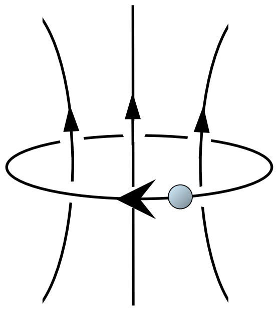
Magnetism in ultrathin films

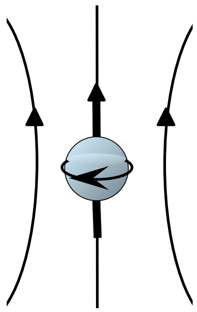
W. Weber

IPCMS Strasbourg

Orbital and Spin moment



Intuitive : Orbital moment



Mysterious : Spin moment

$$m_{orb} = I \cdot F = \left(-q \frac{\omega}{2\pi} \right) (\pi r^2) = -\frac{q}{2m} (m r^2 \omega)$$

$$= -\frac{q}{2m} L = -\frac{q}{2m} \hbar l = -\frac{q\hbar}{2m} l$$

$$m_{orb} = -g_l \mu_B l \quad \text{with} \quad g_l = 1$$

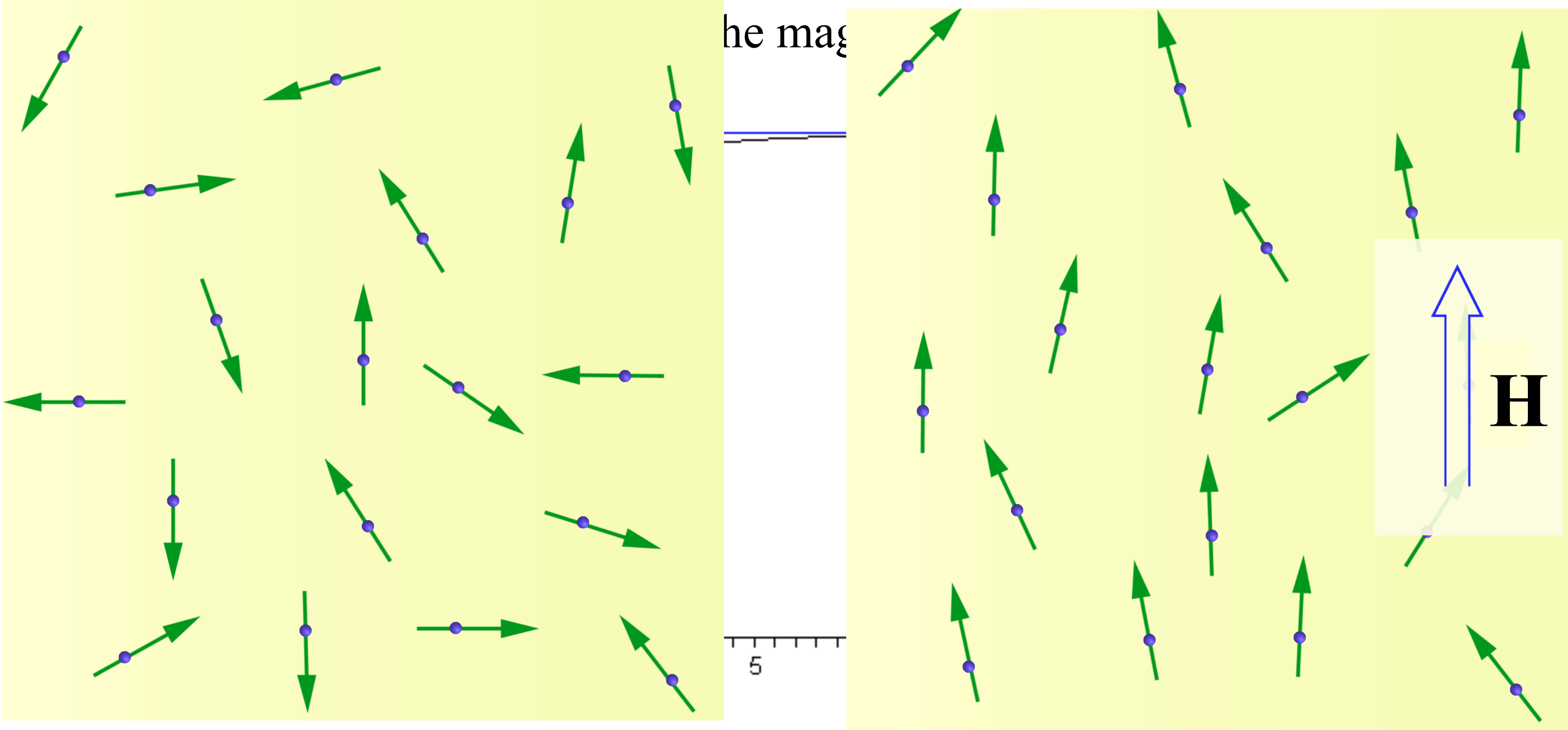
Angular spin momentum : $\hbar s$

$$m_{spin} = -g_s \mu_B s \quad \text{with} \quad g_s = 2$$

Ferromagnetism

Paramagnetic behavior: usually one has to apply an external

he mag

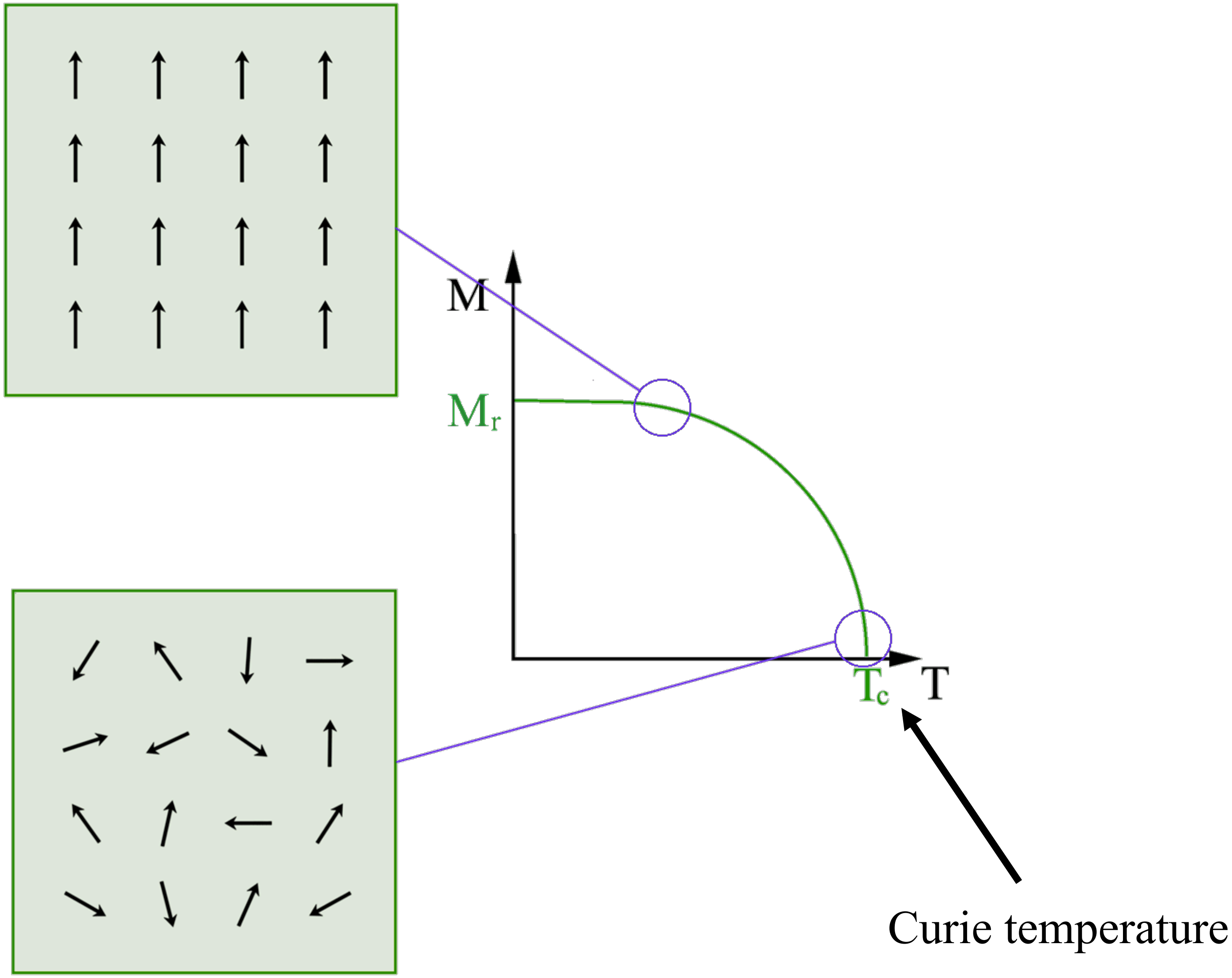


$$\alpha \propto \frac{}{T}$$

Ferromagnetic behavior: magnetization ***without*** an external magnetic field at non-zero temperatures possible

Ferromagnetism

How can we explain magnetic order up to temperatures of 1000 K?



Curie temperature

Ferromagnetism

Early explanation (1907): **Weiss' molecular field**

A molecular field exists within the ferromagnet which orders the moments against the thermal motion. It is so large that the ferromagnet can be saturated even without an external magnetic field.

Order of magnitude:

$$k_B T_c \approx \mu_0 \mu_B H_m$$

$$T_c = 1000\,\mathrm{K} \quad \longrightarrow \quad H_m \approx 10^9\ \mathrm{A/m}$$

Ferromagnetism

What is the physical interaction responsible for it?

Dipole-dipole interaction?

$$E_{dip} = \frac{1}{r^3}\vec{m}_1 \cdot \vec{m}_2 - \frac{3}{r^5}\left(\vec{m}_1 \cdot \vec{r}\right)\left(\vec{m}_2 \cdot \vec{r}\right)$$

Strength $\frac{\mu_0 \mu_B^{\,2}}{a^3} \approx 1\,\mathrm{K}$ Too weak!

Ferromagnetism

Interplay of Pauli principle and Coulomb interaction

Two electrons of opposite spin can share the same orbital and come close

Two electrons of same spin cannot ⇒ farther apart ⇒ Lower Coulomb energy

This interaction does not act like a real magnetic field

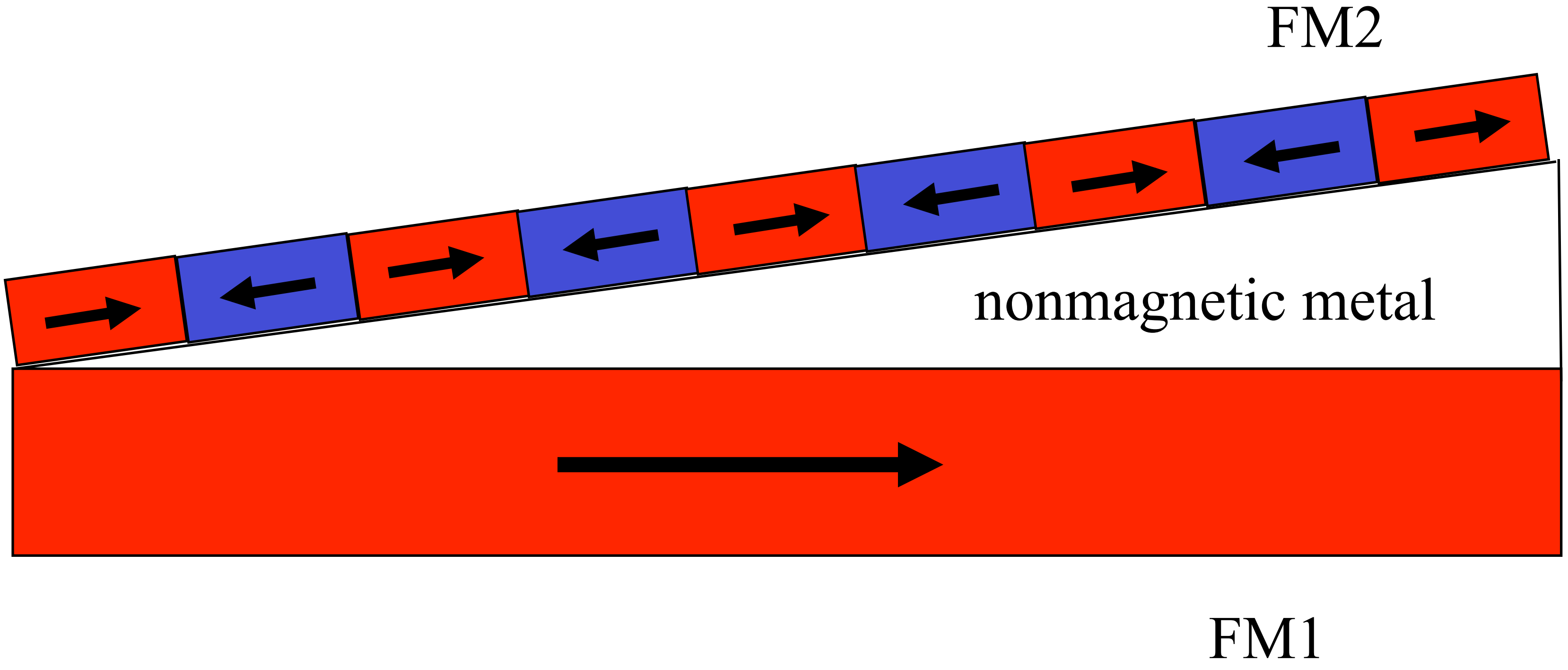
Exchange interaction in a solid

$$H = -J \sum_{i \neq j} \vec{S}_i \cdot \vec{S}_j$$

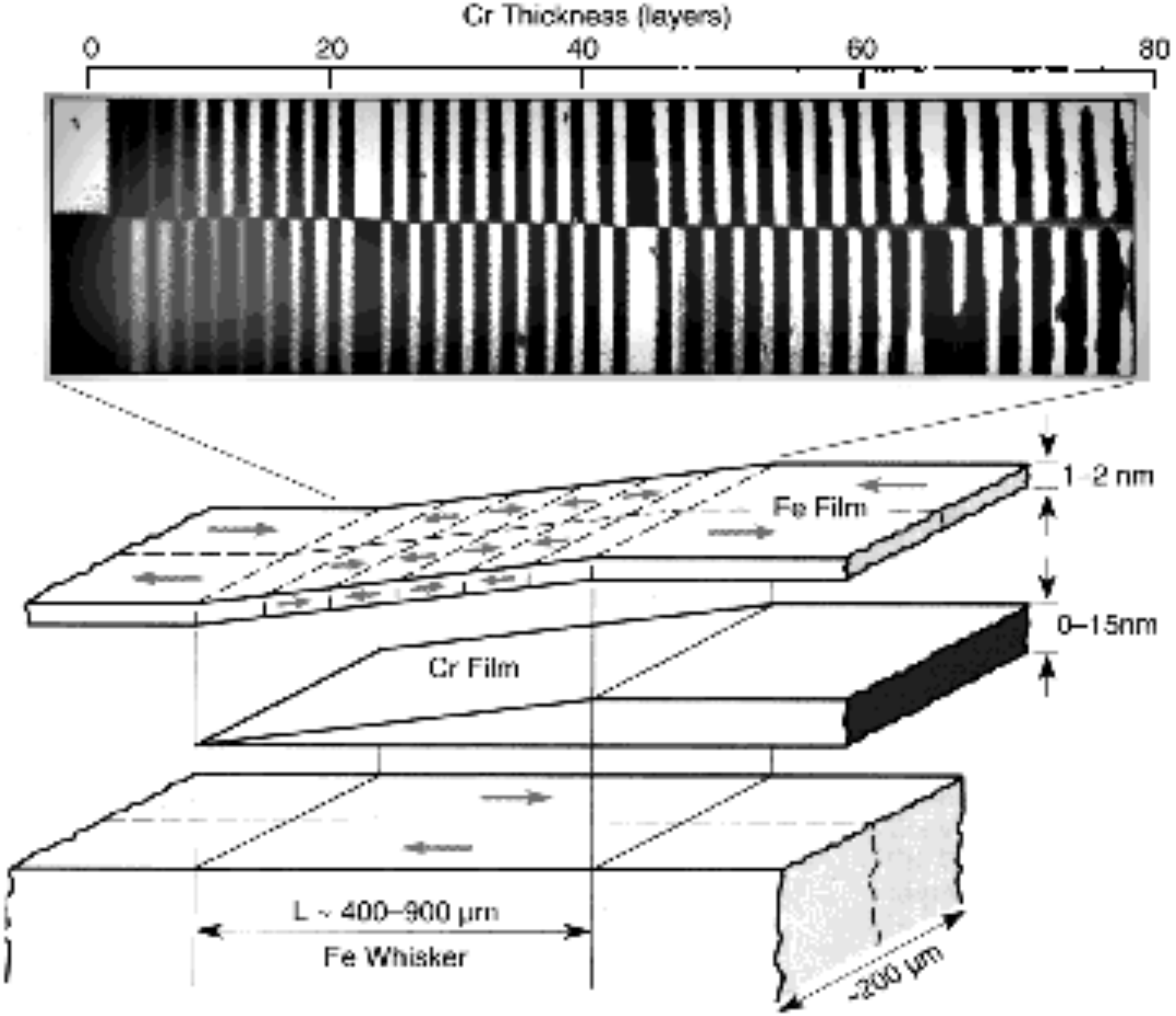
J positive : parallel orientation (ferromagnetic)
J negative : anti-parallel orientation (anti-ferromagnetic)

The strength of the interaction depends on the orbital overlap between neighbouring atoms ⇒ decreases exponentially with distance

Indirect exchange coupling in multilayers



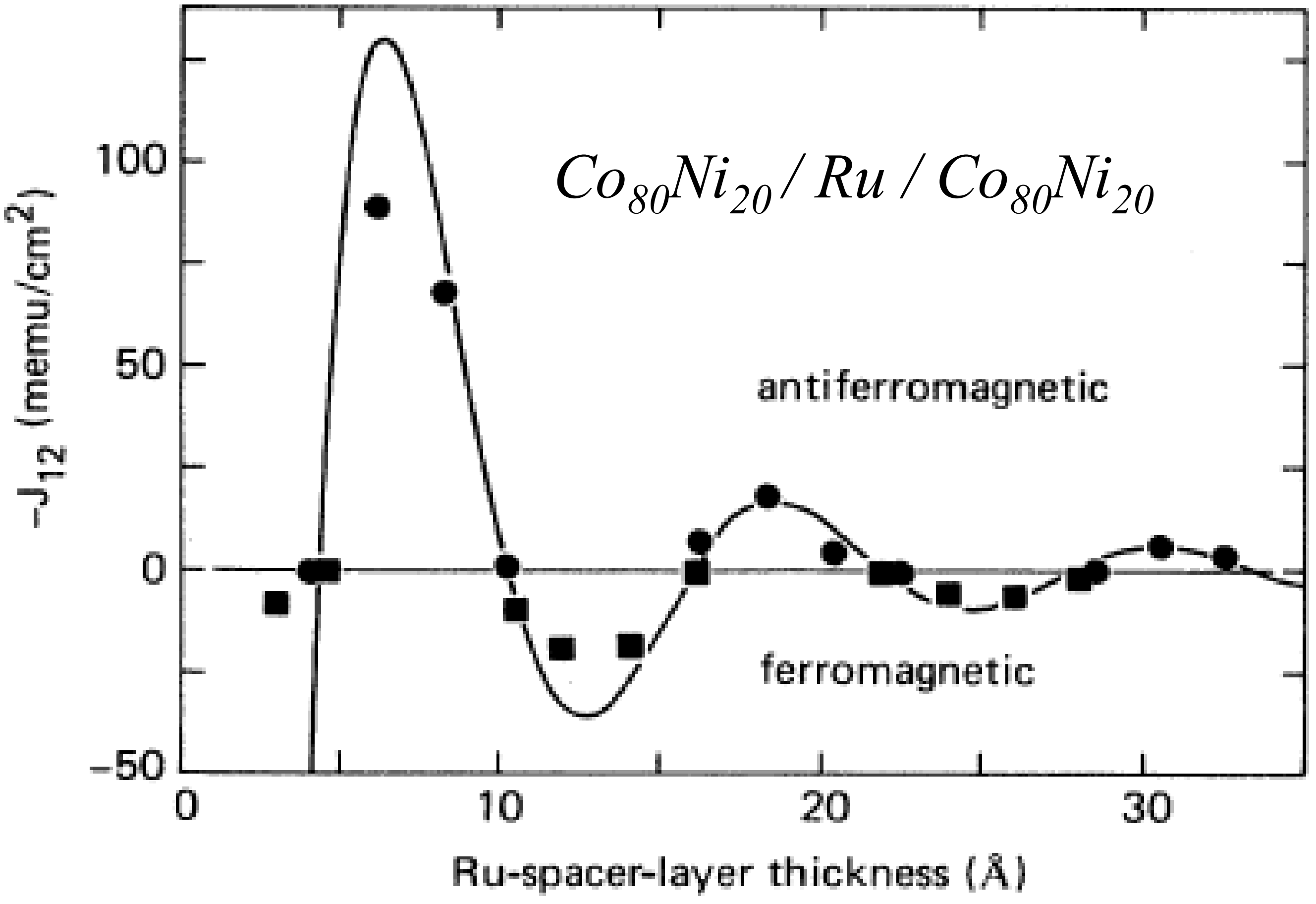
Indirect exchange coupling



Unguris et al., Phys.Rev. B 49, 14 (1994)

Indirect exchange coupling in multilayers

Amplitude of the coupling strength decreases with thickness



Parkin et al., Phys.Rev. B 44, 7131 (1991)

Indirect exchange coupling

RKKY interaction (Ruderman, Kittel,Kasuya, Yosida).

I

V

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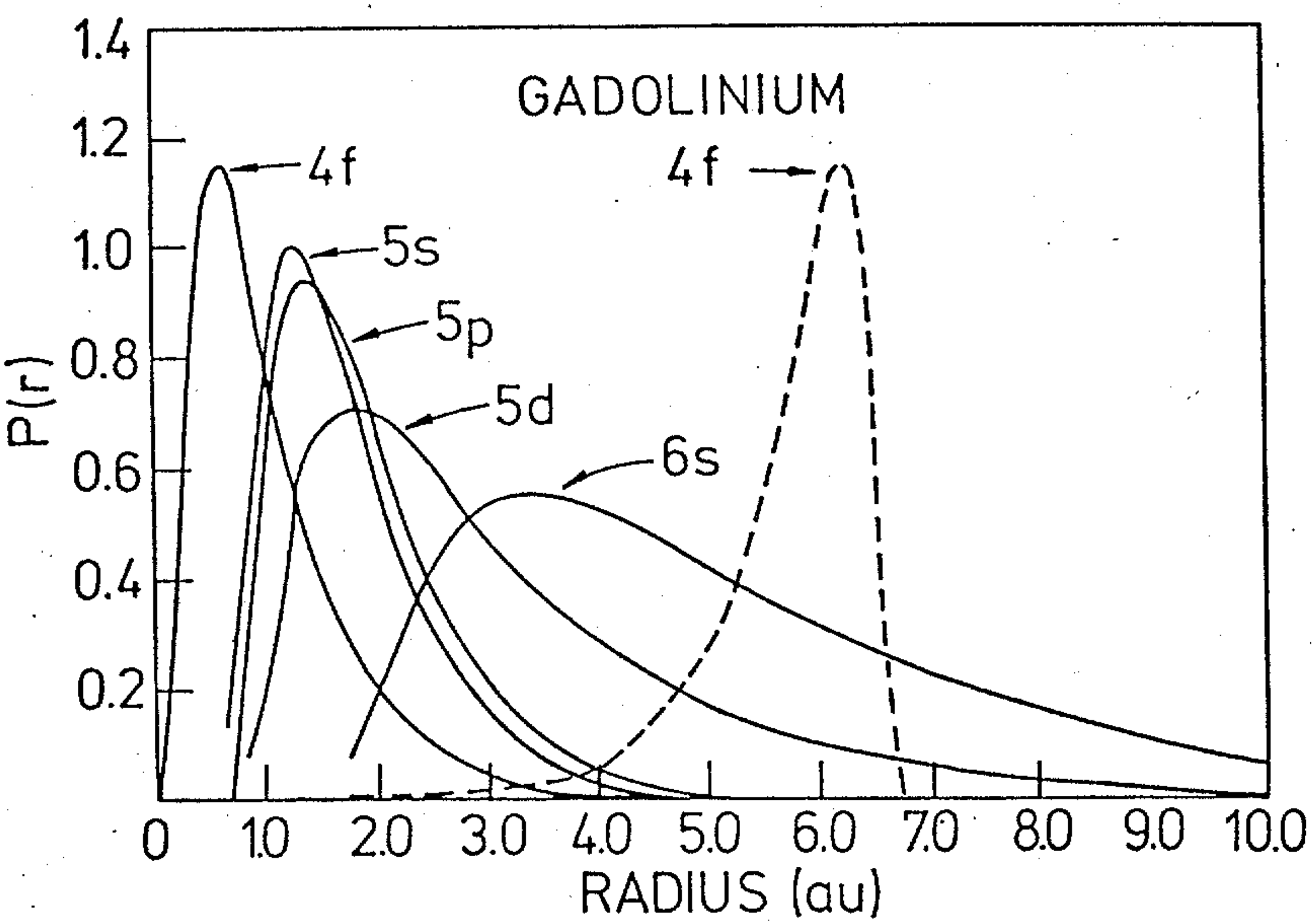
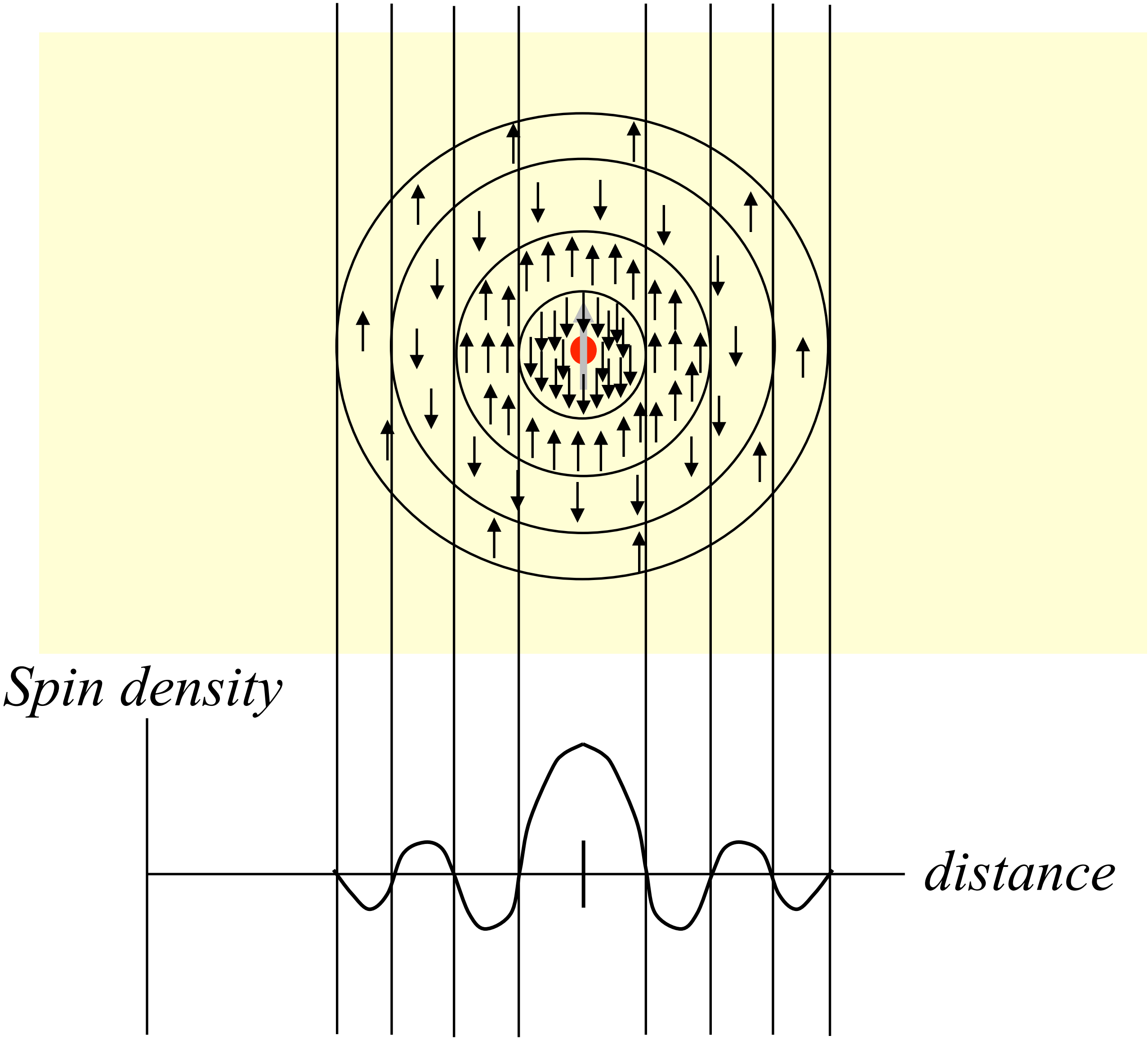
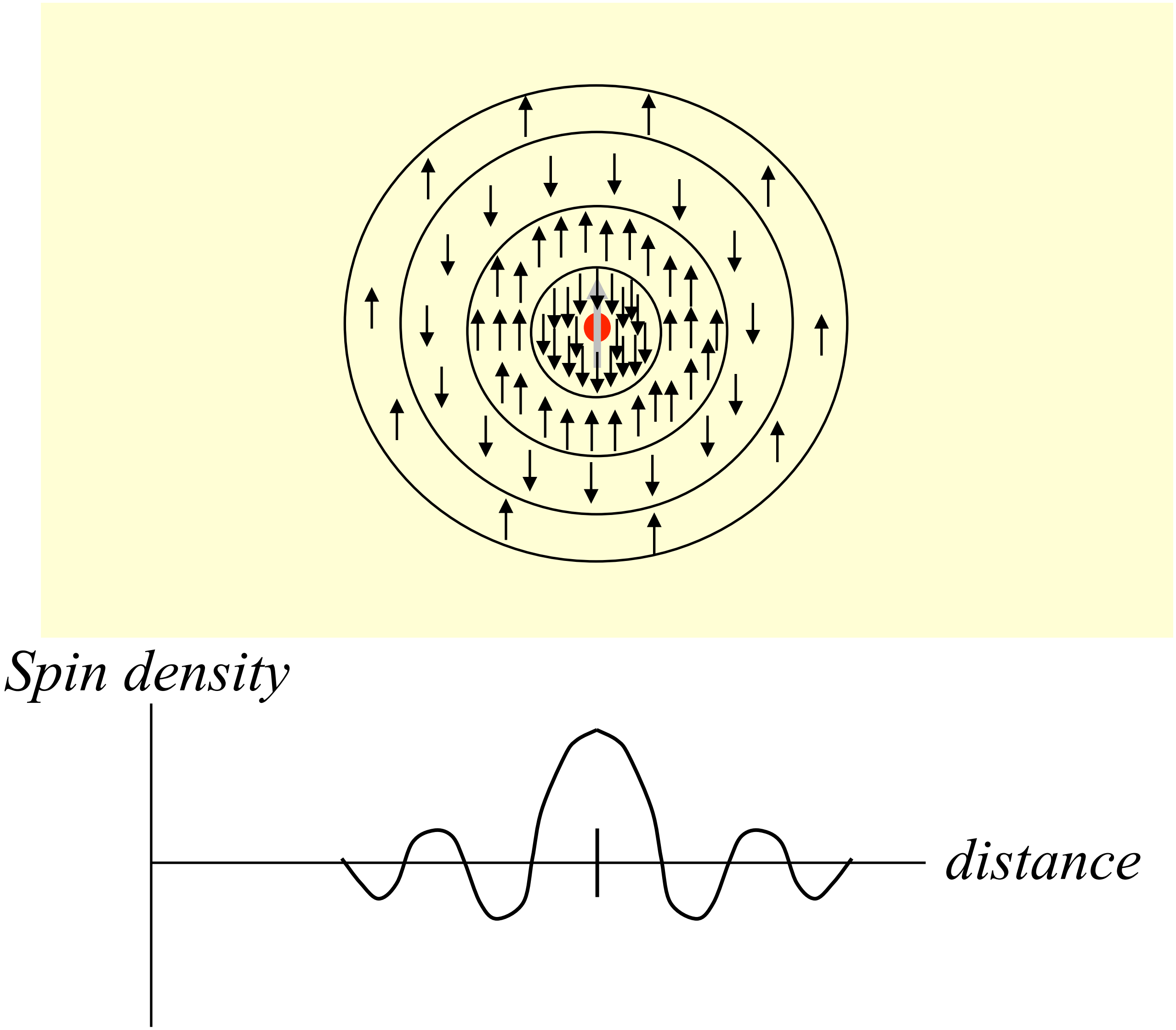


