Ultrafast Spin Dynamics

Adrian Glaubitz

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- 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

$\Longrightarrow$ 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

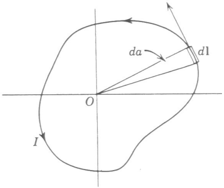
Magnetization is a property of some materials to exhibit a magnetic-field; it is defined as the magnetic moment per volume:

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

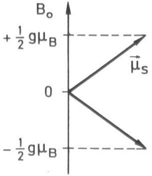
Magnetic moment is classically induced by a moving charge on a closed circuit

$$\vec{m} = \frac{1}{2} \oint \vec{x} \times d\vec{l} \qquad (2)$$

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 $\vec{J}$.



Simple model of a magnetic moment due to a circuit-loop



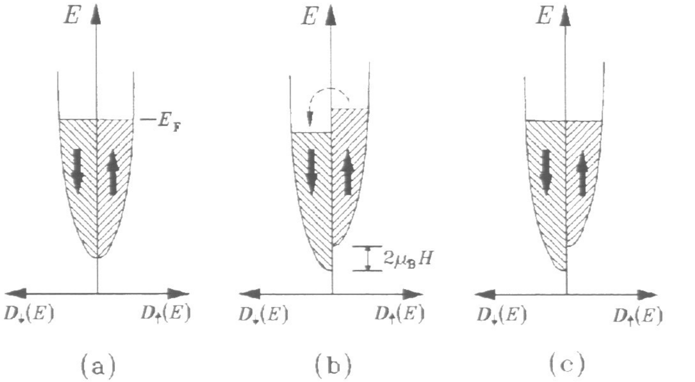
Electronic spin-momentum

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:

$$m = \mu_B \cdot (N^{up} - N^{down}) \quad \text{where} \quad N^{up} - N^{down} = 2\mu_B H D(E_F) \tag{3}$$

- is temperature independant


E
$-E_F$
$D_\downarrow(E)$
$D_\uparrow(E)$
(a)
E
$2\mu_B H$
$D_\downarrow(E)$
$D_\uparrow(E)$
(b)
E
$D_\downarrow(E)$
$D_\uparrow(E)$
(c)

Different time-scales of magnetization

Magnetization changes on different time-scales depending on the circumstances

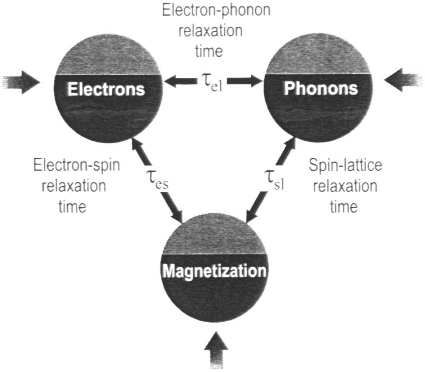
- 10^6 years: earth field (geomagnetism)
- 10^1 years: magnetic storage devices (tape, disk)
- $10^{-3} - 10^{-6}$ seconds: electronic circuits (coils, antennas)
- 10^{-9} seconds: read-write-heads of harddisks
- $10^{-12} - 10^{-15}$ seconds: **Ultrafast Spin Dynamics**

