Magnetism on the Nanoscale

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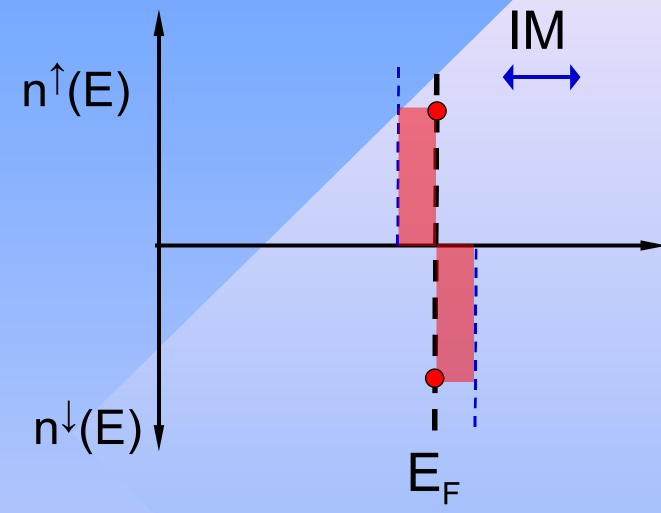
Outline

- Introduction
- Stoner model
- Magnetism in reduced dimensions
- Magnetic anisotropy
- Interlayer Exchange Coupling

Itinerant magnetisms in the Stoner model

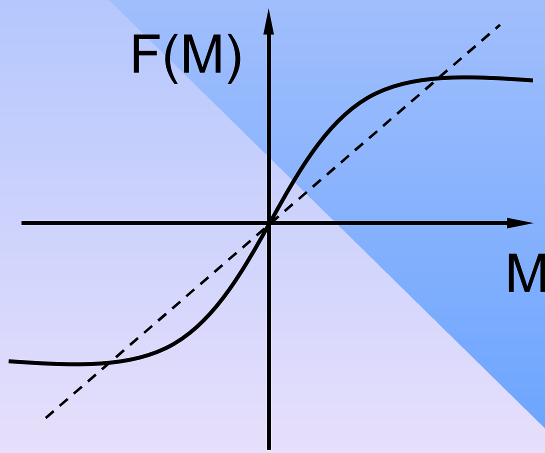
Nonmagnetic density of states

Spin-split density of states



Self-consistent equation for magnetization M

$$M = \int_{E_F - \frac{IM}{2}}^{E_F + \frac{IM}{2}} dE\, n(E) =: F(M)$$



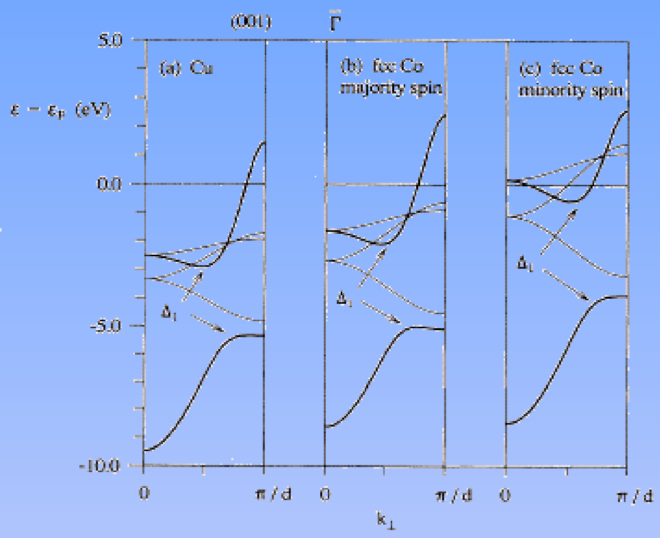
Trivial solution: $M = 0$

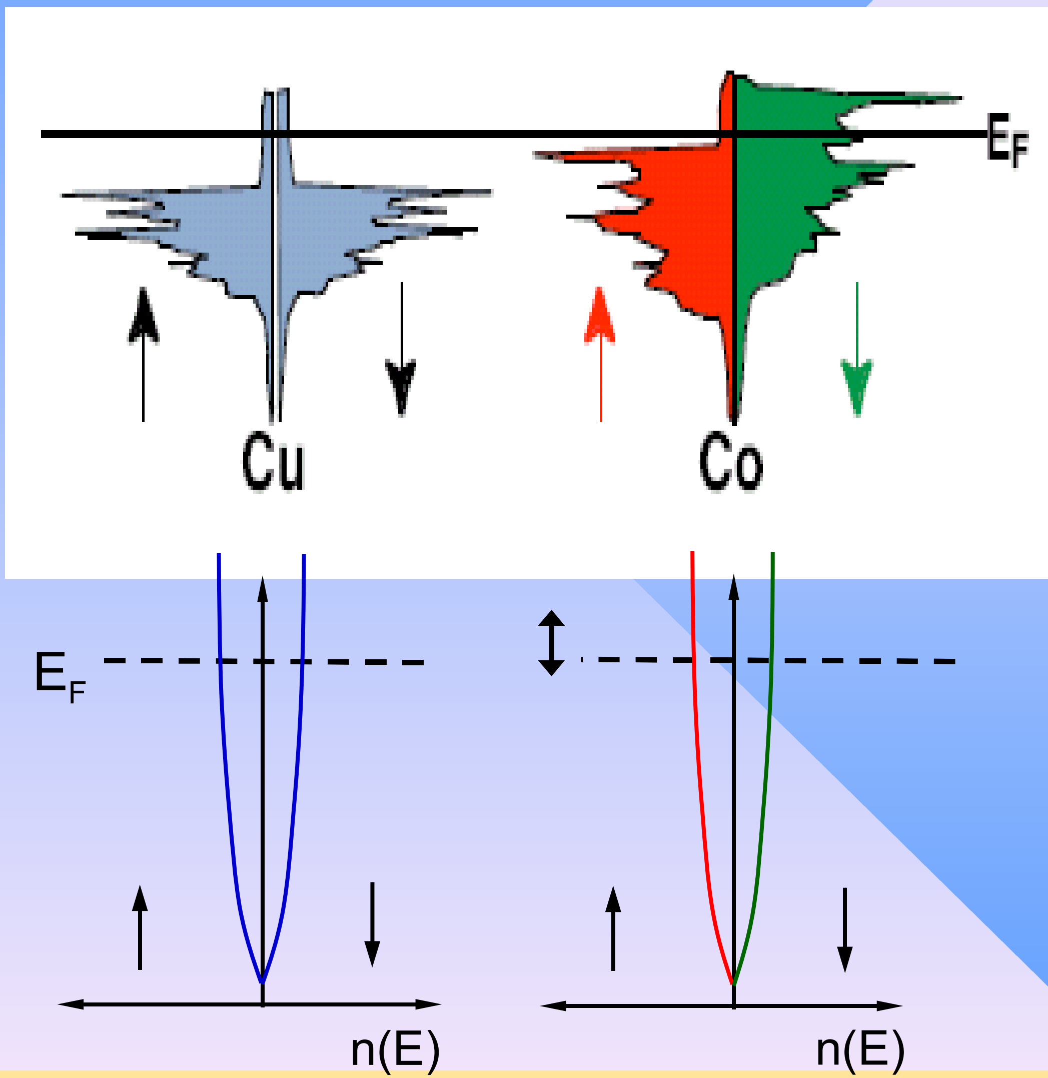
Nontrivial solution: $\frac{dF}{dM} > 1$