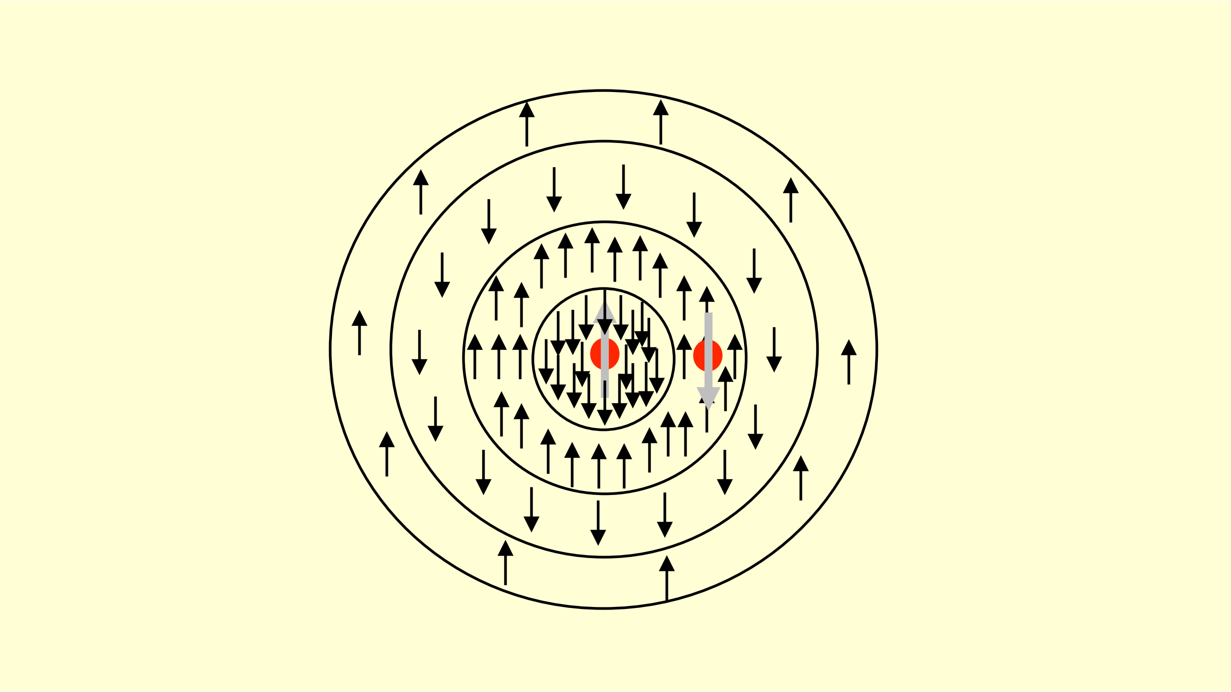
RKKY interaction

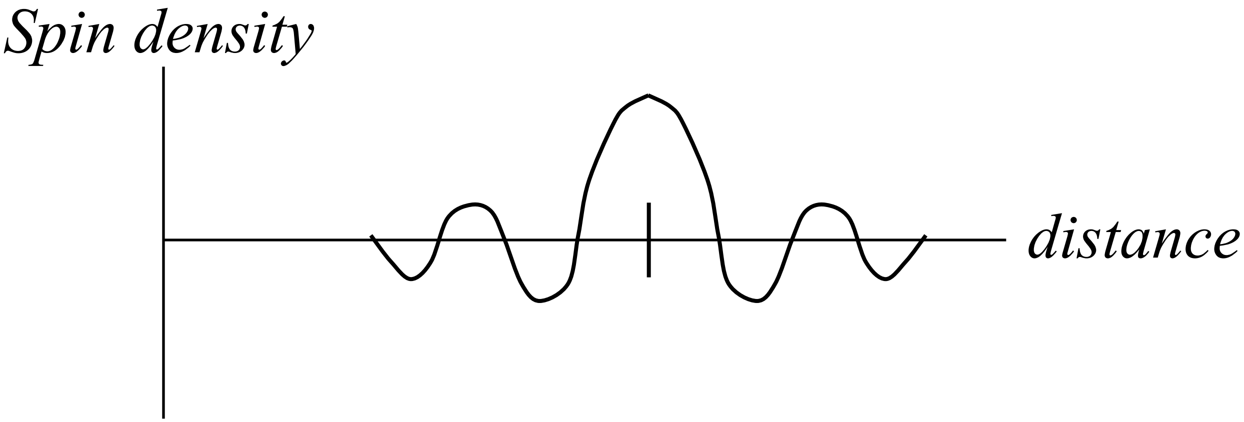


RKKY interaction

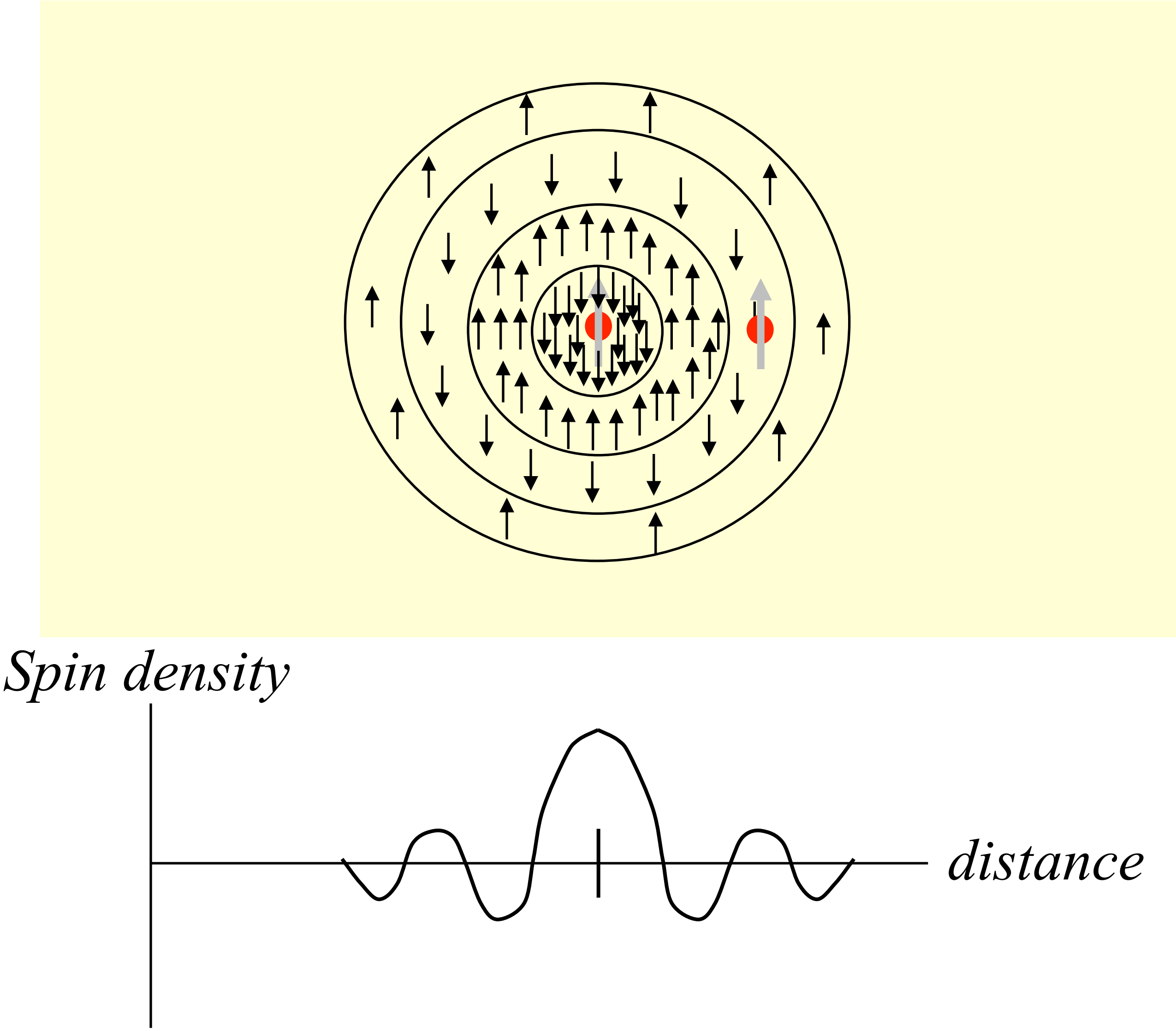


RKKY interaction

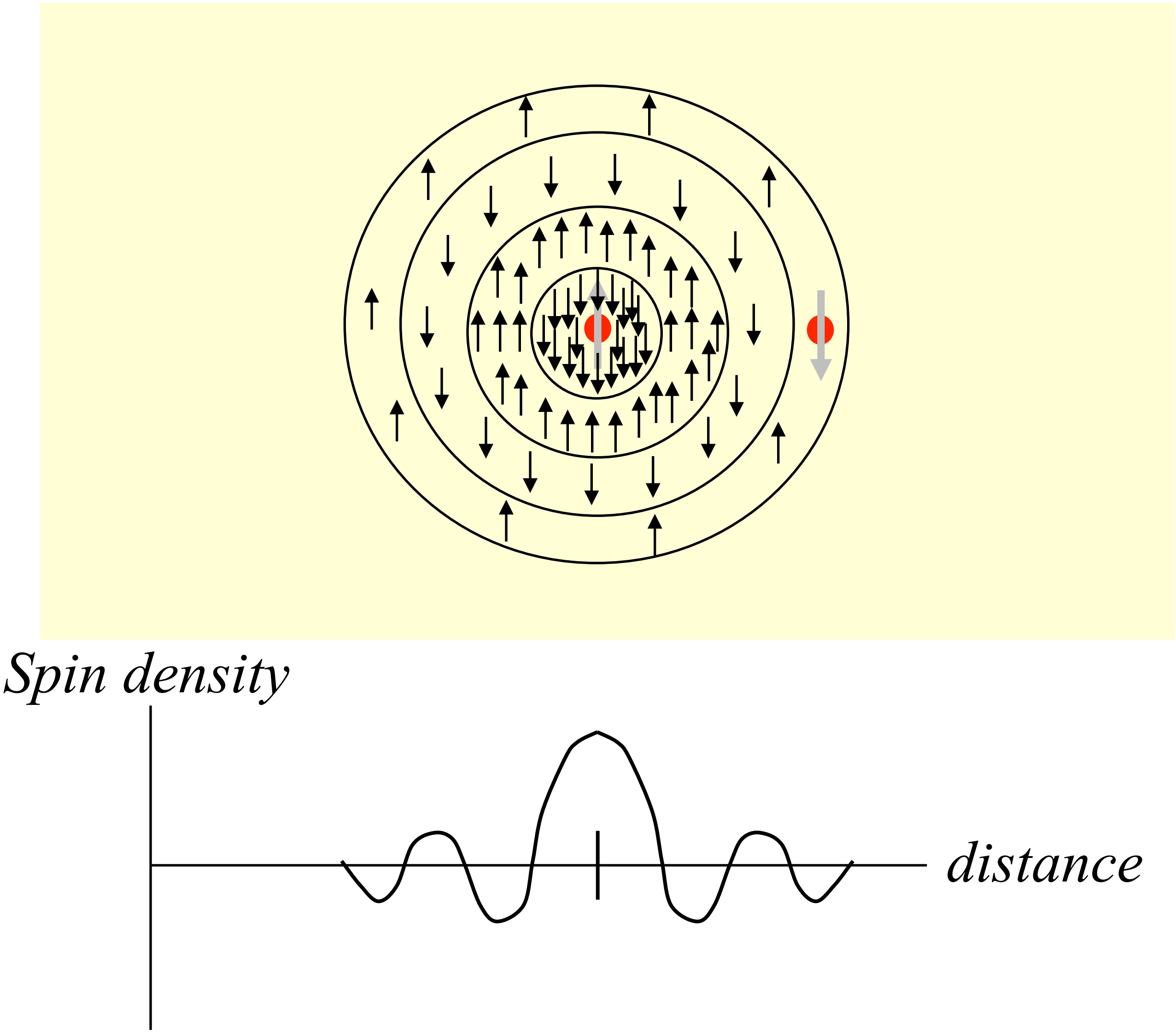




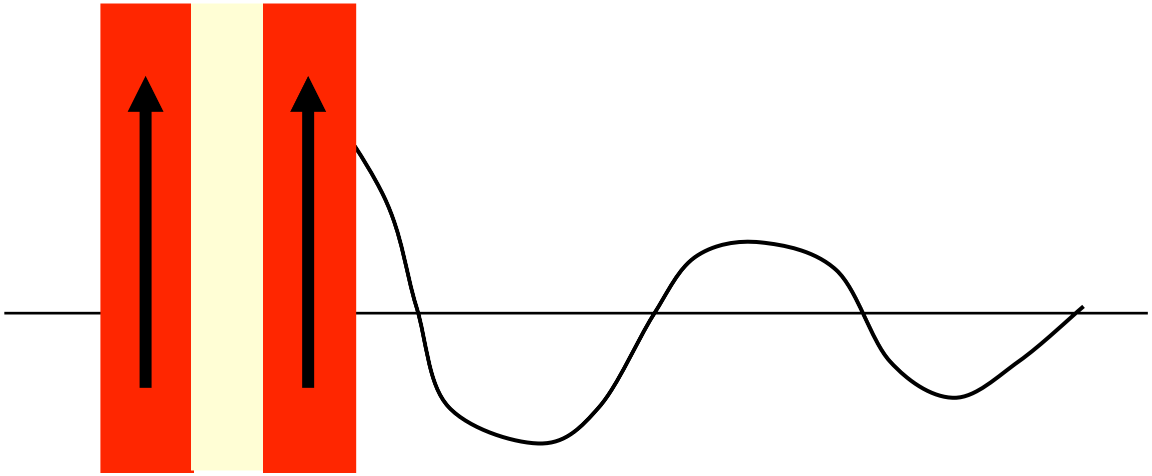
RKKY interaction



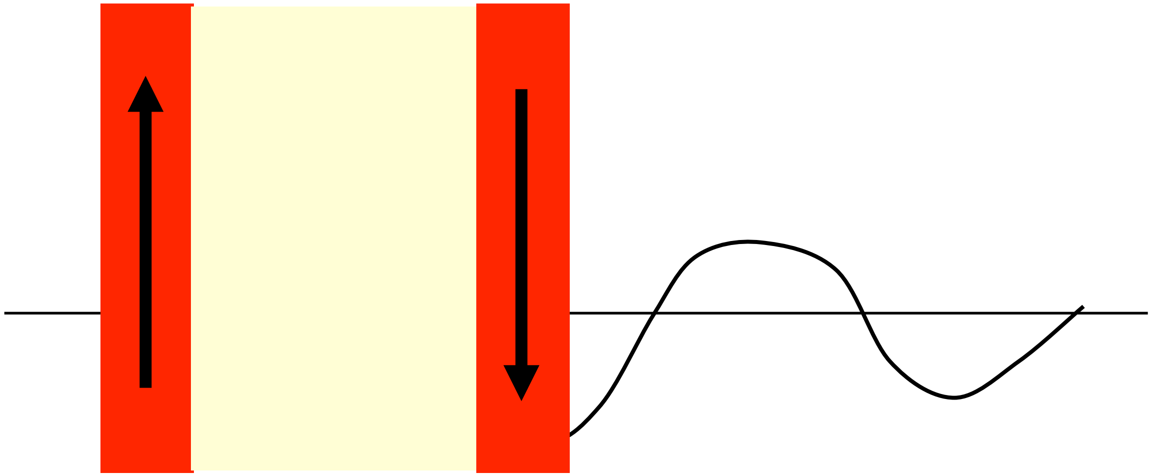
RKKY interaction



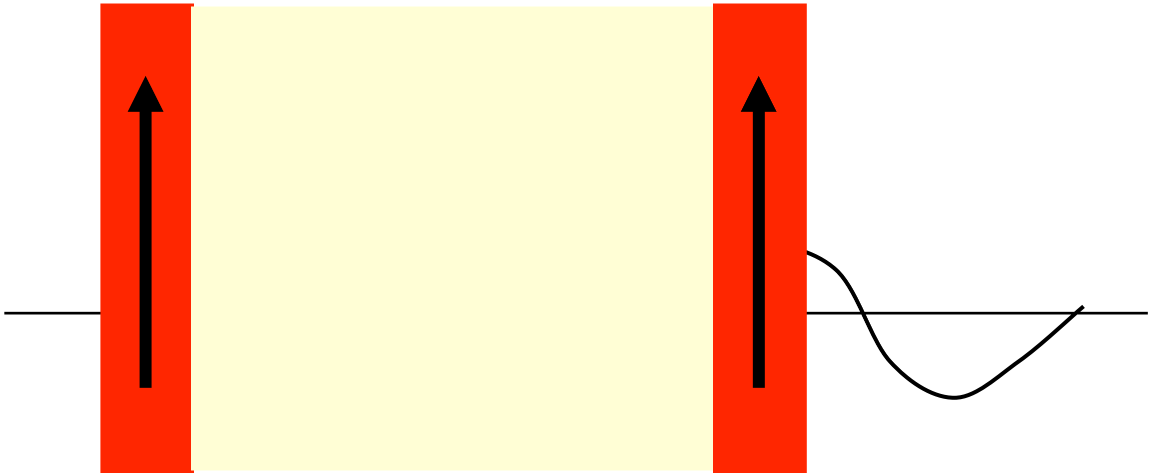
RKKY interaction



RKKY interaction



RKKY interaction



RKKY interaction

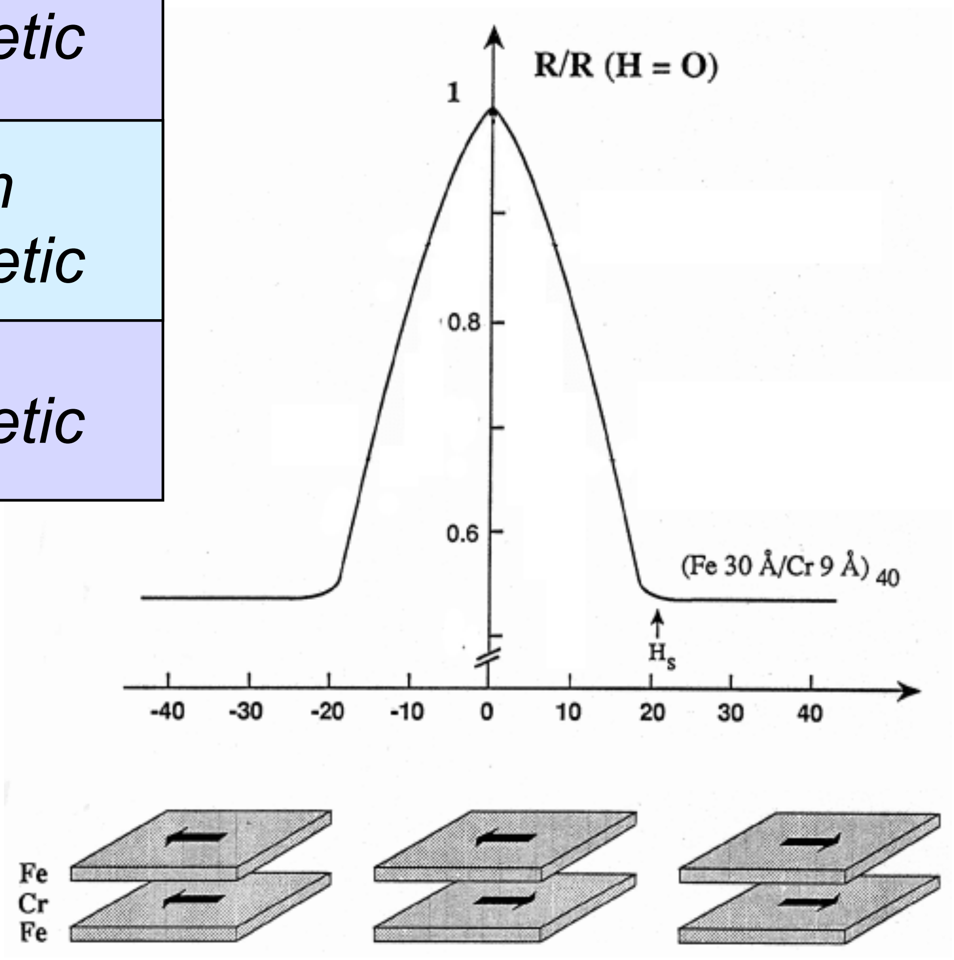
$$J = \frac{1}{R^2}\sin(2k_F R)$$

Giant magnetoresistance

Fe *Magnetic*

Cr *Non magnetic*

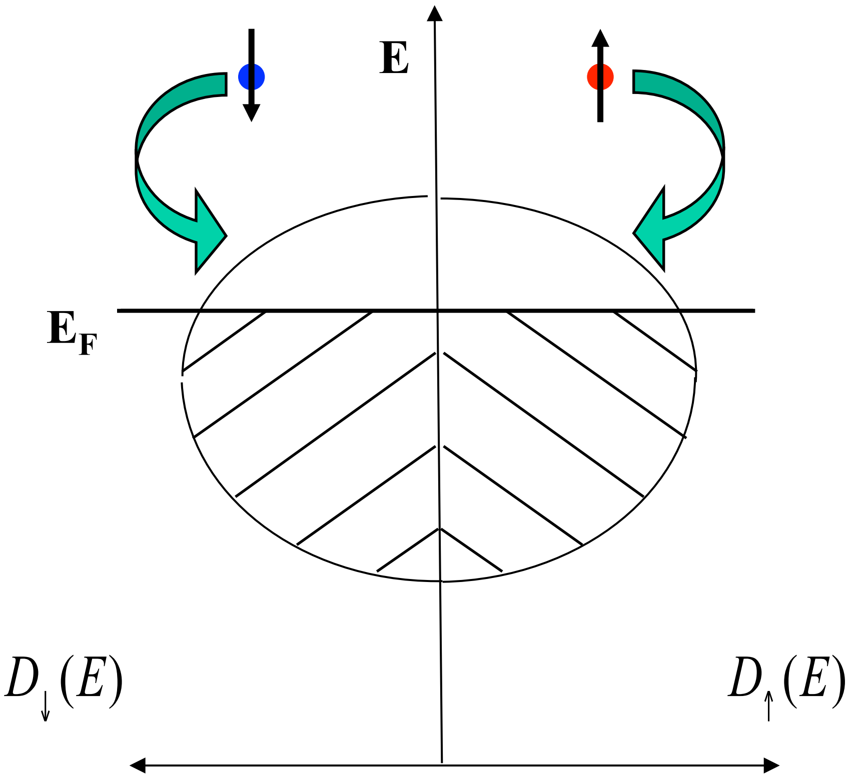
Fe *Magnetic*



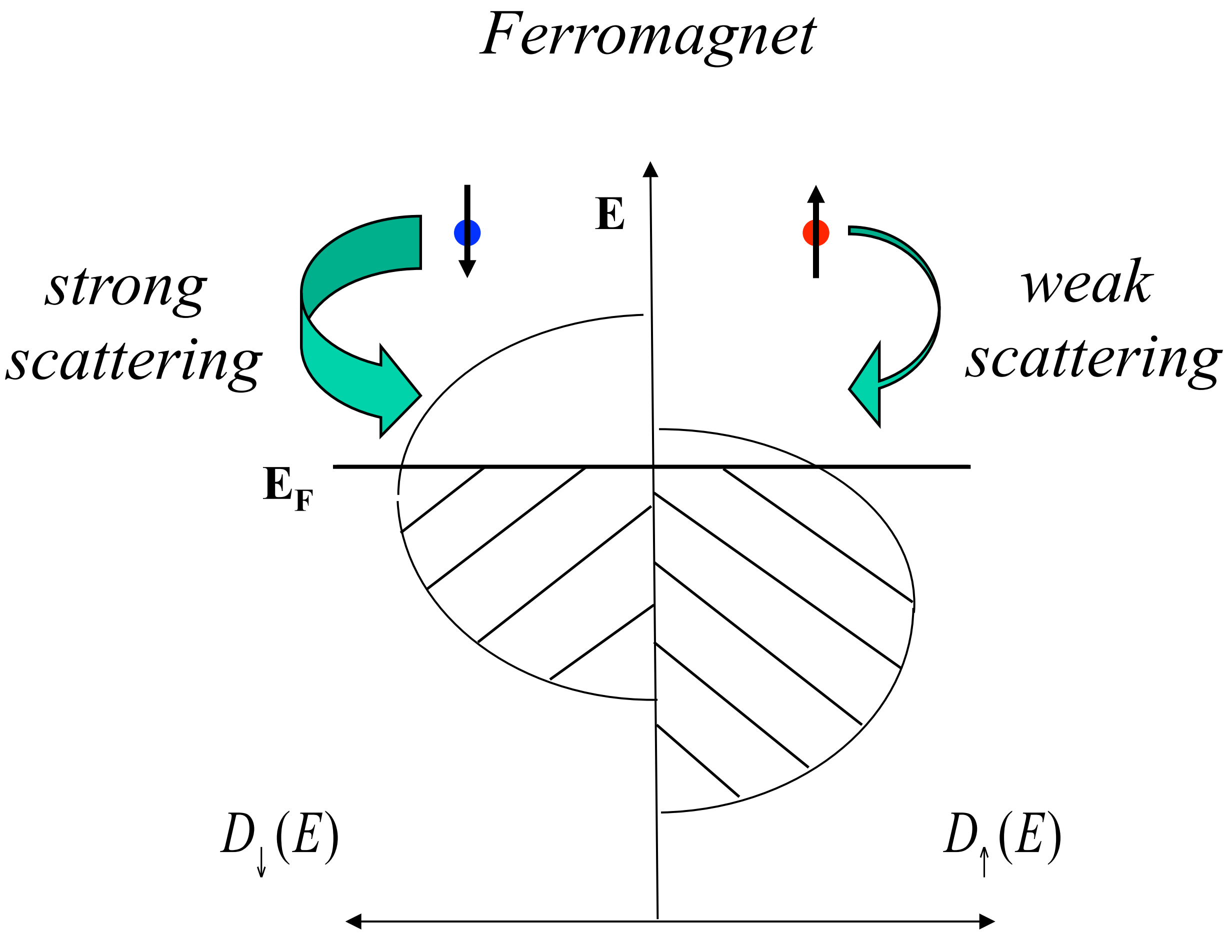
Baibich et al., PRL 61,2472 (1988)

Spinfilter effect

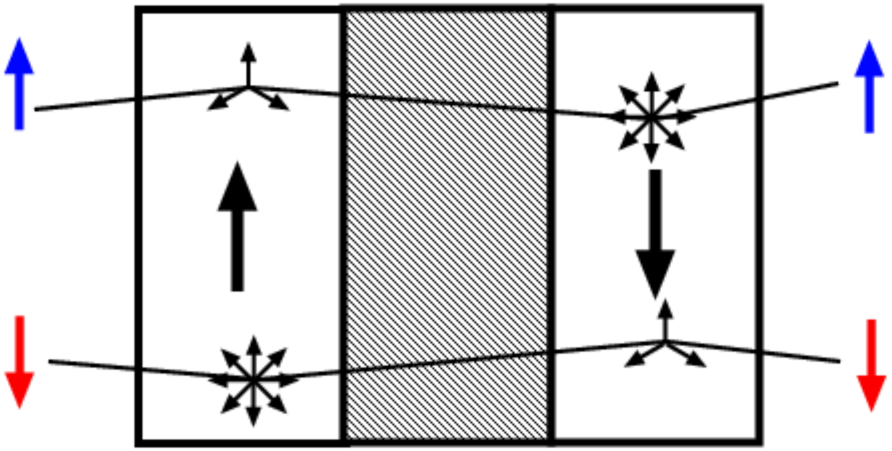
Paramagnet

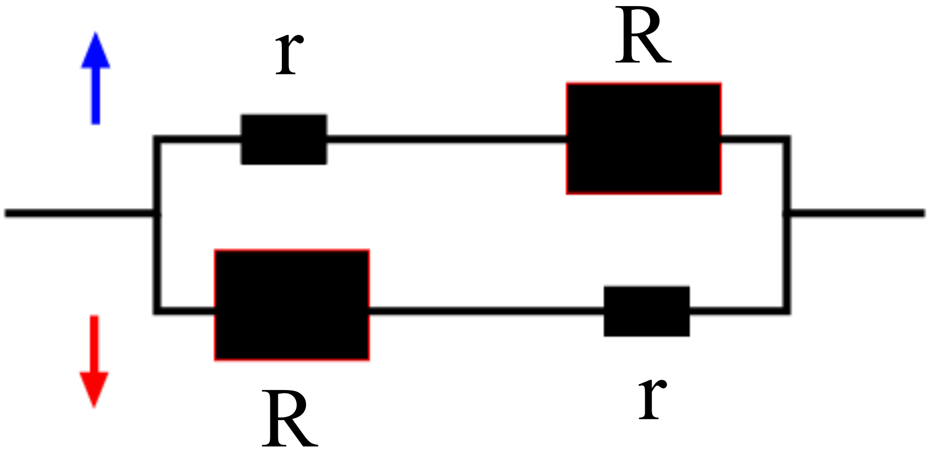


Spinfilter effect



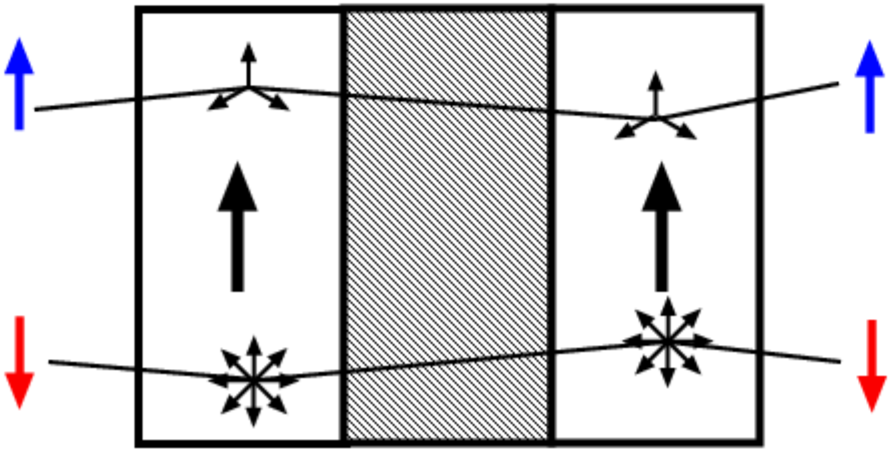
Giant magnetoresistance

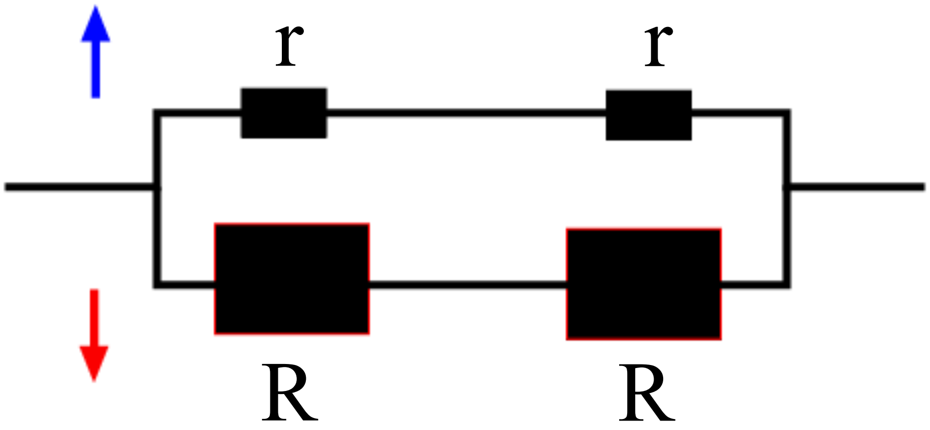




$$R_{tot} = \frac{R+r}{2} \approx \frac{R}{2}$$

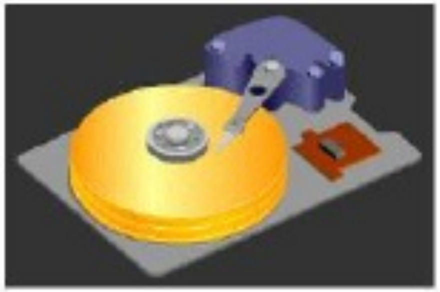
Giant magnetoresistance





$$R_{tot} = \frac{2Rr}{R+r} \approx 2r$$

Spintronics: Applications



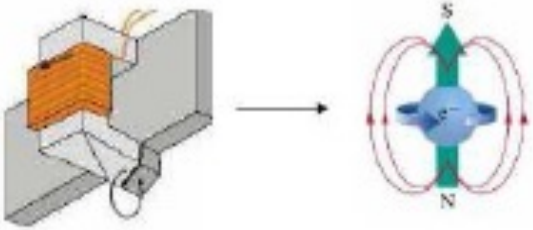
Spintronics explores new avenues for

- **Information reading**

  GMR, TMR sensors

- **Information reading & storage**

  MRAM chips

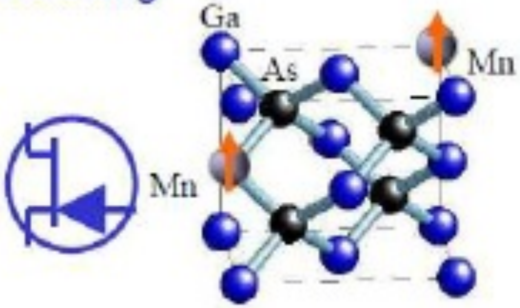


- **Information reading & storage & writing**

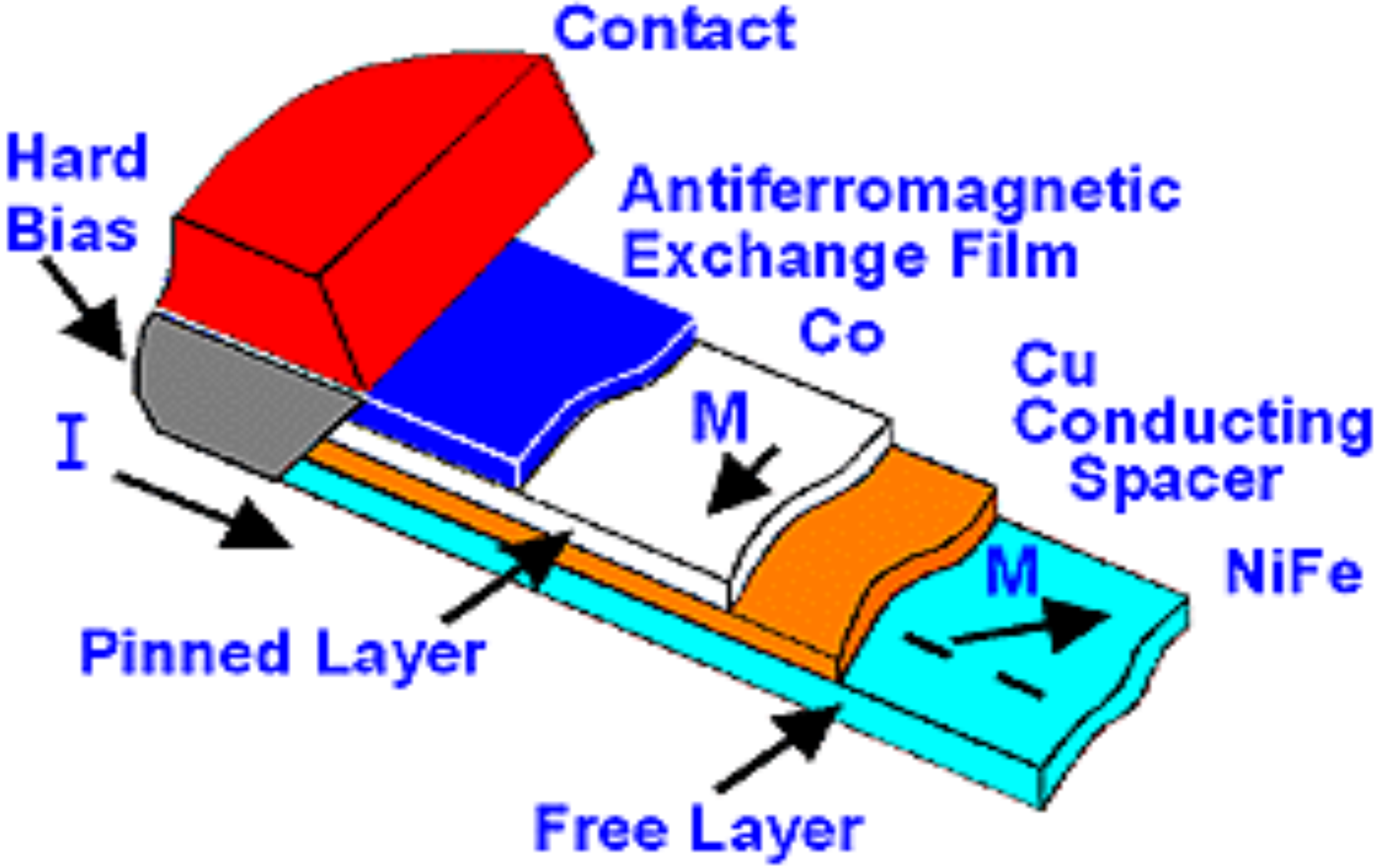
  magnetization switching by spin-currents

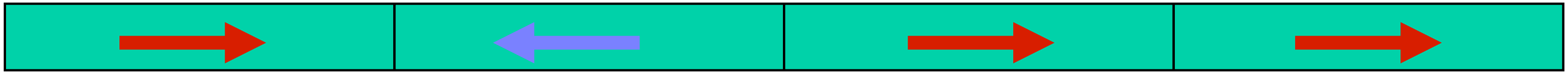
- **Information reading & storage & writing & processing**

