Magnetic Contribution to Friction

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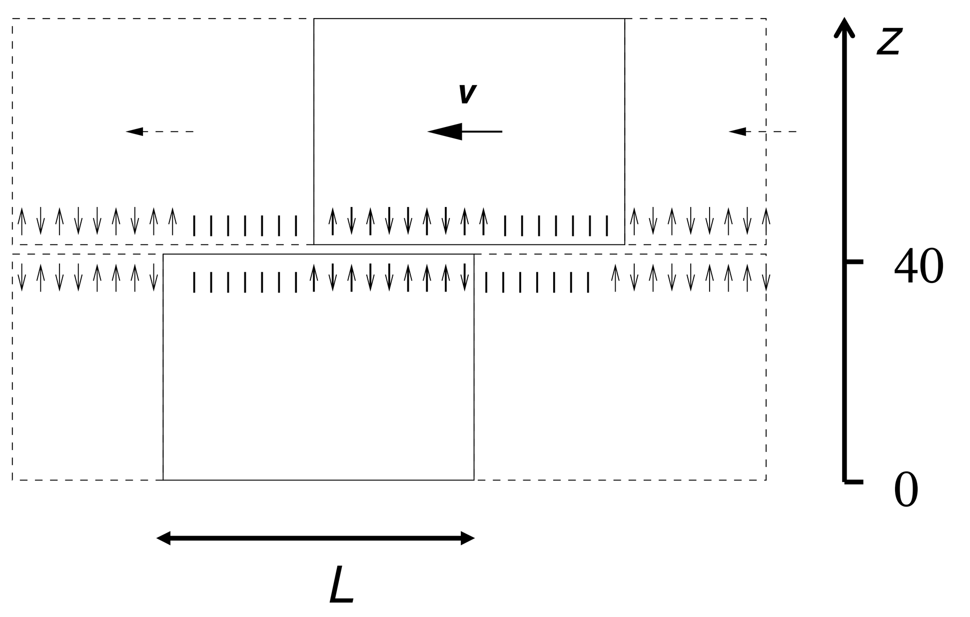
Idea

Tangential relative motion of two Ising spin systems drives the magnetic degrees of freedom out of thermal equilibrium. The energy dissipation due to thermal relaxation corresponds to a magnetic contribution to friction.

Model



Square lattice with periodic boundary conditions

$$H = -J \sum_{\langle i,j \rangle} S_i S_j$$

$$S_i = \pm 1, \quad J > 0$$

(ferromagnet)

Coupling to heat bath of constant temperature *T* lets spin configurations *C* relax towards thermal equilibrium. We consider

(a) fast relaxation with Metropolis rate

$$w_1(C \to C') = \frac{1}{\tau} \min\left(1, e^{-\Delta E / k_B T}\right) \quad \text{with} \quad \Delta E = E(C') - E(C)$$

(b) slow relaxation with rate

$$w_2(C \to C') = \frac{w_1(C \to C')}{1 + e^{-|\Delta E| / k_B T}}$$

$\tau \approx 10^{-8} s$ typical time for relaxation of a spin into the direction of the local Weiss-field (corresponds to one Monte Carlo step).

