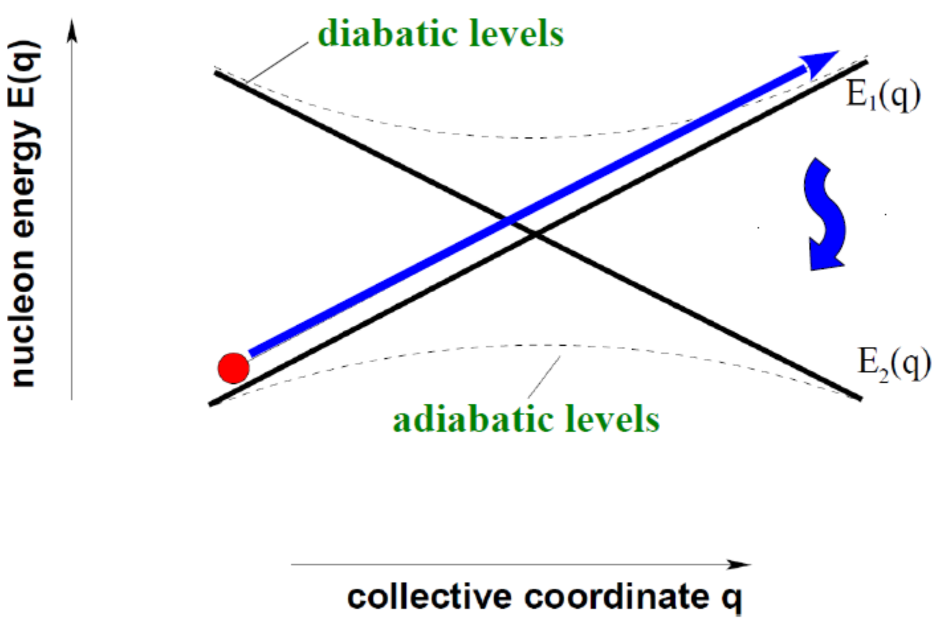
- **Elasto-plasticity** should be **important**.
  - Pre-equilibrium emission.
  - Interaction time *vs.* relaxation time of the dynamical potential.
  - Thermalization of reaction products by two-body collisions.

Summary

- The **diabatic picture** supports the dinuclear model for heavy-ion complete fusion in competition with quasi-fission at energies near the Coulomb barrier.



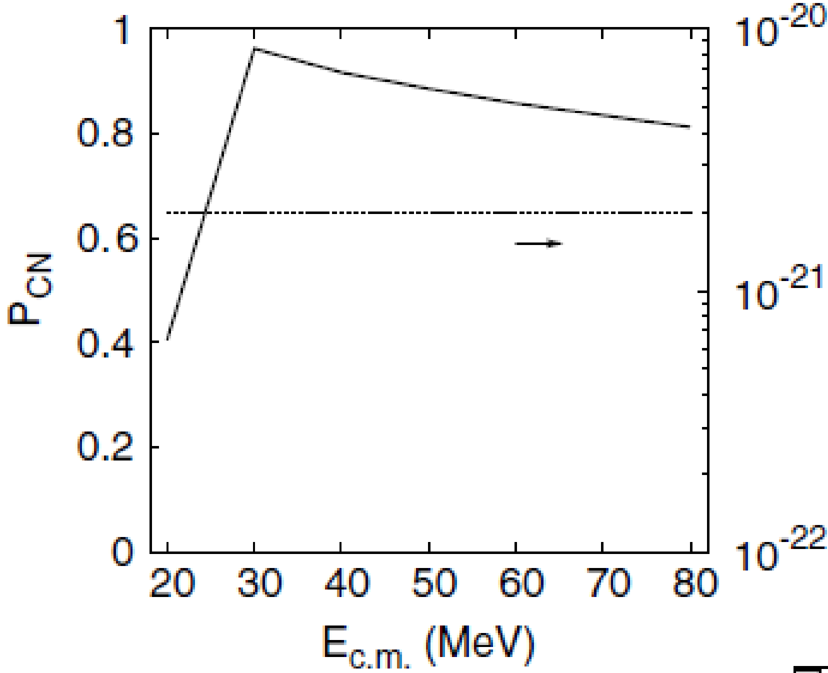
- **Elasto-plastic effects** on the **mass & charge distributions** of the reaction products should be important as energy increases from **Coulomb** to **Fermi energies**.