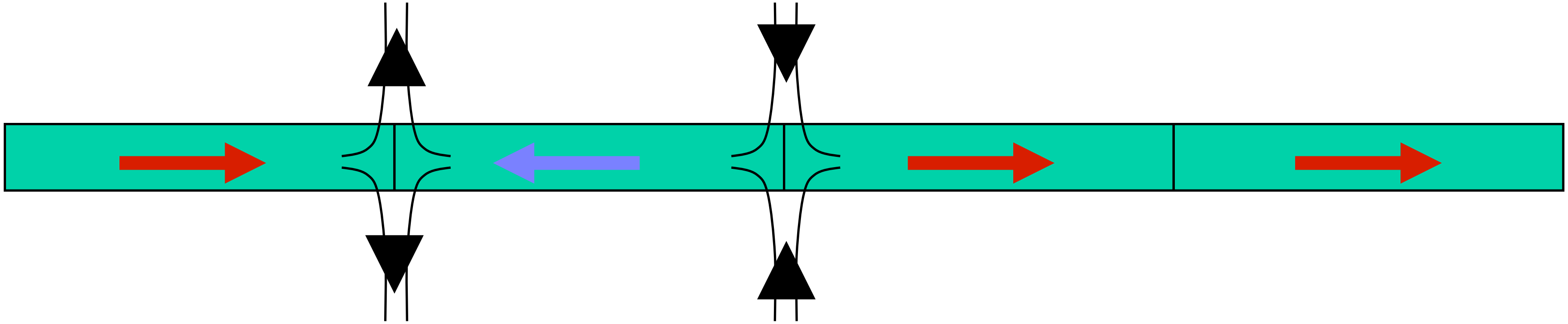
  spins & transistors & semiconductors

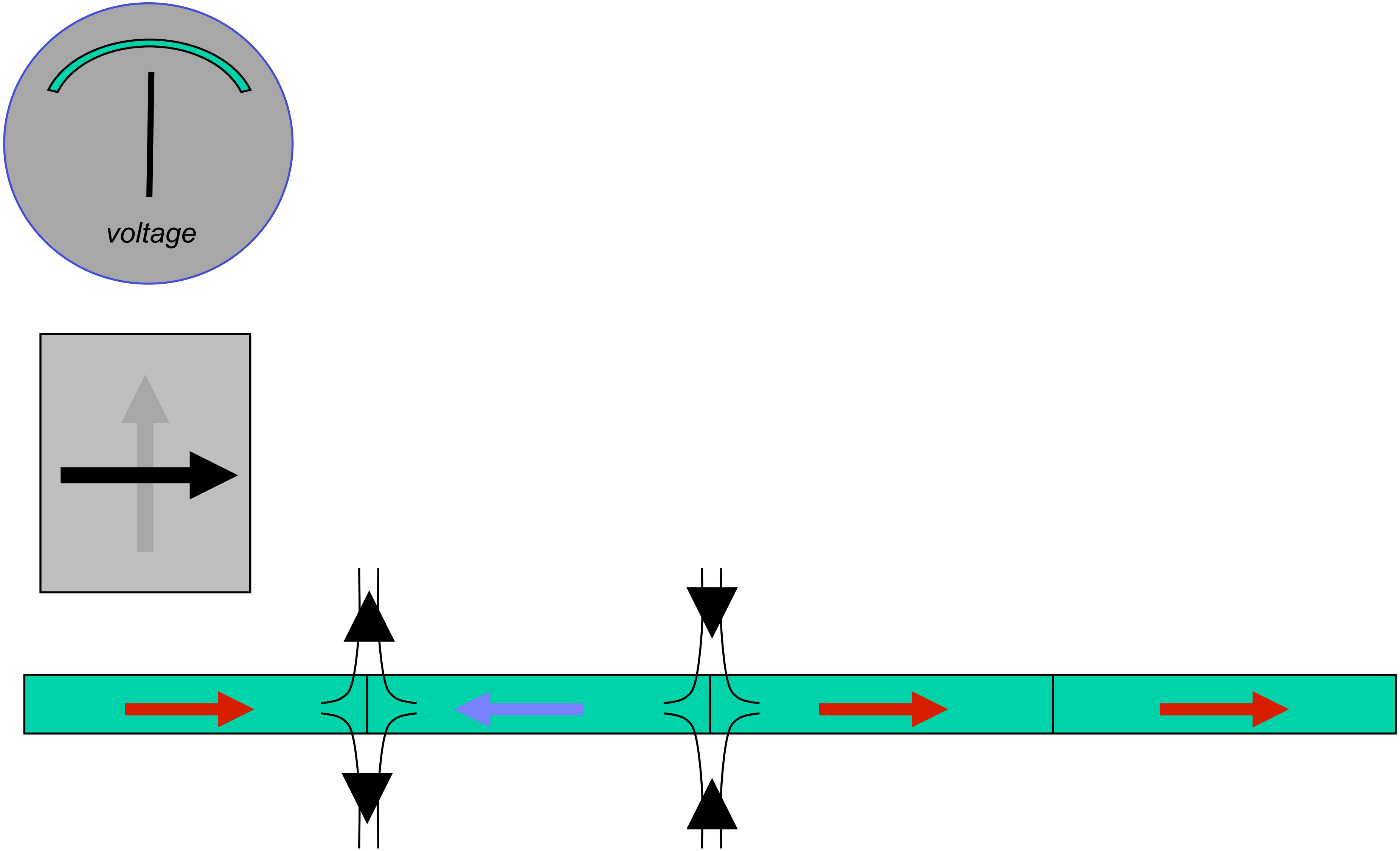


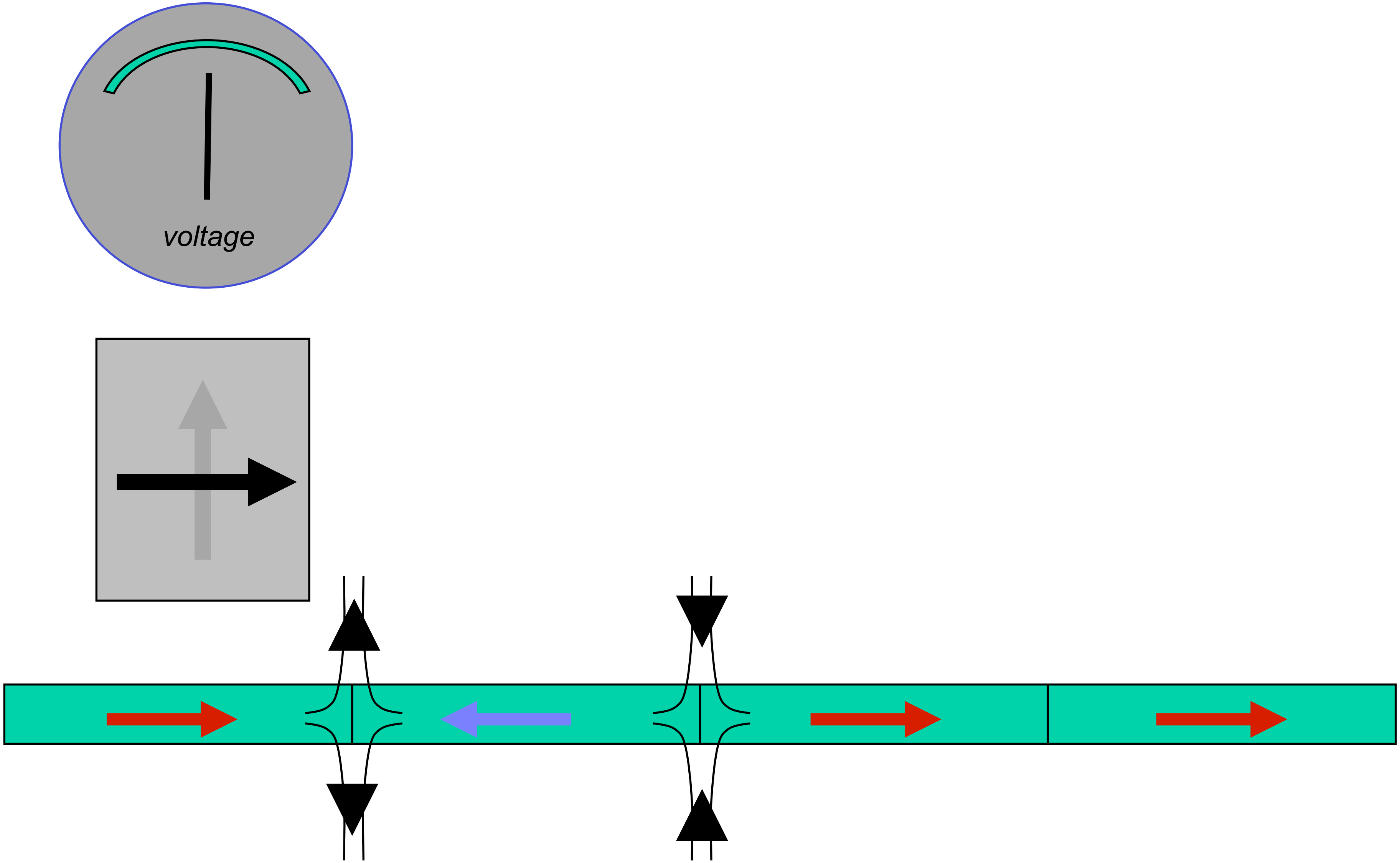
GMR read head

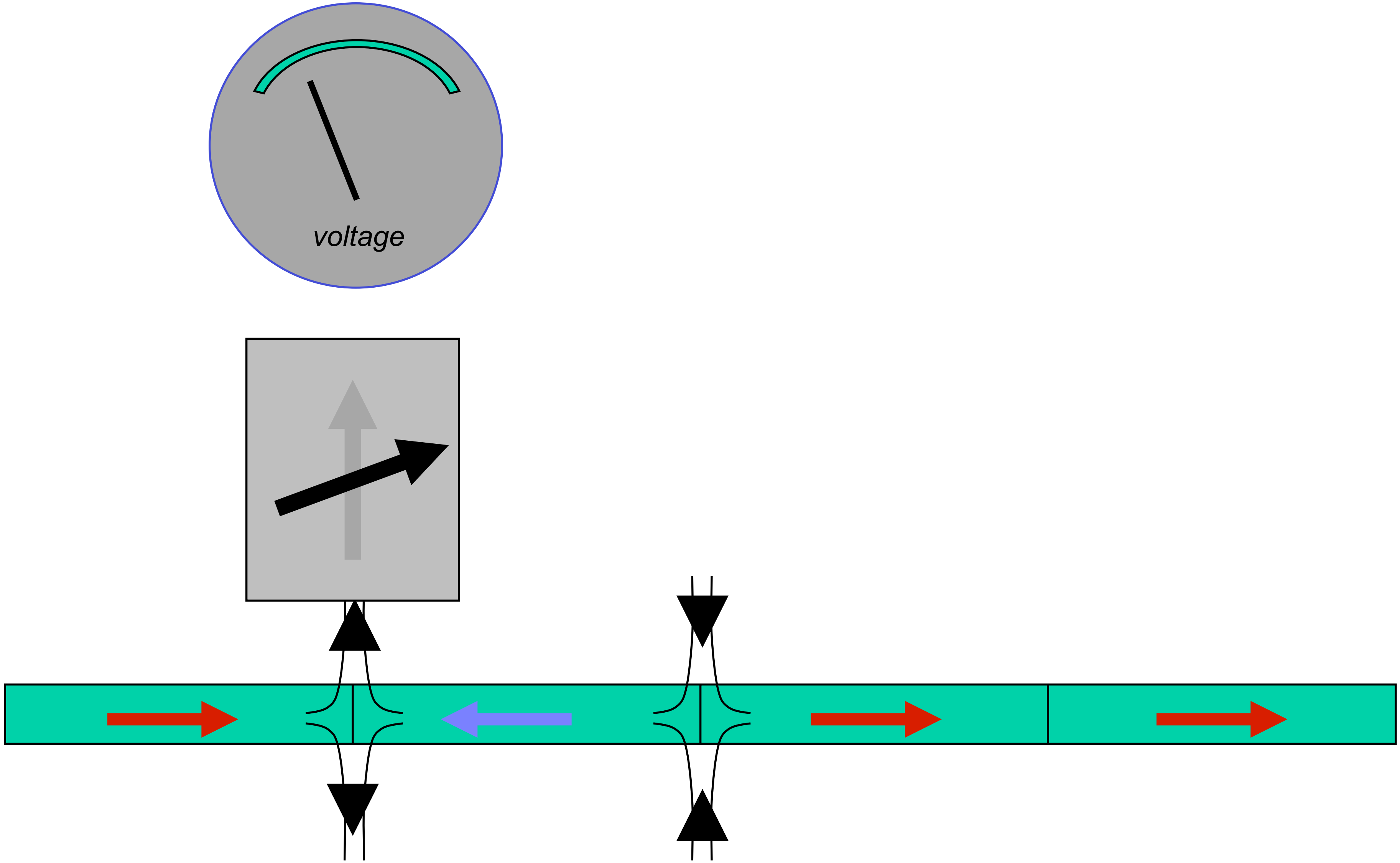


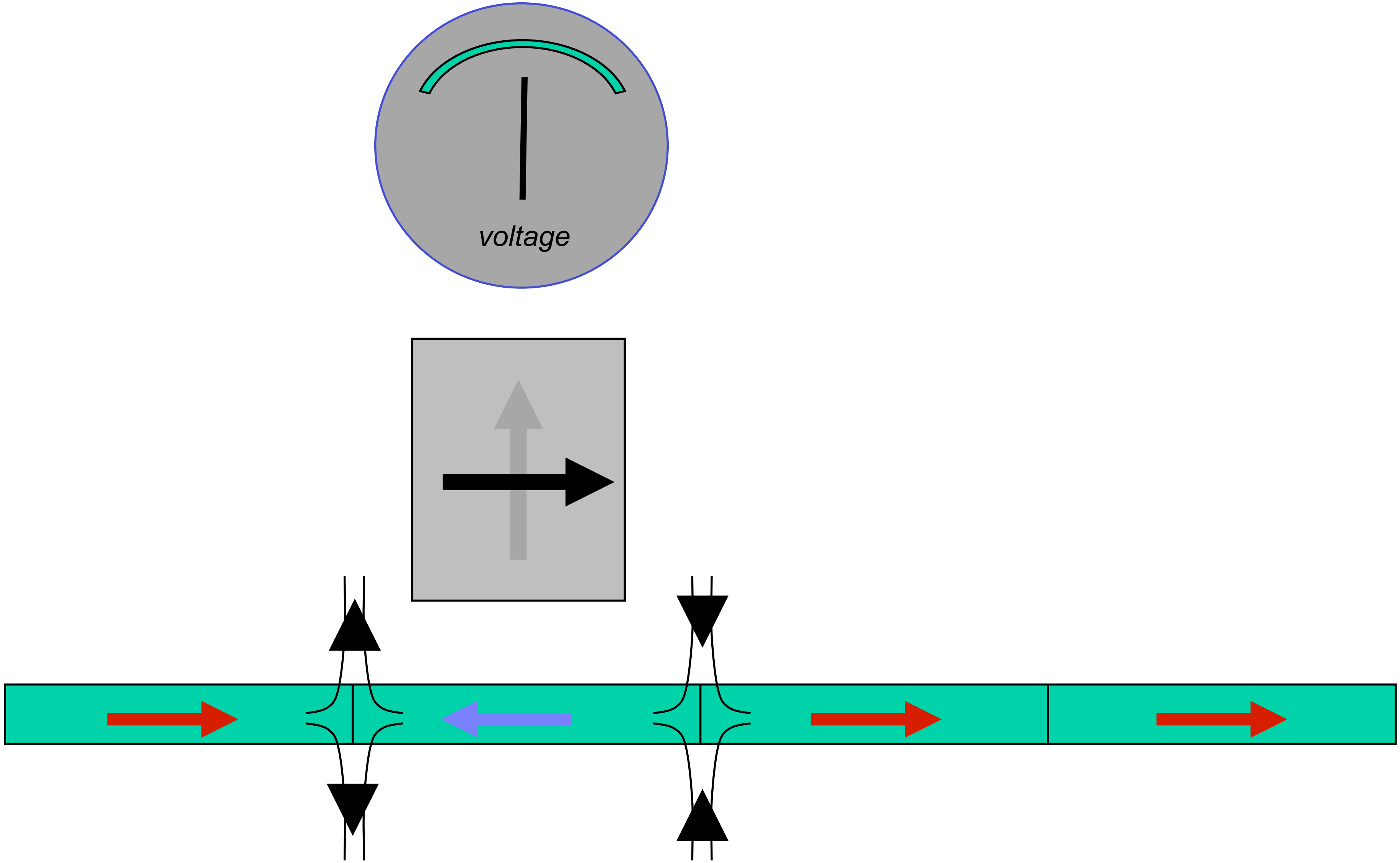


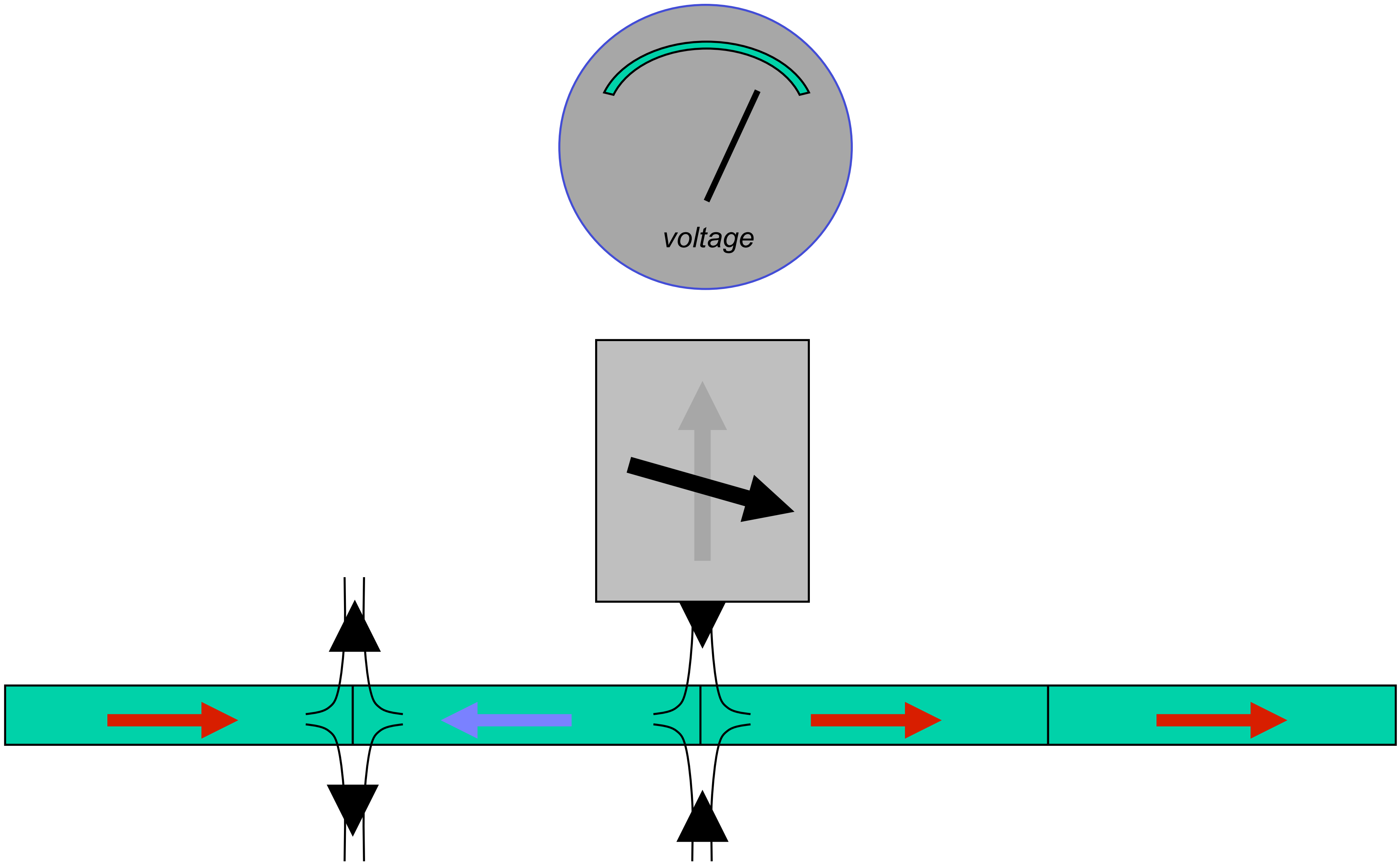



voltage


voltage


voltage


voltage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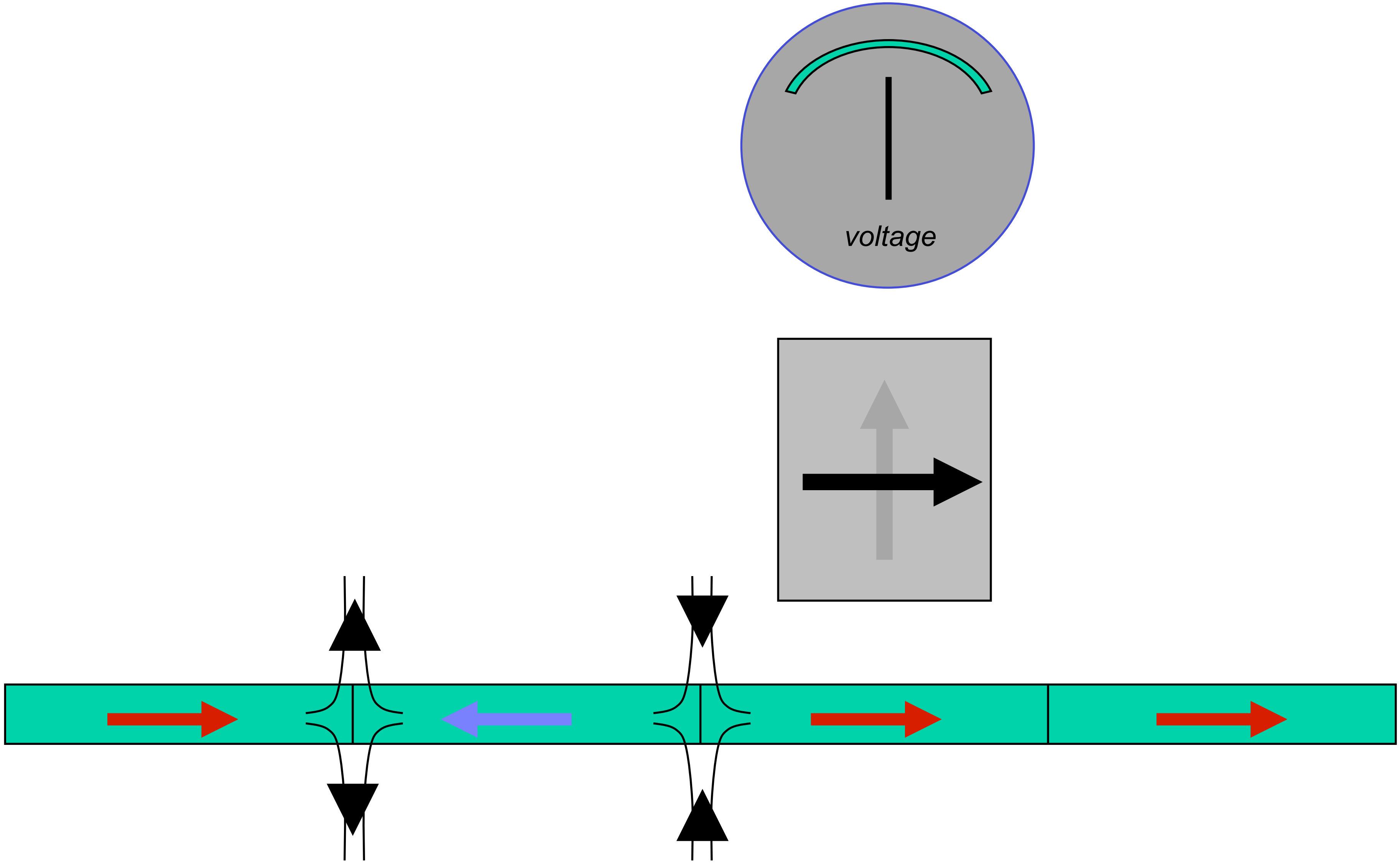
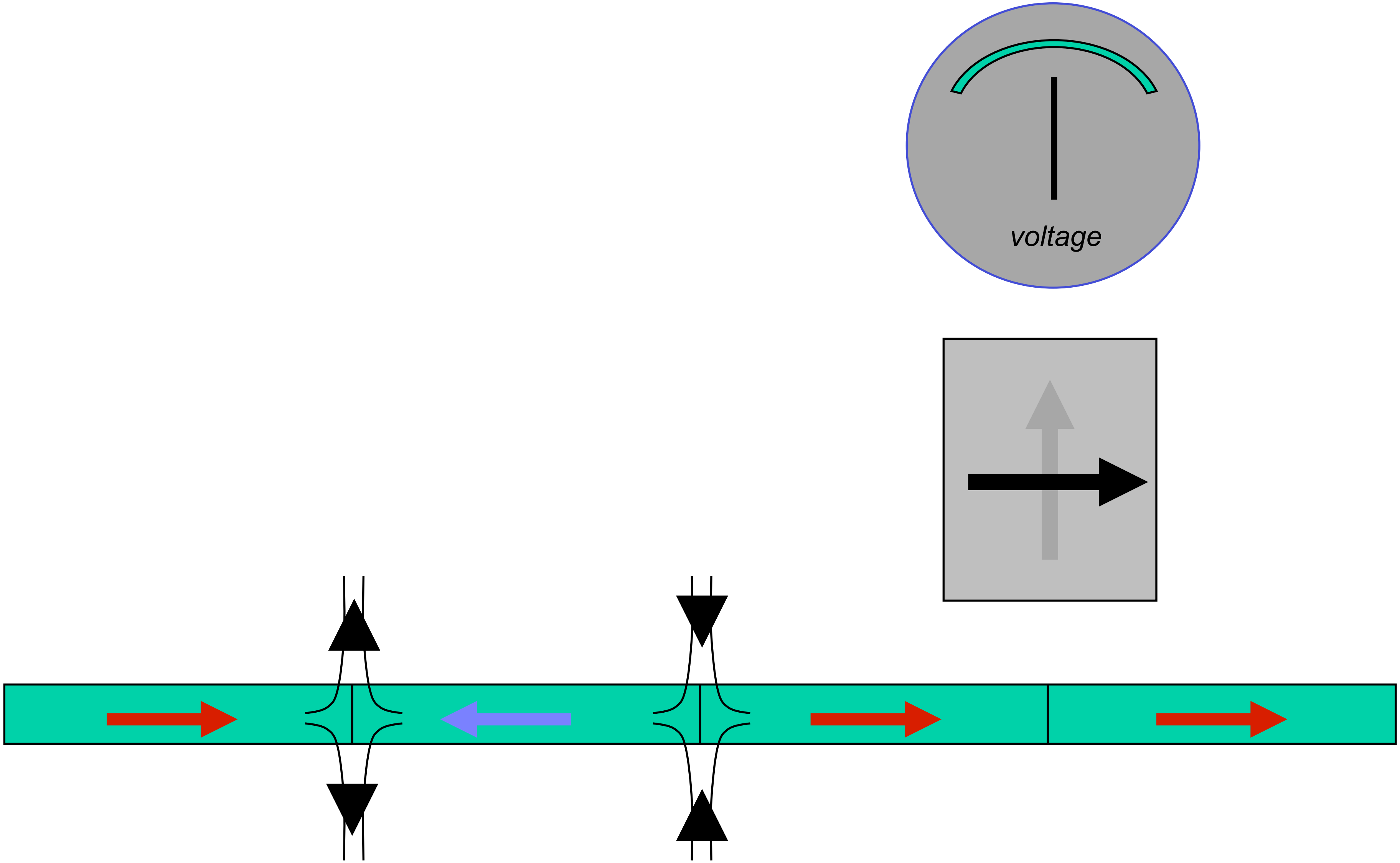
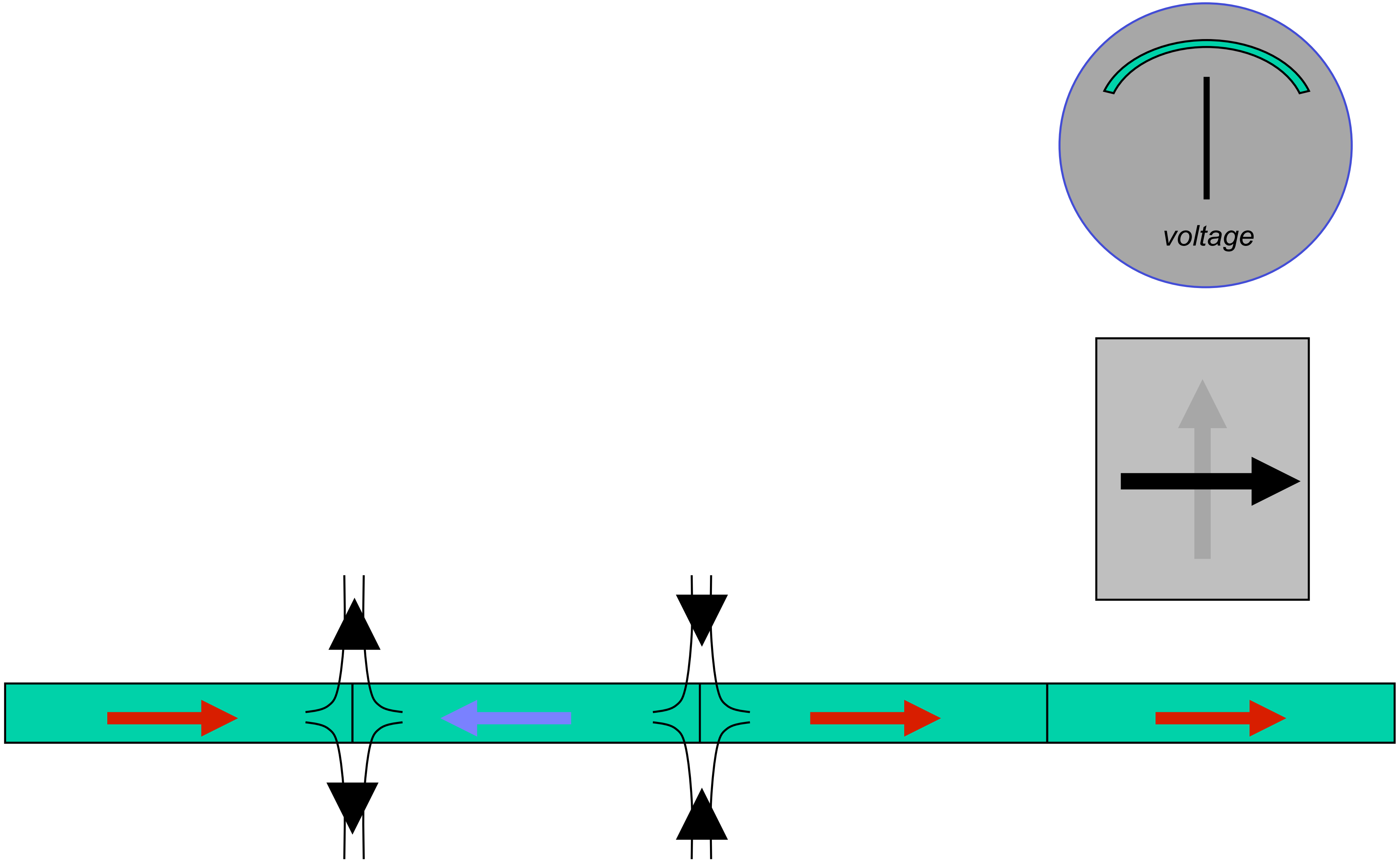
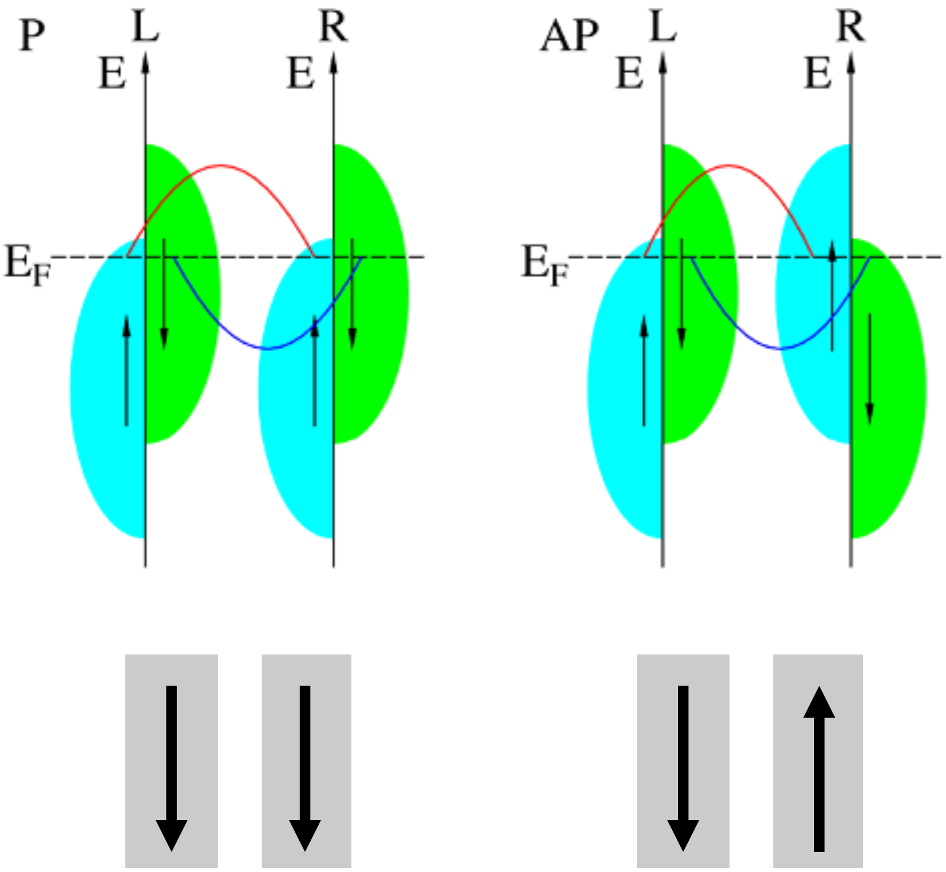

voltage


voltage


voltage

Spin-resolved photoemission spectroscopy on MnPc/Co(001): spin-polarized interface states

Insulating spacer layer : tunneling MR



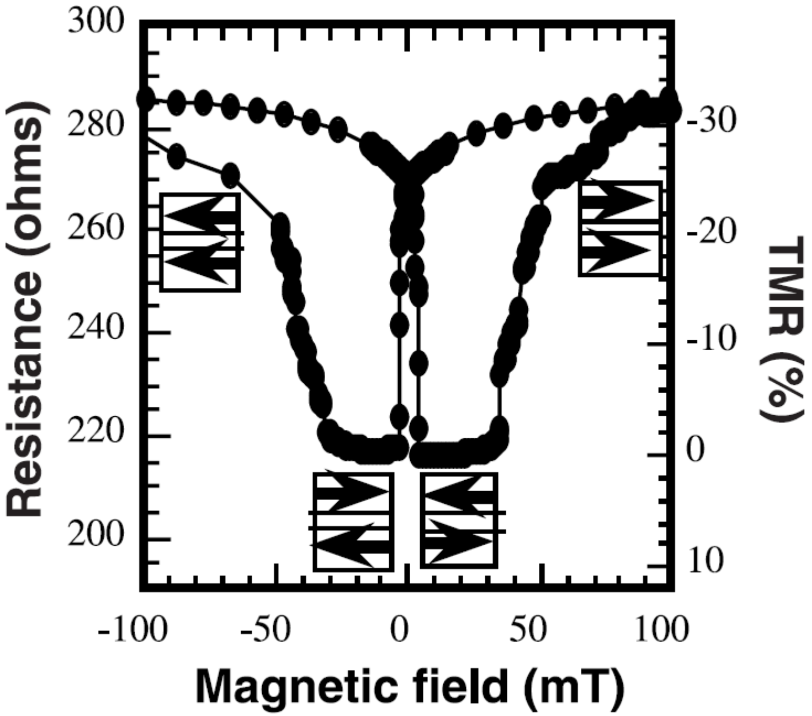
$$\mathrm{TMR} = \frac{2P_1P_2}{1 - P_1P_2}$$

$$P_i = \text{polarisation}$$

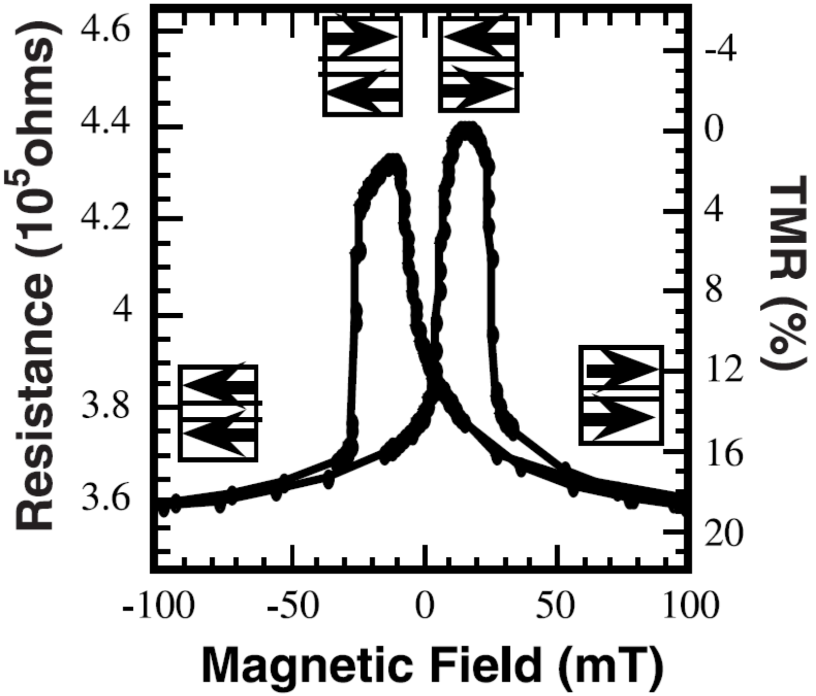
$$= \frac{\mathrm{DOS}^{\uparrow} - \mathrm{DOS}^{\downarrow}}{\mathrm{DOS}^{\uparrow} + \mathrm{DOS}^{\downarrow}}$$

Jullière’s model

Co / STO/ LSMO



Co / ALO/ STO/ LSMO



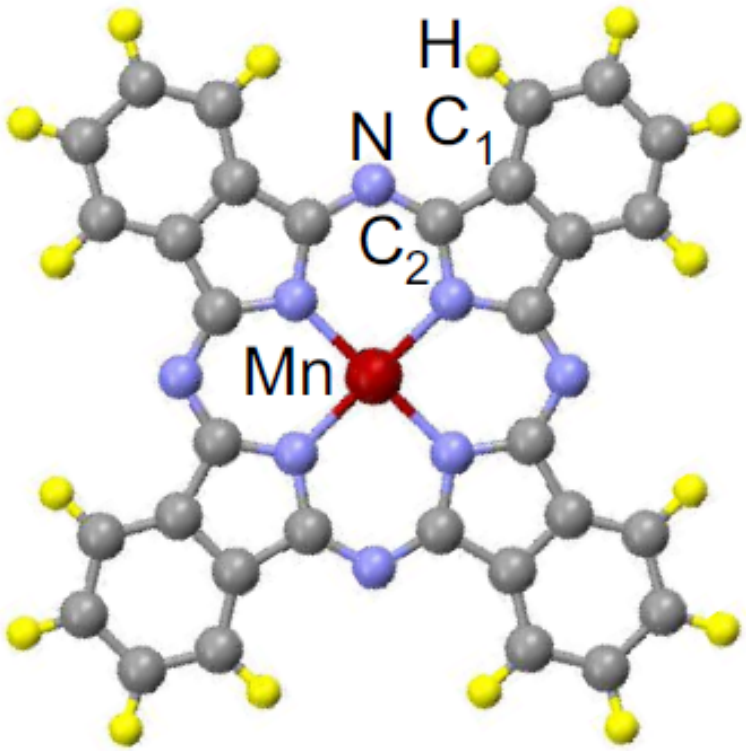
$$\mathrm{TMR} = \frac{2P_{Co}P_{LSMO}}{1 - P_{Co}P_{LSMO}}$$

The polarisation depends on the interface !!

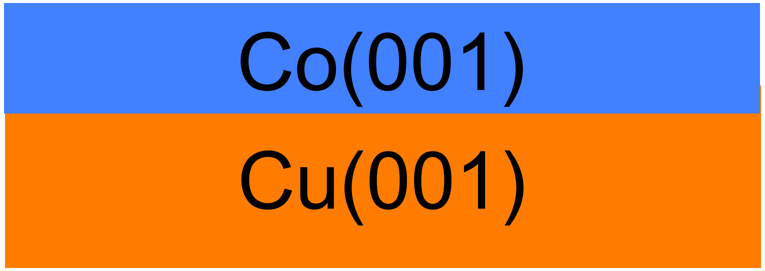
De Teresa et al., Science 286 (1999)

Mn(II)-phthalocyanine : Mn-$C_{32}H_{16}N_8$

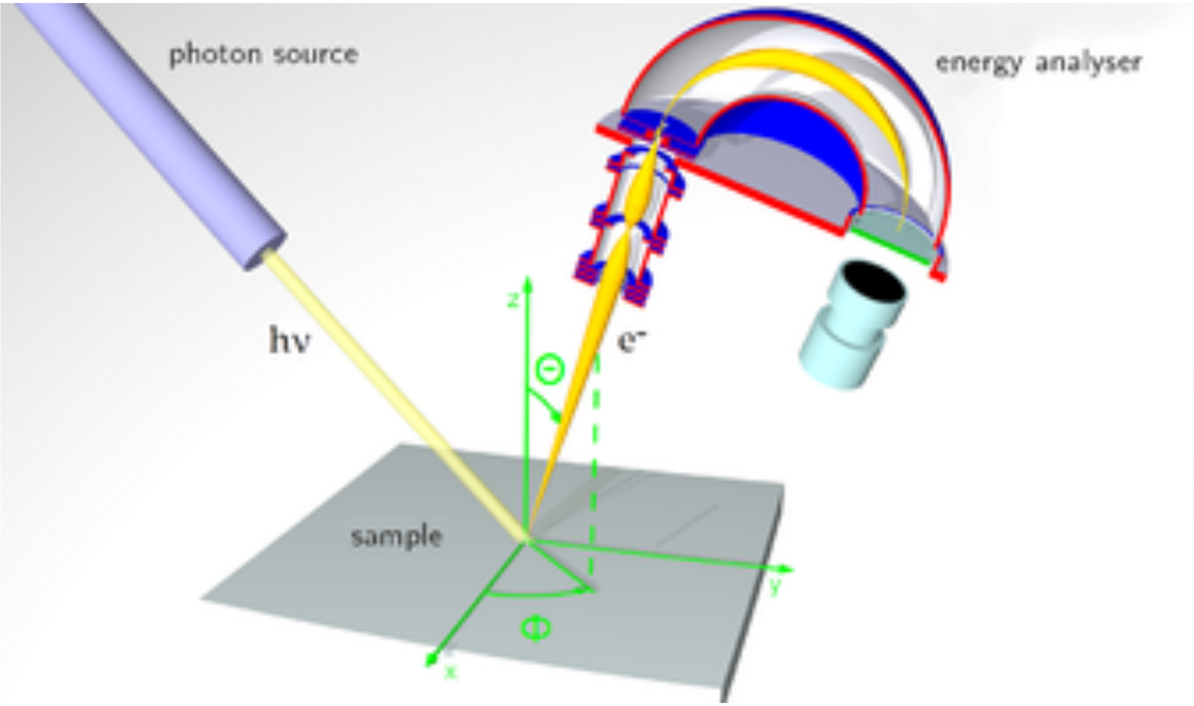
MnPc

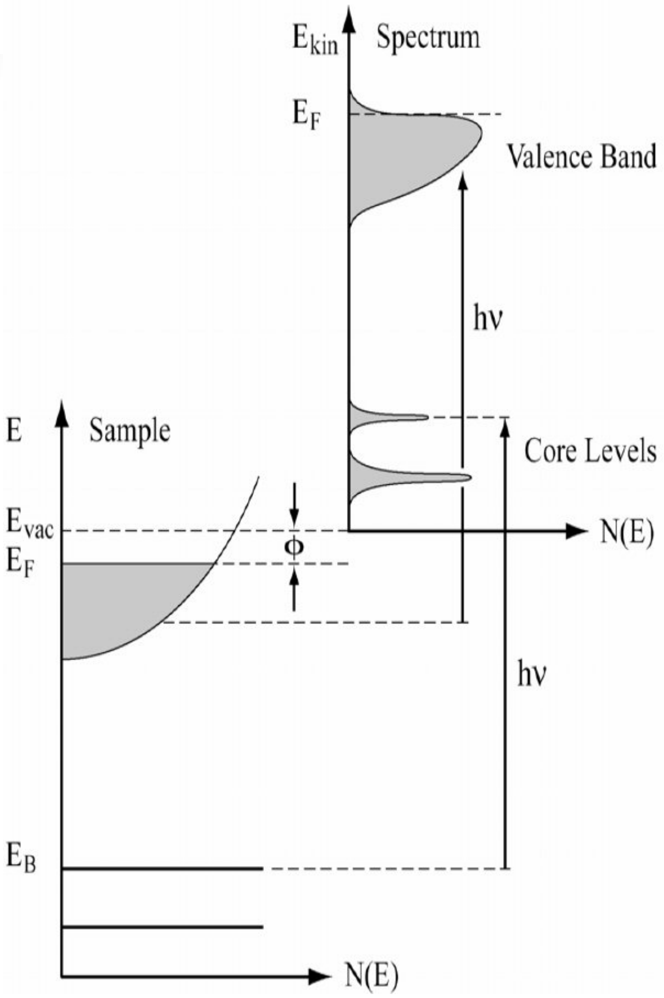


Advantage:
large spin diffusion length expected due to weak spin-orbit coupling in low-Z materials.

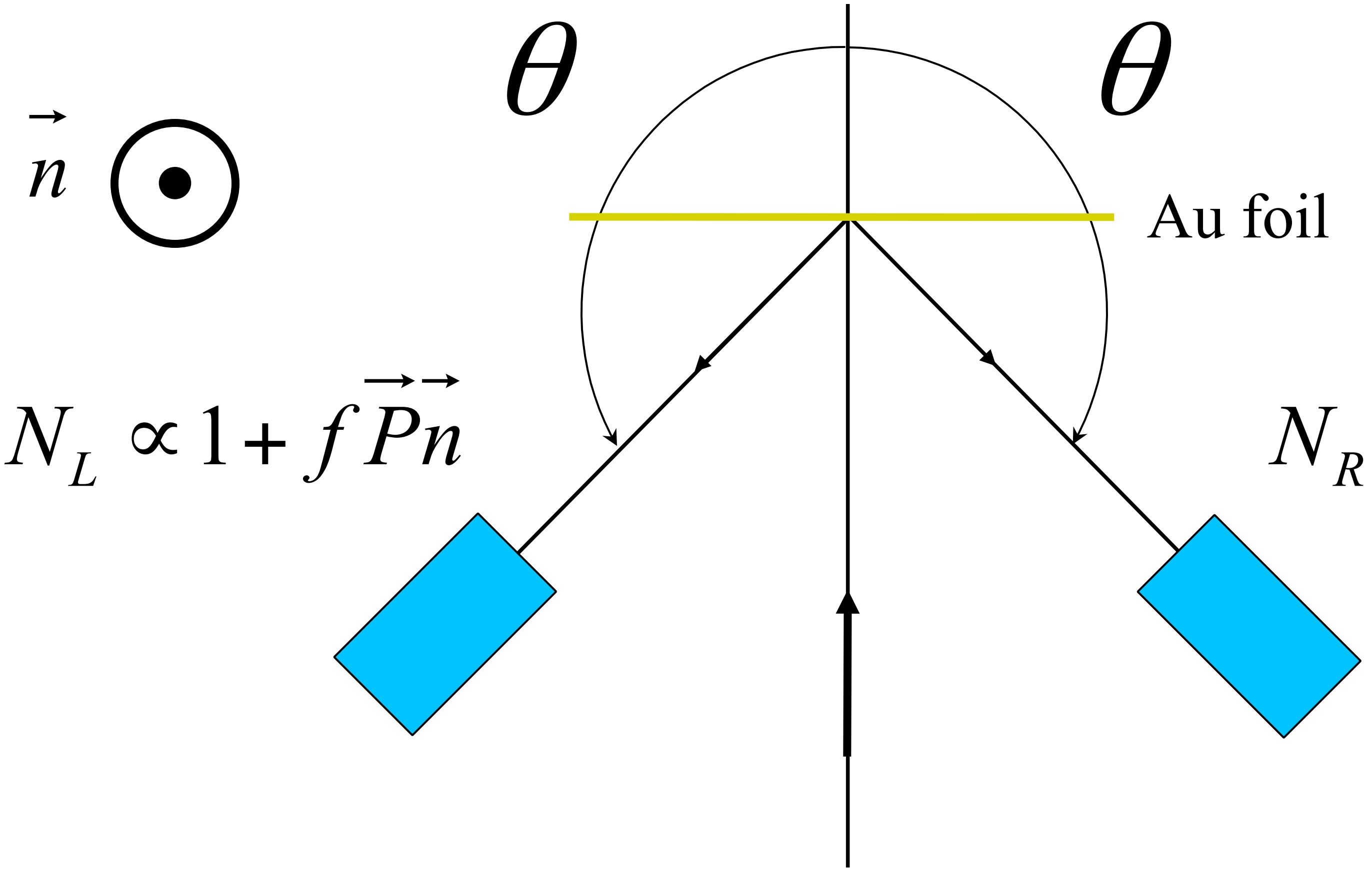

Co(001)
Cu(001)

Photoemission spectroscopy





Spin detector

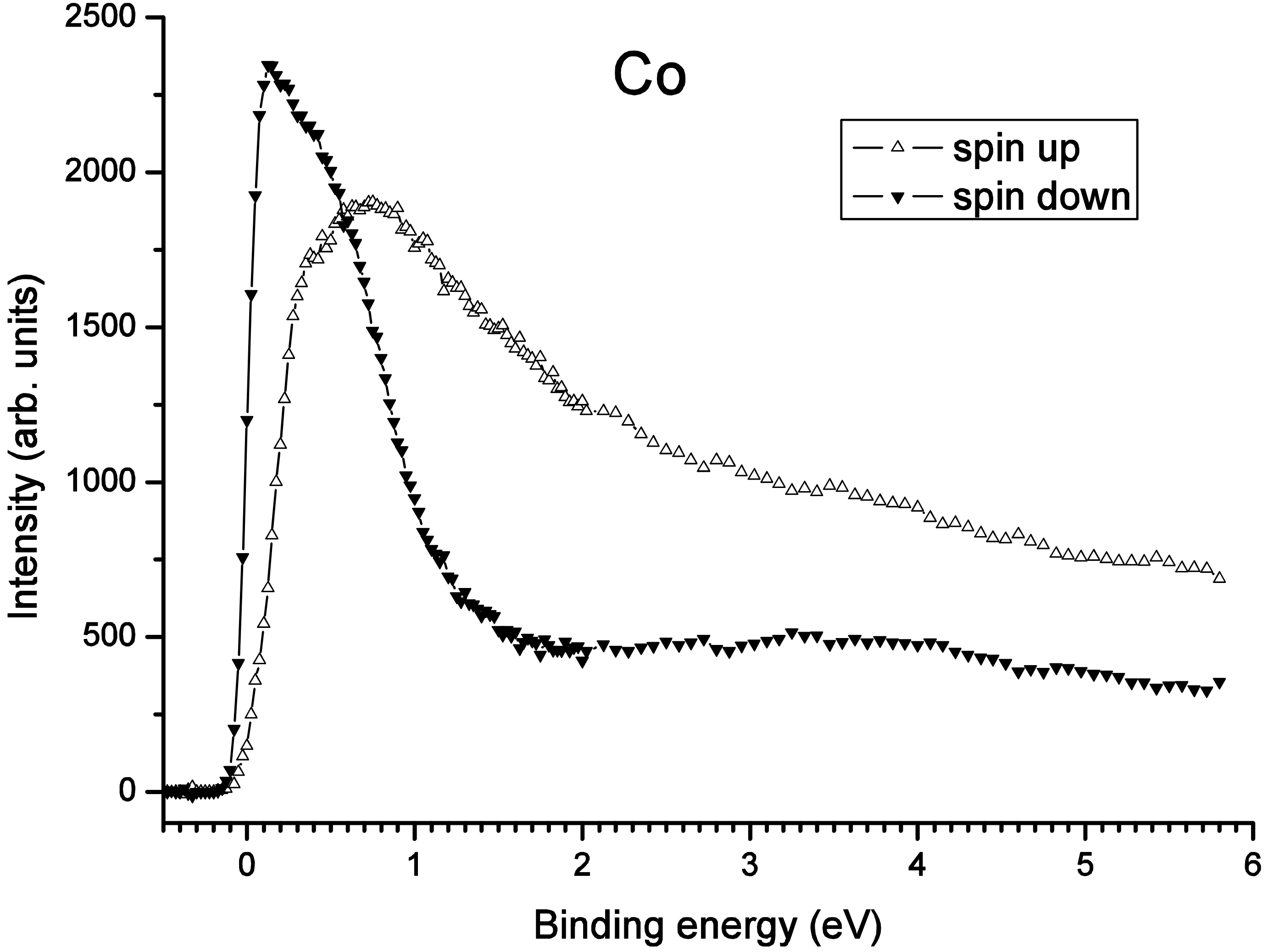


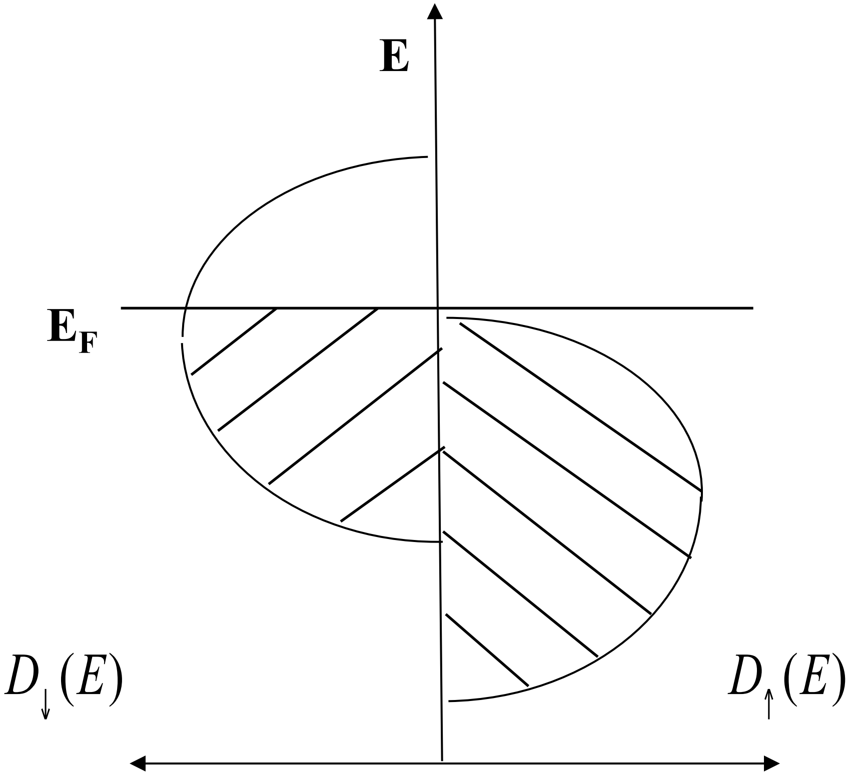
$$N_L \propto 1 + f\vec{P}\vec{n}$$

$$N_R \propto 1 - f\vec{P}\vec{n}$$

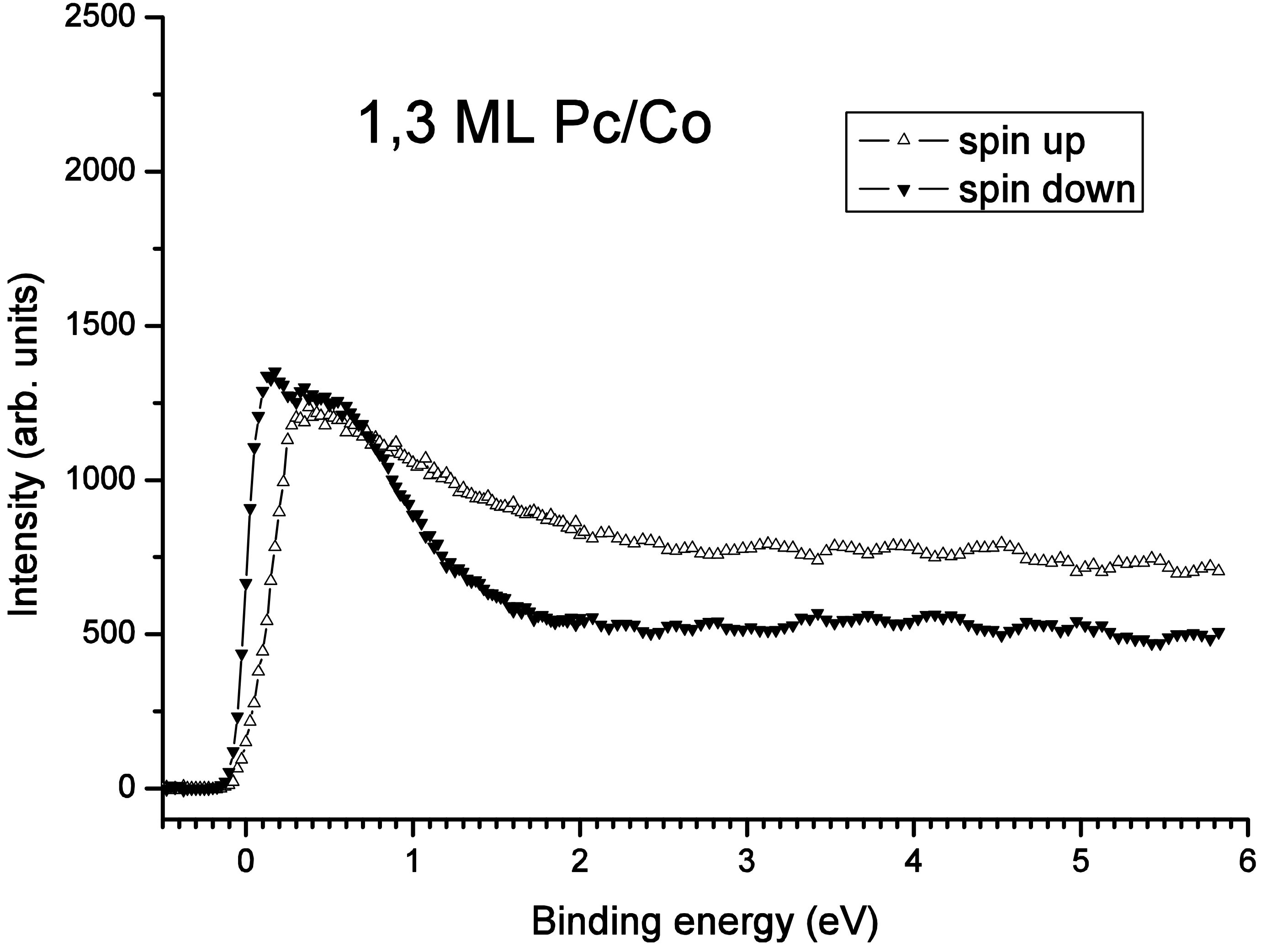
$$A = \frac{N_L - N_R}{N_L + N_R} = f\vec{P}\vec{n}$$