$\rightarrow \quad In(E_F) > 1$

I … exchange integral (0.5 … 1 eV) $\quad I_{3d} > I_{4d} > I_{5d}$

Band structure and spin polarization





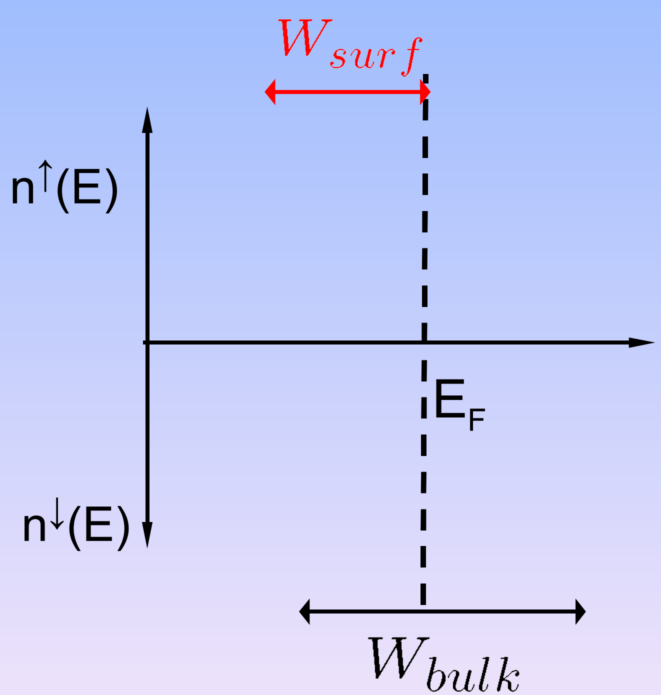
P. Bruno, PRB **52**, 411 (1195)

Magnetism in reduced dimensions

Number of d electrons N_d=5 $$N_d \approx W\, n(E_F) \approx const$$

Band width $$W \propto \sqrt{N_{nn}}\, t_d \qquad n(E_F) \propto \frac{1}{\sqrt{N_{nn}}}$$

Stronger tendency to magnetism at surfaces, interfaces and for defects



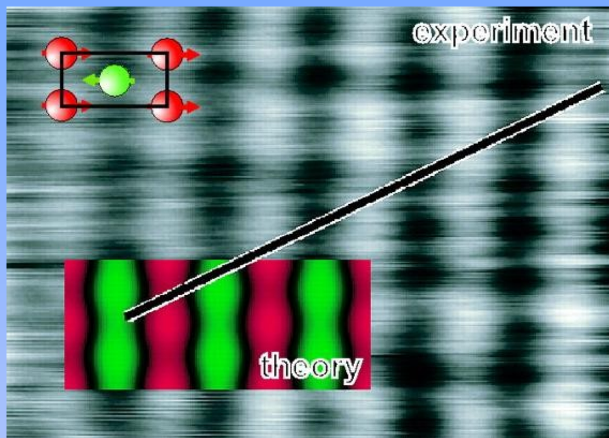
$$W_{bulk} > W_{surf} > W_{defect}$$

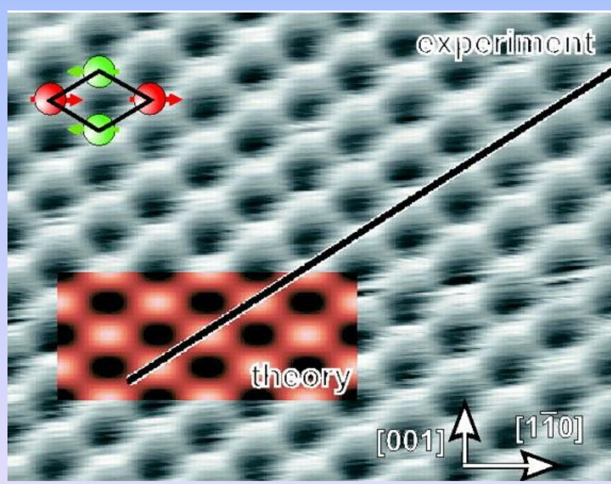
μ_B	Cr	Fe	Co	Ni
$M_{surf}^{(100)}$	2.55	2.88	1.85	0.68
M_{bulk}	¼ .60	2.13	1.62	0.61

