Basic concepts on magnetization reversal (2)
Slow dynamics and thermal related processes

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Introduction: Application considerations

All applications need to work at room temperature
⇒ Thermal activation may become problematic for long time scales

Energy barrier criteria:
\[ \Delta E = KV > (25 - 60)k_B T \]

Thermal activation is crucial for nanoparticles (<25 nm)
It is also relevant for thin films (domain nucleation and domain wall propagation)
I. Superparamagnetism
II. Nucleation
III. Domain wall propagation in disordered magnetic films
IV. Conclusion
Contents

I. Superparamagnetism
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Superparamagnetism: Energy barrier for macrospin

Stoner and Wohlfarth hamiltonian

\[ E = K_{eff} \sin^2 \theta - \mu_0 M_S H \cos(\theta + \theta_H) \]

Volumic quantities

Energy barrier (field aligned with easy axis)

\[ \Delta e = e(\varphi_m) - e(0) \]
\[ = (1 - h^2 + 2h^2) - (-2h) \]
\[ = (1 + h)^2 \]

\[ \Delta E = KV \left(1 + \frac{H}{H_{SW}}\right)^{3/2} \]

Victoria PRL 63, 457 (1989)
Superparamagnetism: Thermodynamics of a macrospin

\[ EV = K_{eff} V \sin^2 \theta - \mu_0 \mu H \cos \theta \]

Macrospin moment

Isotropic case: \( K = 0 \)

\[ Z = 2\pi \int_0^\pi \exp \left( \frac{\mu_0 \mu H \cos \theta}{kT} \right) \sin \theta d\theta \]

\[ \langle \mu \rangle = \mu \left[ \frac{1}{\tanh x} - \frac{1}{x} \right], \quad x = \frac{\mu_0 \mu H}{kT} \]

(Langevin function)

Partition function:

Average moment projected on easy axis:

\[ \langle \mu \rangle = \frac{kT}{\mu_0 Z} \frac{\partial Z}{\partial H} \]

Infinite anisotropy: \( \theta = 0 \) or \( \pi \)

\[ Z = \exp \left( \frac{\mu_0 \mu H}{kT} \right) + \exp \left( - \frac{\mu_0 \mu H}{kT} \right) \]

\[ \langle \mu \rangle = \mu \tanh x, \quad x = \frac{\mu_0 \mu H}{kT} \]

(Brillouin \( \frac{1}{2} \) function)

Initial susceptibility

\[ \chi = \frac{\mu_0 \mu^2}{3kT} \text{ or } \frac{\mu_0 \mu^2}{kT} \]

Scaling with \( 1/T \) (like Curie law)
Superparamagnetism: Thermodynamics of a macrospin

Case with finite anisotropy

\[
\langle \mu \rangle = \mu \left[ -h + 2 \sqrt{\frac{t}{\pi}} \frac{\sinh \left( \frac{2h}{t} \right) \exp \left( \frac{1 + h^2}{t} \right)}{\text{Erfi} \left( \sqrt{\frac{1 + h}{t}} \right) + \text{Erfi} \left( \sqrt{\frac{1 - h}{t}} \right)} \right]
\]

\[h = \frac{H}{H_K}; \quad t = \frac{kT}{KV}; \quad \text{Erfi}(t) = \int_0^t \exp(x^2)dx\]

Brillouin like

Usefull: at low temperature

\[
\chi = \frac{\mu_0 \mu^2}{kT} \left( 1 - \frac{kT}{KV} \right)
\]

Langevin like

Chantrell et al. JMMM 53, 1999 (1985)
Fruchart et al. JMMM 239,224 (2002)

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Superparamagnetism: Thermodynamics of a macrospin

Occupancy probability for a Stoner-Wohlfarth model ($H = 0$)

$kT/KV =$
- Black: 0.1
- Red: 0.2
- Green: 0.3
- Blue: 0.5
- Cyan: 1.0
- Magenta: 5.0
- Dotted: isotropic ($\sin \theta$)
Superparamagnetism: Temperature induced switching