Spin-resolved spectra

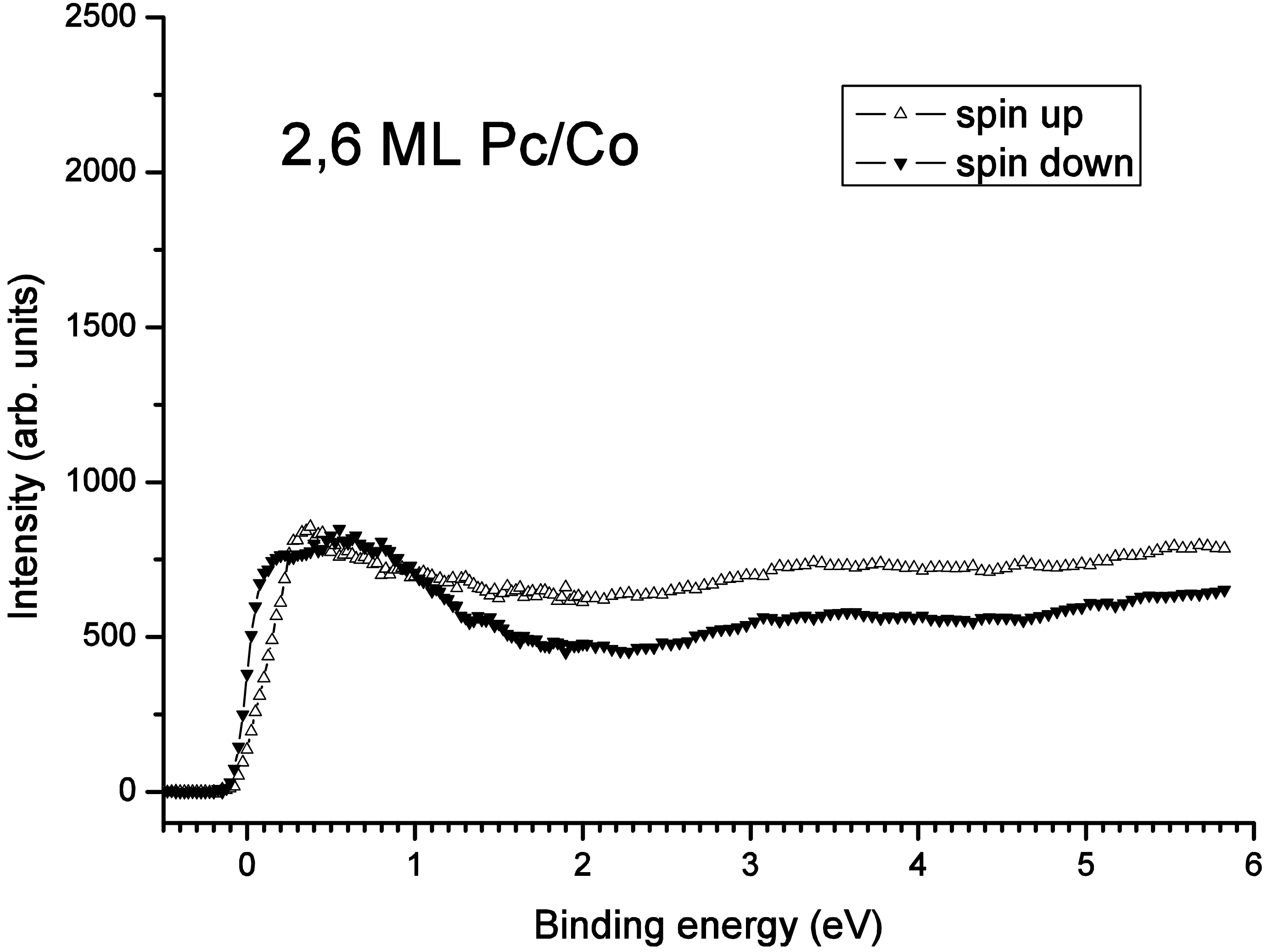



E
E_F
$D_{\downarrow}(E)$
$D_{\uparrow}(E)$

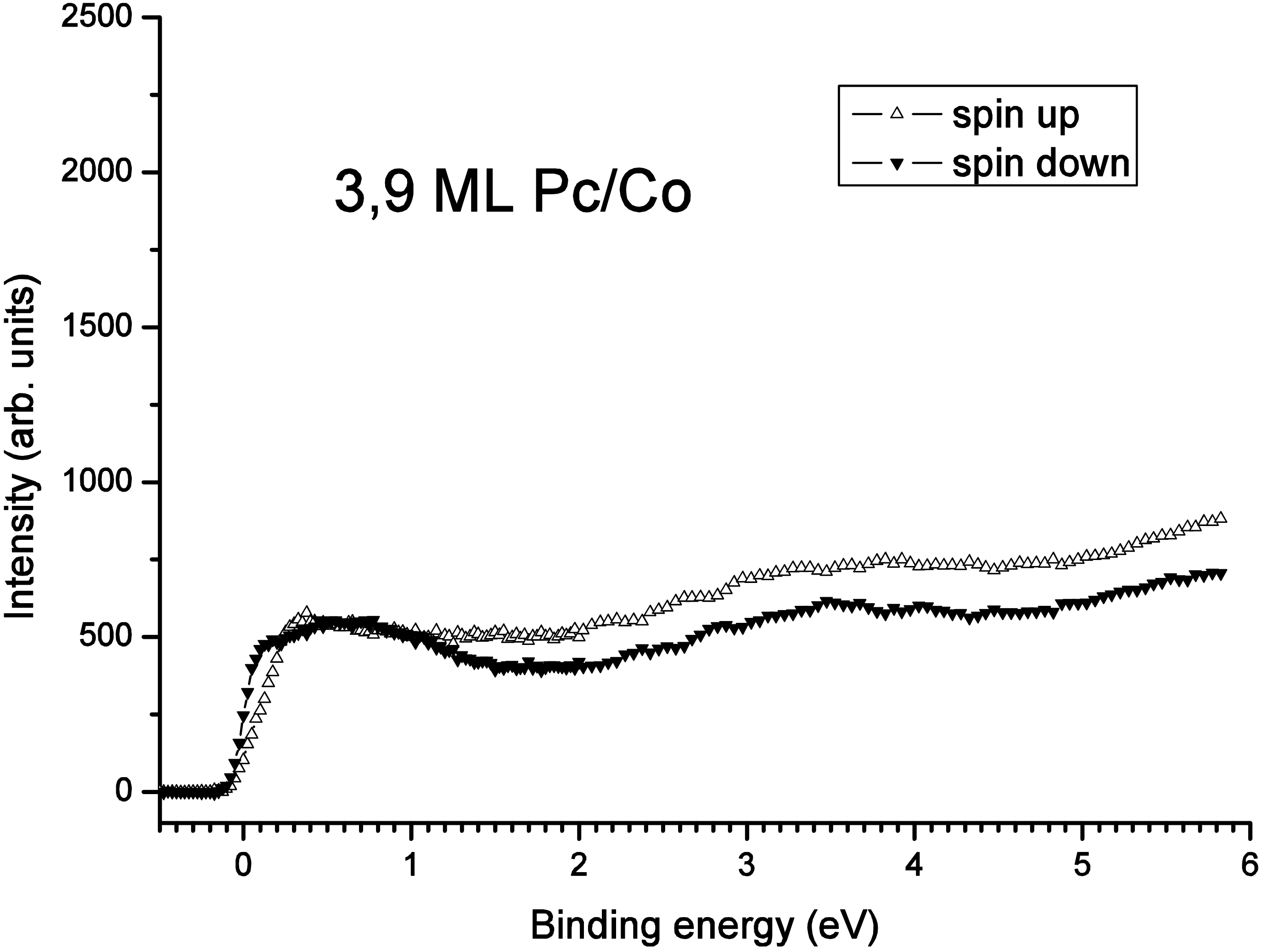
Spin-resolved spectra



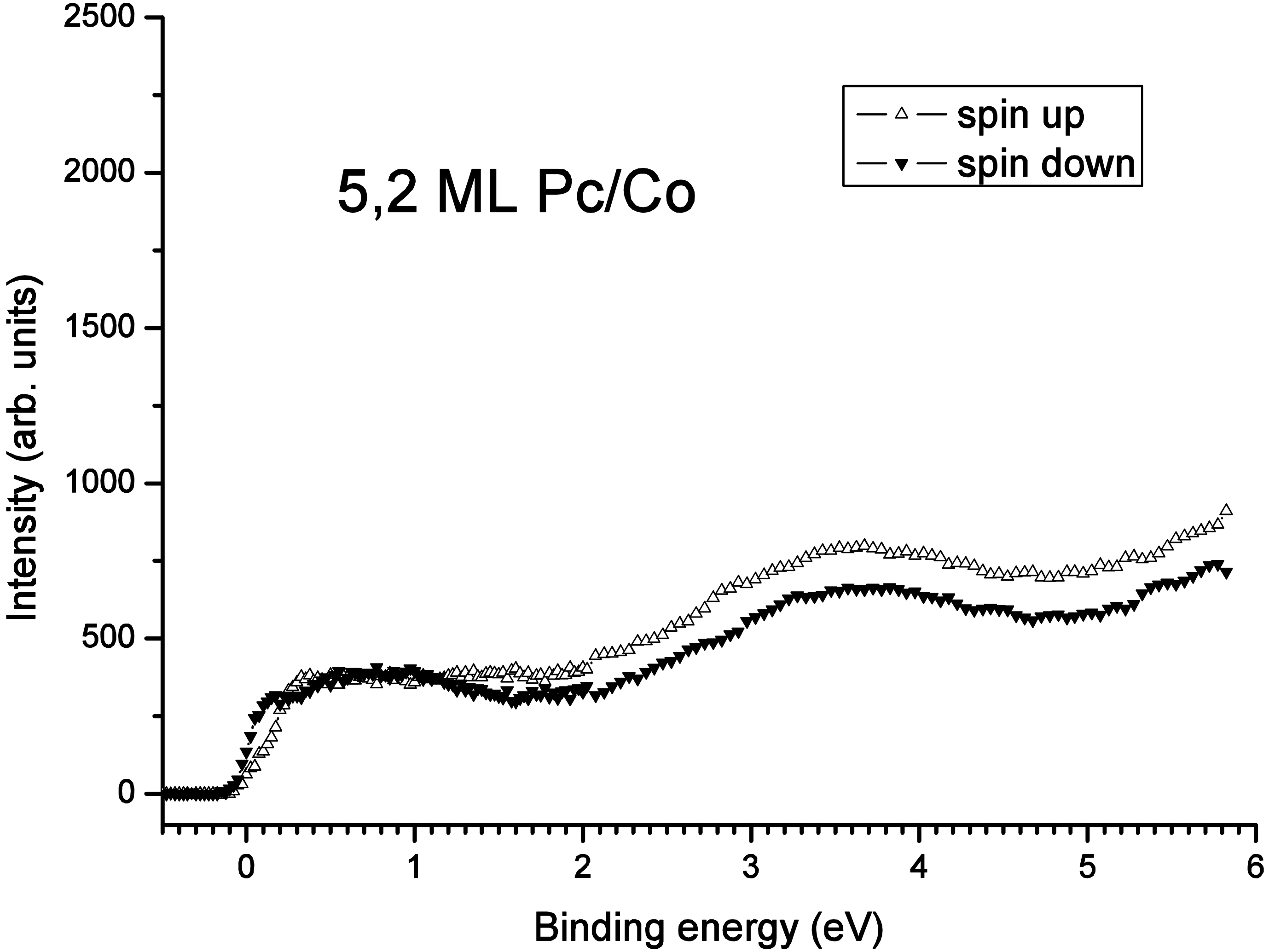
Spin-resolved spectra

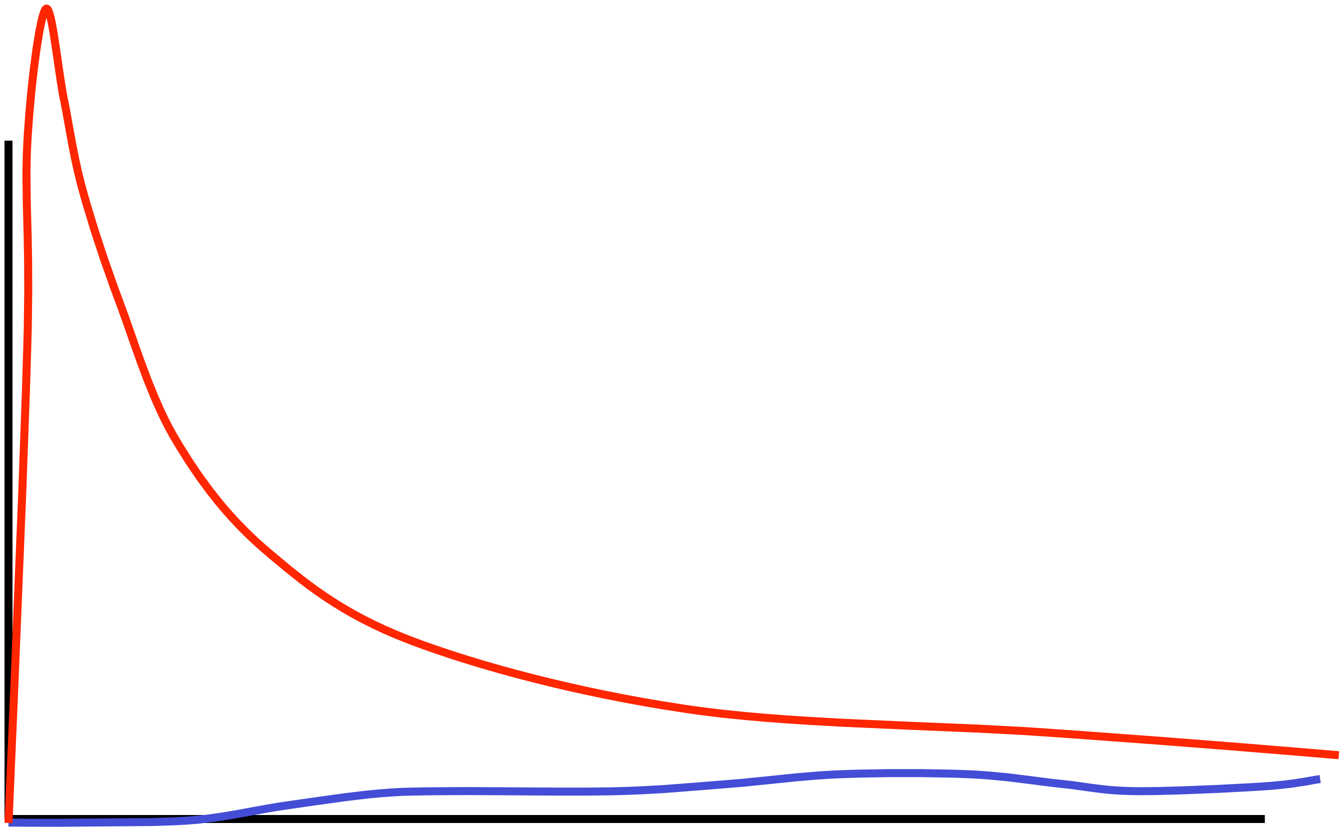


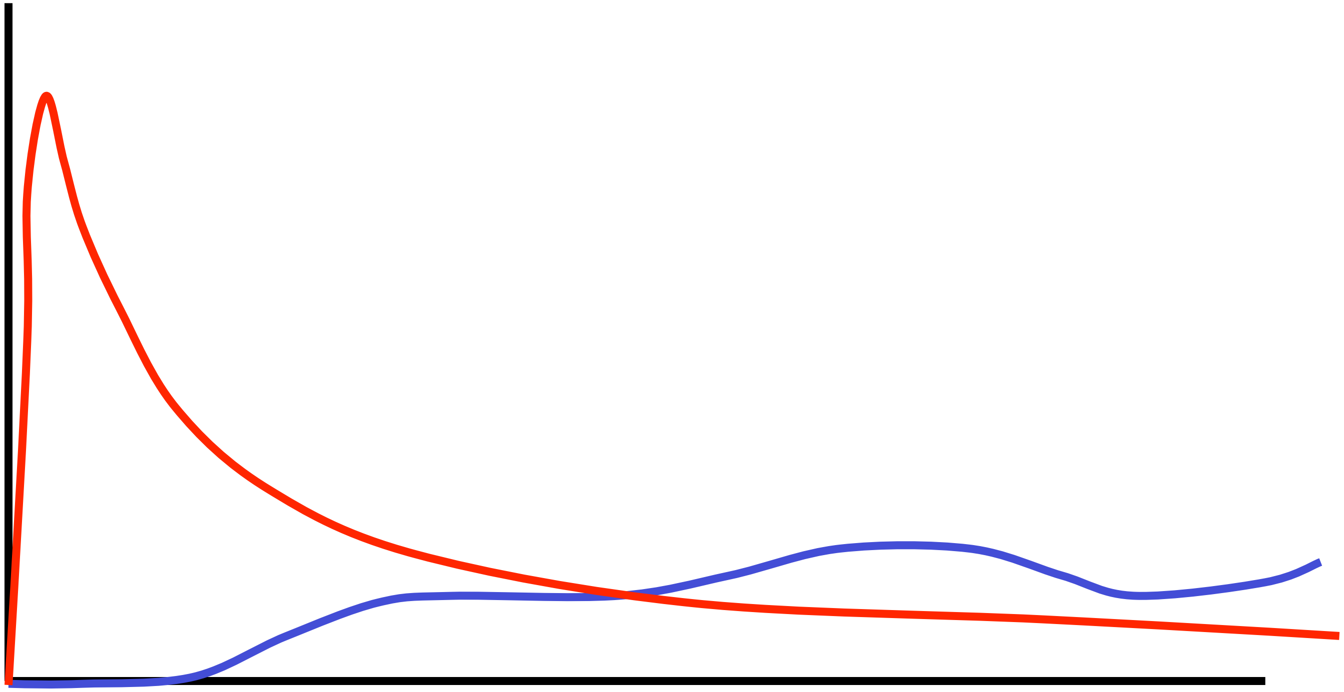
Spin-resolved spectra

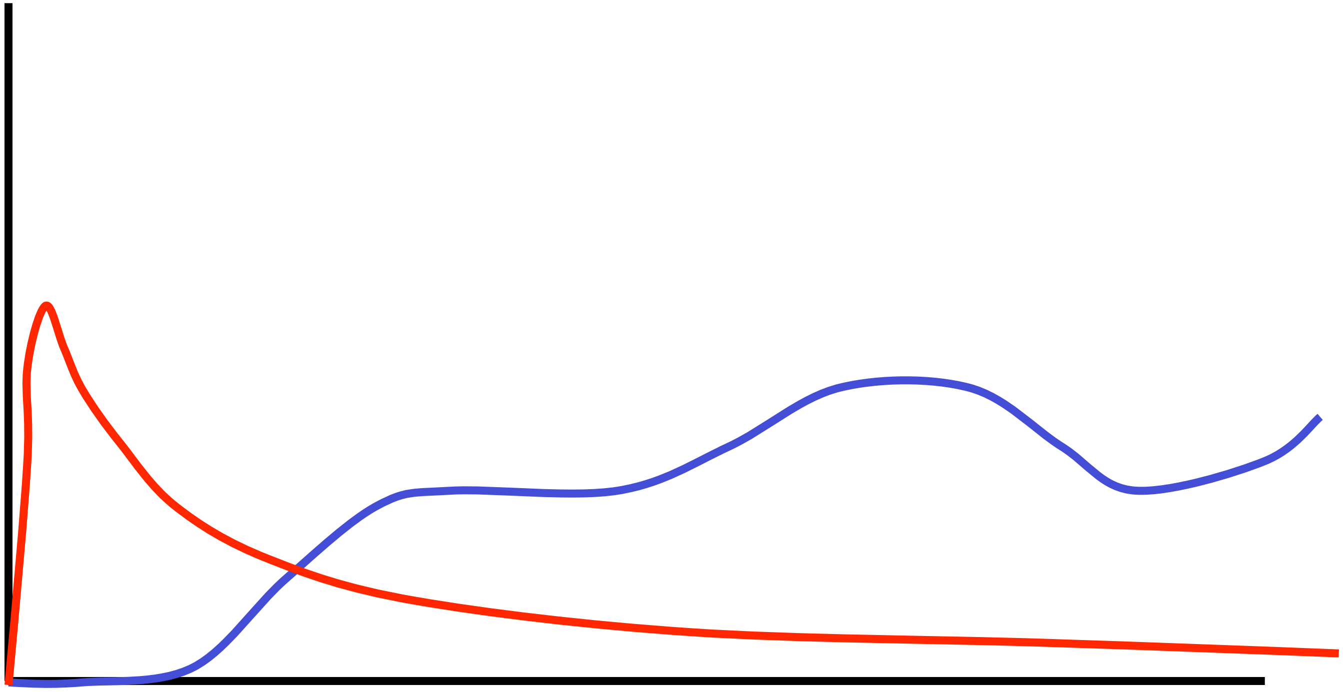


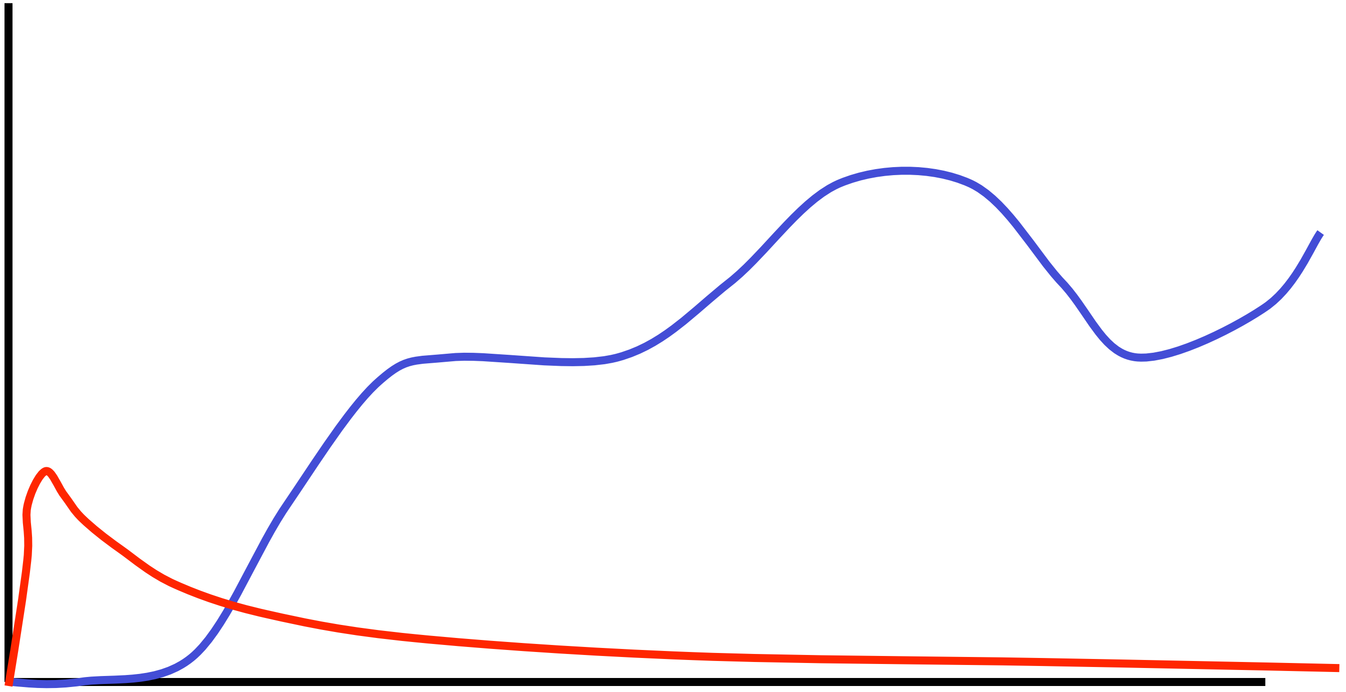
Spin-resolved spectra

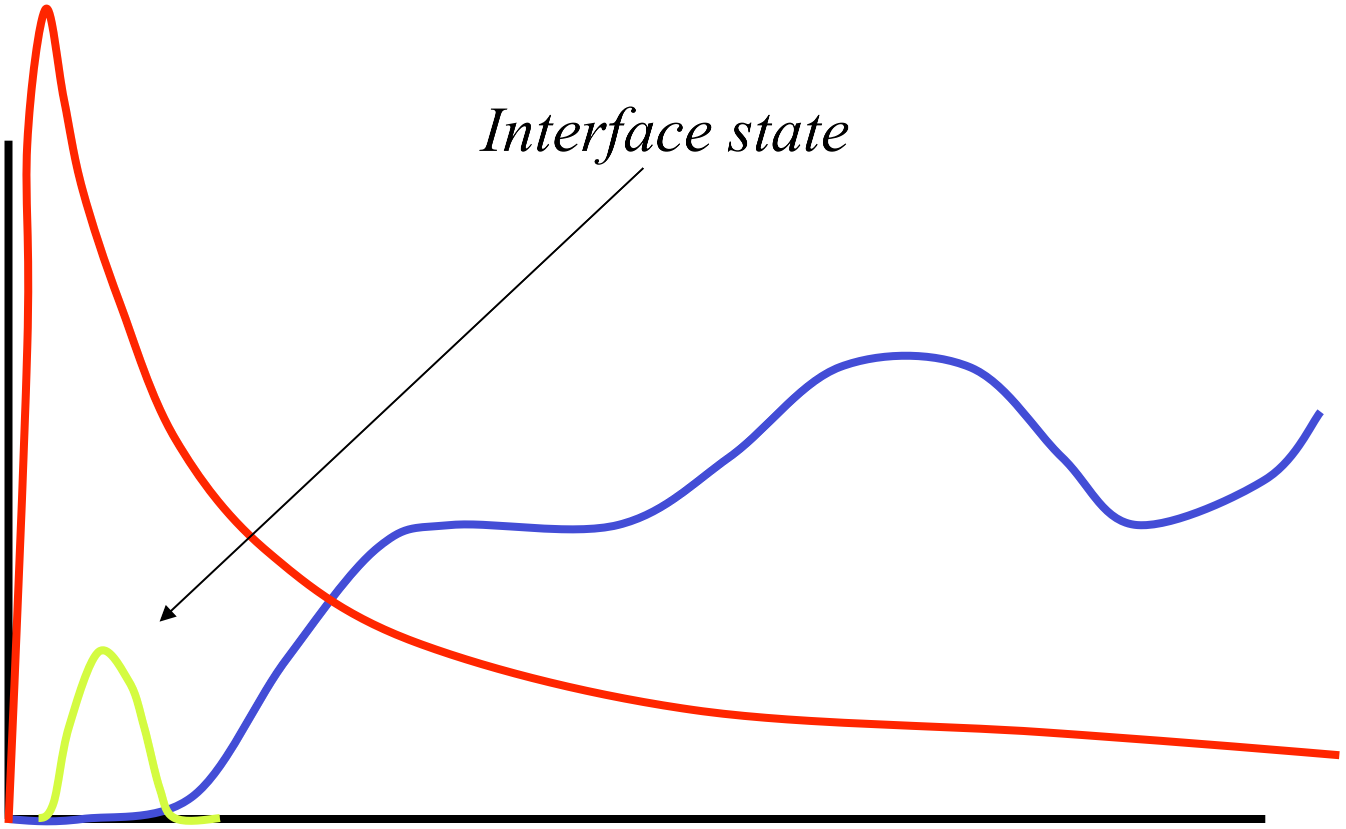




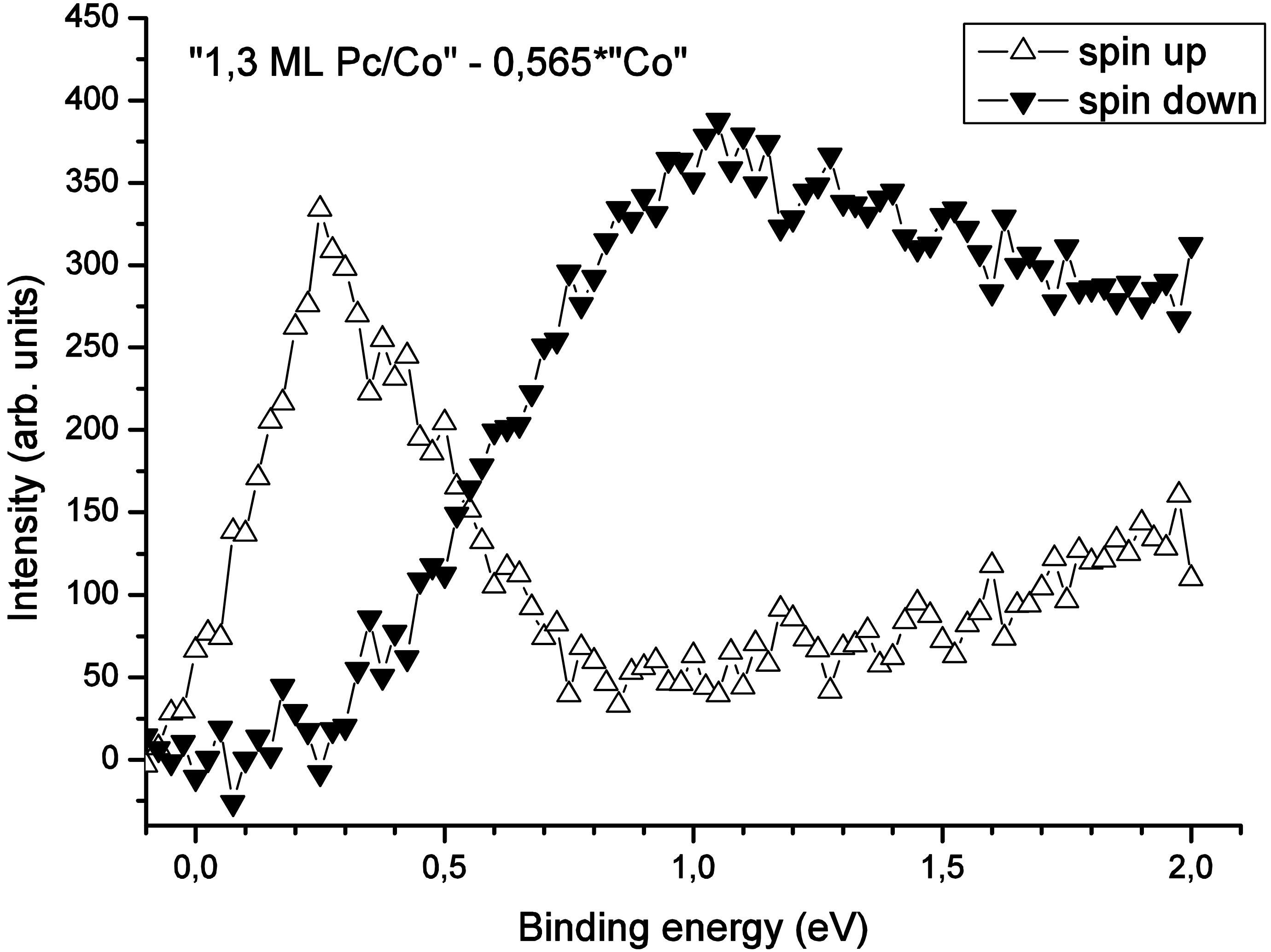




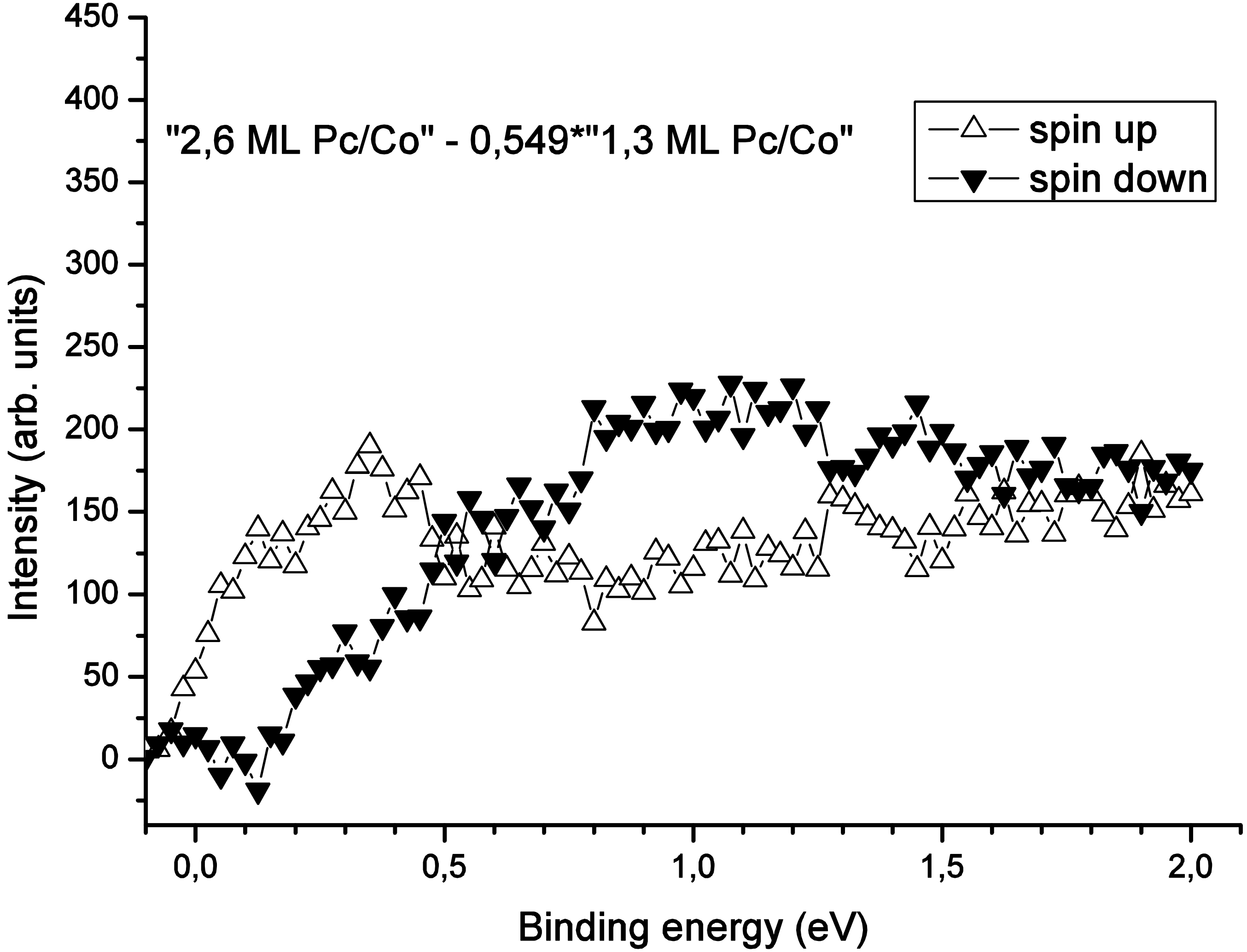



Interface state

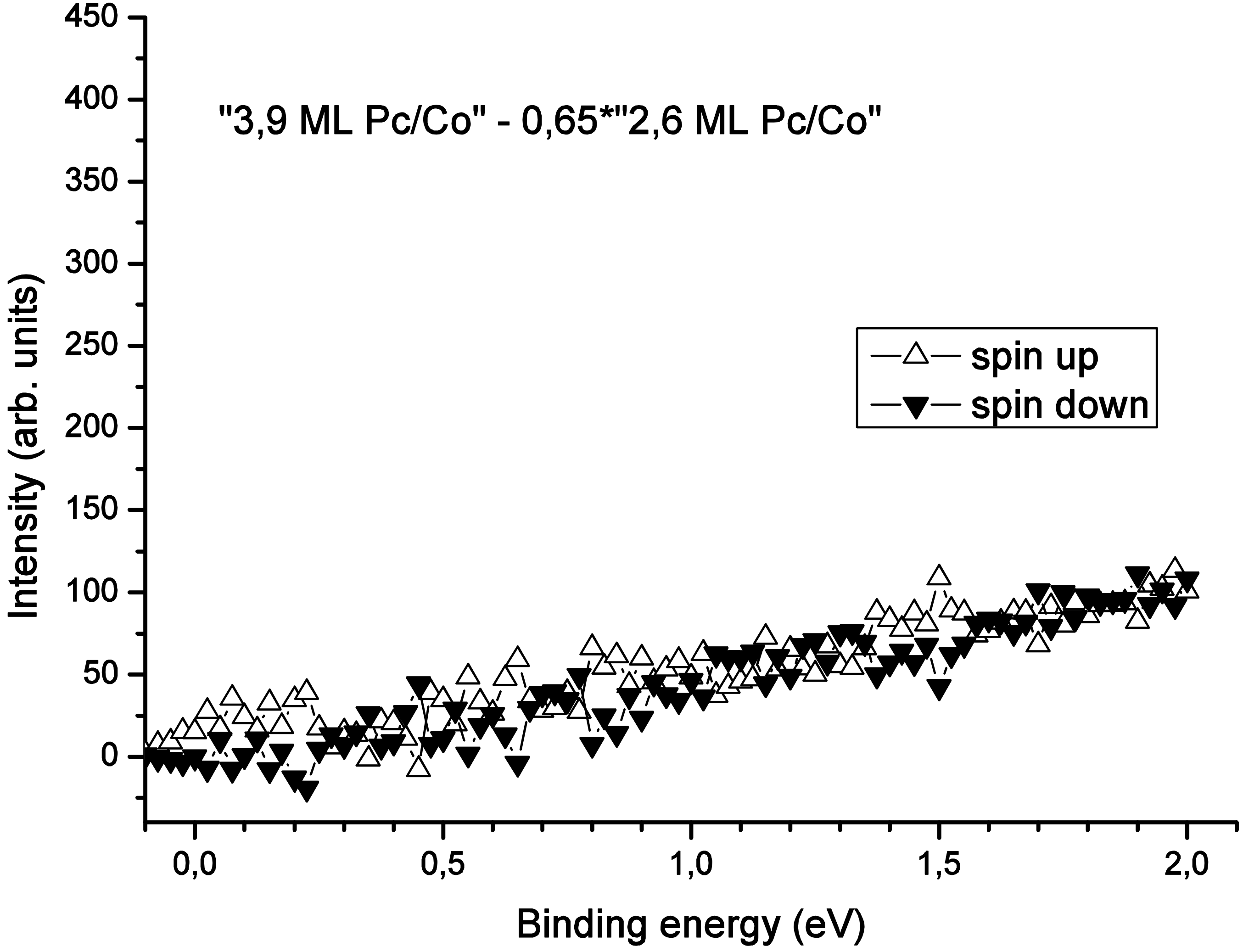
Difference spectra



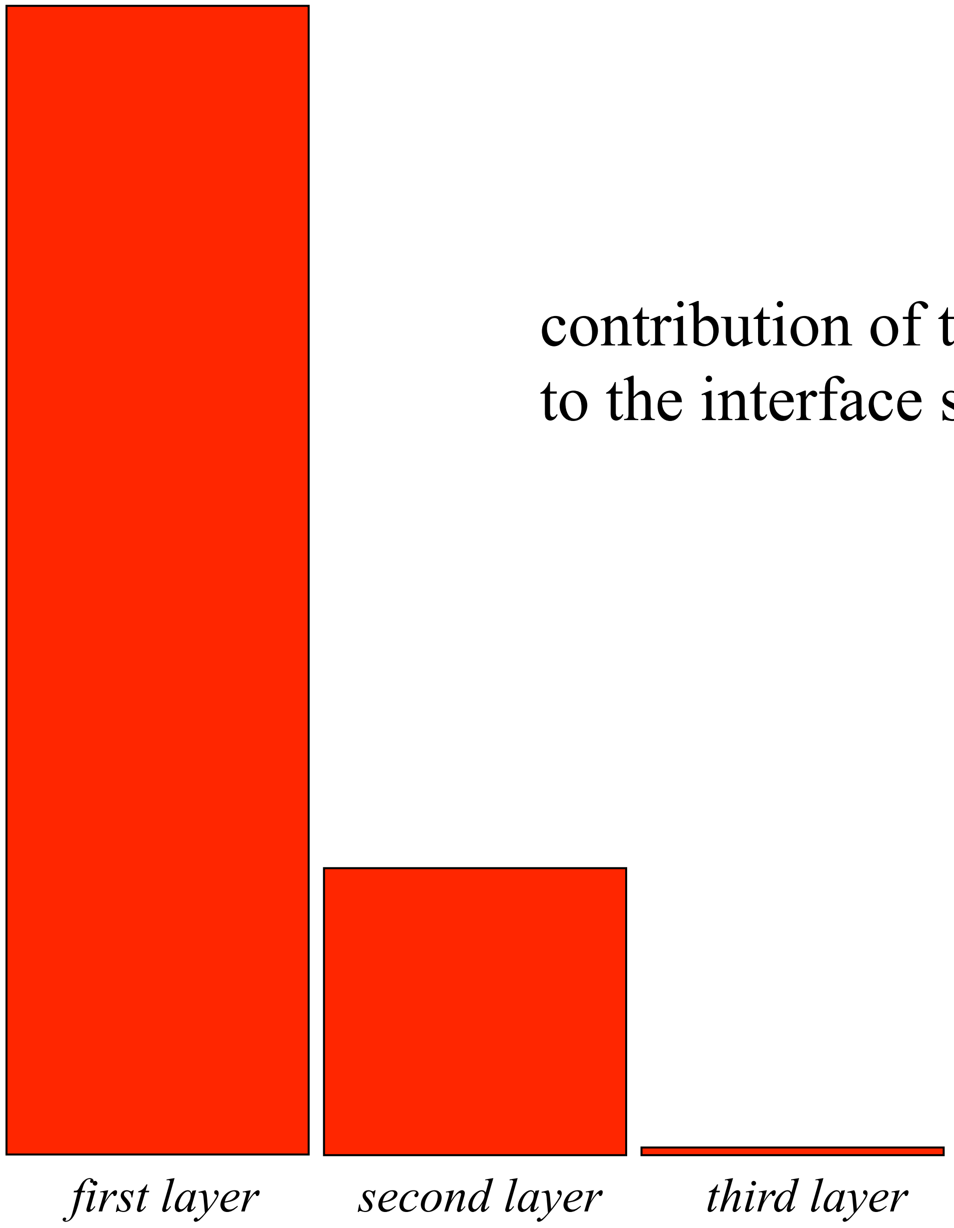
Difference spectra



Difference spectra

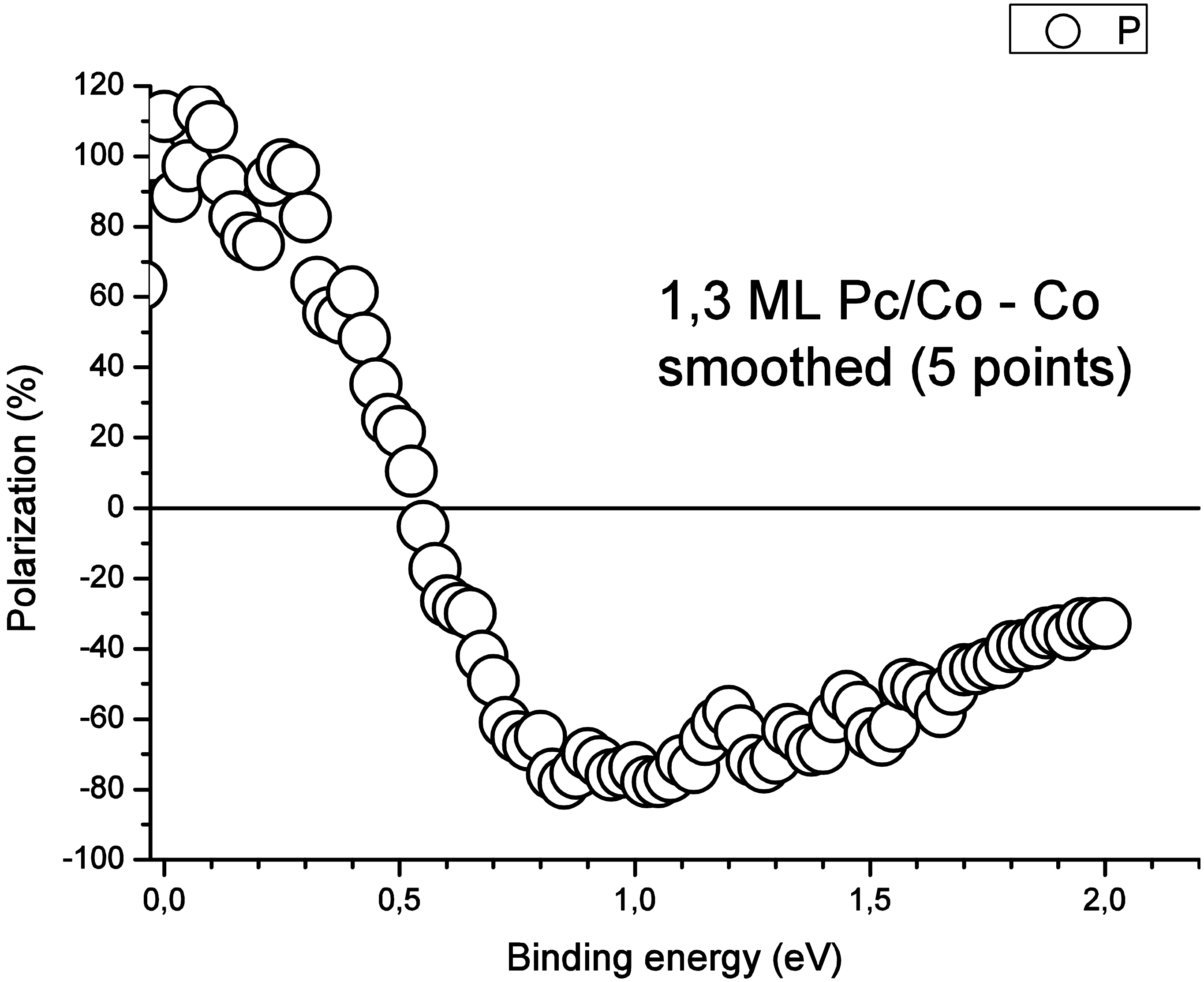


Difference spectra



contribution of the different Pc layers
to the interface states

Polarization of difference spectra



Character of interface states

Determination of the character by exploiting the variation of the cross section with photon energy. By going from 20 to 100 eV the cross sections change by the following factors:

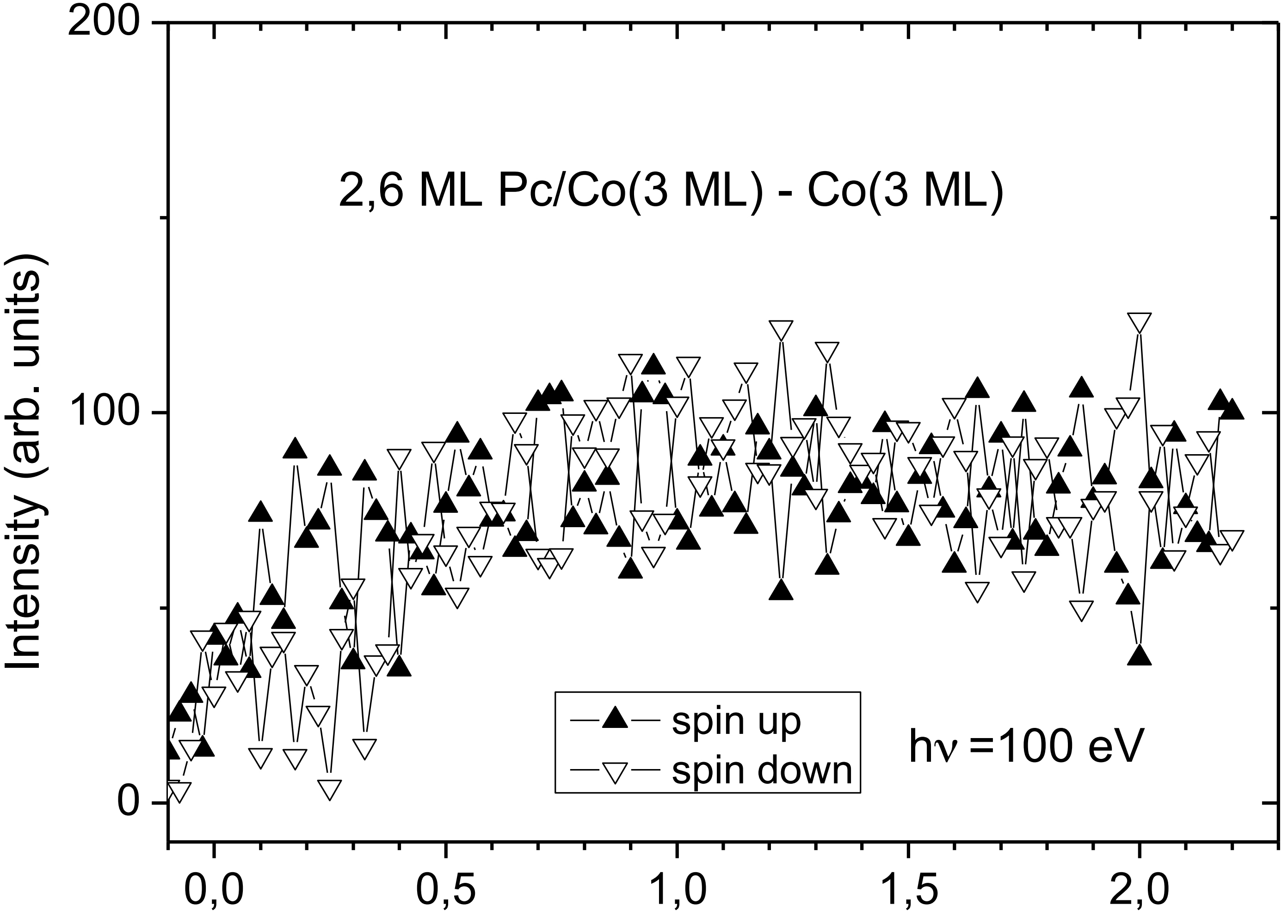
Co 3d: 1.4

Mn 3d: 0.7

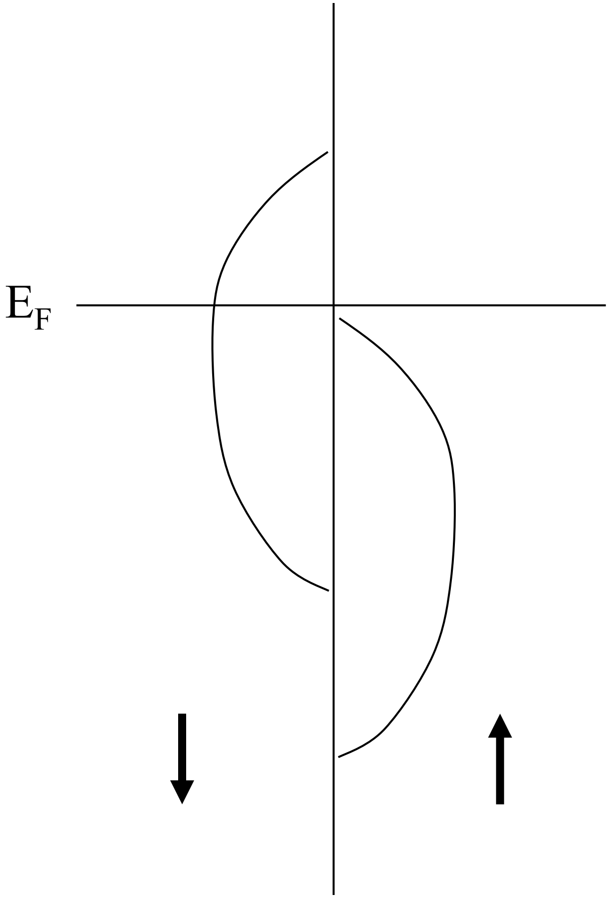
C 2p: 1/40

N 2p: 1/20

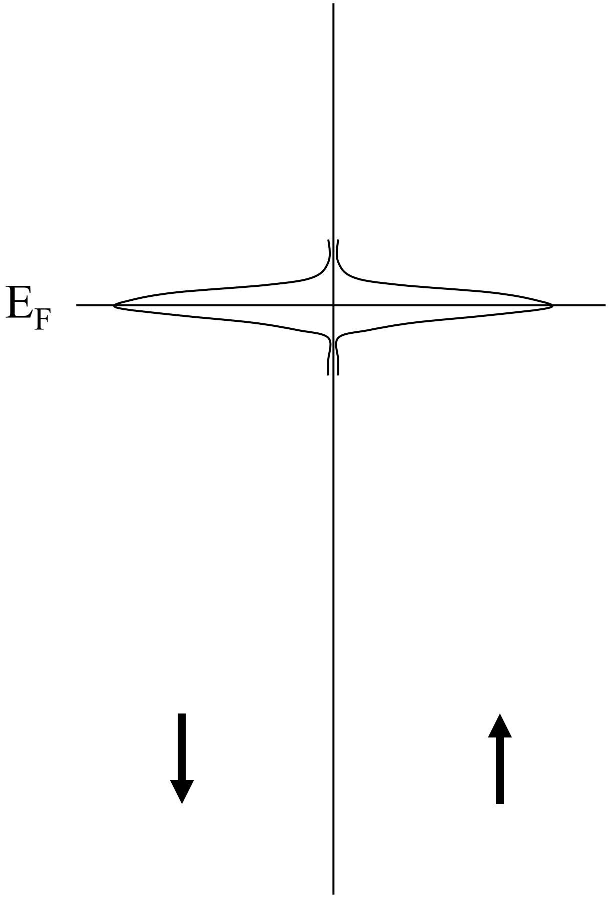
Character of interface states



Co

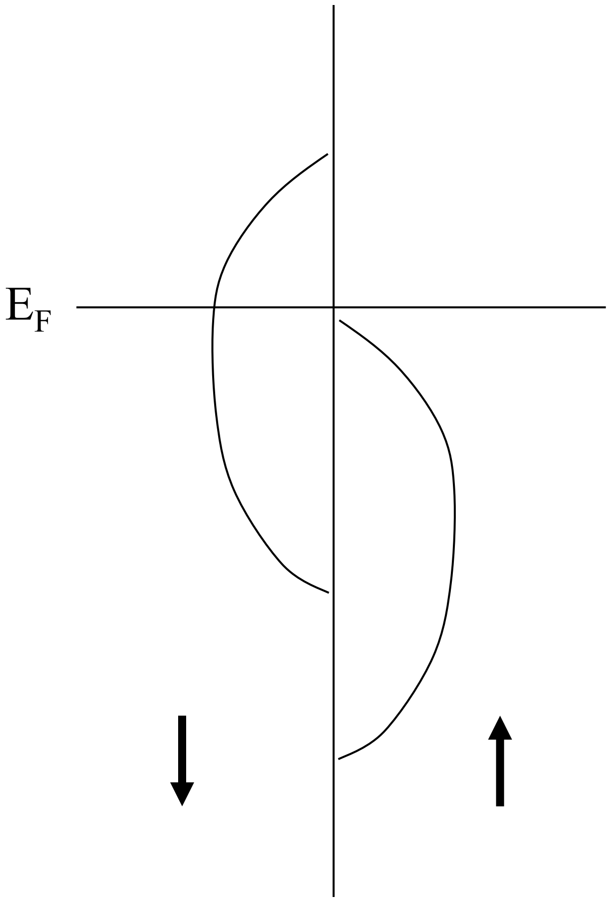


Interface Pc/Co

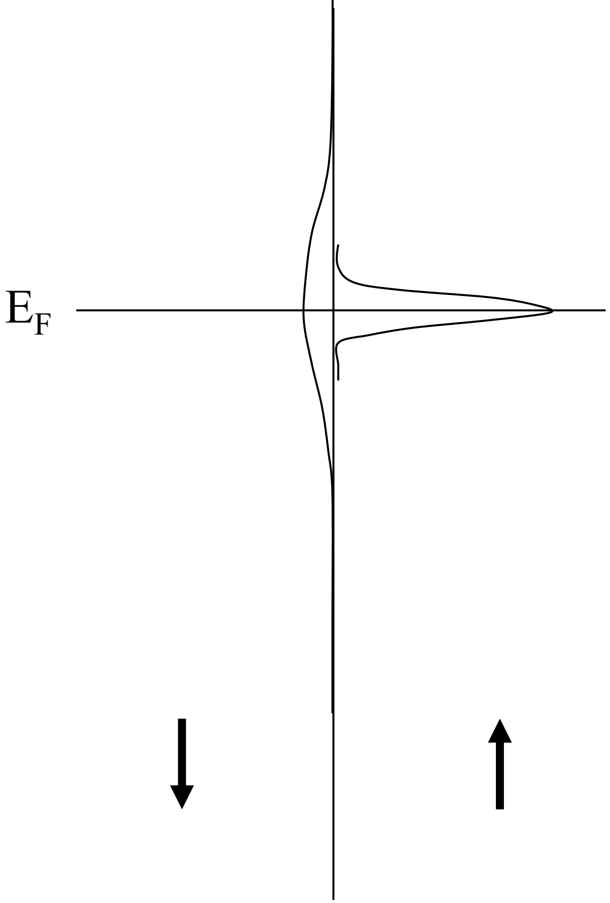


C. Barraud et al., Nature Phys. (2010)

Co

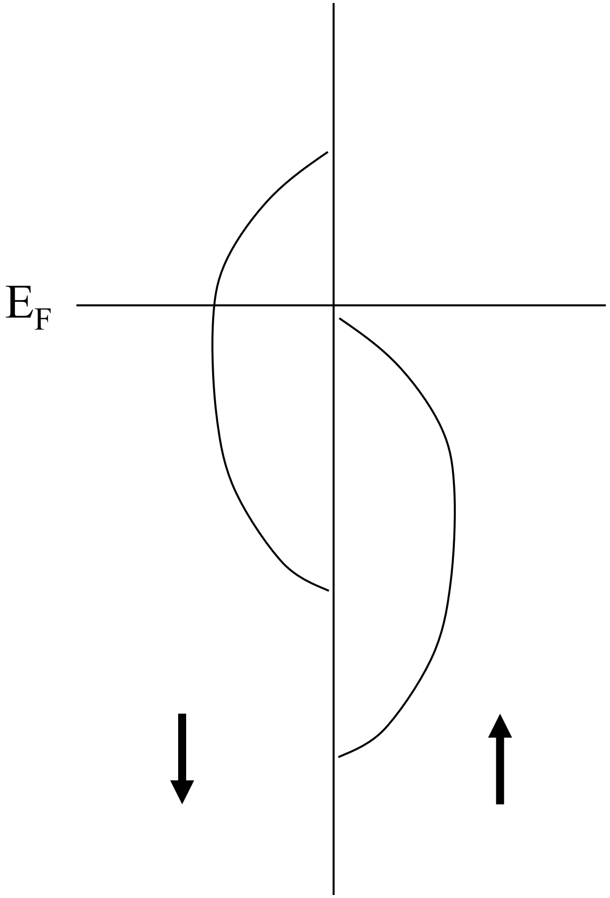


Interface Pc/Co

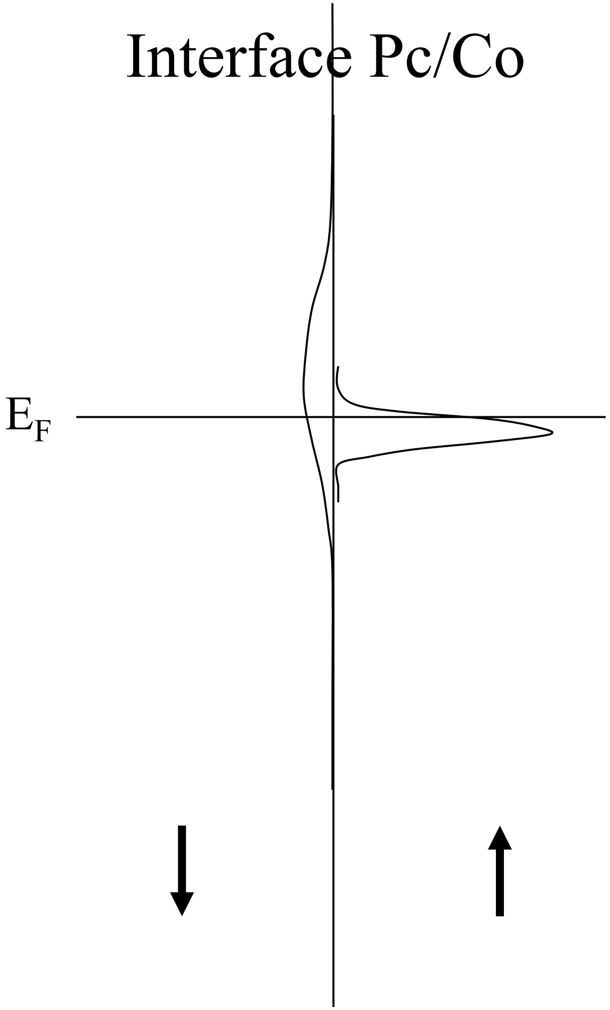


C. Barraud et al., Nature Phys. (2010)

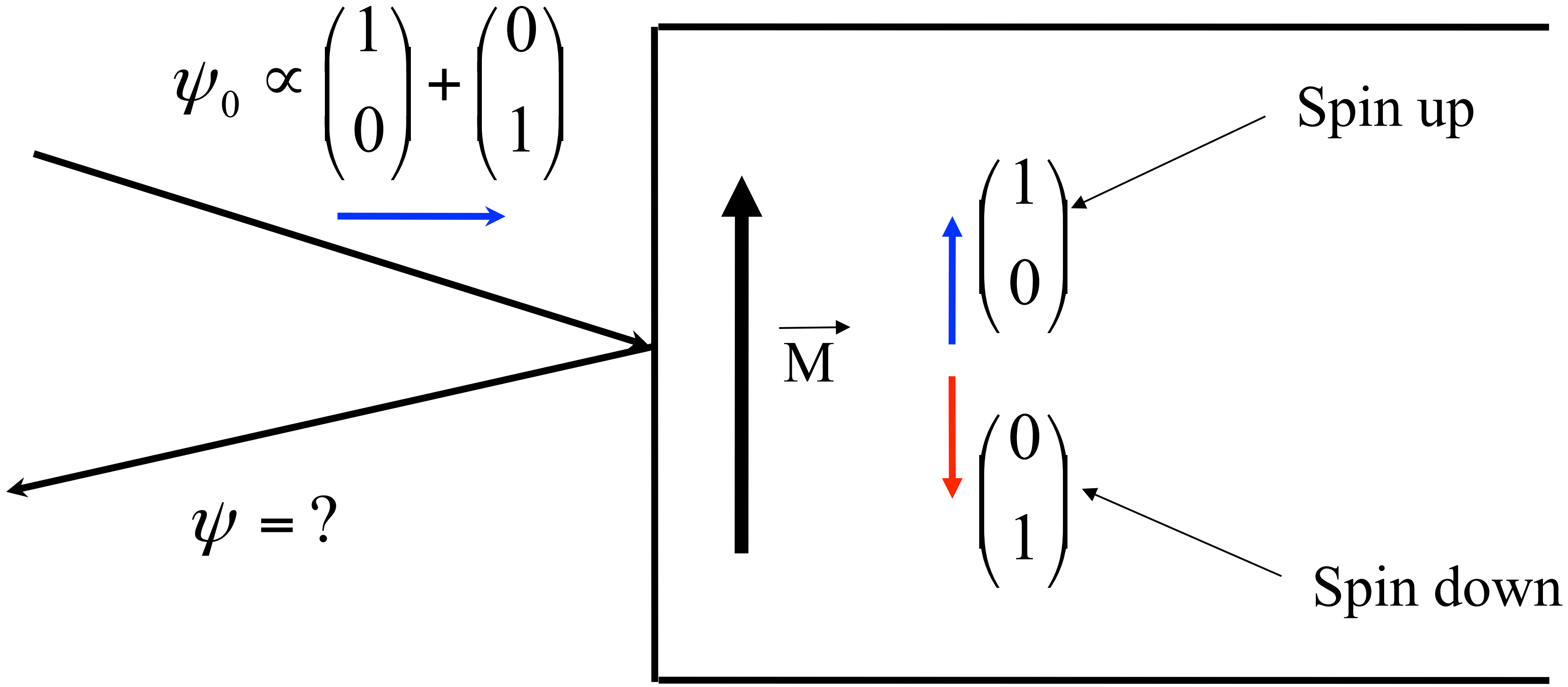
Co



Interface Pc/Co



Electron spin motion: a new tool to study ferromagnetic films



$$\psi_0 \propto \begin{pmatrix}1\\0\end{pmatrix}+\begin{pmatrix}0\\1\end{pmatrix}$$

$$\psi = ?$$

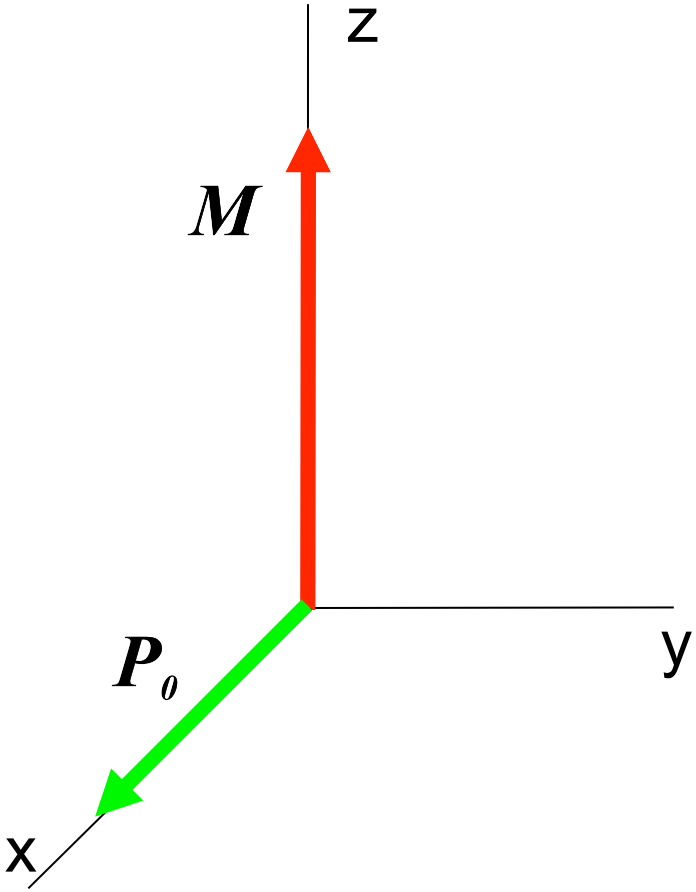
$\overrightarrow{M}$

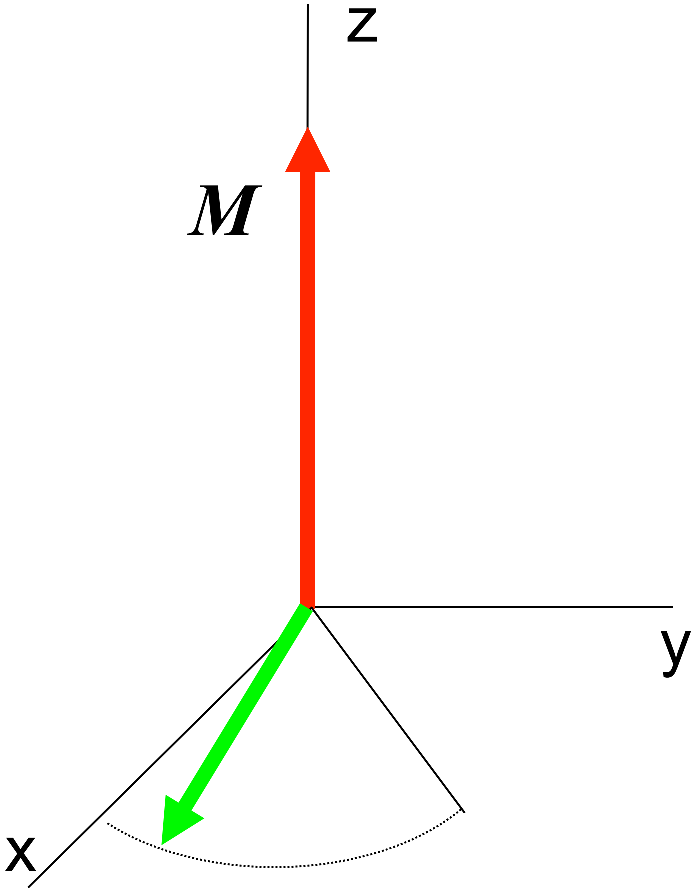
Spin up $\begin{pmatrix}1\\0\end{pmatrix}$

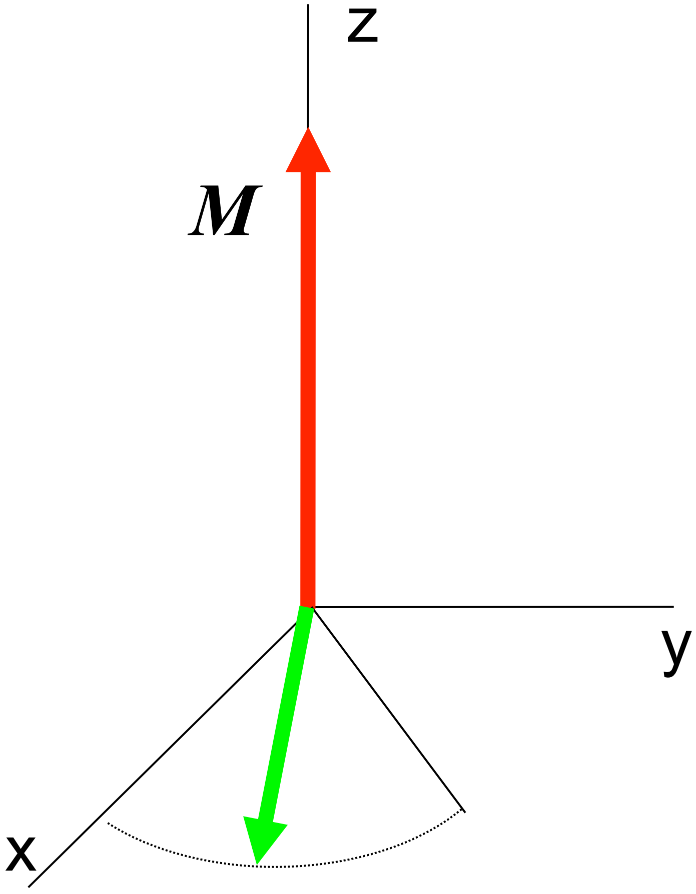
Spin down $\begin{pmatrix}0\\1\end{pmatrix}$

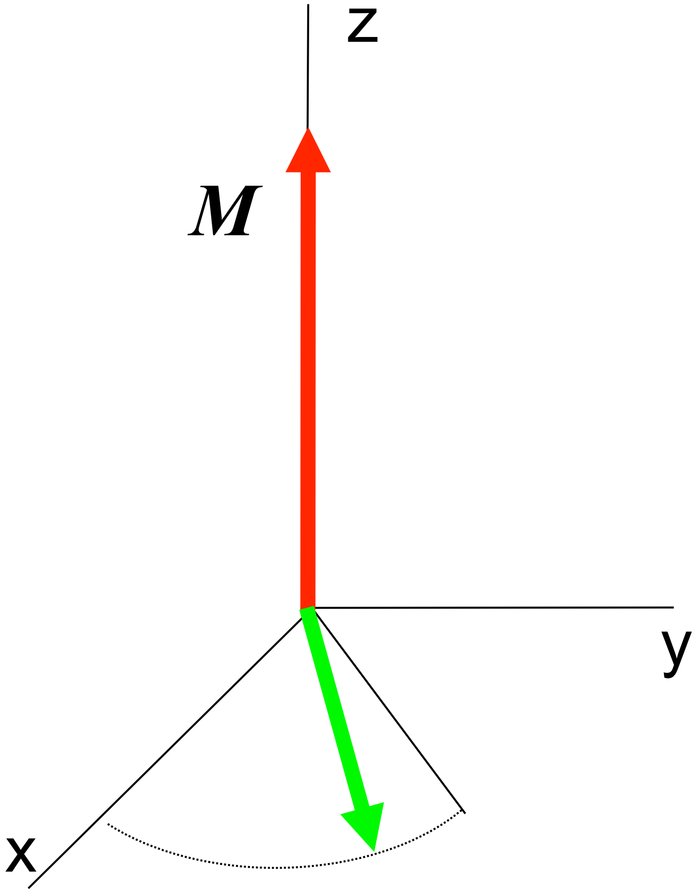
$$\psi \propto \left|r^{\uparrow}\right| e^{i\theta^{\uparrow}} \begin{pmatrix}1\\0\end{pmatrix}+\left|r^{\downarrow}\right| e^{i\theta^{\downarrow}} \begin{pmatrix}0\\1\end{pmatrix}$$

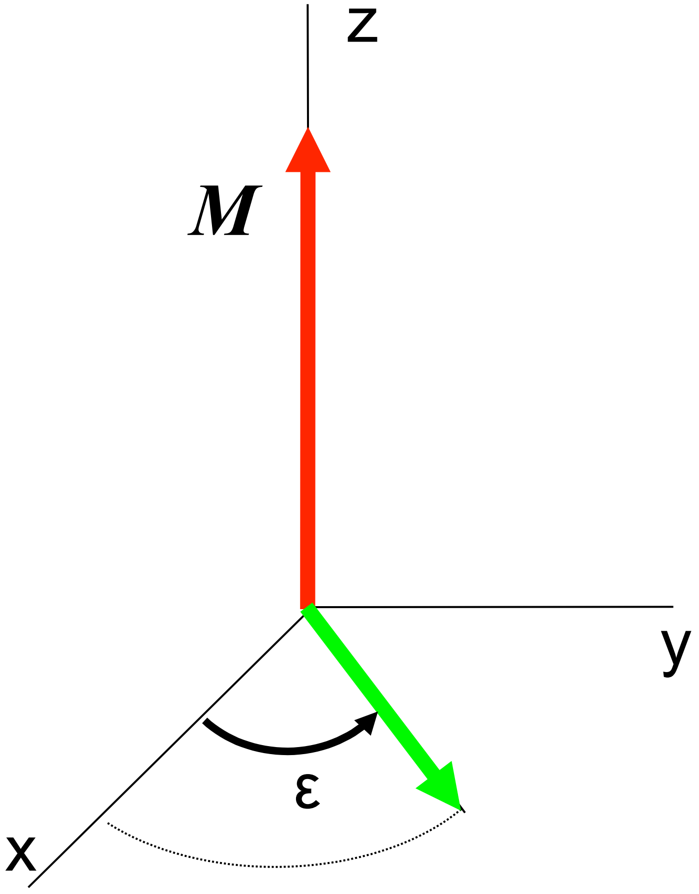
$$\boxed{\varepsilon = \theta^{\downarrow} - \theta^{\uparrow}}$$

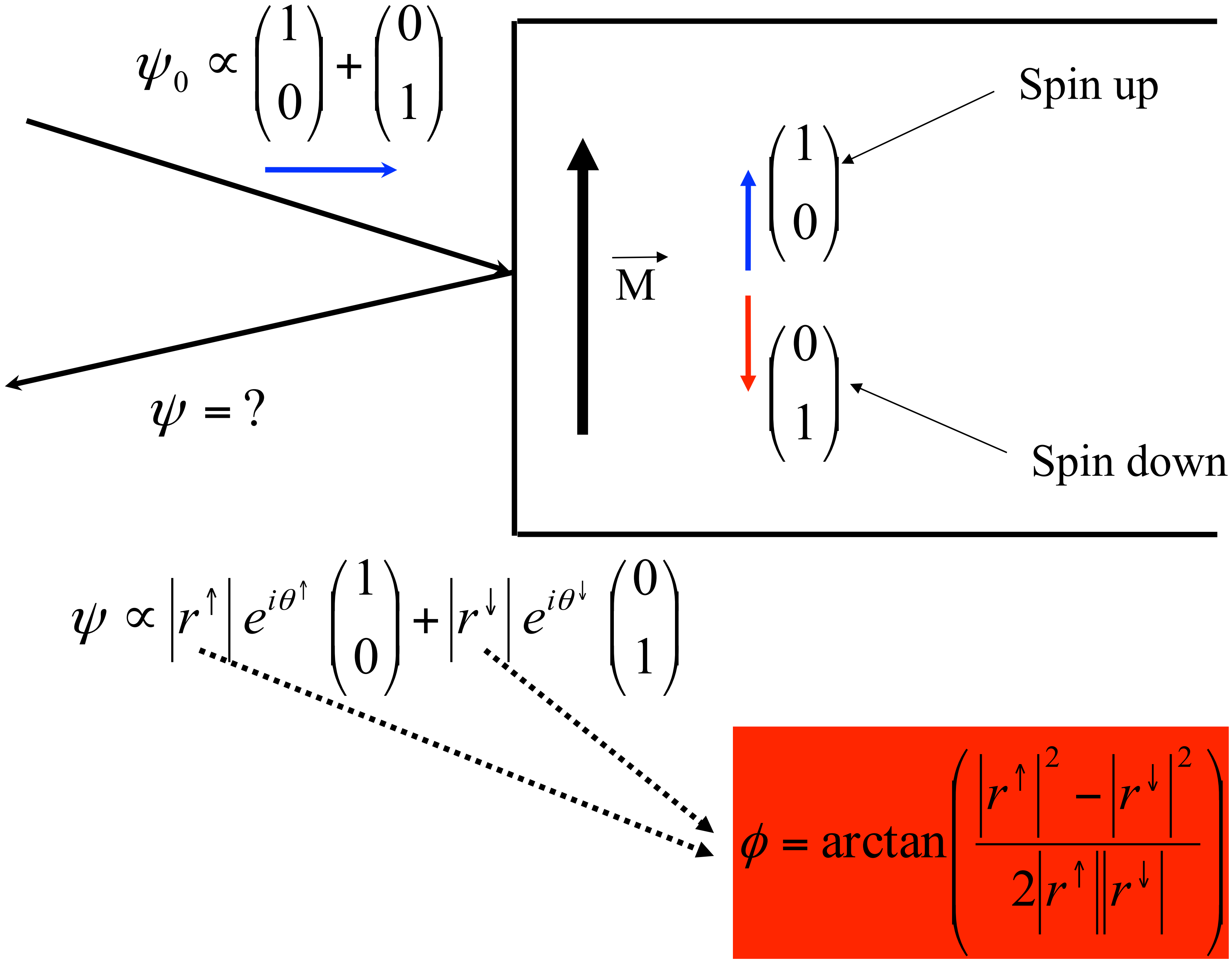

z
M
y
P_0
x


z
M
y
x


z
M
y
x


z
M
y
x


z
M
y
ε
x



$$\psi_0 \propto \begin{pmatrix}1\\0\end{pmatrix} + \begin{pmatrix}0\\1\end{pmatrix}$$

$$\psi = ?$$

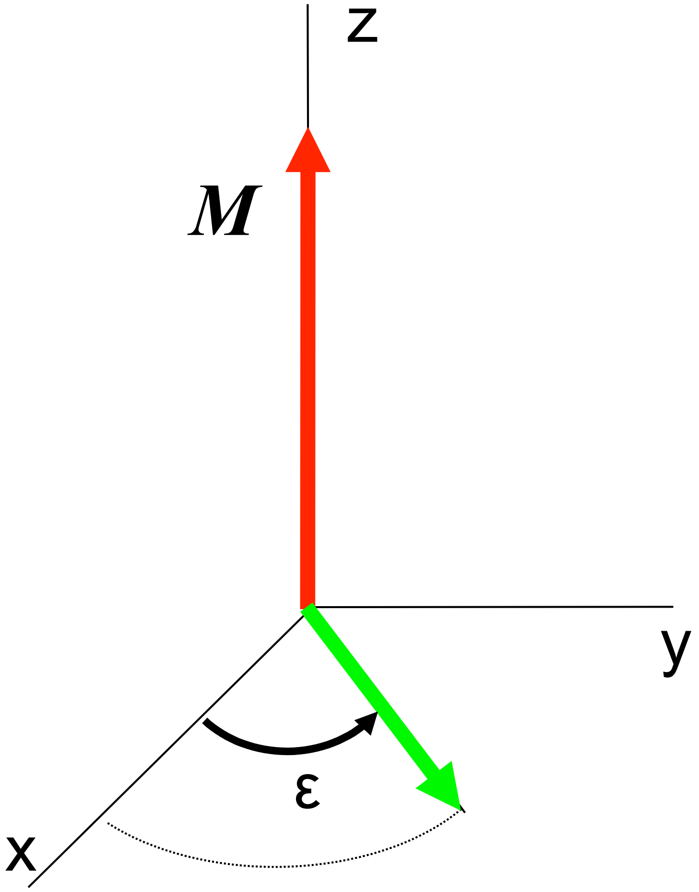
$\vec{M}$

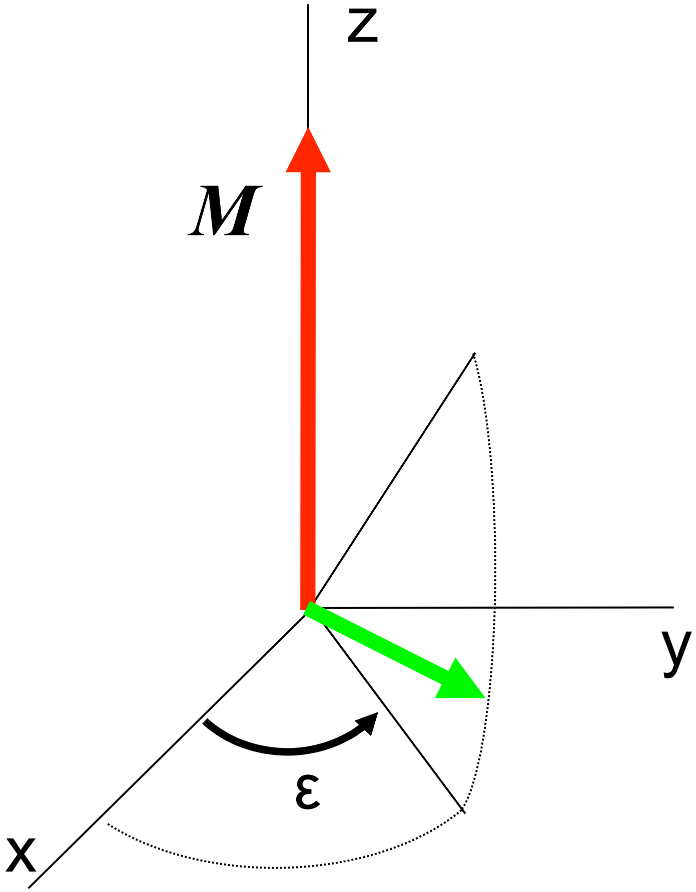
Spin up $\begin{pmatrix}1\\0\end{pmatrix}$

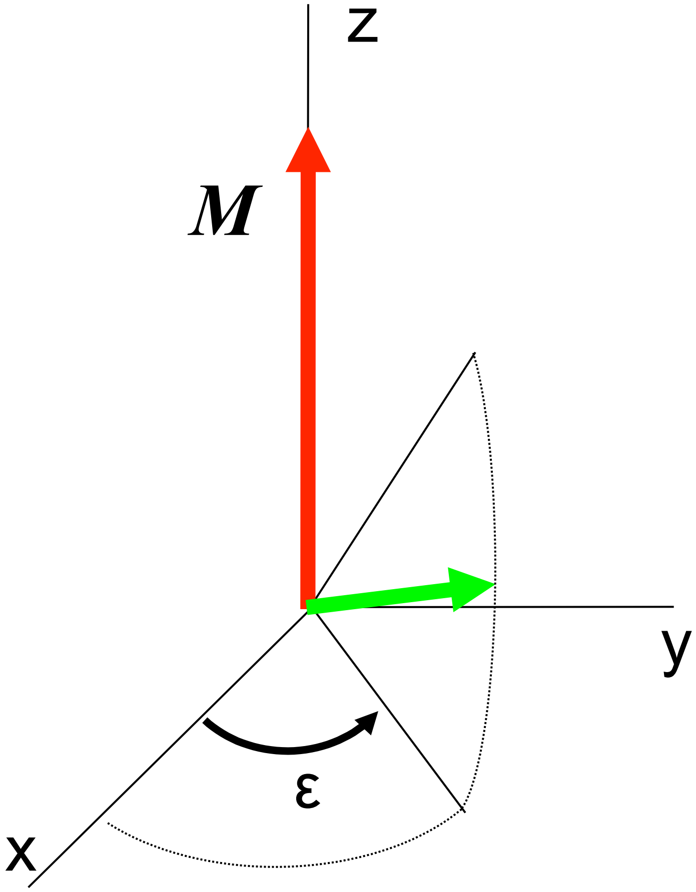
Spin down $\begin{pmatrix}0\\1\end{pmatrix}$

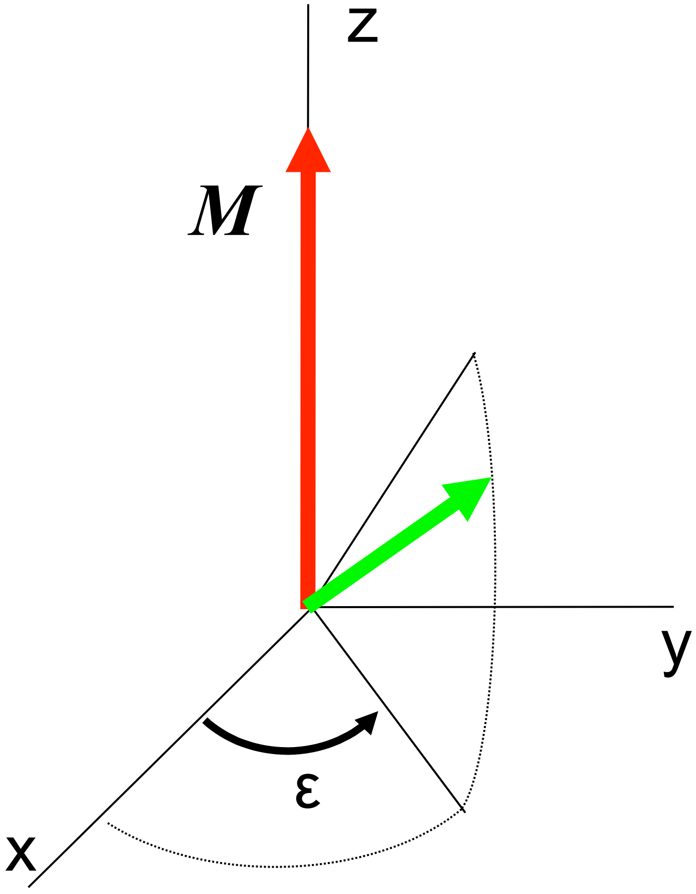
$$\psi \propto \left|r^{\uparrow}\right| e^{i\theta^{\uparrow}} \begin{pmatrix}1\\0\end{pmatrix} + \left|r^{\downarrow}\right| e^{i\theta^{\downarrow}} \begin{pmatrix}0\\1\end{pmatrix}$$

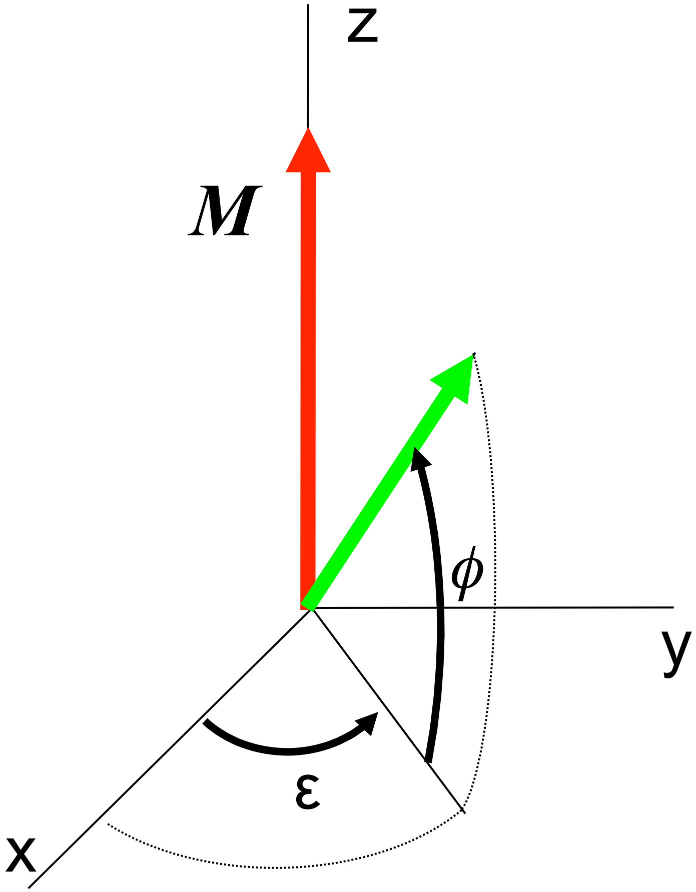
$$\phi = \arctan\left(\frac{\left|r^{\uparrow}\right|^2 - \left|r^{\downarrow}\right|^2}{2\left|r^{\uparrow}\right|\left|r^{\downarrow}\right|} \right)$$


z
M
y
ε
x

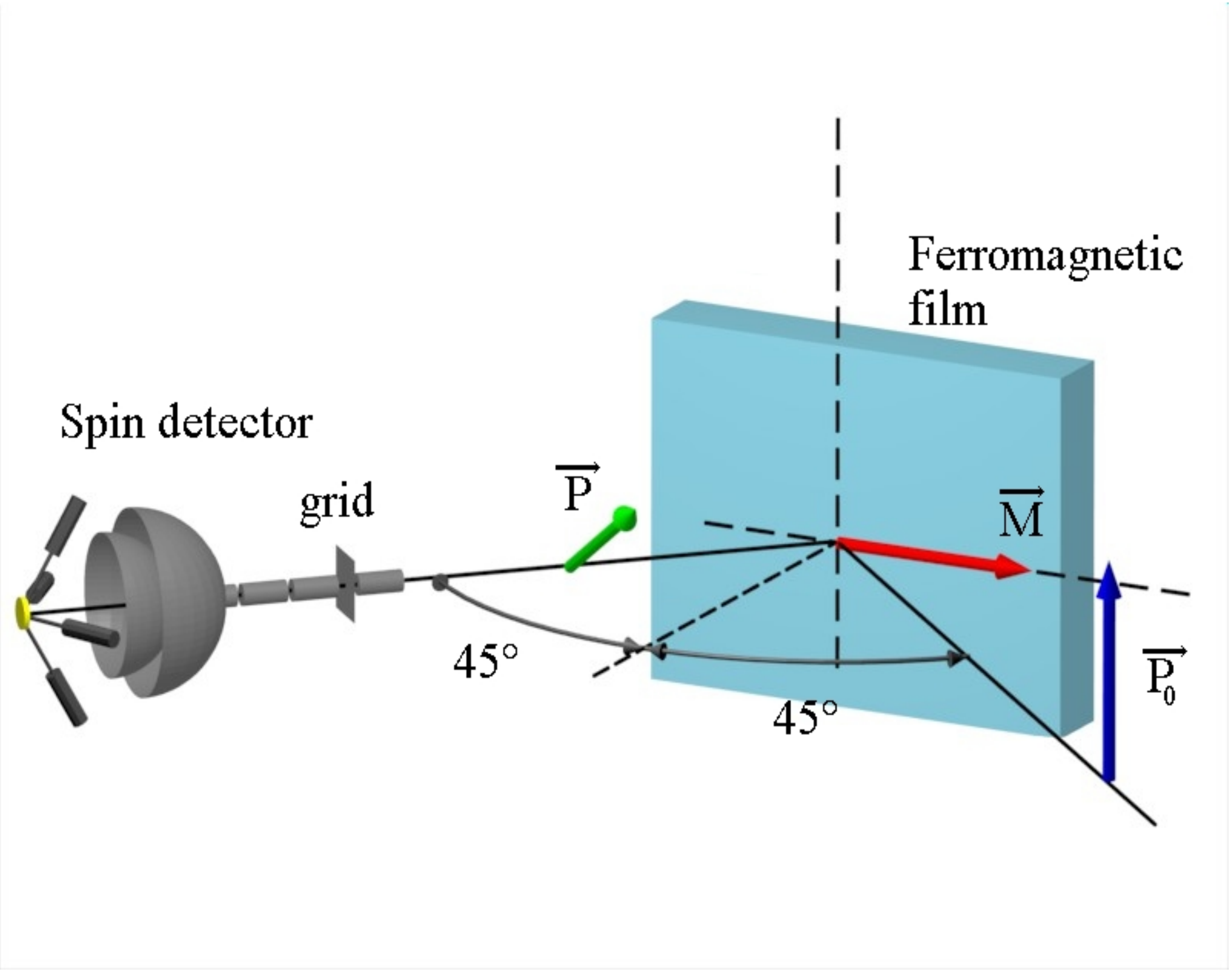

z
M
y
x
ε


z
M
y
ε
x


z
M
y
ε
x

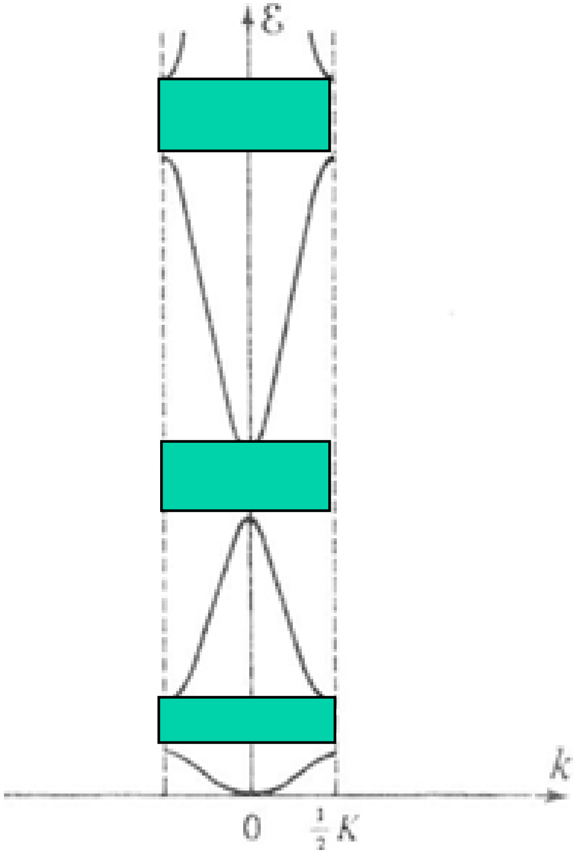

z
M
ϕ
y
ε
x

Experiment

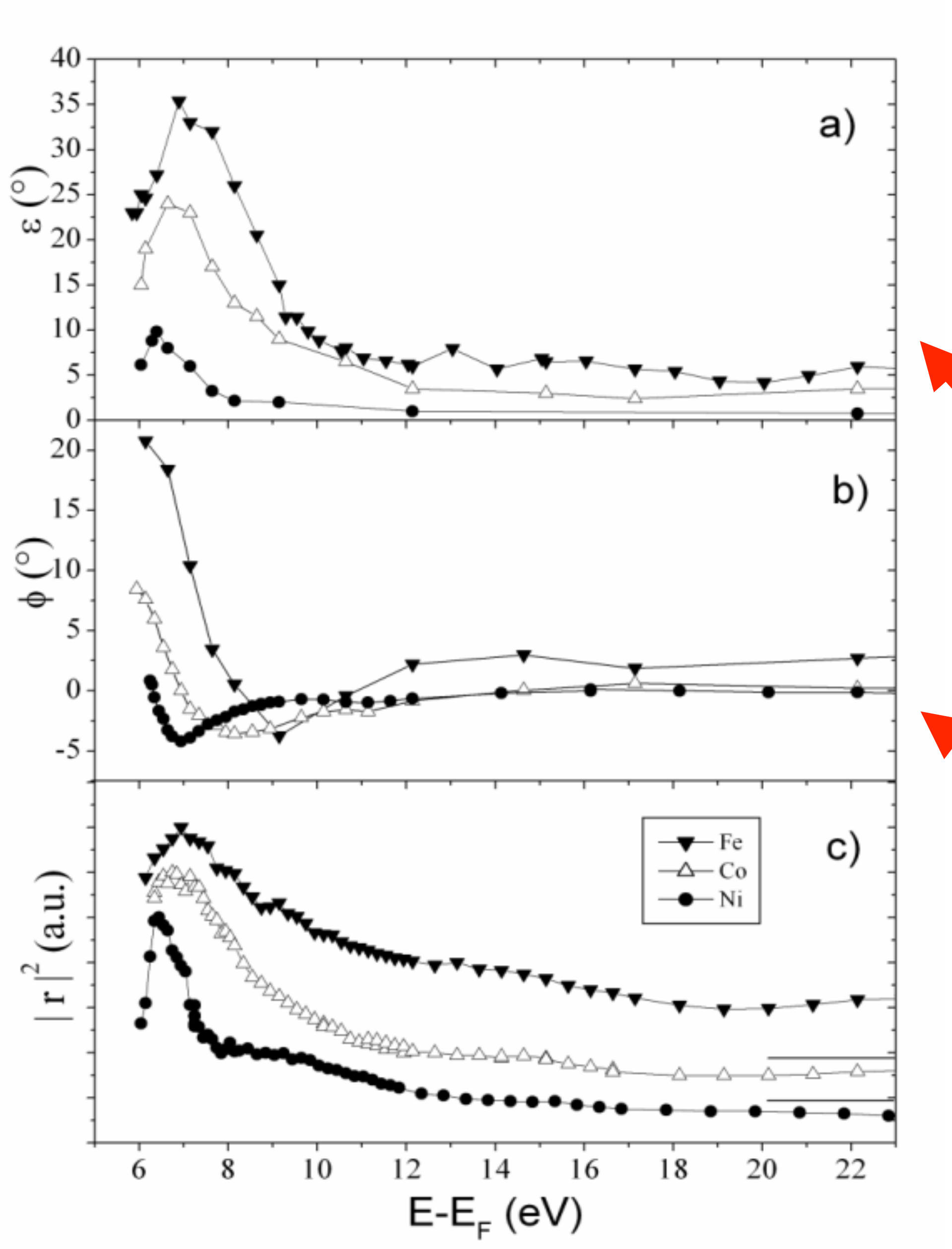

Ferromagnetic film
Spin detector
grid
$\overrightarrow{P}$
$\overrightarrow{M}$
45°
45°
$\overrightarrow{P_0}$

Spin-dependent band gaps and their influence on the electron-spin motion

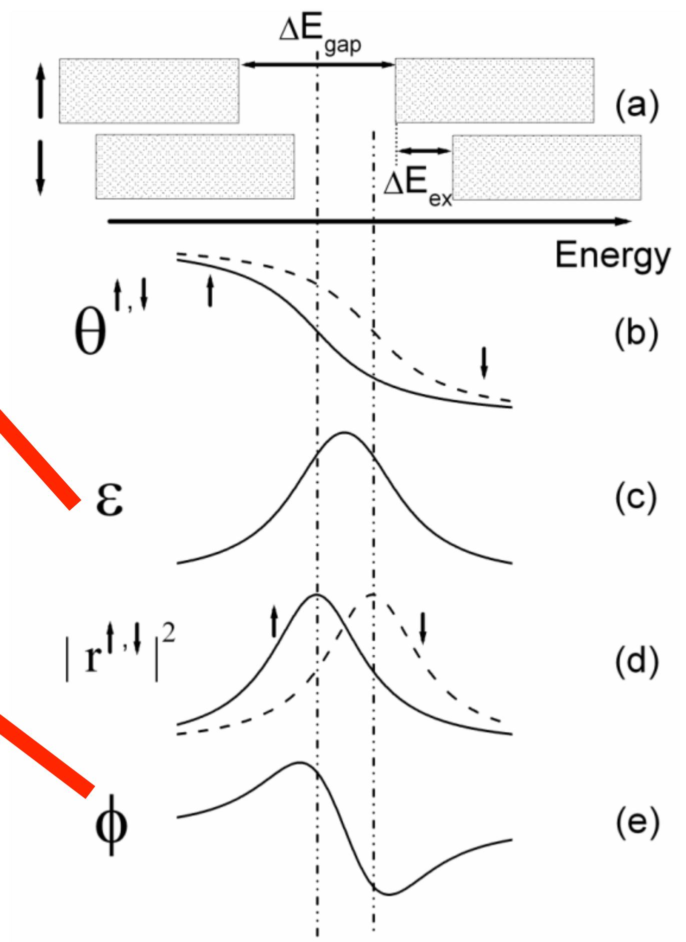
Typical electronic band structure



Experimental results



Theory

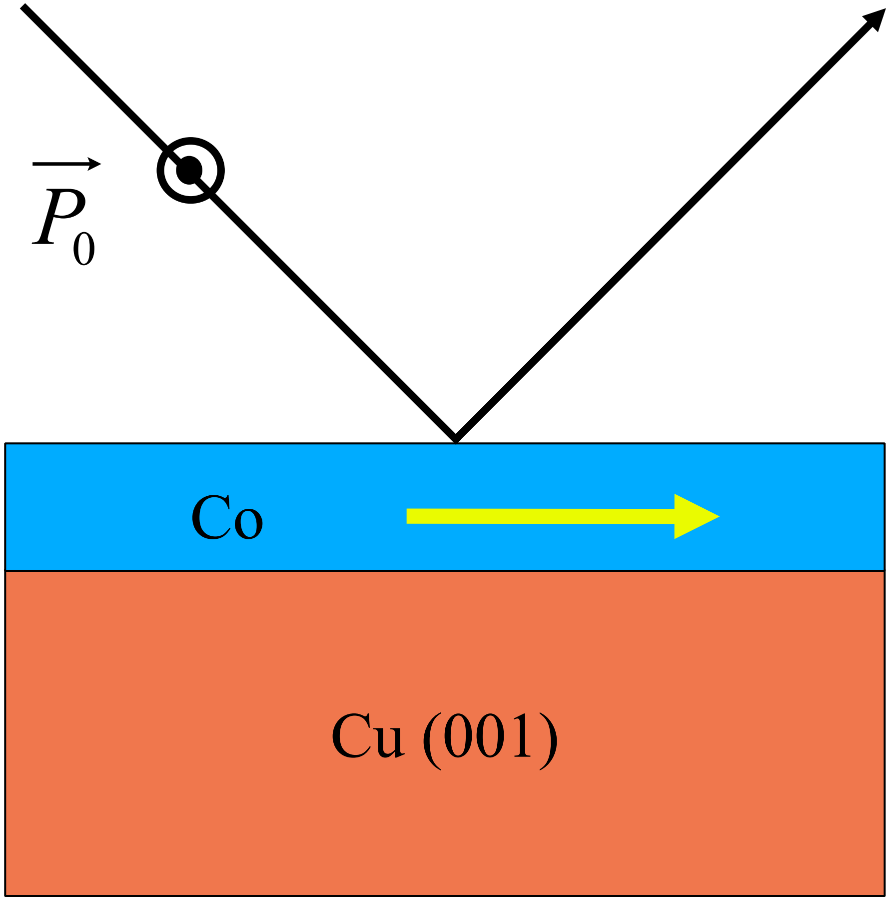


Joly et al., PRL 96, 137206 (2006)

