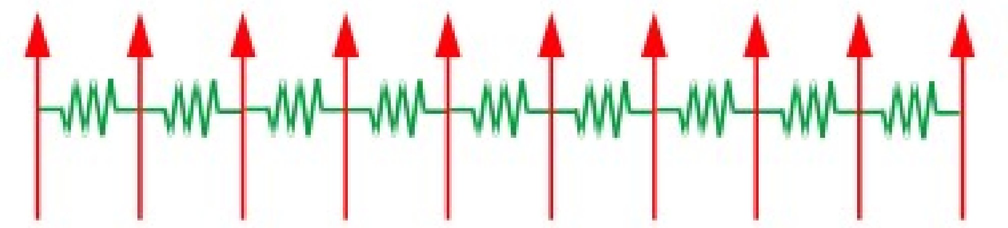
Spin excitations in magnetic structures of different dimensions



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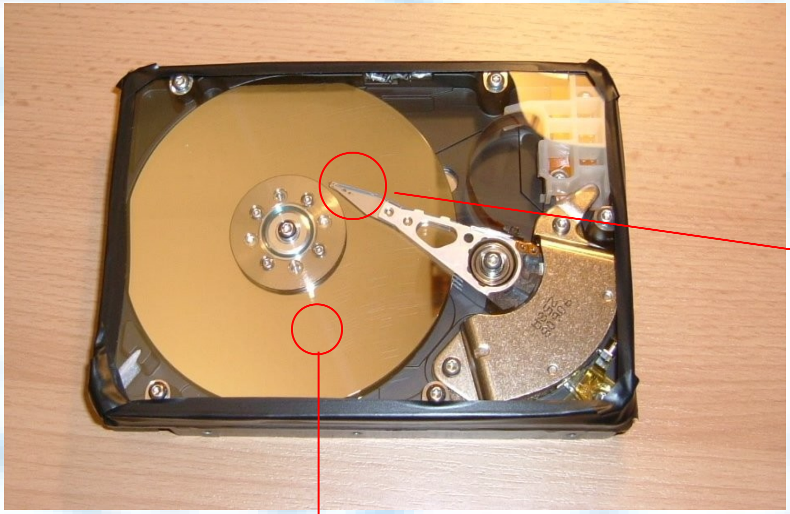
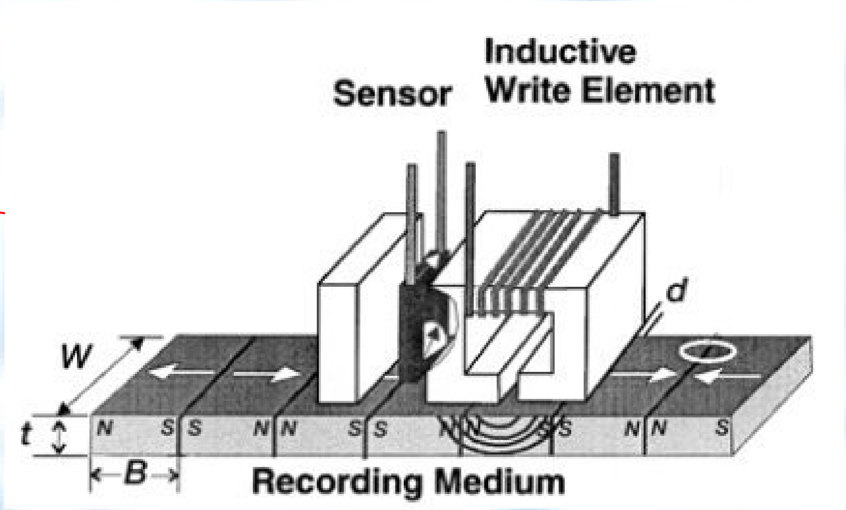
Chapters of spin excitation

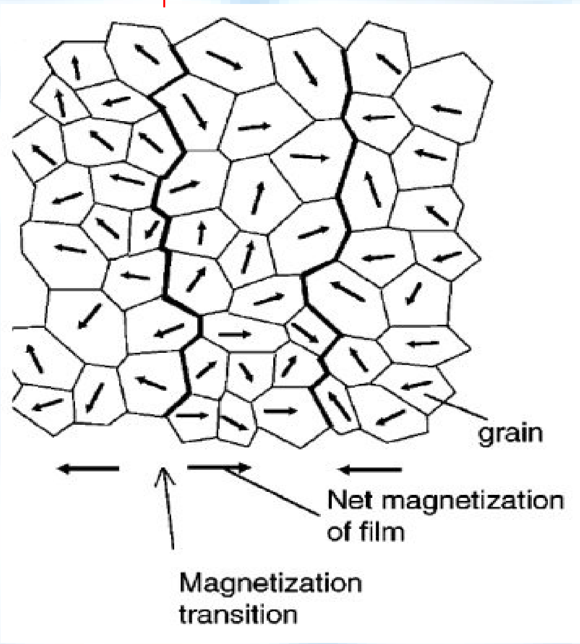
1. Why are excitations of any importance?
2. Excitations of ferromagnets in the Heisenberg model
3. Excitations of antiferromagnets in the Heisenberg model
4. Spin waves in bulk, thin films and stripes
5. Itinerant magnetism
6. Experimental techniques to study excitations

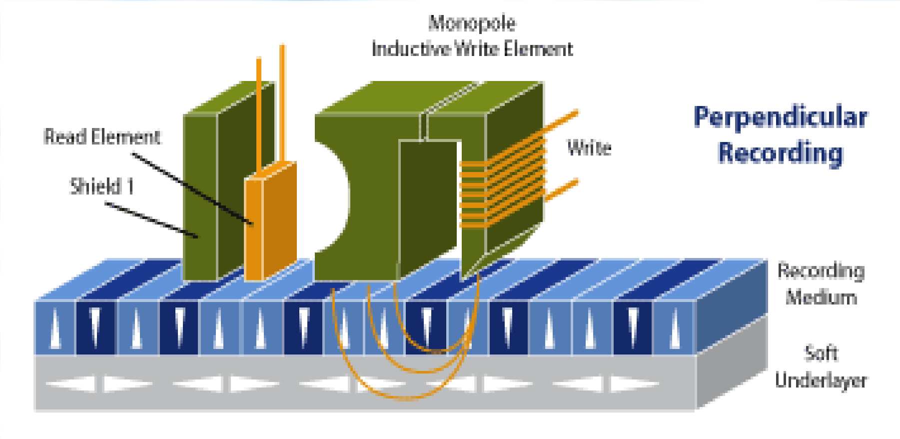
questions

Magnetic data storage

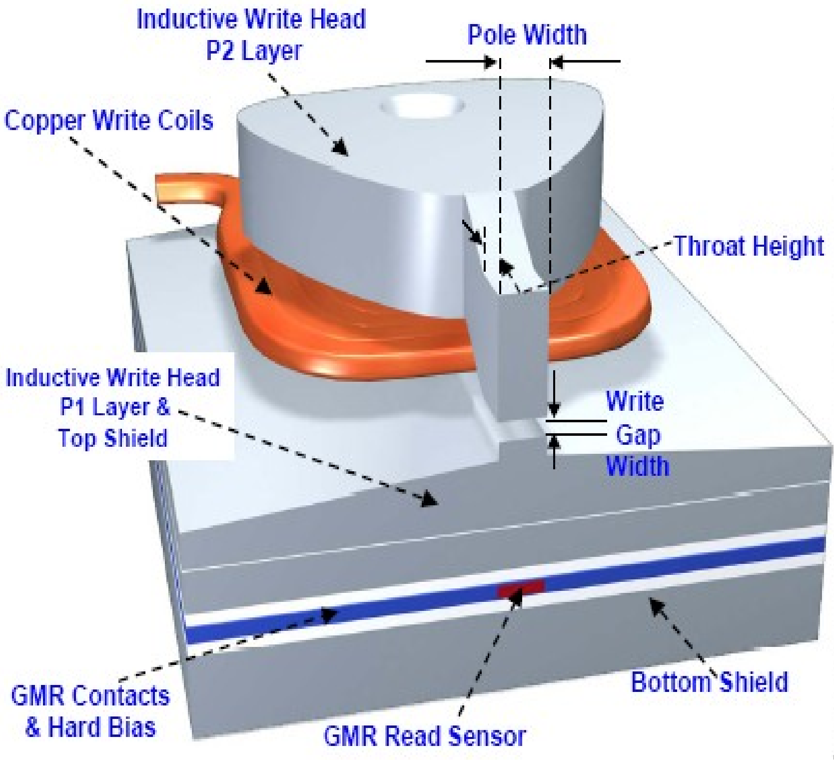


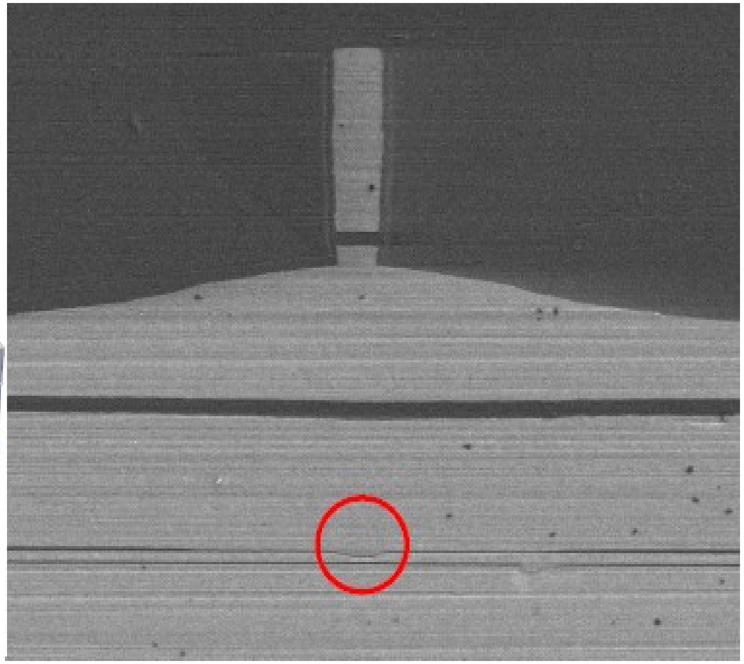




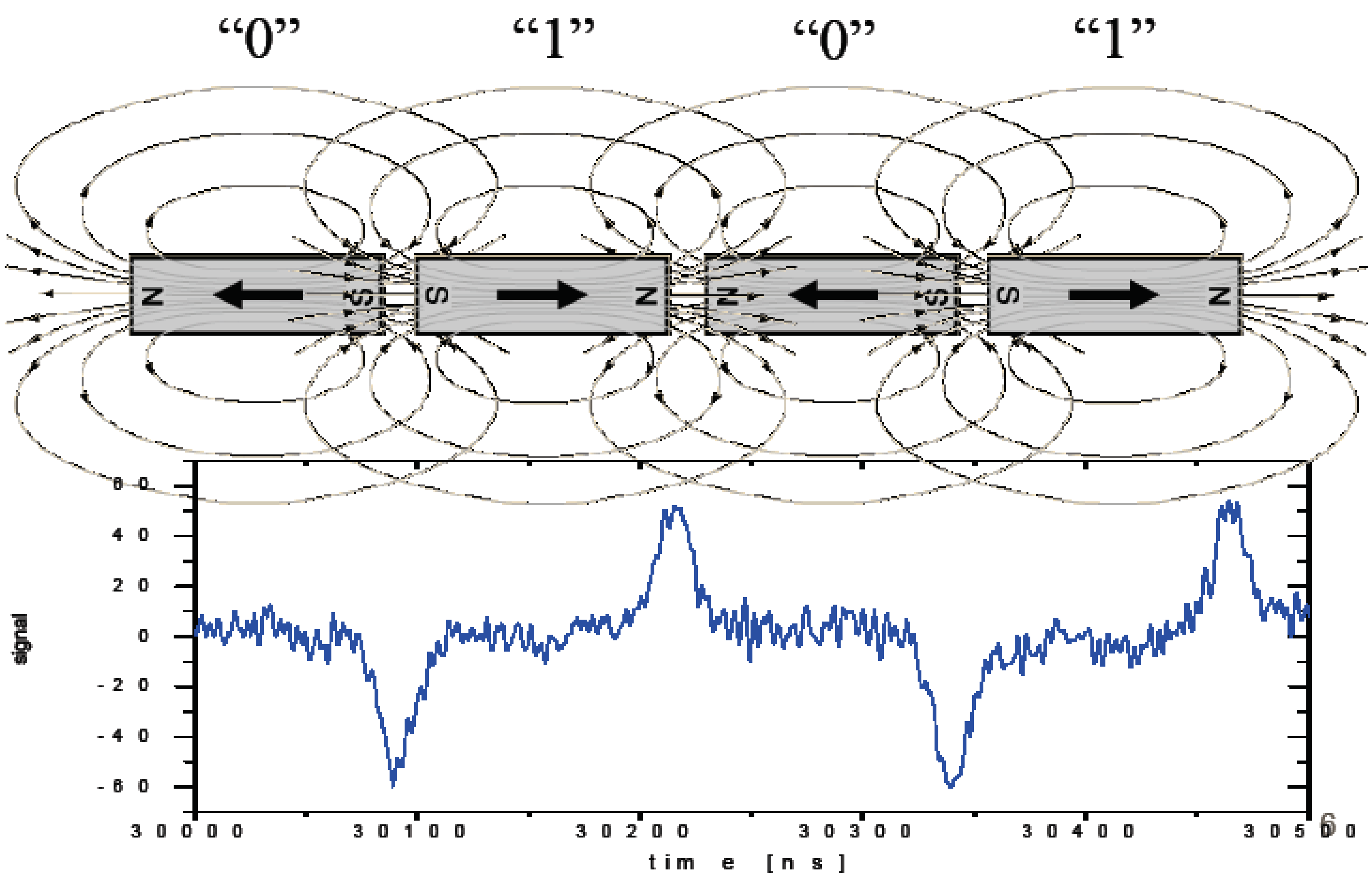


Write poles and GMR sensors



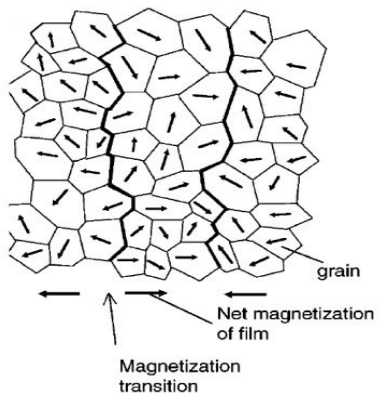


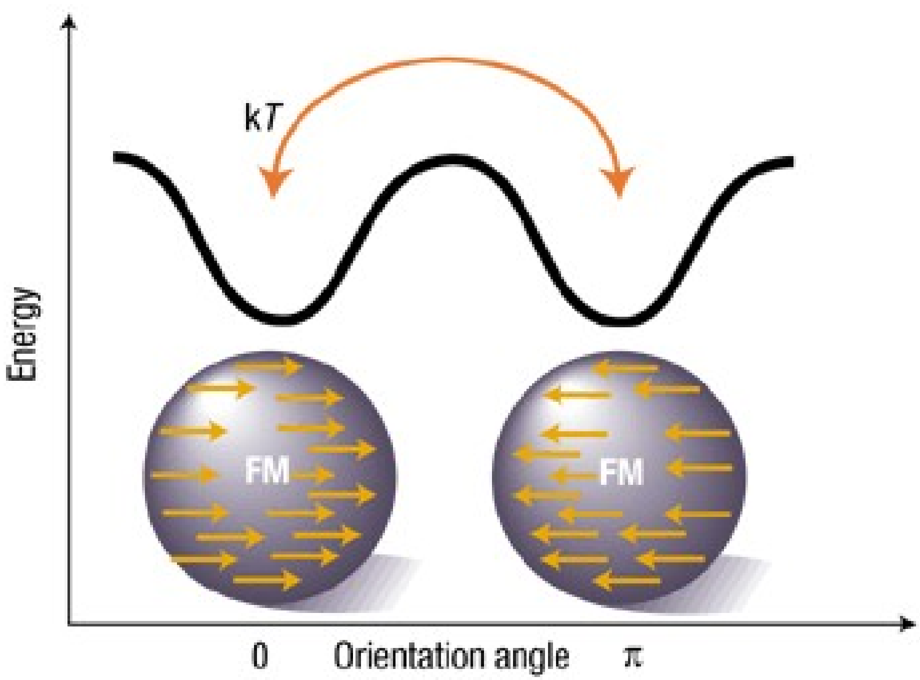
Reading (and writing) data from a disk



Typical data speed: 120MB/sec = 1GHz

Superparamagnetism





A single domain particle with e.g. uniaxial magnetic anisotropy due to magnetocrystalline anisotropy or a elongated shape (shape anisotropy) has two states with minimal energy.

In case the energy barrier given by the anisotropy cannot be overcome thermally within a certain time, the magnetic moment is stable.

In case the barrier can be overcome, the magnetic moment flips randomly between the states and the particle becomes superparamagnetic.

The magnetic moment of a bound electron

Magnetic moment of ring current (orbital moment)

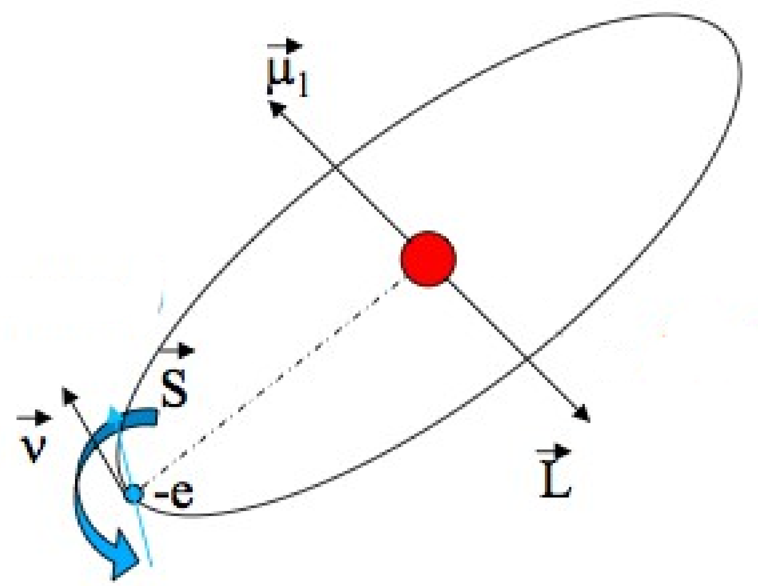
$$\vec{\mu}_l = I\vec{A} = -e\nu\pi r^2 = \frac{-e}{2m}(m\omega r^2) = \frac{-e}{2m}\hbar\vec{l} = -\mu_B\vec{l}$$

Bohr magneton $\mu_B = \frac{e\hbar}{2m} = 9.27\times10^{-24}\,J/T$

Magnetic moment of spin (spin moment)

$$\vec{\mu}_S = -\mu_B g\vec{s}$$

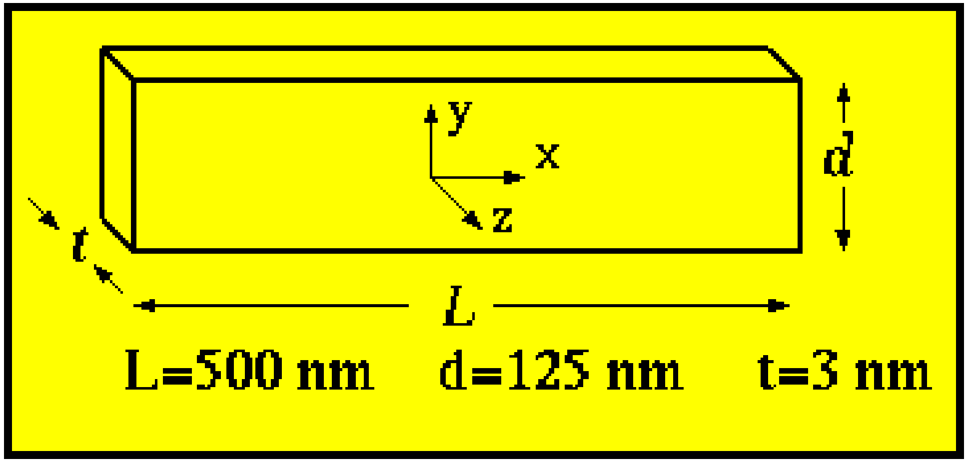
Landé factor of the electron $g = 2.0023 \approx 2$



In bulk spin moment usually dominates $\mu_s \gg \mu_l$

Attention: The magnetic moment behaves like an angular moment (precession).

Dynamic of magnetization reversal



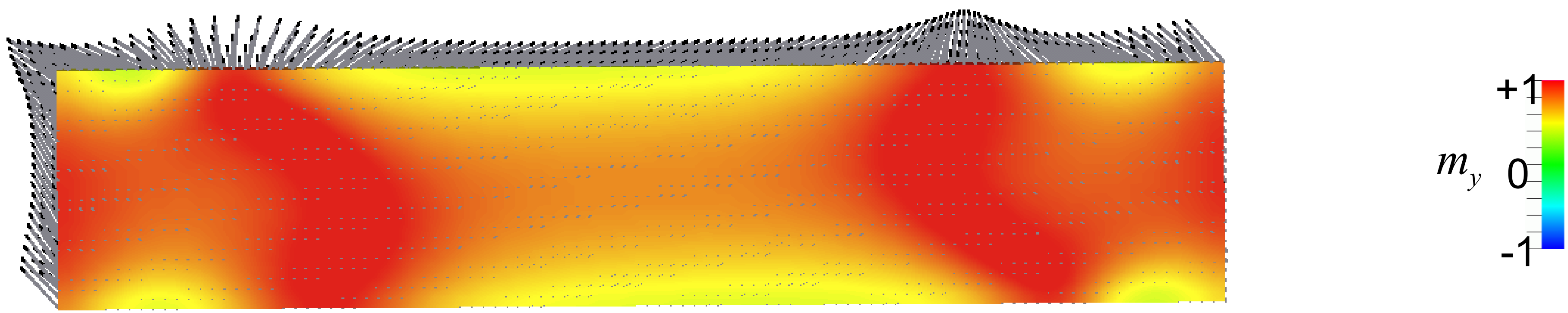
Ground state of magnetic particle is single domain.

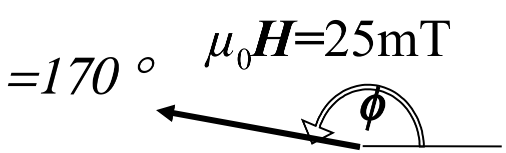
µMAG standard problem #4

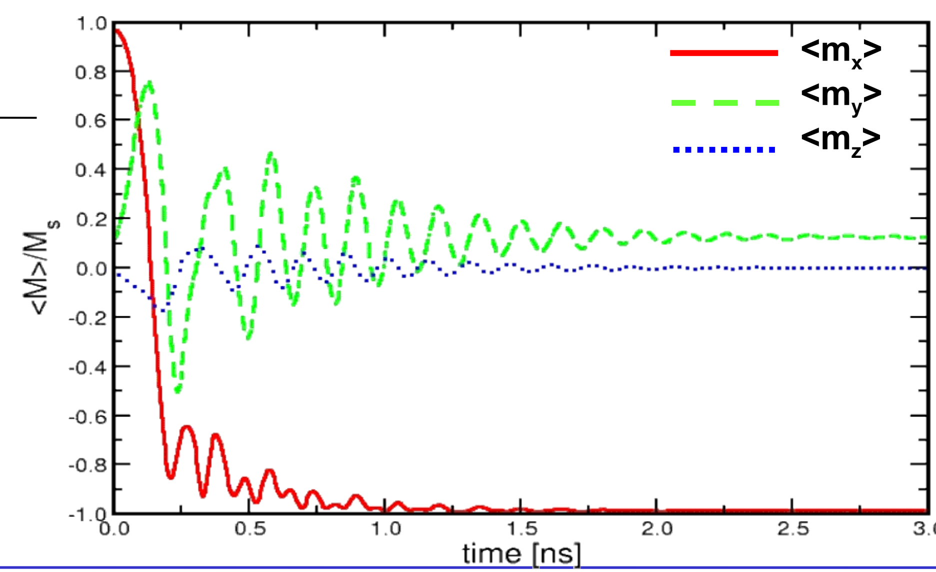
NIST, Maryland (VA) USA, M. Donahue *et al.*

http://www.ctcms.nist.gov/~rdm/mumag.org.html

Magnetization dynamics







During switcheing the partcile is not Single domain anymore.

The magnetistatic energy is converted to spin waves.

Chapters of spin excitation

Direct exchange interaction between two electrons

Quantum mechanical system with two electrons : total wave function must be antisymmetric under exchange of the two electrons, as electrons are fermions.

$$\Psi(1,2) = -\Psi(2,1)$$

Wave function of electron is a product of spatial and spin part: $\Psi(1) = \Psi(r_1) \times \vec{\sigma}(1)$

For antiparallel spins (singlet): $\sigma(1,2) = \frac{1}{\sqrt{(2)}}$ (↑↓ - ↓↑) antisymmetric

For parallel spins (triplet) : $\sigma(١,٢)$ = ↑↑, $\frac{١}{\sqrt{(2)}}$ (↑↓ + ↓↑), ↓↓ symmetric

→ Spatial part of wave function has opposite symmetry to spin part

Direct exchange interaction between two electrons

$$\Psi(r_{1,}r_2)=\frac{1}{\sqrt{2}}(\Psi_a(r_1)\Psi_b(r_2)+\Psi_a(r_2)\Psi_b(r_1))$$ symmetric for singlet

$$\Psi(r_{1,}r_2)=\frac{1}{\sqrt{2}}(\Psi_a(r_1)\Psi_b(r_2)-\Psi_a(r_2)\Psi_b(r_1))$$ antisymmetric for triplet

For the antisymmetric wave function : $\Psi(r_{1,}r_2)=-\Psi(r_{2,}r_1)$

In case $r_1=r_2$ follows : $\Psi(r,r)=0$

→ Coulomb repulsion is lower for antisymmetric spatial wave function and thus its energy
Is lower than that of the symmetrical spatial wave function

Exchange interaction between two spins: difference of the coulomb energy due to symmetry

$$E_S-E_T=2\int\Psi_a^*(r_1)\Psi_b^*(r_2)\frac{e^2}{4\pi\epsilon_0|r_1-r_2|}\Psi_a(r_2)\Psi_b(r_1)\,dr_1\,dr_2$$

Direct exchange between localized electrons

$$J = \frac{E_S - E_T}{2}, \; E_{ex} = -2J\,\vec{S}_1 \vec{S}_2$$

J>0 : parallel spins are favoured (ferromagnetic coupling)

J<0: antiparallel spins are favoured (antiferromagnetic coupling)

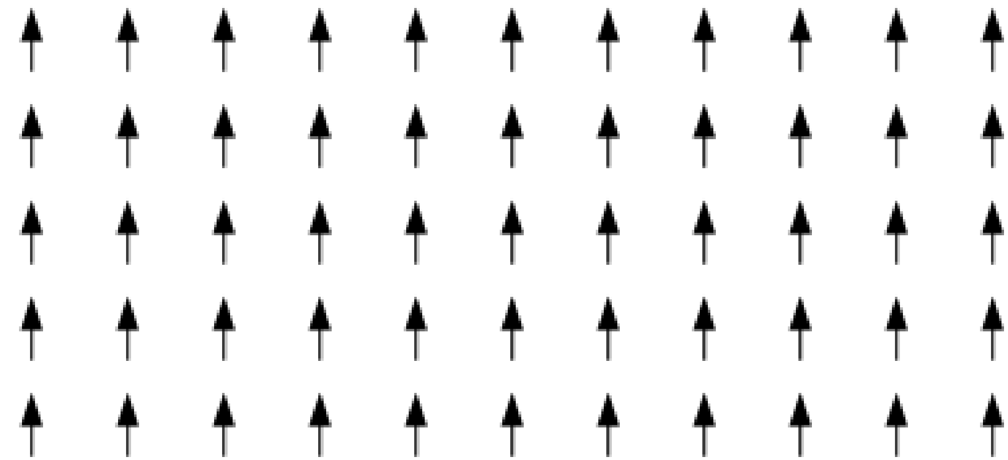
Heisenberg model for N spins: $$E = -\sum_{i,j=1}^{N} J_{ij} \vec{S}_i \vec{S}_j$$

As electrons are assumed as localized, wave functions decay quickly and mainly nearest neighbors contribute to exchange.

Nearest neighbor Heisenberg model: $$E = -\sum_{i,j\ NN} J\,\vec{S}_i \vec{S}_j$$

Ferromagnetism

$J>0$
Spins align in parallel at $T=0$



Elements : Fe, Co, Ni, Gd …
Oxides : Fe_2O_3, CrO …
Semiconductors : GaMnAs, EuS ...

Above Curie temperature Tc, they become paramagnetic.

Fe	1043K	EuS	16.5K
Co	1394K	GaMnAs	ca. 180K
Ni	631K		
Gd	289K		

$$T_C \approx \frac{2 z J_{ex} J(J+1)}{3k_B}$$

z nearest neighbors

Solving the excitation spectrum

Quantum mechanically exact solution is extremely hard if not impossible.

N coupled atoms of spin S have a $(2S+1)^N$ dimensional Hilbert space.

Example: A 3x3x3 Fe cluster (S=2) has 5^{27} = 745.058.059.623.827.125 states.

Let us try in a 1D chain of atoms (S=1/2) with only nearest neighbor interactions:

$$H = -2J \sum_{j=i+1} \vec{S}_i \vec{S}_j = -2J \sum_i \left(S_i^z S_{i+1}^z + \frac{1}{2}\left(S_i^+ S_{i+1}^- + S_i^- S_{i+1}^+ \right) \right)$$

$$S^+ = S_x + iS_y$$
$$S^- = S_x - iS_y$$

$$S^+ \left| +\frac{1}{2} \right> = 0 \qquad S^+ \left| -\frac{1}{2} \right> = \left| +\frac{1}{2} \right>$$

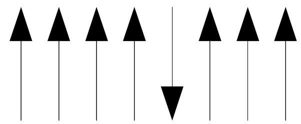
$$S^- \left| +\frac{1}{2} \right> = \left| -\frac{1}{2} \right> \qquad S^- \left| -\frac{1}{2} \right> = 0$$

Solving the excitation spectrum

For the ground state (say $S_i = +S$) : $H|\Phi> = -2NJS^2|\Phi>$

Naïve try for an excited state:

$|j> =$ ....



.... j-th spin is flipped

j

$$H|j> = 2(-NJS^2 + 2JS^2)|j> - SJ|j+1> - SJ|j-1>$$

The single flipped spin is no eigenstate of the Hamiltonian!

Solving the excitation spectrum for a 1D ferromagnetic chain

Solution: excited states are described by the ground state plus small excitations named magnons (quasiparticles) that do not interact.

Shortcomings: in reality, magnons do interact.

$$H = -2J \sum_{j=i+1} \vec{S}_i \vec{S}_j$$

Semiclassical ansatz:

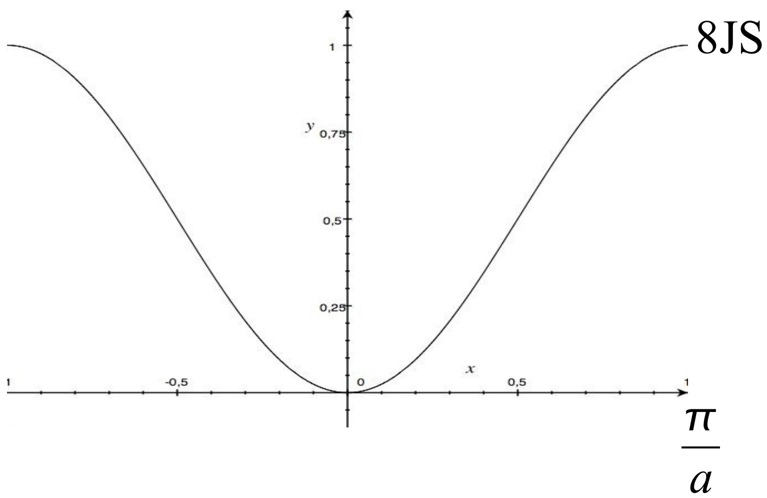
$$S_j^z \approx S$$

$$S_j^x = A\, e^{i(qja - \omega t)}$$

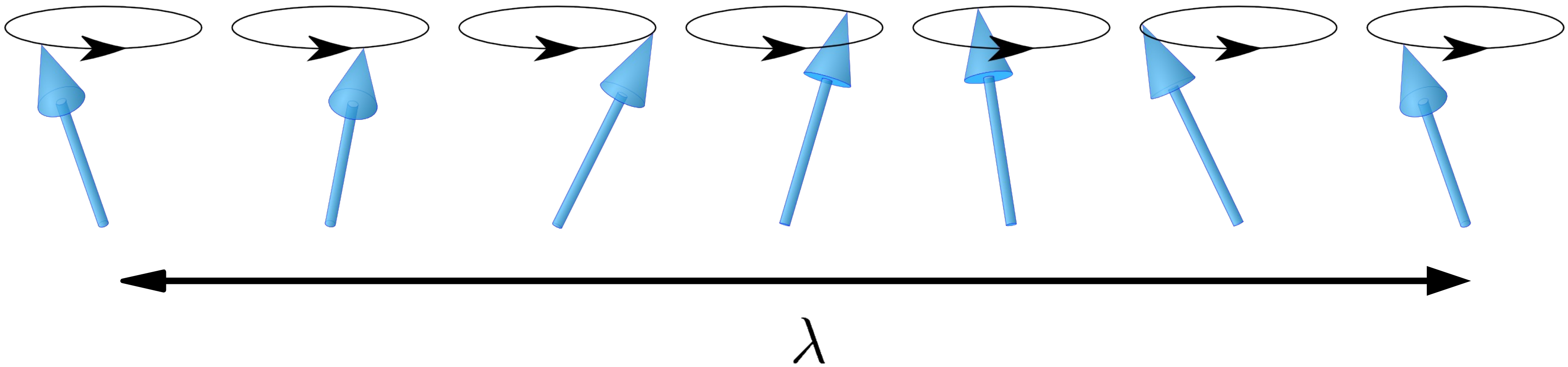
$$S_j^y = B\, e^{i(qja - \omega t)}$$

See blackboard!