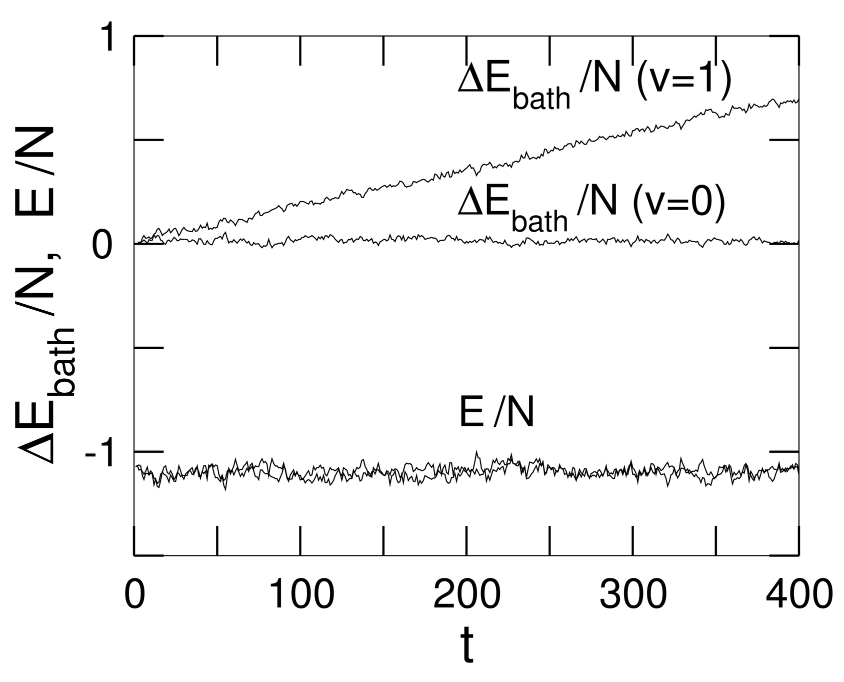
The upper half of the lattice is shifted by one lattice constant $a \approx 10^{-10} m$ to the left in regular time intervals *a/v*, where *v* is the sliding velocity. This drives the system out of thermal equilibrium. (*v=1* in natural units *a/τ* corresponds to 10^{-2}*m/s*) .

Dissipated Energy and Friction Force

ΔE_{bath} = (energy transferred to heat bath) – (energy received from heat bath)

Thermal equilibrium: ΔE_{bath} fluctuates around zero. The total energy per spin, *E/N*, is constant on average.

With relative motion: Net energy transfer to the heat bath. Energy of motion is continuously converted into thermal energy due to magnetic friction. The total energy per spin is still constant on average.



P = dissipated power

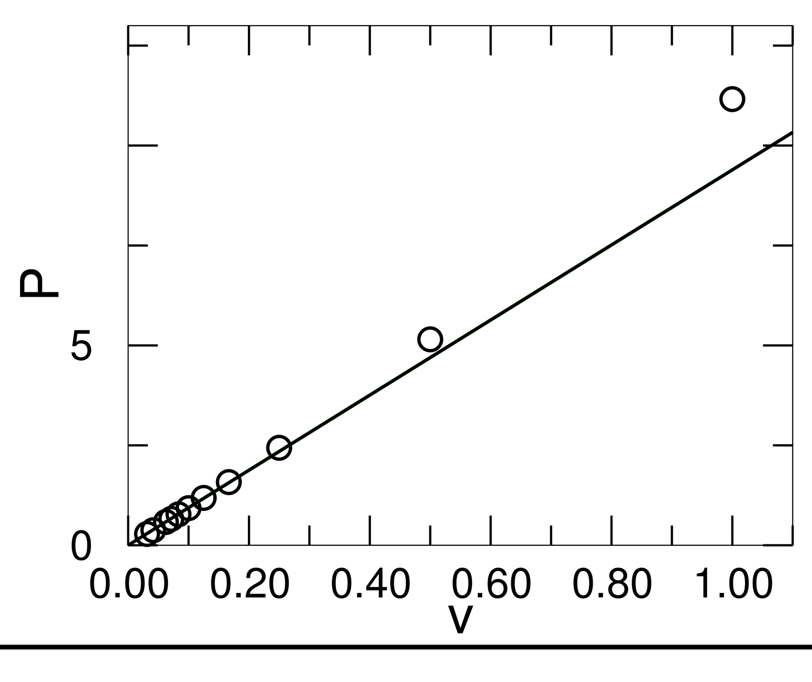
F = friction force

$$\left\langle \frac{\Delta E_{bath}}{\Delta t} \right\rangle = P = F v$$

Resulting friction force:

$$F \approx F_0 + \gamma v \propto L$$

In the following, *v* = 1, so that *P* = *F*.