Phenomenological: Arrhenius law

\[ \tau = \tau_0 \exp(\Delta E / kT) \]

\[ \Delta E \] calculated with the macrospin approach

\[ \tau_0 \] attempt time (~1 ns) : linked with magnetization dynamics

Brown’s model: (Langevin fluctuation of a macrospin)

\[ \tau_0^{-1} = \frac{2\alpha}{1 + \alpha^2} \gamma \mu_0 H_K \sqrt{\frac{\mu_0 M_S H_K V}{2\pi kT}} \]

Brown Phys. Rev. 130, 1677 (1963)

See also Coffey et al. PRL 80, 5655 (1998)

Néel’s model: (Phonon and magnetostriction approach)

\[ \tau_0^{-1} = \left| \frac{eH_K}{m_e} \right| 3G\lambda + \mu_0 D M_S^2 \sqrt{\frac{2V}{\pi GkT}} \]

Néel Ann. Geophys. 5, 99 (1949)
Superparamagnetism: Temperature induced switching

\[ \tau = \tau_0 \exp(\Delta E / kT) \]

Stability criterion: \( \tau > \tau_{\text{measurement}} \)

Blocking temperature

\[ T_B = \frac{KV}{k_B} \ln\left(\frac{t}{\tau_0}\right) \]

If \( \tau_0 = 0.1\text{ns} \)

<table>
<thead>
<tr>
<th>( \tau )</th>
<th>1s</th>
<th>1min</th>
<th>1h</th>
<th>1day</th>
<th>1year</th>
<th>10 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta E/kT )</td>
<td>23</td>
<td>27</td>
<td>31</td>
<td>34</td>
<td>40</td>
<td>43</td>
</tr>
</tbody>
</table>

This problem drives an intense effort of research for high anisotropy materials. Best candidates are Pt-bases ordered alloys like FePt and CoPt (\( K \sim 10 \text{ MJ/m}^3 \) in bulk phase \( \leftrightarrow D_{\text{limit}} \sim 3 \text{ nm} \))

See e.g. Sun et al. Science 287, 1989 (2000)

Warning: it is difficult to predict \( T_B \) from volumic anisotropy measurements as in nanoparticles \( K \) is generally dominated by surface effects/low coordinated atoms

See Jamet et al. PRL 86, 4676 (2001)
Superparamagnetism: Characteristic time in experiments

Stability criterion: \( \tau > \tau_{\text{measurement}} \)

\[ T_B = \frac{KV}{k_B} \ln\left( \frac{t}{\tau_0} \right) \]

- Loop measurement in SQUID -> \(~10\text{min} - 1\text{h}\)
- ZFC-FC in squid -> \(~1\text{s}\)
- Magneto optical kerr effect (resistive coils) -> \(~1\text{s}\)
- SP-STM / microSQUID: 100 ms
- ac susceptibility: 1ms - 10s
- Moessbauer: 0.1 \(\mu\)s

In sweeping (field or temperature) experiments, characteristic time is ambiguous
-> rather speak of sweeping rate

see e.g. Kurkijarvi PRB 6 832 (1972) (field sweep)
Rohart et al PRB 74, 104408 (2006) (temperature sweep)
Superparamagnetism: Rate equation model

Brown’s model is difficult to use.

⇒ Simpler model: rate equations

\[ H \neq 0 \iff \Delta E_{\uparrow \downarrow} \neq \Delta E_{\downarrow \uparrow} \]

\[ \iff \tau_{\uparrow \downarrow} \neq \tau_{\downarrow \uparrow} \]

\[
\begin{align*}
\frac{dn_{\uparrow}}{dt} &= \frac{n_{\downarrow}}{\tau_{\downarrow \uparrow}} - \frac{n_{\uparrow}}{\tau_{\uparrow \downarrow}} \\
\frac{dn_{\downarrow}}{dt} &= -\frac{n_{\downarrow}}{\tau_{\downarrow \uparrow}} + \frac{n_{\uparrow}}{\tau_{\uparrow \downarrow}}
\end{align*}
\]

\[ \iff \frac{dn_{\uparrow}}{dt} = \frac{1}{\tau_{\uparrow \downarrow}} - n_{\uparrow}\left(\frac{1}{\tau_{\uparrow \downarrow}} + \frac{1}{\tau_{\downarrow \uparrow}}\right) \]