E. Wimmer et al., PRB **30**, 3113 (1984)

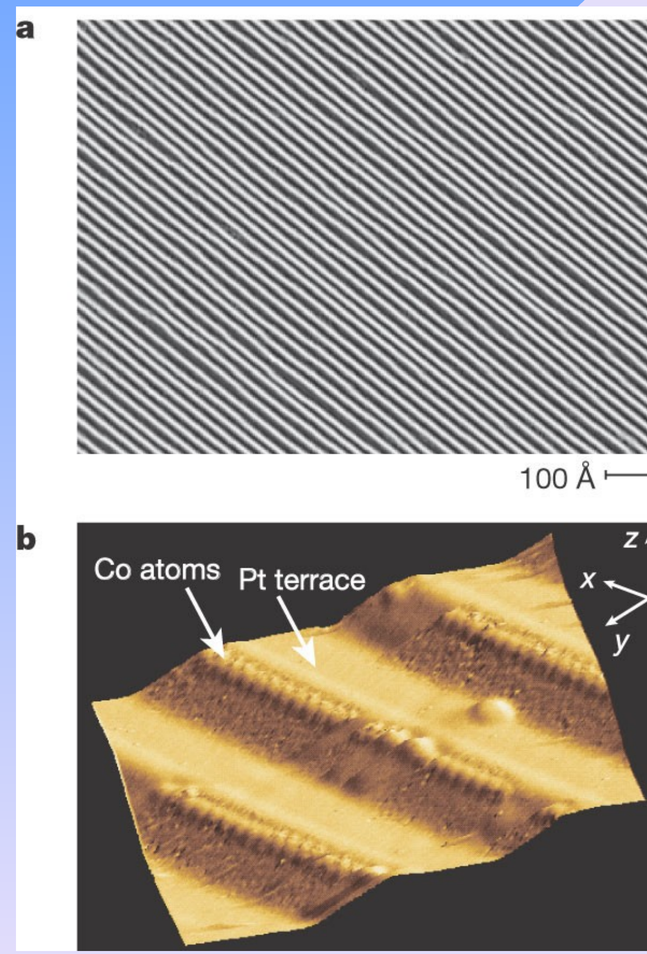
Magnetic adlayers and wires

1ML Mn on W(110)





Co wires on Pt(997)

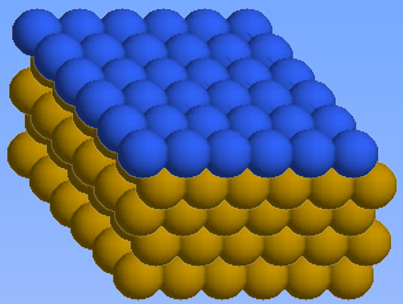


M. Bode et al., Science **288**, 1805 (2000)

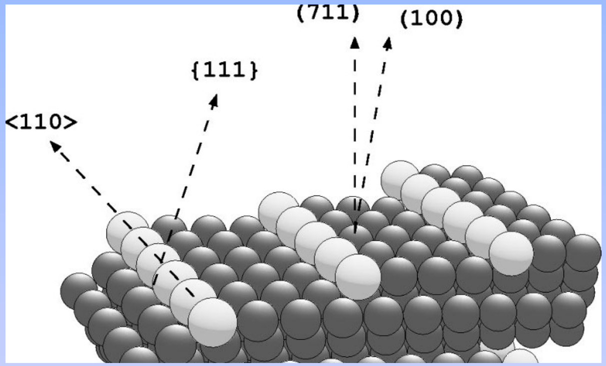
P. Gambardella, Science (2002)