Dissipation Mechanism

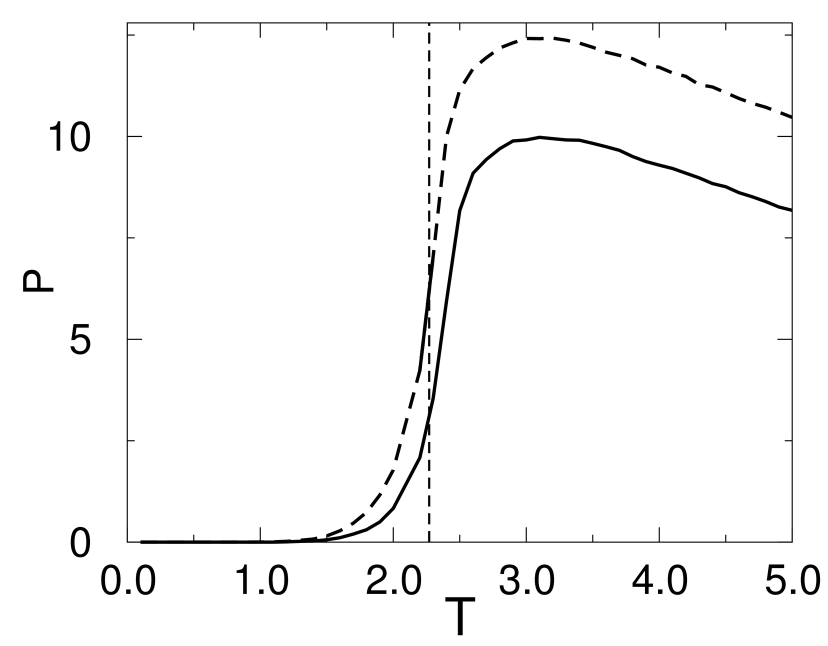
Relative motion destroys equilibrium correlations between spins on opposite sides of slip plane

Magnetic friction vanishes for $T \to \infty$ and $T \to 0$, because there are no correlations to be perturbed.

Steady nonequilibrium state: Slower relaxation back to equilibrium implies smaller effective correlation length in the slip plane, hence smaller dissipation rate.

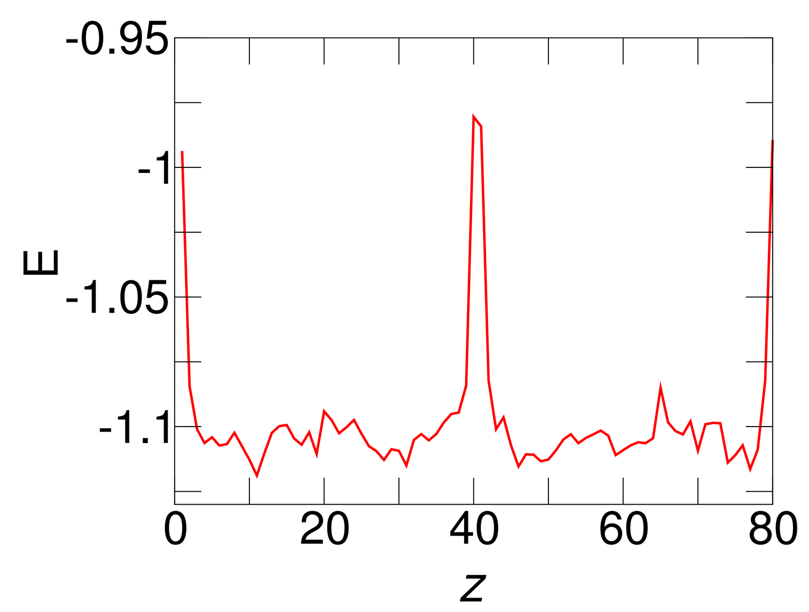
Temperature Dependence

Maximum of magnetic friction force slightly above the critical temperature, T_C = 2.27, where the correlation length is large, hence the driving out of equilibrium is most efficient.



