16th ASRC International Workshop:
Nuclear Fission and Structure of Exotic Nuclei

JAEA, Tokai, Japan, 18–20 March 2014

Nuclear One-Body Dissipation: Implications for damped reactions and fission

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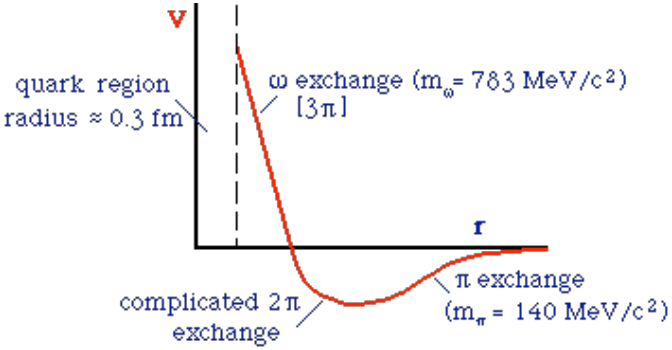
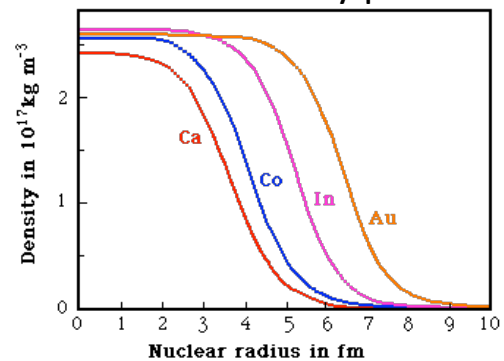
Basic features of nuclei

NN interaction

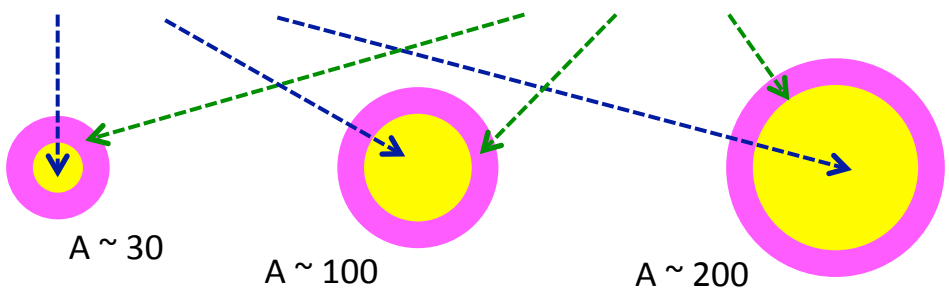


Nuclear density profile



Same bulk density

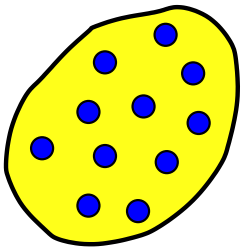
Same surface thickness



Nuclei matter saturates: $R \sim A^{1/3}$

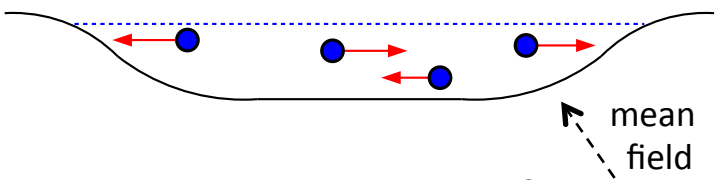
Heavy nuclei are leptodermous

Nuclear dynamics at moderate excitations



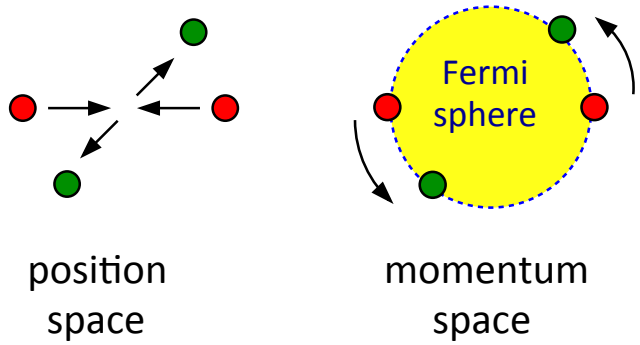
Individual nucleons move in common one-body field while occasionally experiencing Pauli-suppressed binary collisions

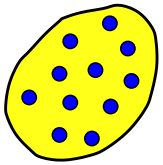
One-body motion dominates: h



One-body Hamiltonian: $$h[f](r,p) = \frac{p^2}{2m} + U[\rho](r)$$

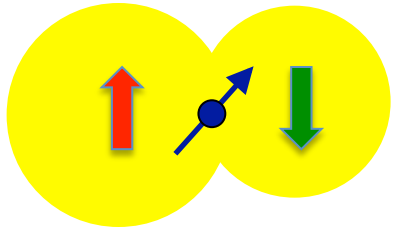
Two-body collisions are Pauli suppressed: $\lambda \approx R$





Implications for the dynamics of a dinucleus: Nucleon exchange in damped reactions *)

Window dissipation



STRONG!
≈T-indep.

