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

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Basic features of nuclei

**NN interaction**
- Quark region radius \( \approx 0.3 \text{ fm} \)
- \( \omega \) exchange \( (m_\omega = 783 \text{ MeV}/c^2) \)
- Complicated \( 2\pi \) exchange
- \( \pi \) exchange \( (m_\pi = 140 \text{ MeV}/c^2) \)

**Nuclear density profile**

Same bulk density
- \( A \sim 30 \)
- \( A \sim 100 \)
- \( A \sim 200 \)

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: $\lambda \approx R$

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

\[ Q = -\Delta E_{\text{rel}} \]
\[ \mathcal{N} = \sigma_A^2 \]


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

Comparison of the
Nucleon-Exchange Transport model
with experimental data

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

1. Evolution of the correlated mass and charge distribution: \( P(N,Z) \)
2. Evolution of angular momentum in the dinuclear complex: \( P(S_A, S_B) \)
3. Evolution of the fragment excitations (equal \( E^* \) \(-\rightarrow\) 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

Energy dissipation rate: \[ \dot{Q} = \rho \bar{v} \int V^2 d\sigma \]

Fission dynamics with various types of dissipation

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].
Langevin shape dynamics

Shape family: \( \chi = \{\chi_i\} \)

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

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

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

Driving force: \( F^\text{pot}_i(\chi) = -\frac{\partial U(\chi)}{\partial \chi_i} \)

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

Friction force: \( F^\text{fric}_i(\chi) = -\sum_{ij} \gamma_{ij}(\chi) \dot{\chi}_j \)

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

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

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

\[ \text{dissipation} \Rightarrow \text{fluctuation} \]
Strongly damped nuclear shape dynamics => Metropolis walk

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:

\[ P_{\text{down}} = 1 \quad P_{\text{up}} = \exp(-\Delta U/T) \]

Metropolis et al. (1953):
Metropolis walk ...

Metropolis et al. (1953):

\[
P_{\text{down}} = 1 \quad P_{\text{up}} = \exp(-\Delta U/T)
\]

... on the potential-energy surface:

Start at ground-state (or isomeric) minimum

Walk until the neck has become narrow
$P(A_i)$ from $^{240}$Pu* and $^{236,234}$U*

Odd-even effects: Talk by Peter Möller
Potential energy: **Macroscopic-microscopic method**

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

**Finite-range liquid drop:**

\[ E_{\text{macro}}(Z, N, \chi) = -a_{\text{vol}}(1-\kappa_{\text{vol}}I^2)A - a_{\text{surf}}(1-\kappa_{\text{surf}}I^2)B_1 A^{2/3} + c_1 \frac{Z^2}{A^{1/3}} B_3 + \ldots \]

**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

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

Comparison with data from K.H. Schmidt et al., NPA 665 (2000) 221
P(Z_f) for isotopes at E*=11 MeV

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

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Summary

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

**Nuclear fission dynamics:**
Formal framework: Langevin shape dynamics
Strong dissipation: Brownian shape evolution
Quick relaxation: Metropolis walk on $U$ lattice

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

*) Has long been used successfully in the macroscopic limit

Stay tuned!