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

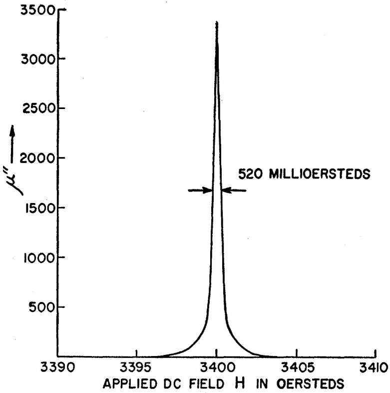


Heat reservoirs in a ferromagnetic metal

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

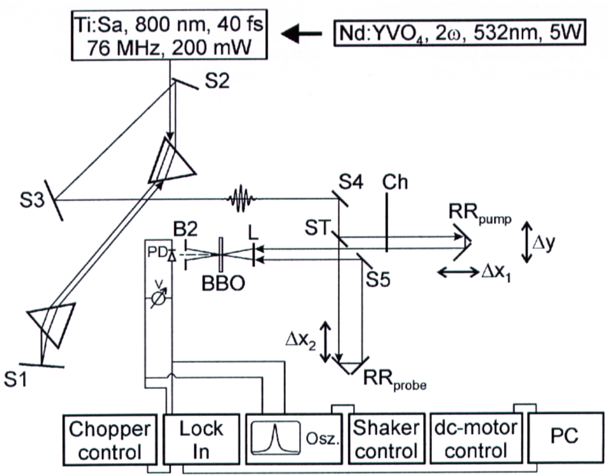


- when a short magnetic-field pulse is applied externally, the magnetization moves out its equilibrium and starts to precess around the axis of the external field
- since the total angular momentum needs to be conserved, the magnetic field experiences a torque opposite but equal to the precessional torque 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 transfered to the lattice, excitating 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 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


Ti:Sa, 800 nm, 40 fs
76 MHz, 200 mW
Nd:YVO$_4$, 2ω, 532nm, 5W
S2
S3
S4
Ch
RR$_{pump}$
Δy
B2
L
ST
PD
BBO
S5
Δx$_1$
V
Δx$_2$
S1
RR$_{probe}$
Chopper control
Lock In
Osz.
Shaker control
dc-motor control
PC

Probing magnetization

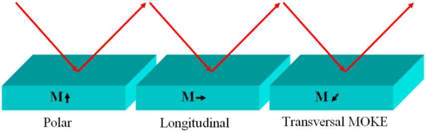
- after excitation we want to measure how magnetization has changed
- an important requirement of the probing is that it does not alter the magnetization induced with the pump-pulse; thus the probe-pulse needs to be small in amplitude so that it won't deposit additional energy
- also the probe pulse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

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)

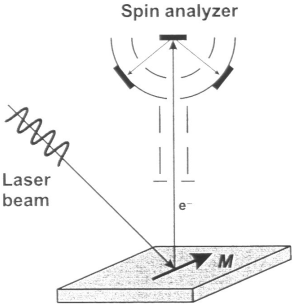
The magneto-optic Kerr-effect is well known method to measure the magnetization of a sample optically; it is quite mature and already widely used in technology



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

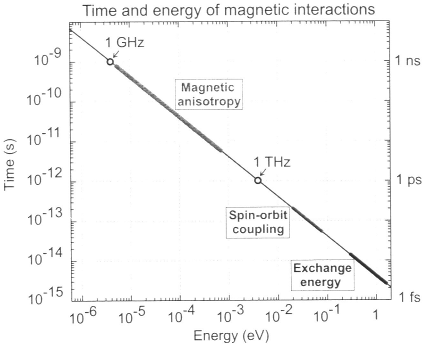
Today widely used in Magneto-Optical storage devices

By measuring the spin of Photoelectrons



setup for spin-detection

- 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 of the probing UV-pulse sets the time-span (other processes such as the transport of the photoelectrons to the surface and detector occur instantanouesly)



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

Many interesting interactions and phenonema on atomic-scale are in the time-scale of $10^{-12} - 10^{-15}$ s; thus they can be examined with USD-methods

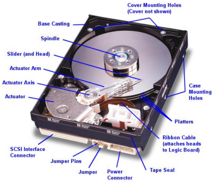
- magnetic anisotropy ($10^{-6} \leq 10^{-3}$ eV):
- atomic spin-orbit coupling energy ($10^{-2} \leq 10^{-1}$ eV)
- interatomic exchange energy ($E \approx 3 \times 10^{-1}$ eV)

Switching the Magnetization

Switching the magnetization refers to the process of completely rotating the magnetization by 180°, 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 **H**-field

- switching with a (Oersted) 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 excitated thermally before so that **M** moves out of its easy-axis (if **M** is perfectly anti-parallel to **H** the field cannot act on it - similar to NMR-measurements)
- since the change of angle between **H** and **M** involves a momentum-transfer to the lattic ($\approx$ 100 ps), this process is speed-limited in the spin-lattice relaxation time

Switching with spin-injection

a newer, sophisticated method for changing **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 **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 ususally induced and probed with femtosecondlasers (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

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