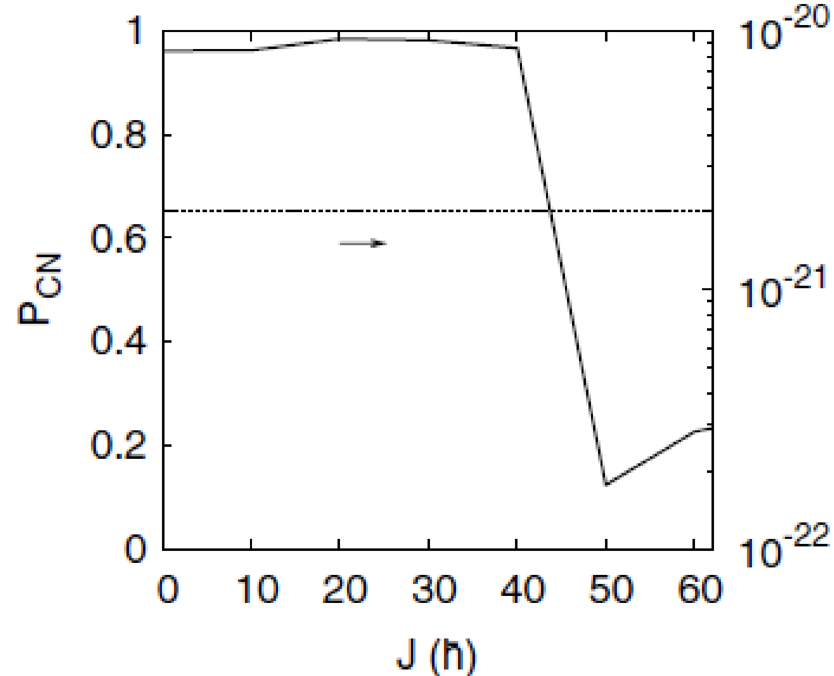


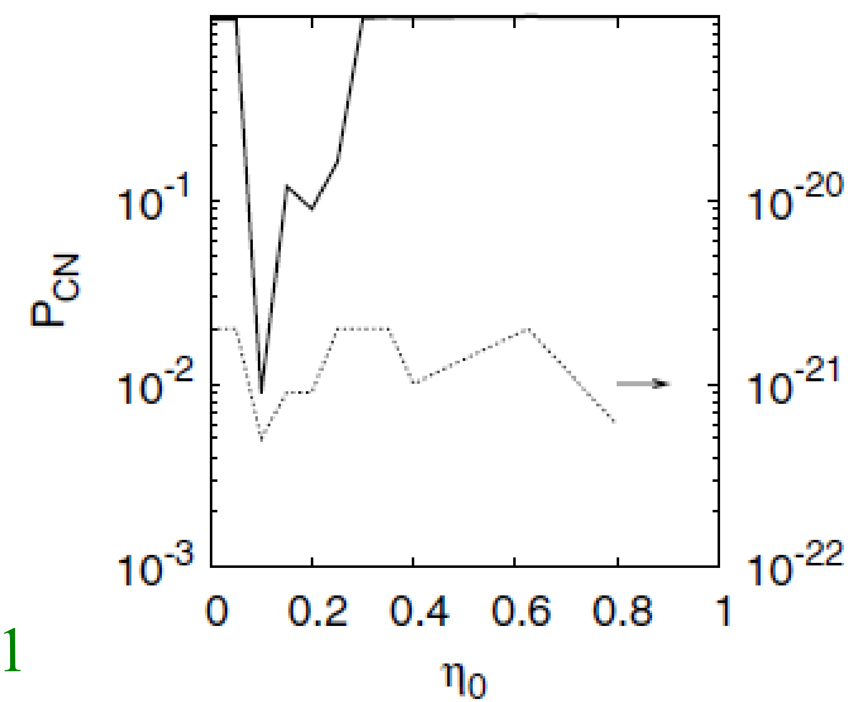
How does elasto-plasticity impact on observables?