Upper curve Metropolis rate (a), lower curve slower rate (b). Magnetic friction force is stronger for fast relaxation. For antiferromagnets the magnetic friction is even stronger (not shown).

Local Energy and Magnetization

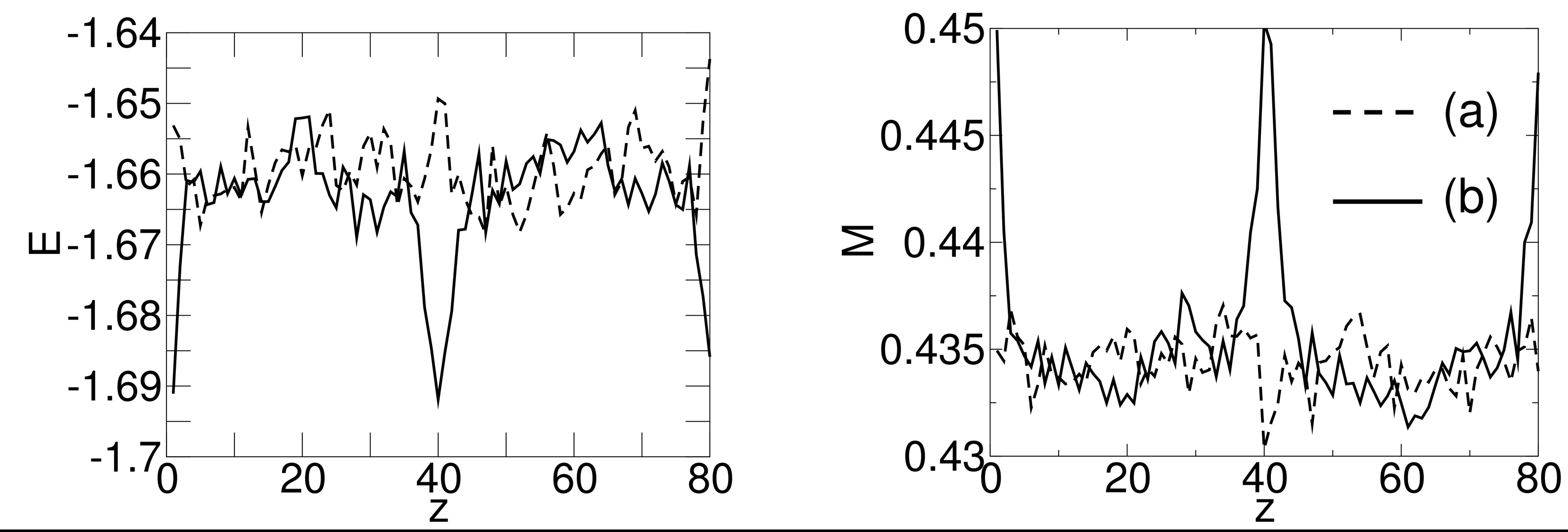


$T > T_C$:

Smaller correlation length corresponds to an effectively increased temperature at the slip plane, hence a locally increased energy.

$T < T_C$:

Smaller correlation length corresponds to an effectively lowered (spin-)temperature and increased Weiss field. The relative motion acts as a heat pump, cooling the spin system. This is borne out clearly for the slow relaxation rate (b).



Experimental Suggestions

Take ferrimagnetic (or antiferromagnetic) insulator like magnetite (Fe_3O_4) in order to avoid Joule-dissipation due to eddy currents.

Relative motion in a small but finite distance in order to have strong magnetic interaction, but reduced phononic contributions to friction .

Look for friction anomalies around the Curie- (respectively Neel-) temperature.