For constant field and temperature

(switching rates are constant)

\[ n_{\uparrow} = \frac{\tau_{\uparrow \downarrow}}{\tau_{\uparrow \downarrow} + \tau_{\downarrow \uparrow}} + \frac{\tau_{\uparrow \downarrow}}{\tau_{\uparrow \downarrow} + \tau_{\downarrow \uparrow}} \exp(-t/\tau) \]

with \[ \frac{1}{\tau} = \frac{1}{\tau_{\uparrow \downarrow}} + \frac{1}{\tau_{\downarrow \uparrow}} \]

- First order decay law with relaxation time \( \tau \)
- If \( t_{\text{meas}} \gg \tau \),

\[ \frac{\langle \mu \rangle}{\mu} = 2n_{\uparrow} - 1 = \frac{\tau_{\uparrow \downarrow}}{\tau_{\uparrow \downarrow} + \tau_{\downarrow \uparrow}} = \tanh\left(\frac{\mu_0 \mu H}{kT}\right) \]

This equation can be used for any field orientation (if switching rates are known...)

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Superparamagnetism: Hysteresis loop

Simulation of mean hysteresis loops with rate equations

Coercive field is not intrinsic
-> depend on temperature AND sweeping rate

\[
H_C = H_K \left[ 1 - \frac{kT}{KV} \ln \left( \frac{t_{\text{meas}}}{\tau_0} \right) \right] \\
\equiv H_K \left[ 1 - \sqrt{\frac{T}{T_B}} \right]
\]

Scharrook JAP 76, 6413 (1994)
IEEE Trans Mag 26, 193 (1999)
Superparamagnetism: experimental evidence

Experimental Evidence of the Néel-Brown Model of Magnetization Reversal

W. Wernsdorfer,1 E. Bonet Orozco,1,2 K. Hasselbach,1 A. Benoit,1 B. Barbara,2 N. Demoney,3,4 A. Loiseau,4 H. Pascard,3 and D. Mailly5

Presented are the first magnetization measurements of individual ferromagnetic nanoparticles (15–30 nm) at very low temperatures (0.1–6 K). The angular dependence of the hysteresis loop evidenced the single domain character of the particles. Waiting time, switching field, and telegraph noise measurements showed for the first time that the magnetization reversal of a well prepared ferromagnetic nanoparticle can be described by thermal activation over a single-energy barrier as originally proposed by Néel and Brown. The “activation volume” estimated by these measurements was close to the particle volume. [S0003-4916(07)02465-4]

FIG. 2. Probability of not switching of magnetization as a function of the time at different applied fields at 4 K and for θ ∼ 12°. Full lines are fits to the data with an exponential [Eq. (2)].

⇒ Anisotropy precisely determined from asteroid at 35 mK
⇒ Volume determined by SEM imaging
⇒ First perfect agreement with Néel-Brown model

FIG. 6. Telegraph noise measurements for three temperatures and μ0H_y = 396.2 mT.
First observation (2D): Co (D = 25 nm) cluster
Wernsdorder et al. PRL 78, 1791 (1997)

In 3 D: (same Co cluster) E. Bonnet et al PRL 83, 4188 (1999)

3 nm Co cluster: M. Jamet PRL 86, 4676 (2001)
Superparamagnetism: experimental evidence

Jamet et al. PRL 86, 4676 (2001)

Simulation of macrospin dynamics (Brown’s model)
(with exp. Data from Jamet et al.)
Superparamagnetism:
Experimental observation in practical