Fermi speed

$$Q \sim V_{AB} v_F \mathcal{N}$$

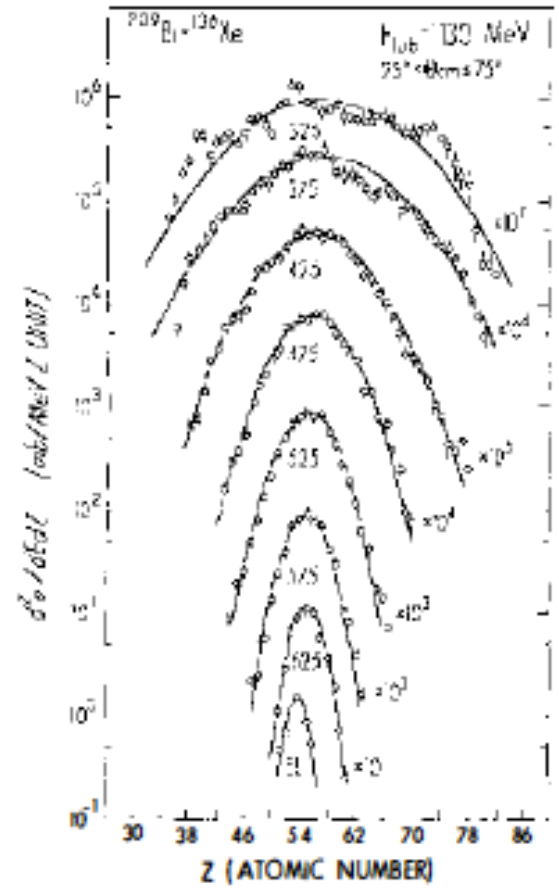
Dissipated energy

Nucleons exchanged

$$Q = -\Delta E_{\rm rel} \qquad \mathcal{N} = \sigma_A^2$$

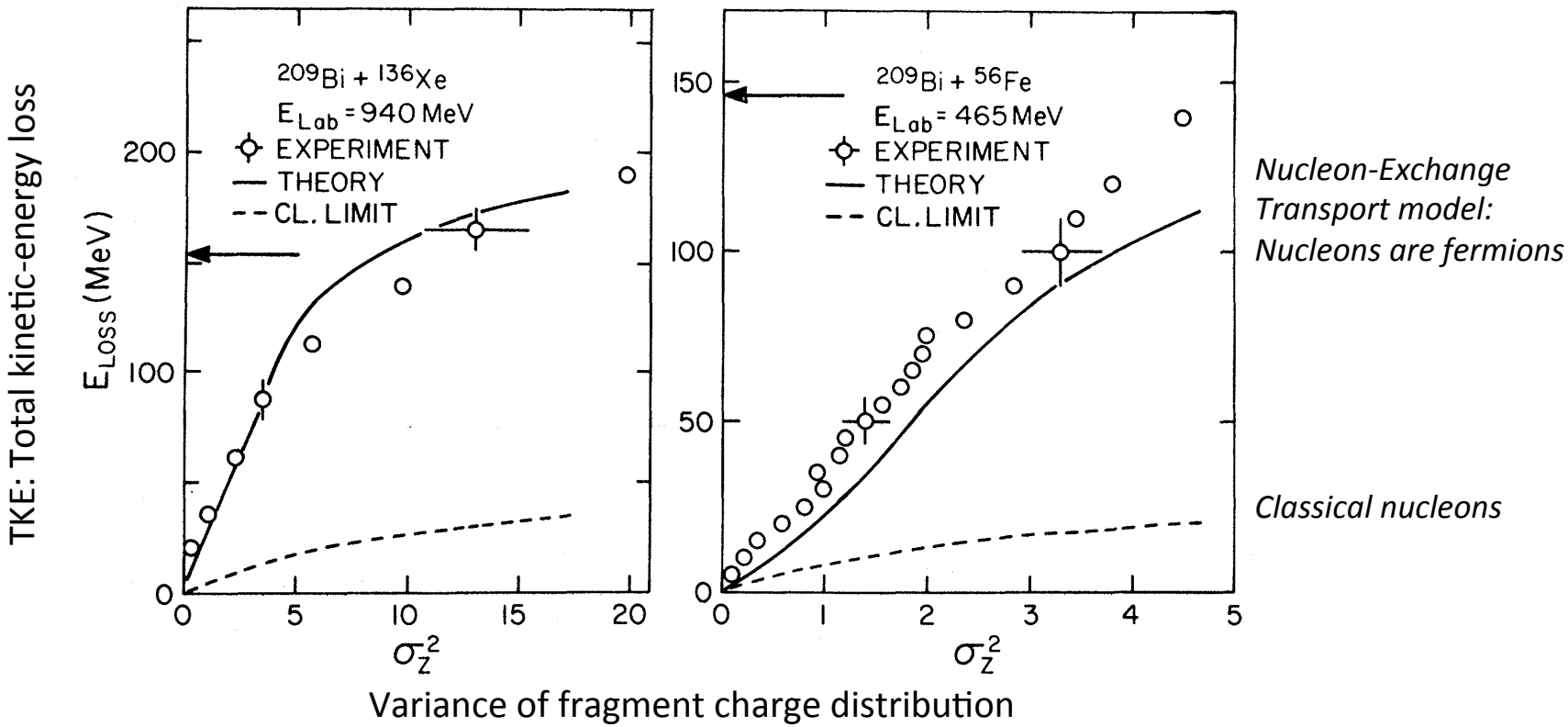
J. Randrup, Nucl. Phys. A307 (1978) 319; A327 (1979) 490

*) $E_{\rm beam} \approx 10$ MeV/A: Suitable for HI @ J-PARC



W.U. Schröder and J.R. Huizenga, Ann. Rev. Nucl. Sci. 27, 465 (1977)

Comparison of the *Nucleon-Exchange Transport model* with experimental data

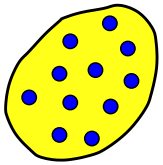


W.U. Schröder, J.R. Birkelund, J.R. Huizenga, W.W. Wilcke, J. Randrup, PRL 44 (1980) 308

Nucleon-Exchange Transport
can account quantitatively for many aspects
of damped nuclear reactions:

- Evolution of the correlated mass and charge distribution: $P(N,Z)$
- Evolution of angular momentum in the dinuclear complex: $P(\boldsymbol{S}_A,\boldsymbol{S}_B)$
- Evolution of the fragment excitations (equal E^* -> equal T): $P(T_A,T_B)$