Solution: $\hbar\omega = 4JS(1 - \cos qa)$



Magnons or spin waves



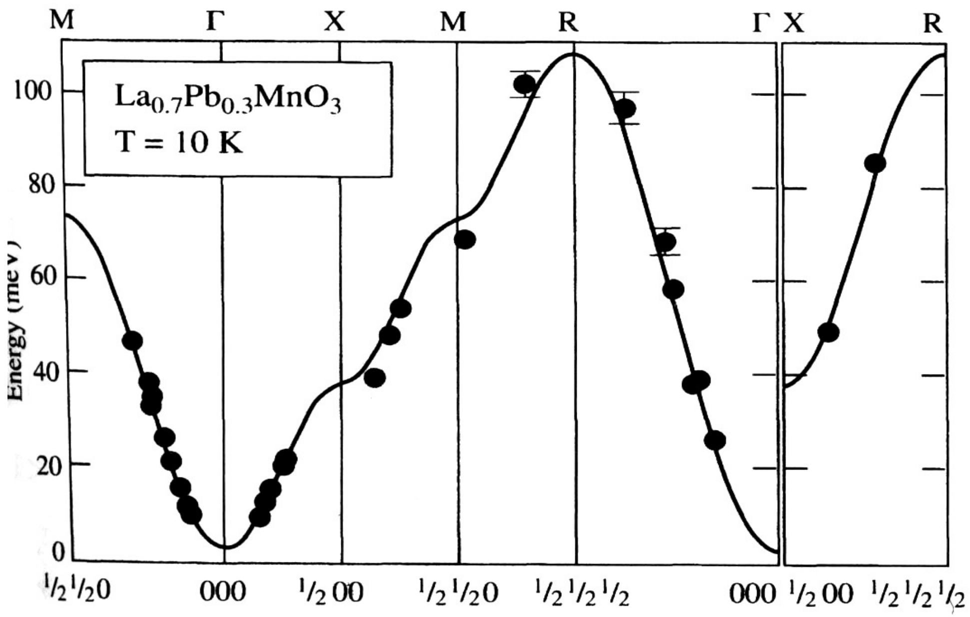
$$q = \frac{2\pi}{\lambda}$$

Excitation of spin 1

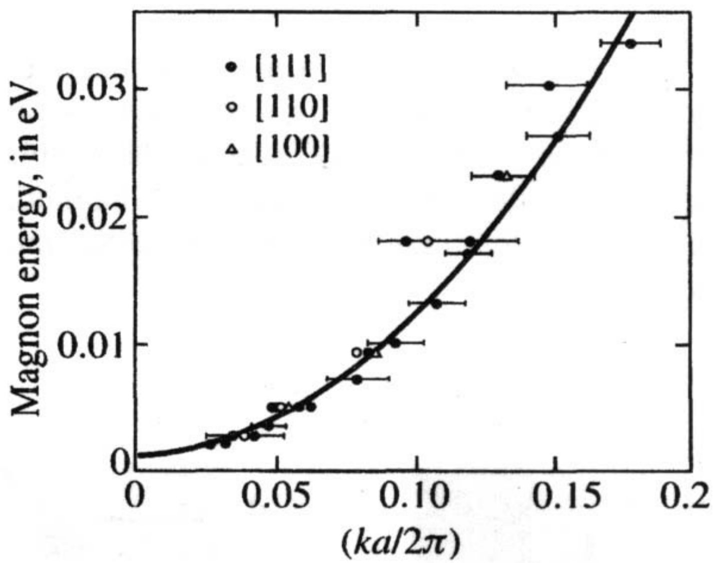
Magnons

Lindis Pass, NZ

Magnons in ferromagnets



fcc Co



Dispersion : $\hbar\omega = 4JS(1-\cos qa) \approx 2JS a^2 q^2 = D q^2$

D is called spin wave stiffness and behaves like an inverse mass

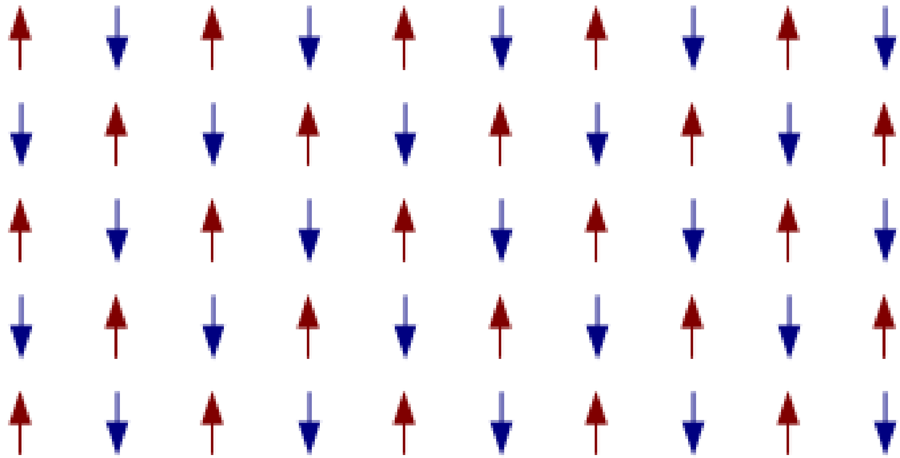
	Fe	Co	Ni
D [meVÅ^2]	281	500	364

from Blundell

Chapters of spin excitation

Antiferromagnetism

$J<0$
Spins align antiparallel at $T=0$

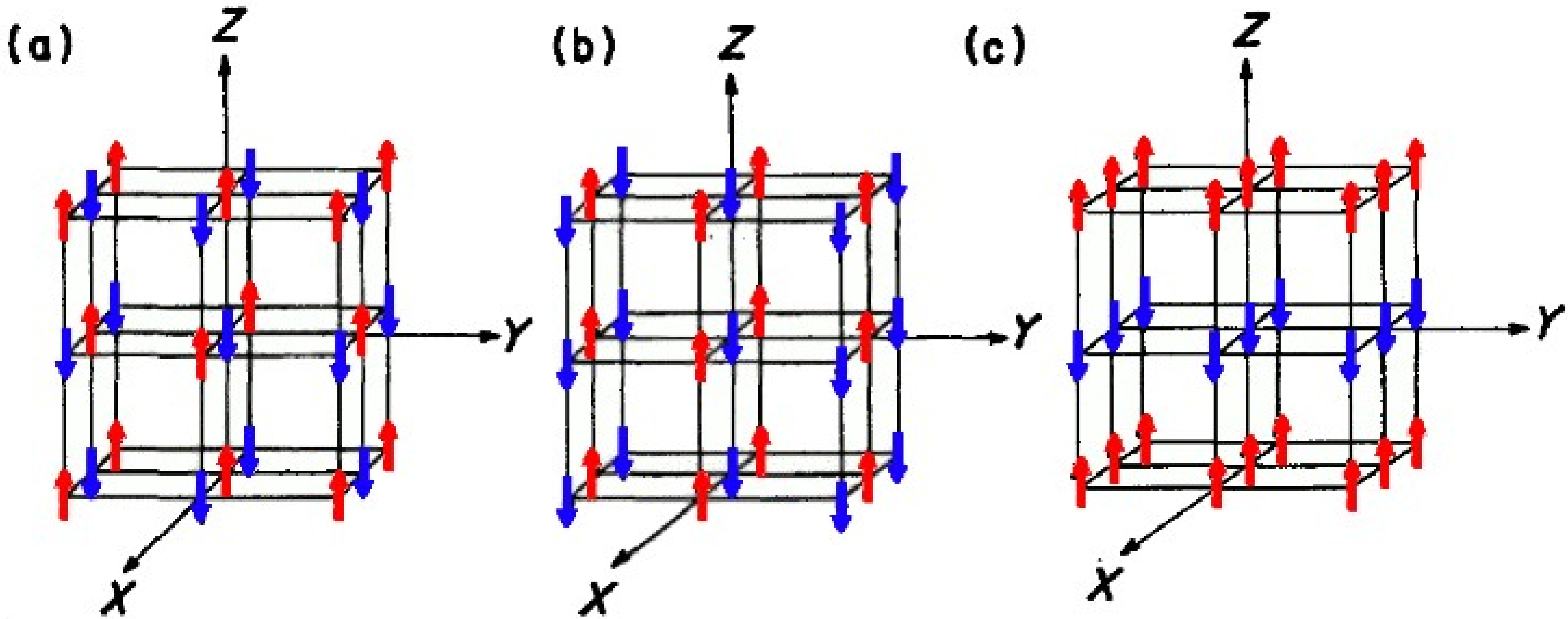


Elements	: Mn, Cr …
Oxides	: FeO, NiO …
Semiconductors	: URu_2Si_2 …
Salts	: MnF_2 ...

Above Néel temperature T_N, they become paramagnetic.

Cr	297K
FeO	198K
NiO	525K

Antiferromagnetic configurations



Depending on the crystal structure, many different antiferromagnetic configurations may exist.

Magnon dispersion of antiferromagnets

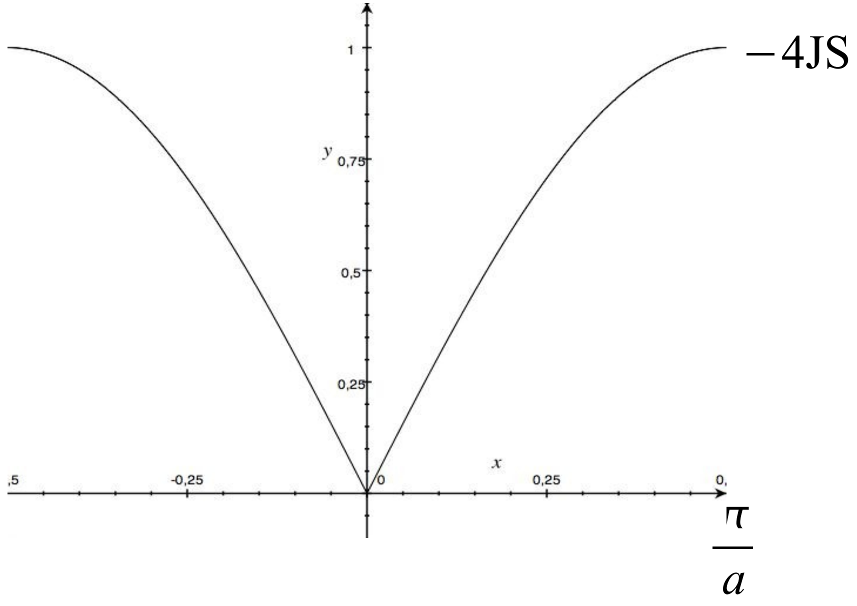
Solution: two ferromagnetic sublattices that couple antiferromagnetically.

$$H = -2J \sum_{j=i+1} \vec{S}_i \vec{S}_j, J < 0$$

Ansatz: $S^z_{2p} = +S, S^z_{2p+1} = -S$

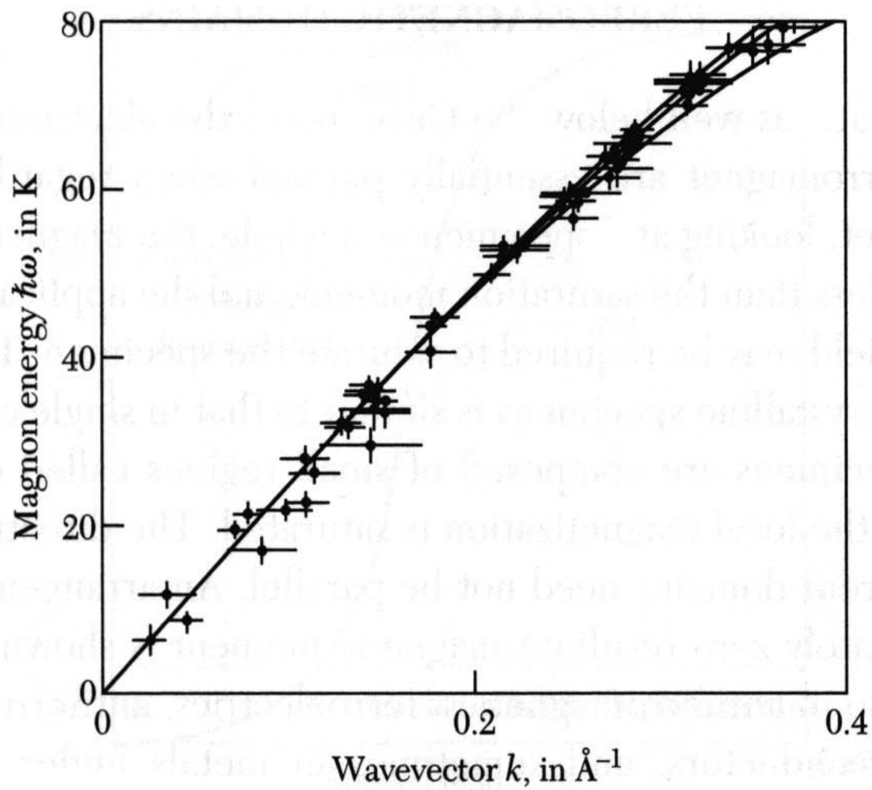
See blackboard!

Solution: $\hbar\omega = -\varepsilon JS|(\sin(qa))|$



Magnones in antiferromagnets

$RbMnF_3$



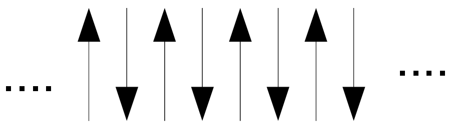
Dispersion : $\hbar\omega = -4JS\sin qa \approx -ƐJSa\, q = v\, q$

v is called spin wave velocity; magnons behave like massless objects

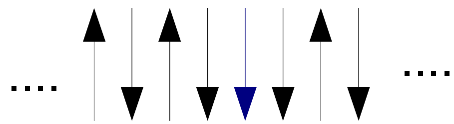
from Kittel

Spinons

Ground state



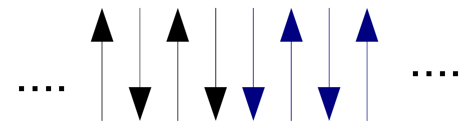
Excited state



ΔS=1

Magnon

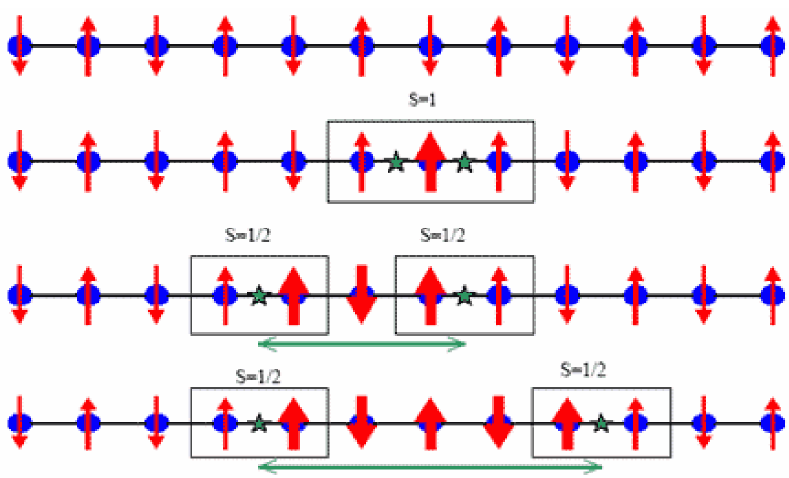
Excited state



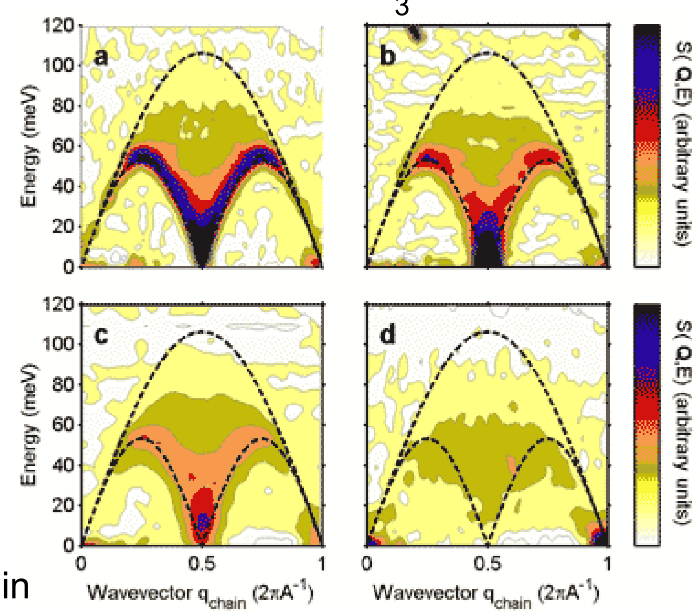
ΔS=1/2

Spinon

Magnon= 2 * Spinon



$KCuF_3$



From Helmholtz Center Berlin

Chapters of spin excitation

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questions

Thermodynamics of ferromagnets

Bloch´s $T^{3/2}$ law

Thermal occupation number of a magnon: $$<n_q> = \frac{1}{e^{\hbar\omega(q)/kT} - 1}$$

Total number of magnons: $$N = \int_{BZ} <n_q> dq = \int_{o}^{\infty} D(\omega) <n(\omega)> d\omega$$

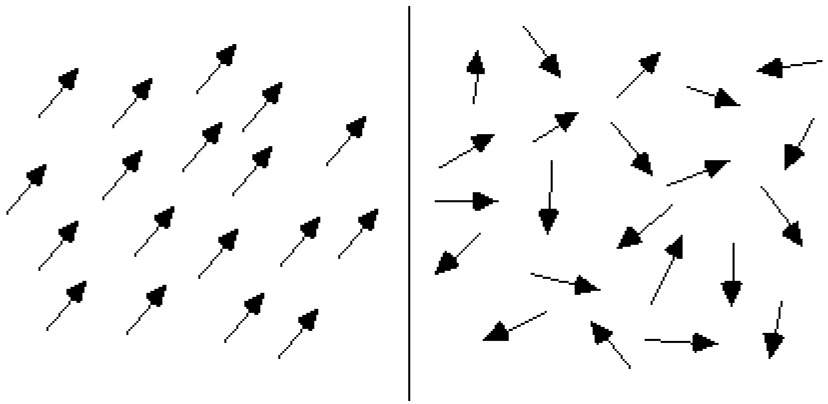
With parabolic dispersion within the BZ and in 3 dimensions: $D(\omega)\,\alpha\,\omega^{۱/۲}$

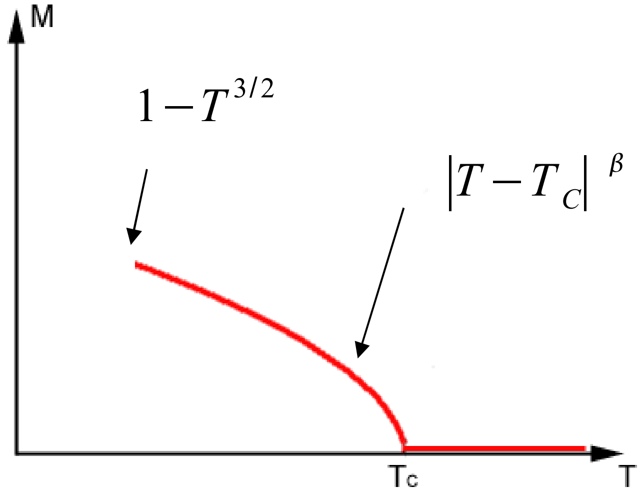
$$N\,\alpha\,\frac{T^{3/2}}{D}$$

Thermodynamics of magnets

Phase transition between ferromagnetic (T<Tc) and paramagnetic (T>Tc).

Magnetic phase transitions are of 2nd order, i.e. M continuously goes to zero when Tc is approached.





$$M_S \propto |T_C - T|^{\beta} \qquad M_{T=T_C} \propto \pm |H|^{1/\delta}$$

$$\chi \propto |T - T_C|^{-\gamma} \qquad \xi \propto |T_C - T|^{-\nu}$$

Critical exponents describe the properties of the magnet near Tc.

Critical exponents of some model systems

Ising : spin can only point along $\pm z$ direction
XY : spin lies in the xy-plane
Heisenberg : spin can point in any direction in space
Landau : classical theory

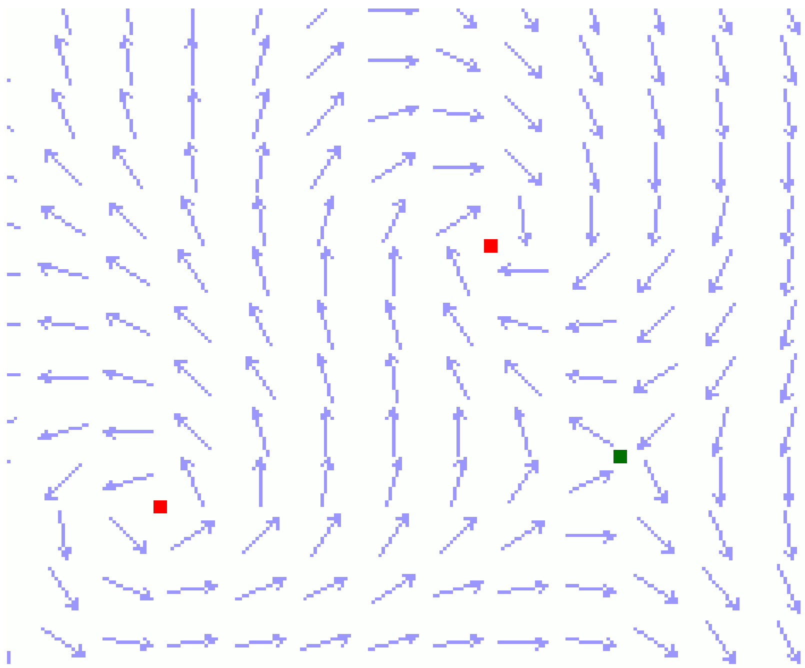
Exponent	β	γ	δ	ν
Landau-Theory	0,5	1	3	0,5
2d-Ising	0,125	1,75	15	1
2d-XY	0,23	2,2	10,6	1,33
3d-Ising	0,325	1,240	4,816	0,630
3d-XY	0,345	1,316	4,810	0,669
3d-Heisenberg	0,365	1,387	4,803	0,705

The Mermin-Wagner theorem

The Mermin-Wagner theorem predicts Tc=0K for three dimensional spins in two dimensions that interact via the exchange interaction.

Spin waves
of parabolic dispersion
in 2 dimensions:

$$D(\omega)=const$$



A Kosterlitz-Thouless phase transition (self similar vortex state) is predicted for T=0.

2D Heisenberg - model

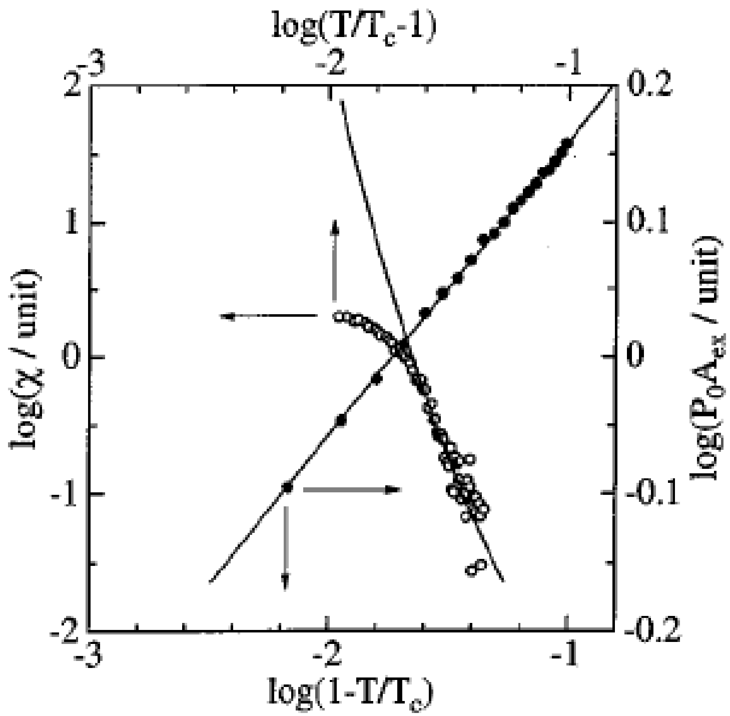


FIG. 3. Double logarithmic plot of susceptibility χ(○) and spontaneous magnetization M(●) vs reduced temperatures (data from Fig. 2). The full lines represent fits to the power law and to the exponential law, respectively

2 atomic layers of Fe/W(100)

Two easy direction in the film plane, hard axis normal to the plane

Expected ordering temperature 0K, observed 207K

HJ Elmers, J. Appl. Phys. (1996)

Beyond exchange interaction

The magnetic moments of a ferromagnet feel other forces than only the exchange.

Zeeman energy density : $H = -\mu_0 g \mu_B \vec{H}_{ext} \vec{S}$

Dipolar energy density : $H = \int_V \frac{\mu_0 M}{2} \frac{\vec{m}(\vec{r}) \vec{\nabla}' (\vec{m}(\vec{r}')(\vec{r}' - \vec{r}))}{4\pi |\vec{r} - \vec{r}'|^3} d\vec{r}'$

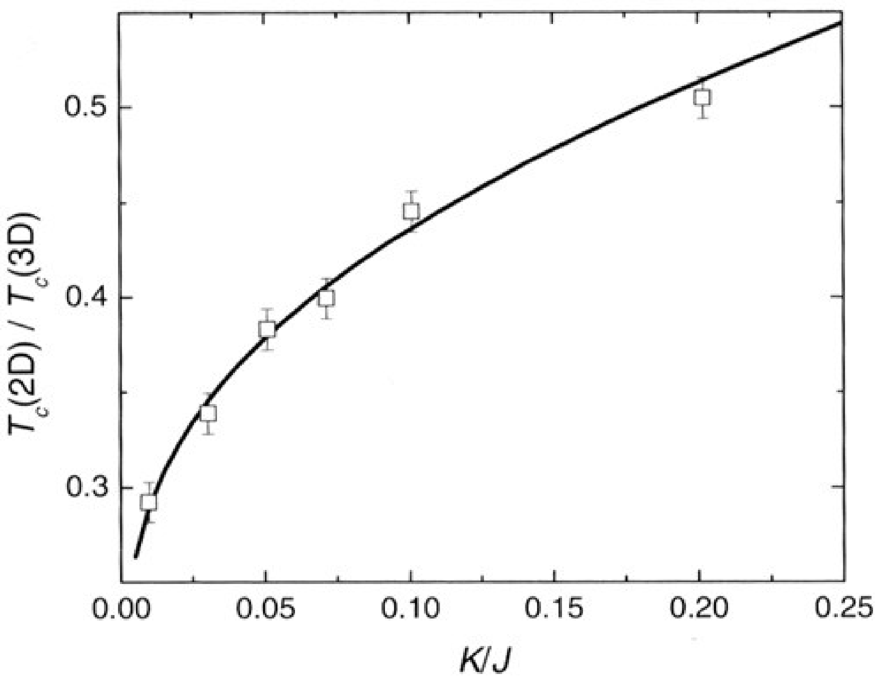
Anisotropy energy density : $H = f(\vec{S})$ e.g.: $H = K \cos^2(\vec{S}, \vec{z}) = K S_z^2$

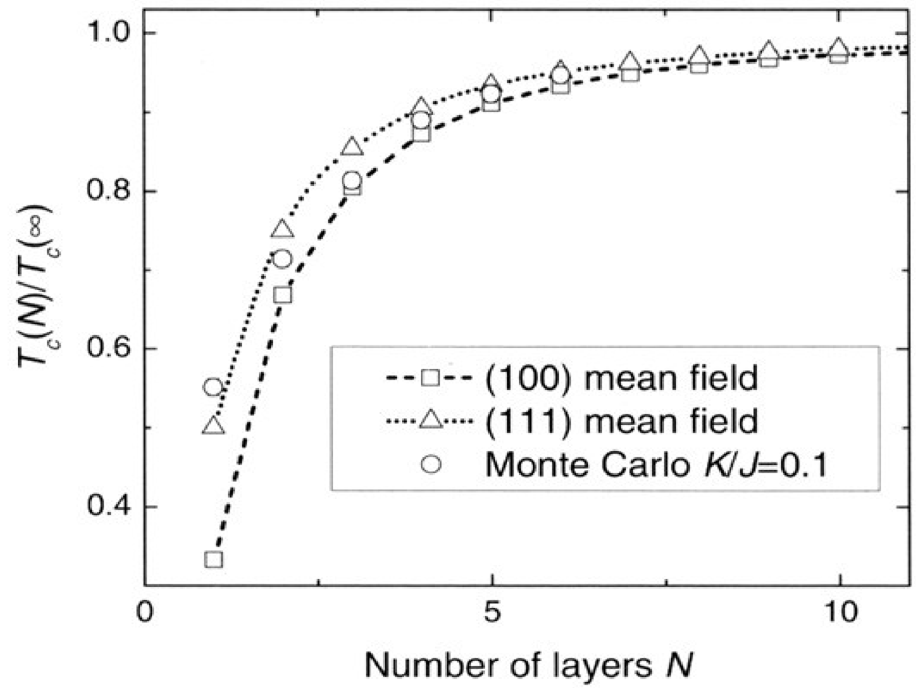
These can be written as an effective field favouring a certain direction in the ground state. A magnon, in which the spin deviates from this ground state, will cost additional energy. For the magnon at q=0, i.e. the coherent rotation, the frequency is then given by the Larmor frequency of the spin in the effective field:

$$\hbar \omega(\mathrm{q}=0) = \mu_0 g \mu_B H_{eff}$$

A magnon gap evolves!

Limits of the Mermin-Wagner theorem

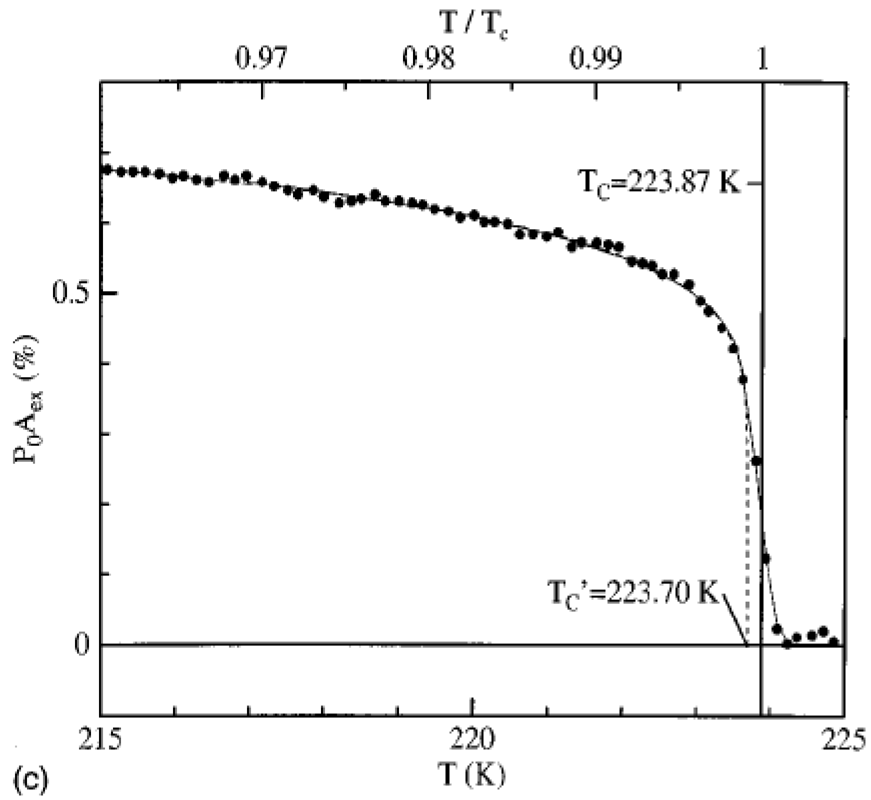




Even slightest anisotropies lead to break down of Mermin-Wagner theorem (magnon gap). A magnetization for T>0 results.

