Spin-wave and spin-current dynamics in ultrafast demagnetization experiments

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Spin-waves exited by femtosecond laser pulses.
Terahertz spintronics

Outline

• Femtosecond spin(-wave) injection
  • Localized and delocalized nature of spin dynamics
  • Thermal model of ultrafast demagnetization
• Modification of electronic processes
  • Half metals
  • FePt “noble metal”
• Spin-wave propagation in thermal confinements
• Summary
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Localized nature of spin dynamics

$\Delta E_{\text{ex}}$

Spin flip on fs time scales (laser induced)
Localized nature of spin dynamics

Time (~10 fs)

Length (~nm)
Localized nature of spin dynamics

Stoner excitations (localized)

Electronic equivalent

\( \Delta E_{ex} \)

\( \Delta - E_F \)

Stoner continuum

Spin-waves
Delocalized nature of spin dynamics

\[ \frac{df(E)}{dE} \]

Fermi energy

\[ n(E) \]

Metal


- Electron -
- Hole +
Delocalized nature of spin dynamics

Ferromagnet, Metal

Ferromagnet, Half metal

Fermi energy

\[ n_{\uparrow}(E) \]

\[ n_{\downarrow}(E) \]

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Thermal model of ultrafast demagnetization

Electronic view

Spin ensemble

Energy

Occupation

1600 K

λ

Easy axis

x

y

z

m_i

M_0

M(τ)
Thermal model of ultrafast demagnetization

Electronic view

Energy

Occupation

1600 K

Spin ensemble

Easy axis

$\lambda$

Energy density $l$

Spin ensemble $m_i$

Magnetic moment $M_0$

Magnetic field $M(\tau)$

Energy $\Delta$
Thermal model of ultrafast demagnetization

Magnetization dynamics: Landau-Lifshitz-Gilbert equation (LLG)

Single spin (Quantum mechanics QM)

\[
\frac{i\hbar}{\gamma} \frac{d}{dt} \langle s_i \rangle(t) = \langle [s_i, H(t)] \rangle
\]

"Macroscopic" ensemble

\[
\frac{dm}{dt} = \gamma m \times H_{\text{eff}}
\]

No spin-scattering
Thermal model of ultrafast demagnetization

Magnetization dynamics with magnetic fluctuations

\[ \frac{d m_i}{d t} = \gamma m_i \times H_{\text{eff}}(T_{el}, \lambda) + \frac{\gamma \alpha}{m^2} m_i \times m_i \times H_{\text{eff}} \]

Include stochastic fluctuations of the spin system by a Fokker-Planck equation

Thermal model of ultrafast demagnetization

Magnetization dynamics: Landau-Lifshitz-Bloch equation $m$, $\alpha$ and $H_{\text{eff}}$, are coupled to electron temperature $T_{\text{el}}$

$$\frac{dm}{dt} = \gamma m \times H_{\text{eff}}(T_{\text{el}}) + \frac{\gamma \alpha_{\parallel}(T_{\text{el}})}{m^2} (m \cdot H_{\text{eff}}(T_{\text{el}})) m - \frac{\gamma \alpha_{\perp}(T_{\text{el}})}{m^2} m \times m \times H_{\text{eff}}(T_{\text{el}})$$

Gilbert damping $\alpha_{\perp} = \alpha(T \ll T_c)$

“thermal macrospin” $M(T_{\text{el}})$

Thermal model of ultrafast demagnetization

Magnetization dynamics: Landau-Lifshitz-Bloch equation \( m, \alpha \) and \( H_{\text{eff}} \), are coupled to electron temperature \( T_{\text{el}} \)

\[
\frac{dm}{dt} = \gamma m \times H_{\text{eff}}(T_{\text{el}}) + \frac{\gamma \alpha_{\parallel}(T_{\text{el}})}{m^2} (m \cdot H_{\text{eff}}(T_{\text{el}}, m_e))m - \frac{\gamma \alpha_{\perp}(T_{\text{el}})}{m^2} m \times m \times H_{\text{eff}}
\]

\[
H_{\text{therm}} = \frac{1}{\tilde{\chi}_{\parallel}} \left( 1 - \frac{m^2}{m_e(T_{\text{el}})^2} \right) m \quad T \leq T_c
\]

“thermal macrospin” \( M(T_{\text{el}}) \)

\( m \): actual magnetization

\( m_e \): equilibrium magnetization \( m(T) \)