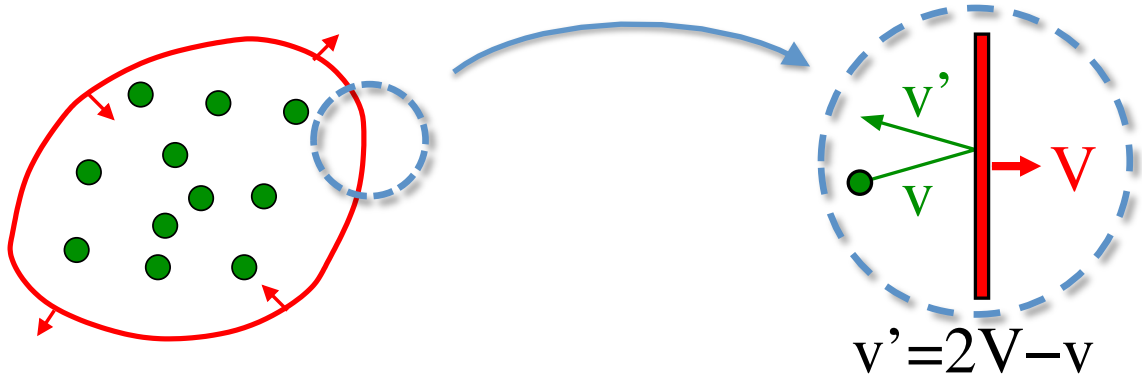
… without the introduction of any adjustable parameters!



Implications for the dynamics of a mononucleus: Wall formula for the dissipation rate

Saturation => incompressible => shape dynamics

Leptodermous => dissipation occurs at the surface



Wall dissipation

Slowly deforming nucleus

~ Fermi speed

Wall formula

Energy dissipation rate: $\dot{Q} = \rho\bar{v} \oint V^2 d\sigma$

STRONG!
≈T-indep.

J. Blocki, Y. Boneh, J. R. Nix, J. Randrup, M. Robel, A. J. Sierk, and W. J. Swiatecki, Ann Phys **113** (1978) 330: *One-Body Dissipation and the Super-Viscidity of Nuclei*

Fission dynamics with various types of dissipation

J. Blocki, Y. Boneh, J. R. Nix, J. Randrup, M. Robel, A. J. Sierk, and W. J. Swiatecki, Ann Phys **113** (1978) 330: *One-Body Dissipation and the Super-Viscidity of Nuclei*

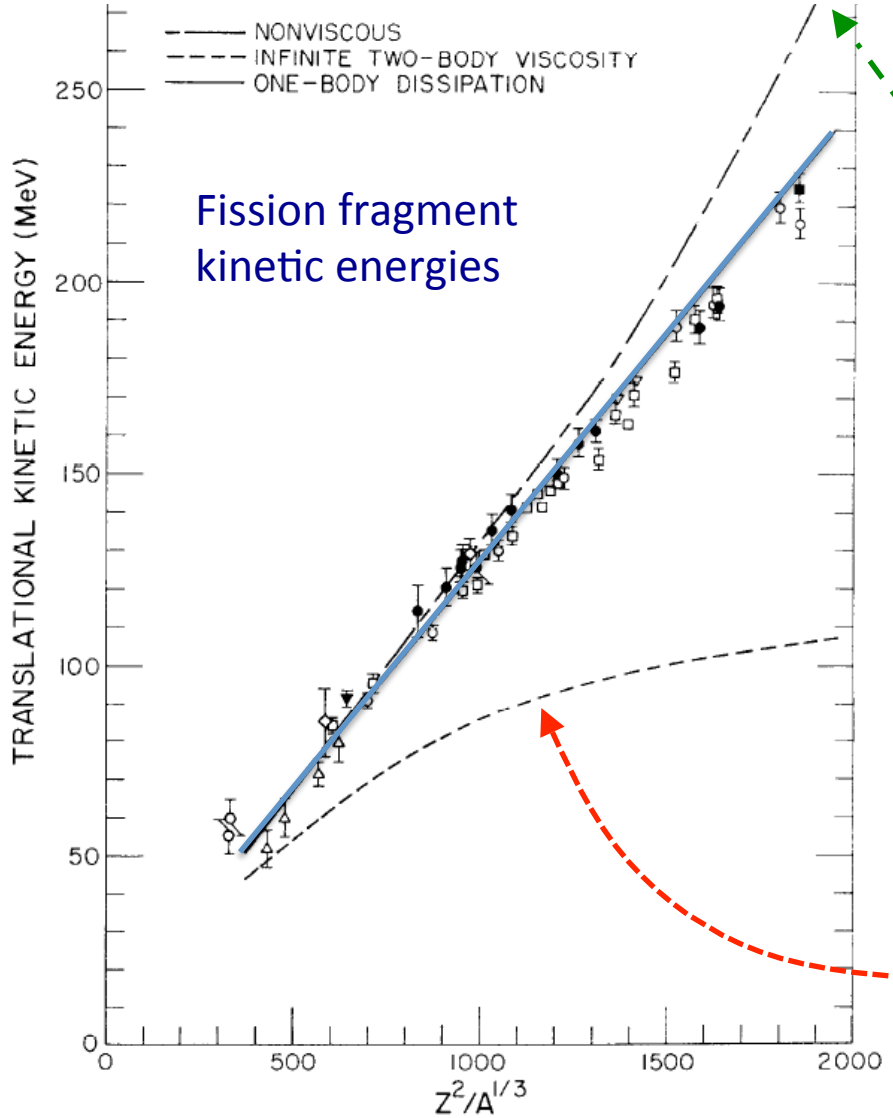
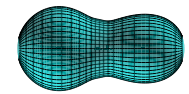
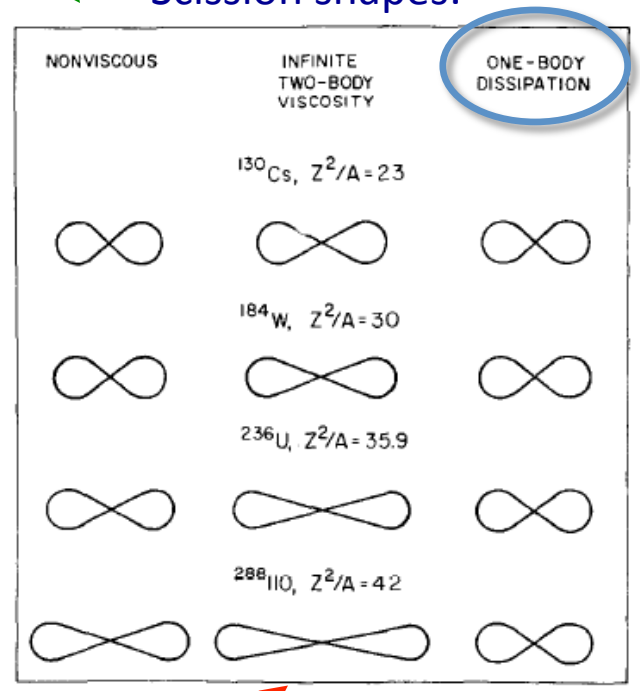
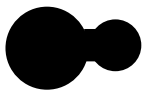