- Single particle measurements are difficult
- Hysteresis loops are generally long to measure

Temperature variation of initial susceptibility

\[
\chi(\omega) = \frac{\chi_{eq}}{1 - i\omega\tau} \propto \frac{1}{T} \frac{1}{1 - i\omega\tau_0 \exp(\Delta E / kT)}
\]

\(\omega\) : Pulsation of the magnetic field

Field cooled-Zero field cooled measurements

Model for zfc, measuring from low to high T

\[
M(T) \propto \frac{1}{T} \left[ 1 - \exp\left(-\frac{\delta t}{\tau(T)}\right) \right] \text{ with } \delta t = \frac{kT^2}{KdT / dt}
\]

Pt clusters in different matrices
Rohart et al. PRB 74, 104408 (2006)
See also Tamion et al; APL 95, 062503 (2009)

Co nanodots on Au(111) with increasing size
Rohart et al. PRL 104, 137202 (2010)

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Superparamagnetism: beyond macrospin?

If $L >> \delta$ : it is possible to nucleate and propagate a reversed domain

Braun PRL 1993
(same approach as Brown 1963)

\[ \tau = \tau_0 (H) \exp \left( \frac{A \sigma}{kT} \right) \]

$\tau_0$ - Strongly depends on $H$ (size of the critical nucleus to reverse magnetization)
- Proportionnal to $L$ (nucleation occurs in the particle – edges are neglected)
Superparamagnetism: beyond macrospin?

Superparamagnetism and nucleation-propagation magnetization reversal

Experimental check:

Single particle measurement by spin polarized STM

Monte Carlo simulation

$\tau_0$ decrease with length, increase with the width

$\Rightarrow$ edge nucleation

Krause et al. PRL 103, 127202 (2009)
Superparamagnetism: beyond macrospin?

Superparamagnetism and spin waves

Atomic scale micromagnetic calculation on Co flat nanodots

• Homogeneous magnetization ground state
• Coherent rotation at $T = 0$

But coherent reversal over estimates switching rates at $T \neq 0$

At finite $T$, high excitation modes are excited

Rohart et al. PRL 104, 137202 (2010)

Explains experiments from Rohart et al. 2010 and Rusponi et al. Nature Mat. 2003
I. Superparamagnetism
II. Nucleation
III. Domain wall propagation in disordered magnetic films
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Nucleation processes: Droplet model

-> 2D problem : apply to thin films with weak disorder

Energy:

\[ E(r) = 2\pi r \sigma t - \pi r^2 t \times 2\mu_0 M_S H \]

Domain wall energy cost  
Zeeman energy gain

Important process for thin films
Energy barrier scales with 1/H

Nucleation rate
\[ R(H) = R_0 \exp(-\Delta E / kT) \]

Barbara JMMM 129, 79 (1994)
Vogel et al. CR Physique 7, 977 (2006)
Nucleation processes:
Magnetization reversal in constant magnetic field

-> Nucleation rate vs. Domain expansion:

\[
\frac{dN}{dt} = (N_0 - N)R \Rightarrow N = N_0 \left(1 - \exp(-Rt)\right)
\]

Domain nucleation

\[
S_N(t) = \pi \left(r_c + v_0 t\right)^2
\]

Surface of the domain nucleated at \(t=0\)

Pertinent parameter:

\[
K = \frac{v_0}{R r_c}
\]
defines if the magnetization reversal is propagation or nucleation limited

Variation of the non reversed area for different \(K\)

Labrune et al. JMMM 80, 211 (1989)
Nucleation processes: Magnetization reversal in constant magnetic field

Fig. 4. Magnetization versus reduced time $t_R$ for a GdFe sample ($k = 2000$) and a TbCo one ($k = 0$), corresponding domain structure observed by Kerr effect.

