Depinning transition for domain walls with an internal degree of freedom

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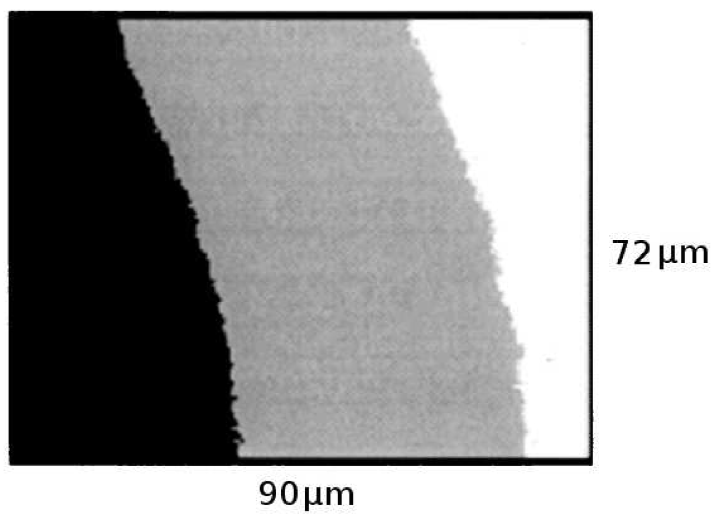
Abstract

We examine the dynamics of a domain wall subject to a pinning potential, in situations where the position of the wall is coupled to an internal degree of freedom (e.g. a spin phase, in magnetic domain walls). We investigate the corresponding depinning transition, which displays several novel features when compared to standard cases. At zero temperature, there exists a bistable regime for low forces, with a logarithmic behavior close to the transition. For weak pinning, there occurs a succession of bistable transitions corresponding to different modes of the phase evolution, separated by topological transitions. At finite temperature, using techniques from stochastic dynamical systems, we show that the force-velocity characteristics is non-monotonous, as an effect of the zero-temperature topological transitions [1]. We compare our results to recent experiments [2] on permalloy nanowires.

Interfaces & depinning transition

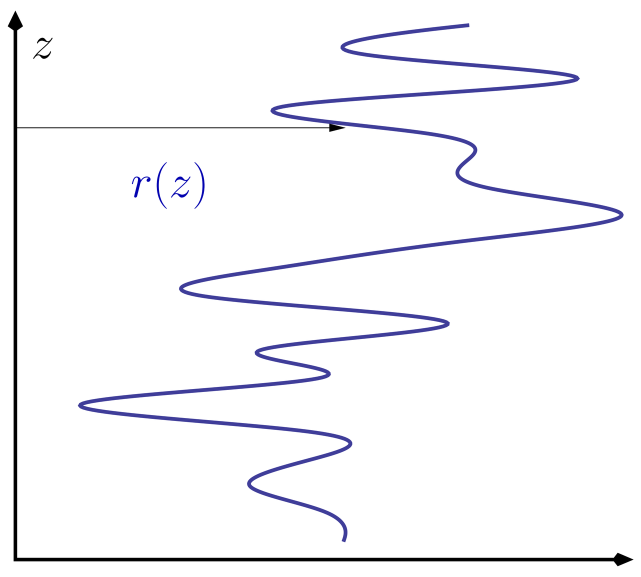


from Lemerle et al., PRL 80 **849** (1998)

Examples of interfaces:

- ⋆ magnetic domain wall (figure on the left)
- ⋆ contact line
- ⋆ growth interface
- ⋆ propagating crack

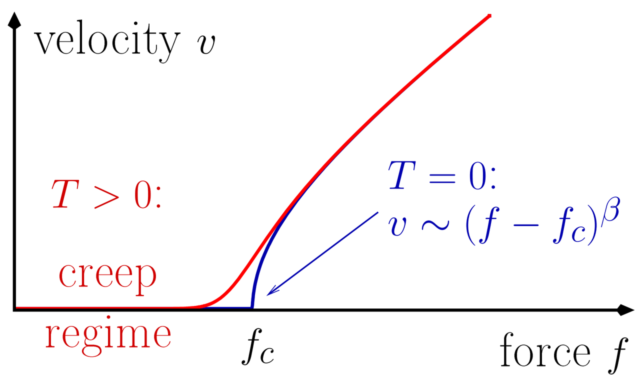
→ large variety of time and space scales