Thermal model of ultrafast demagnetization

Magnetization dynamics: Landau-Lifshitz-Bloch equation

\[
\frac{dm}{dt} = \gamma m \times H_{\text{eff}}(T_{el}) + \frac{\gamma\alpha_\parallel(T_{el})}{m^2} (m \cdot H_{\text{eff}})
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H_{\text{therm}} = \frac{1}{\tilde{\chi}_\parallel} \left(1 - \frac{m^2}{m_e(T_{el})^2}\right) m \quad T \leq T_c
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Modification of electronic processes: half metals

Spin-orbit coupling:
- Mixes spin-up and spin-down states

\[ \lambda \sim \frac{E_{SO}}{E_{Ex}} \]

Elliott-Yafet process

Modification of electronic processes: half metals

Elliott- process and Gilbert damping

Spin-orbit coupling $\sim \lambda_{LS}$:
- Mixes spin-up and spin-down states

Intraband scattering with a phonon $q$, $\Delta E$:
- No spin conservation

$E_\psi$, $q_{ph}$, $\Delta E$

Modification of electronic processes: half metals

Elliott process: Ultrafast time scales

\[ W_{\uparrow\downarrow} \sim n_e^{\uparrow}(E_F) c^2 n_h^{\downarrow}(E_F) \]

Spin mixing:

\[ c \sim \zeta_{SO}/\Delta E_{exch} \]

Spin polarization P dependent relaxation

\[ \tau_{el-sp} = \frac{\tau_{el,0}}{c^2} \frac{1}{(1-P_n)} \]

Supression factor

\[ P \rightarrow 1, \text{ rate } \tau_{el-sp}^{-1} \sim 0 \]


Modification of electronic processes: half metals

Three temperature model: half metal

- Spin-flip processes are prohibited
- Electron and spin system are isolated

G. M. Müller et al., Nature Mater. 8, 56 (2009)
Modification of electronic processes: half metals

Fast:
Ni, Fe, Py,
Heusler Co$_2$MnSi

Slow:
Manganite LSMO, Magnetite; CrO$_2$

Additional materials:
- Chalcospinels
- Manganites
- Ruthenates,
  Double perovskites

Modification of electronic processes: half metals

- **HGST, San Jose**
  Pseudogap high polarized materials, spin transport (GMR)

- **Department of Physics, Bielefeld University**
  Isoelectronic Heusler films, spin-transport (TMR)

S. Maat, HGST

A. Thomas, U Bielefeld
Modification of electronic processes: half metals

$\text{Co}_2\text{MnSi (CMS)}$ $\quad$ $\text{Co}_2\text{FeSi (CFS)}$

(plus one electron)

Demagnetization by hole channels

- Spin-flips are determined by Fermi level and gap width

Modification of electronic processes: half metals

Co$_2$MnAl  Co$_2$MnSi  Co$_2$FeSi

(plus two electrons)

- Decreased Gilbert damping in the gap region

## Modification of electronic processes: half metals

<table>
<thead>
<tr>
<th>Material</th>
<th>[ps]</th>
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<th>Method</th>
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<tbody>
<tr>
<td>Ni</td>
<td>0.160 (10) [10]</td>
<td>0.45 [37]</td>
<td>Mes. Tedr.</td>
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<td>Py</td>
<td>0.175 (5) [47]</td>
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<td>CrO\textsubscript{2}</td>
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<td>0.99 [45]</td>
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Isolelectronic Heusler Co$_2$FeAl, Co$_2$MnSi, Co$_2$MnGe (same number of electrons: 29)
Modification of electronic processes: half metals

Growth optimization \( \text{Co}_2\text{FeAl}/\text{MgO}(100) \)
- \( P = 86\% \) (RT) from spin transport experiments

Comparison Co$_2$FeAl/ Co$_2$MnSi/ Co-Fe-B pseudogap

- Vanishing magnon peak (IETS) for negative bias shows half metallicity

Modification of electronic processes: half metals

For a one band model

\[ n_\uparrow(E) \quad n_\downarrow(E) \quad -\partial_E f(E) \]

Energy dependent polarization

\[ \tau_{el-sp}^{-1}(E) = \left\langle \sum_{\mu,\nu} n_{\nu\downarrow}(E) c_{\mu,\nu}^2 n_{\mu\uparrow}(E) k_{\mu,\nu}(E) \delta(E_\mu - E_\nu - \omega) \right\rangle_{el,lat} \]

\[ = \frac{c^2}{\tau_{el,0}} \left\langle \sum_{\mu,\nu} (1 - P(E)_{\mu,\nu}) k_{\mu,\nu} \delta(E_\mu - E_\nu - \omega) \right\rangle_{el,lat} \]

- Start with generalized Kambersky multiband approach
- Transitions in terms of band polarization \( P(E)_{\nu,\mu} \)