Labrune et al. JMMM 80, 211 (1989)
Nucleation processes: Coercive field and droplet model

![Graphs showing M/M_s vs H (KoE) and Hc vs Ln(dH/dt (Oe/s))]  

Au/Co/Au films and nanostructures  
Raquet et al. PRB 54, 4128 (1996)

Pt/Co/Pt films and nanostructures  
Moritz et al. PRB 71, 100402(R) (2005)
Nucleation processes:
Droplet model in reduced dimensions

⇒ Confined droplet model (circular dot)

Nucleation is generally easier at the edge

Critical droplet size:

\[ \rho_c = \frac{\sigma}{2\mu_0 HM_S} \quad \text{(same as thin films)} \]

\[ L_c = R_{ext} \left( 1 - \frac{\xi}{\sqrt{1 + \xi^2}} \right) \quad \text{with} \quad \xi = \frac{R_{ext}}{\rho_c} \]

Magnetic configuration at the maximum energy

(Same as Braun 1993)

Numerical application:
Parameters for Pt/Co(0.5 nm)/Pt film


See also 3D theory: Hinzke and Nowak PRB 58 265 (1998)
Nucleation processes:

Coalescence between nucleated domains

⇒ The experiment validates the picture of nucleation/propagation

⇒ Coalescence between domains is difficult

⇒ Nucleation of 360° domain walls

Dipolar repulsion between domains

⇒ Saturation may be difficult to reach

⇒ Poison for magnetization reversal

Pt/Co(0.5 nm)/Pt

Time between frame : 400 s

Nucleation field : 5 Oe

Propagation field : 30e (to reduce DW velocity)

Bauer et al. PRL 94, 207211 (2005)


Hehn et al. APL 92, 072501 (2008) (in MRAM nanoelements)
I. Superparamagnetism
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Domain wall motion in disordered films

Pt/Co(0.5 nm)/Pt with perpendicular magnetization
H = 42 Oe
Time between frame : 100s

Domain wall is not extended as a straight line (minimisation of length) but also feels some weak defects.

⇒ Competition between elasticity and pinning

Driving force : \( H \)

Elasticity : \( \varepsilon = \sigma t = 4t\sqrt{AK} \)

Pinning : \( f_{\text{pin}} \)

(roughness, thickness variation...)

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Domain wall motion in disordered films
From Creep to viscous motion

Viscous regime
Defects and disorder are not pertinent
-> DW velocity given by magnetization dynamics theory

Universal law
-> Apply to ferroelectric DW
-> Superconducting vortices
-> Charge density waves
-> Fluid propagation in porous media

Chauve et al PRB 62 6241 (2000)

f = H for magnetic DW
Domain wall motion in disordered films
Propagation and roughness

$H \ll H_{\text{crit}}$: very small velocity
$\Rightarrow$ DW adapts to defects
$\Rightarrow$ Significant roughness

$H \gg H_{\text{crit}}$: large velocity
$\Rightarrow$ Limited role of disorder
$\Rightarrow$ Small roughness

$\Rightarrow$ Velocity with universal behavior on 10 orders of magnitude.

S. Lemerle et al, PRL.80, 849 (1998)

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Domain wall motion in disordered films

Elastic energy

For a DW length L:

\[ \nu \sim \Delta \nu(x,t) \text{ mean of transverse fluctuations} \]

Elastic energy: *increase in DW length*

\[ \Delta L = 2L_1 - L = \nu^2 / L \]

\[
E_{\text{elastic}} = \int_0^L \frac{\varepsilon}{2} \left( \frac{d\nu}{dx} \right)^2 \, dx \approx \frac{\varepsilon \nu^2}{L}
\]

\[ L_1 = L/2 \left(1 + 4\nu^2 / L^2\right)^{1/2} \]

\[ \Rightarrow \text{Roughness and fluctuation} \leftrightarrow \text{Elastic energy cost} \]
Domain wall motion in disordered films