Common underlying description of interfaces:

- ⋆ complex object described by its mere position $r(z)$
- ⋆ elasticity tends to flatten the interface
- ⋆ disorder tends to deform it

→ competition btw "order" and "disorder"
nontrivial landscape of energy
yielding metastability, roughness, pinning



Depinning transition:

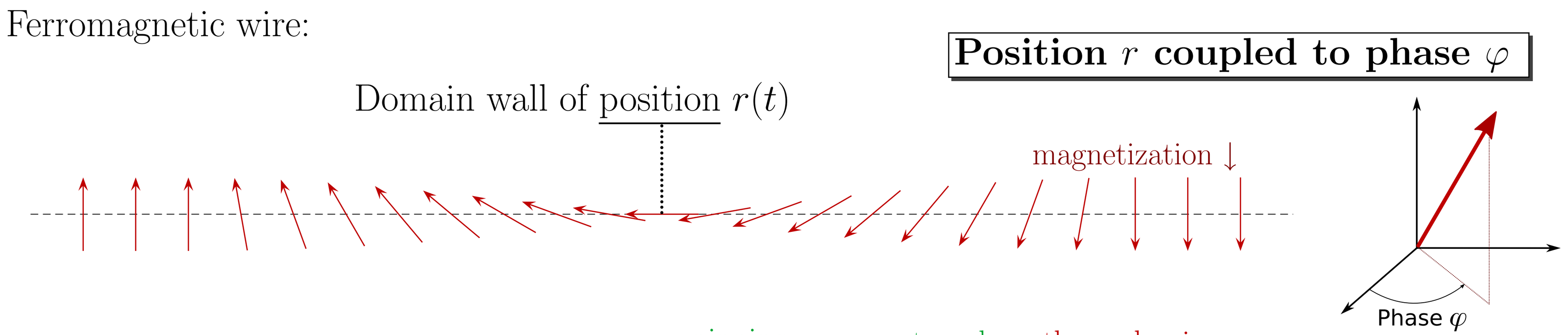
- ⋆ at $T = 0$: pinning up to a critical force f_c
- ⋆ depinning above f_c, reminiscent of static phase tr.
- ⋆ BUT: depinning is dynamical
- ⋆ at $T > 0$: creep, thermal rounding

Question & model

- **Is $r(z)$ containing enough information?**
  → examine models with r coupled to an internal degree of freedom φ

$$(\partial_t r, \partial_t \varphi) \;=\; f_{\text{pinning}}(r,\varphi) \;+\; f_{\text{ext}}$$