FIG. 6. Comparison of calculated and experimental most probable fission-fragment kinetic energies as a function of $Z^2/A^{1/3}$. The kinetic energies calculated for nonviscous flow are given by the dot–dashed curve. The dashed curve shows the results for infinite two-body viscosity, and the solid curve shows the results for the one-body dissipation considered here. The experimental data are for cases in which the most probable mass division is into two equal fragments; the open symbols represent values for equal mass divisions only and the solid symbols represent values averaged over all mass divisions. The original sources for the experimental data are given in [18].



Scission shapes:





Langevin shape dynamics

Shape family:  $\boldsymbol{\chi} = \{\chi_i\}$

Potential energy: $U(\boldsymbol{\chi}) = U(\{\chi_i\})$

Inertial mass tensor: $\boldsymbol{M}(\boldsymbol{\chi}) = \{M_{ij}(\{\chi_k\})\}$

Dissipation tensor: $\boldsymbol{\gamma}(\boldsymbol{\chi}) = \{\gamma_{ij}(\{\chi_k\})\}$

Driving force: $F_i^{\rm pot}(\boldsymbol{\chi}) = -\partial U(\boldsymbol{\chi})/\partial\chi_i$

Kinetic energy: $K(\boldsymbol{\chi},\dot{\boldsymbol{\chi}}) = \frac{1}{2}\sum_{ij} M_{ij}(\boldsymbol{\chi})\dot{\chi}_i\dot{\chi}_j$

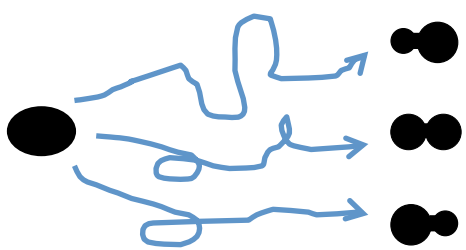
Friction force: $F_i^{\rm fric}(\boldsymbol{\chi}) = -\sum_{ij}\gamma_{ij}(\boldsymbol{\chi})\dot{\chi}_j$

Lagrangian function: $\mathcal{L}(\boldsymbol{\chi},\dot{\boldsymbol{\chi}}) \equiv K(\boldsymbol{\chi},\dot{\boldsymbol{\chi}}) - U(\boldsymbol{\chi})$

Rayleigh function: $\mathcal{F}(\boldsymbol{\chi},\dot{\boldsymbol{\chi}}) = \frac{1}{2}\sum_{ij}\gamma_{ij}(\boldsymbol{\chi})\dot{\chi}_i\dot{\chi}_j$

=> *Langevin equation of motion:*

$$\frac{d}{dt}\frac{\partial\mathcal{L}}{\partial\dot{\chi}_i} = \frac{\partial\mathcal{L}}{\partial\chi_i} - \frac{\partial\mathcal{F}}{\partial\dot{\chi}_i} + \Gamma_i$$



dissipation => fluctuation

Strongly damped nuclear shape dynamics => Metropolis walk

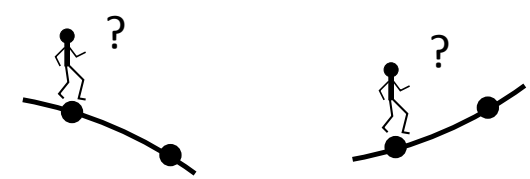
Dissipation is *strong* => Creeping evolution => Acceleration and (velocity)^2 are small => The inertial mass ***M*** is unimportant

If the inertial mass is unimportant then the Langevin equation simplifies to the Smoluchowski equation:

$$\cancel{\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\chi}_i}} = \frac{\partial \mathcal{L}}{\partial \chi_i} - \frac{\partial \mathcal{F}}{\partial \dot{\chi}_i} + \Gamma_i$$

Dissipation is *strong* => Large degree of equilibration => Little sensitivity to the structure of the dissipation tensor γ

If the dissipation tensor is isotropic then a Metropolis random walk on the potential-energy lattice provides an exact simulation of the Smoluchowski shape evolution:

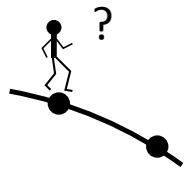


$P_{down} = 1$ $P_{up} = \exp(-\Delta U/T)$

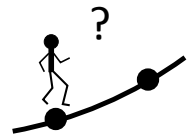
Metropolis *et al.* (1953):

Metropolis walk …

Metropolis *et al.* (1953):