Pinning

\[ f_{\text{pin}} \]  
\[ v(x,t) \]  
\[ \xi \]

\[ \xi \]: Correlation length of disorder

\[ n_i = \text{pinning center density} \]
\[ f_{\text{pin}} : \text{pinning force of one center} \]

\[ \Rightarrow \] Random force of individual forces

\[ \Rightarrow \] Only density fluctuations can collectively pin the domain wall

\[ \Delta = \langle \text{collective force} \rangle \text{ coming from disorder} \]
\[ \Delta = f_{\text{pin}}^2 n \xi \]

Pinning energy:
\[ E_{\text{pinning}} = -f_{\text{pin}} \sqrt{n_i \xi L \xi} = -\sqrt{\xi^2 L \Delta} \]
Domain wall motion in disordered films

Competition between pinning and elasticity

Two critical lengths: $L_c$ and $\nu_c$

$$E_C = E_{\text{pinning}}(L_c) = E_{\text{elastic}}(L_c)$$

$$\sqrt{\nu_c^2 L_c \Delta} = \frac{\varepsilon \nu_c^2}{L_c}$$

$$L_c = \left(\frac{\varepsilon^2 \nu_c^2}{\Delta}\right)^{1/3}$$

Larkin length $L_c \sim 0.025$ µm

(for Pt/Co/Pt ultrathin films)

Small scales:
Disorder characteristic length
~ grain size
~ Transverse fluctuations

\begin{align*}
E_{\text{elastic}} & \quad + E_{\text{pinning}} \\
E_{\text{pinning}} & \\
E_{\text{elastic}}
\end{align*}

Energie (erg/cm$^3$) vs $L$ (µm)
Domain wall motion in disordered films
Scaling law – Renormalization group theory

For $L > L_c > n_c$

$\nu = \nu_c \cdot \left( \frac{L}{L_c} \right)^{\zeta}$

Scaling law for fluctuations

$\zeta = 2/3$: universal exponent (for a 1D interface in motion in a 2D medium with weak disorder)

- **Elastic energy**
  
  $E_{\text{elastic}} = \frac{\varepsilon \nu_c^2}{L} \left( \frac{L}{L_c} \right)^{2\zeta}$

  $E_C = E_{\text{pinning}}(L_c) = E_{\text{elastic}}(L_c)$

- **Pinning energy**
  
  $E_{\text{pinning}} = E_C \cdot \left( \frac{L}{L_c} \right)^{2\zeta - 1}$

- **Zeeman energy**
  
  $E_{\text{Zeeman}} = M_S \cdot t \nu L H = M_S \cdot V_C \cdot H \left( \frac{L}{L_c} \right)^{\zeta + 1}$

**Critical volume:** $V_c = L_c \nu_c t$
Domain wall motion in disordered films
Activation energy and regime of motion

Thermally activated regime in creep regime

\[ E_{activation} = E_{Zeeman} + E_{pinning} \]
\[ \Delta E = -M_S V_C H + E_C \cdot \left( \frac{L}{L_C} \right)^{2\zeta-1} \]

⇒ Activation energy as a function of external field

With \( \zeta = 2/3 \)

\[ v = v_0 \exp \left[ -\frac{E_C}{k_B T} \left( \frac{H_{crit}}{H} \right)^{1/4} \right] \]

In the vicinity of the depinning field

\[ H_{crit} = \frac{E_C}{M_S V_C} \]
\[ E_{pinning}(L_C) = E_{Zeeman}(L_C) \]

Flow regime \( v = \mu H \)

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Domain wall motion in disordered films
ex: Pt/Co/Pt ultrathin films

\[ v = \sigma(H - H_{\text{crit}}) \]

For \( H > H_{\text{crit}} \)

\[ E_{\text{c, non irr}} = 46 \text{kT} \quad E_{\text{c, irr}} = 26 \text{kT} \]

For \( H < H_{\text{crit}}/5 \)

Unpublished results
See also S. Lemerle et al, PRL.80, 849 (1998)
Domain wall motion in disordered films
ex: Pt/Co/Pt ultrathin films

\[ t_{\text{Co}} = 0.5 \text{ nm} \]

\[ t_{\text{Co}} = 0.6 \text{ nm} \]

\[ t_{\text{Co}} = 0.7 \text{ nm} \]