Effect of the dimensionality: calculation

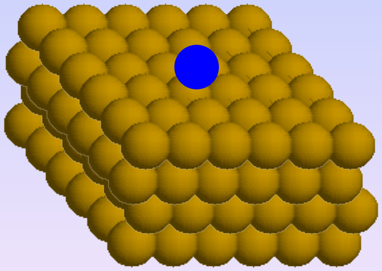
Adlayer

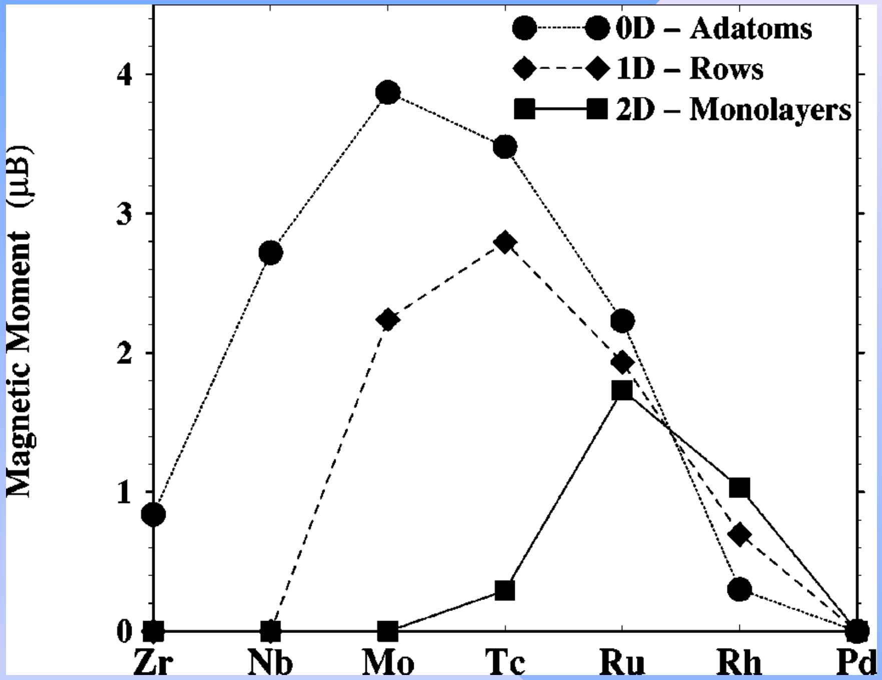


Wire



Defect

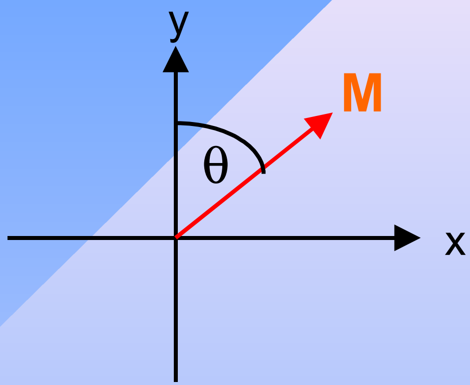




V. Bellini et al., PRB (2001)

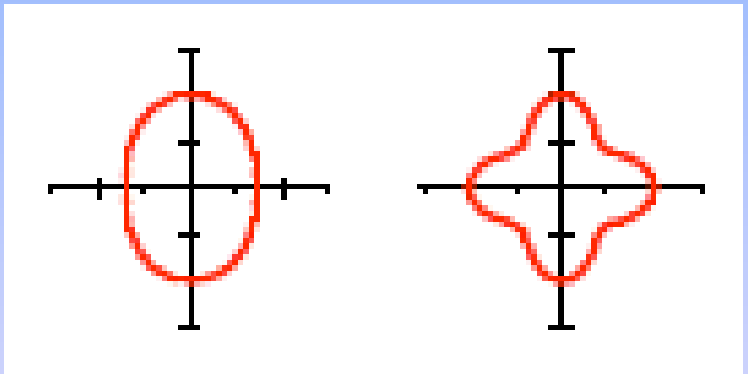
Magnetic Anisotropy

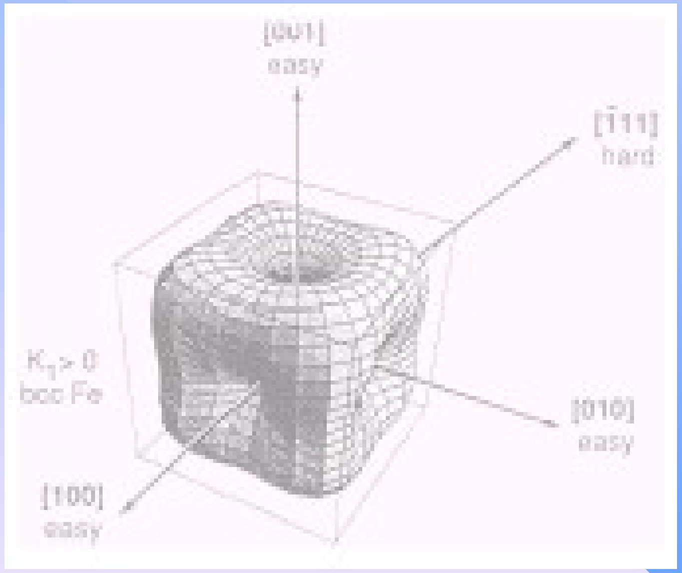
Spin-Orbit Coupling of Spin and Orbital Momentum



Magnetic anisotropy energy (uniaxial)

