Low Dimensional Magnetism Workshop

European School on Magnetism
Timisoara, Sept. 08, 2009

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Outline

1. P. Gambardella (P. F. de Châtel)

- *Magnetic order in one- and two-dimensional systems*
- *Influence of magnetic anisotropy on magnetic order*

2. P. Gambardella

- *Intrinsic magnetization properties and dimensionality effects: magnetization, orbital moments, induced magnetism in nonmagnetic materials*
- *Magnetocrystalline anisotropy*
- *Metal-organic layers and single-molecule magnets*

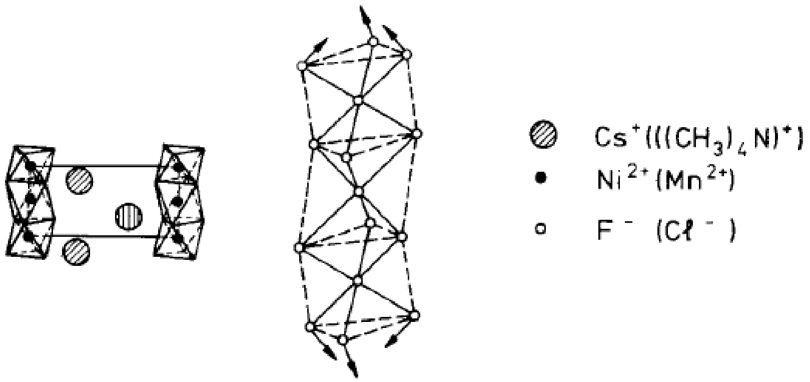
3. O. Fruchart

- *Superparamagnetism*
- *Thermal activation, nucleation and propagation of domains*
- *Magnetization reversal in thin films and nanoparticles*