When film thickness increases, the ordering temperature of the 2D-system quickly approaches that of the 3D system.

1 ML Fe/W(110): 2D-Ising



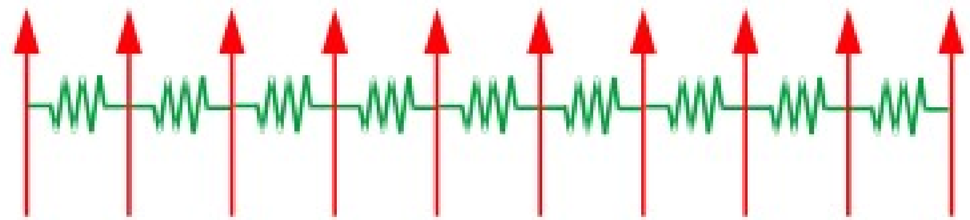
Uniaxial magnetic anisotropy in the film plane results in 2D Ising model

Critical exponent: β=0.133 (0.125)

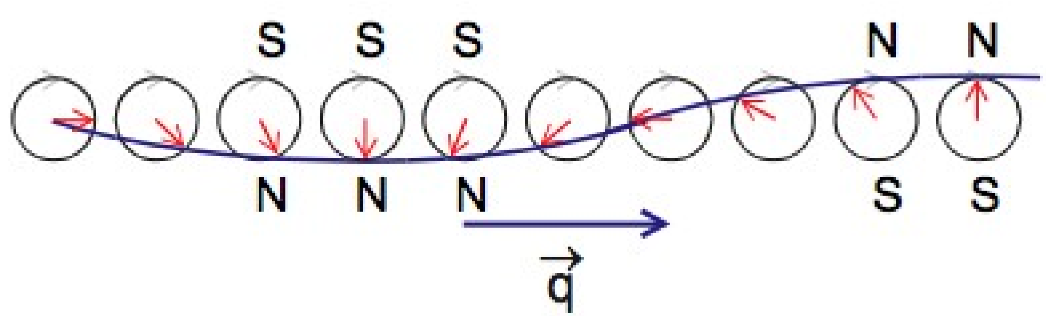
HJ Elmers, Phys. Rev. B (1996)

Thin film modes inc. dipolar and shape anisotropy

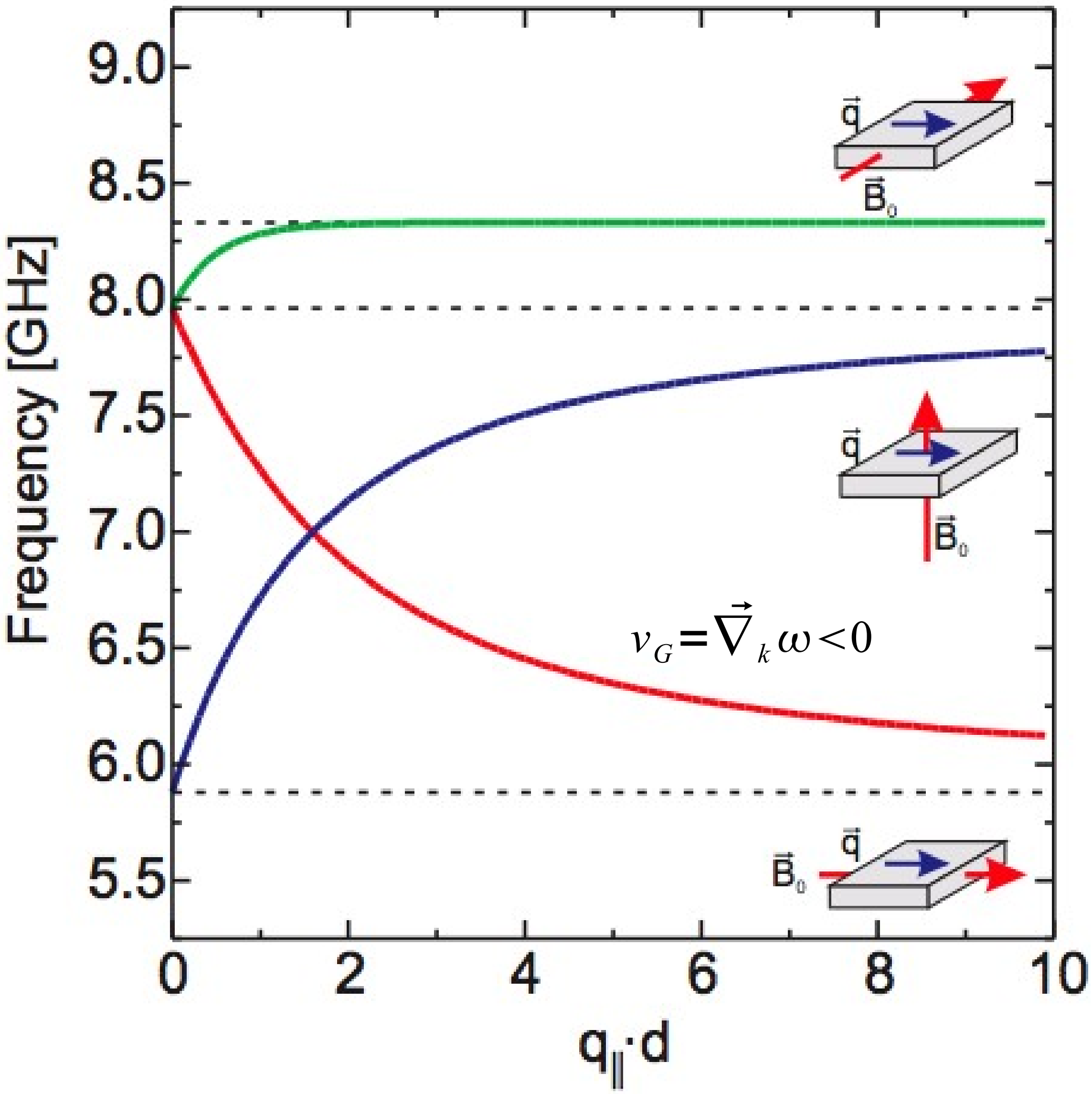
At large q, spin wave dispersion is dominated by exchange



At small q, spin wave dispersion is dominated by dipolar energy (shape anisotropy)



Thin film modes inc. dipolar and shape anisotropy



B_0 : effective field defining ground state

Surface spin waves

$$\omega^2 = \omega_0(\omega_0 + \omega_M) + \frac{\omega_M^2}{4}\left[1 - e^{-2kd}\right]$$

Forward volume spin waves

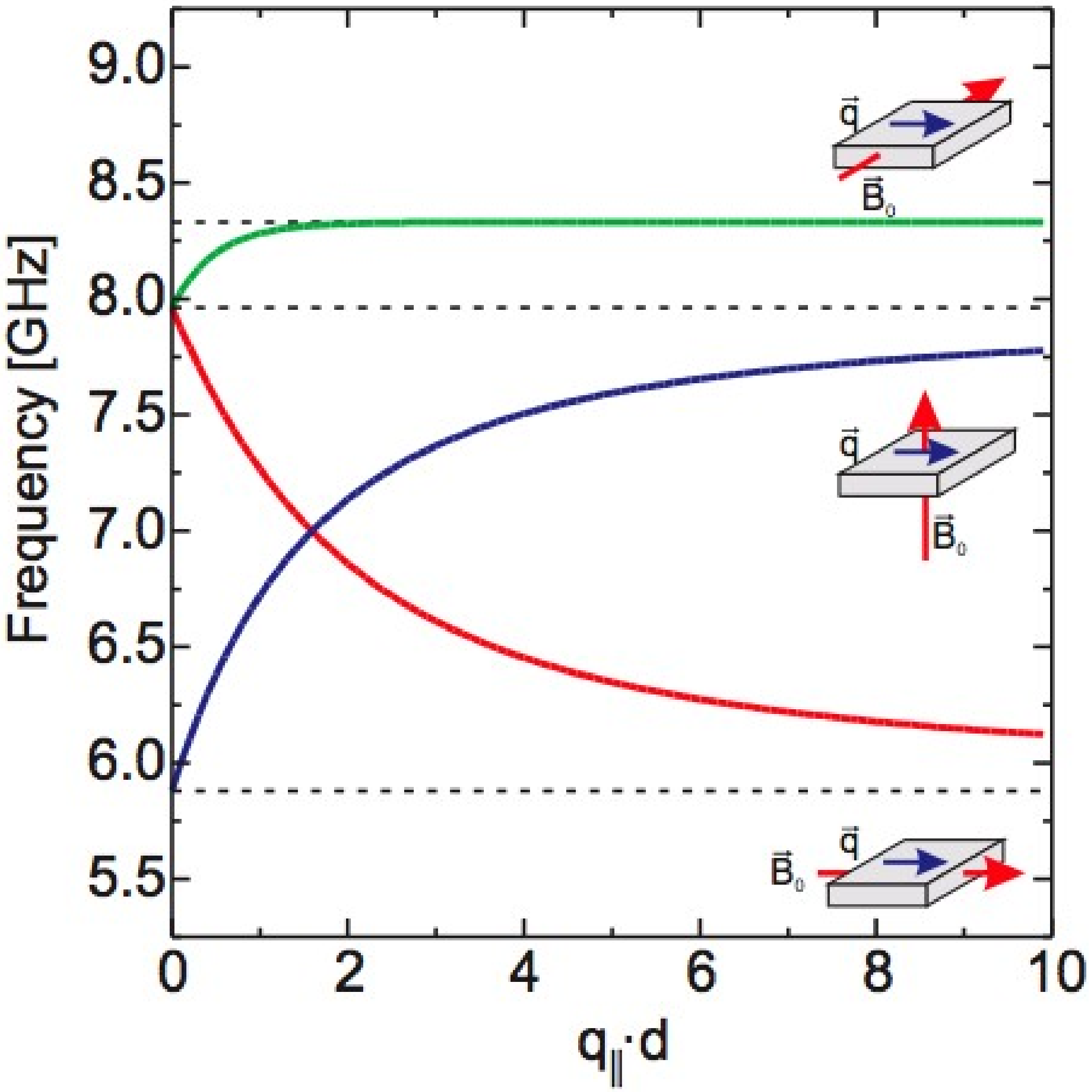
$$\omega^2 = \omega_0\left[\omega_0 + \omega_M\left(1 - \frac{1 - e^{-k_t d}}{k_t d}\right)\right]$$

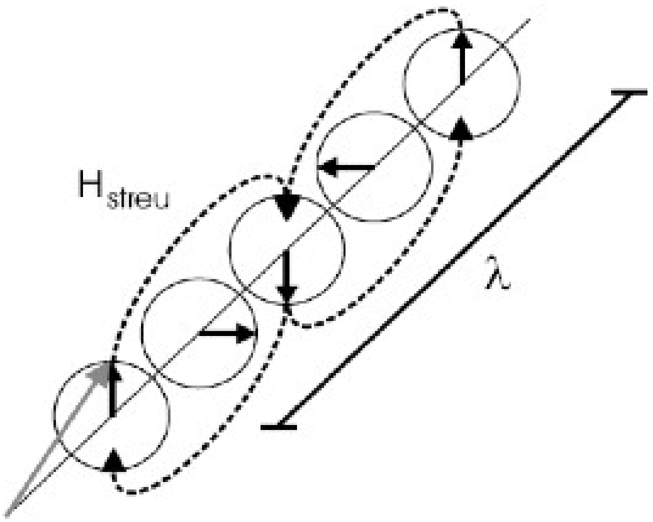
Backward volume spin waves

$$\omega^2 = \omega_0\left[\omega_0 + \omega_M\left(\frac{1 - e^{-k_z d}}{k_z d}\right)\right]$$

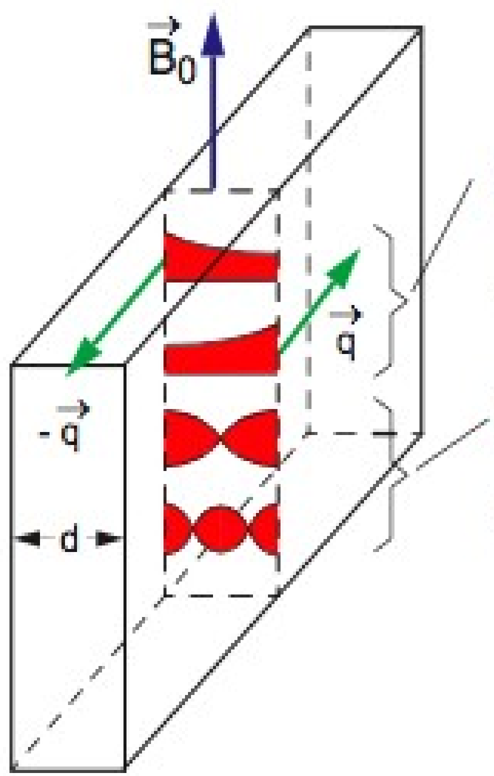
Figure: B. Hillebrands

Thin film modes inc. dipolar and shape anisotropy





Thin film modes inc. dipolar and shape anisotropy



Dipolar Damon-Eshbach modes

$$\omega^2/\gamma^2 = [B_0(B_0 + J_s) + (J_s/2)^2\,(1 - e^{-2qd})]$$

Standing spin waves

$$\frac{\omega}{\gamma} = \frac{2A}{M_s} \cdot q^2 = \frac{2A}{M_s}\left(\frac{n\pi}{d}\right)^2 \qquad n = 1,2,\ldots$$

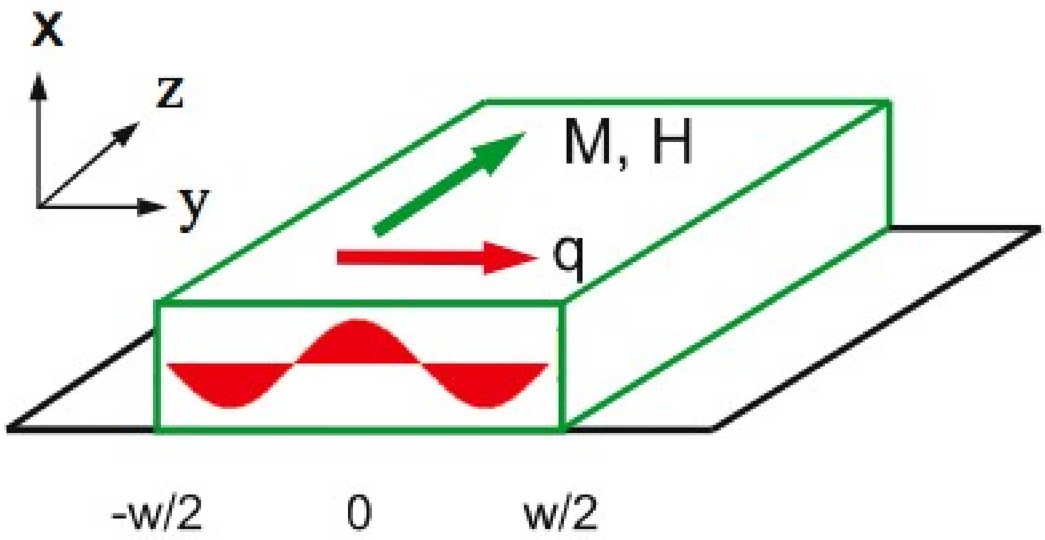
A: exchange constant

M_s: magnetization

Perpendicular to the plane, the modes have high q due to small thickness.
Thus the modes are determined by the exchange leading to open boundary conditions.

Figure: B. Hillebrands

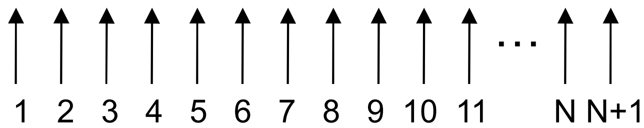
Magnon modes in stripes



In the stripe plane, the modes have small q due to large width (tens to hundreds of nm). Thus the modes are determined by dipolar energy leading to fixed boundary conditions (nodes) to avoid magnetic surface charges.

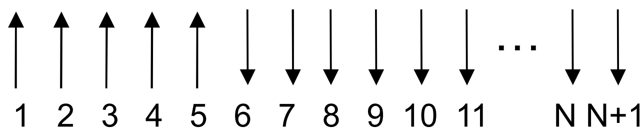
Figure: B. Hillebrands

The 1D-Ising chain



$$H = -\sum_{i=1}^{N} J\, \vec{S}_i^{(z)} \vec{S}_{i+1}^{(z)} = -\frac{1}{2} N J$$

One domain wall



Energy cost: $\Delta E = \frac{J}{4}$

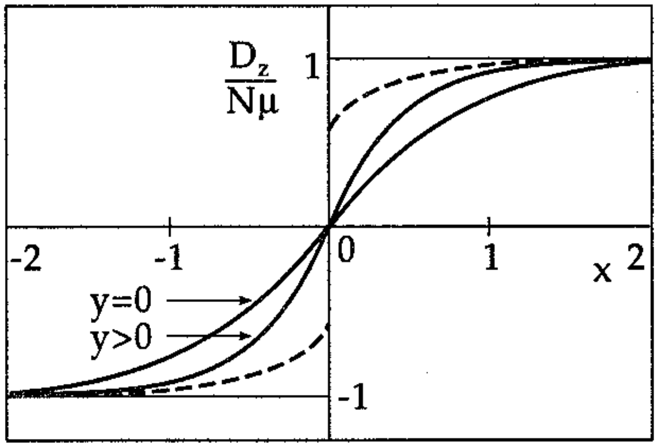
Entropy gain: $\Delta S = k_B \ln(N)$

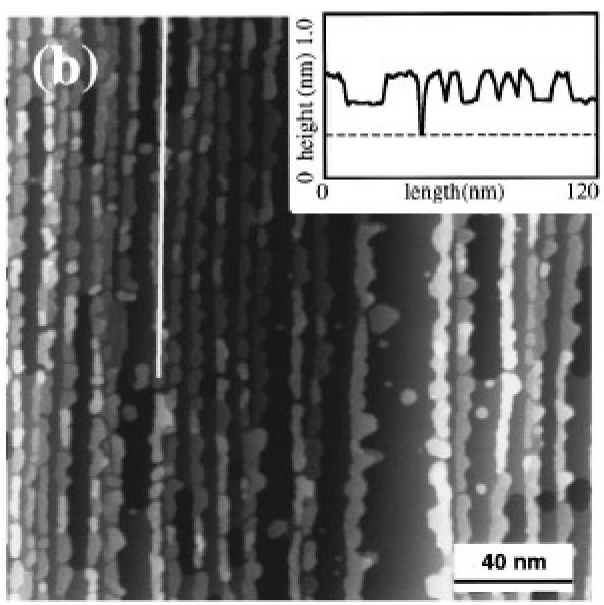
long Ising chain: $N \rightarrow \infty \Rightarrow \Delta S \rightarrow \infty$

$$F = (U + \Delta E) - T \underbrace{(S + \Delta S)}_{\rightarrow \infty} \rightarrow -\infty$$

Entropy wins and no ordering occurs.

1D Ising chain



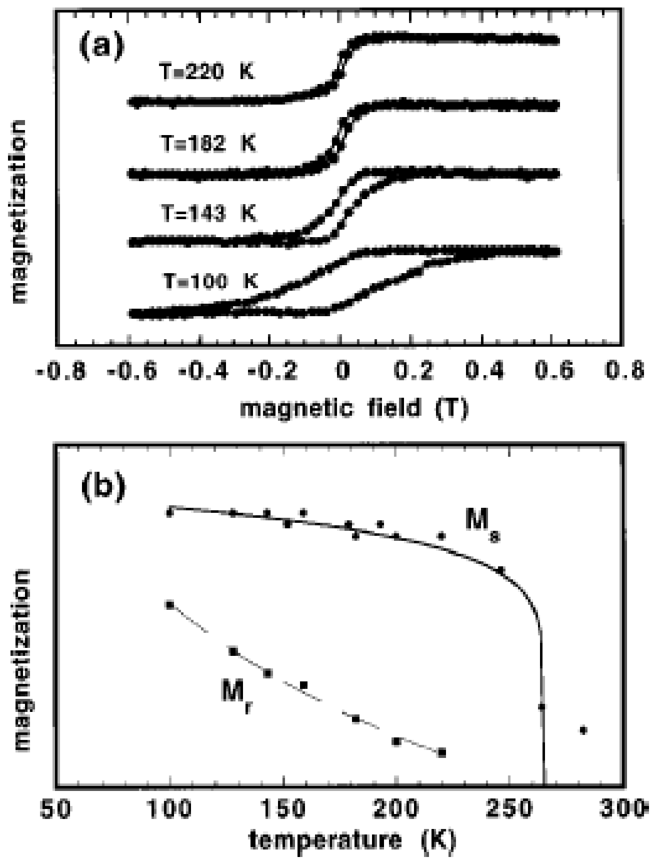


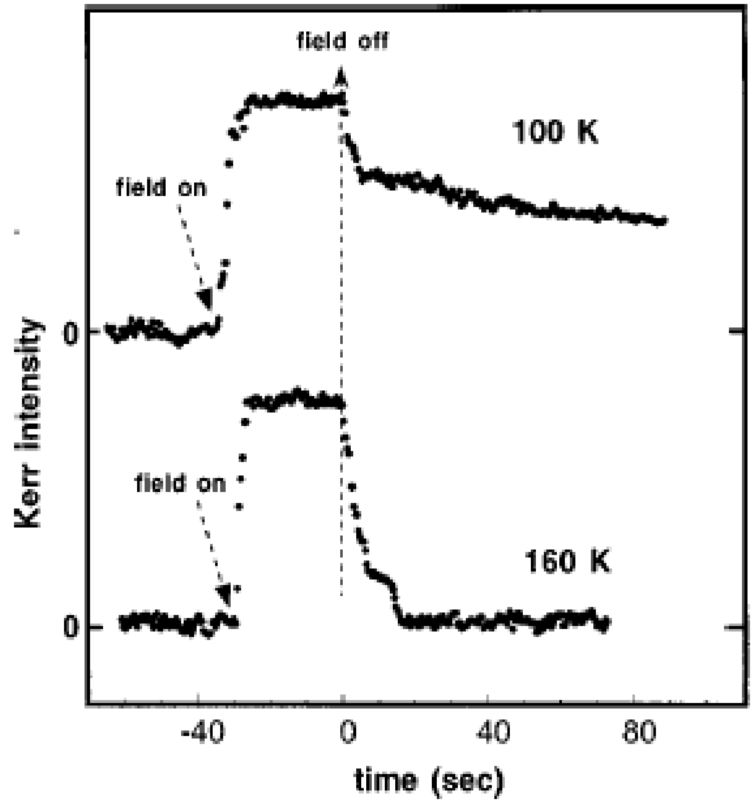
M=0 for H=0 independent of temperature.

Experimental realisation by step edge decoration of Cu(111) steps with Co.

Co shows magnetization perpendicular to the plane due to surface anisotropy.

Glauber dynamic



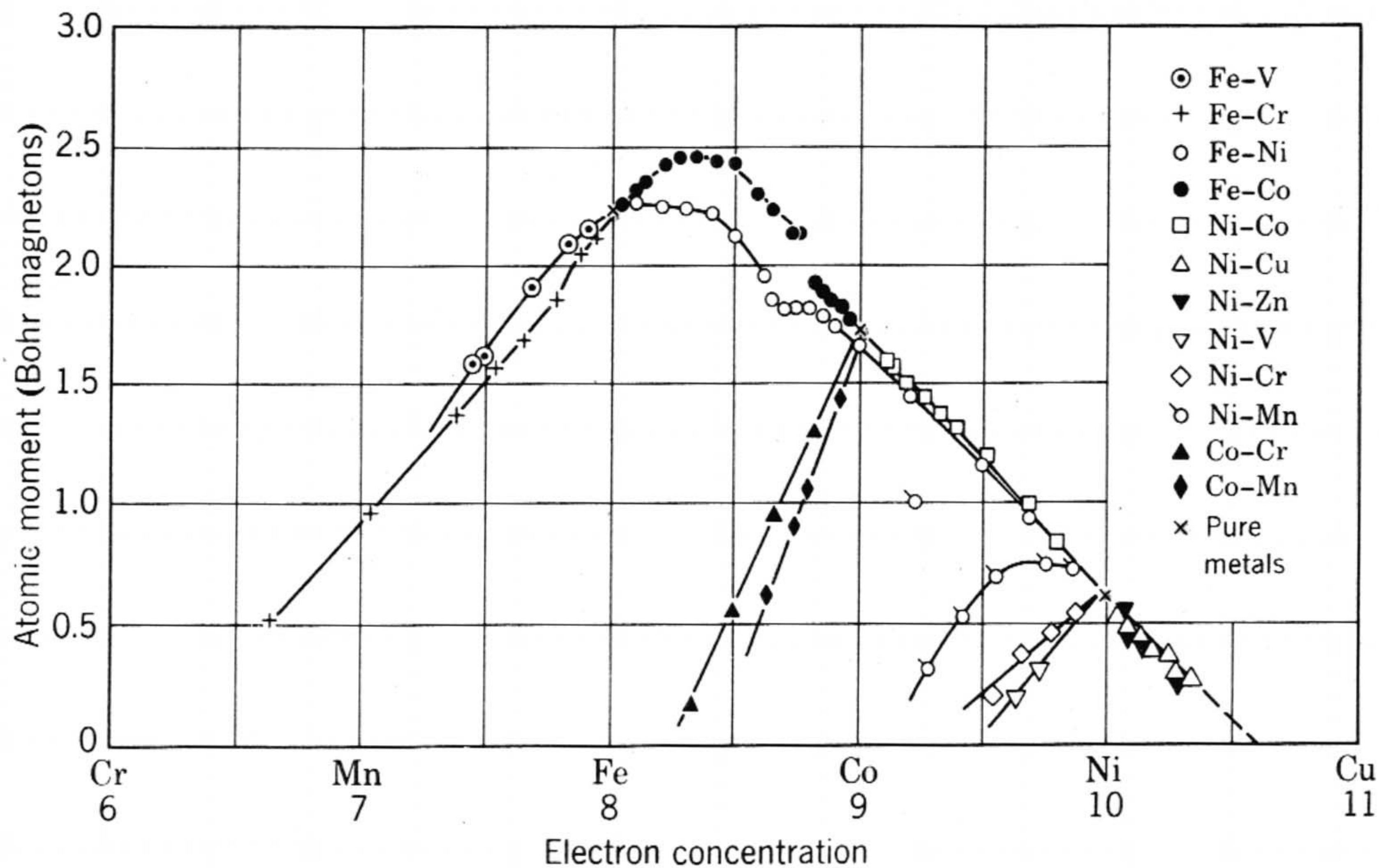


Experiment shows remanence in the MOKE loop.
Magnetization is only metastable.

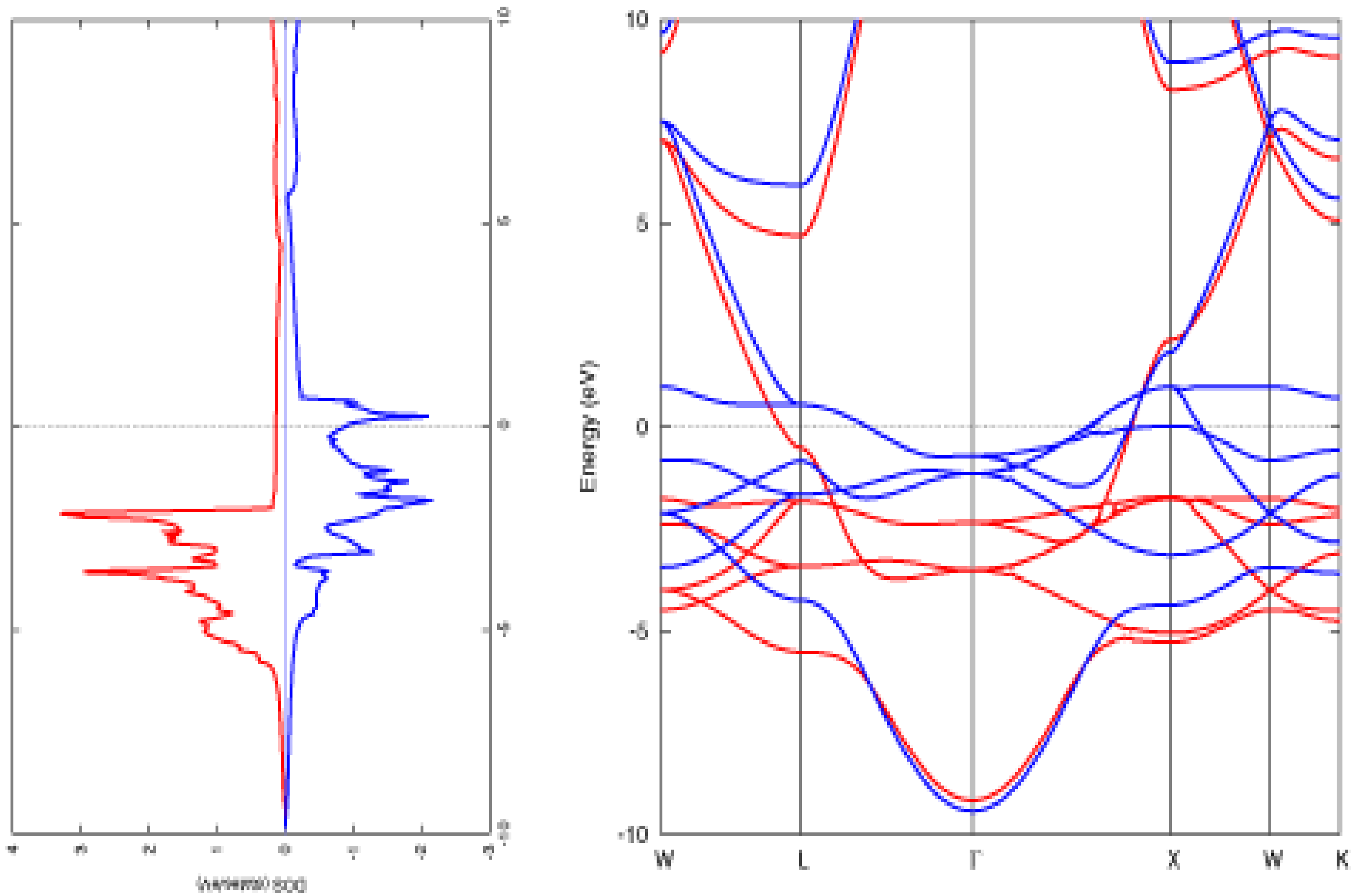
J.Shen Phys. Rev. B (1997)

Chapters of spin excitation

Slater-Pauling curve

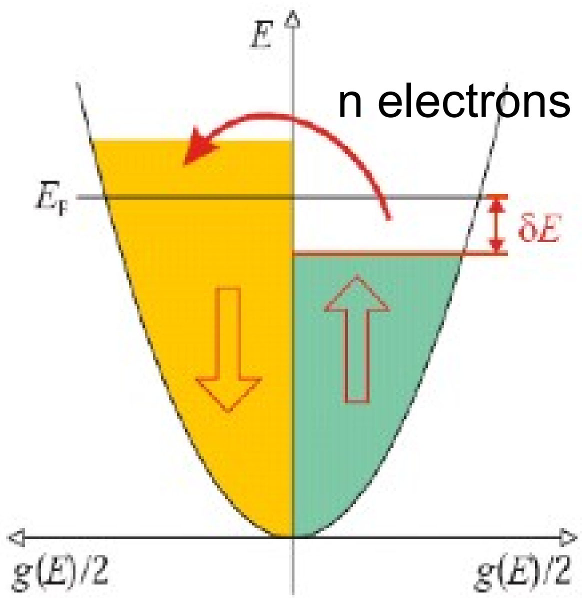


Band structure of fcc Ni



Electrons are delocalized and form electron bands. In itinerant ferromagnets, bands are spin split and thus electron occupation for spin up and spin down differ.
Difference can be a non integer number resulting in irrational spin moments per atom.