Flow regime
\[ \rightarrow v \propto H \]
Precessional motion of domain wall (\( H > H_{\text{walker}} \))


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Mobilité/ champ critique/ champ de Walker

Interprétation cohérente des observations expérimentales à fort champ

⇒ Evaluer $H_w$, confinement pris en compte

Mouvement visqueux observé = régime précessionnel

Paramètre d’amortissement de Gilbert $\alpha \sim 0.25$ compatible avec résultats FMR et valeurs utilisées pour des simulations numériques

Domain wall motion in disordered films

Divergence of energy barrier

Evidence of energy barrier for $H / H_{\text{crit}} \ll 1$

$$\Delta E = E_C \left( \frac{H_{\text{crit}}}{H} \right)^{1/4}$$

$H = 2 \text{ Oe (0.01 } H_{\text{crit}})$ $Dt = 200 \text{ seconds}$

$H = 4 \text{ Oe (0.02 } H_{\text{crit}})$ $Dt = 1 \text{ second}$

$\Rightarrow L_{\text{jump}}$ is defined at the energy barrier

$$\Delta E = E_C \cdot \left( \frac{L}{L_C} \right)^{1/3} + M_S t H v_C L_C \left( \frac{L}{L_C} \right)^{5/3}$$

Jump length

$\Rightarrow$ Barkhausen jumps with $1/H^{4/3}$ jump length

$\Rightarrow$ Motion through avalanche processes

Domain wall motion in disordered films
Roughness analysis

\[ \nu_L = \nu_{L_c} \cdot \left( \frac{L}{L_c} \right)^\zeta \]
\[ \zeta = \frac{2}{3} \]

Correlation on a given length \( L \)

\[ C^2(L) = \left\langle [\nu(x) - \nu(x + L)]^2 \right\rangle_L \propto \left( \frac{L}{L_c} \right)^{4/3} \]

Critical exponent is independent of \( H \) (for \( H < 0.9H_c \))
Sligh increase of \( L_c \) for \( H/H_c > 0.2 \)

A. Mougin et al. unpublished results
Domain wall motion in disordered films
Creep in confined geometry

Domain wall propagation in nanowires (Pt/CoFe0.3nm/Pt)

Cross over between creep motion (2D like) and hoping (1D like)

Universal scaling:

\[ \frac{w}{L_{col}} \propto \frac{w}{L_C H^{3/4}} \]

- \( w \): Wire width
- \( L_{col} \): Segment length for jump
- \( L_c \): Larkin length

Domain wall motion in disordered films
Magnetization reversal with strong pining

Epitaxial FePt(40nm)/Pt film: presence of micromacle than pins the domain walls.

Domain wall propagation is channeled between micromacles: fast fractal-like domain growth.
Saturation needs to overcome strong pinning barriers:
⇒ Slow high field saturation
⇒ Thermal activation (slow dynamics)

Attane et al. PRL 93, 257203 (2004)
Conclusion

Take home message

• When dealing with long time scales, thermal activation plays an essential role.
• Many properties (like coercive field) depend on the time scale (field sweeping time, waiting time)...

To go further

• Toward quantum fluctuations: already observed in molecular magnets
  -> quantum fluctuation and tunneling of a domain wall is still a challenge...
  Wernsdorfer and Sessoli Science 284, 133 (1999)
  Gunther and Barbara Quantum Tunneling of Magnetization-QTM’94 (Kluwer, Netherlands, 1995)
• Magnetization reversal under spin polarized current
  -> Creep law with a different driving force (spin transfert torque)

Some readings

• Skomski and Coey Permanent magnetism (Taylor & Francis Group 1999)
• Aharoni Introduction to the theory of ferromagnetism (Oxford 1996)
• Fiorani Surface effects in Magnetic Nanoparticles (Springer 2005)