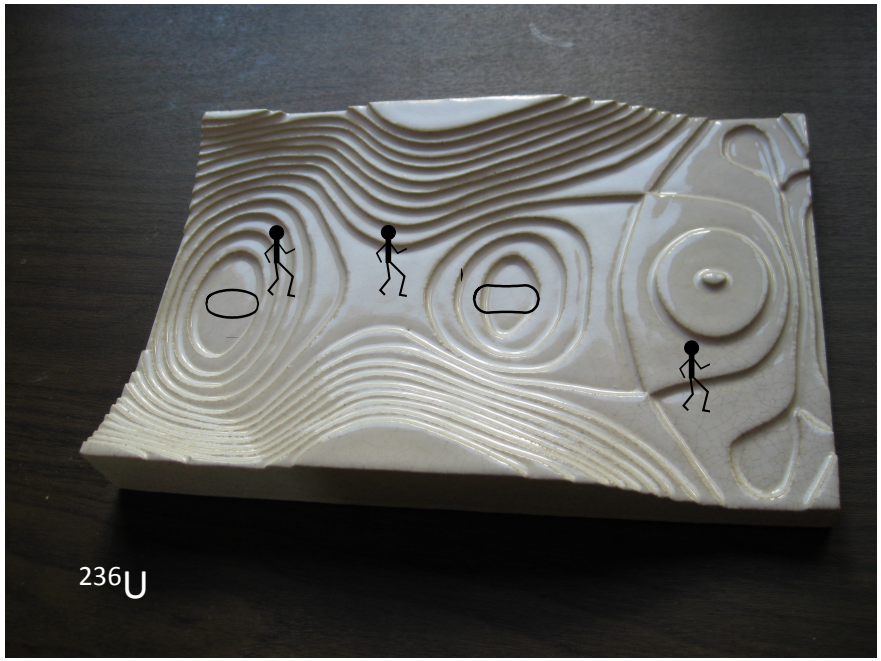
$P_{down} = 1$



$P_{up} = \exp(-\Delta U/T)$

… on the potential-energy surface:

Start at ground-state (or isomeric) minimum



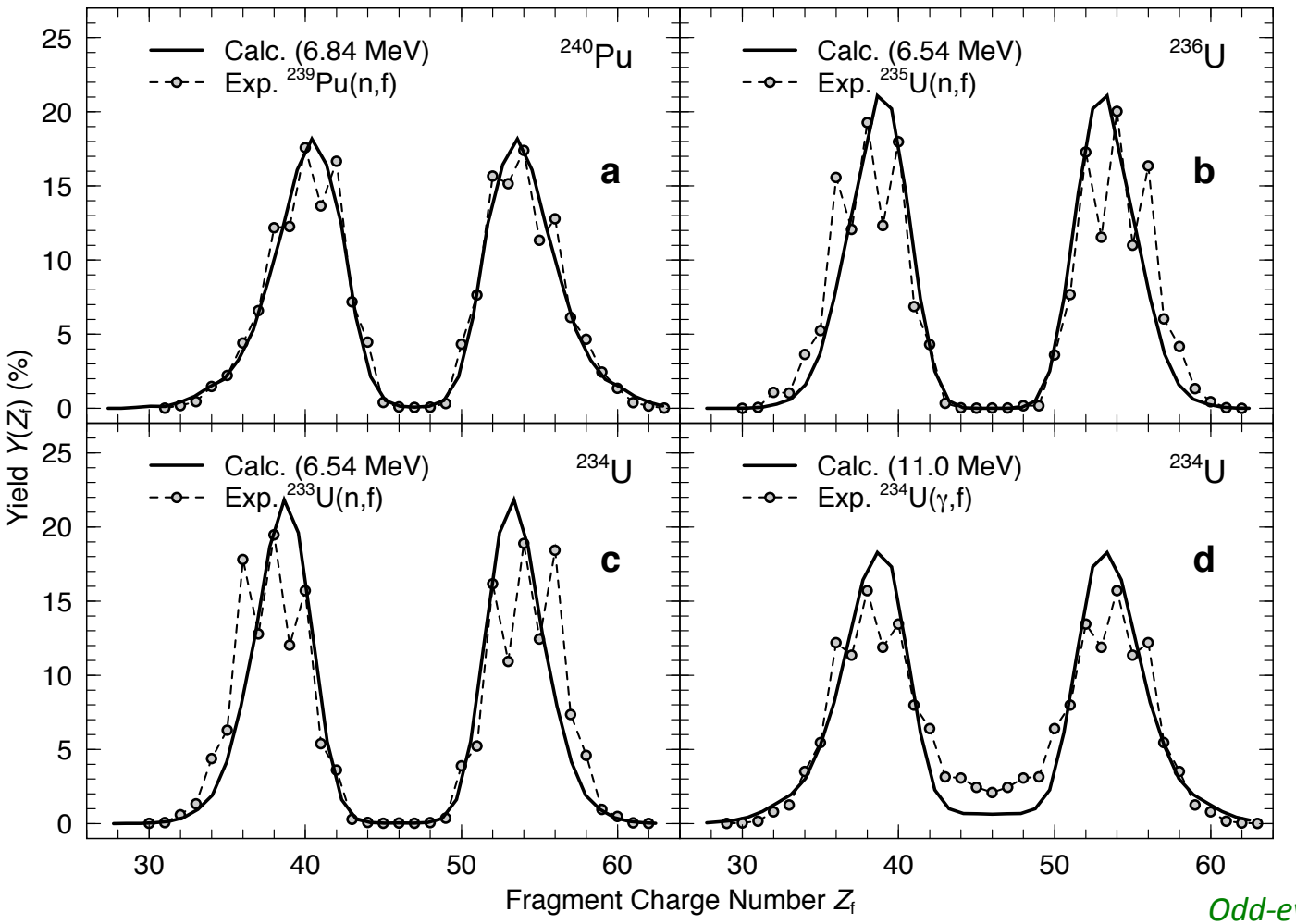
Elongation

Asymmetry

Walk until the neck has become narrow

$P(A_f)$ *from* $^{240}Pu^*$ *and* $^{236,234}U^*$

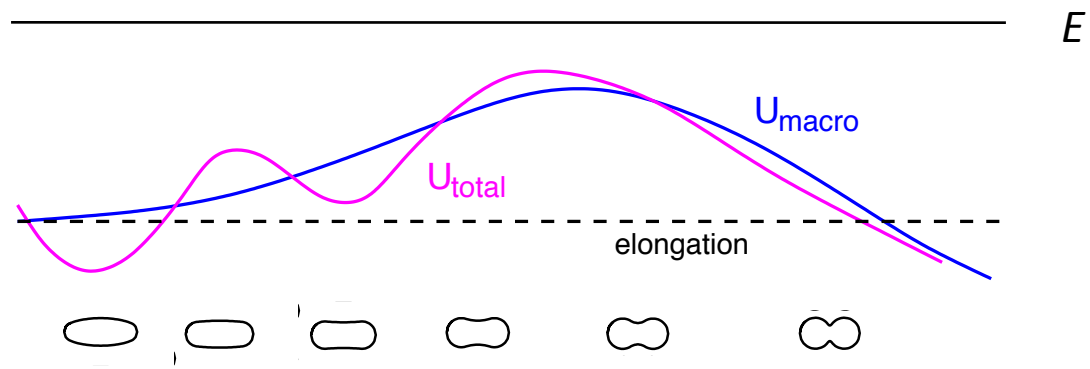
5D Metropolis walks



J. Randrup & P. Möller, PRL 106 (2011) 132503

Odd-even effects:
Talk by Peter Möller

Potential energy: Macroscopic-microscopic method



*E**-dependent suppression

$$U(Z,N,\text{shape}) = U_{\text{macro}}(Z,N,\text{shape}) + U_{\text{micro}}(Z,N,\text{shape}) \times S(E^*)$$

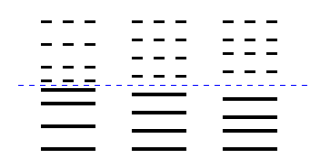
Finite-range liquid drop:

$$E_{\text{macro}}(Z,N,\chi) = -a_{\text{vol}}(1-\kappa_{\text{vol}}I^2)A - a_{\text{surf}}(1-\kappa_{\text{surf}}I^2)B_1A^{2/3} + c_1\frac{Z^2}{A^{1/3}}B_3 + \ldots$$

Shell & pairing:

$$E_{\text{micro}}(Z,N,\chi) = E_{\text{shell}}(Z,N,\chi) + E_{\text{pair}}(Z,N,\chi)$$