$$E(\theta) = K_0 \cos^2\theta + K_1 \cos^2 2\theta + \ldots$$



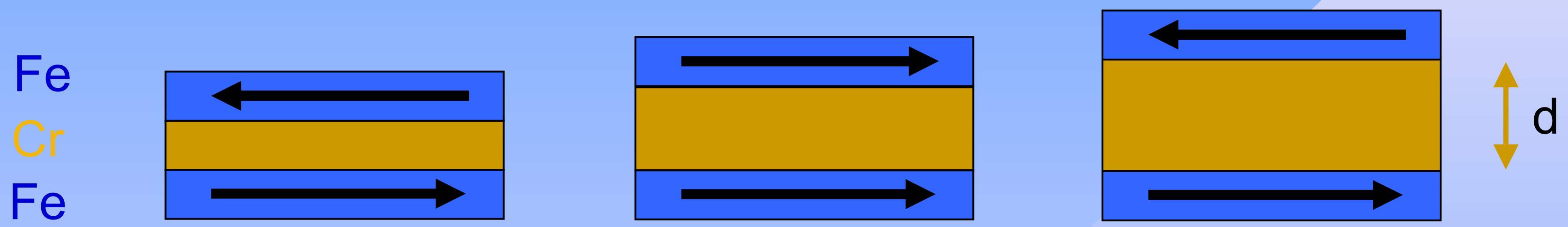


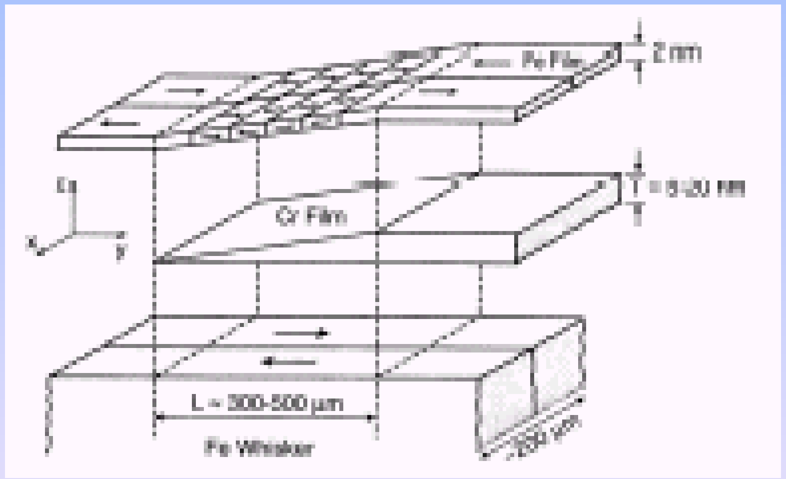
Fe: $E_{(111)} - E_{(100)} = 1.4\mu eV$

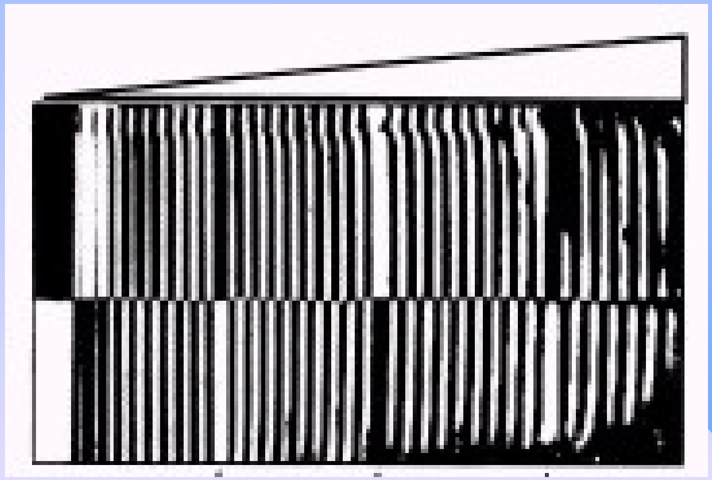
Ni: $E_{(100)} - E_{(111)} = 65\mu eV$

Interlayer Exchange Coupling

P. Grünberg et al., PRL **57**, 2442 (1986)

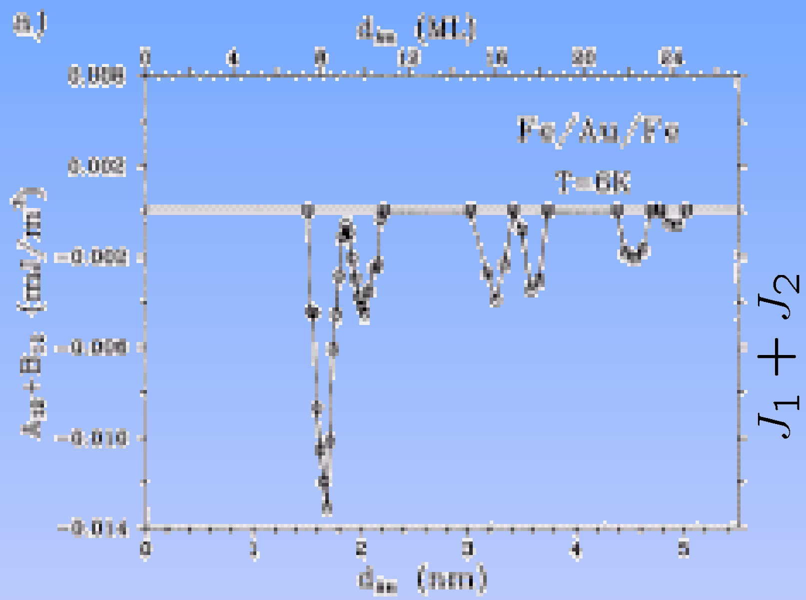


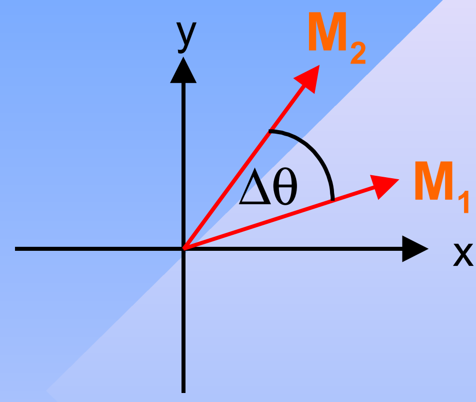




J. Unguris et al., PRL **67**, 140 (1991), PRL **69**, 1125 (1992)

Oscillatory interlayer coupling



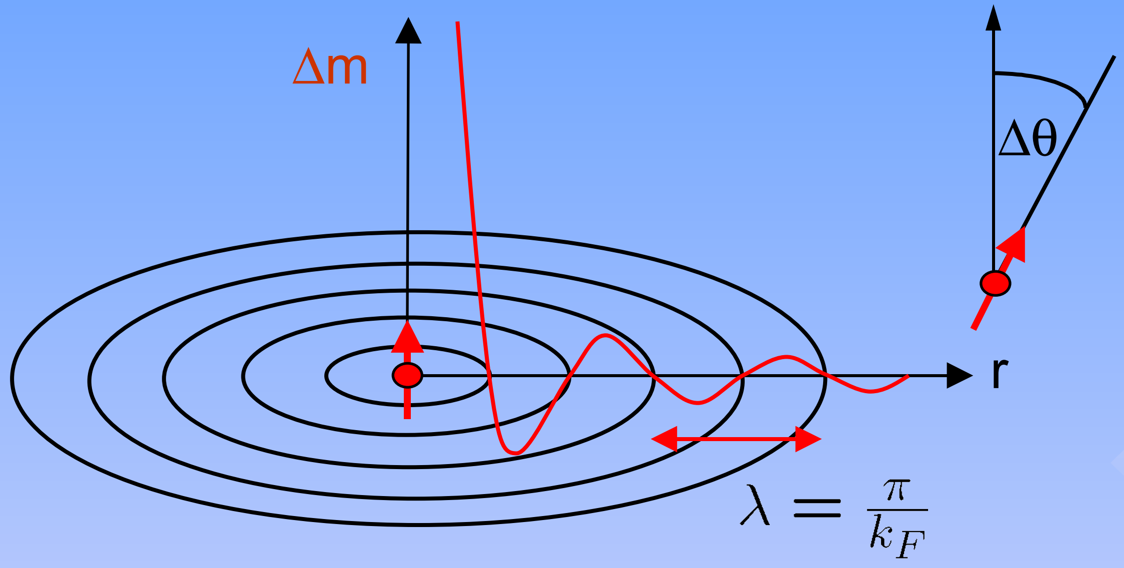


$$E(\Delta\theta) = -J_1 \cos(\Delta\theta) - J_2 \cos^2(\Delta\theta)$$

$J_1 > 0$ Ferromagnetic coupling Δθ = 0

$J_1 < 0$ Antiferromagnetic coupling Δθ = 180°