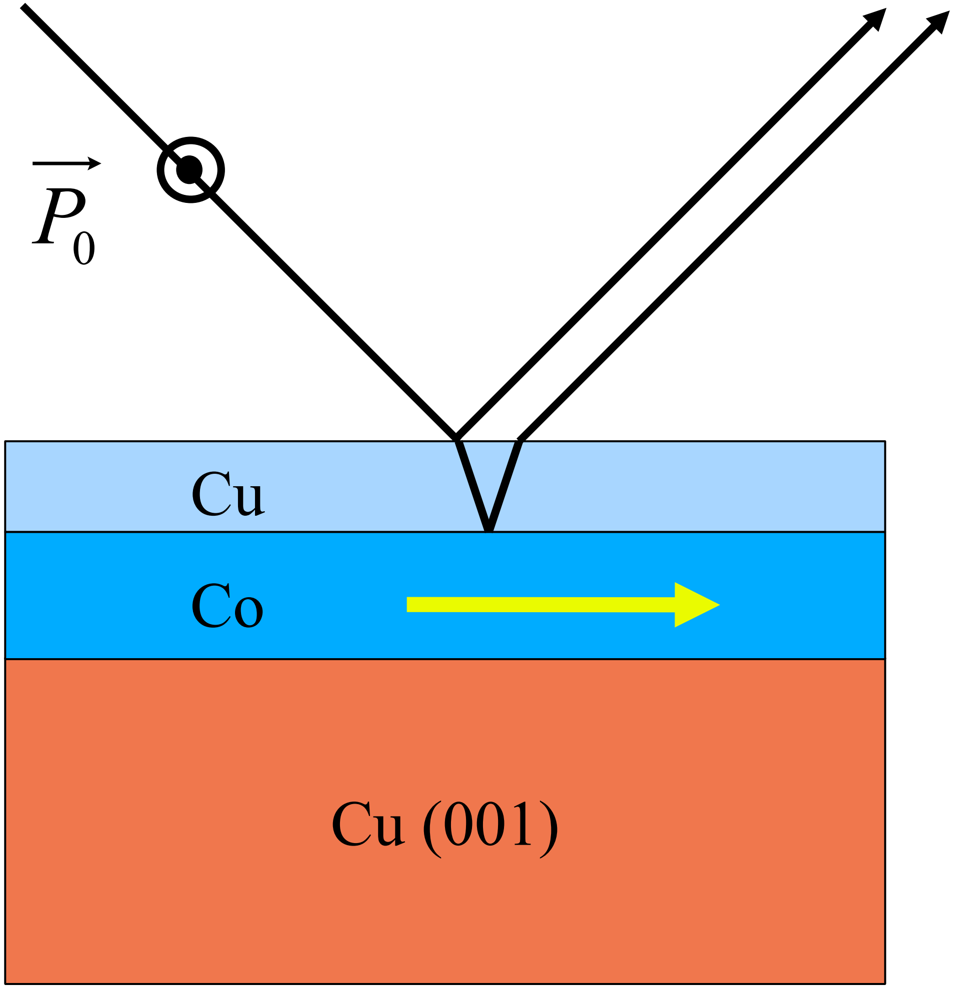
Spin-dependent band gaps and their influence on the electron-spin motion

Fabry-Pérot experiments with spin-polarized electrons

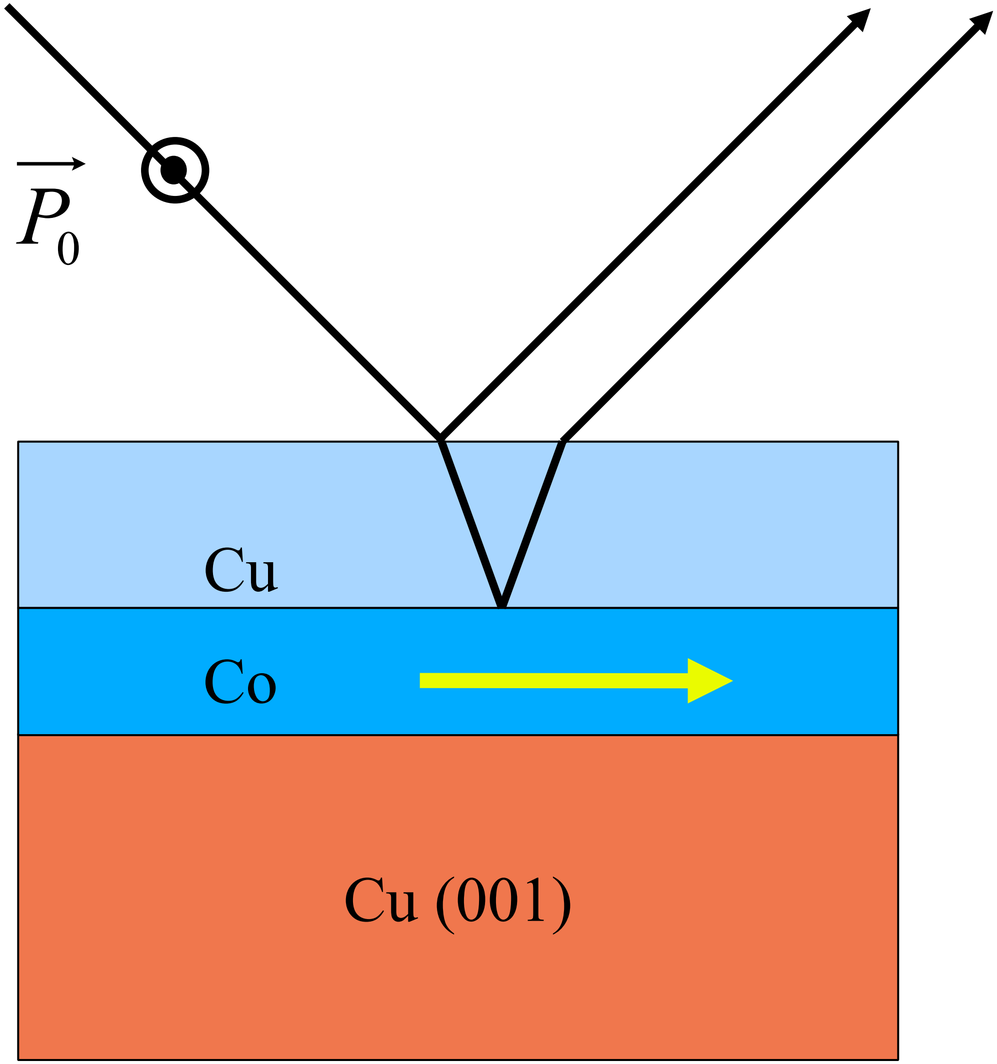
Quantum interference



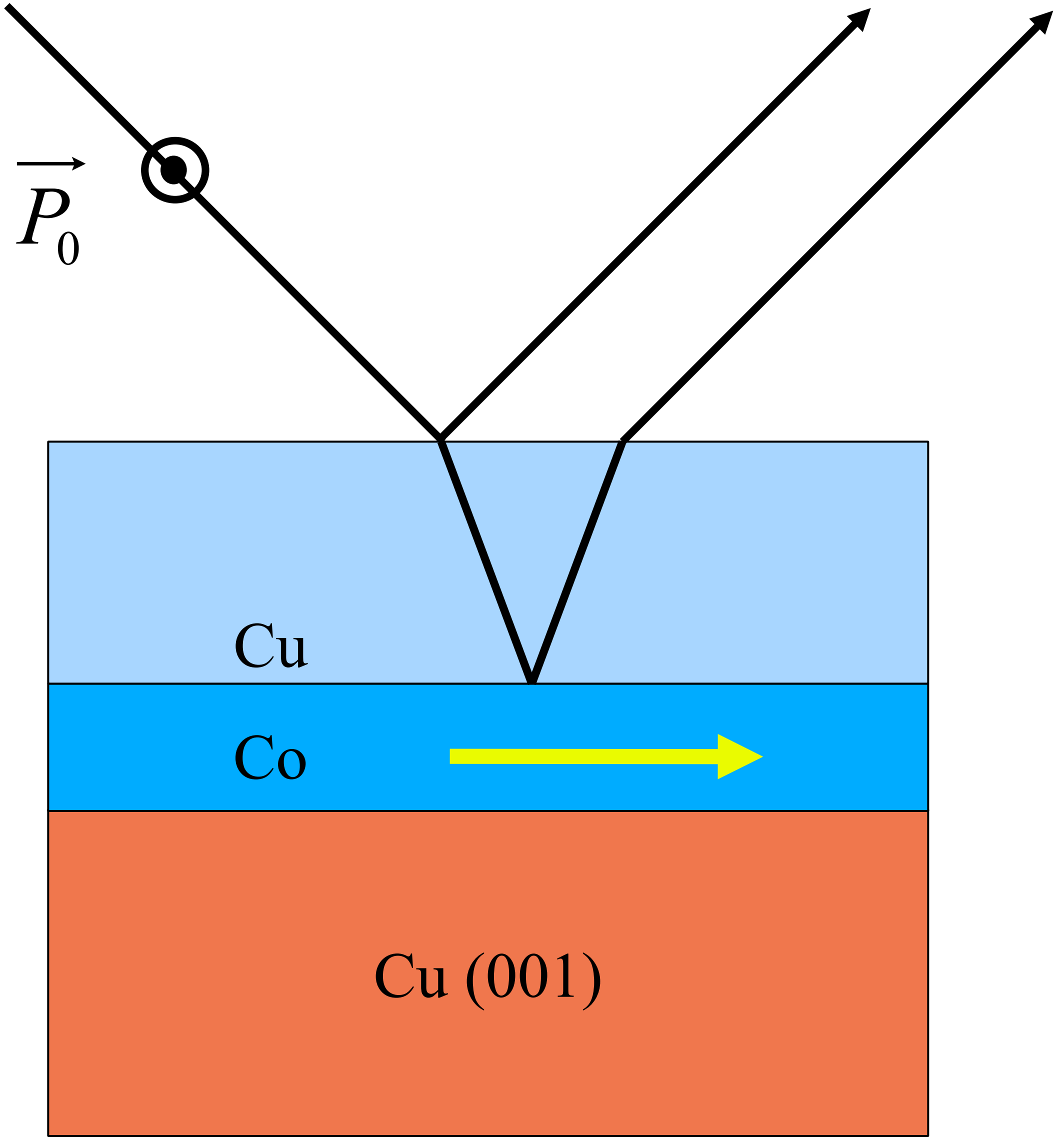
Quantum interference



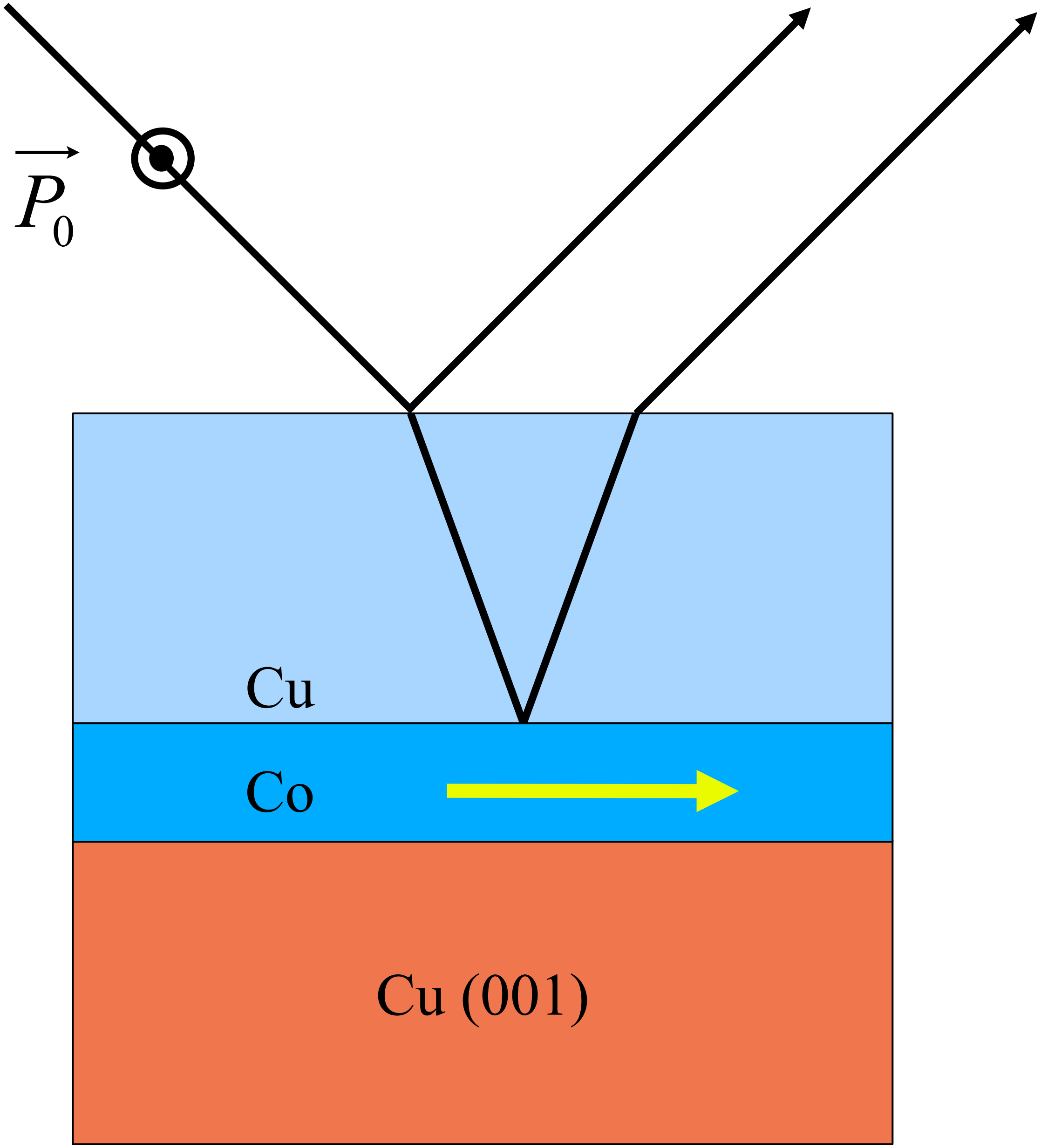
Quantum interference



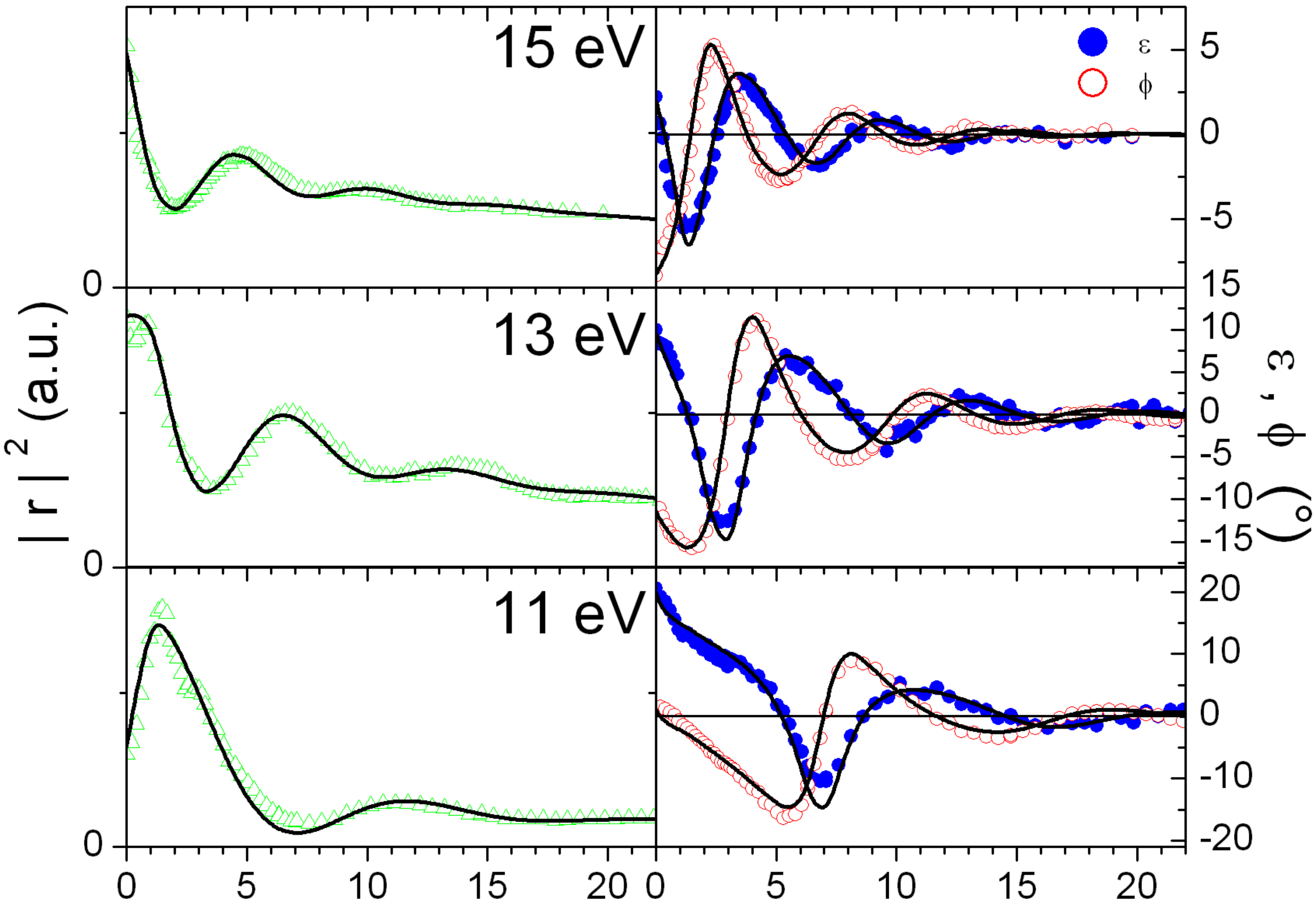
Quantum interference



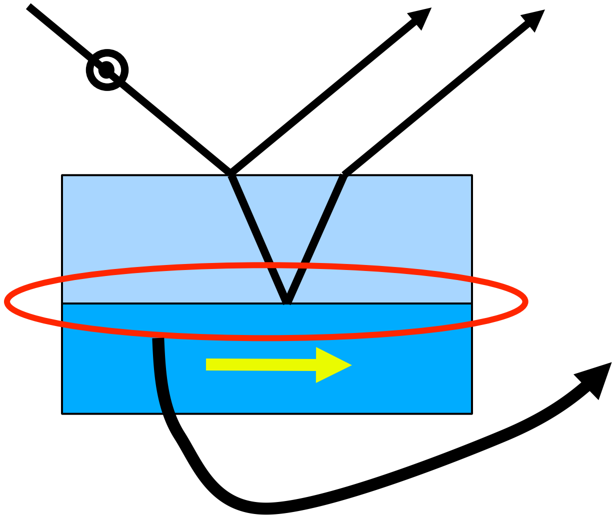
Quantum interference

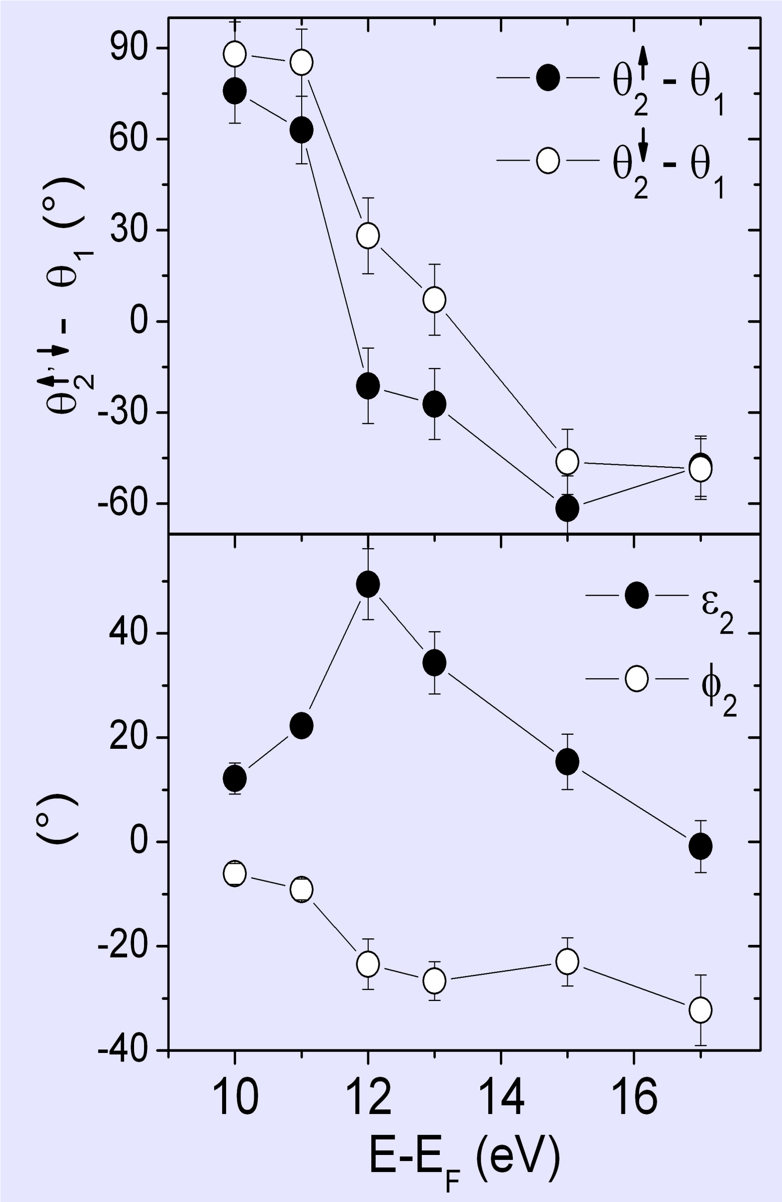


Experimental results and simulations



Joly et al., PRL 97, 187404 (2006), Joly et al., PRB 76, 104415 (2007)





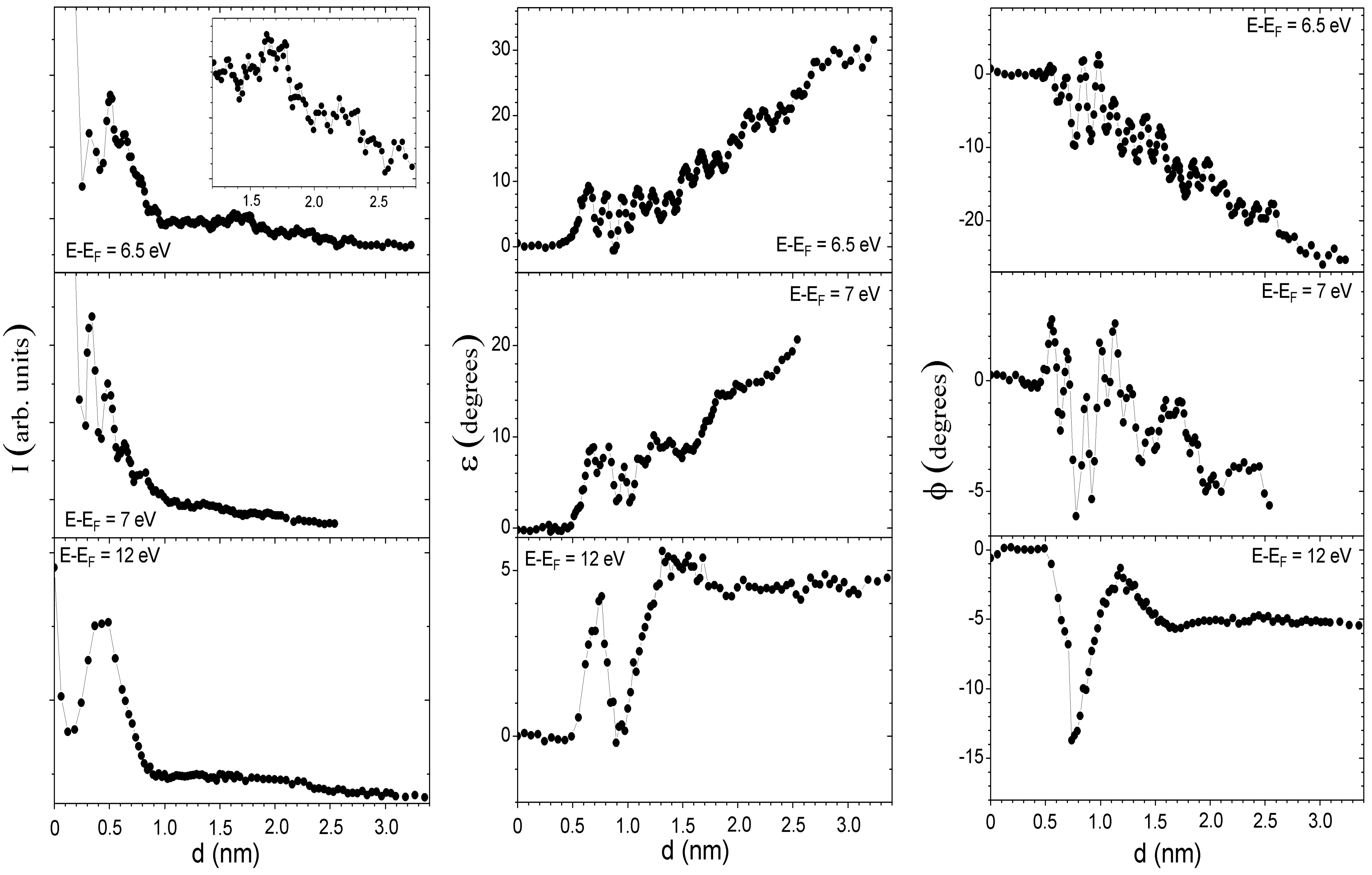
Joly et al., PRL 97, 187404 (2006), Joly et al., PRB 76, 104415 (2007)

Spin-dependent band gaps
and their influence on the
electron-spin motion

Fabry-Pérot experiments
with spin-polarized electrons

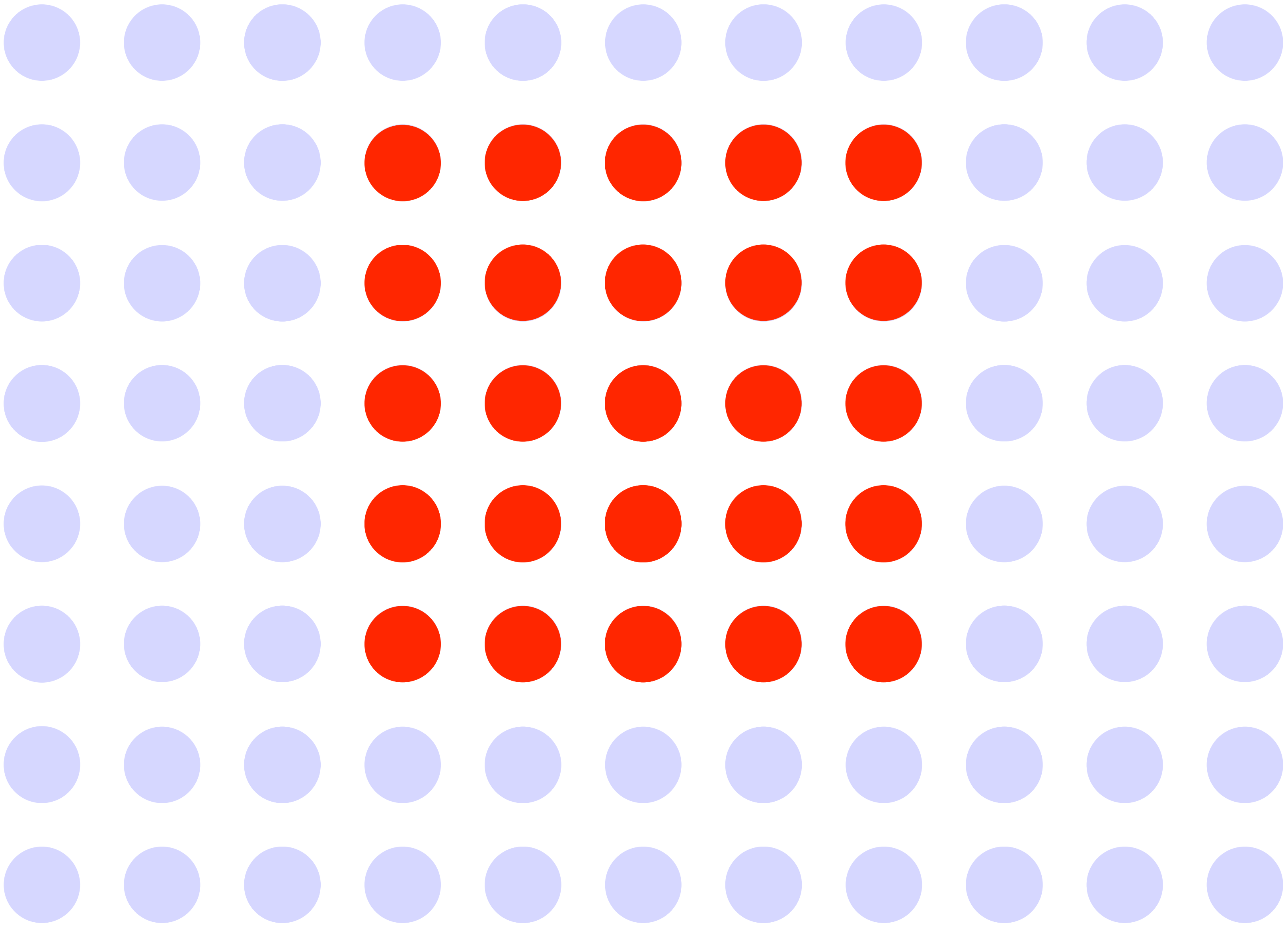
Morphology-induced
oscillations of the electron-
spin precession

Fe/Ag(001)

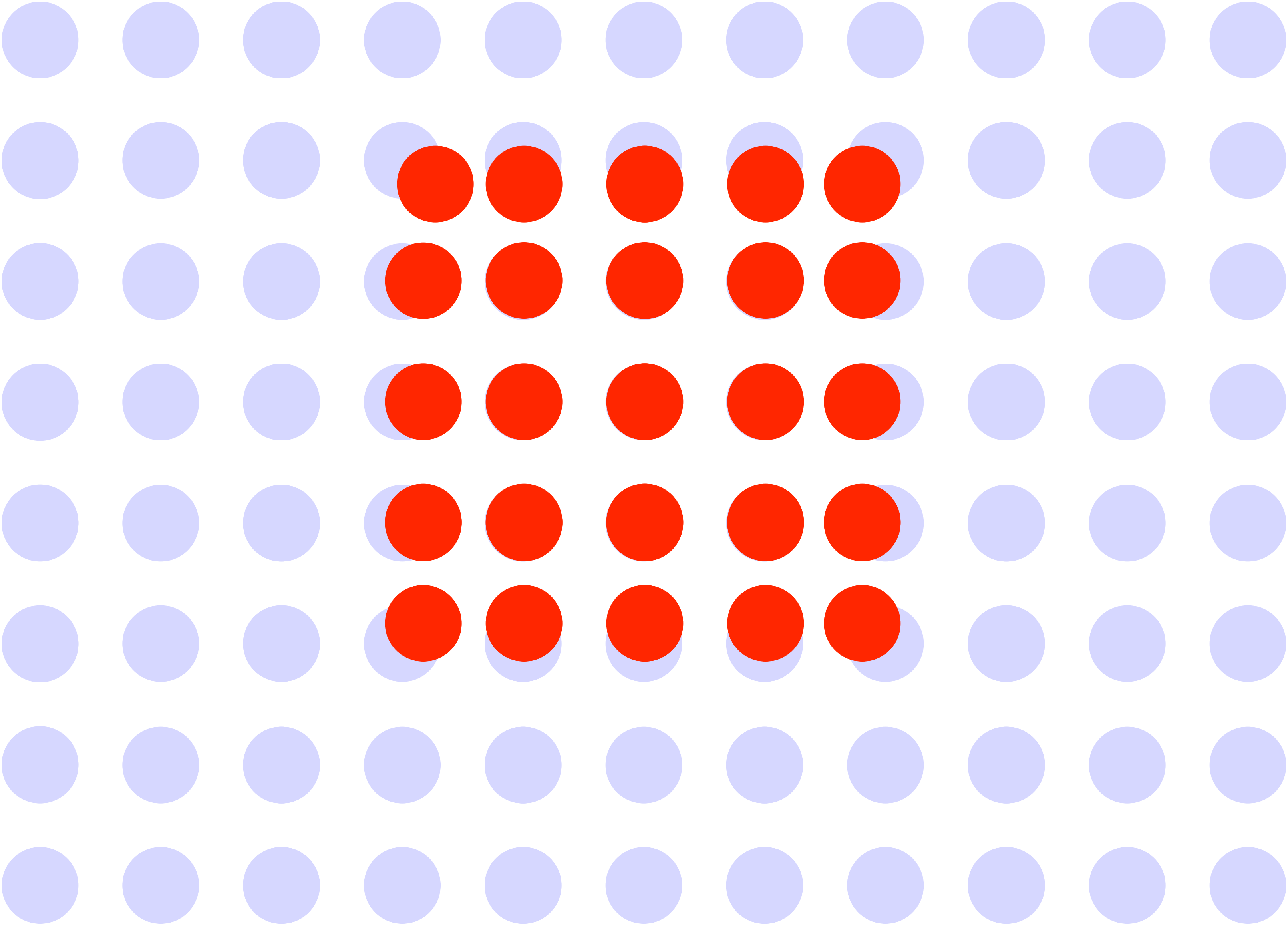


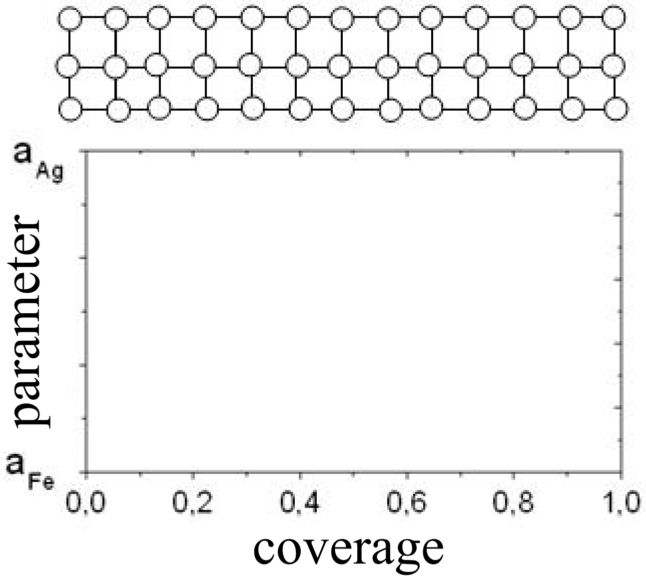
Tati Bismaths et al., PRB 77, 220405(R) (2008)

A/B without relaxation at the islands edges

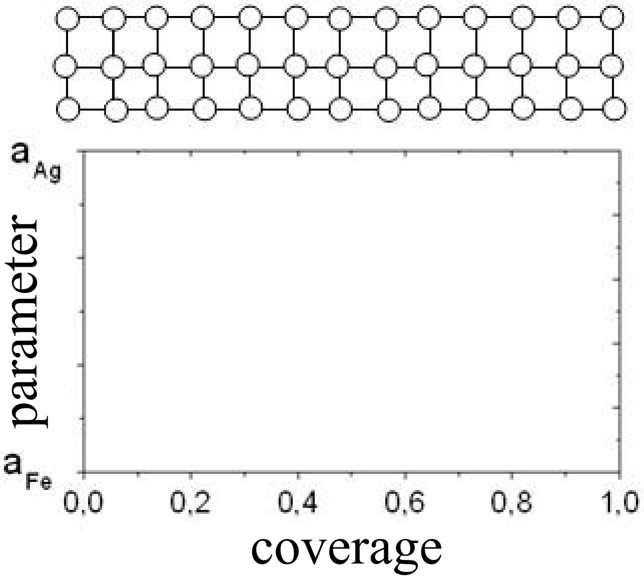


A/B with relaxation at the islands edges





a Ag
a Fe
parameter
0,0
0,2
0,4
0,6
0,8
1,0
coverage


a_{Ag}
parameter
a_{Fe}
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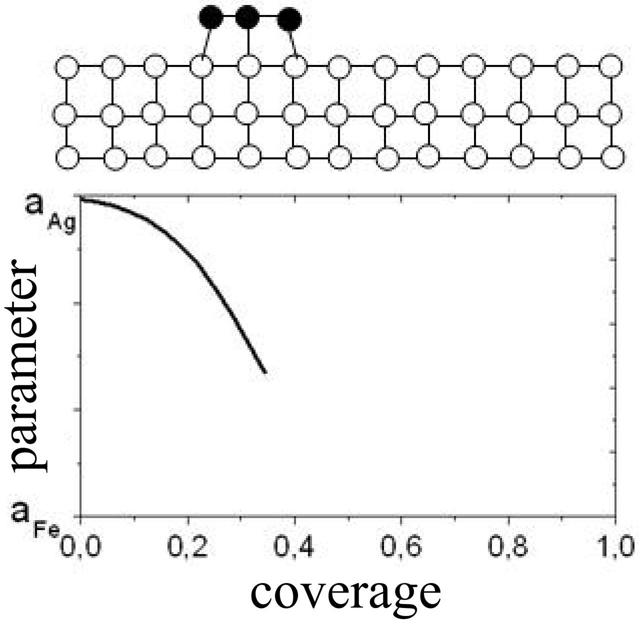
0,2
0,4
0,6
0,8
1,0
coverage


a_{Ag}
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a_{Fe}
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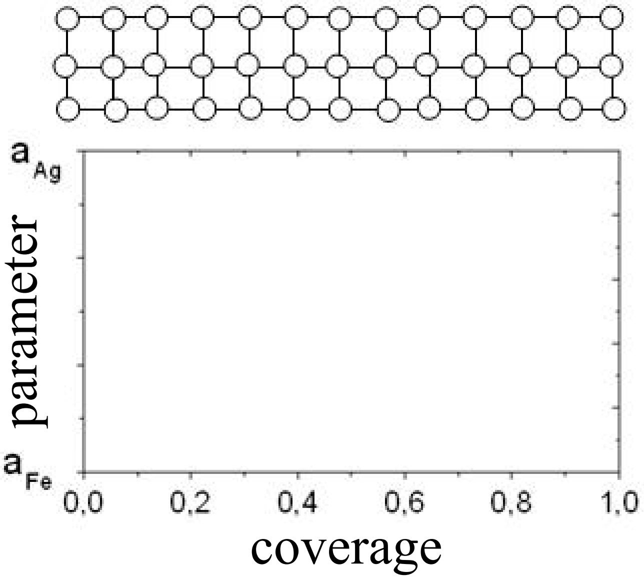
0,4
0,6
0,8
1,0
coverage



a Ag
parameter
a Fe
0,0
0,2
0,4
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0,8
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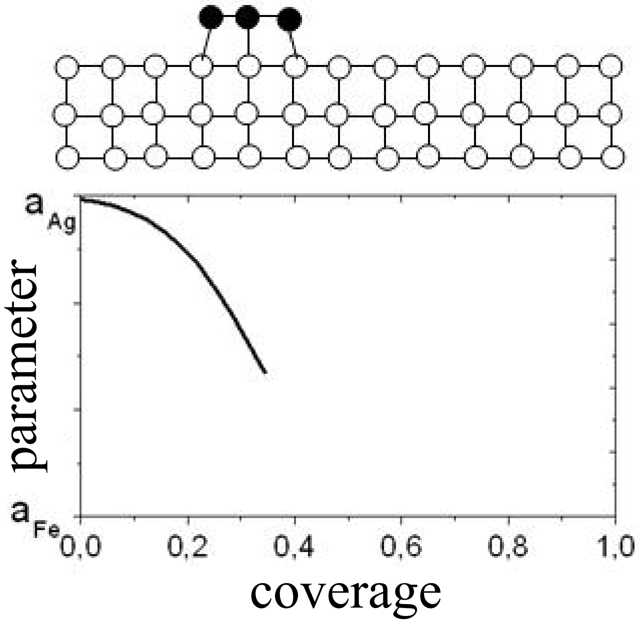
coverage



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parameter
a Fe
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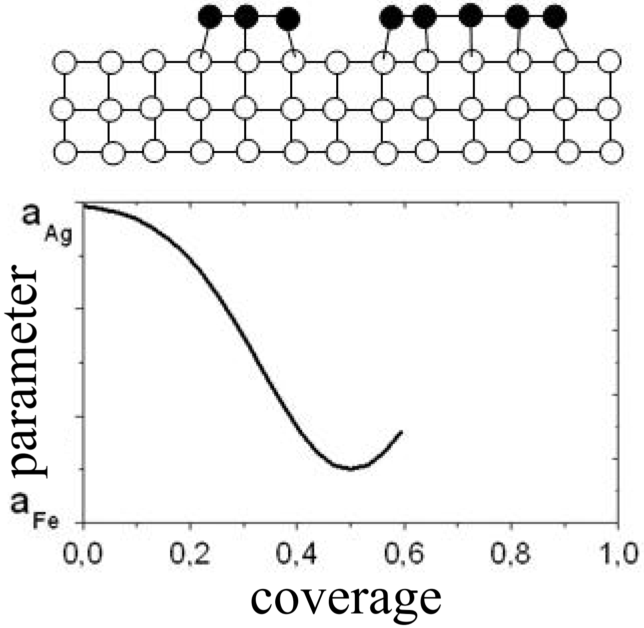
0,2
0,4
0,6
0,8
1,0
coverage



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a Fe
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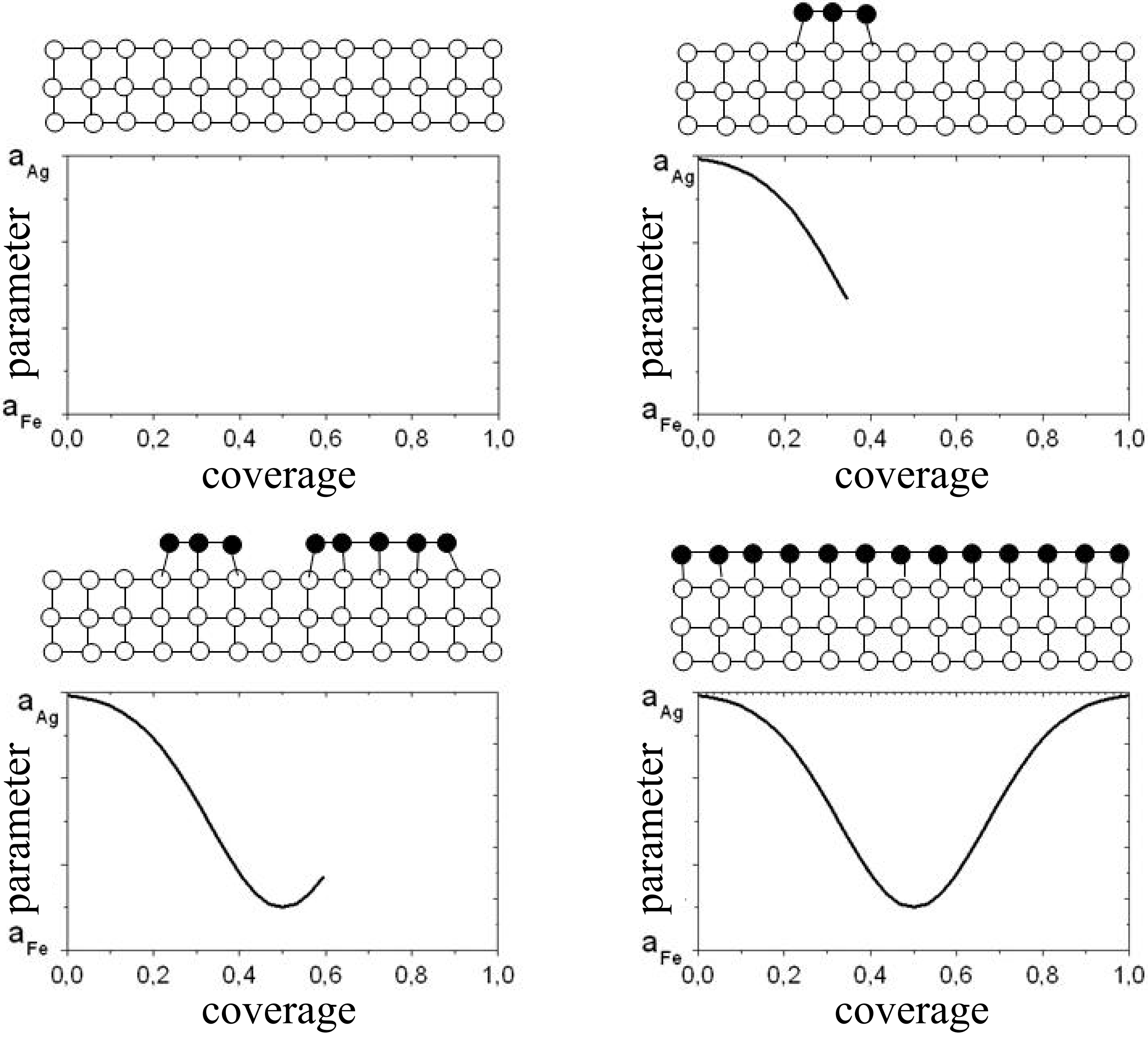
coverage


a Ag
a Fe
parameter
0,0
0,2
0,4
0,6
0,8
1,0
coverage
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a Fe
parameter
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0,4
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0,8
1,0
coverage
a Ag
a Fe
parameter
0,0
0,2
0,4
0,6
0,8
1,0
coverage
a Ag
a Fe
parameter
0,0
0,2
0,4
0,6
0,8
1,0
coverage