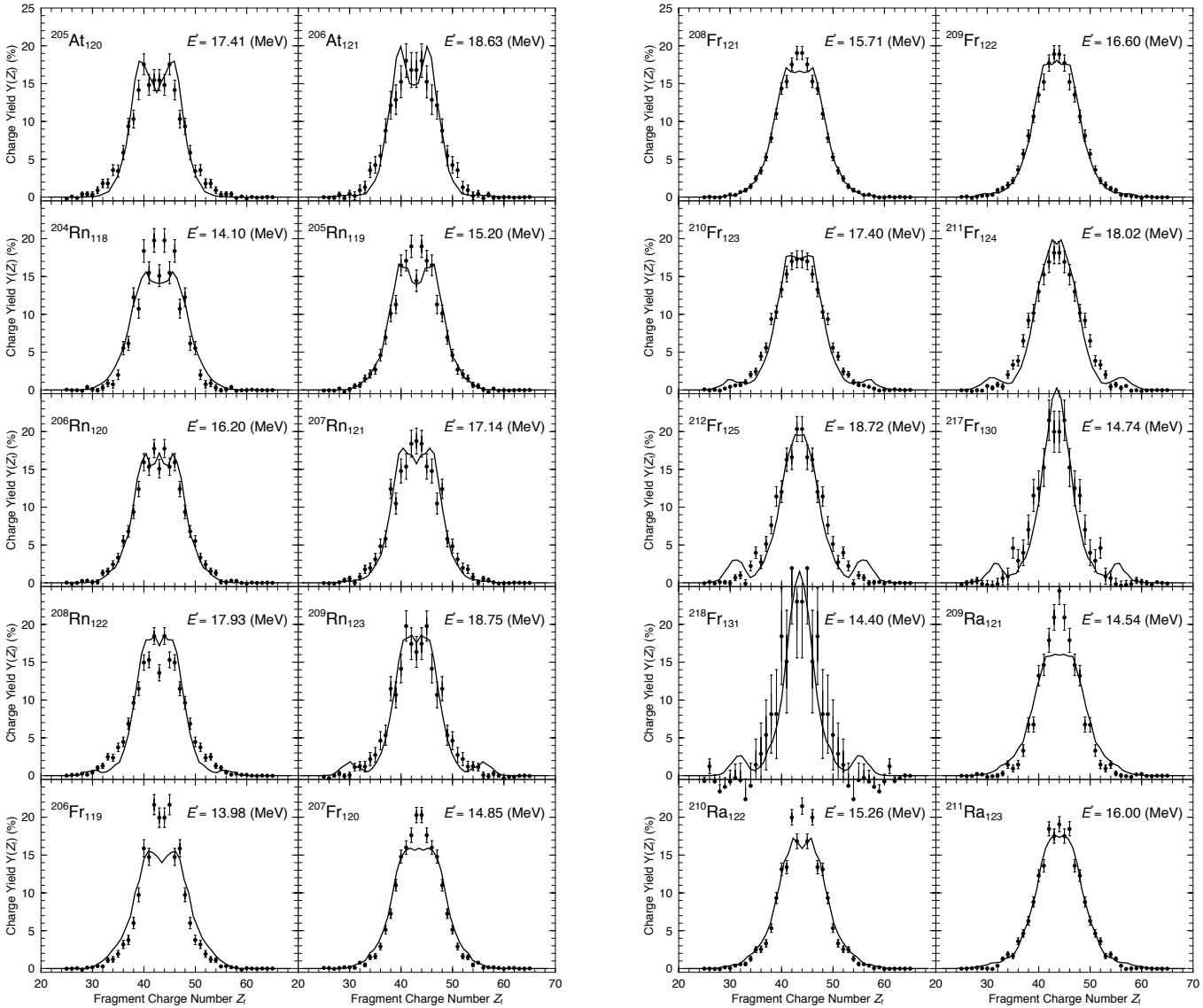
Strutinsky *BCS*



Single-particle levels in the effective field

$P(Z_f)$ for isotopes at E^*=11 MeV

Comparison with data from K.H. Schmidt *et al.*, NPA 665 (2000) 221



J. Randrup & P. Möller, Phys. Rev. C **88**, 064606 (2013)

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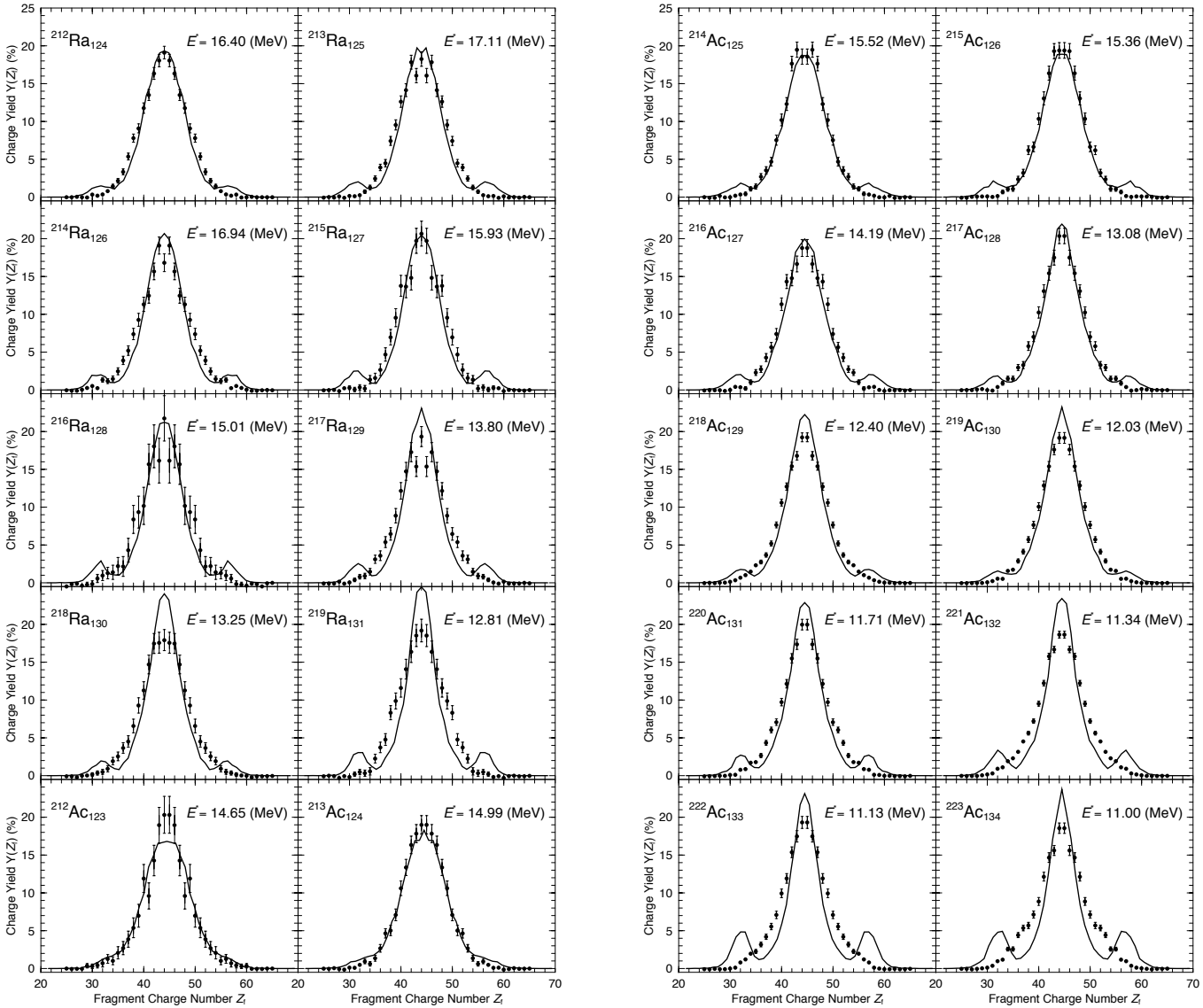