Stoner criterion



Cost due to kinetic energy:

$$E_{kin} = \delta E\, n > 0 \qquad n = \frac{g(E_F)}{2} \delta E$$

$$\rightarrow E_{kin} = \frac{g(E_F)}{2} (\delta E)^2$$

Magnetization:

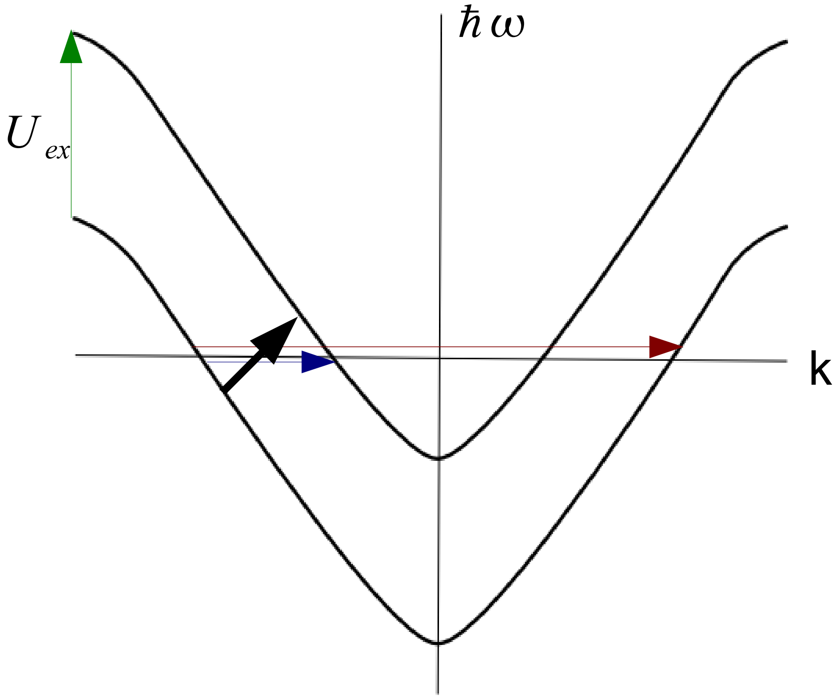
$$M = \mu_B (n_{down} - n_{up}) = 2 \mu_B n = \mu_B g(E_F) \delta E$$

Potential energy :

$$dF = -M\, dB = -\mu_0 M\, dM \qquad E_{pot} = -\frac{1}{2} U_{ex} (g(E_F) \delta E)^2$$

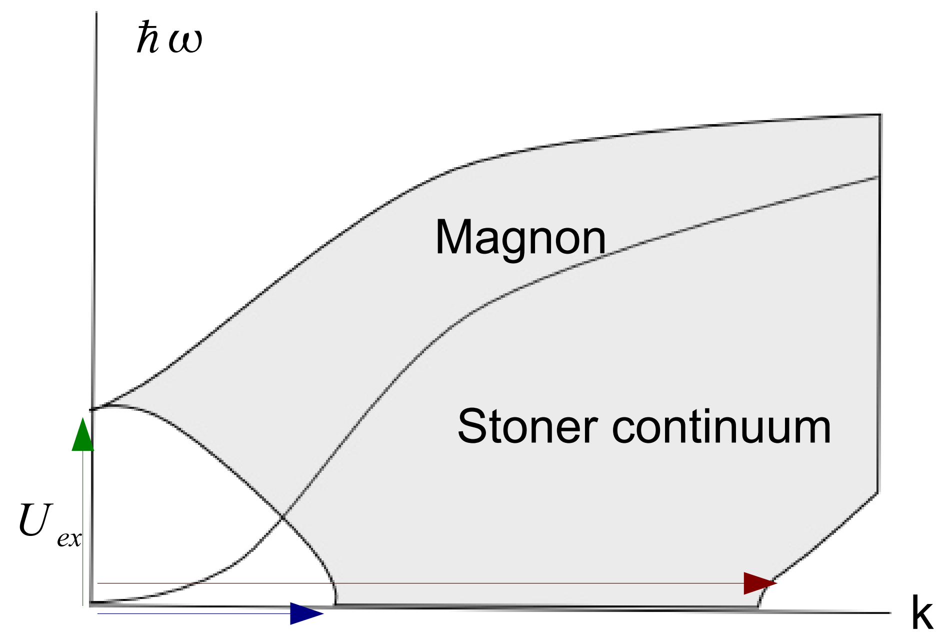
Spontaneous magnetization develops for : $U_{ex}\, g(E_F) > 1$

Stoner excitations and magnon life times



Excitation of an majority electrons below to a minority electron above the Fermi edge.

Excitation has spin 1, a wave vector and an energy, just like a magnon but forms a continuum.



Magnons and Stoner excitations can couple where they overlap leading to magnon decay into Stoner excitations and thus to short magnon life times (damping).

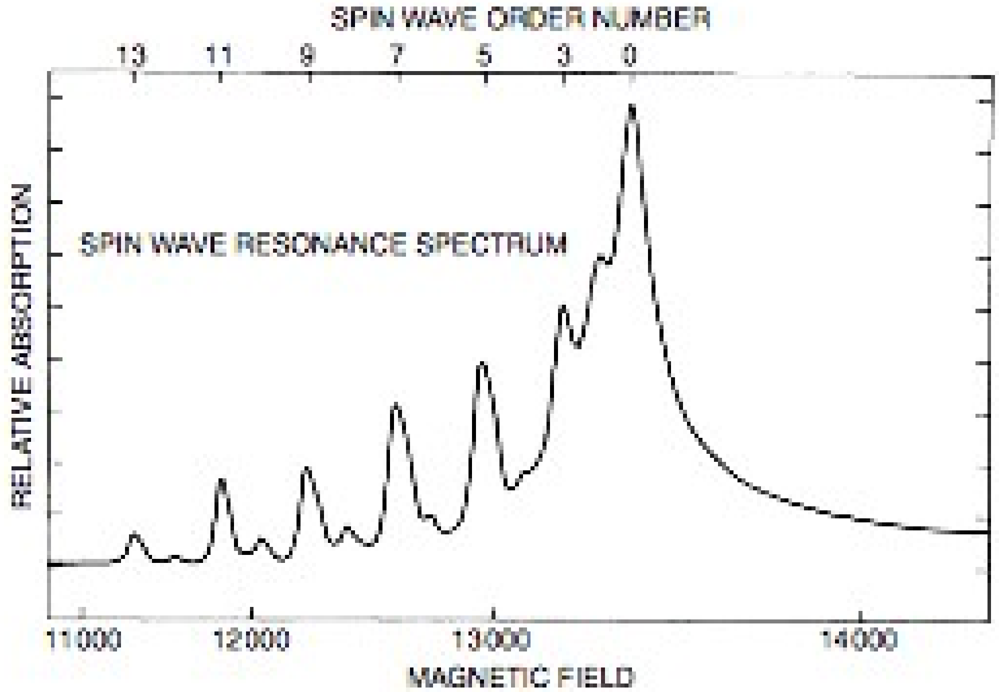
Chapters of spin excitation

Ferromagnetic resonance (FMR)

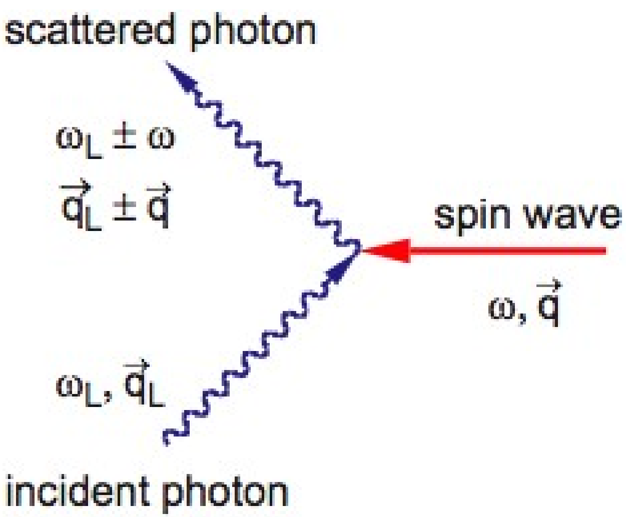
Microwave absorption in a magnetic filed

Often a constant frequency is used and the Larmor frequency is tuned into resonance by changing the applied field.

Photon wavevector q=0, thus FMR detects mainly coherent precession modes.



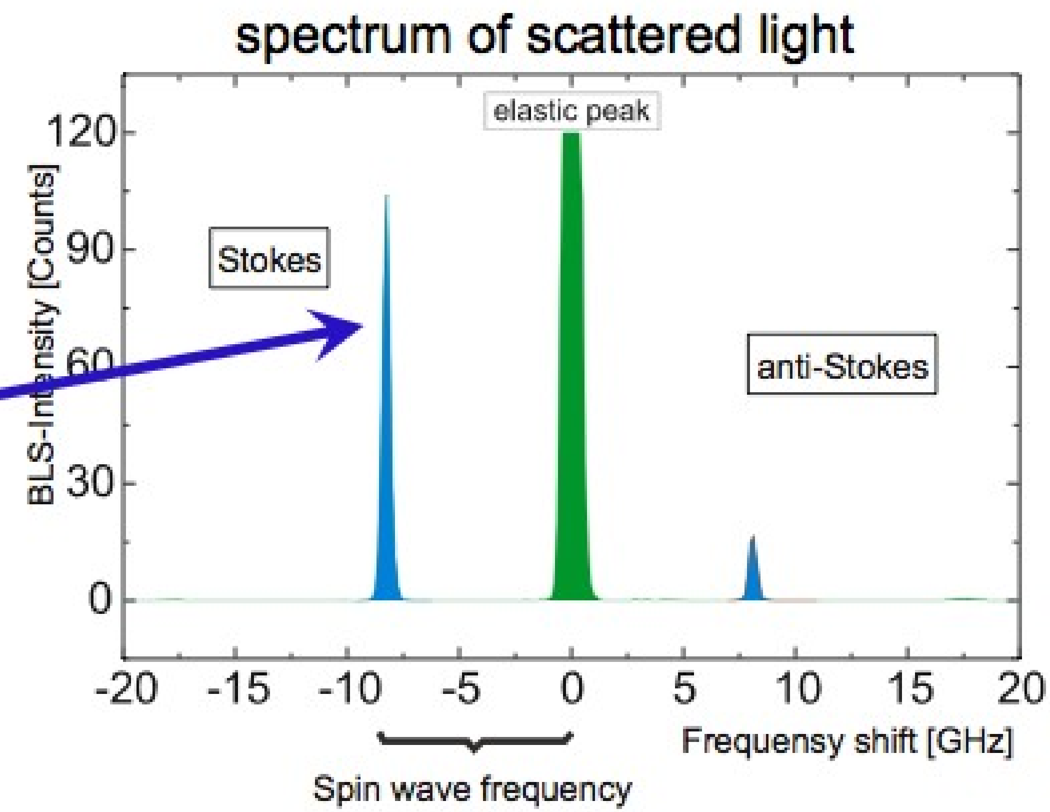
Brillouin light scattering (BLS)



$$\vec{q}_{SC} = \vec{q}_L \pm \vec{q}$$

$$\omega_{sc} = \omega_L \pm \omega$$

Only q near the zone center accessible



proportional to the spin wave intensity $|\varphi|^2$

Brillouin light scattering (BLS)

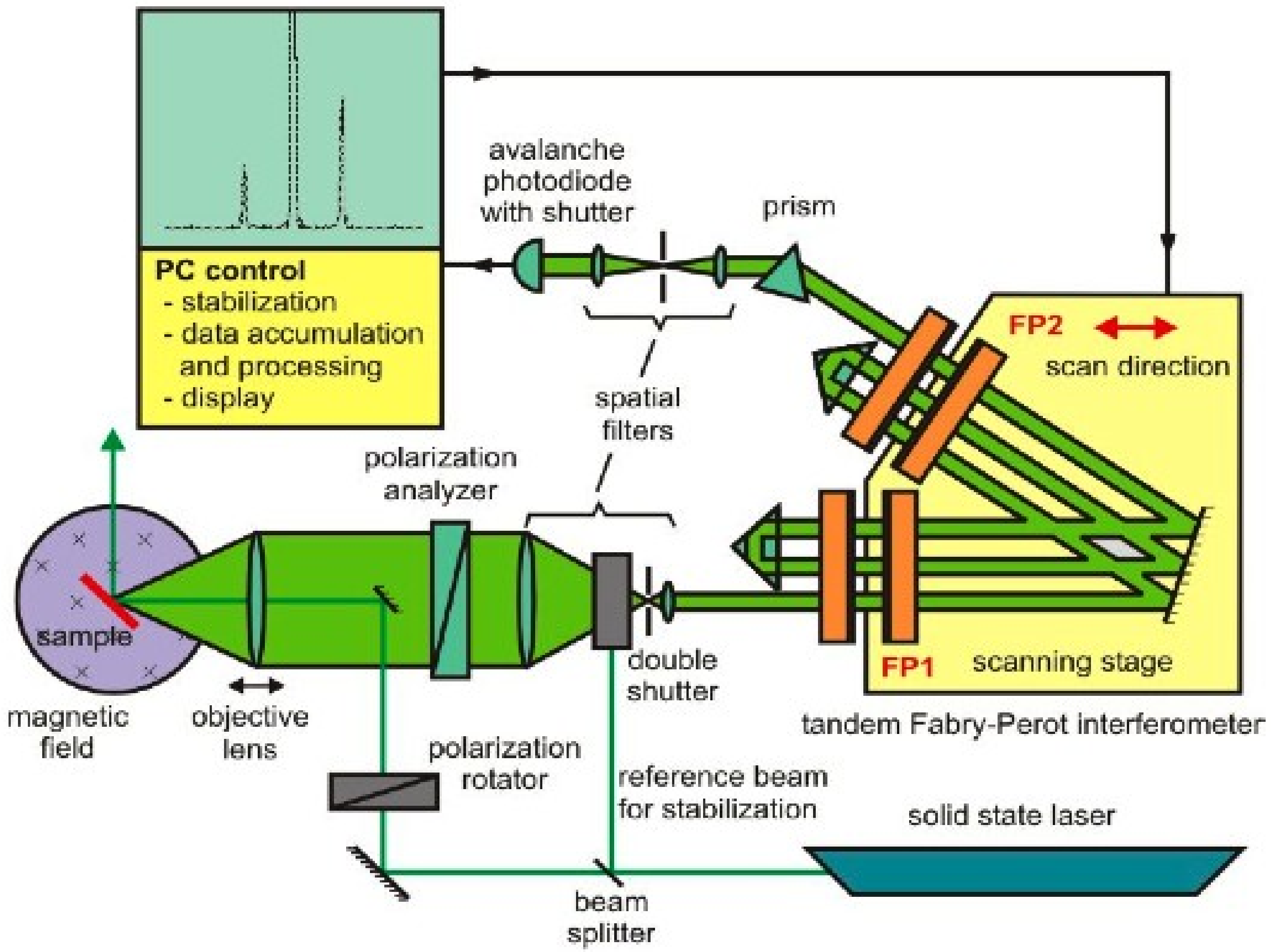
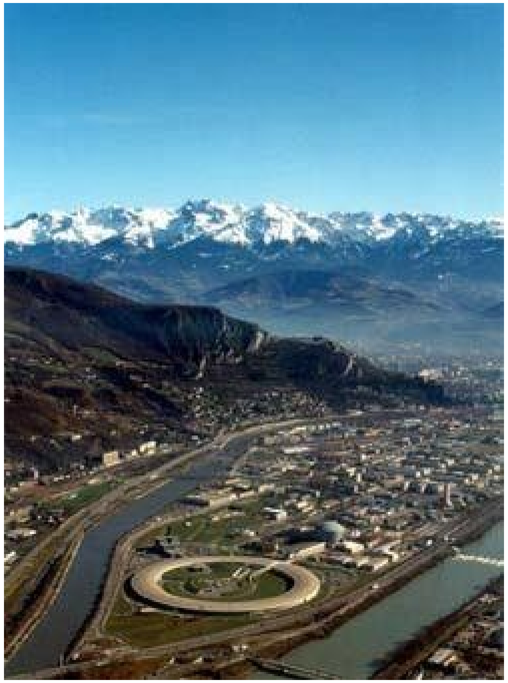


Figure: B. Hillebrands

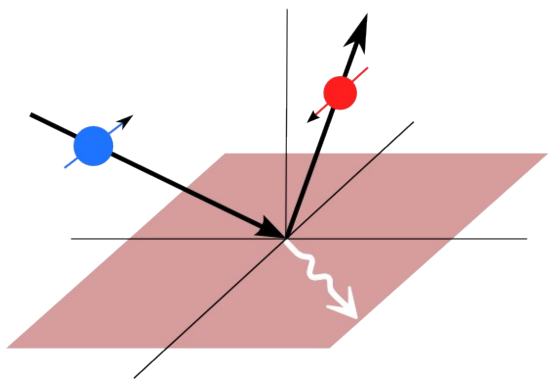
Neutron Scattering

European neutron source in Grenoble



Spallation neutron source in Oakridge, USA

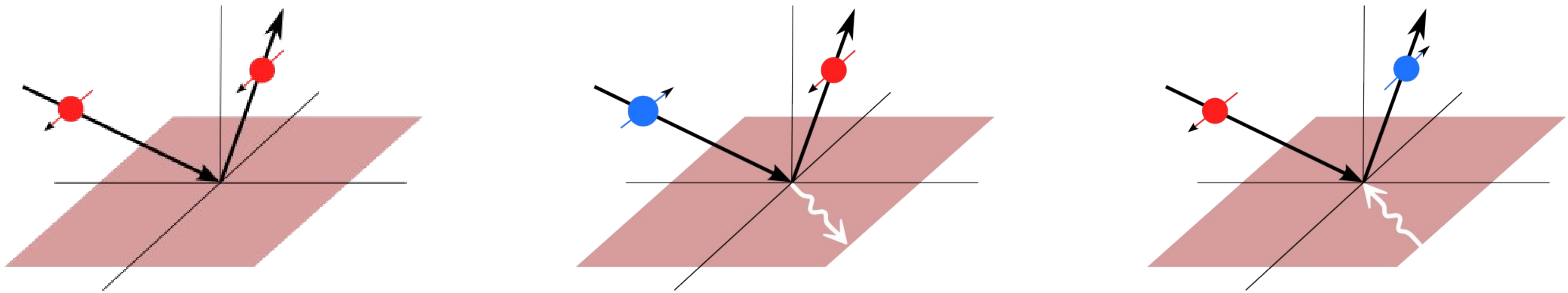
Inelastic neutron Scattering



Inelastic (spin-flip) scattering of the neutron

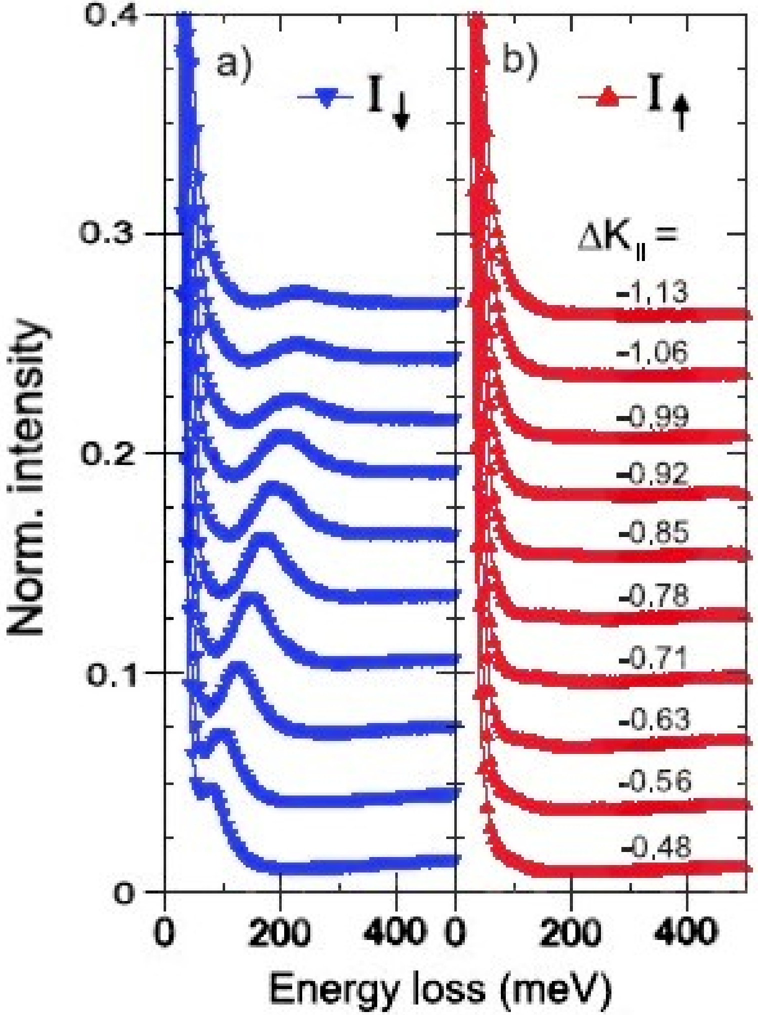
Access to full BZ but difficult near specular reflection (q=0).
High energy resolution better than 1 meV possible.
Only bulk samples due to weak interaction of neutrons with matter.

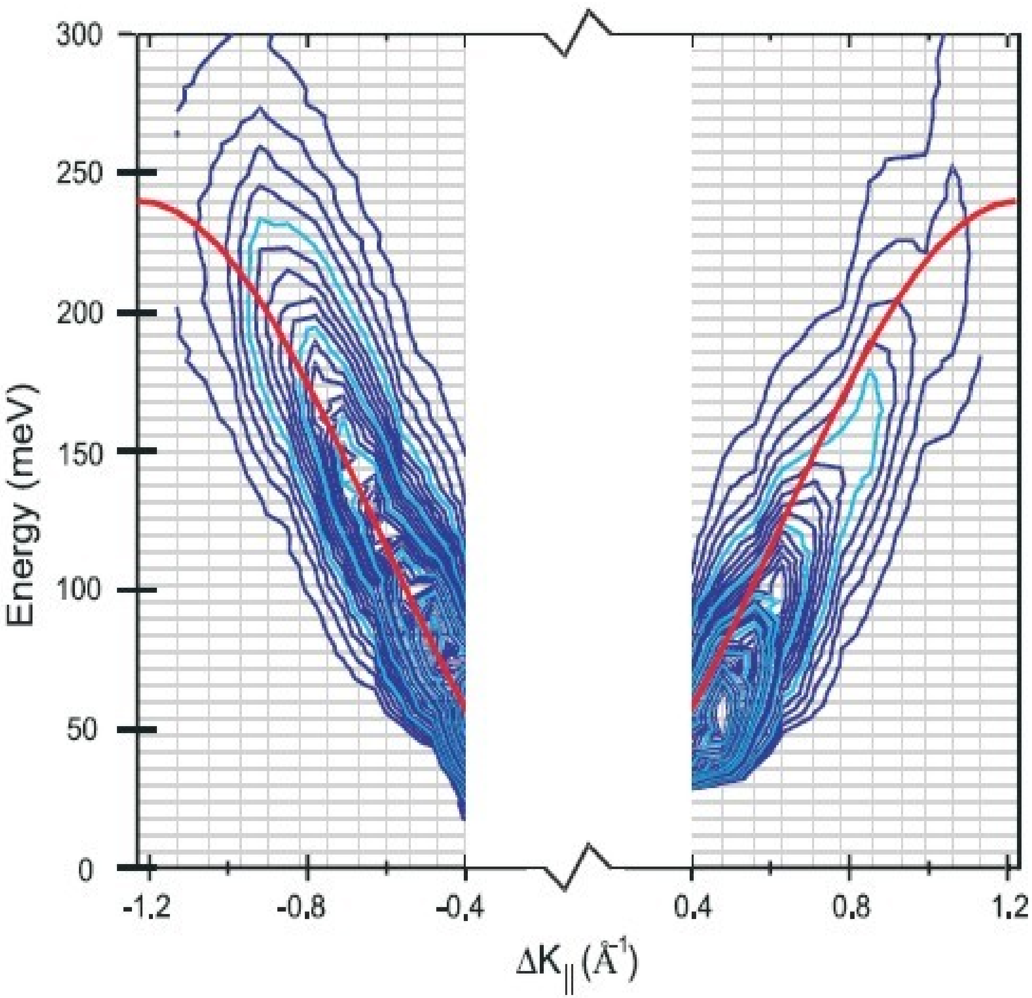
Spin-polarized Electron Energy Loss Spectroscopy (Sp-EELS)



- Spin moment is transferred in the scattering process only by minority electrons.
- Δq and ΔE of the scattered electron give q and E of the magnon.
- Full access to the BZ but only at energies above a few 10 meV.

Sp-EELS of 8 ML fcc Co on Cu(100)





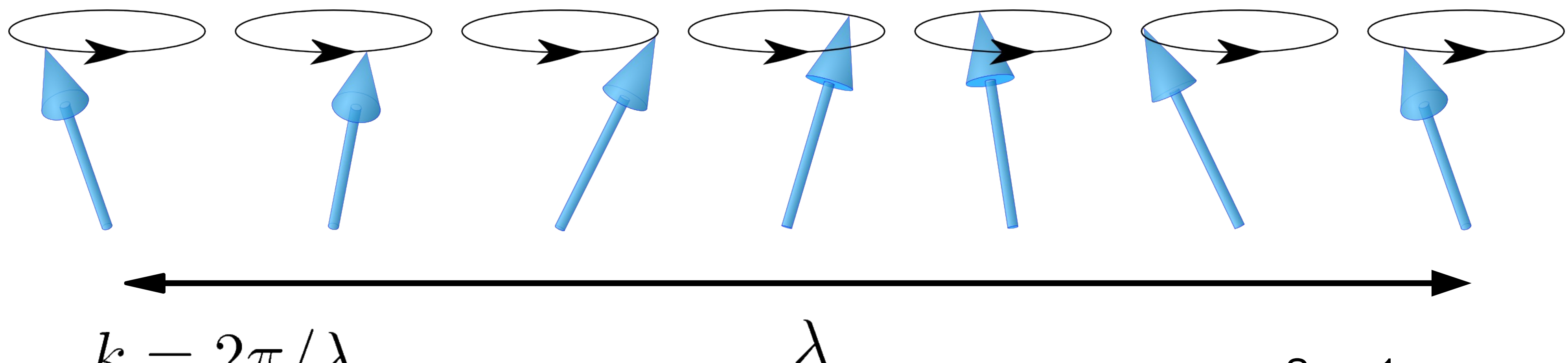
M. Etzkorn, PhD thesis Universität Halle 2005

Chapters of spin excitation

1. Why are excitations of any importance?
2. Excitations of ferromagnets in the Heisenberg model
3. Excitations of antiferromagnets in the Heisenberg model
4. Spin waves in bulk, thin films and stripes
5. Itinerant magnetism
6. Experimental techniques to study excitations