RKKY interaction



$$E(\Delta\theta) = J(r)\cos(\hat{M}_1\hat{M}_2) = J(r)\cos(\Delta\theta)$$

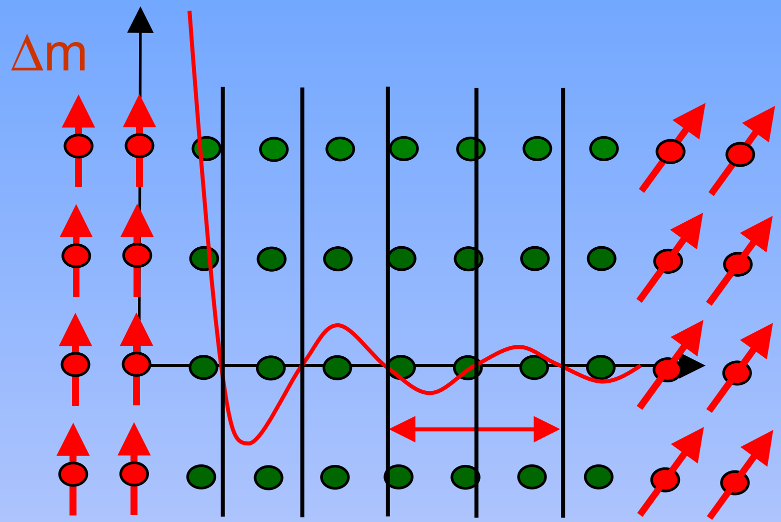
$$J(r) \propto \frac{\cos(2k_F r)}{r^3} \qquad k_F r \gg 1$$

M.A. Ruderman, C. Kittel, Phys. Rev. **96,** 99 (1954)

T. Kasuya, Progr. Theor. Phys. (Japan) **16**, 45 (1956)

K. Yosida, Phys. Rev. **106**, 893 (1957)

RKKY interaction of two planes



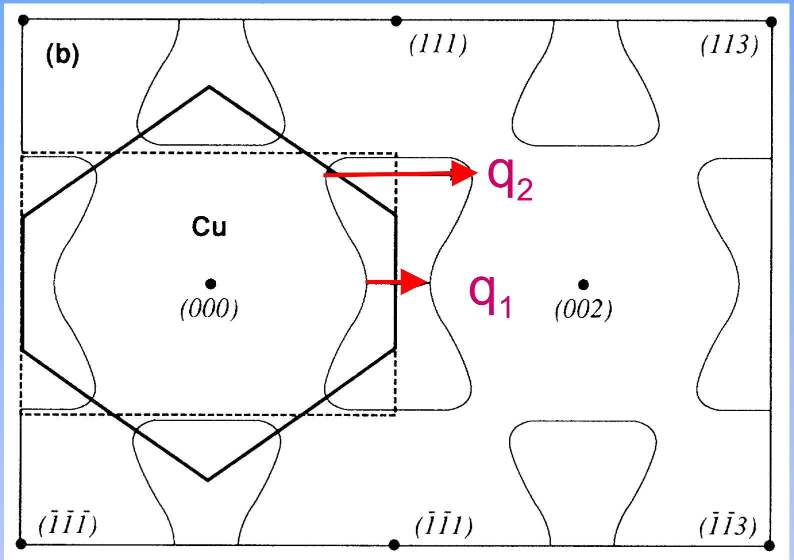
$$\lambda = \frac{\pi}{k_F}$$

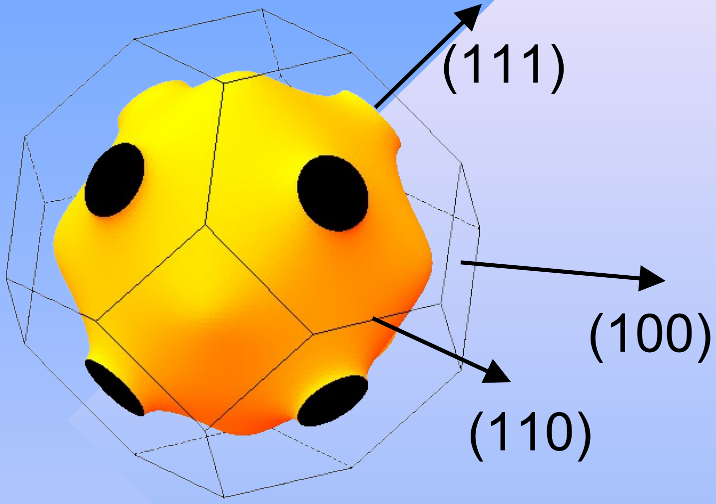
$$E(\Delta\theta) = J(d)\cos(\hat{M}_1 \hat{M}_2) = J(d)\cos(\Delta\theta)$$

$$J(d) \propto \frac{\cos(2k_F d + \phi)}{d^2} \qquad k_F d \gg 1$$

P. Bruno and C. Chappert, PRL **67**, 1602 (1991)

Fermi surface nesting





Cu(100):