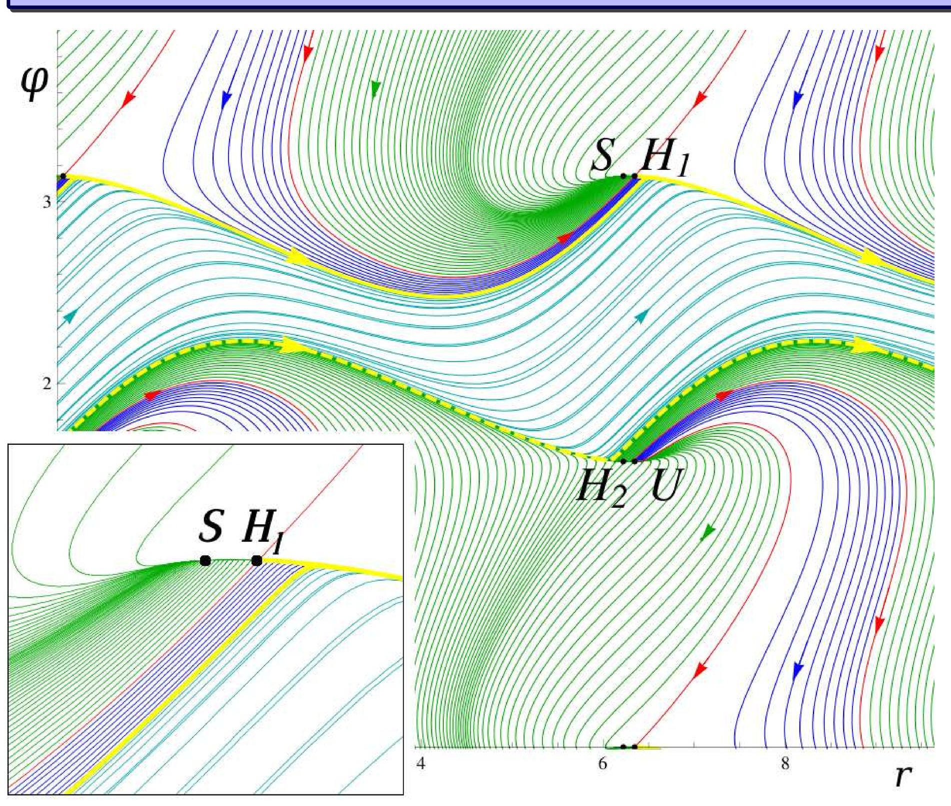
- Example situations:
  - ⋆ underdamped motion in a periodic potential [3]
  - ⋆ viscously coupled elastic manifolds [4]
  - ⋆ domain walls in ferromagnetic materials [5]
- Ferromagnetic wire:



effective equations [6]:

$$\begin{cases} \alpha\partial_t r - \partial_t\varphi = \overbrace{-\cos\kappa r}^{\text{pinning}} + \overbrace{f}^{\text{external}} + \overbrace{\eta_1}^{\text{thermal noise}} \\ \alpha\partial_t\varphi + \partial_t r = -\frac{1}{2}K_\perp \sin 2\varphi + \eta_2 \end{cases}$$

Phase space



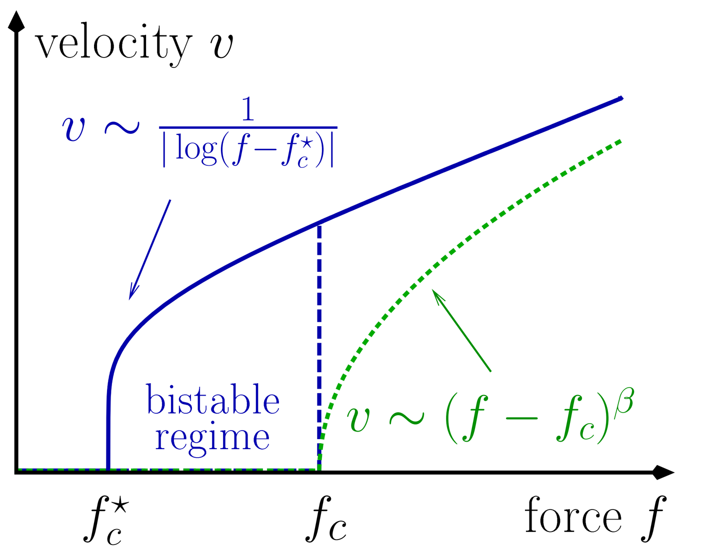
For some regime of force, **bistability** occurs.

Trajectories in the periodic (r,φ) phase space

- are determined through the fixed points:
  - ⋆ S is stable (attractive)
  - ⋆ U is unstable (repulsive)
  - ⋆ H_1 and H_2 are hyperbolic (stable+unstable directions)
- and split into those
  - ⋆ ending at S (having $v = 0$) (green)
  - ⋆ rolling to the limit circle (turquoise,blue) (having $v > 0$)

At $f = f_c^\star$ occurs a homoclinic bifurcation.