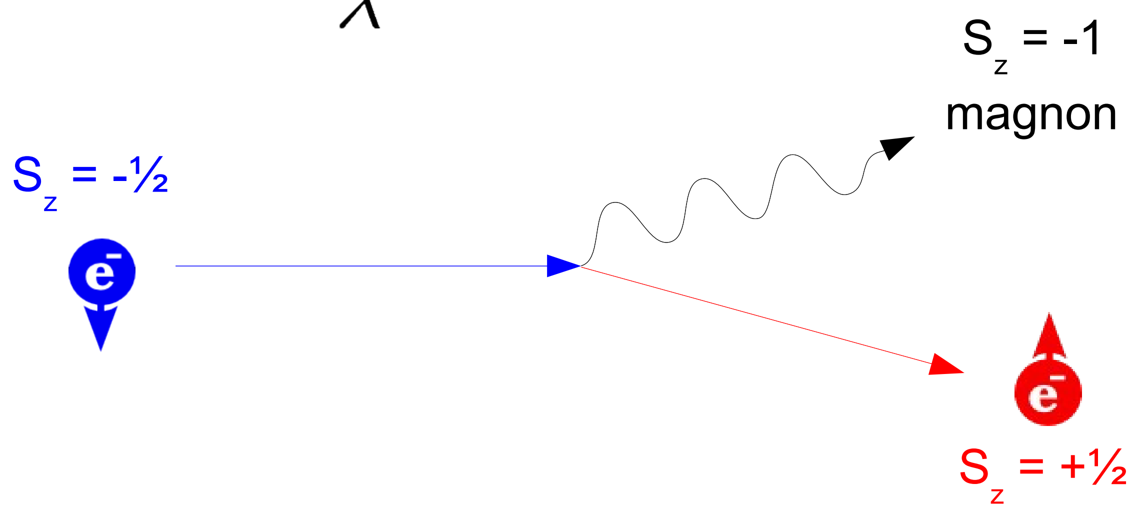
questions

Excitations of a ferromagnet

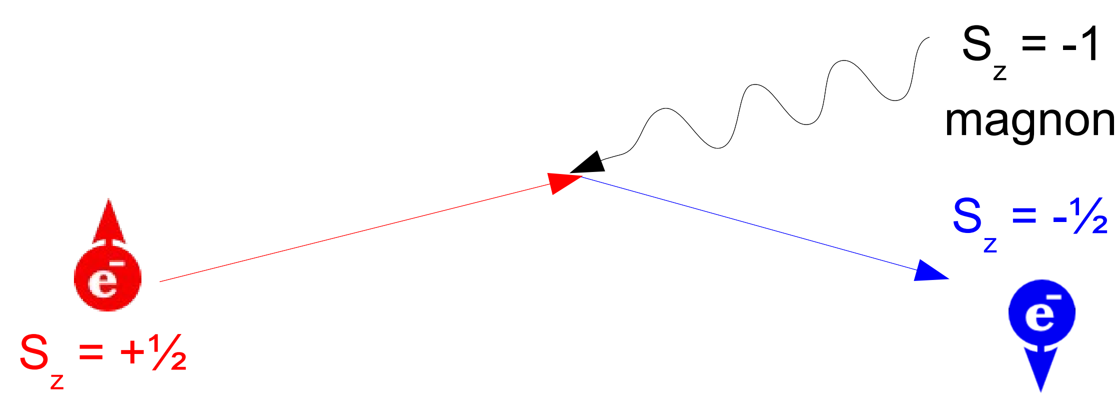


$$k = 2\pi/\lambda$$

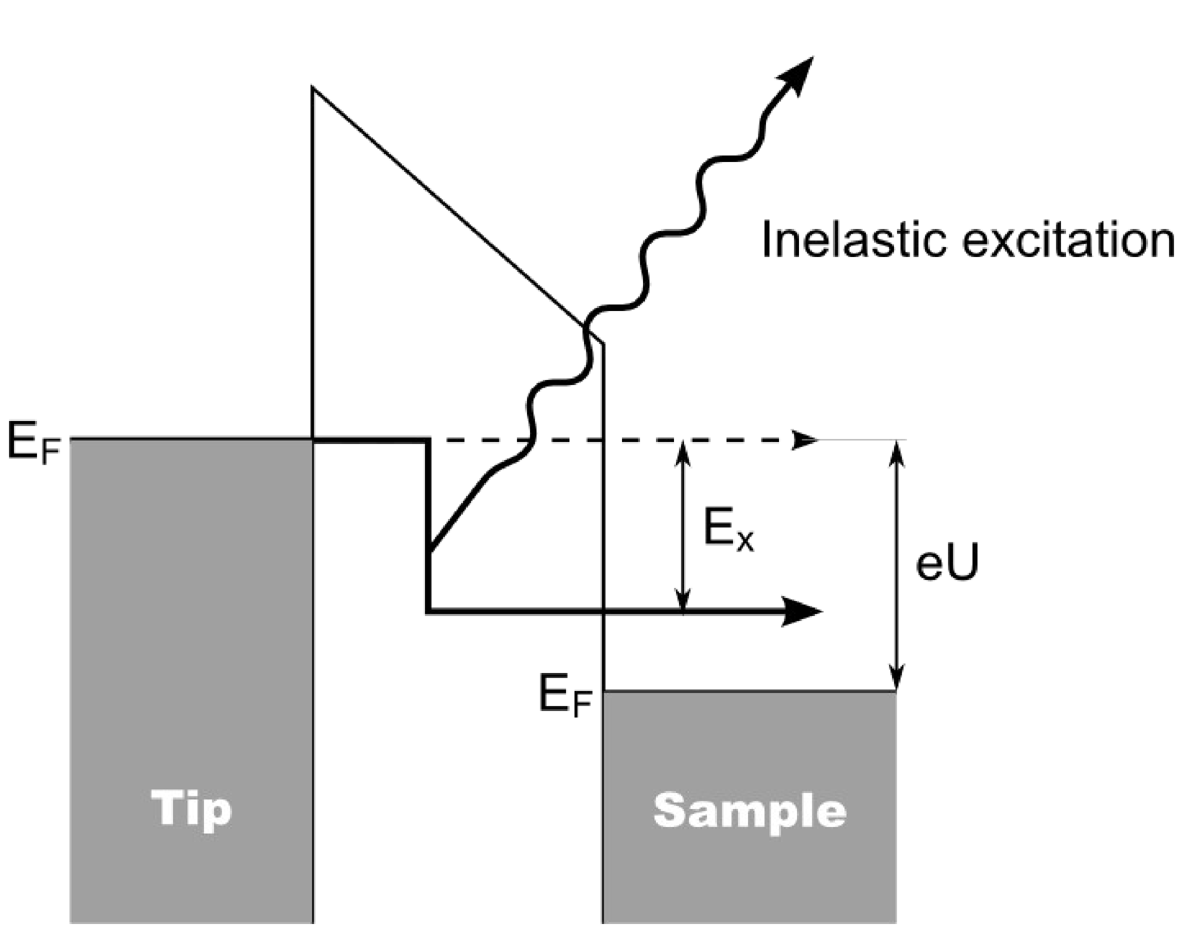
Magnon creation

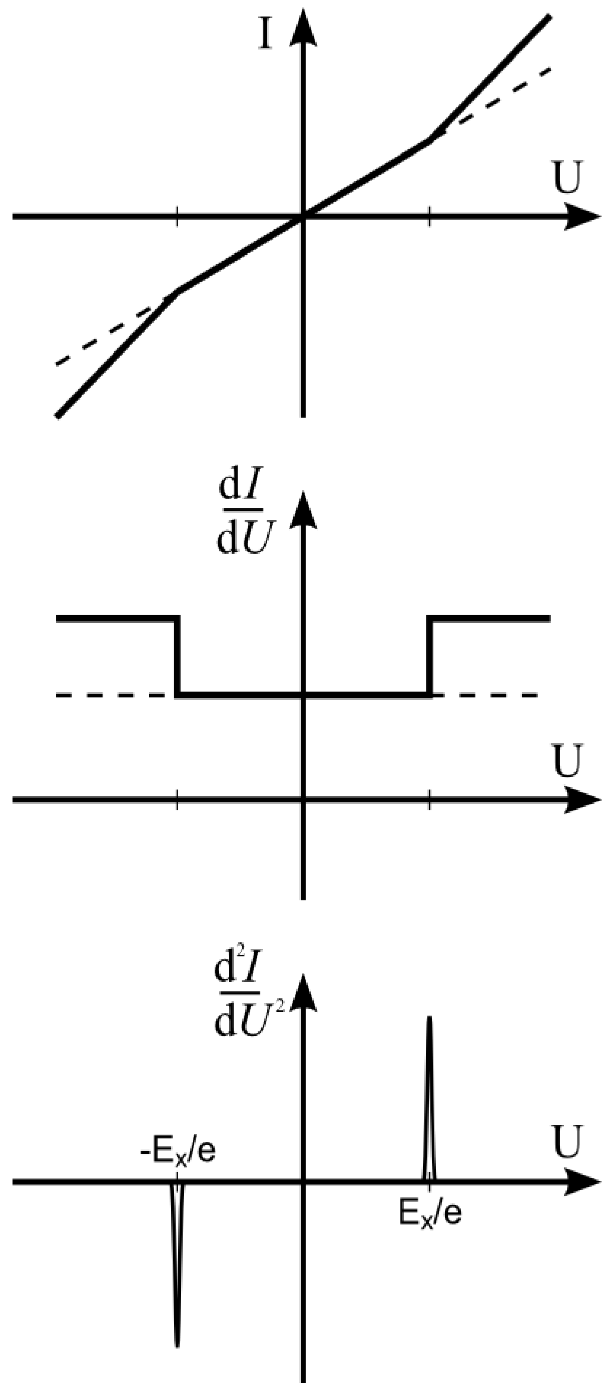


Magnon annihilation



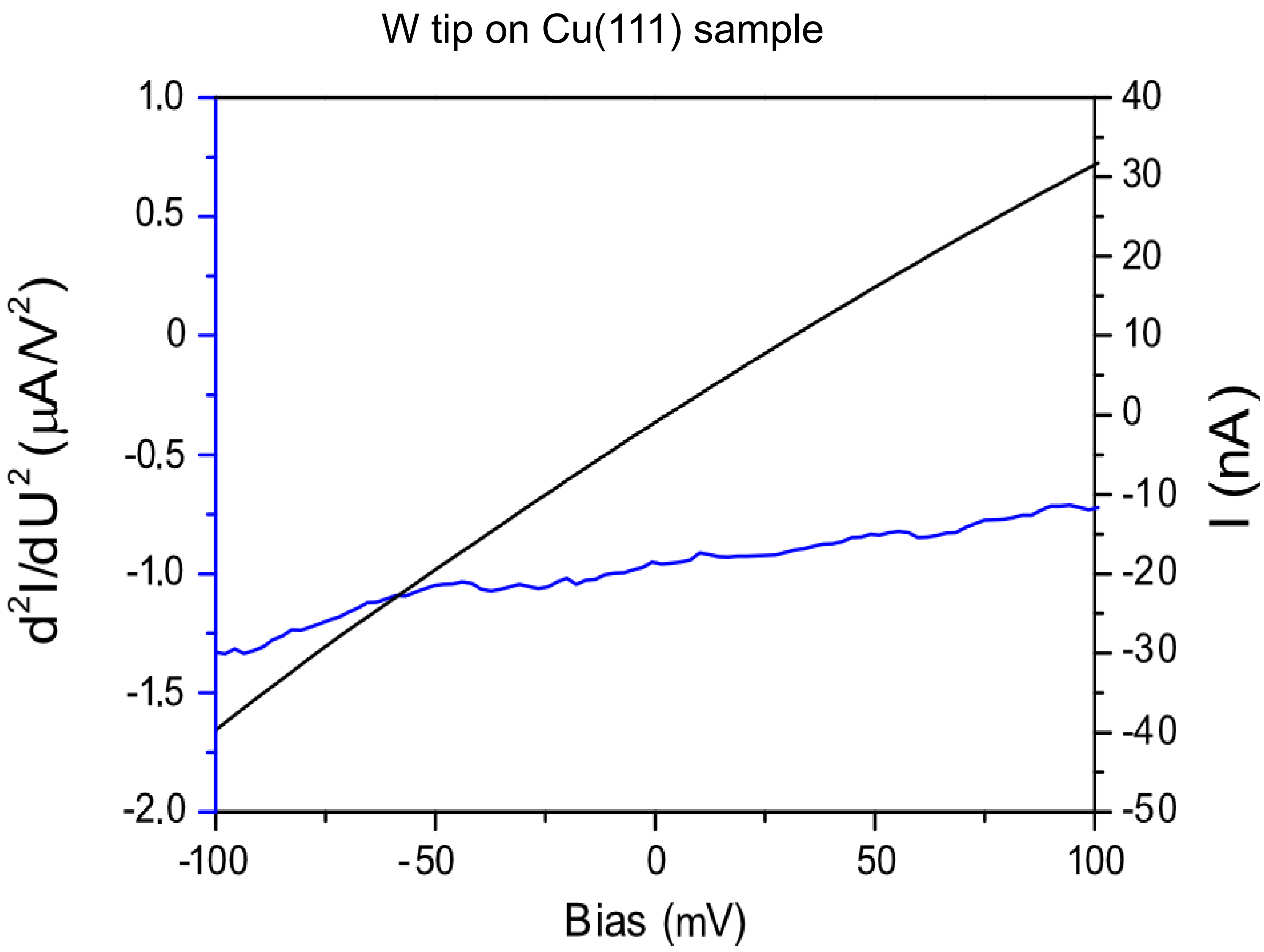
Inelastic tunneling spectroscopy





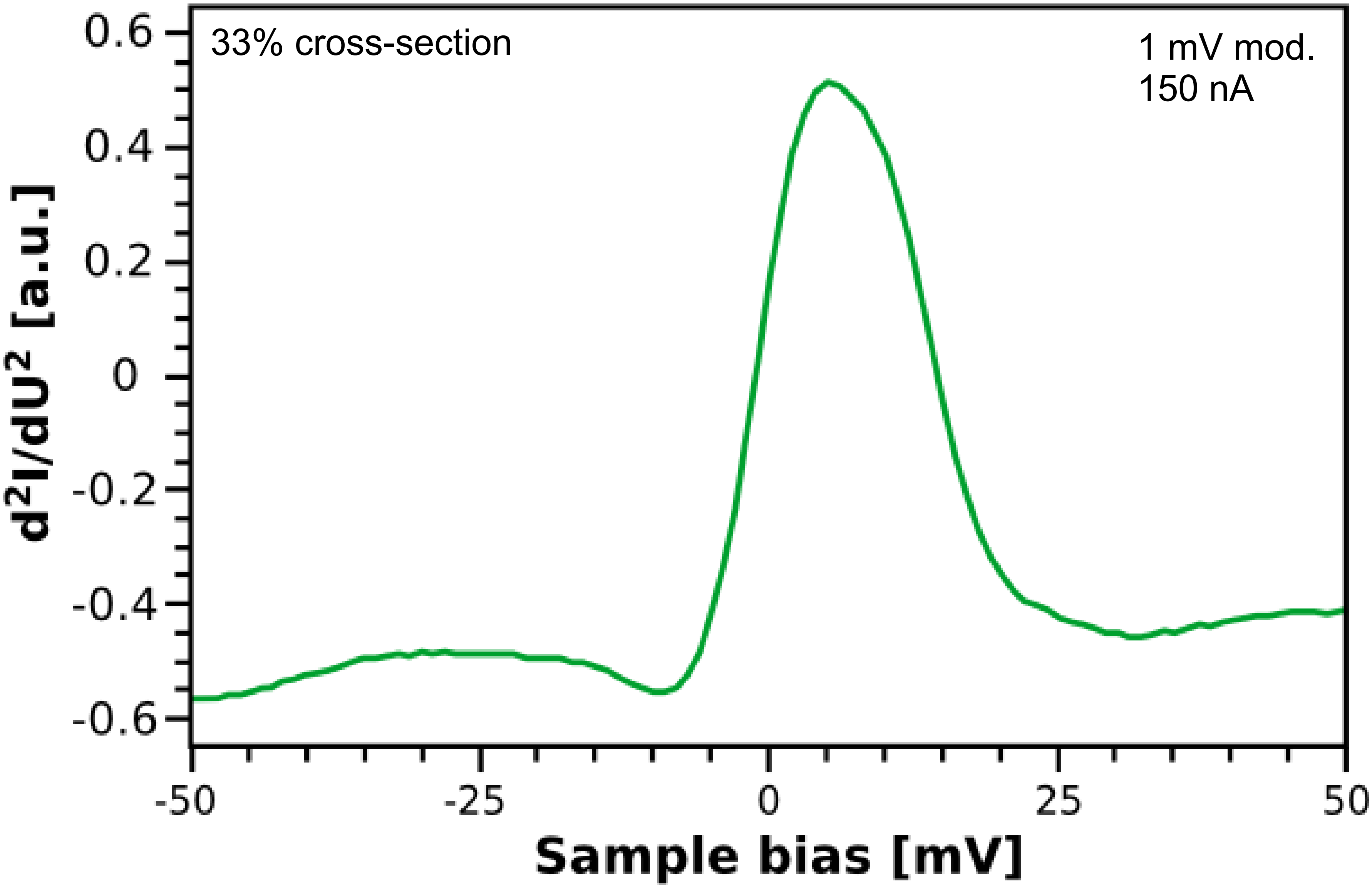
- Inelastic tunneling processes increase the number of final states above a threshold.
- d^2I/dU^2 is proportional to density of excitations if elastic DOS is constant.

Inelastic tunnelling spectroscopy on paramagnets at 4K



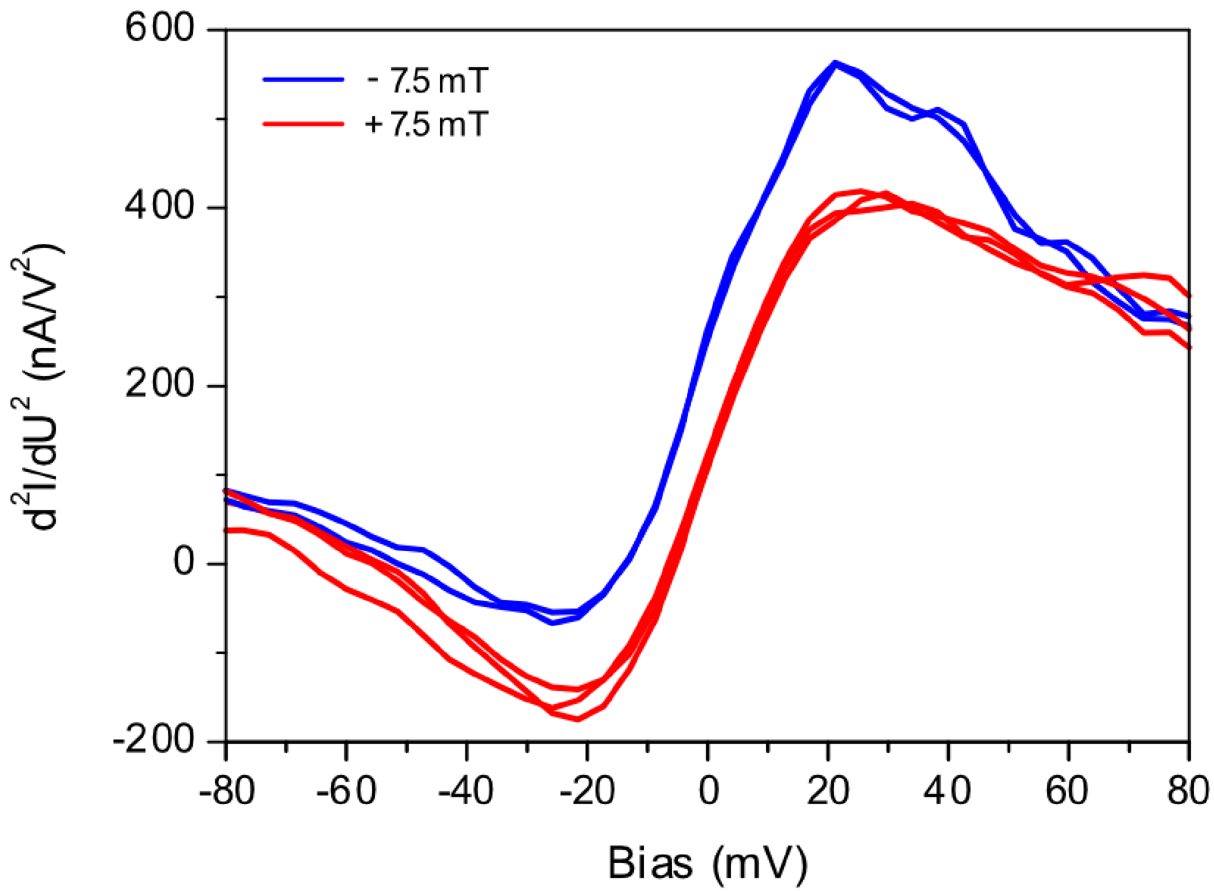
Clear spectrum, no features in DOS, no inelastic excitation channels

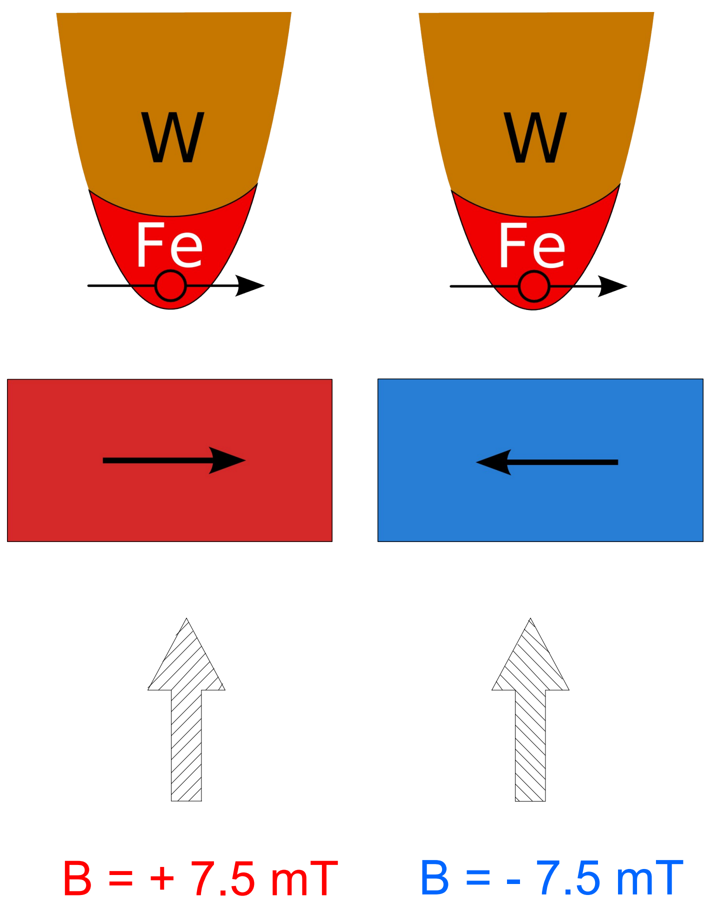
ITS on Fe(100) with W tip at 4K



Selection rules for magnon creation

Fe coated W tip on Fe(001) sample



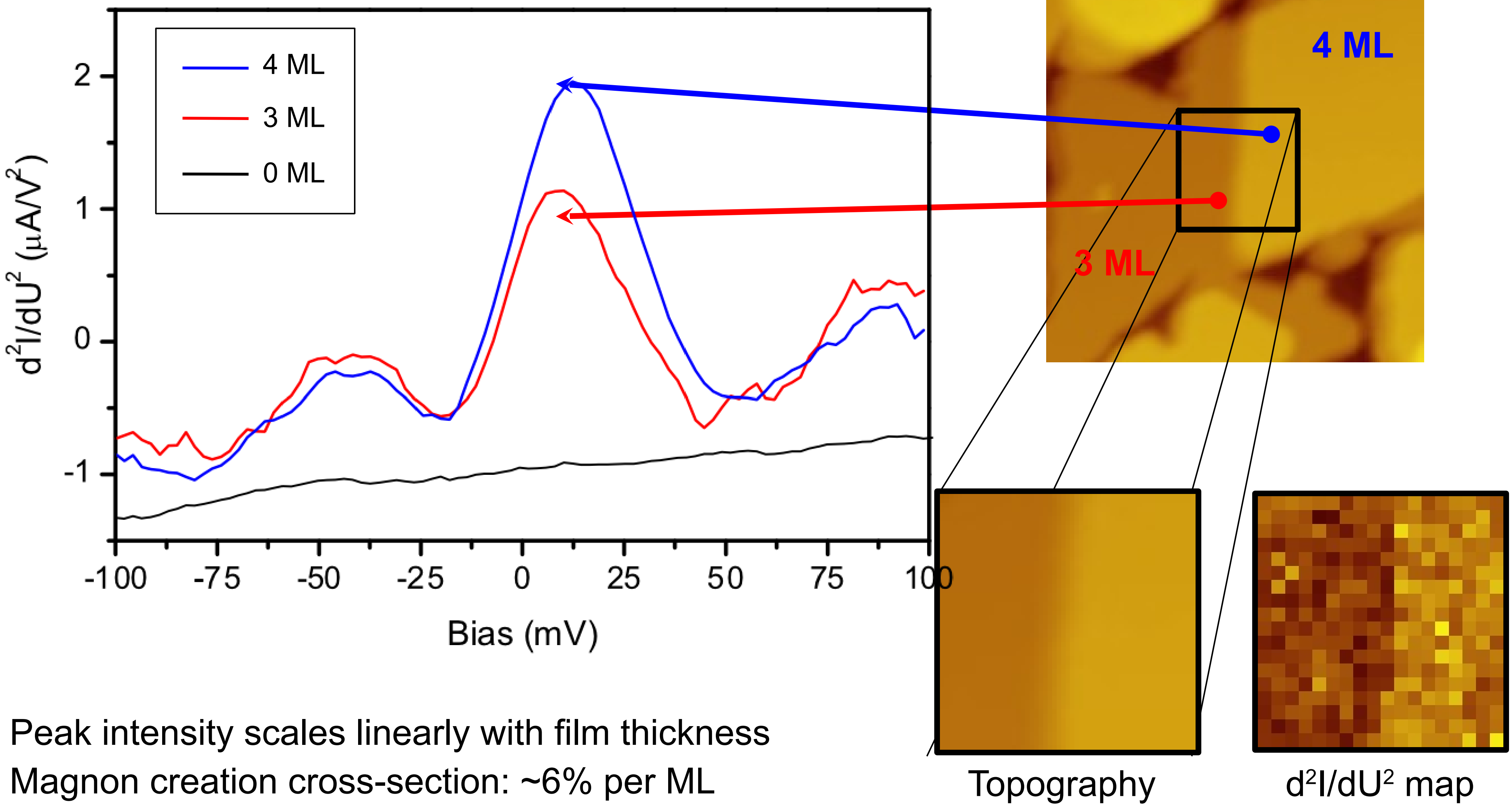


- Excitation depends on direction of magnetic field
- Prove of magnons and exclusion of phonons

Balashovet al., PRL 97, 182201 (2006)

Local excitation of magnons: Co/Cu(111)

R = 2.05/2.85 = 0.72 ≈ ¾

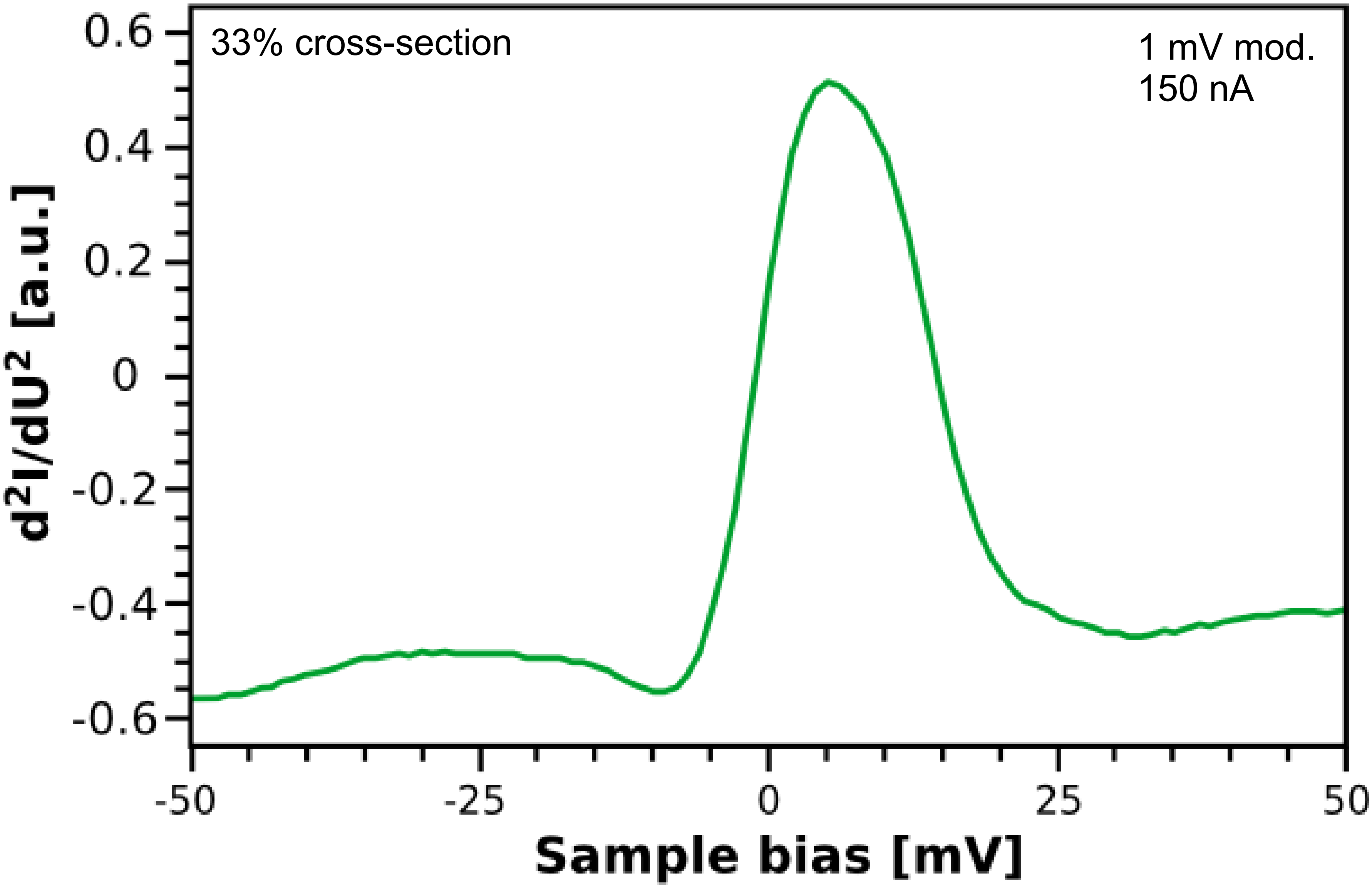


- Peak intensity scales linearly with film thickness
- Magnon creation cross-section: ~6% per ML

Mean free path λ ≈ 3 nm

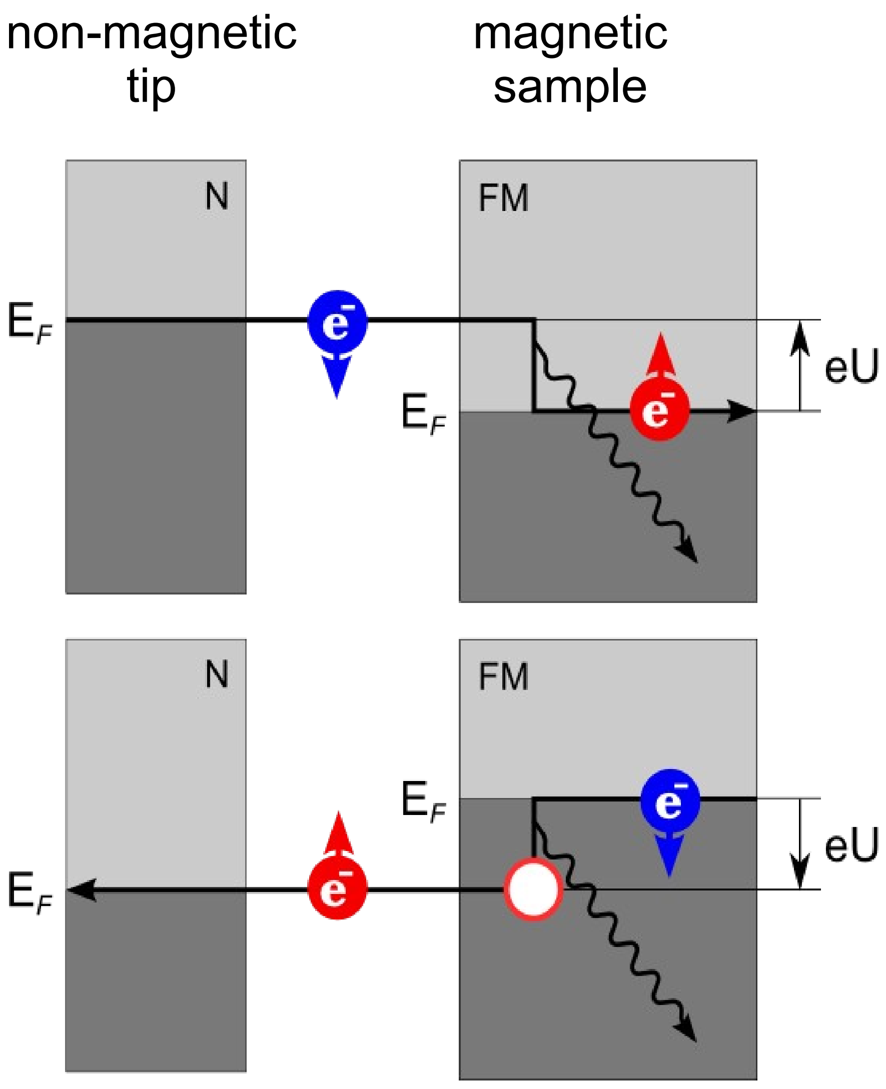
Balashovet al., PRL 97, 182201 (2006)

ITS on Fe(100) with W tip at 4K



Why does the magnon creation depend on the tunneling direction?