$$J(d) \propto \sum_i \frac{\cos(q_i d + \phi_i)}{d^2} \qquad q_i d \gg 1$$

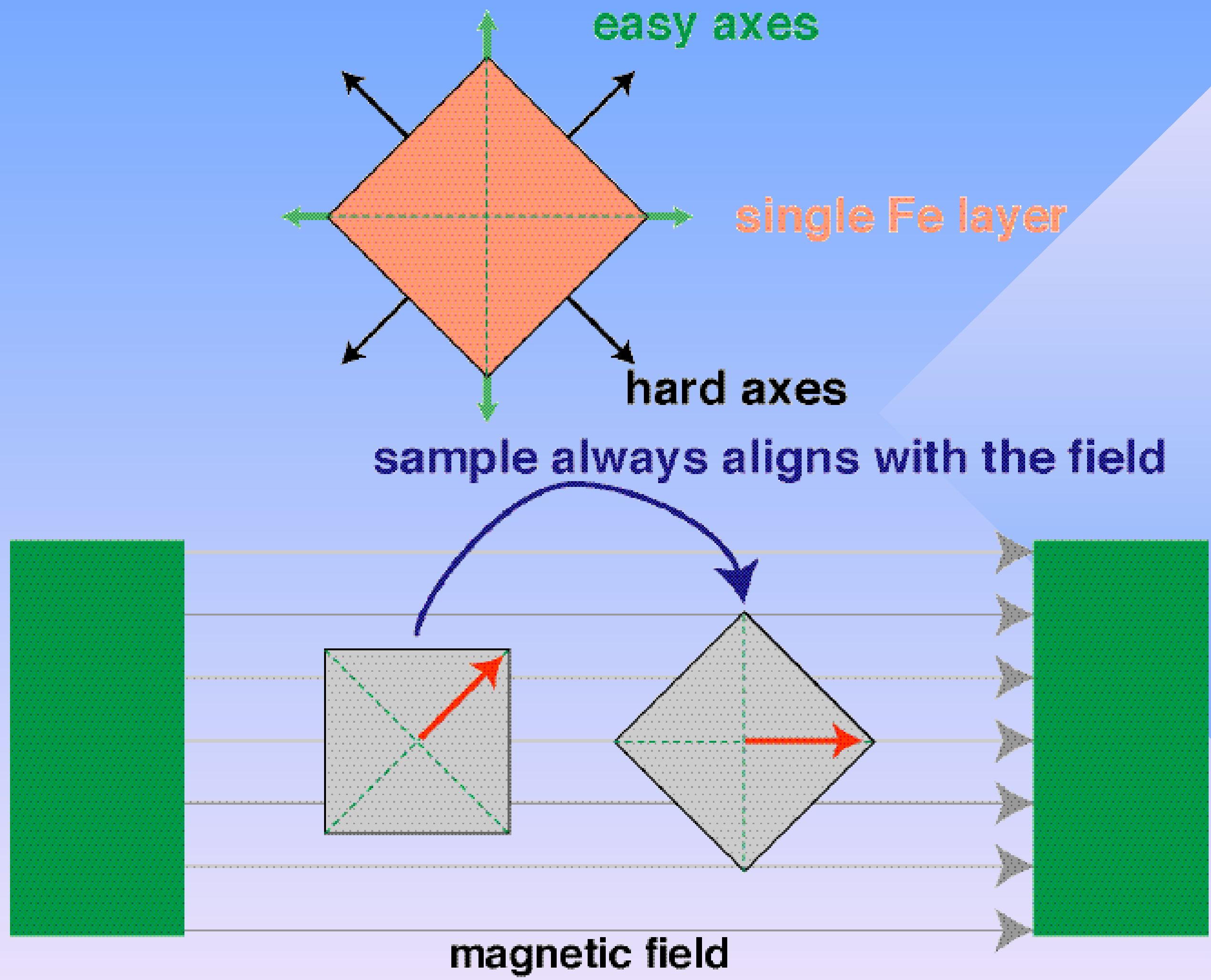
$$\lambda_1 = \frac{2\pi}{q_1} = 5.88ML$$

$$\lambda_2 = \frac{2\pi}{q_2} = 2.56ML$$

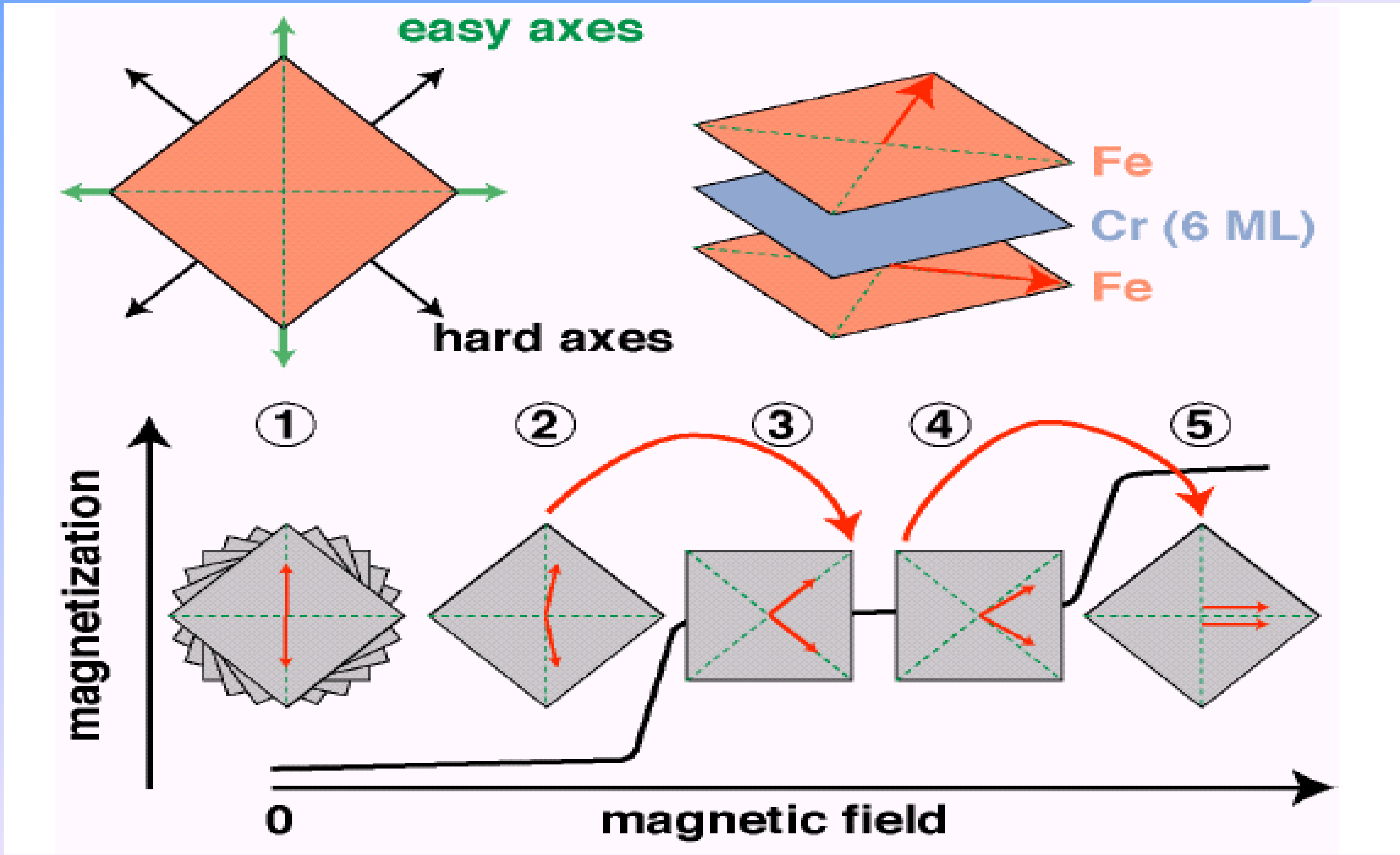
P. Bruno and C. Chappert, PRL **67**, 1602 (1991)