Results at zero temperature



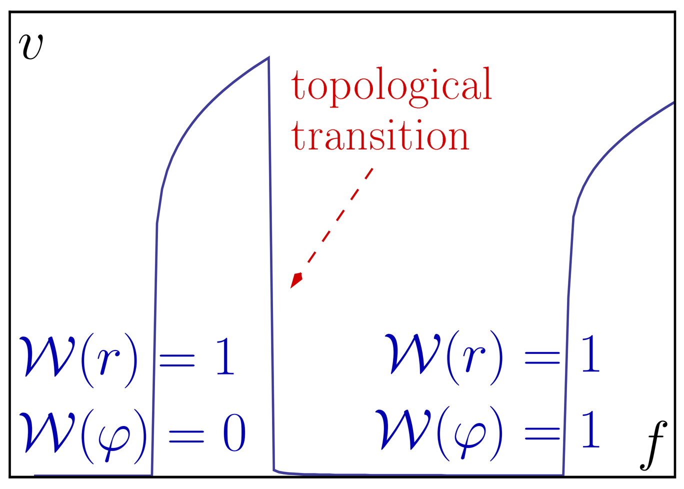
Dramatic change in the depinning law:

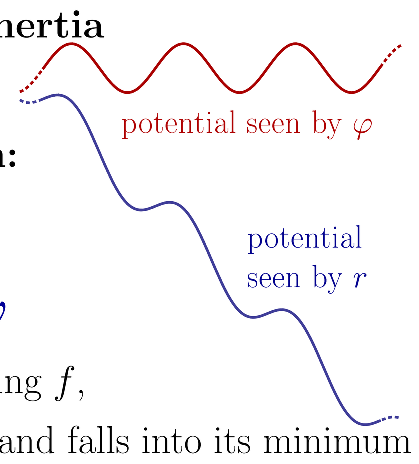
- ⋆ $v \sim \frac{1}{|\log(f-f_c^\star)|} \neq$ the standard $v \sim (f - f_c^\star)^\beta$
- ⋆ bistable regime for $f_c^\star < f < f_c$

Interpretation: for $f_c^\star < f < f_c$, the wall is

- ⋆ either pinned
- ⋆ or r slides down its tilted potential while φ oscillates around its own minimum, helping r to cross its barriers

→ φ plays the rôle of **inertia**





Topological transition:

- ⋆ successive regimes
- ⋆ characterized by winding numbers $\mathcal{W}$

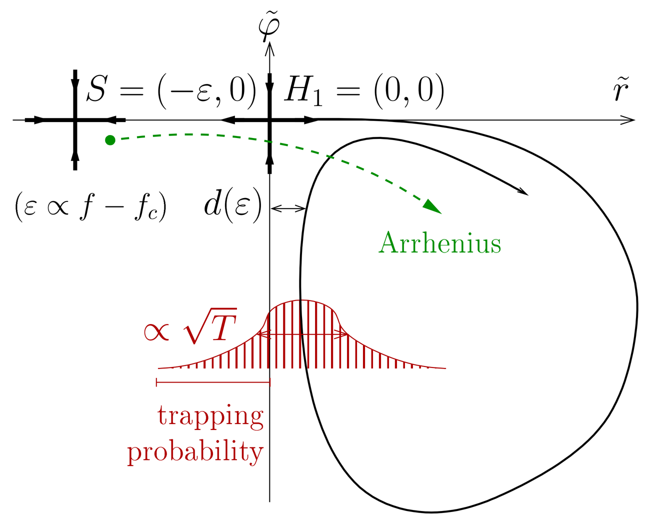
Interpretation: increasing f,

- ⋆ φ crosses its barrier and falls into its minimum

⇒ dissipation increases and φ cannot help r anymore

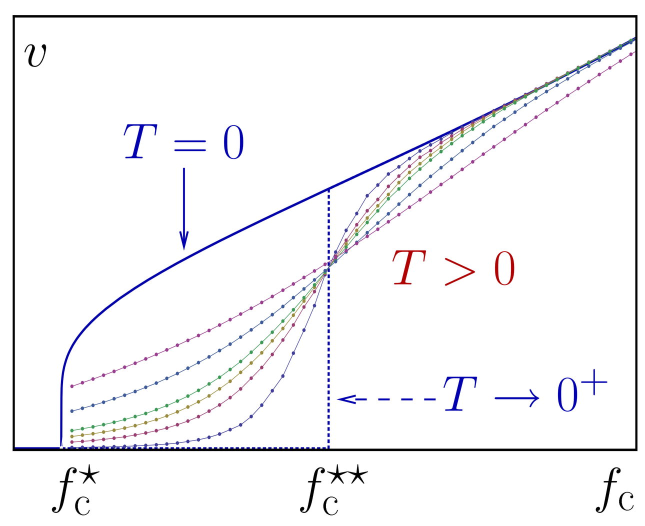
- ⋆ at larger f: revival with both r and φ increasing

Results at finite temperature



$$\text{velocity} \;\sim\; \frac{\text{characteristic length}}{\text{escape time}}$$

$$\text{escape time} \;\sim\; \underbrace{\exp\left(\frac{\varepsilon^3}{T}\right)}_{\text{Arrhenius}} \underbrace{\exp\left(-\frac{A}{T}(\varepsilon - \varepsilon_c)^2\right)}_{\text{trapping probability}}$$



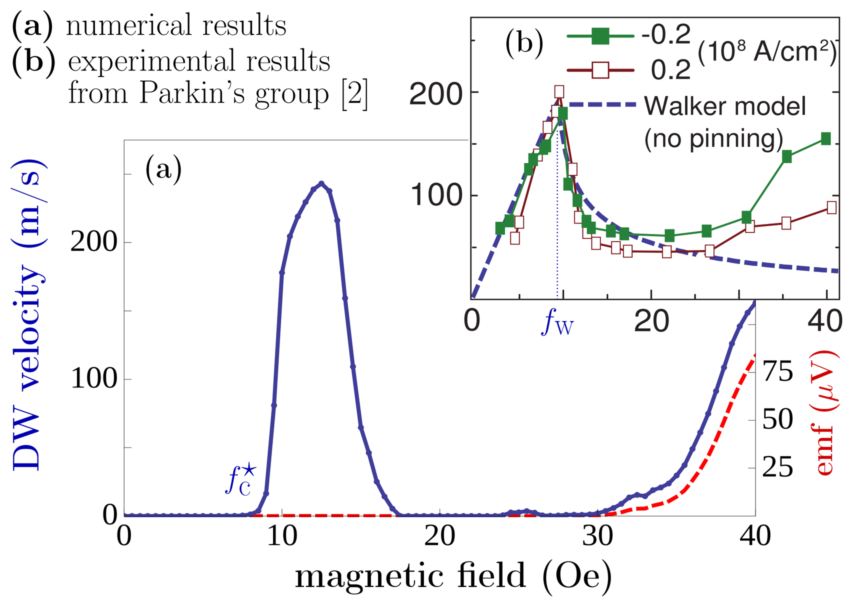
Depinning law $v(f)$ at finite temperature:

- ⋆ all curves cross at fixed force $f_c^{\star\star}$
- ⋆ contrasts with standard thermal rounding
- ⋆ in the $T \to 0^+$ limit: $v(f)$ is discontinuous in $f_c^{\star\star}$

Topological transition at finite temperature:
the depinning law $v(f)$ is non-monotonous

Comparison to experiment

(a) numerical results
(b) experimental results from Parkin's group [2]



- Experimental results [2]: non-monotonous $v(f)$ with two peaks
- Walker's model [5] (no pinning potential): only one peak
- Our results (simple pinning potential):
  - ⋆ two peaks in $v(f)$ for reasonable parameters
  - ⋆ prediction: the emf ($\propto \langle\dot\varphi\rangle$) increases at the second peak

Conclusion & outlook

Effect of coupling to an internal degree of freedom:

- ⋆ unusual depinning law
- ⋆ bistability
- ⋆ non-monotonous $v(f)$ at finite T
- ⋆ link with experiments

Perspective:

- ⋆ Current driven wall
- ⋆ Interface with elasticity

→ modified creep law?

- ⋆ Experiments:periodic patterning

References

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