EXTRA SLIDES

Probability of Compound-Nucleus Formation







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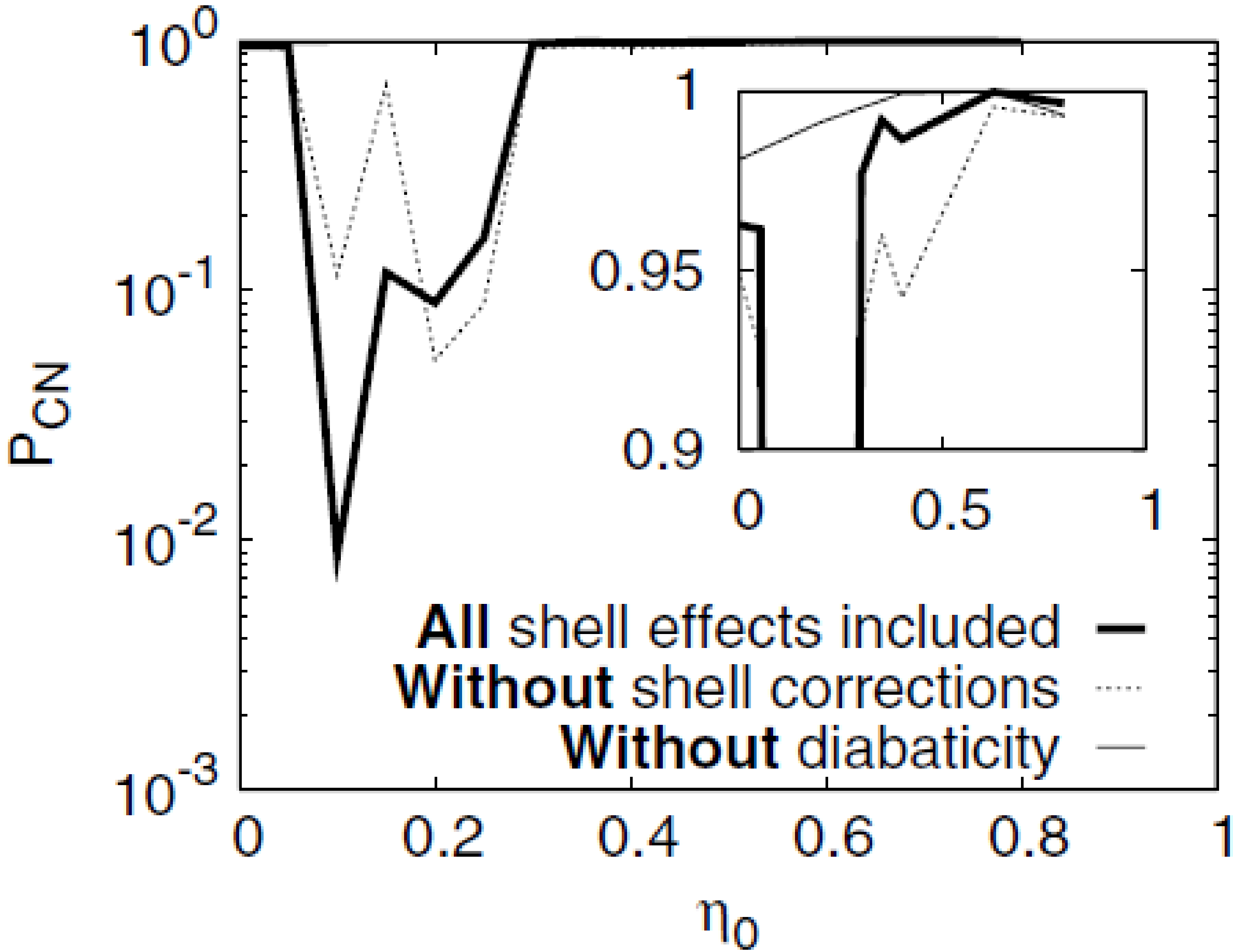
PRC **74** (2006) 064601

Probability of Compound-Nucleus Formation



Initial Density Matrix

$$\hat{\rho}^{rs}_{\alpha\alpha'}(0) = \underbrace{< \alpha|\hat{\sigma}(0)|\alpha' >}_{\text{Internal states}} \otimes \underbrace{g^*(z_r)\, g(z_s)}_{\text{Radial motion}}$$

$$\hat{\sigma}(0) = \sum_i w_i\, |i >< i|$$

$$w_i = \delta_{ij}$$ **Pure state**

$$w_i = \frac{e^{(-\frac{E_i}{k_B T})}}{\mathrm{Tr}[e^{(-\frac{\hat{H}_0}{k_B T})}]}$$ **Mixed state**