Selection rules for magnon creation in tunneling experiments



Magnon creation occurs in the minority channel for positive bias

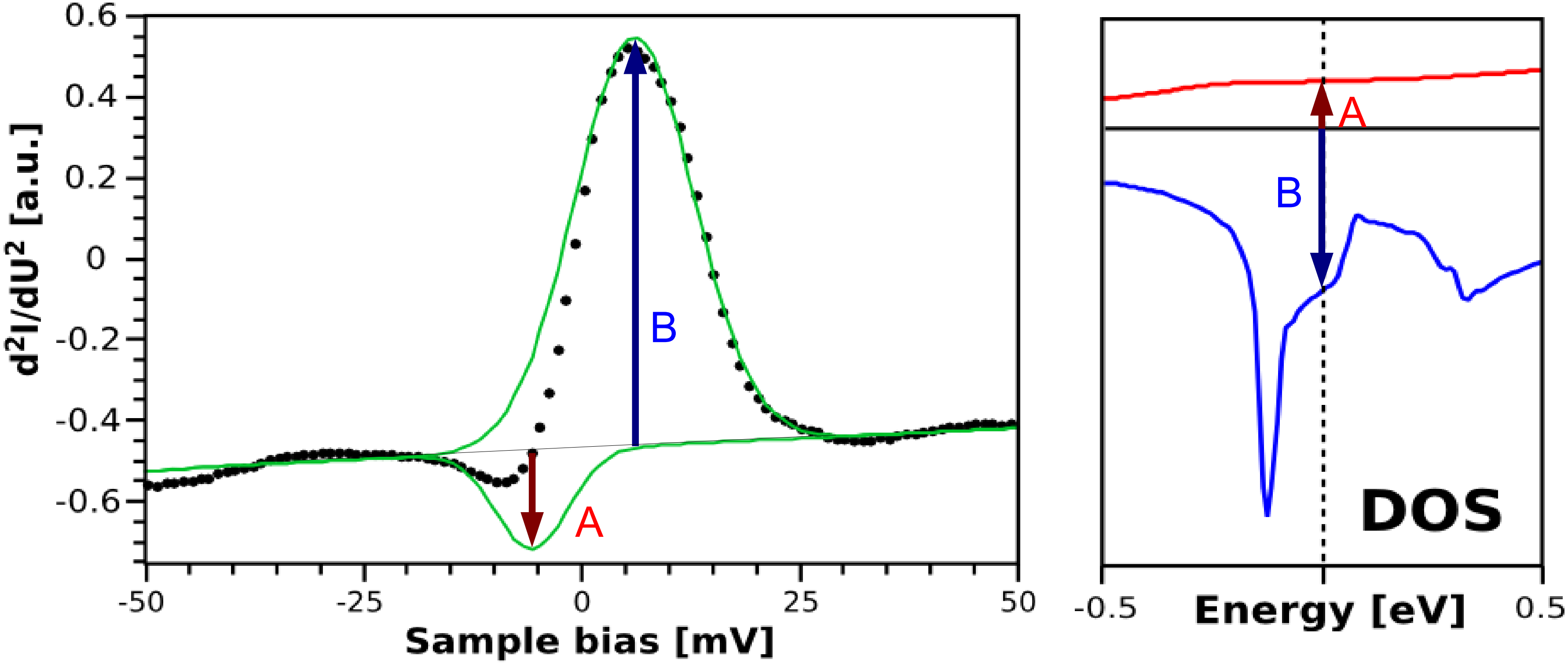
Shows up as peak

Magnon creation occurs in the majority channel for negative bias

Shows up as dip

Forward-backward asymmetry of magnon creation

Fe(100)



$$P = \frac{A - B}{A + B}$$

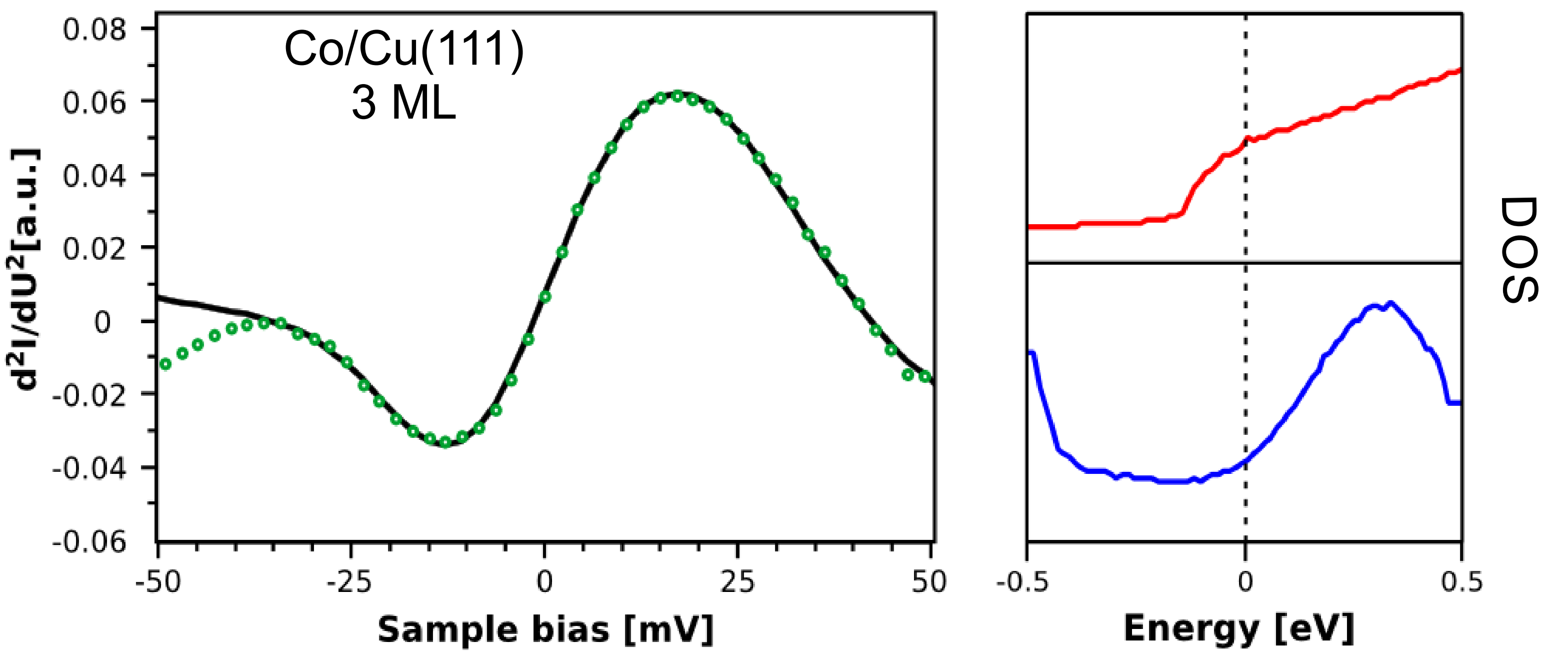
-61±3%

-54%

Forward-backward asymmetry of magnon creation

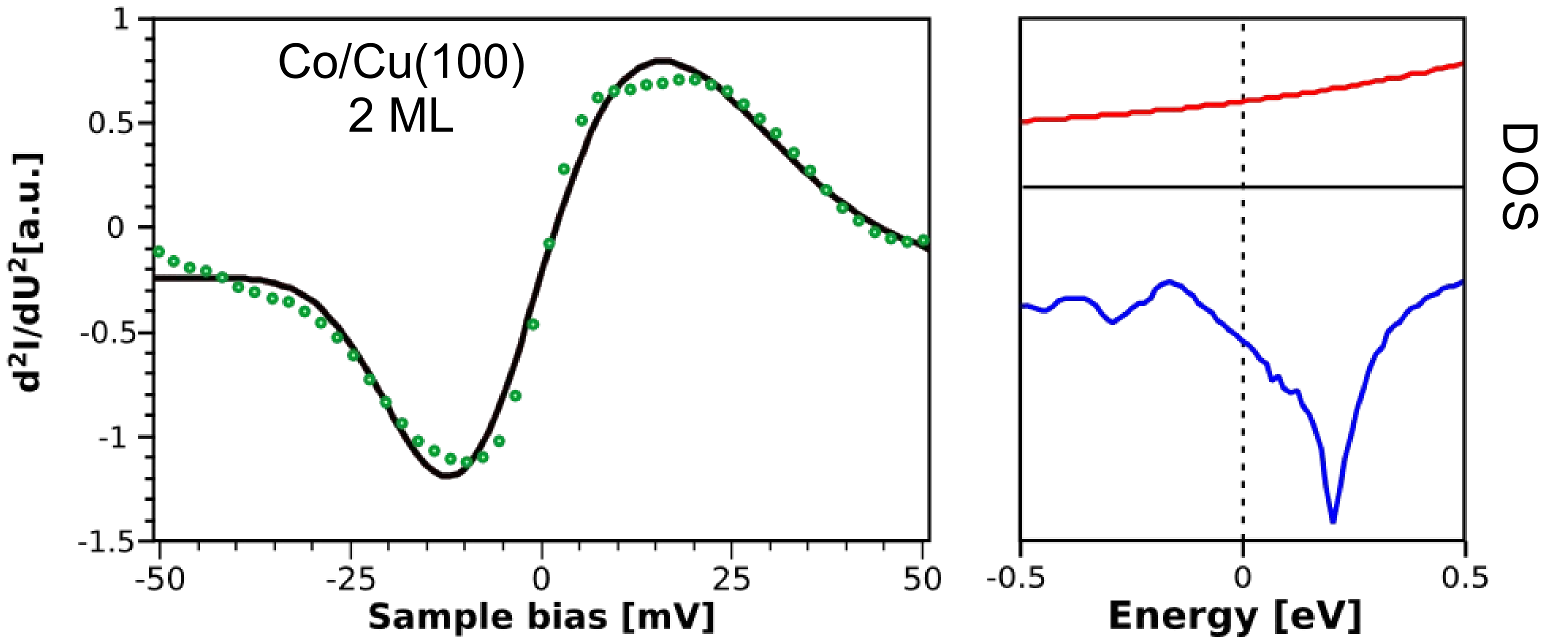
P_{exp} = -28±4%

P_{theor} = -26%

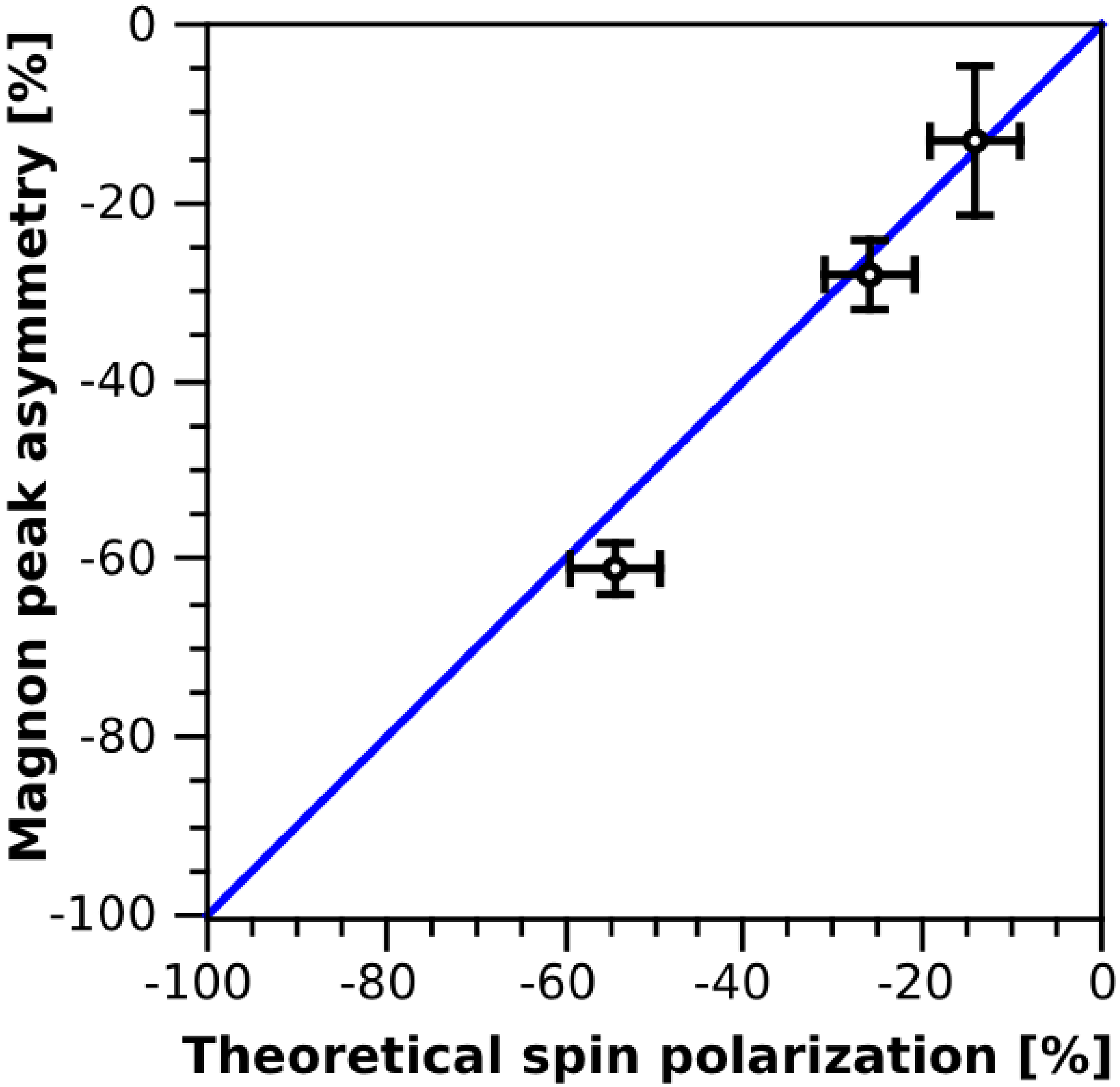


P_{exp} = -13±8%

P_{theor} = -14%

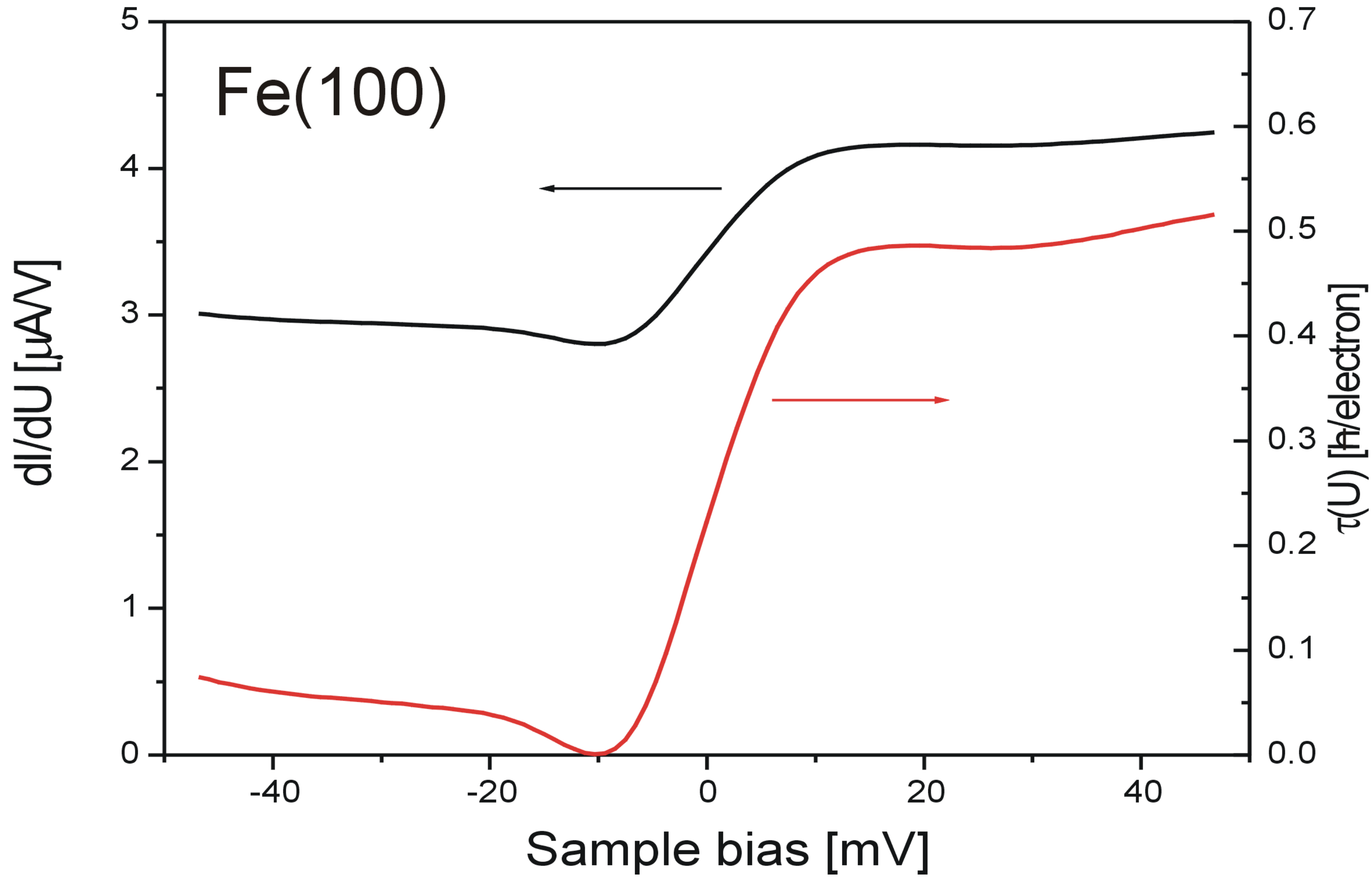


Spin polarization and the spin torque



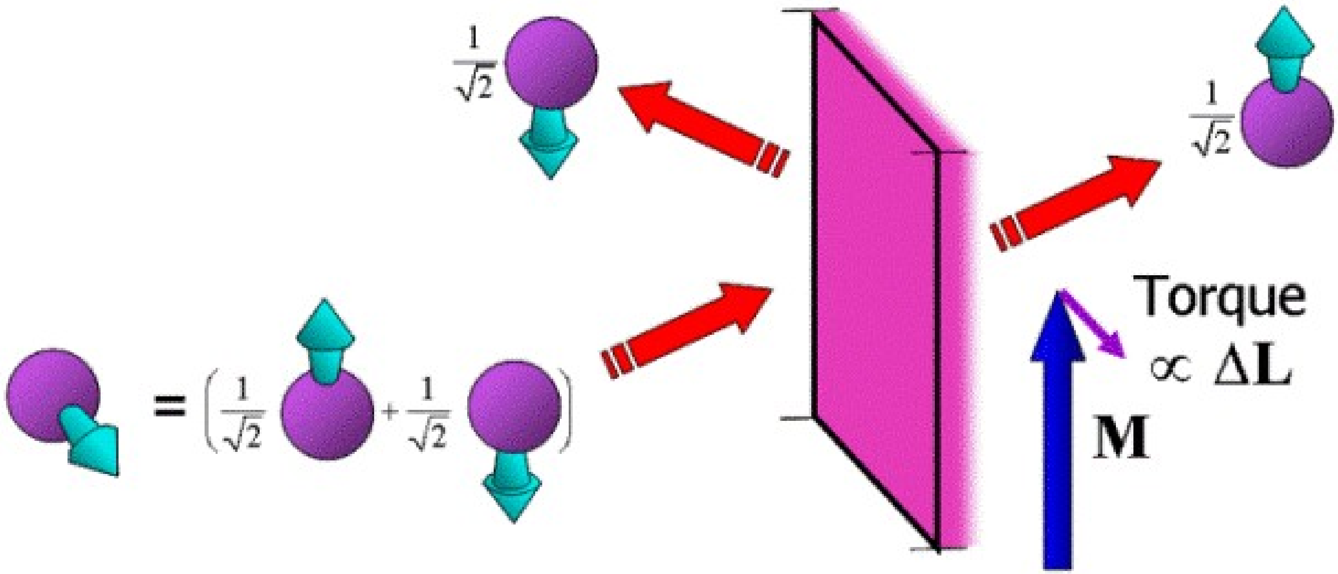
Spin transfer due to magnon creation is proportional to the polarization of the tunneling current.

Quantum efficiency of the spin torque

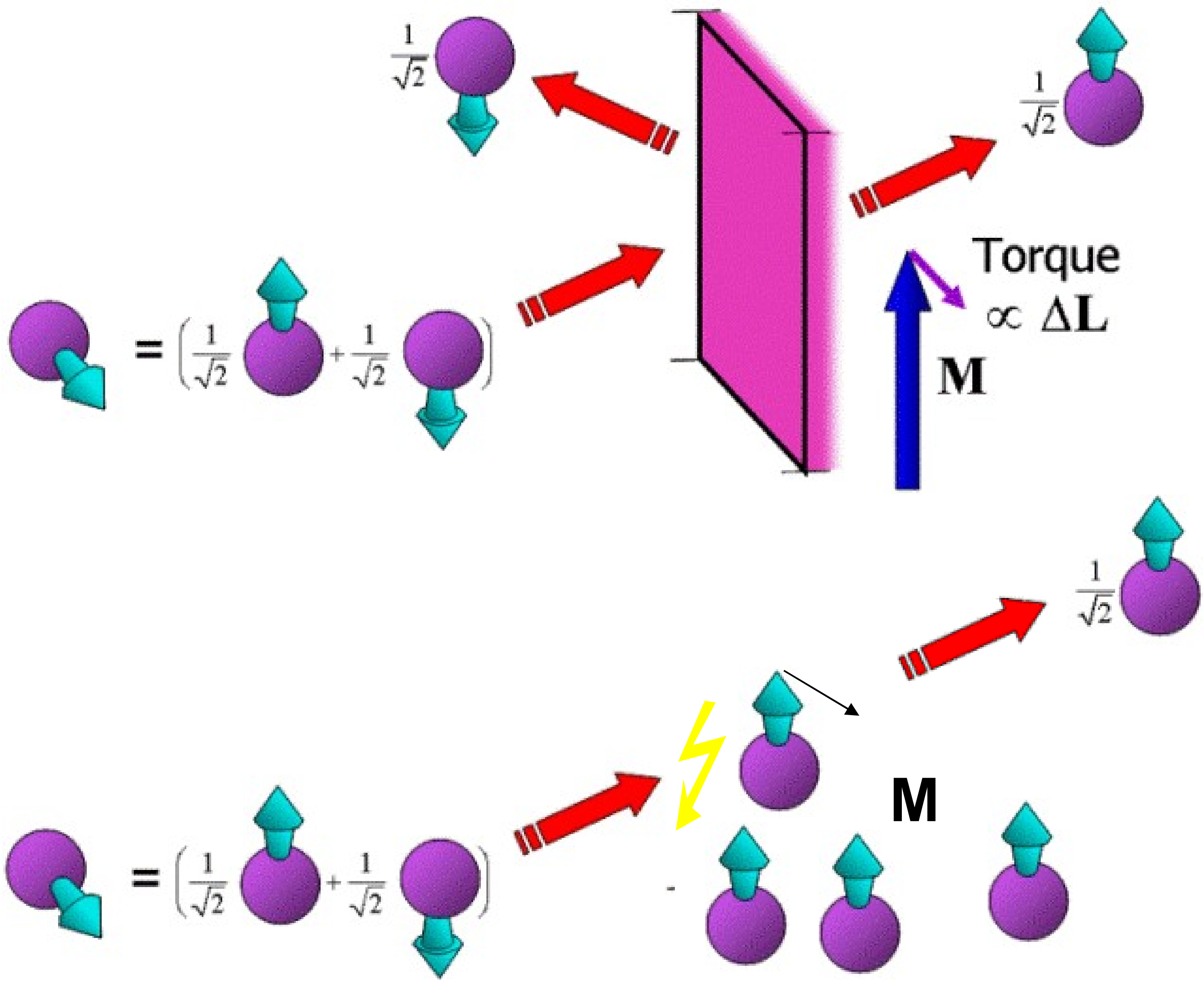


- Step in dI/dU is proportional to number of scattered electrons
- High efficiency of transfer of spin moment from current to magnetization

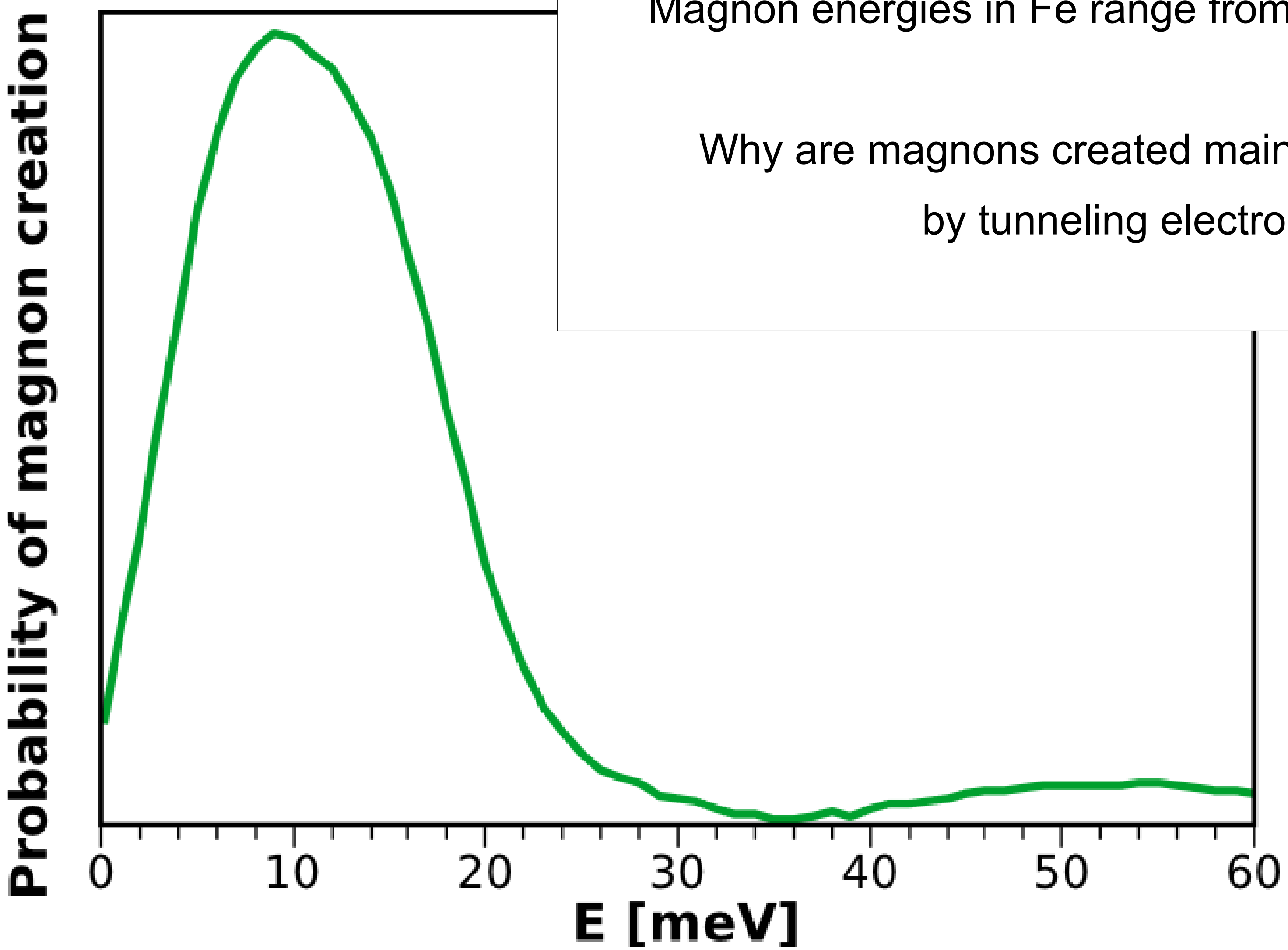
Spin-torque effect



Spin-torque effect



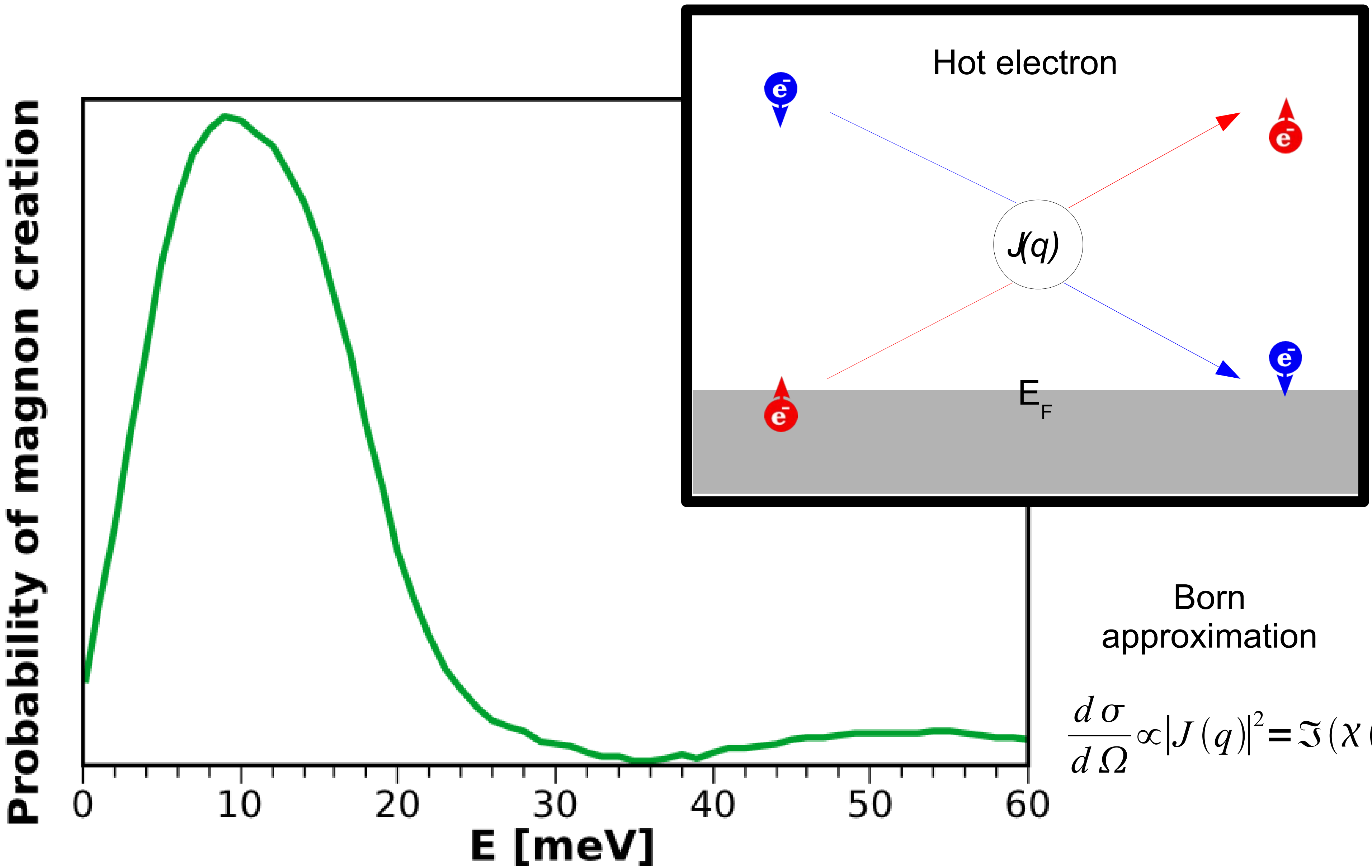
Spin-flip scattering mechanism



Magnon energies in Fe range from 0 to 600 meV

Why are magnons created mainly near 10 meV by tunneling electrons?

Spin-flip scattering mechanism



Born approximation

$$\frac{d\sigma}{d\Omega} \propto |J(q)|^2 = \Im(\chi(q))$$

Spin-flip scattering mechanism

Direct exchange between delocalized electrons

In analogy to the exchange of localized electrons, the exchange for any two delocalized electrons is given by:

$$E_S - E_T = 2\int\int \Psi_a^*(r_1)\Psi_b^*(r_2)\frac{e^2}{4\pi\epsilon_0|r_1-r_2|}\Psi_a(r_2)\Psi_b(r_1)\,dr_1\,dr_2$$

$$= \frac{2e^2}{4\pi\epsilon_0}\frac{1}{(2\pi)^6}\int\int\int_{|k_1|<k_F}\int_{|k_2|<k_F}\frac{e^{(k_1-k_2)(r_1-r_2)}}{|r_1-r_2|}dr_1\,dr_2\,dk_1\,dk_2$$ (decomposition in Bloch waves inside Fermi sphere)

with $\int_{|k|<2k_F} e^{kr}\,dk = \frac{4\pi}{r}\int_0^{2\mathrm{k}_F} k\sin(kr)\,dk = -4\frac{\pi}{r^3}(2\mathrm{k}_F\cos(k_F r) - \sin(2\mathrm{k}_F r))$

follows $E_S - E_T = \frac{-e^2}{\pi\epsilon_0(2\pi)^4}\int\frac{2k_F\cos(2K_F r) - \sin(2K_F r)}{r^4}dr$

Oscillatory exchange: Rudeman-Kittel-Kasuya-Yoshida (RKKY) interaction

Spin-flip scattering mechanism

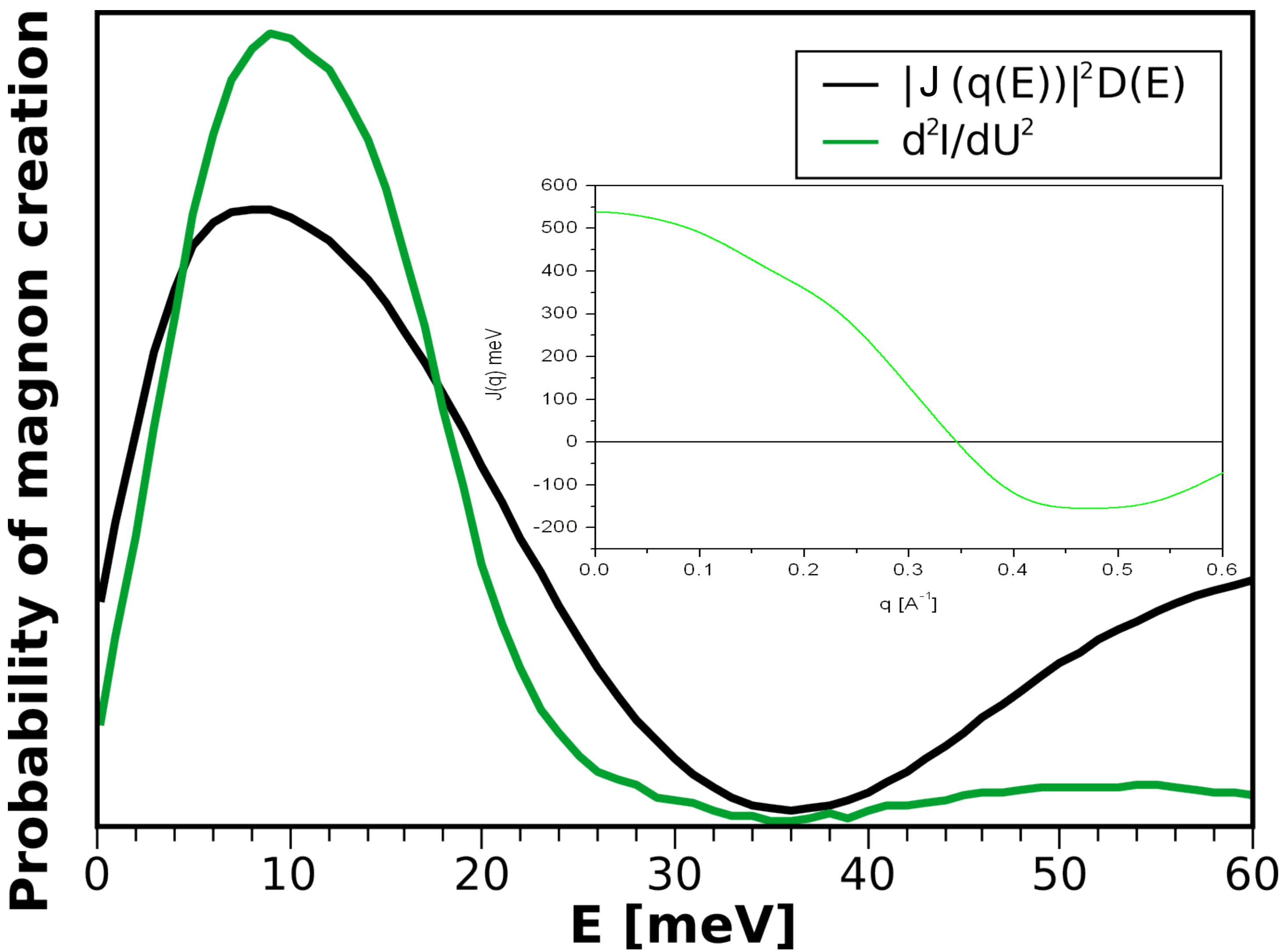
Direct exchange between delocalized electrons

In metals (e.g. Fe, Co, Ni) electrons are delocalized and form bands. Thus, exchange interaction extends beyond nearest neighbors.