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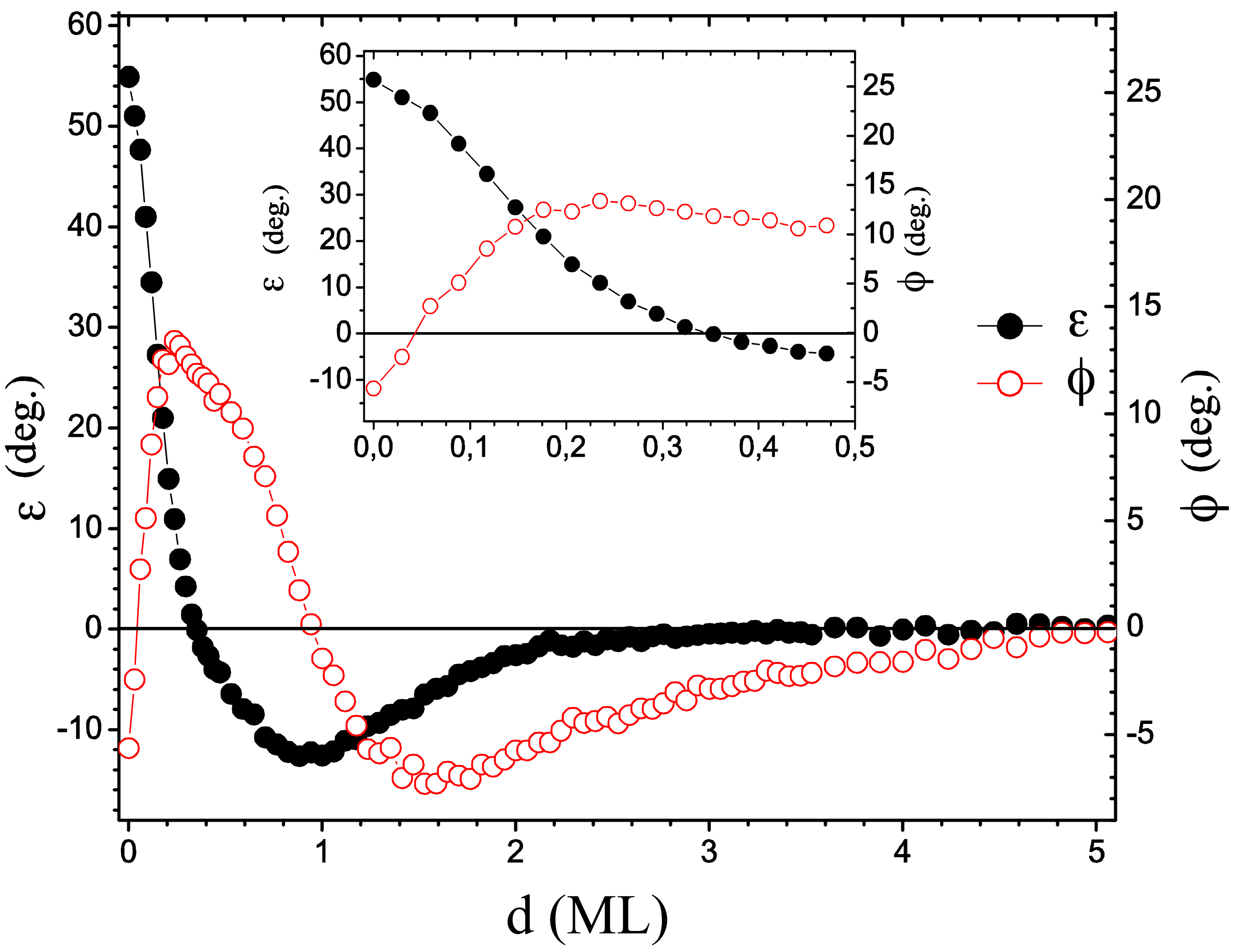
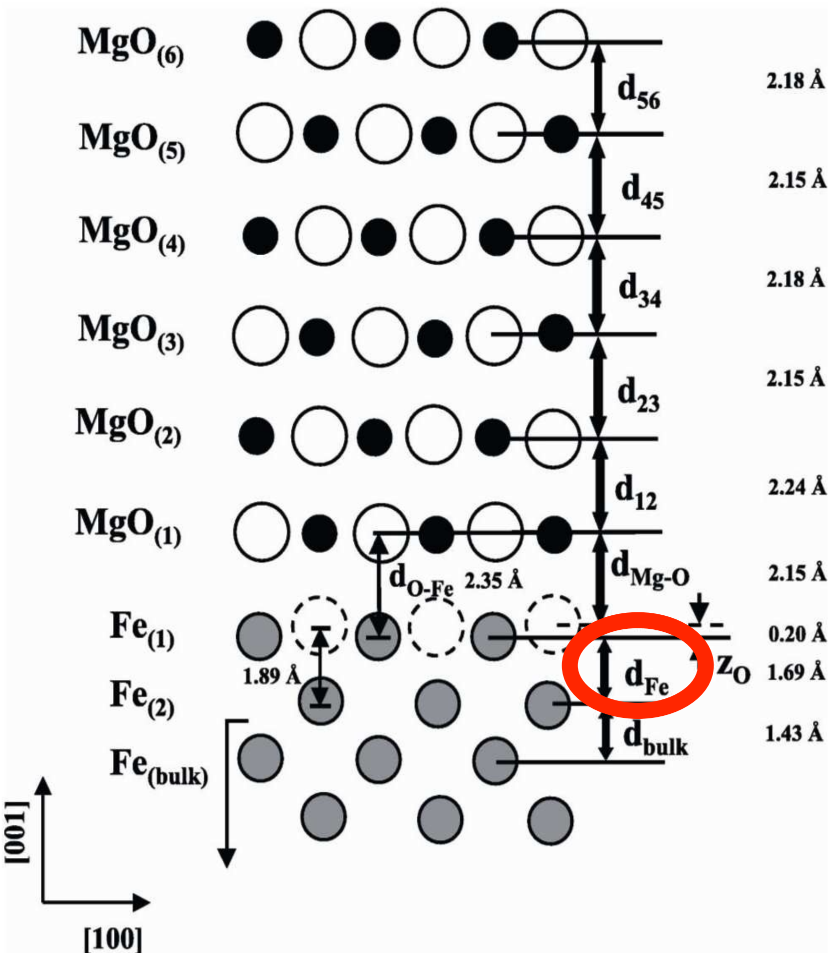
Influence of sub-monolayer MgO coverages on the spin-dependent reflection properties of Fe



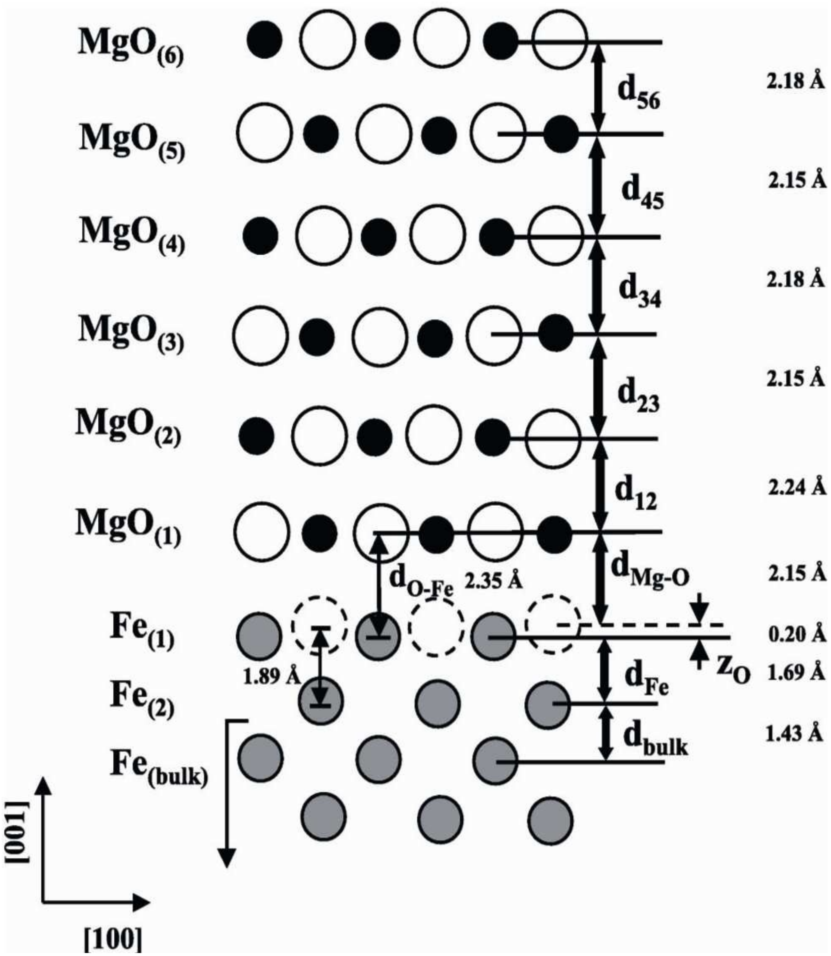
T. Berdot *et al.*, PRB **82**, 172407 (2010)

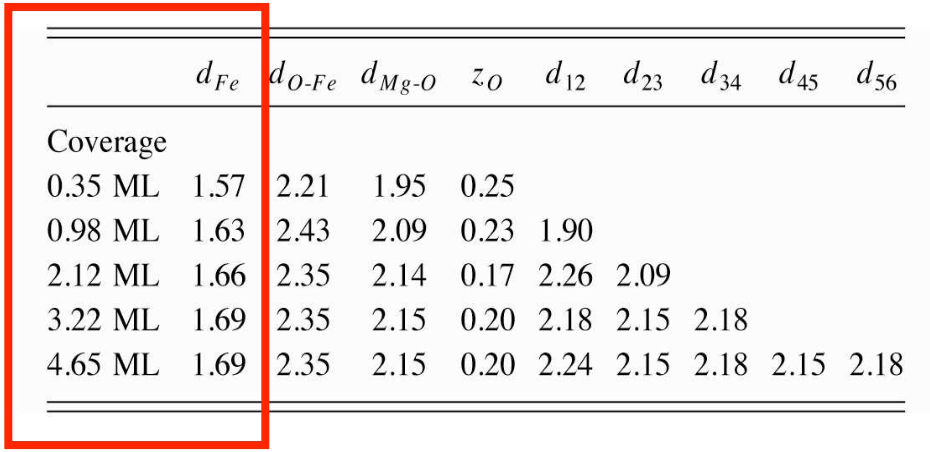
MgO-induced perpendicular relaxation of the Fe surface



H.L. Meyerheim *et al.*, Phys. Rev. B **65**, 144433 (2002)

MgO-induced normal relaxation of the Fe surface

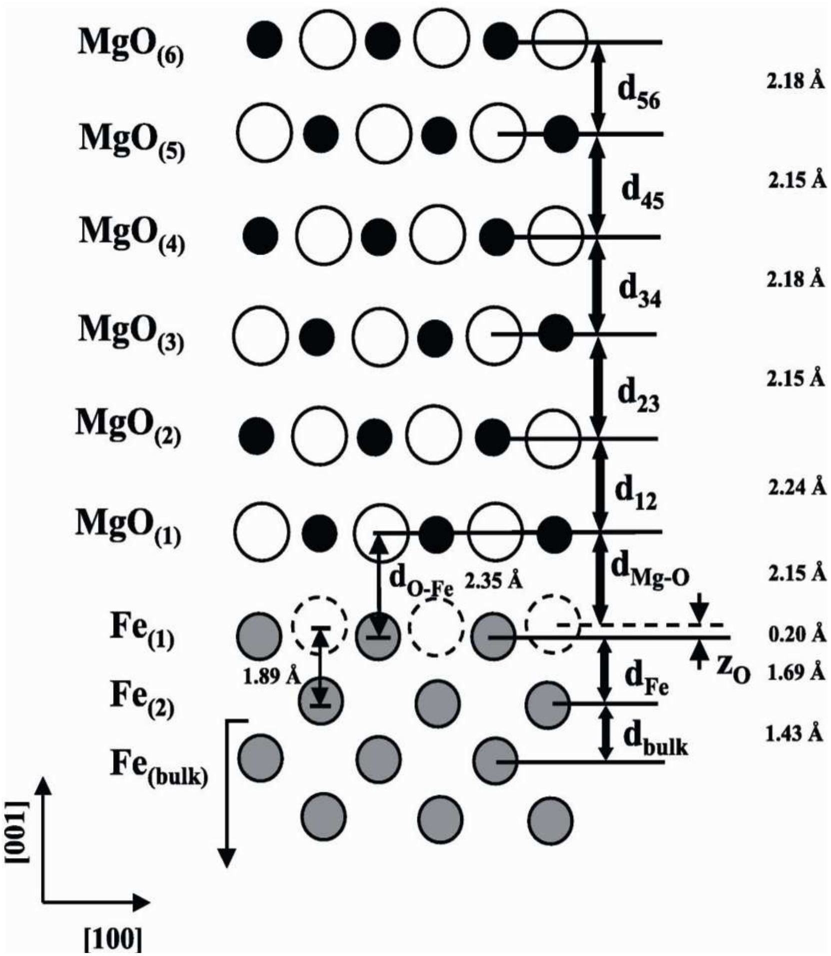


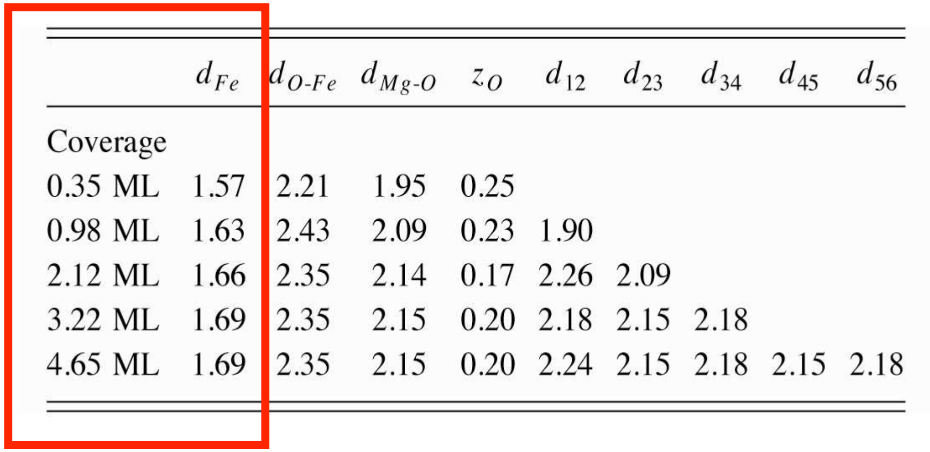


	d_{Fe}	$d_{O\text{-}Fe}$	$d_{Mg\text{-}O}$	z_O	d_{12}	d_{23}	d_{34}	d_{45}	d_{56}
Coverage									
0.35 ML	1.57	2.21	1.95	0.25					
0.98 ML	1.63	2.43	2.09	0.23	1.90				
2.12 ML	1.66	2.35	2.14	0.17	2.26	2.09			
3.22 ML	1.69	2.35	2.15	0.20	2.18	2.15	2.18		
4.65 ML	1.69	2.35	2.15	0.20	2.24	2.15	2.18	2.15	2.18

H.L. Meyerheim *et al.*, Phys. Rev. B **65**, 144433 (2002)

MgO-induced normal relaxation of the Fe surface





	d_{Fe}	$d_{O\text{-}Fe}$	$d_{Mg\text{-}O}$	z_O	d_{12}	d_{23}	d_{34}	d_{45}	d_{56}
Coverage									
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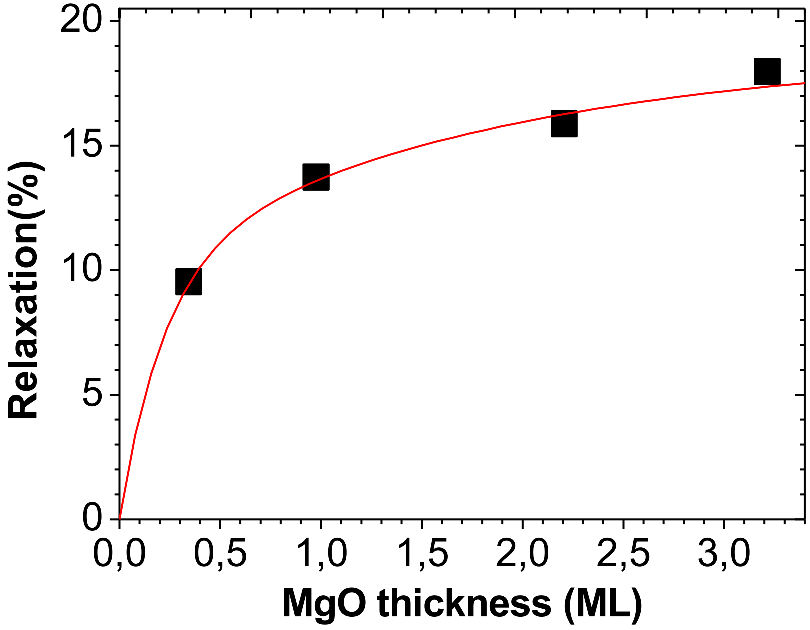
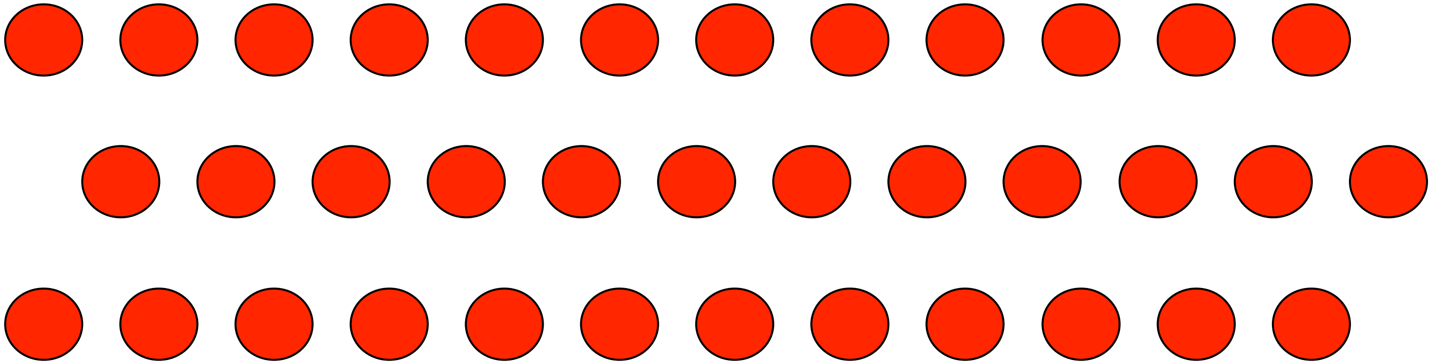
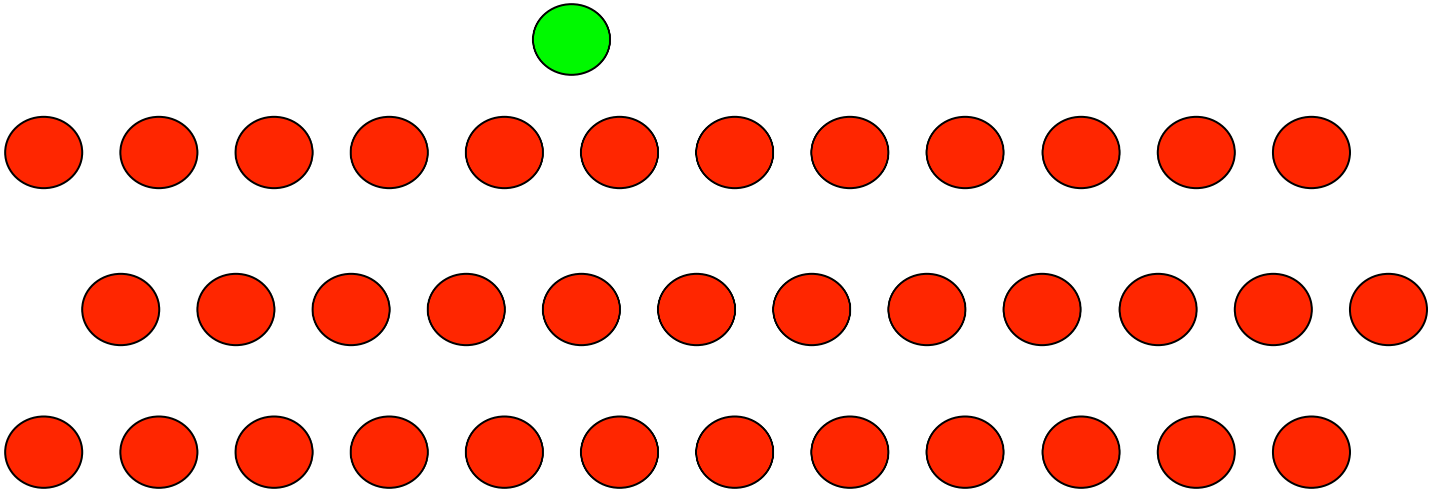
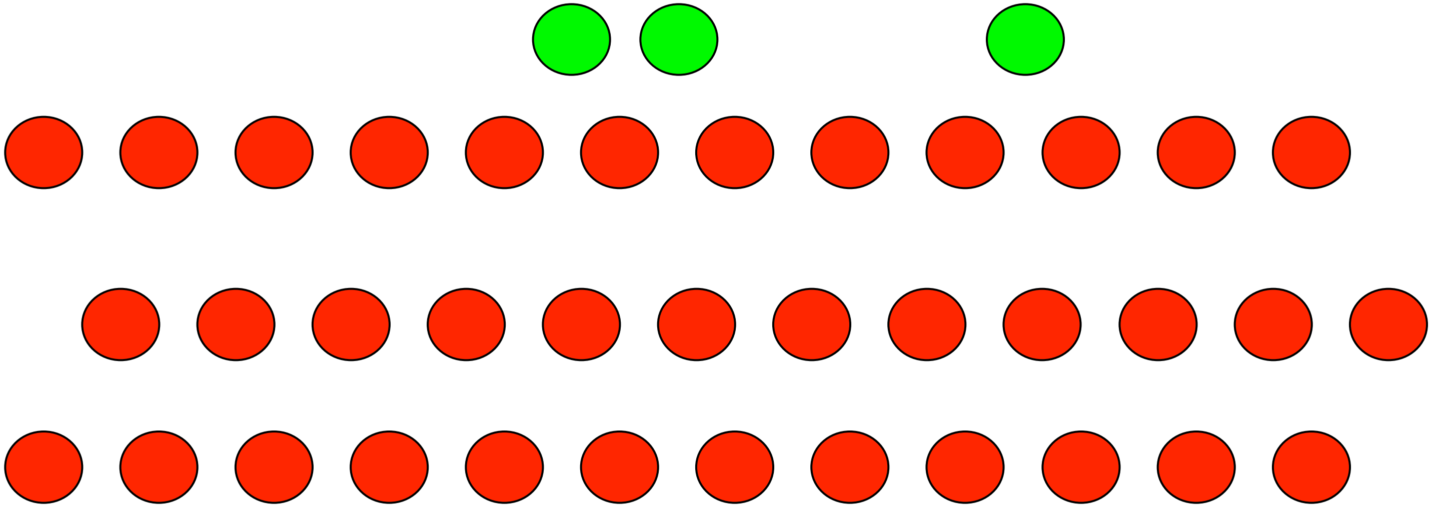
3.22 ML	1.69	2.35	2.15	0.20	2.18	2.15	2.18		
4.65 ML	1.69	2.35	2.15	0.20	2.24	2.15	2.18	2.15	2.18

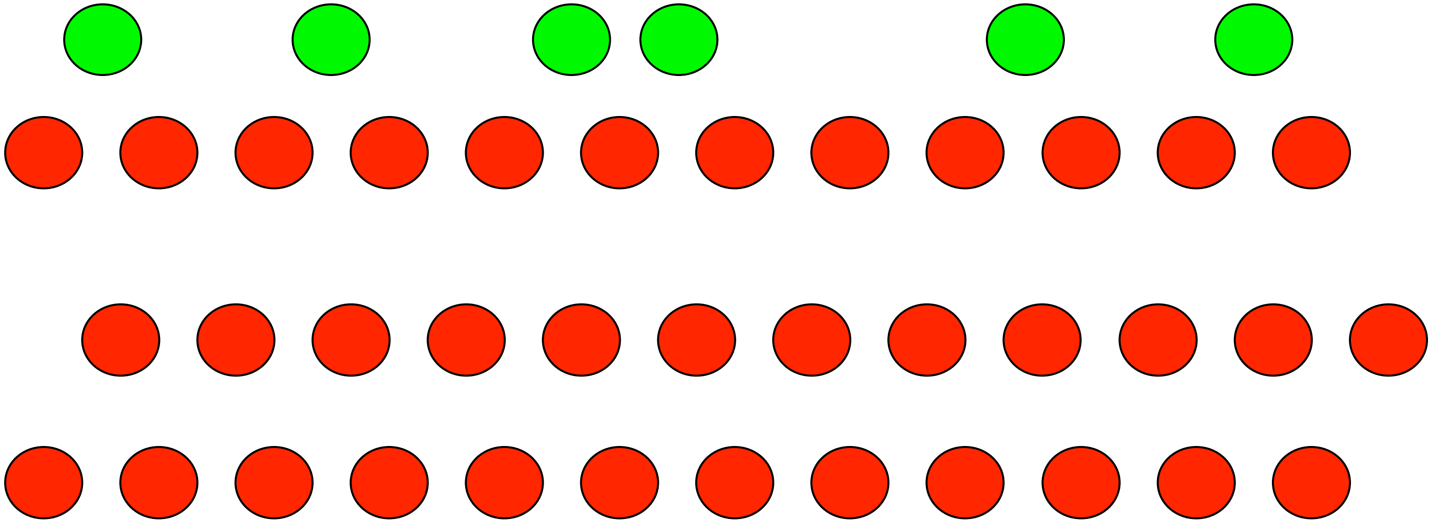


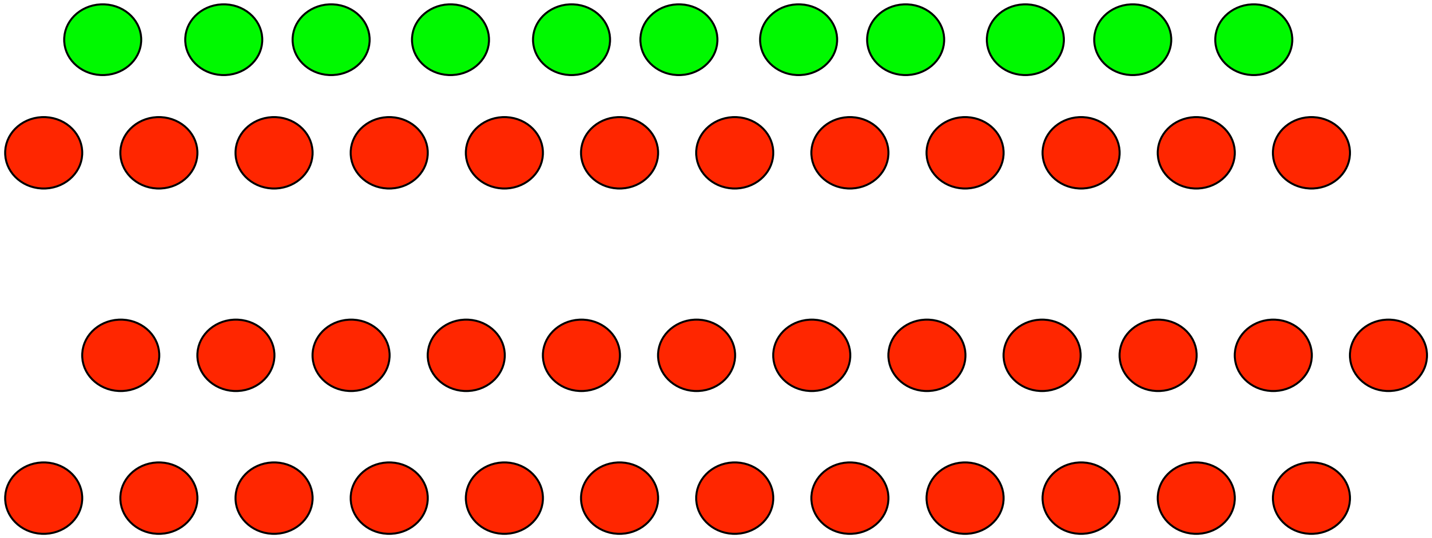
H.L. Meyerheim *et al.*, Phys. Rev. B **65**, 144433 (2002)









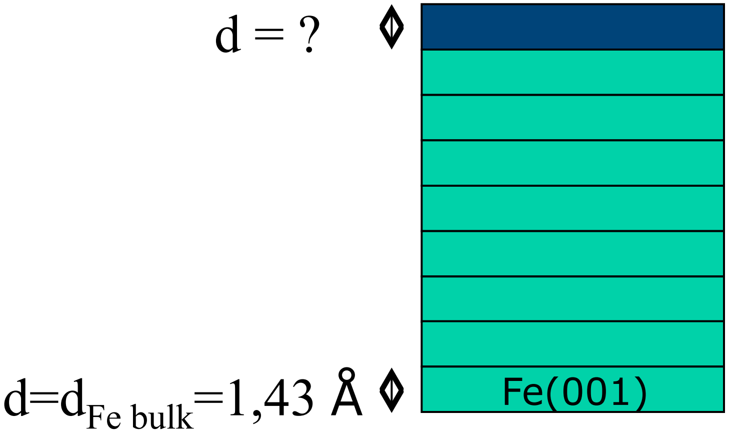


Ab initio calculations

Ab initio calculations based on linear muffin-tin orbital method (LMTO) and the Korringa-Kohn-Rostoker (KKR) method.

- 9 ML Fe

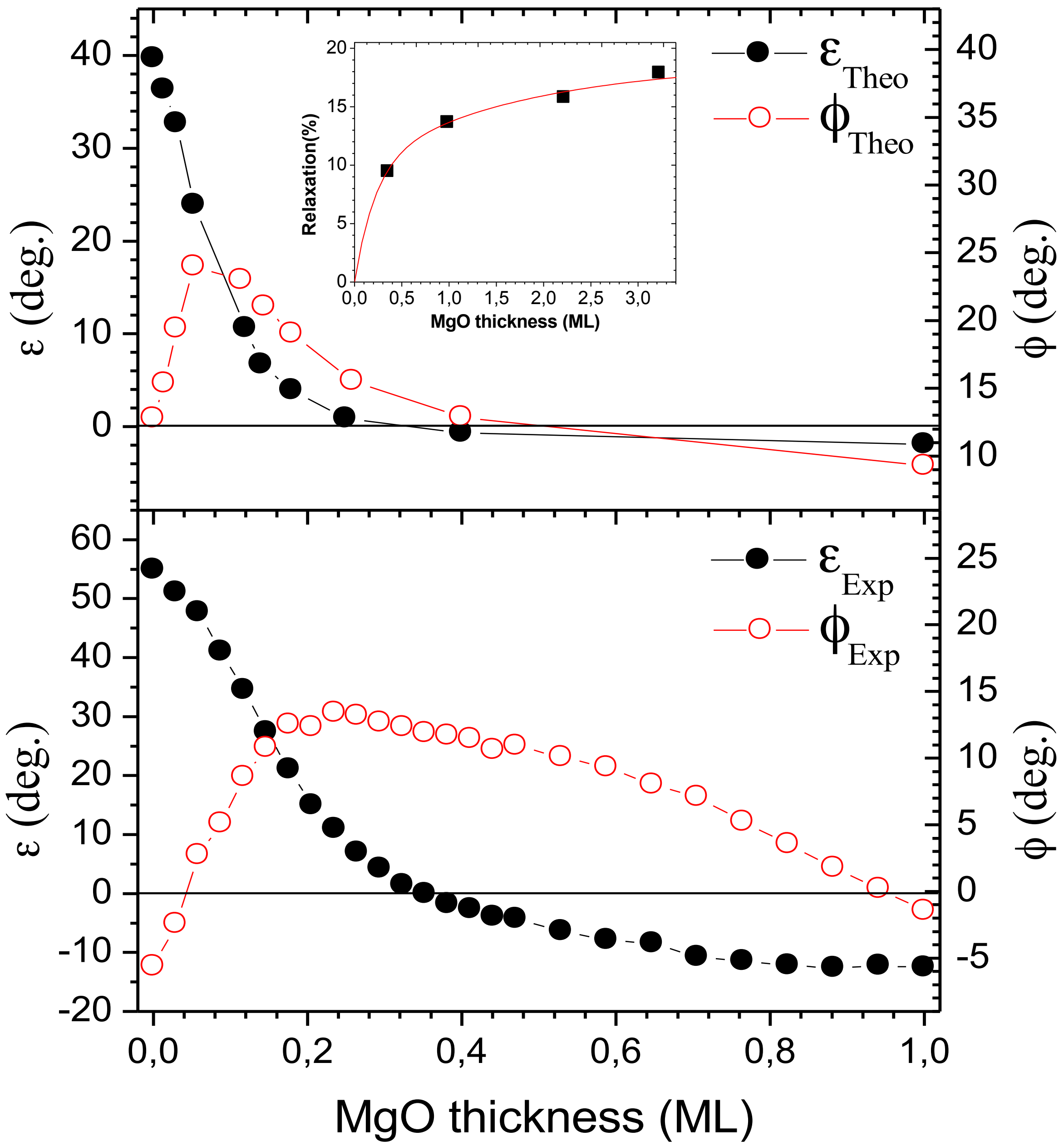
- First interlayer distance is relaxed without actually putting MgO on top of Fe



$d = ?$

$d=d_{\text{Fe bulk}}=1{,}43$ Å

Fe(001)



T. Berdot *et al.*, PRB **82**, 172407 (2010)

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Morphology-induced oscillations of the electron-spin precession

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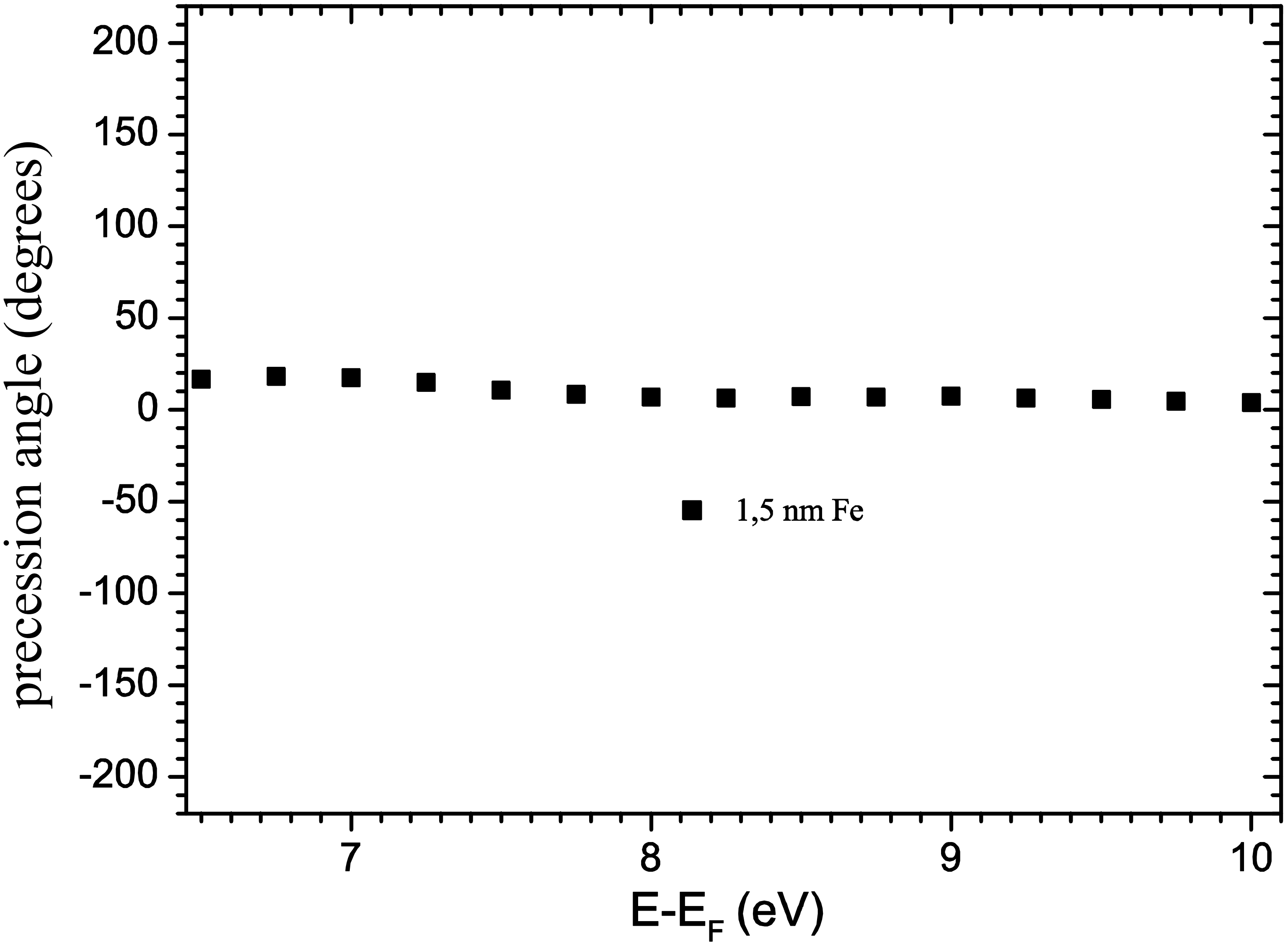
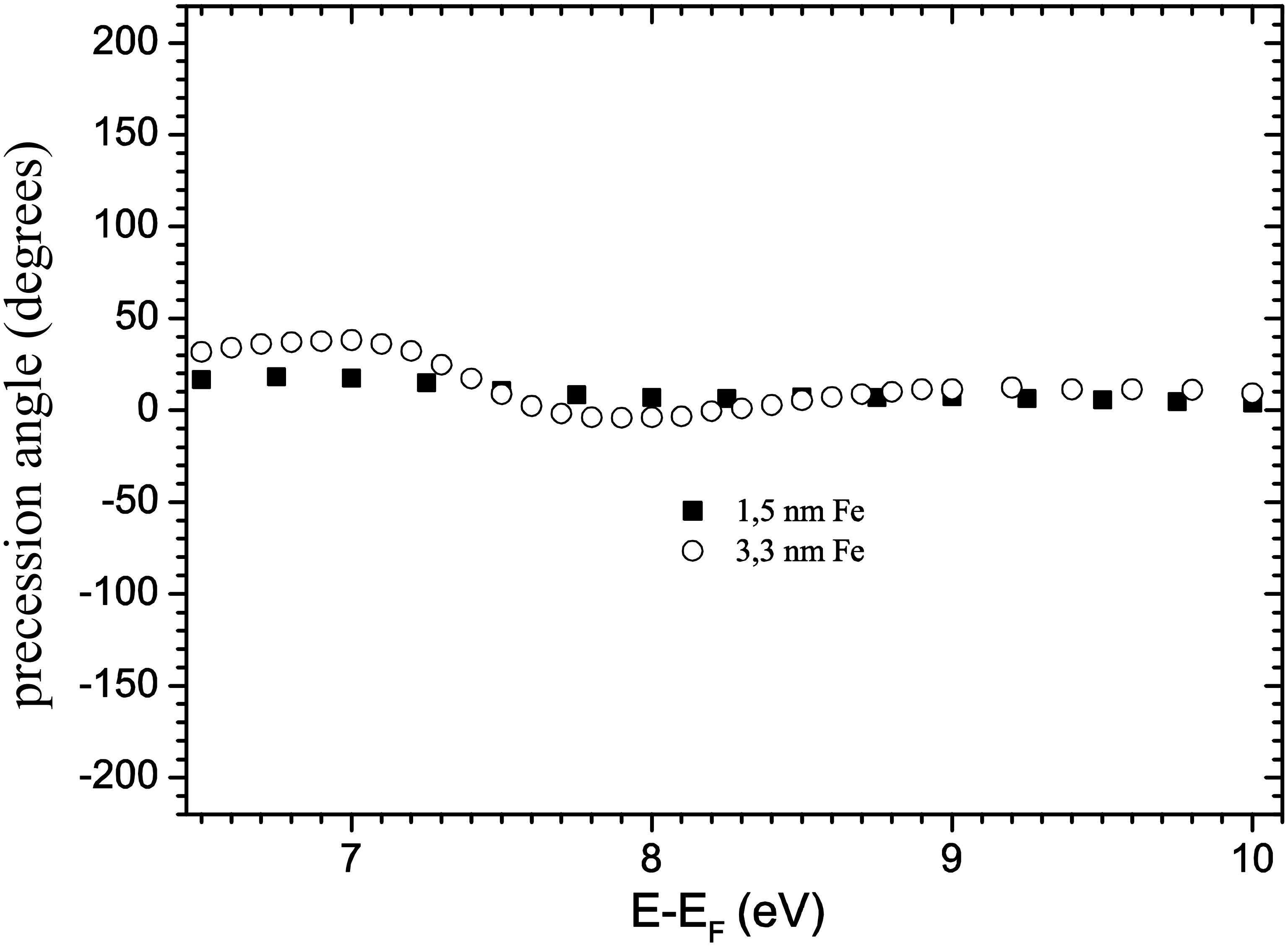
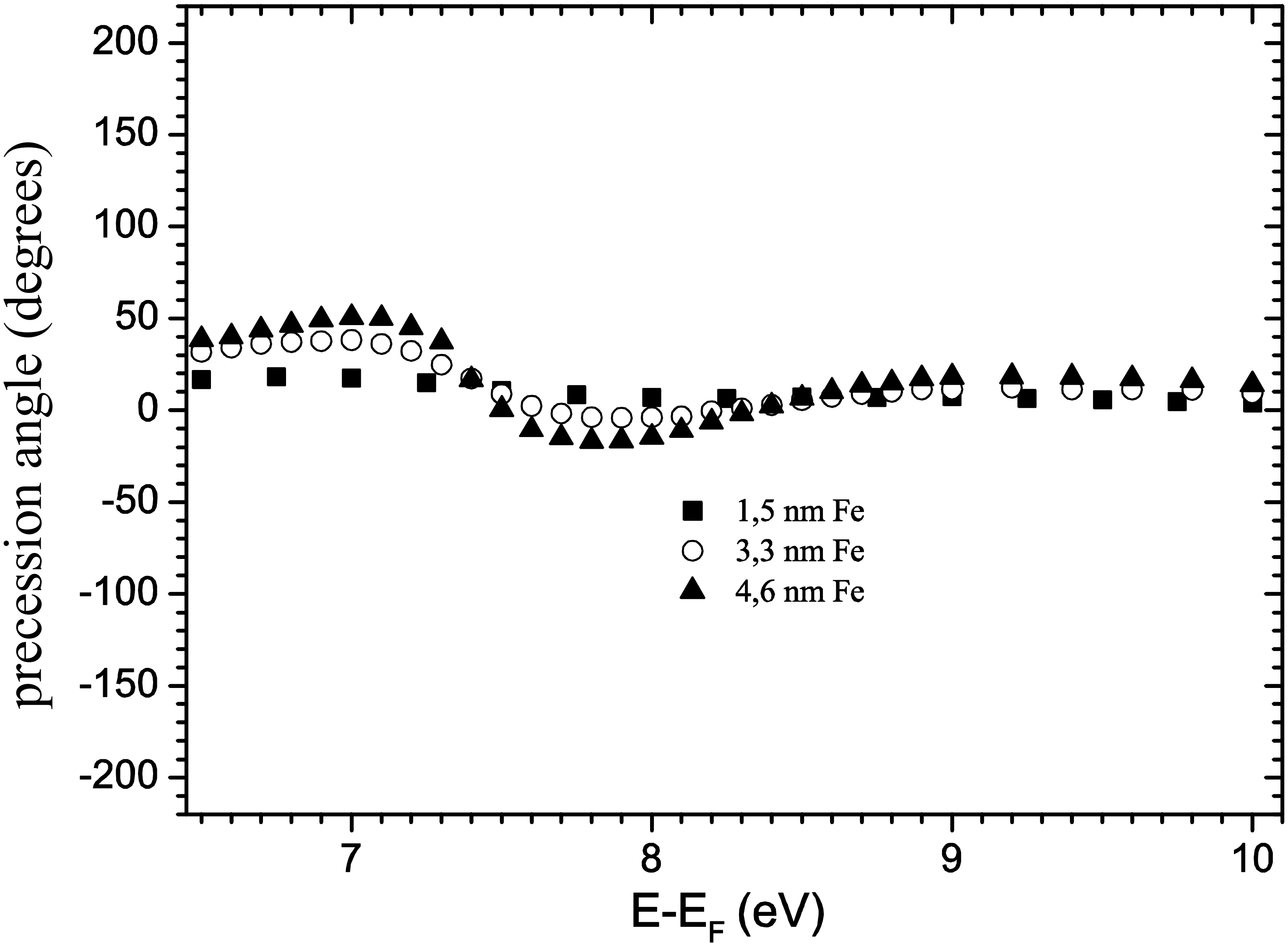


