Ultrafast Spin Dynamics

Adrian Glaubitz

24.01.2008
1 Introduction

2 Theoretical Aspects
   ■ Model of Magnetization
   ■ Changing of M due to external forces

3 Experimental realisation
   ■ How to induce fast magnetization
   ■ Probing magnetization

4 Applications
   ■ Examination of atomic interactions
   ■ Magnetic Switching

5 Summary and References
   ■ Summary
   ■ References
Ultrafast Spin Dynamics deals with very fast changes ($\leq 10^{-12}$s) in magnetization.

- Can be triggered in pump-probe-experiments with femto-second-lasers.
- Allows to control (change) magnetization on small length-scales and short time-scales.

$\Rightarrow$ GOALS:

- Better understanding of important magnetic interactions like magnetic anisotropy, atomic spin-orbit interaction, interatomic magnetic exchange.
- Satisfy the demand for “smaller and faster” in high-tech electronics (e.g. data-storage).
Model of Magnetisation

Magnetization is a property of some materials to exhibit a magnetic-field; it is defined as the magnetic moment per volume:

$$\vec{M} = \frac{\partial \vec{\mu}}{\partial V}$$  \hspace{1cm} (1)

Magnetic moment is classically induced by a moving charge on a closed circuit

$$\vec{m} = \frac{1}{2} \int \vec{x} \times d\vec{l}$$  \hspace{1cm} (2)

In electronic systems on the atomic scale, magnetic moments exist, when the total angular-momentum \( \vec{J} \) is non-zero; both the orbital angular-momentum \( \vec{L} \) and the spin \( \vec{S} \) contribute to \( \vec{J} \).
Pauli-Magnetism

- refers to the small magnetic moment \(10^{-4} \mu_B\) per atom that is induced by an external \(H\)-field

- the external magnetic field causes an *imbalance* of spin-up and spin-down conduction electrons; thus the magnetic moment can be calculated from absolute difference of number of spin-up and spin-down:

\[
m = \mu_B \cdot (N_{up} - N_{down}) \quad \text{where} \quad N_{up} - N_{down} = 2\mu_B HD(E_F) \quad (3)
\]

- is temperature independant
Model of Magnetization

Changing of $M$ due to external forces

Adrian Glaubitz
Ultrafast Spin Dynamics
Different time-scales of magnetization
Magnetization changes on different time-scales depending on the circumstances

- $10^6$ years: earth field (geomagnetism)
- $10^1$ years: magnetic storage devices (tape, disk)
- $10^{-3} - 10^{-6}$ seconds: electronic circuits (coils, antennas)
- $10^{-9}$ seconds: read-write-heads of harddisks
- $10^{-12} - 10^{-15}$ seconds: **Ultrafast Spin Dynamics**
The magnetization of a solid-state can be changed to due:

- Temperature
- external magnetic fields
- external mechanical force

The reason for having several ways of change is that the respective heat reservoirs couple with each other:

- electrons couple with the spins due to the spin-orbit-coupling
- phonons and electrons couple due lattice deformation
- magnetization couples with spins over spin-wave-scattering

Heat reservoirs in a ferromagnetic metal
Excitation via the electronic heat-reservoir

- The electronic reservoir is a **degenerate electron gas** with heat-capacity $C \ll 1$. It is usually excited with a LASER and since $C$ is very small, $T$ rises rapidly to $> 1000K$.

- The gas cools down quite quickly though by exciting lattic-vibrations.

- Magnetization now changes, once $T > T_C$ (Curie-Weiss-law). Experiments show that the heat-capacity of the magnetization has a peak at $T = T_C$, thus changing the magnetization with heat is a 1st-order phase-transition.
Excitation directly with a magnetic field

- when a short magnetic-field pulse is applied externally, the magnetization moves out of its equilibrium and starts to precess around the axis of the external field.

- since the total angular momentum needs to be conserved, the magnetic field experiences a torque opposite but equal to the precessional torque applied into the spin-system.

- after the field-pulse is gone, the magnetization starts to precess around the anisotropy axis.

- the energy and momentum absorbed by the spin-system is ultimately transferred to the lattice, exciting phonons.

- relaxation time of spin-system into equilibrium is proportional to the FMR-line-width.
How to induce fast magnetization

- Magnetization on such a short time-scale can only be induced, if the source of induction itself is very fast (short pulse).

- This can only be achieved by using **femto-second-lasers**.