Modification of electronic processes: half metals

Modification of electronic processes: half metals

Materials with small gap

300 meV

Pseudo gap

1 eV, 0.67 P
Modification of electronic processes: half metals

• Co-Fe-Ge, Co$_2$FeAl: increase compared to $\tau_{el,0}$ by 3-4
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Modification of electronic processes: FePt

- **CSIC, Madrid**
  Thermal macrospin modelling
  Pablo Nieves, Oksana Chubykalo-Fesenko

- **HGST Western Digital**
  FePt storage media
  Simone Pisana, Tiffany Santos
Modification of electronic processes: FePt

Fe (bcc)

FePt L10 “noble metal”

Energy

Density of states

Small electron specific heat

\[ c_e = \gamma_e T \]

Occupation

Energy

950 K

1600 K
Modification of electronic processes: FePt

$\gamma_e = 110 \text{ J/m}^3\text{K}^2$

$\gamma_e = 1700 \text{ J/m}^3\text{K}^2$

Modification of electronic processes: FePt

- Low specific heat for FePt
- Large temperatures

- Increase above $T_c$
Modification of electronic processes: FePt

- Low specific heat for FePt
- Large temperatures

- Type I - one time scale
- Type II – second slow time scale appears
Modification of electronic processes: FePt

- Type I - one time scale
- Type II – second slow time scale appears at 25 mJ/cm²

Electron temperature determines the spin dynamics

This is a new knob to design new materials for ultrafast spin dynamics

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Spin-wave propagation in thermal confinements

- Simulation of the laser pulse excitation – spin-wave on the picosecond and nanometer time scale

Spin-wave propagation in thermal confinements

- also: microscopic model for ultrafast demagnetization

Spin-wave propagation in thermal confinements

Schematic dispersion:

• Spin waves from the GHz to THz range

\[ \lambda = \frac{2\pi}{q} \]

Spin-wave propagation in thermal confinements

Schematic dispersion:

- Spin waves from the GHz to THz range

Spin-wave propagation in thermal confinements

E, H_{eff}

Magnetic film

Magnonics

Exchange interactions

$\omega/\text{THz}$

$\sim k^2$

$\pi/10-100\text{nm}$

Dipolar interactions

$\omega/10\text{GHz}$

$k_{\perp}M$

$k_{\parallel}M$

$\pi/\mu\text{m}$

$\pi/10 \mu\text{m}$

Spin-wave propagation in thermal confinements

- Kerr rotation (a.u.) vs. Time delay (ps)
  - $\mu_0 H = 150 \text{mT}$
  - $\mu_0 H = 0 \text{mT}$

- Fourier Power (a.u.) vs. Frequency (GHz)

20 nm Ni

Spin-wave propagation in thermal confinements

$D = 0.7 \, \mu m; \ a = 3.5 \, \mu m$

DE wave vector is imprinted
$k = 0.99(5) \, \mu m^{-1}
\approx \pi / a$

Spin-wave propagation in thermal confinements

- Simulation with reduced $M_S(T)$:

$$\omega_{\text{kinel}} = \gamma \mu_0 \sqrt{H_x (H_x + M_S)}$$

$$\omega_{\text{PSSW}} = \gamma \mu_0 \sqrt{(H_x + \frac{2A}{\mu_0 M_S} k^2)(H_x + M_S + \frac{2A}{\mu_0 M_S} k^2)}$$

$$\omega_{\text{DE}} = \gamma \mu_0 \sqrt{(H_x + \frac{2A}{\mu_0 M_S} k^2)(H_x + M_S + \frac{2A}{\mu_0 M_S} k^2) + \frac{\mu_0 M_S^2}{4} (1 - e^{(-2|\kappa d|)})}$$
Spin-wave propagation in thermal confinements

- Heating results in a frequency shift
Spin-wave propagation in thermal confinements

- Heating results in a frequency shift
Spin-wave propagation in thermal confinements

- Potential application: Thermal spin-wave traps (~1 GHz/ 50 µm)
People who do the work

Priority program SpinCaT
Five bullet points – ultrafast dynamics

Thesis 1: Difficulty lies in the complexity, not in the nature of the process

Thesis 2: Models have to take into account localized and delocalized character of magnetism

Thesis 3: Electronic structure is modified and interacts with dynamics (spin-flip rate, electron temperature, exchange splitting etc.)

Thesis 4: Critical behavior plays a crucial role

Thesis 5: As a consequence of spin-orbit interaction, momentum conservation does not give insights for ferromagnets (different for two sublattice spin systems)