Quantum well picture of interlayer coupling

The normal compass (D. Bürgler, FZ Jülich)

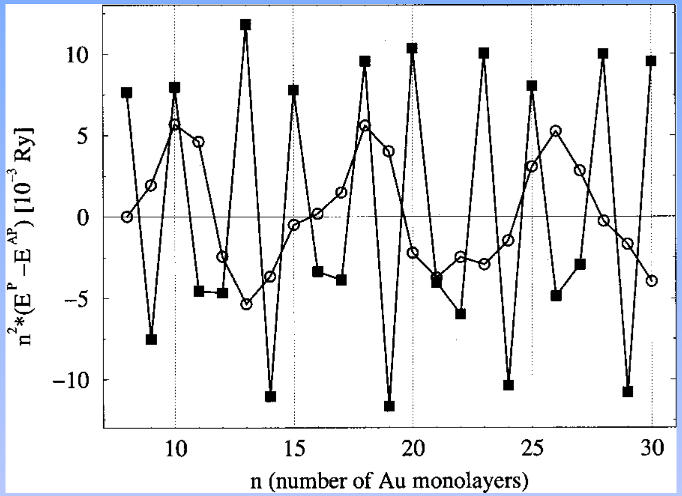


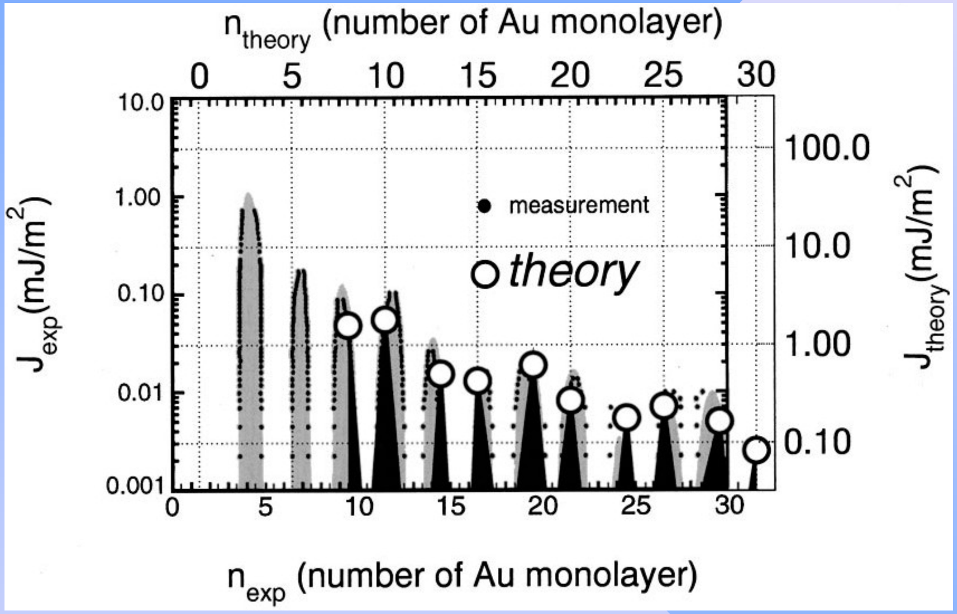
"The crazy compass" (D. Bürgler, FZ Jülich)



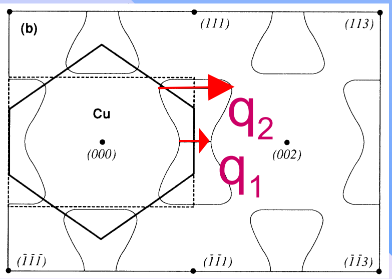
Ab initio calculation

Fe/Au/Fe(100)





$$\Delta E = E^P - E^{AP} = \Delta E(q_1) + \Delta E(q_2) \propto \frac{1}{n^2} \propto \frac{1}{d^2}$$



J. Opitz, P. Zahn, J. Binder, and I. Mertig, PRB **63**, 094418 (2001)

Summary

- Magnetization is strongly influenced by confinement and anisotropy
- New phenomena are found in artifical superstructures