- A high-energy pump-pulse is sent into thin-magnetic films to ensure homogenous deposition of energy.

- Such a Laser excites the electronic heat-reservoir; to excite phonons one must use IR-band-LASERs.
Probing magnetization

- after excitation we want to measure how magnetization has changed
- an important requirement of the probing is that it does not alter the magnetization induced with the pump-pulse; thus the probe-pulse needs to be small in amplitude so that it won’t deposit additional energy
- also the probe pulse should laterally confined to the region excited

Popular methods for probing

- Optical measurement of the spin with Magneto-Optic Kerr-Effect (MOKE)
- Measurement via spin-detection of photoelectrons
- X-ray dichroism employing tunable synchrotron radiation with polarized X-ray (not discussed)
Magneto-optic Kerr effect (MOKE)

The magneto-optic Kerr-effect is a well known method to measure the magnetization of a sample optically; it is quite mature and already widely used in technology.

A polarized light-beam is directed onto the sample and reflected; the polarization will change by a few degrees allowing to determine magnetization of the sample.

Today widely used in Magneto-Optical storage devices.
By measuring the spin of Photoelectrons

- high-energy ultra-violet photon pulses excite photoelectrons
- the spin-polarization $P$ of the photo-electrons is *statistically* parallel to the magnetization
- since one *cannot* select the photoelectrons emitted, the measurement has to be cycled several times; $P$ will be statistically distributed according to the magnetization
- time-resolution is mainly limited by optical absorption, thus the pulse-length of the probing UV-pulse sets the time-span (other processes such as the transport of the photoelectrons to the surface and detector occur instantaneously)
Many interesting interactions and phenomena on atomic-scale are in the time-scale of $10^{-12} - 10^{-15}$ s; thus they can be examined with USD-methods:

- magnetic anisotropy ($10^{-6} \leq 10^{-3}$ eV):
- atomic spin-orbit coupling energy ($10^{-2} \leq 10^{-1}$ eV)
- interatomic exchange energy ($E \approx 3 \times 10^{-1}$ eV)

The time-scales are plotted using $t = \frac{h}{E}$
Switching the Magnetization

Switching the magnetization refers to the process of completely rotating the magnetization by $180^\circ$, from one parallel orientation to the easy axis to another.

This technique is used in magnetic (computer) storage devices such as hard-disks.

Primary requirement is a stable switching, so that the magnetization remains in its new position for a lasting time. The flip-time is not so important, since reading takes place much later than writing.
Switching with a $\mathbf{H}$-field

- switching with a (Oersted) $\mathbf{H}$-field is the classical method to change magnetization

- a magnetic field anti-parallel to the magnetization is applied, so that the spins will flip into the direction parallel to the external field

- switching can only occur though, when the magnetization has been excited thermally before so that $\mathbf{M}$ moves out of its easy-axis (if $\mathbf{M}$ is perfectly anti-parallel to $\mathbf{H}$ the field cannot act on it - similar to NMR-measurements)

- since the change of angle between $\mathbf{H}$ and $\mathbf{M}$ involves a momentum-transfer to the lattice ($\approx 100$ ps), this process is speed-limited in the spin-lattice relaxation time
Switching with spin-injection

a newer, sophisticated method for changing $\mathbf{M}$ is by injecting a spin-polarized electron current

this method directly acts a angular-momentum on the spins in the lattice, so the speed-limitation is only given by the duration and amplitude of the injection pulse

thus the spin-lattice-bottleneck is avoided, allows switchting on femto-second-scale switchting with spin-injection is very difficult, since it requires optimum angle between $\mathbf{M}$ and spin of injected current, faster switching also requires higher currents, so power-considerations have to be made in devices
Summary and Conclusion

- Ultra-fast spin dynamics deals with changes in magnetization on a time-scale $10^{-12} - 10^{-15}$

- such fast changes in magnetization are interesting for examination of fast magnetic interactions on the atomic-scale (spin-orbit-coupling, interatomic exchange etc)

- are usually induced and probed with femtosecond lasers (probing is also done with MOKE)

- on the technological hand ultra-fast spin-dynamics are necessary to develop faster and smaller (higher data density) storage media (magnetic switches)
References

- Chapter 15: Ultrafast Magnetization Dynamics
- J.D. Jackson; Classical Electrodynamics, Wiley 1962
- Haken, Wolf; Atom und Molekülphysik, Springer 19xx