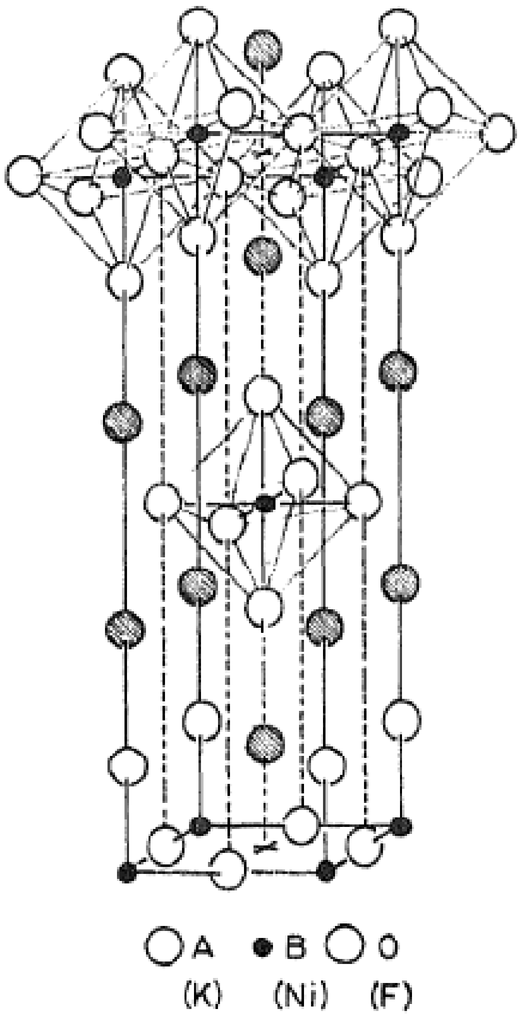
4. W.Wulfhekel

- *Magnetic excitations in thin films and clusters probed by STM*

Prototype 1D and 2D crystals



TMMC
tetra methyl ammonium manganese chloride
1D, FM interaction

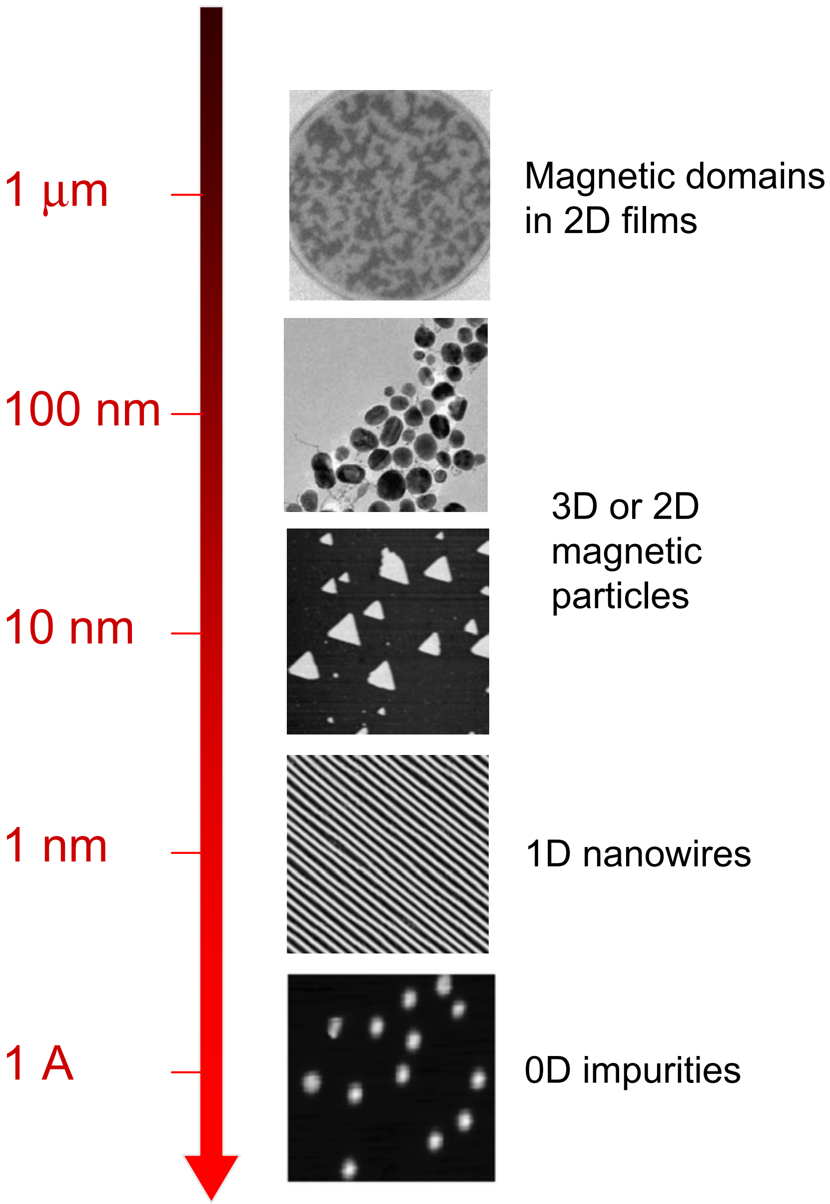


K_2NiF_4
2D AFM

Reviews:

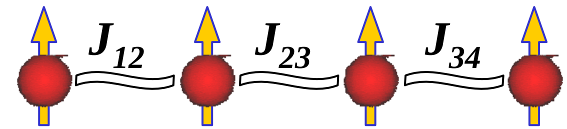
- Hone and Richards, Annu. Rev. Mater. Sci. 4, 337 (1974).
- de Jongh and Miedema, Adv. Phys. 50, 947 (2001 – publ. 1974).
- Steiner, Villain, and Windsor, Adv. Phys. 25, 87 (1976).