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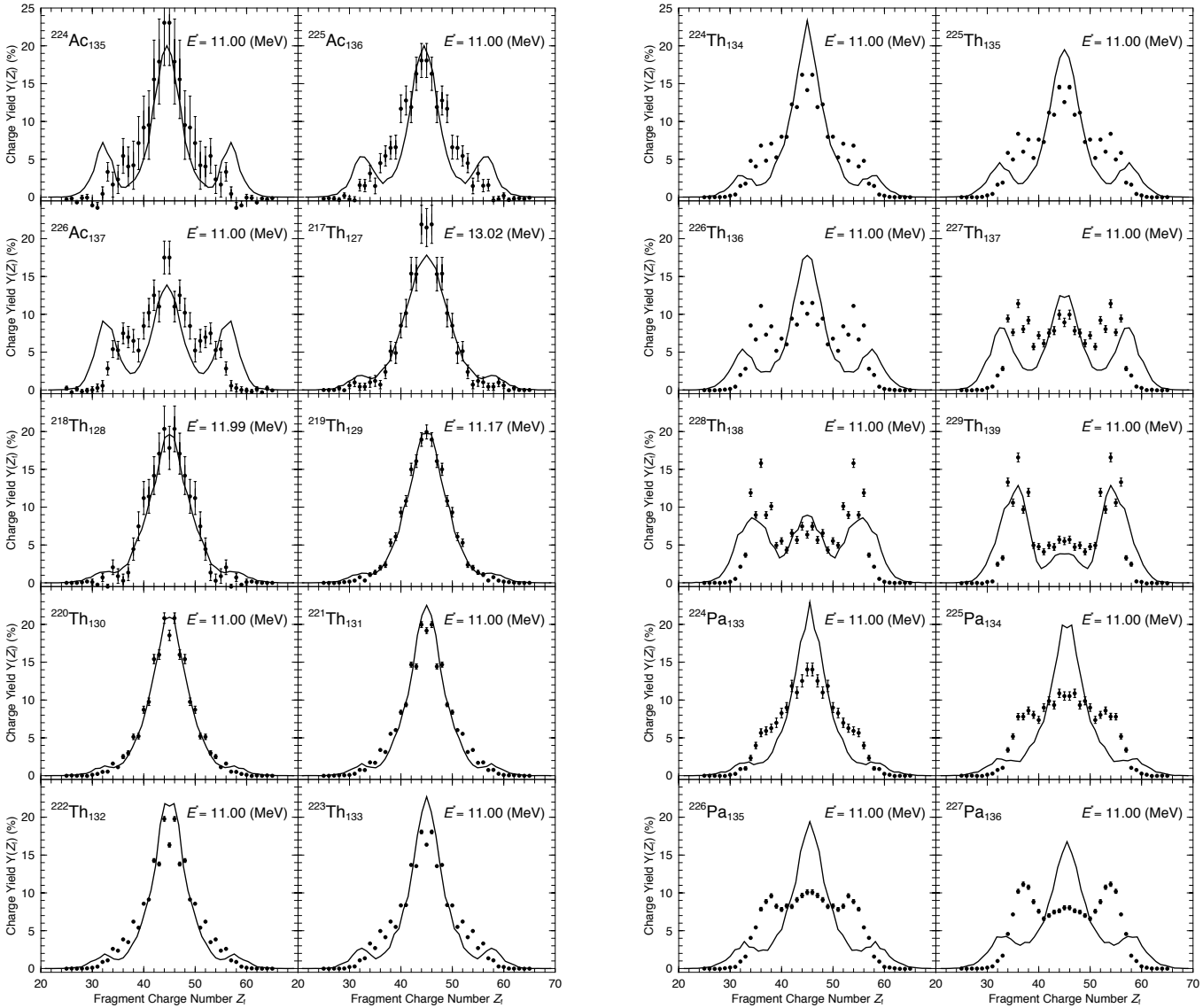

J. Randrup & P. Möller, Phys. Rev. C **88**, 064606 (2013)

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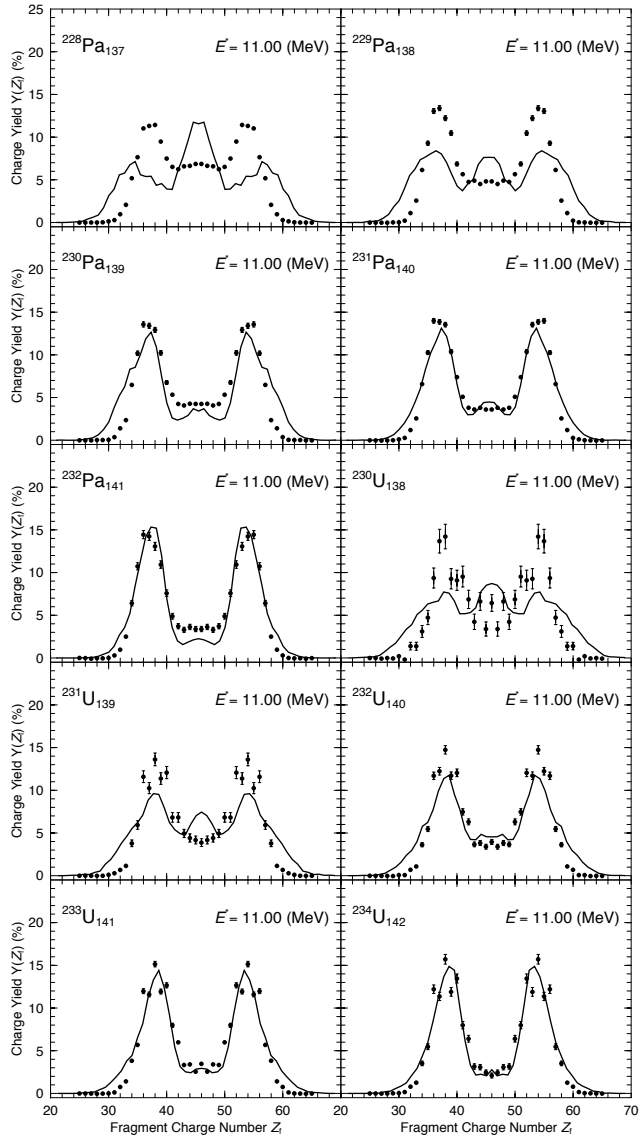
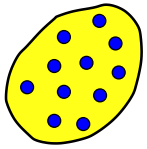


J. Randrup & P. Möller, Phys. Rev. C **88**, 064606 (2013)

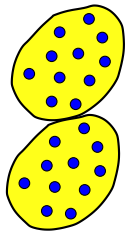
Summary



Mononucleus:
WALL

One-body dissipation:

General mechanism in low-energy nuclear dynamics that dominates in both *damped reactions* and *fission*



Dinucleus:
WINDOW

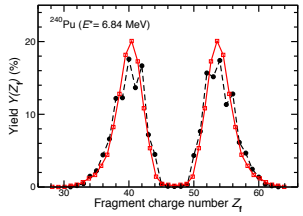
Nuclear fission dynamics:

Formal framework: Langevin shape dynamics — $U(\chi)$, $\mathbf{M}(\chi)$, $\gamma(\chi)$

Strong dissipation: Brownian shape evolution — $U(\chi)$, $\gamma(\chi)$

Quick relaxation: Metropolis walk on U lattice — $U(I,J,K,L,M)$

While convenient, very fast, and remarkably successful, the Metropolis walk method is *not* always satisfactory, nor could it provide time scales or kinetic energies: the *complete Langevin treatment* is highly desired*)



Developments towards this goal are well underway by Arnie Sierk (LANL) … and by JR

Stay tuned!

*) Has long been used successfully in the macroscopic limit