Fe (bcc)			Co (fcc)			Ni (fcc)		
$\mathbf{R}_{0j}$	N_s	J_{0j} (mRy)	$\mathbf{R}_{0j}$	N_s	J_{0j} (mRy)	$\mathbf{R}_{0j}$	N_s	J_{0j} (mRy)
$(\frac{1}{2}\frac{1}{2}\frac{1}{2})$	8	1.432	$(\frac{1}{2}\frac{1}{2}0)$	12	1.085	$(\frac{1}{2}\frac{1}{2}0)$	12	0.206
(100)	6	0.815	(100)	6	0.110	(100)	6	0.006
(110)	12	−0.016	$(1\frac{1}{2}\frac{1}{2})$	24	0.116	$(1\frac{1}{2}\frac{1}{2})$	24	0.026
$(\frac{3}{2}\frac{1}{2}\frac{1}{2})$	24	−0.126	(110)	12	−0.090	(110)	12	0.012
(111)	8	−0.146	$(\frac{3}{2}\frac{1}{2}0)$	24	0.026	$(\frac{3}{2}\frac{1}{2}0)$	24	0.003
(200)	6	0.062	(111)	8	0.043	(111)	8	−0.003
$(\frac{3}{2}\frac{3}{2}\frac{1}{2})$	24	0.001	$(\frac{3}{2}1\frac{1}{2})$	48	−0.024	$(\frac{3}{2}1\frac{1}{2})$	48	0.007
(210)	24	0.015	(200)	6	0.012	(200)	6	−0.001
(211)	24	−0.032	$(\frac{3}{2}\frac{3}{2}0)$	12	0.026	$(\frac{3}{2}\frac{3}{2}0)$	12	−0.011
$(\frac{3}{2}\frac{3}{2}\frac{3}{2})$	8	0.187	$(2\frac{1}{2}\frac{1}{2})$	24	0.006	$(2\frac{1}{2}\frac{1}{2})$	24	0.001

Pajda et al. Phys. Rev. B 64, 17442 (2001)

RKKY: Spin-flip scattering mechanism

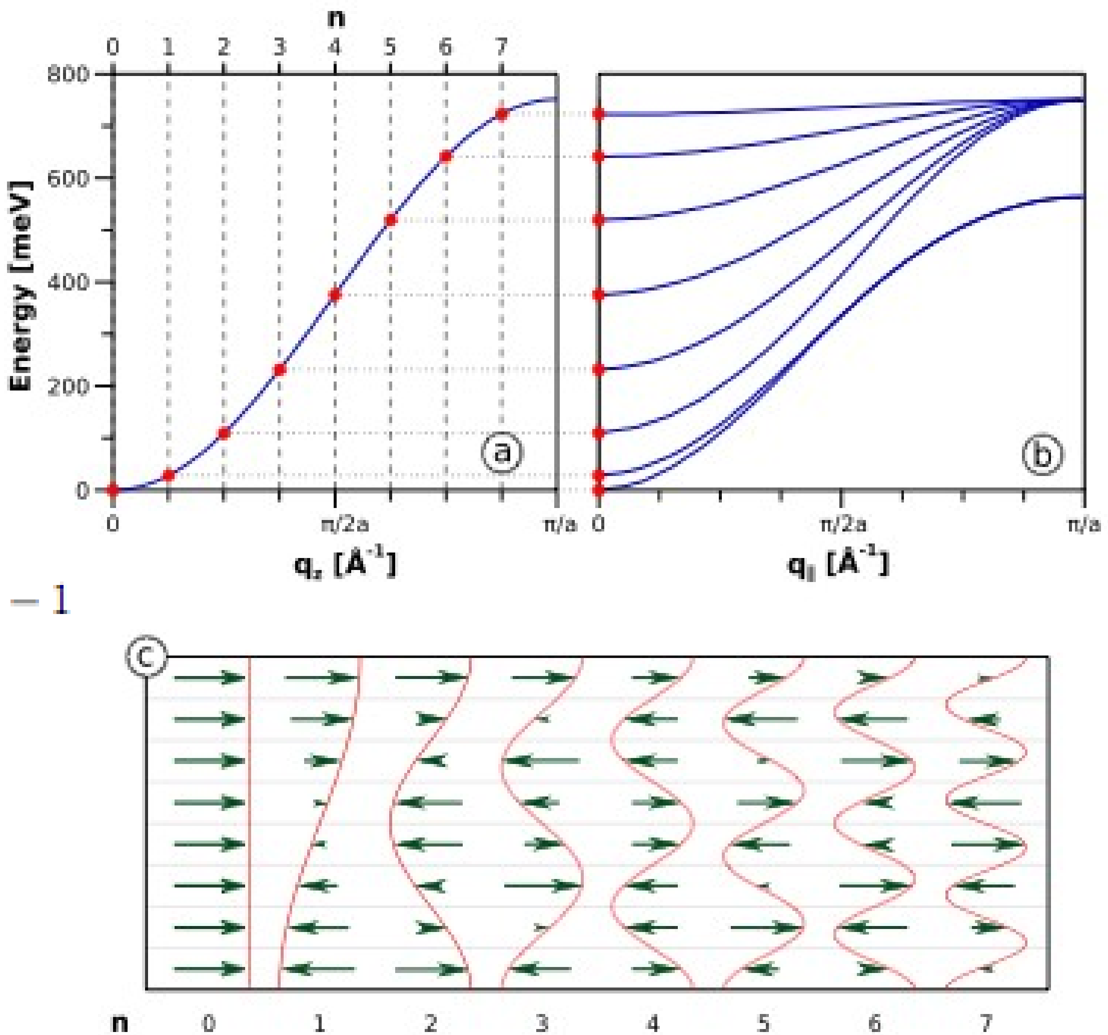


Transfer of angular momentum between the tunneling current and the magnetic material reflects exchange interaction between delocalized electrons.

Balashov et al., PRB (2008)

Magnons in thin films

Quantized standing magnons

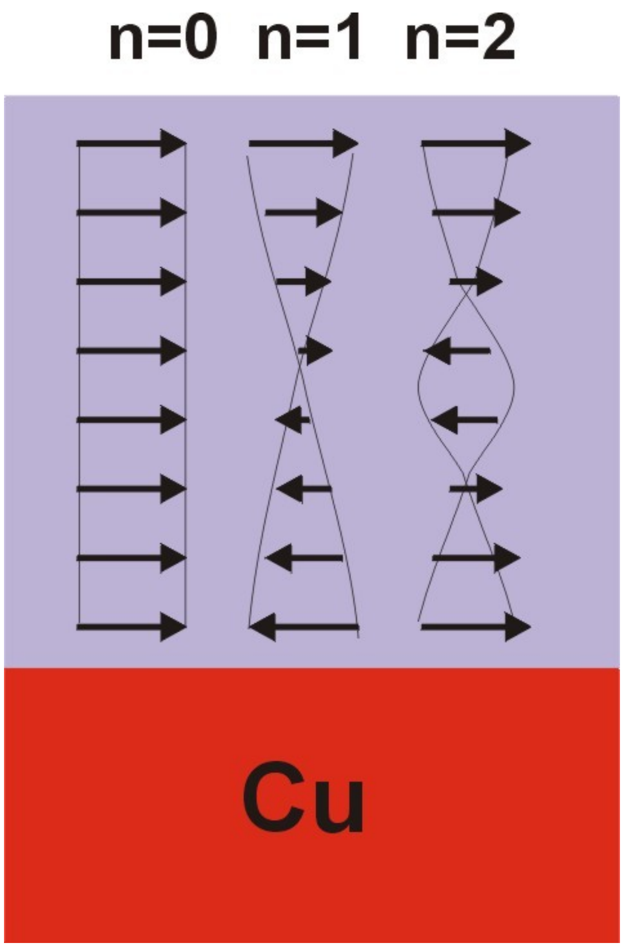


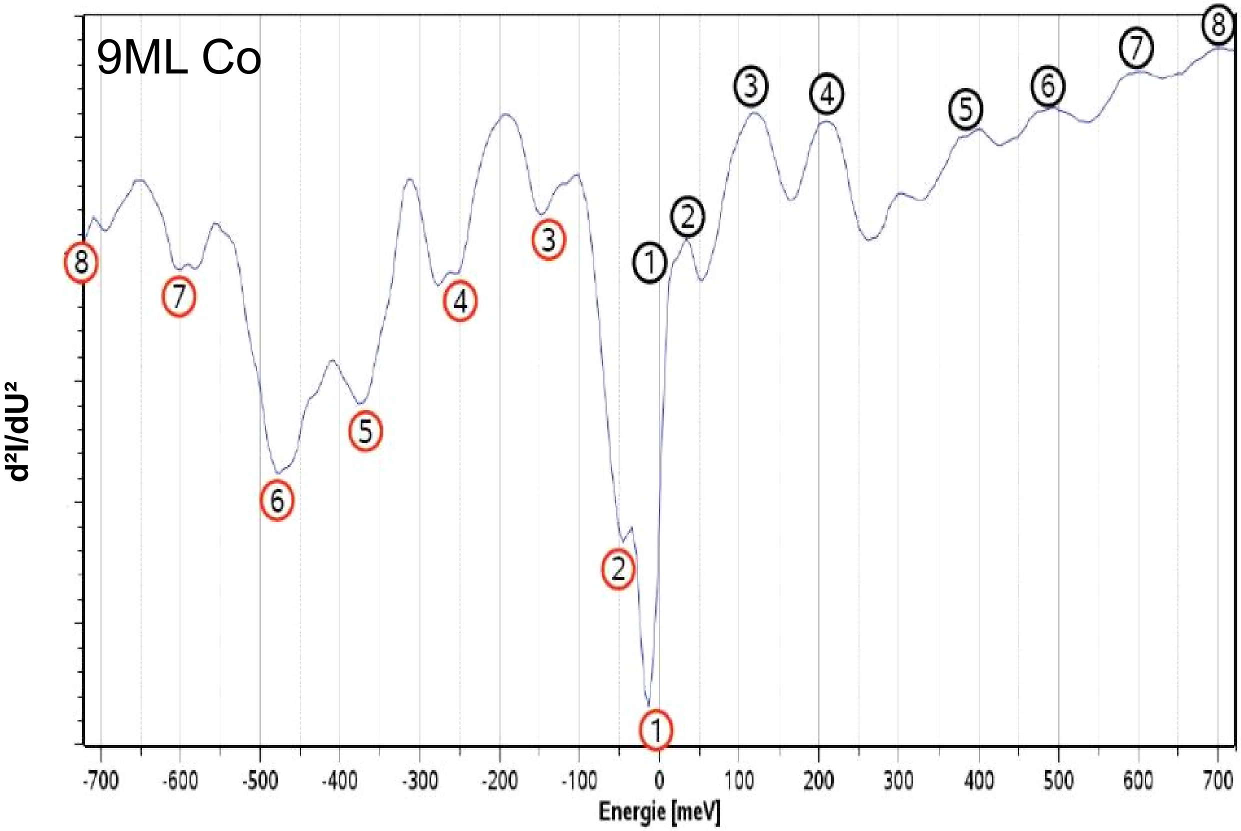
$$q_n = \frac{n}{N} Q_{\max}, n = 0, \ldots, N-1$$

- Series of magnon branches confined in the magnetic layer.
- One branch for every atomic layer.
- Quasi-momentum perpendicular to the film plane.

Magnon dispersion of fcc Co

fcc Co/Cu(100)

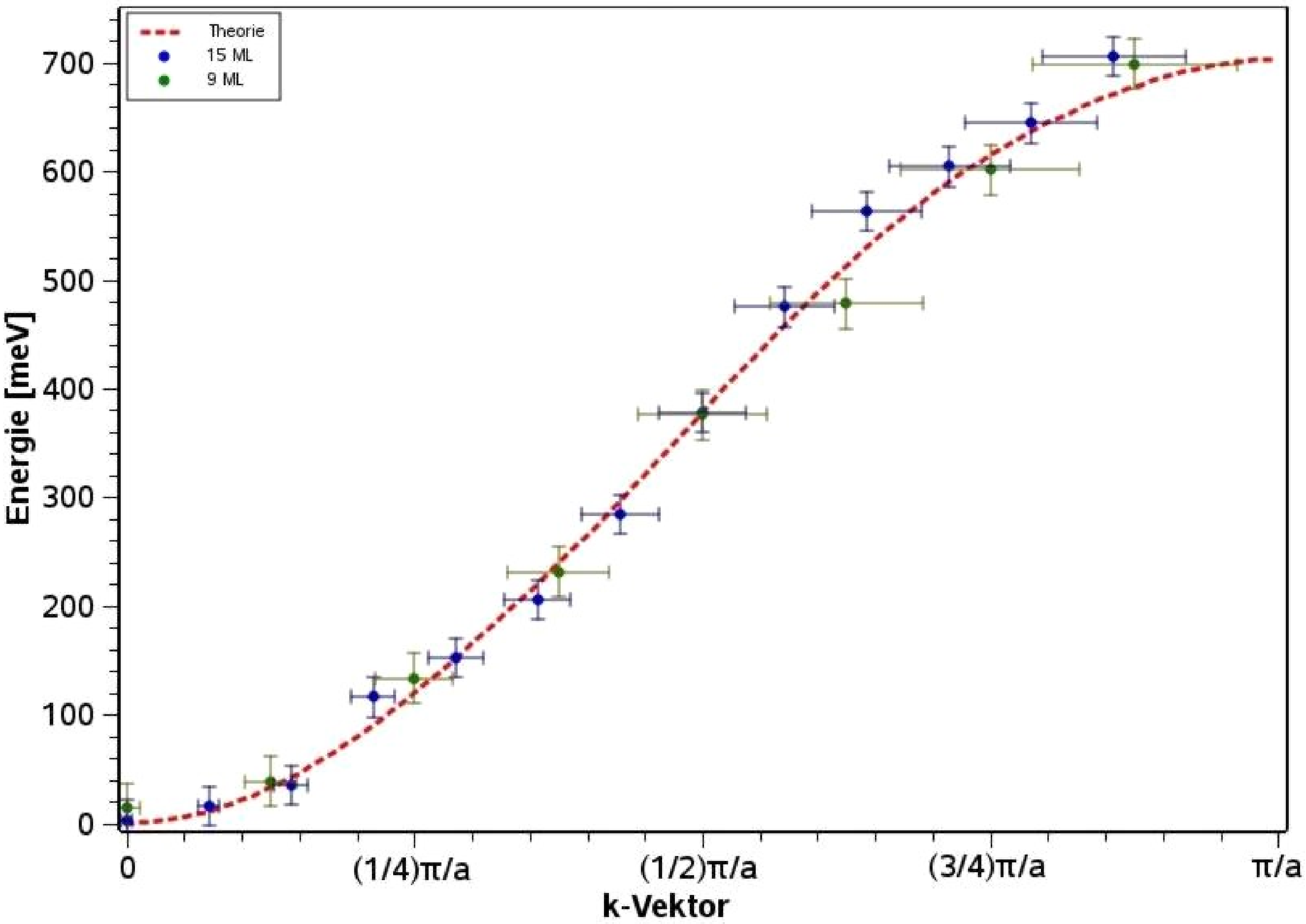




• Series of standing magnons confined in the magnetic layer.
• From energy, order and film thickness the dispersion relation can be obtained.

Magnon dispersion of fcc Co

fcc Co/Cu(100)



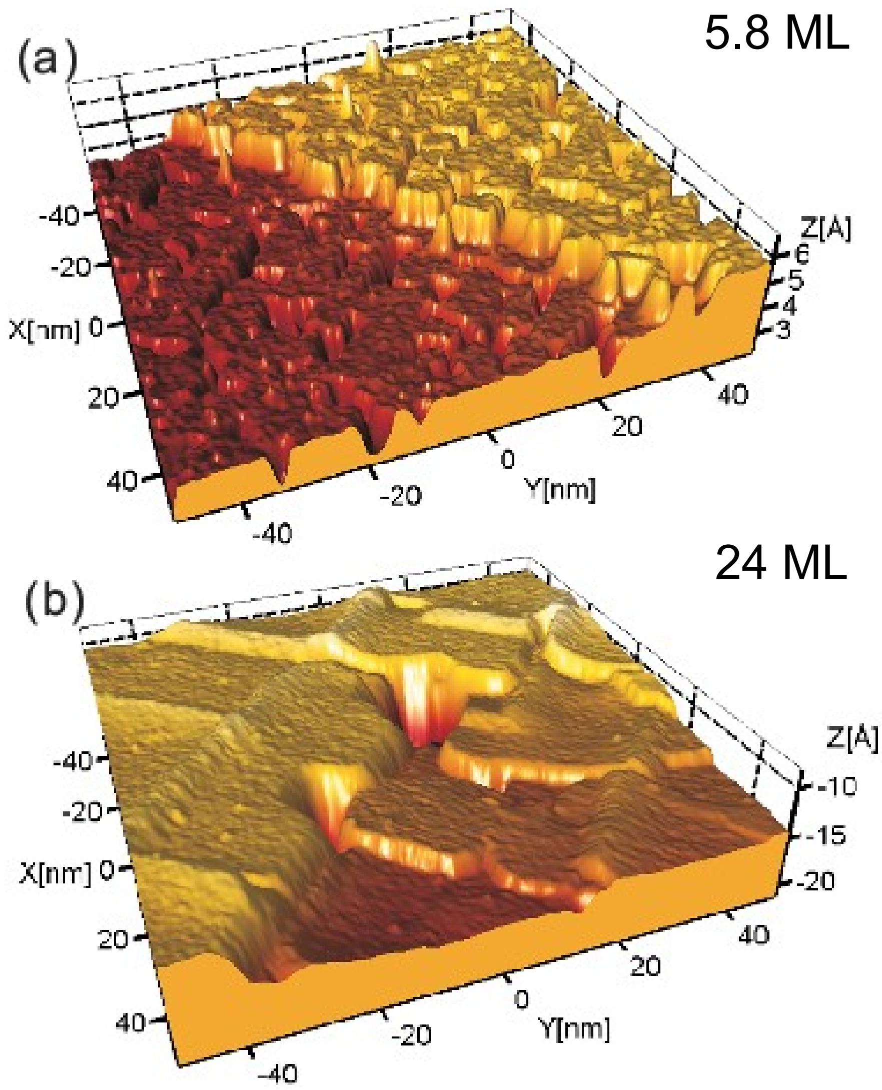
- STM measurements agree well with neutron scattering data as well as with ab initio theory.
- Spin wave stiffness of D=660 meVÅ² is determined.

Neutron scattering: Shirane et al., J. Appl. Phys. (1968)
ab initio: Pajda et al., Phys. Rev. B (2001)

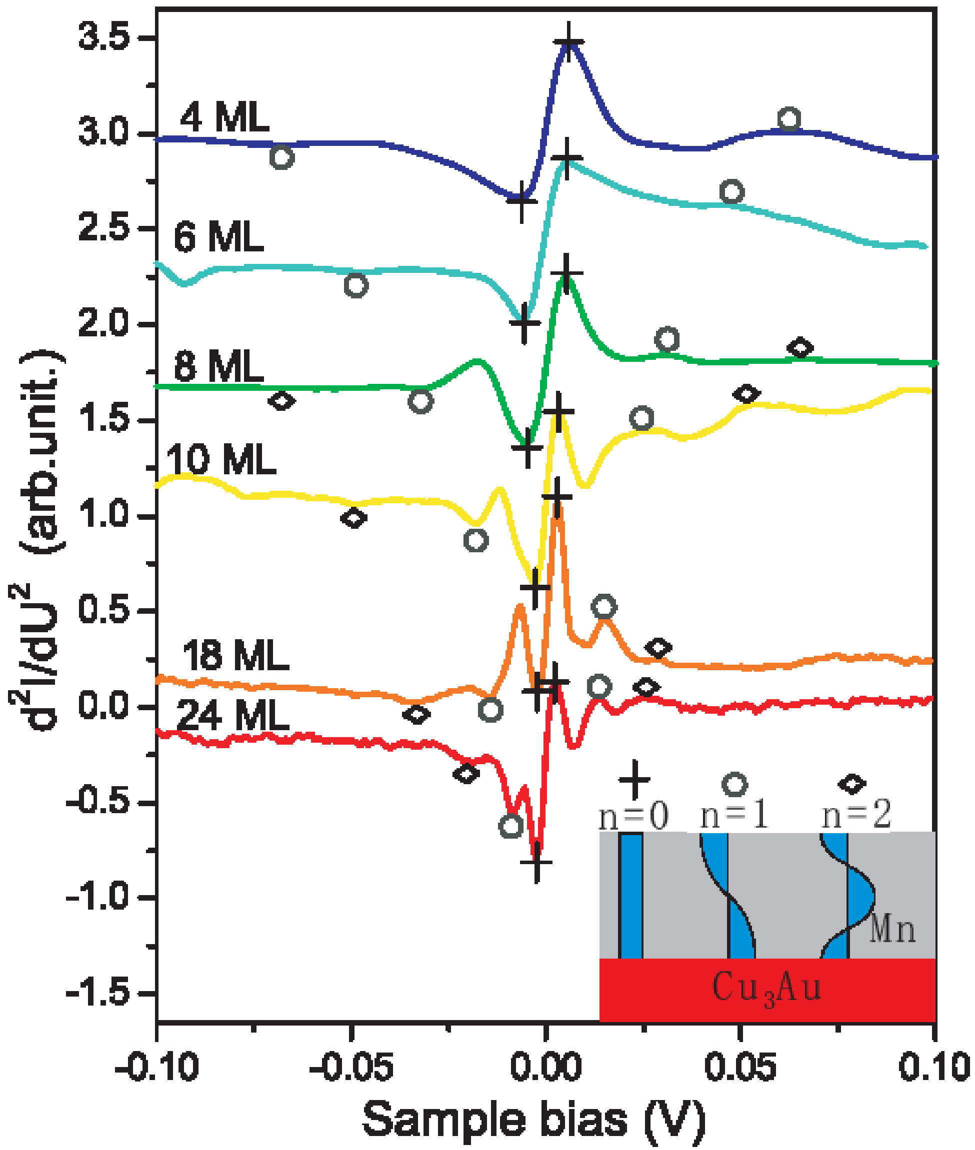
Magnon dispersion of antiferromagnetic fcc Mn

fcc Mn/$Cu_3Au(100)$

5.8 ML



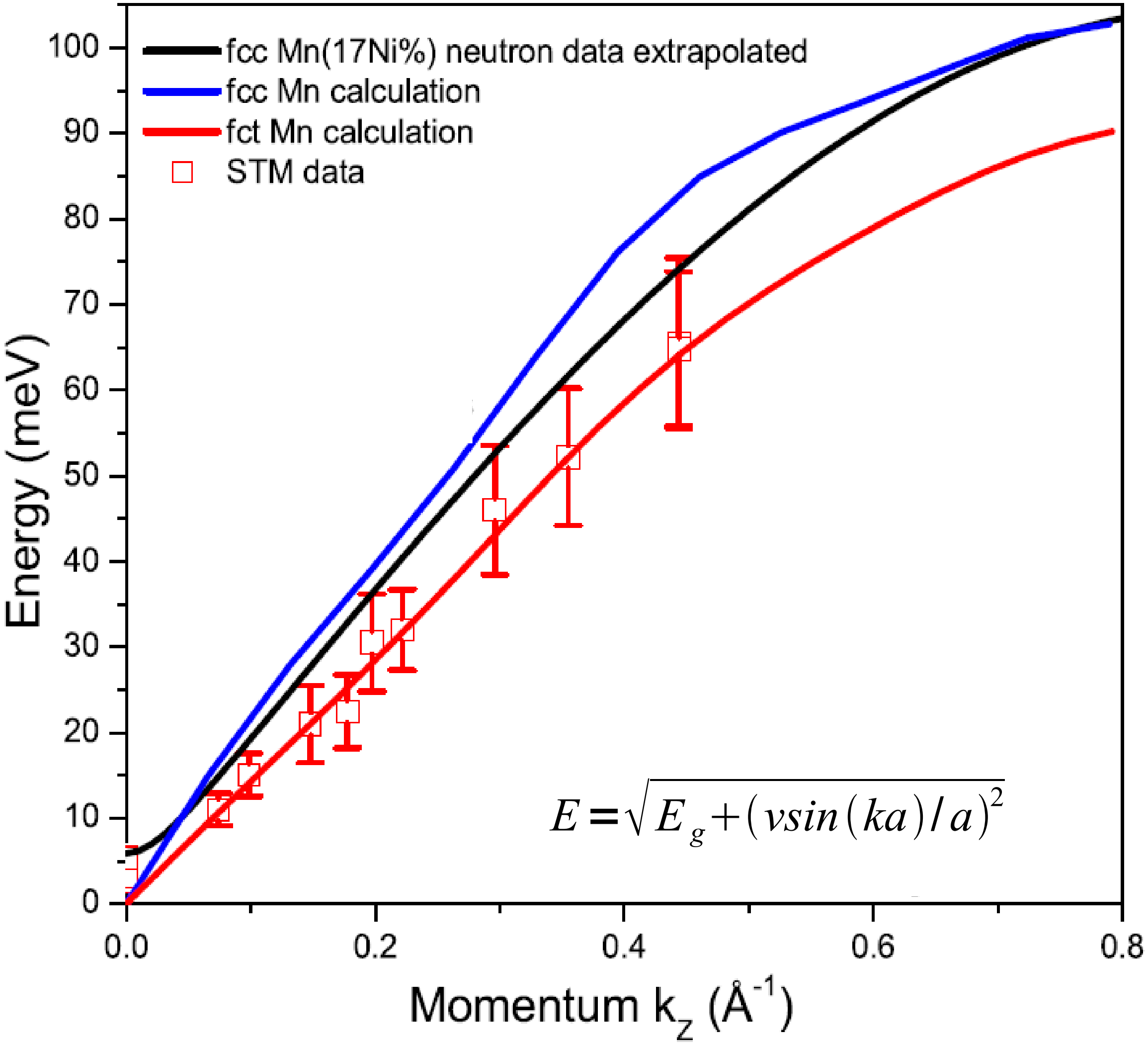
24 ML



• Series of standing magnons confined in the antiferromagnetic layer.

Magnon dispersion of antiferromagnetic fcc Mn

fcc Mn/Cu_3Au(100)



Neutron scattering

E_g=5.9 ± 0.2 meV
v=185 ± 12 meVÅ

STM measurements

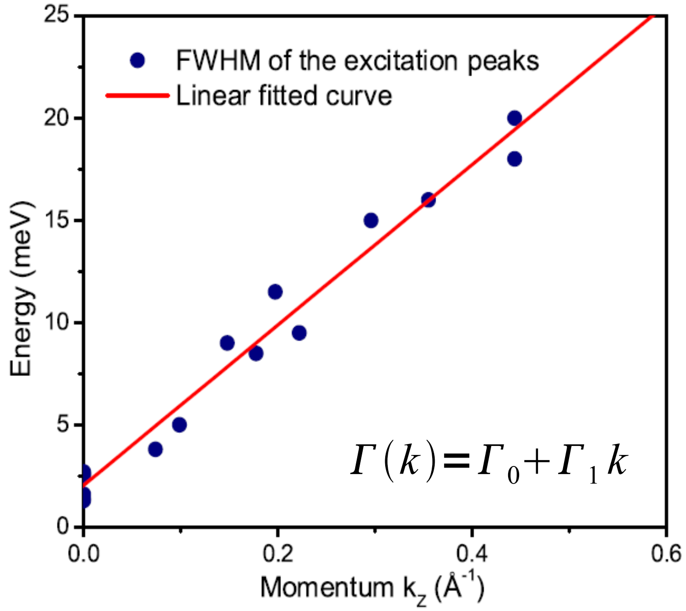
E_g=2.7 - 5.5 meV
v=160 ± 10 meVÅ

Jankowska et al, *JMMM*,140, 1973 (1995)

- Dispersion nicely matches ab initio calculation and neutron scattering data.

Magnon dispersion of antiferromagnetic fcc Mn

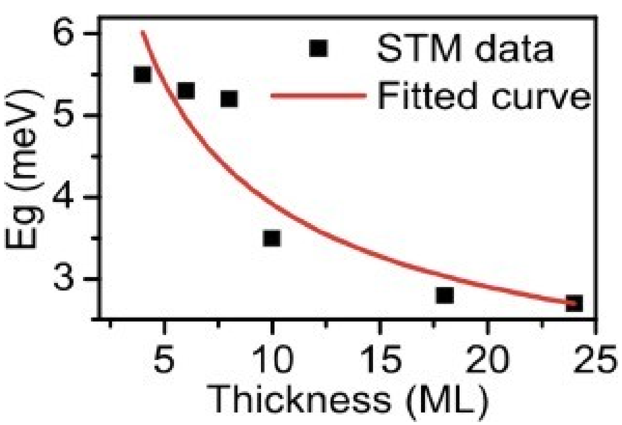
Damping of spin waves



fcc Mn(17%Ni): Γ_1= 85±18 meVÅ

This work: Γ_1= 39±8 meVÅ

Magnetic anisotropy energies



$$E_g = \sqrt{2E_A E_E + E_A^2},\ E_A = E_{AB} + E_{AS}/t$$

Exchange energy E_E=25 meV

Bulk anisotropy E_{AB}=0.02±0.03 meV

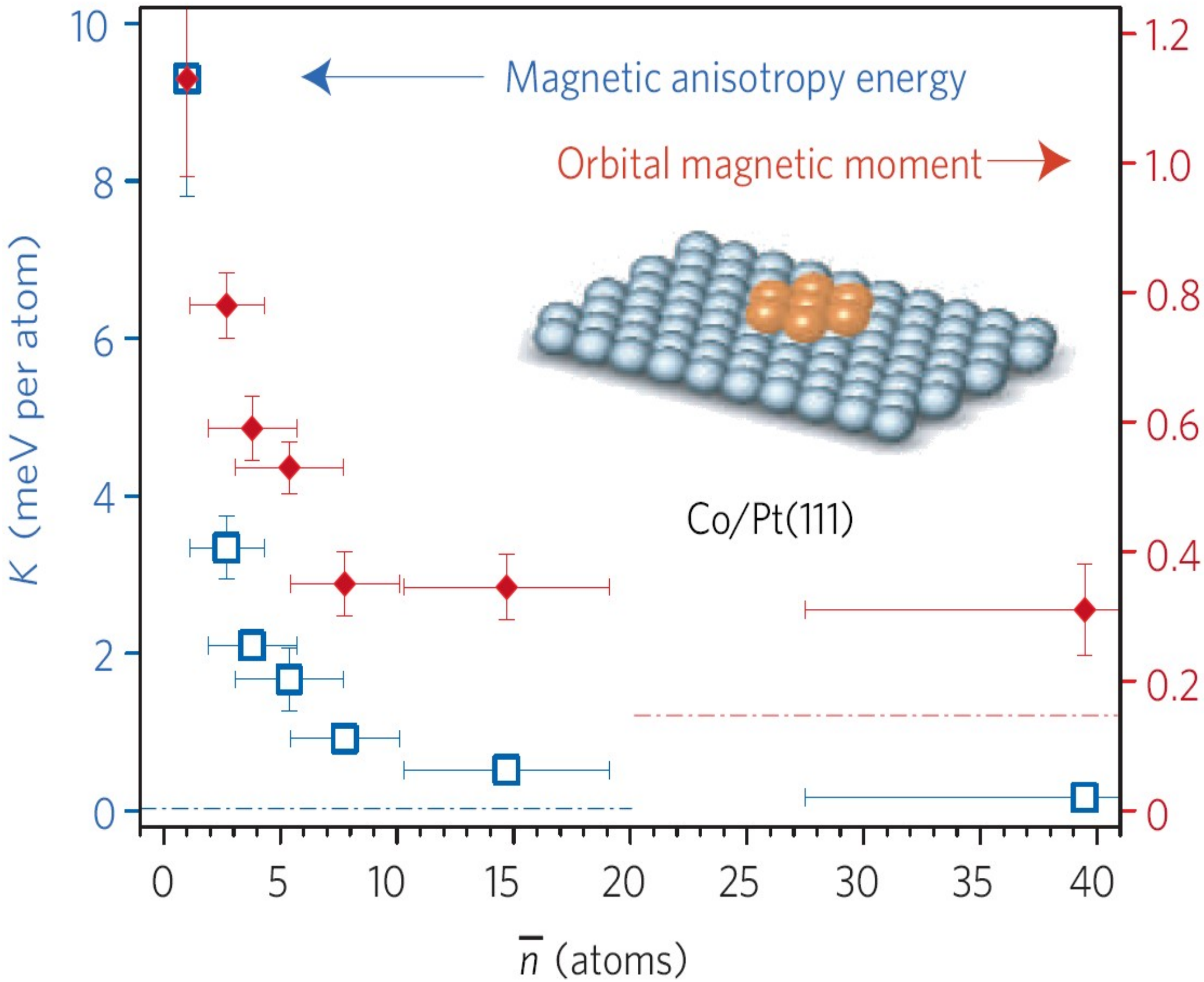
Surface anisotropy E_{AS}=1.4±0.2 meV

• STM can measure magnon life times and surface anisotropies.