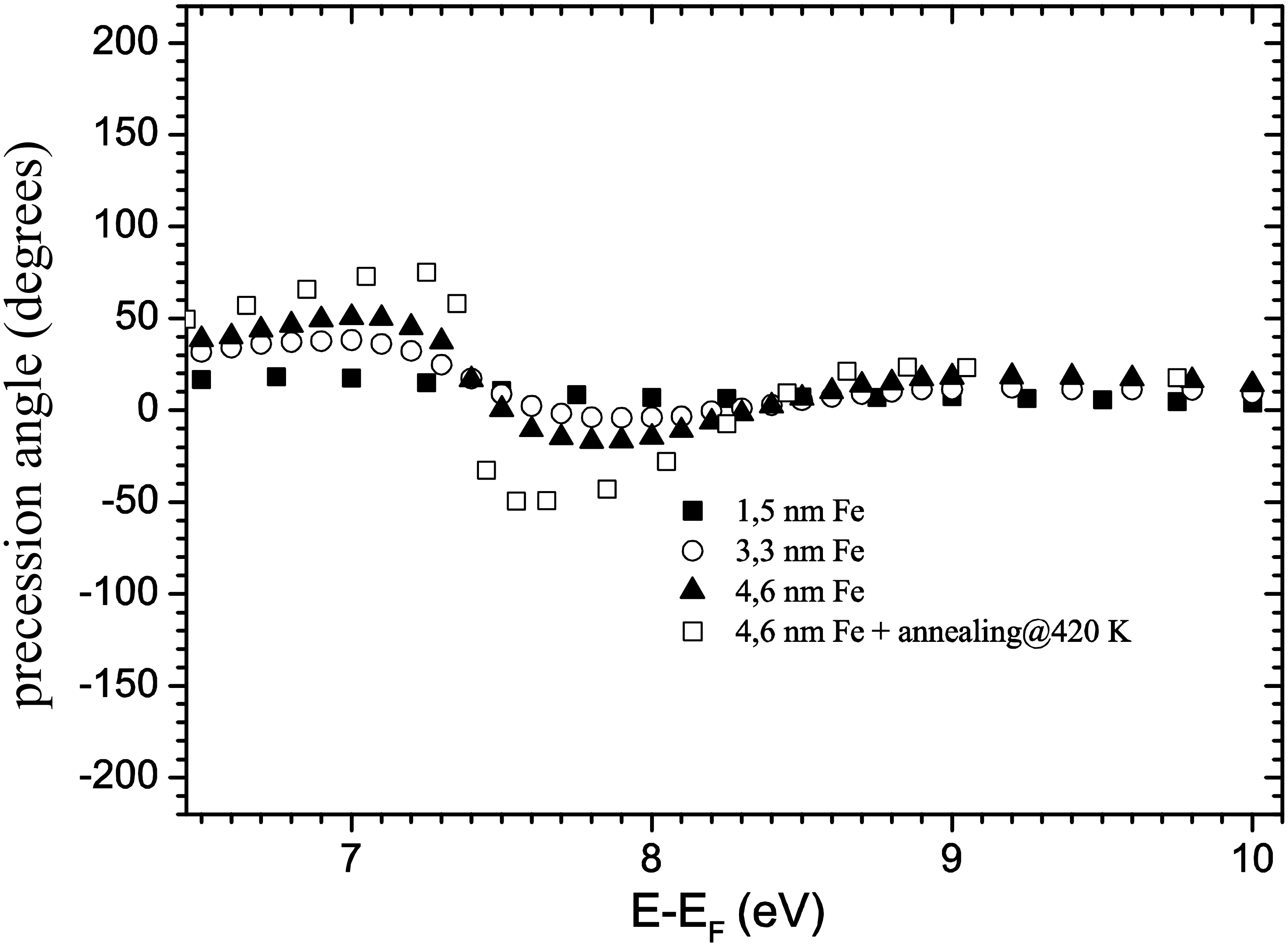
A. Hallal *et al.*, PRL **107**, 087203 (2011)



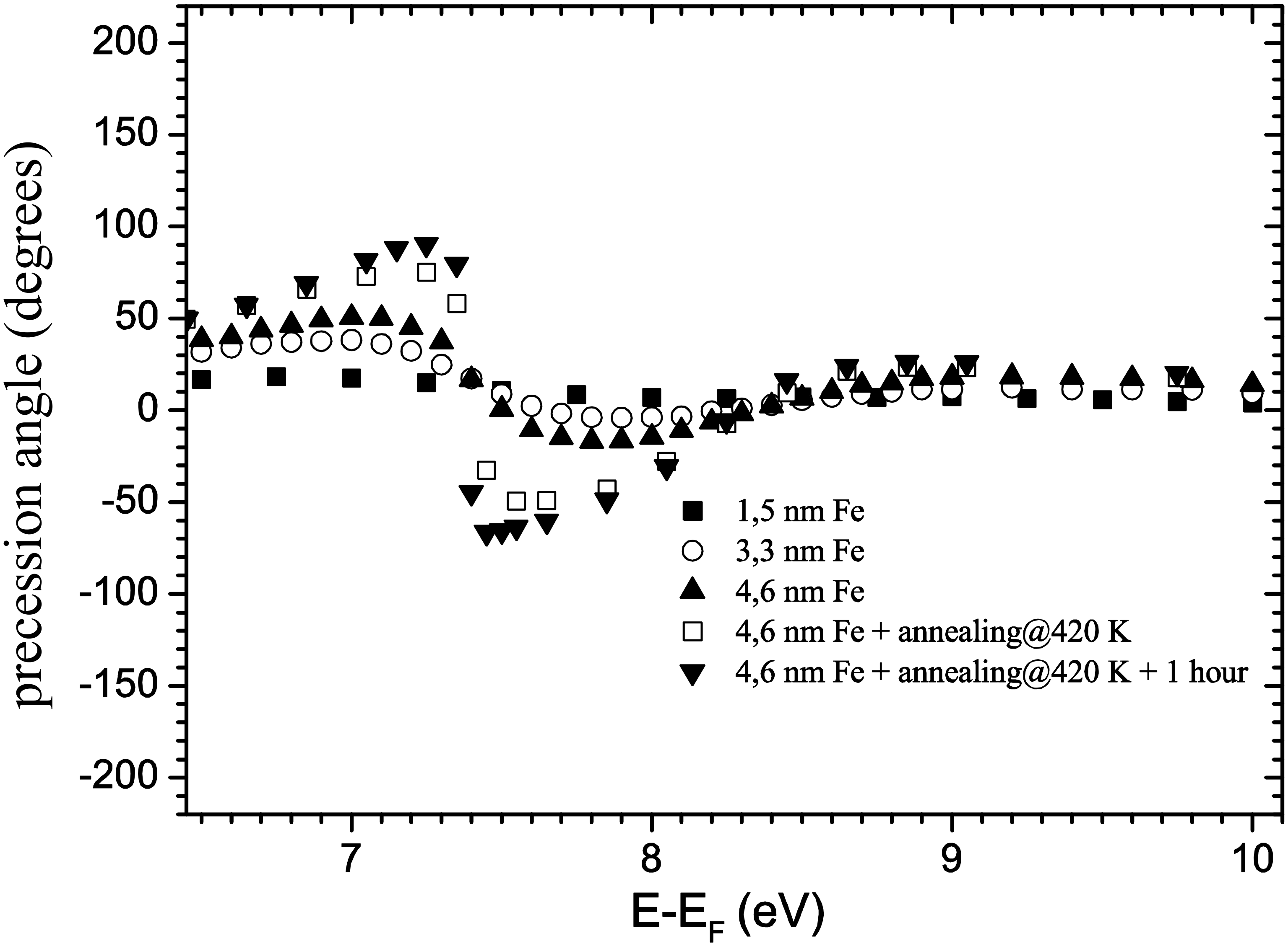
A. Hallal *et al.*, PRL **107**, 087203 (2011)



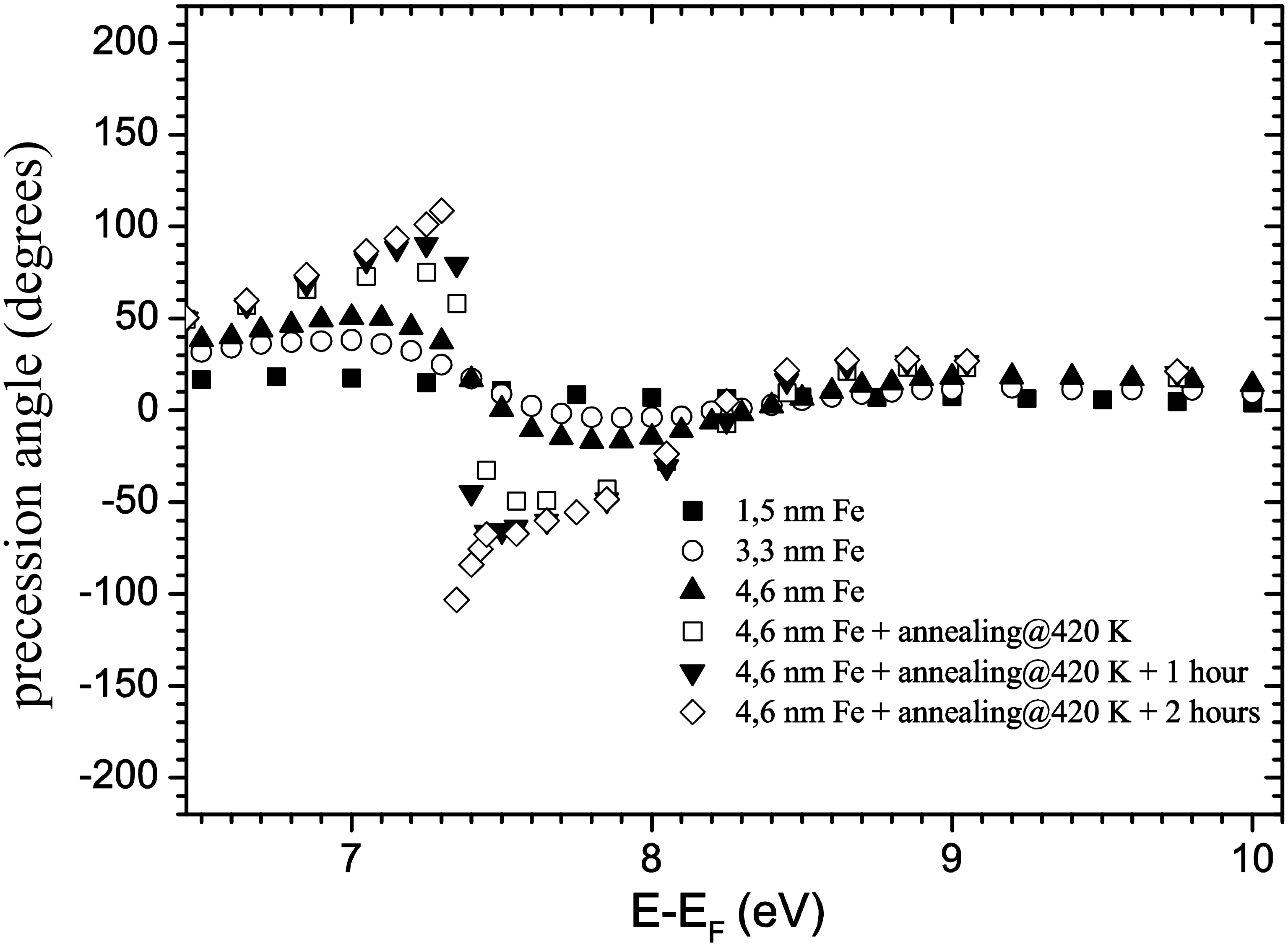
A. Hallal *et al.*, PRL **107**, 087203 (2011)



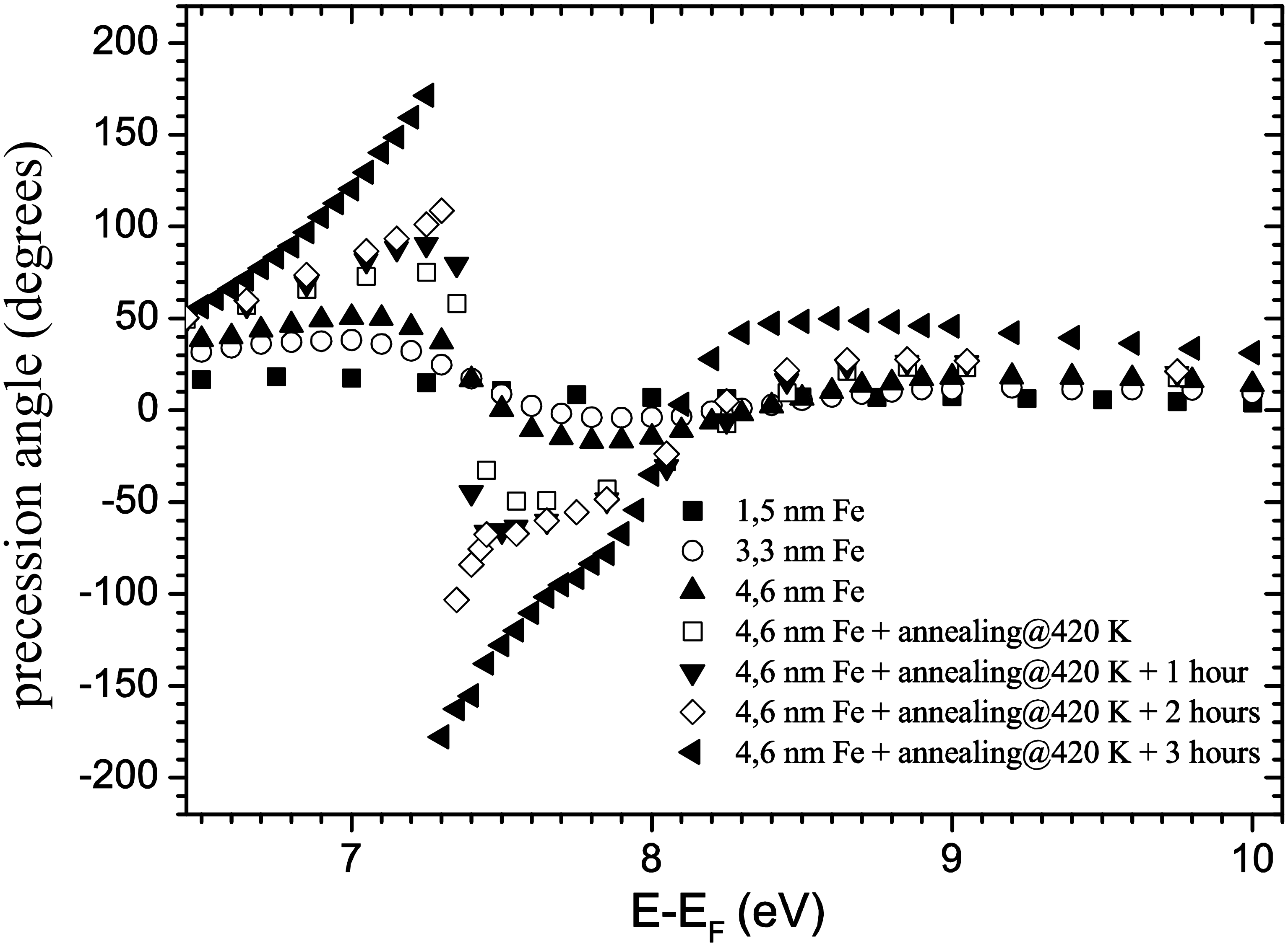
A. Hallal *et al.*, PRL **107**, 087203 (2011)



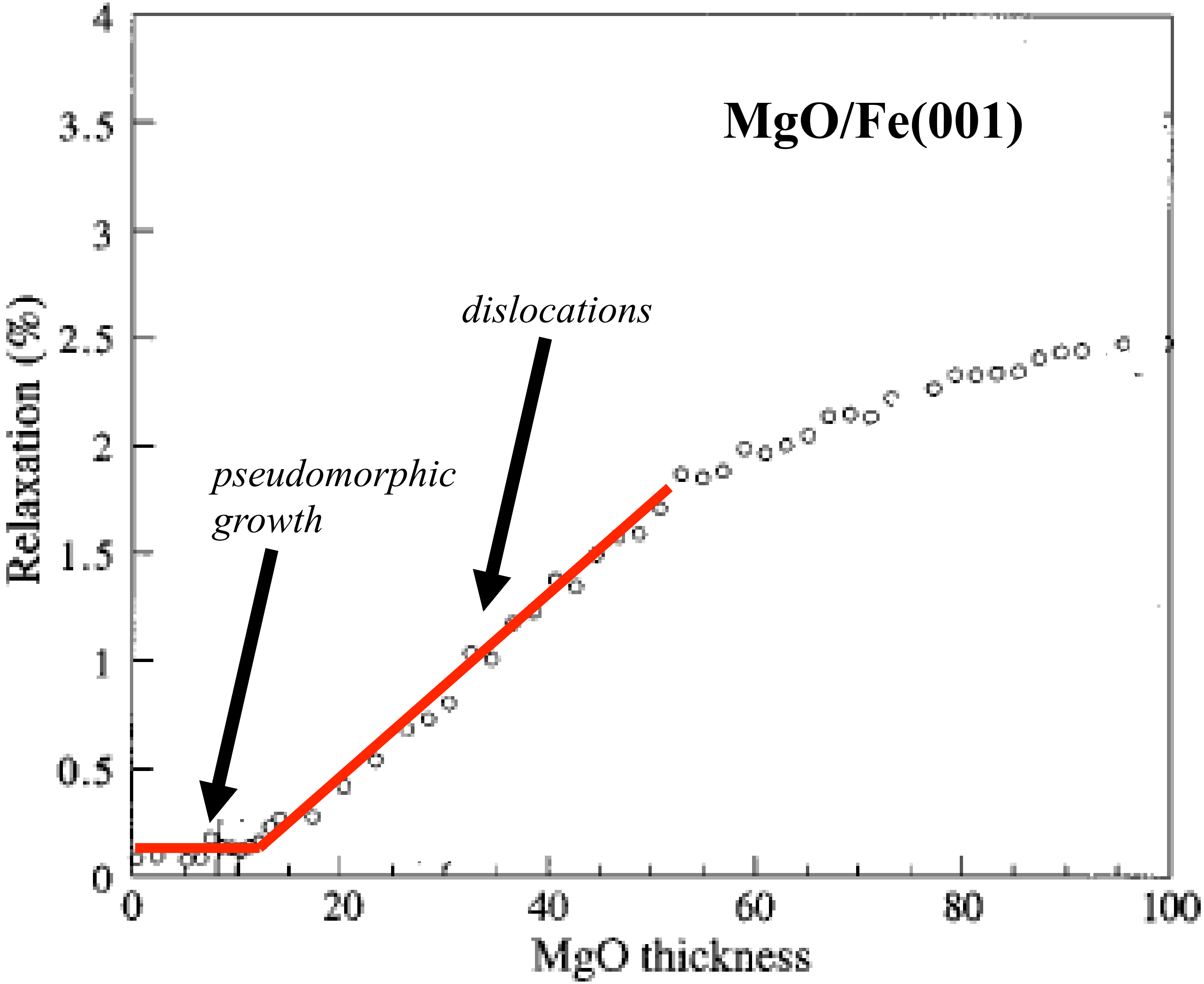
A. Hallal *et al.*, PRL **107**, 087203 (2011)



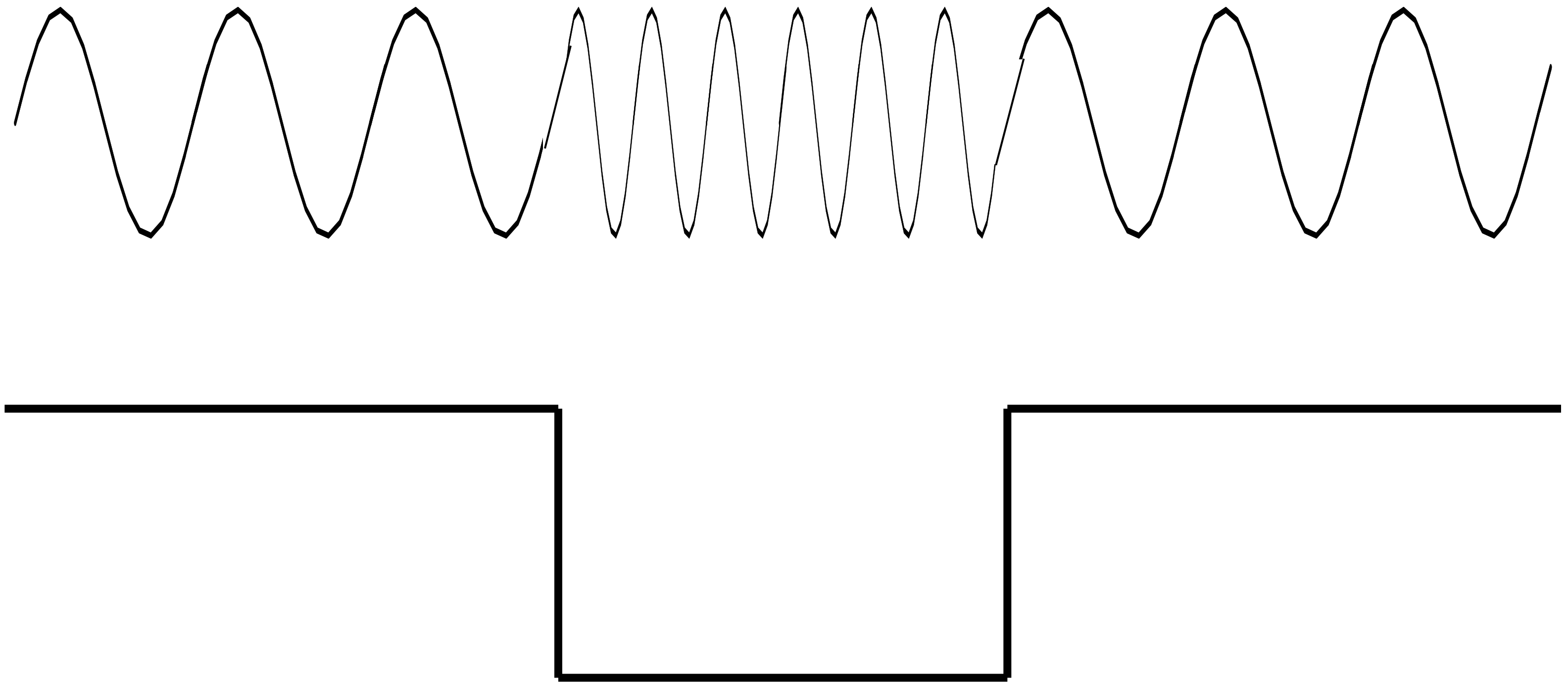
A. Hallal *et al*., PRL **107**, 087203 (2011)



A. Hallal *et al*., PRL **107**, 087203 (2011)

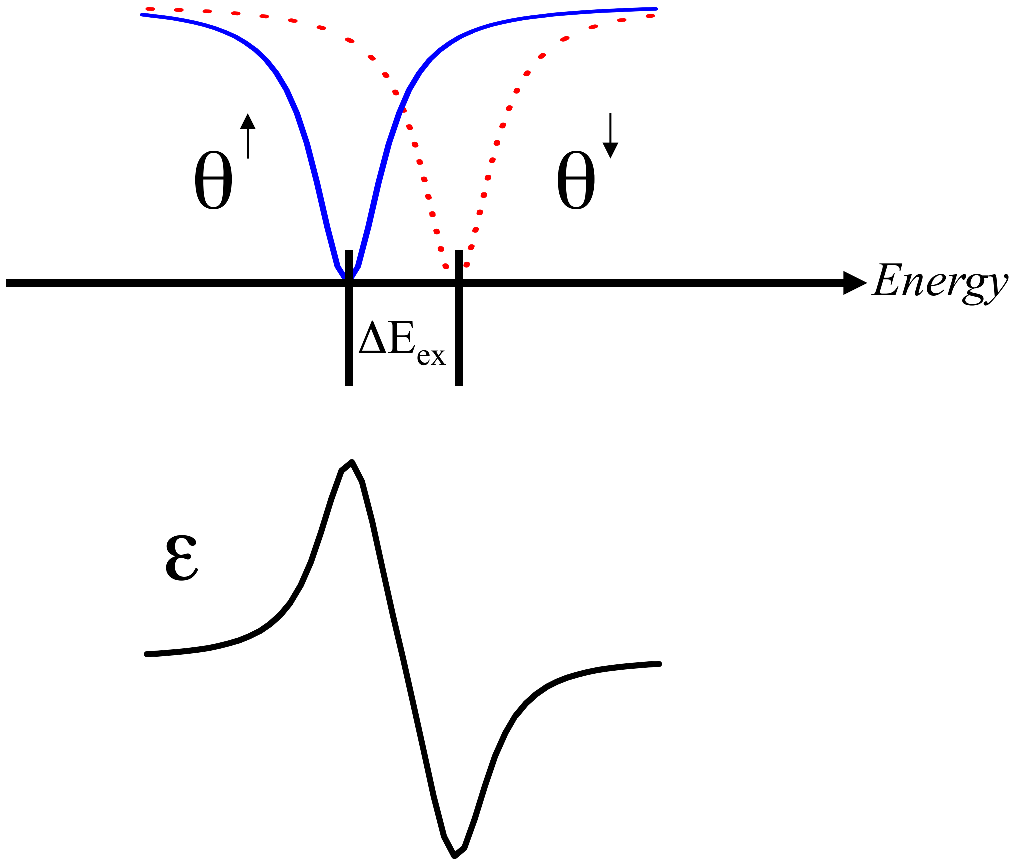

MgO/Fe(001)
dislocations
pseudomorphic
growth
Relaxation (%)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
20
40
60
80
100
MgO thickness

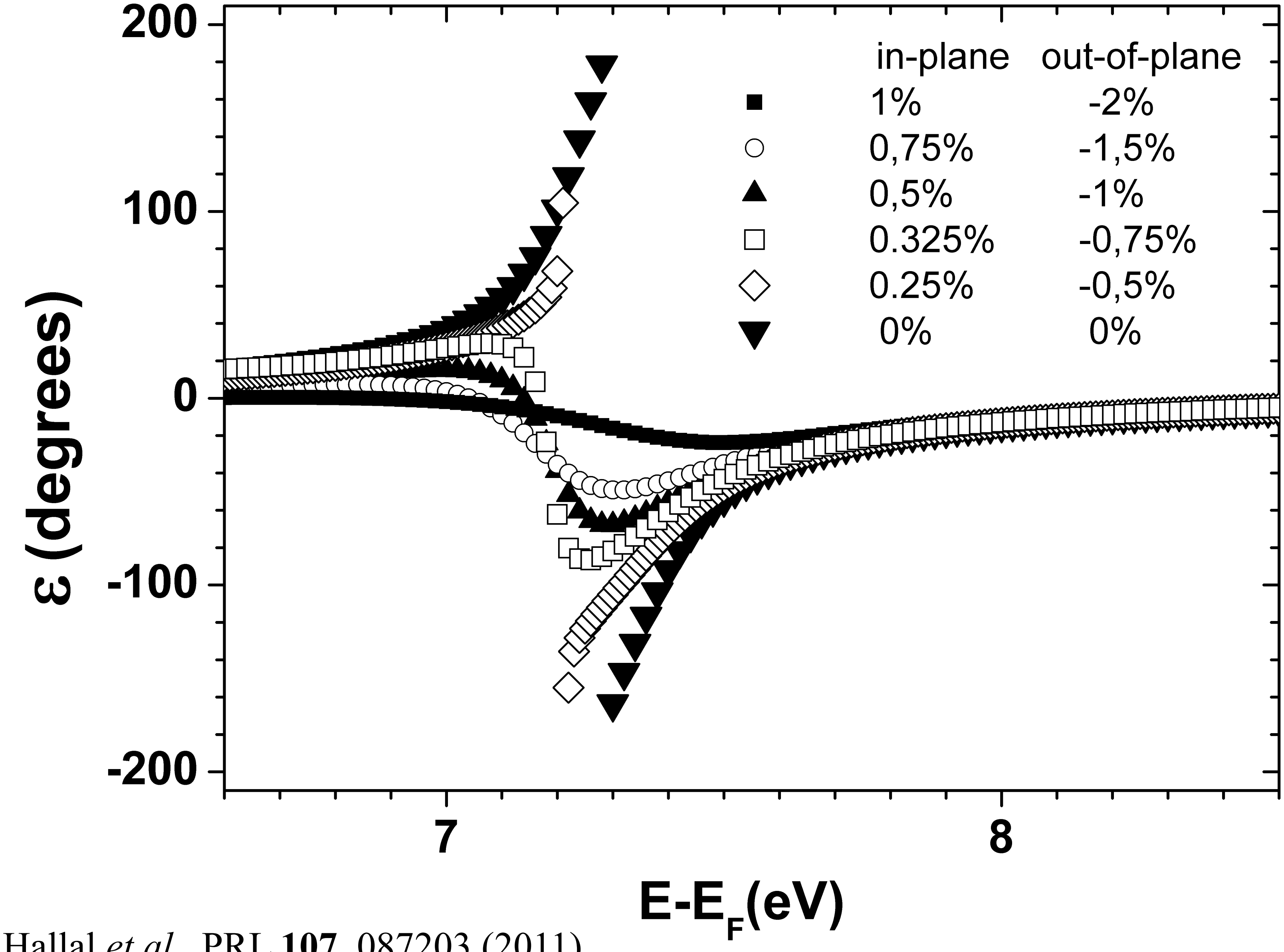
Ramsauer-Townsend effect



Resonance condition → *weak scattering* *on-resonance* → *scattering phase is zero*

off-resonance → *scattering phase is non-zero*





A. Hallal *et al*., PRL **107**, 087203 (2011)

Spin-dependent band gaps and their influence on the electron-spin motion

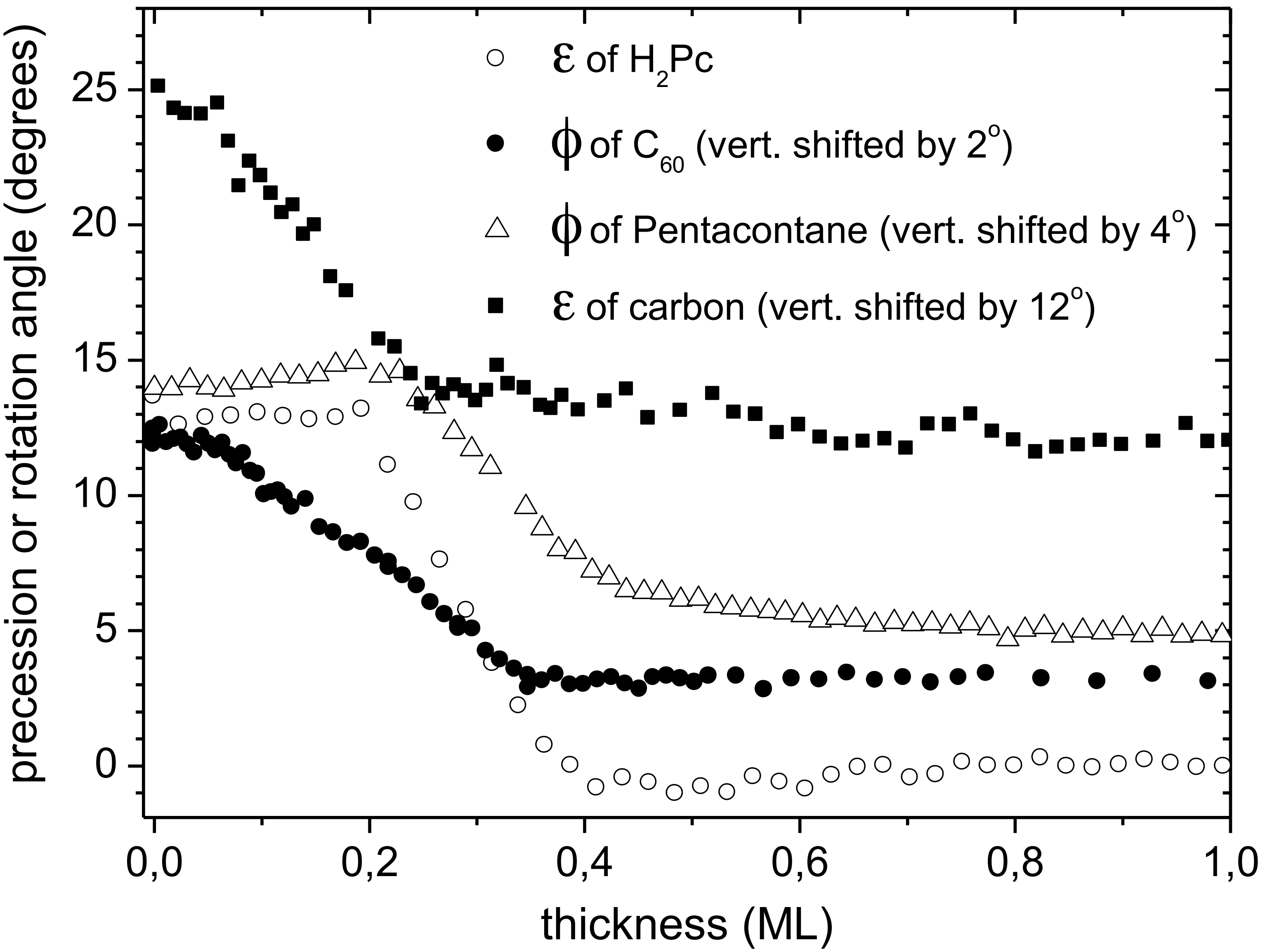
Organic molecules on ferromagnetic surfaces

Fabry-Pérot experiments with spin-polarized electrons

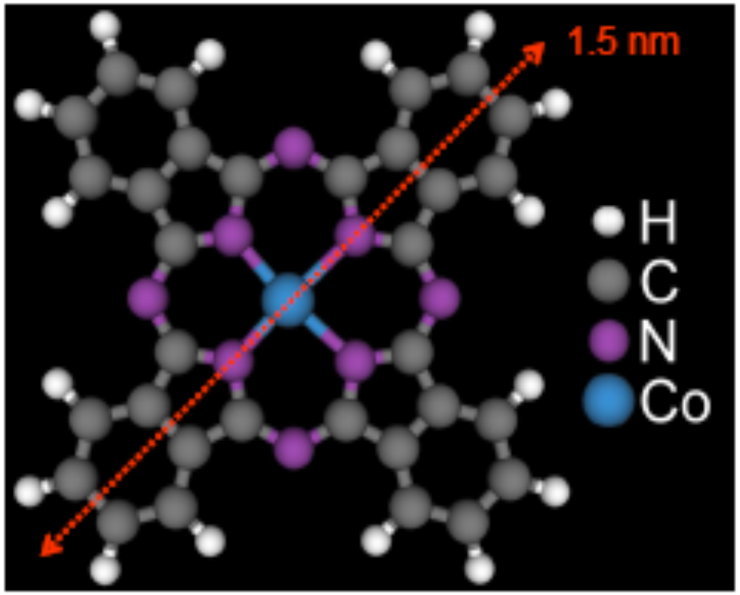
Influence of lattice relaxation on the spin precession in Fe/Ag (001)

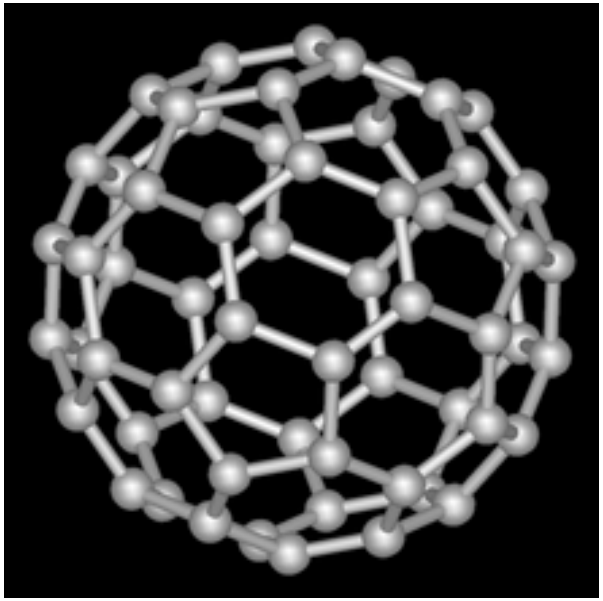
Morphology-induced oscillations of the electron-spin precession

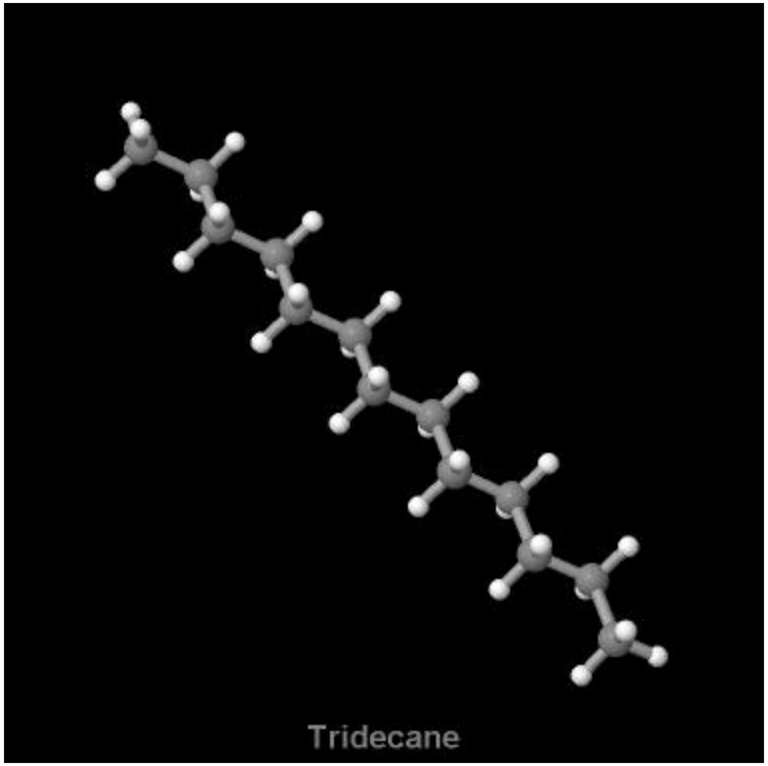
Influence of sub-monolayer MgO coverages on the spin-dependent reflection properties of Fe

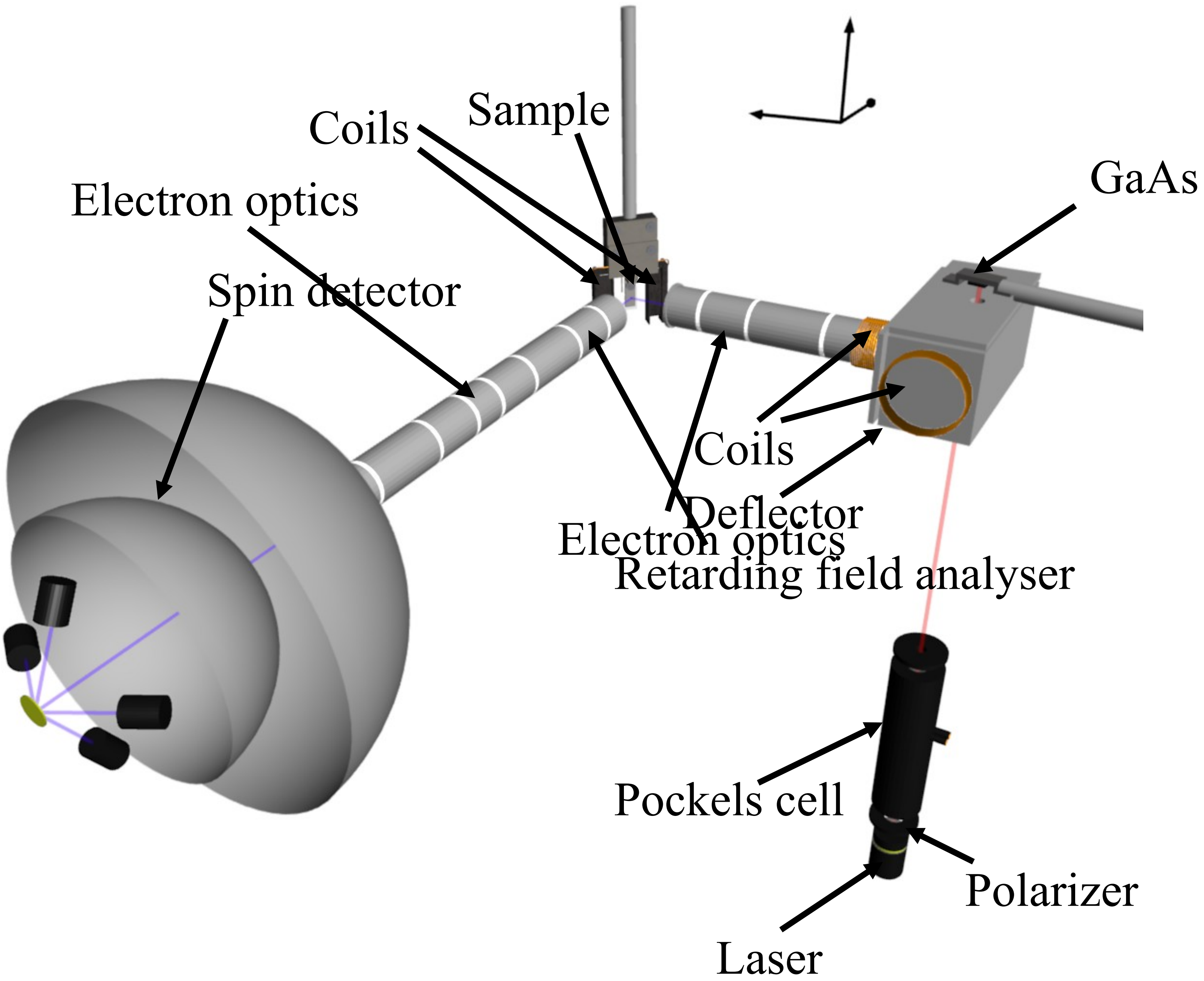


ε of H_2Pc
ϕ of C_{60} (vert. shifted by 2°)
ϕ of Pentacontane (vert. shifted by 4°)
ε of carbon (vert. shifted by 12°)
precession or rotation angle (degrees)
thickness (ML)
0
5
10
15
20
25
0,0
0,2
0,4
0,6
0,8
1,0

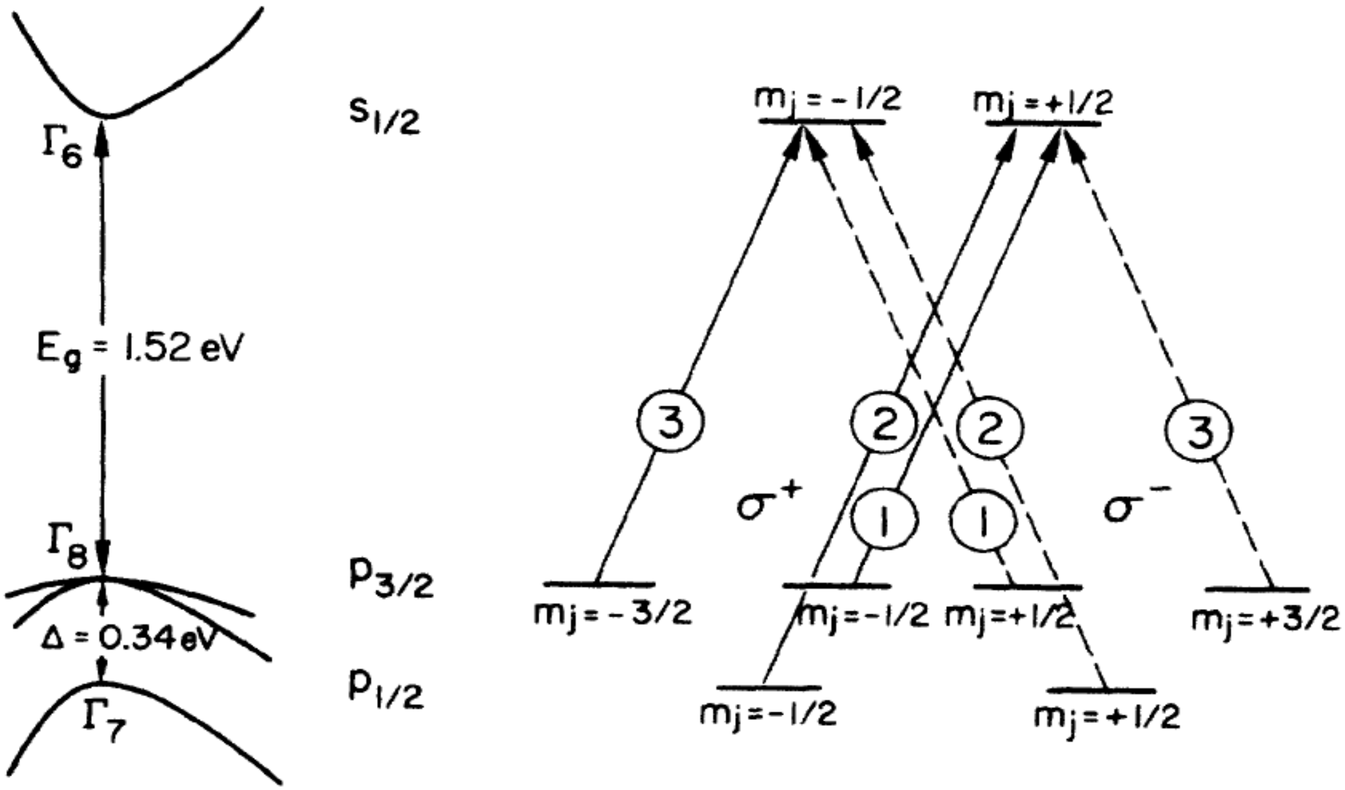

1.5 nm
H
C
N
Co




Tridecane


Coils
Sample
GaAs
Electron optics
Spin detector
Coils
Deflector
Electron optics
Retarding field analyser
Pockels cell
Polarizer
Laser

GaAs : Source of polarized electrons



$$P = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = 50\,\%$$