C.L. Gao et al., PRL (2008)

Giant magnetic anisotropy

Uniaxial out-of-plane magnetic anisotropy of Co clusters on Pt(111)



Giant magnetic anisotropy of 9.3 meV per Co atom due to large orbital moment and thus large spin orbit interaction

MAE drops quickly with cluster size

Measurements by XMCD on ensemble of atoms or clusters

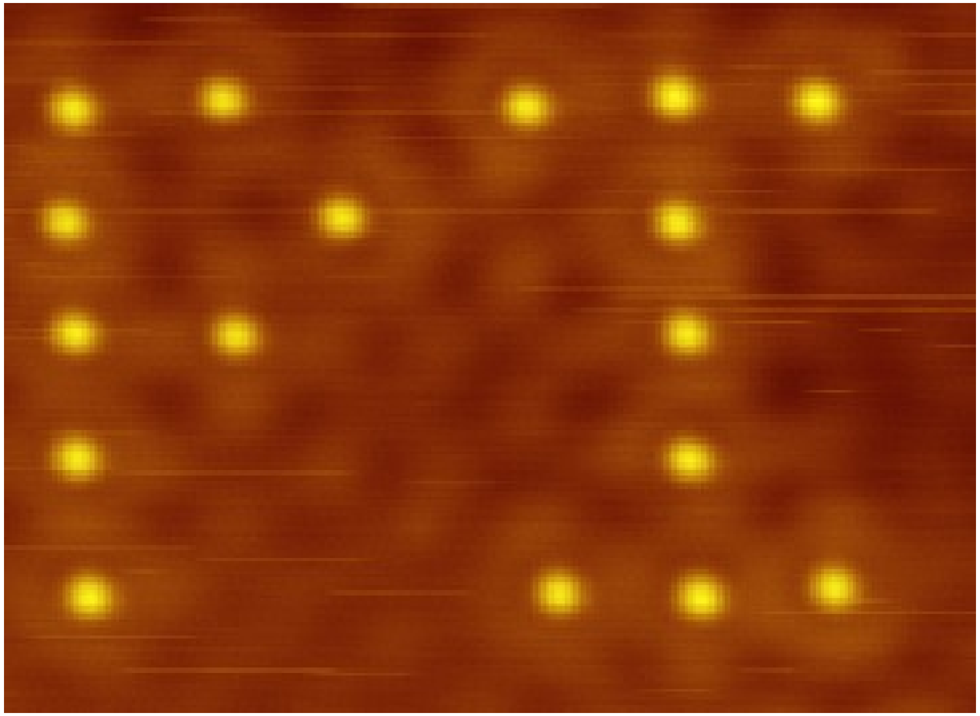
Large uncertainty on cluster sizes

P. Gambardella *et al*. Science **300** 1130 (2003)

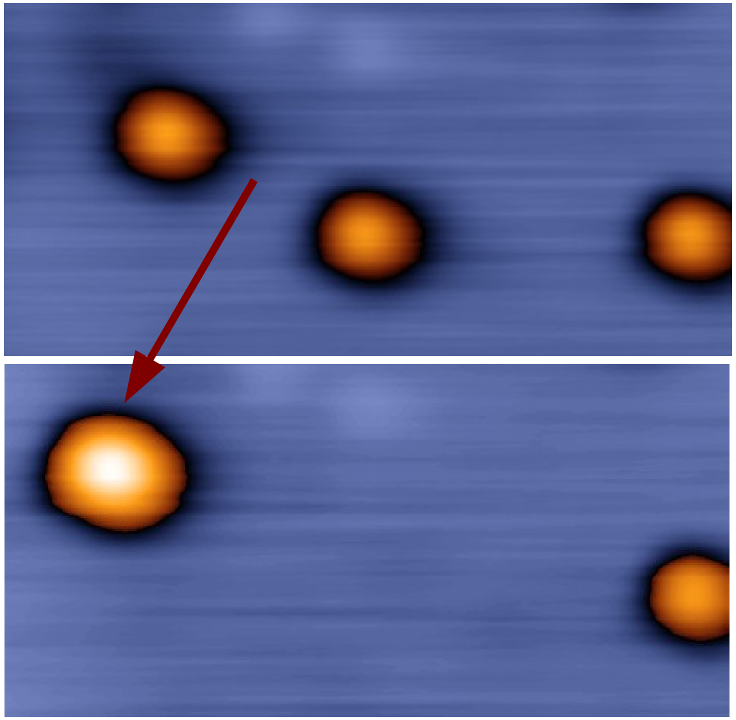
Atomic manipulation

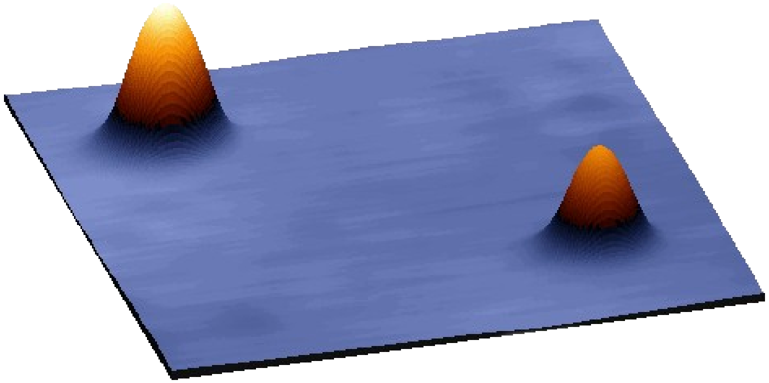
Manipulation of the atoms by the STM tip

17 Fe atoms on Cu(111)



Forming a Co dimer on Pt(111)

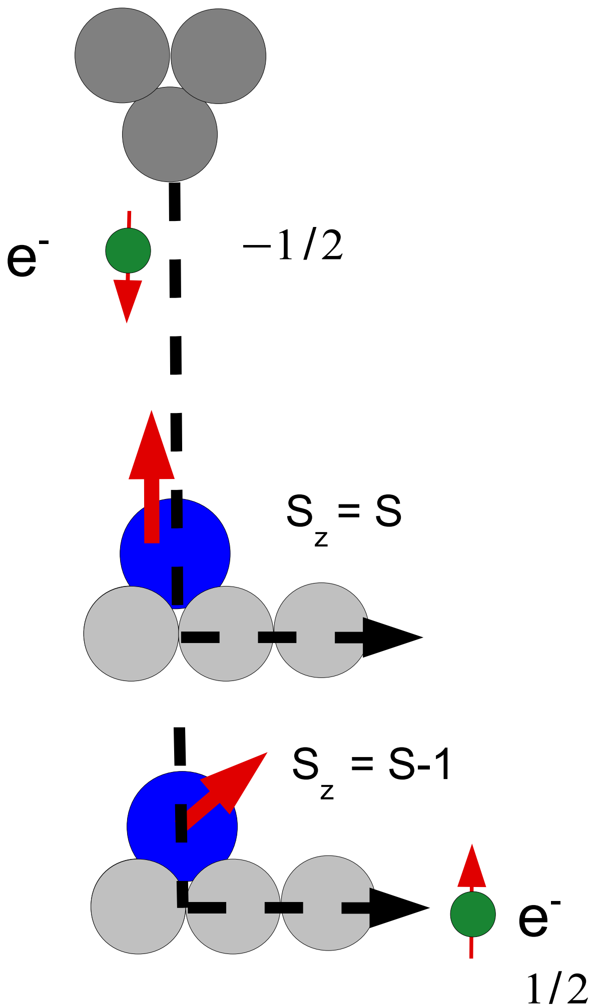


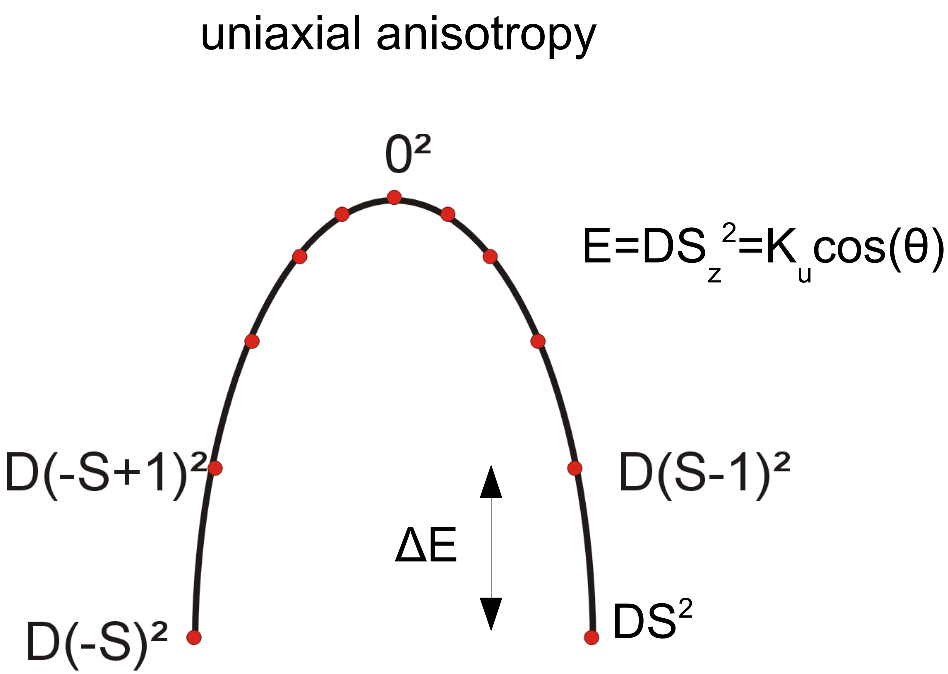


- Atoms are imaged with high tunneling resistance (R>10MΩ) and moved with low tunneling resistances (R<300kΩ).
- Dimers and trimers appear higher than atoms.

Excitation due to tunneling electrons

Spin-flip scattering of a tunneling electron





D and $K_u < 0$

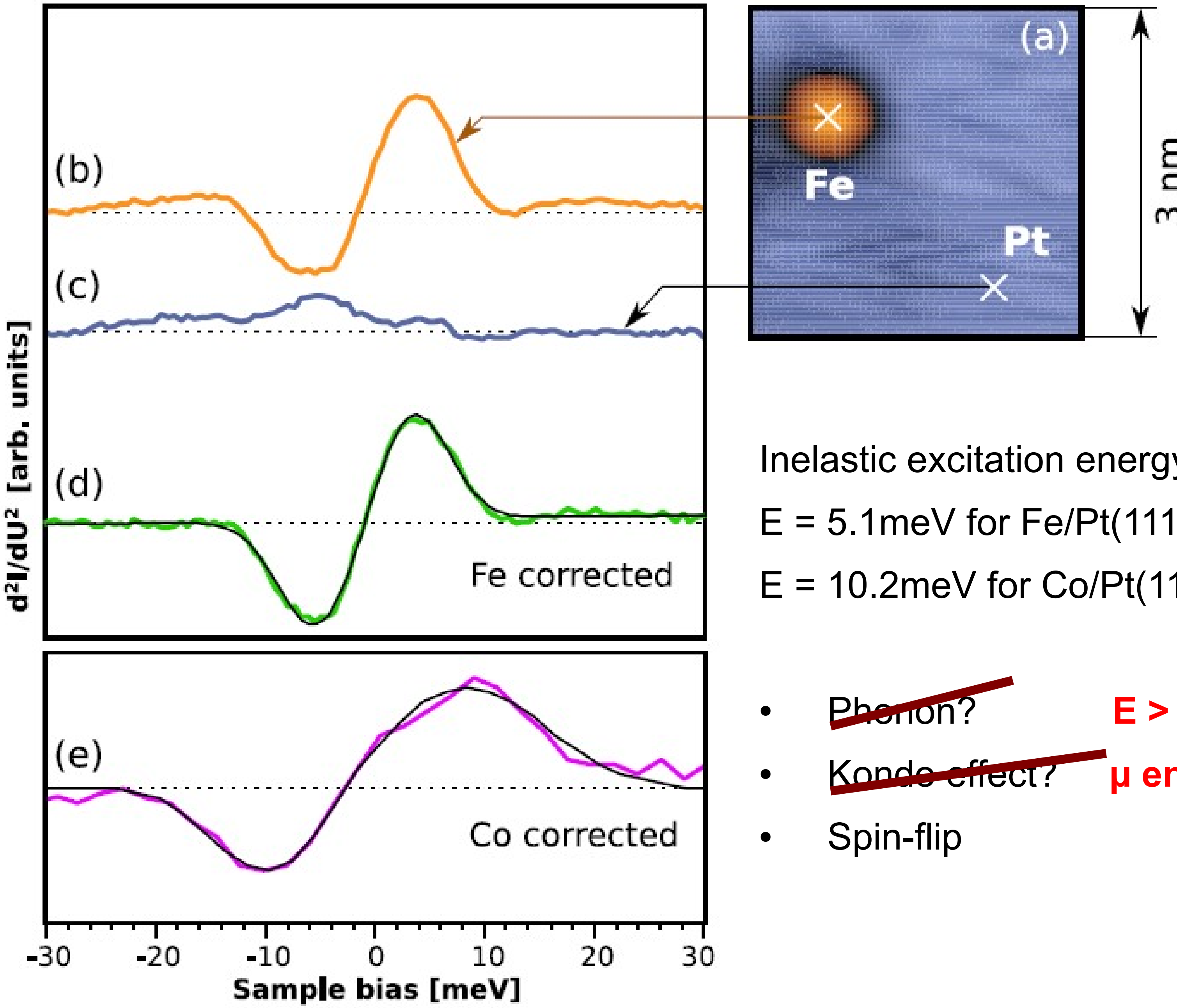
$\cos(\theta)=S_z/S$

$K_u = \Delta E * 2S^2/(2S-1)$

A.J. Heinrich et al. *Science* **306** 466 (2004)

The energy loss of the tunneling electron equals the magnetic excitation energy.

Inelastic tunneling spectroscopy



Inelastic excitation energy

E = 5.1meV for Fe/Pt(111)

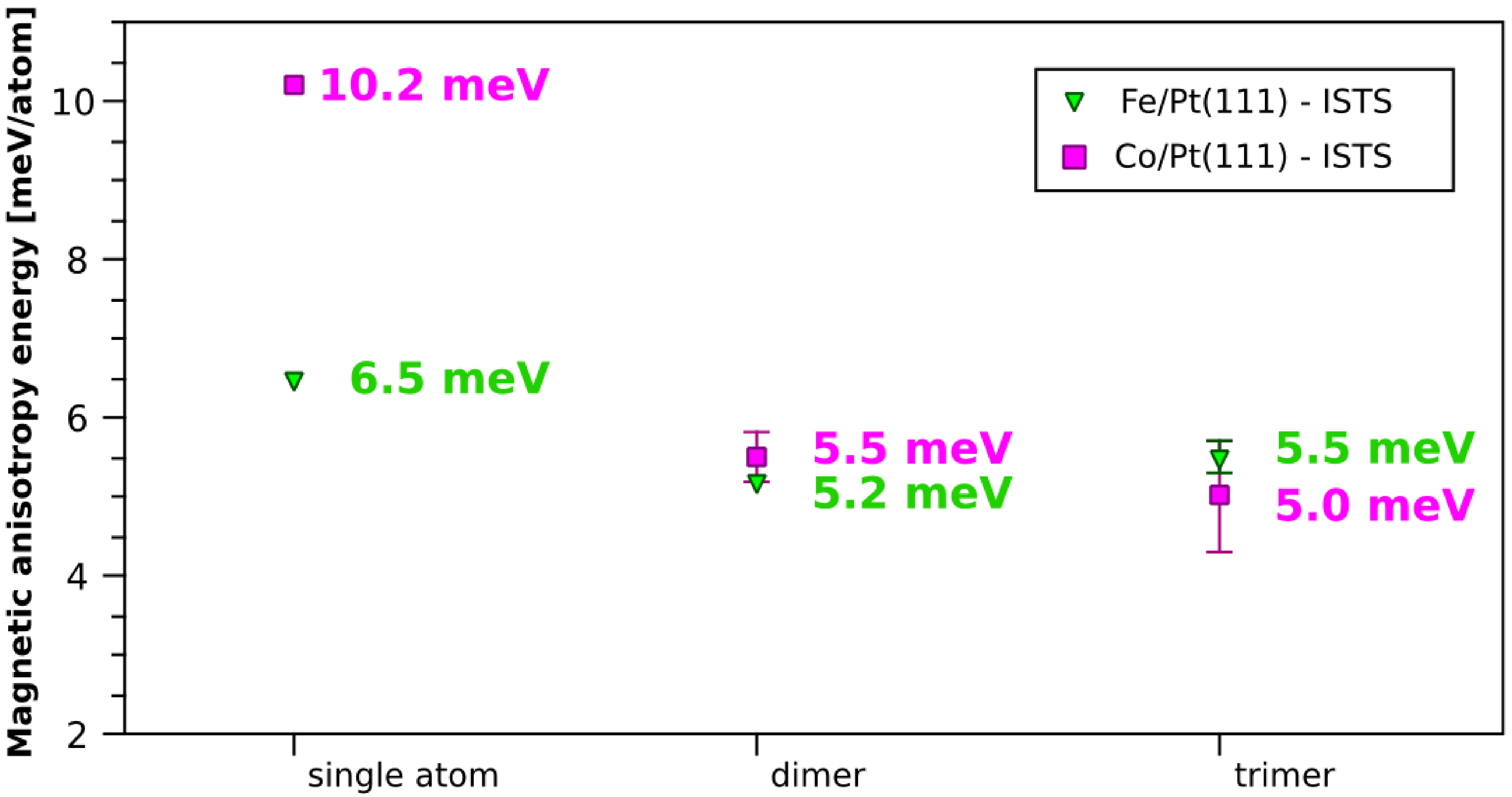
E = 10.2meV for Co/Pt(111)

- ~~Phonon?~~ **E > 27meV**
- ~~Kondo effect?~~ **μ enhanced ***
- Spin-flip

* T. Hermannsdörfer et al., *J. Low Temp.* **104** 49 (1996)

What is the MAE of adatoms and clusters?

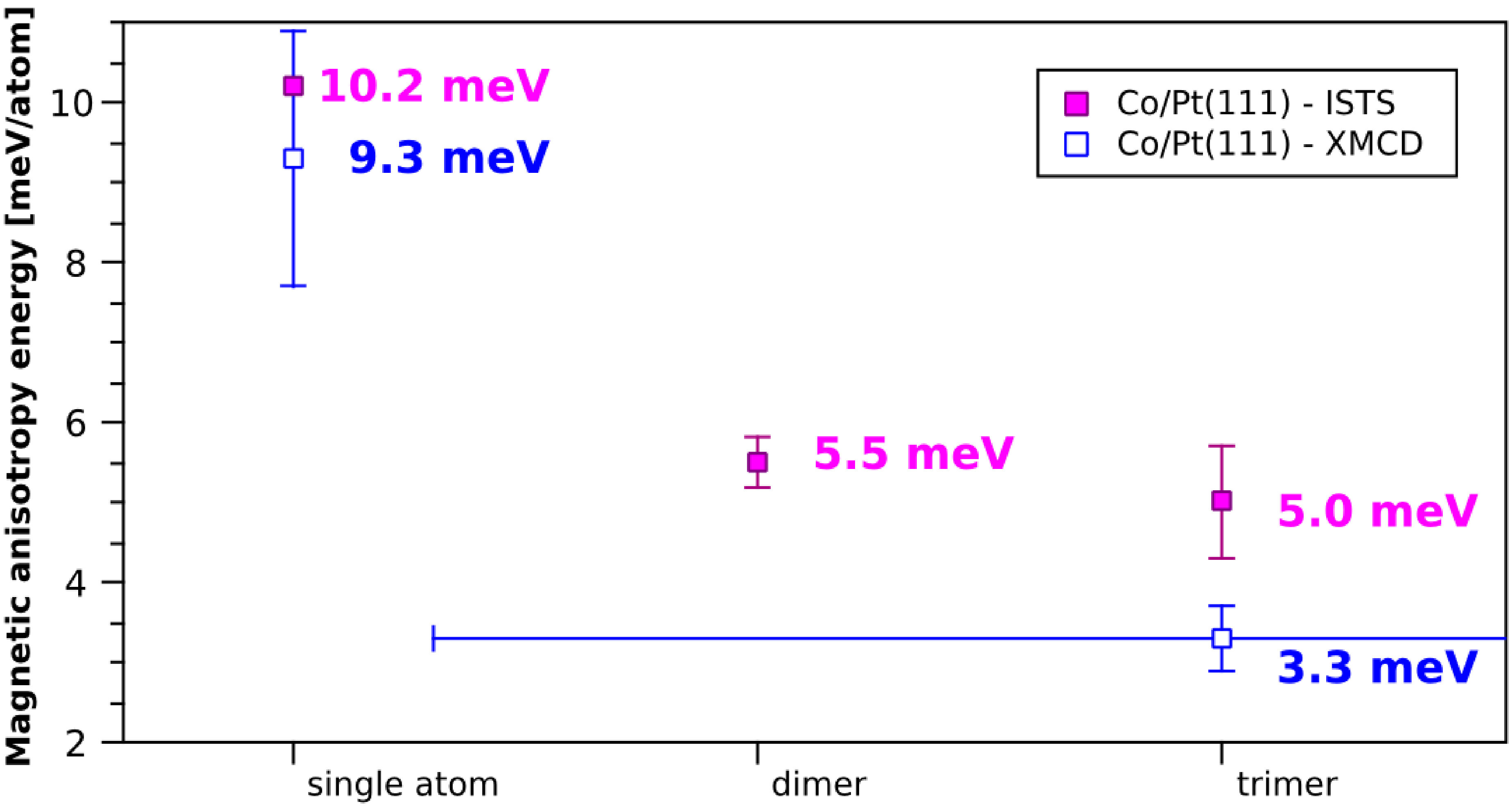
$$S_{\mathrm{Fe}} = 3/2 \qquad S_{\mathrm{Co}} = 1$$



Balashov et al., PRL (2009)

What is the MAE of adatoms and clusters?

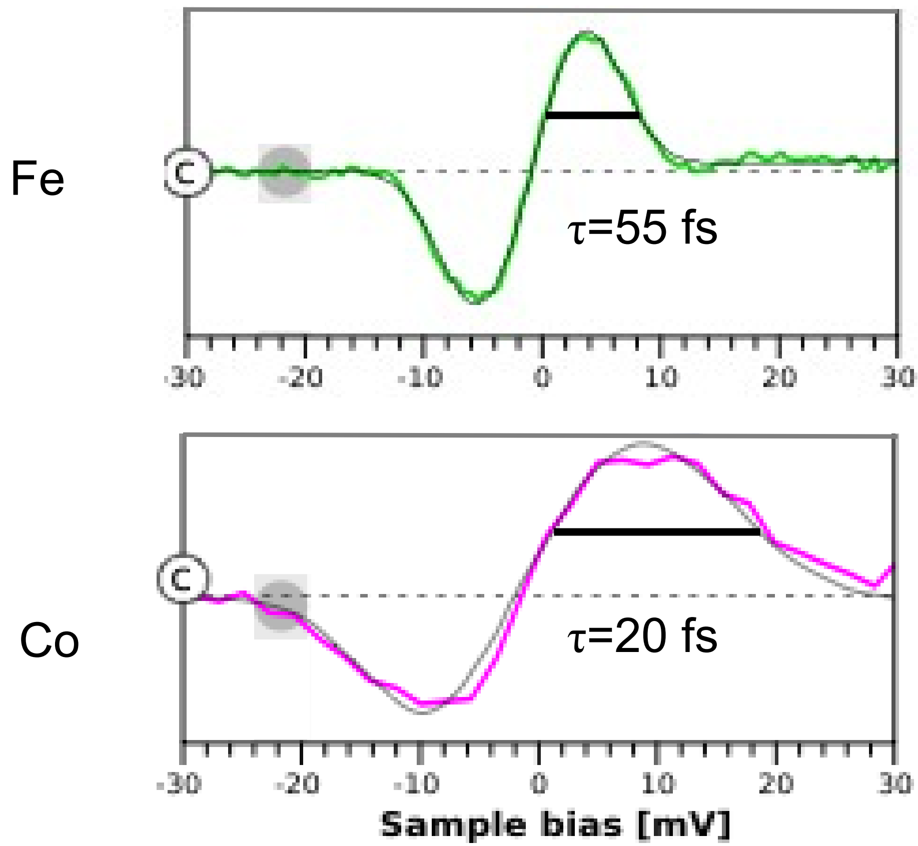
Comparison with XMCD data

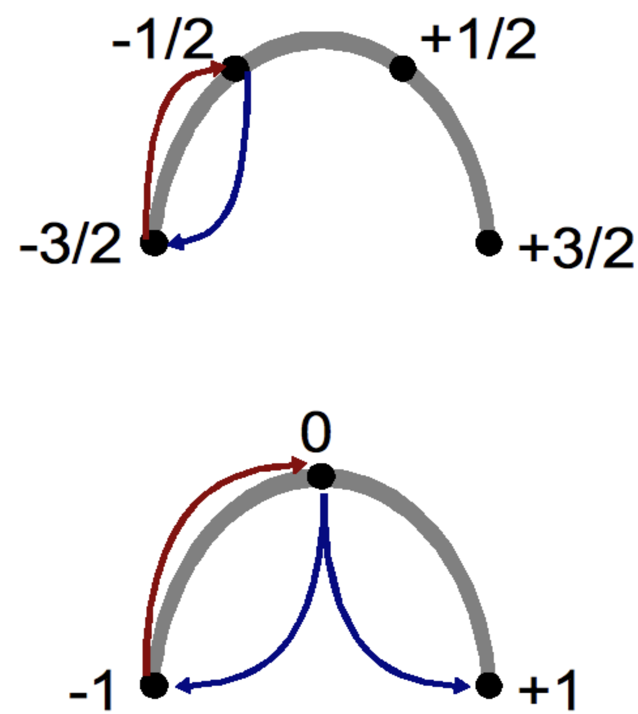


P. Gambardella *et al*. Science **300** 1130 (2003)

What is the life time of the excited state?

Relaxation of the excited state



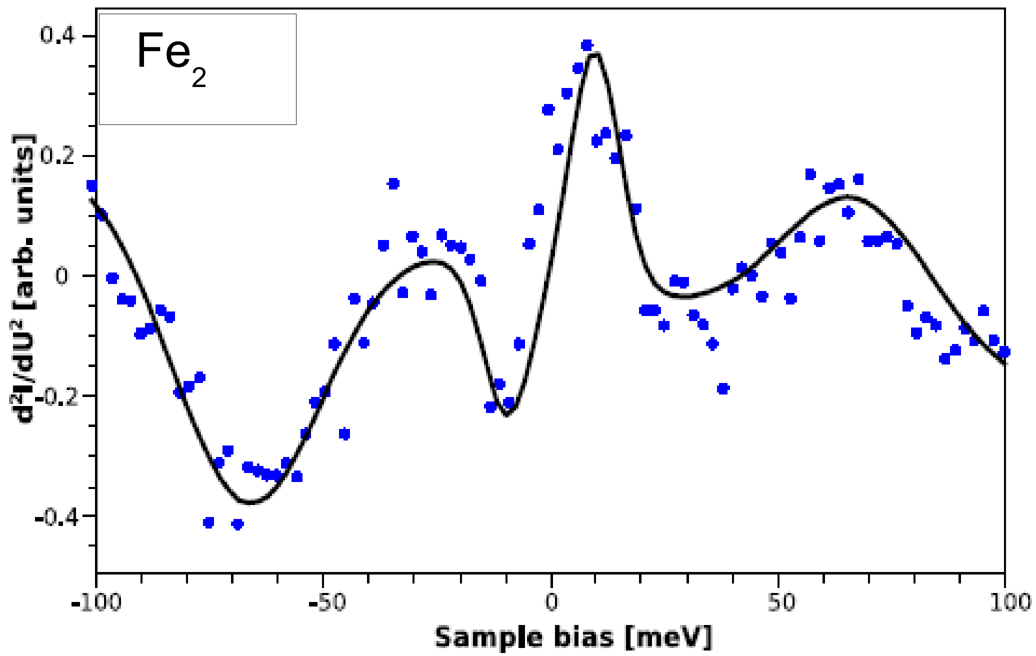


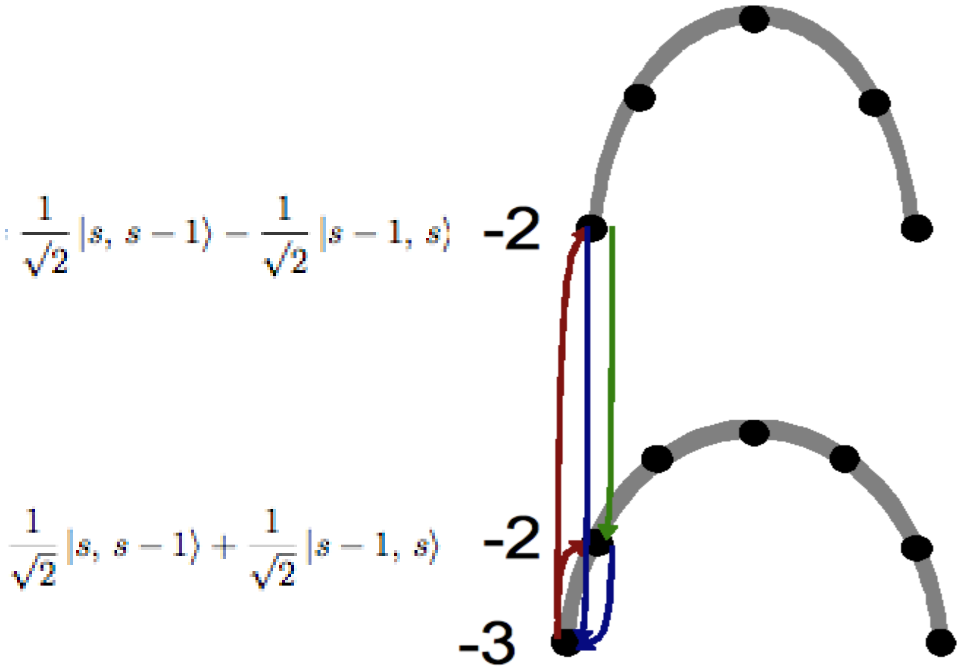
- Life times can be extracted from excitation width, corrected for instrumental broadening

High energy excitations of clusters

Anisotropy and exchange

- For coherent rotation of all magnetic moments (rotation of total spin) the MAE has to be overcome ($S=3$, $S_z=3 \rightarrow S=3$ $S_z=2$). **$\Delta E = -(3^2-2^2)D = -5D$**
- Also non collinear excitations are possible. In these cases also exchange energy has to be paid ($S=3$, $S_z=3 \rightarrow S=2$ $S_z=2$). **$\Delta E = -5D+3J$**





- Fit to data gives $J = 16 \pm 1$ meV for Fe_2
- Ab initio calculation of relaxed Fe dimer : J = 11 meV
- Fast relaxation of non-collinear state (10fs) via additional non spin flip process