Low-dimensional magnetism in metal nanostructures

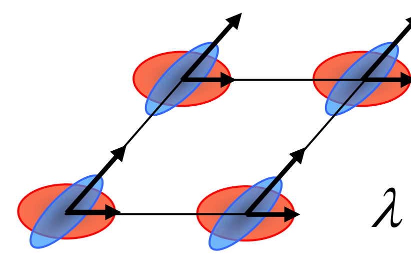


MAGNETIC ORDER

$$-\sum_{i\neq j} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$



MAGNETIC ANISOTROPY



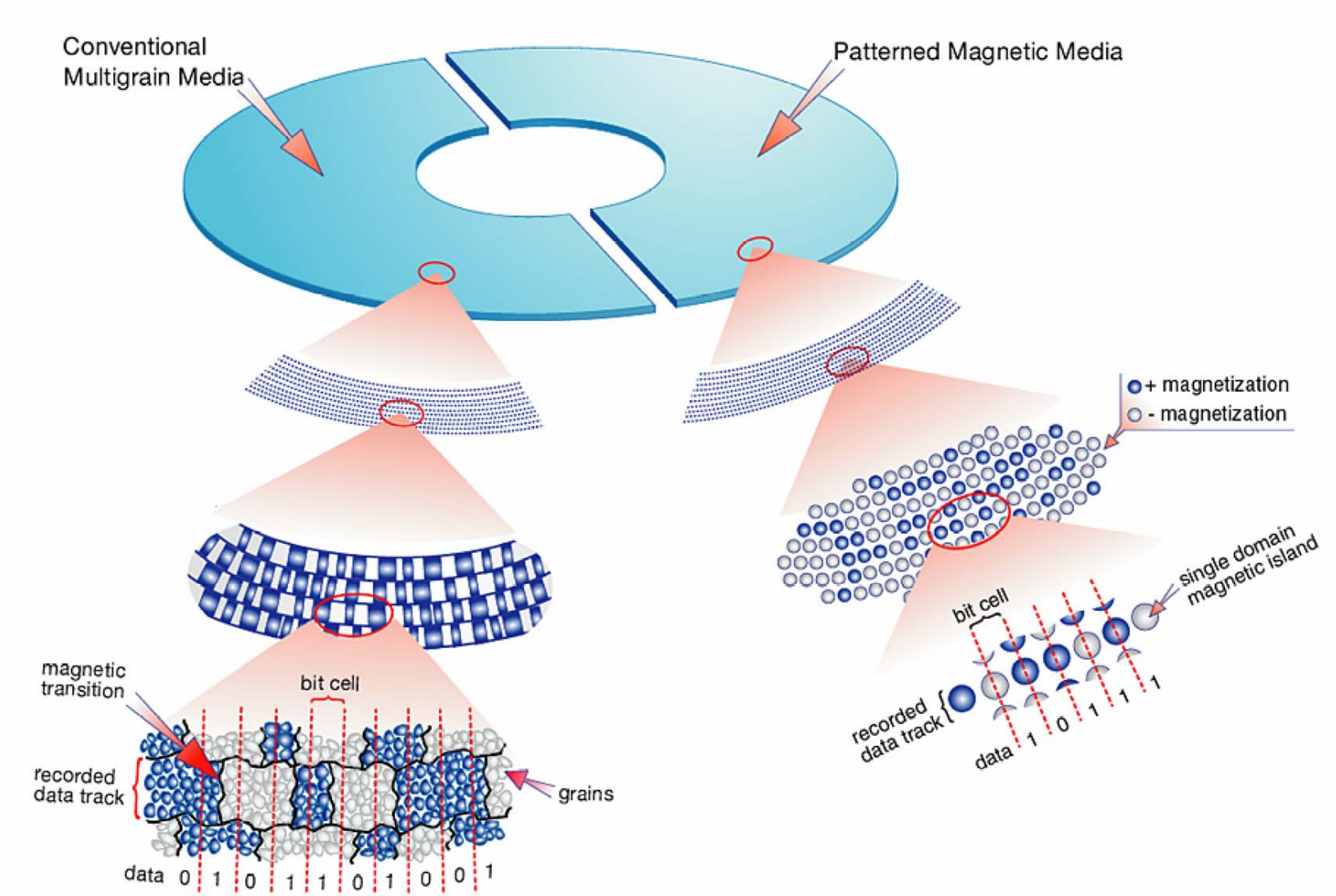
$$\lambda \mathrm{L} \cdot \mathbf{S}$$

LOCAL MAGNETIC MOMENTS

d or *f* electrons

Hund's rules

Magnetic storage media



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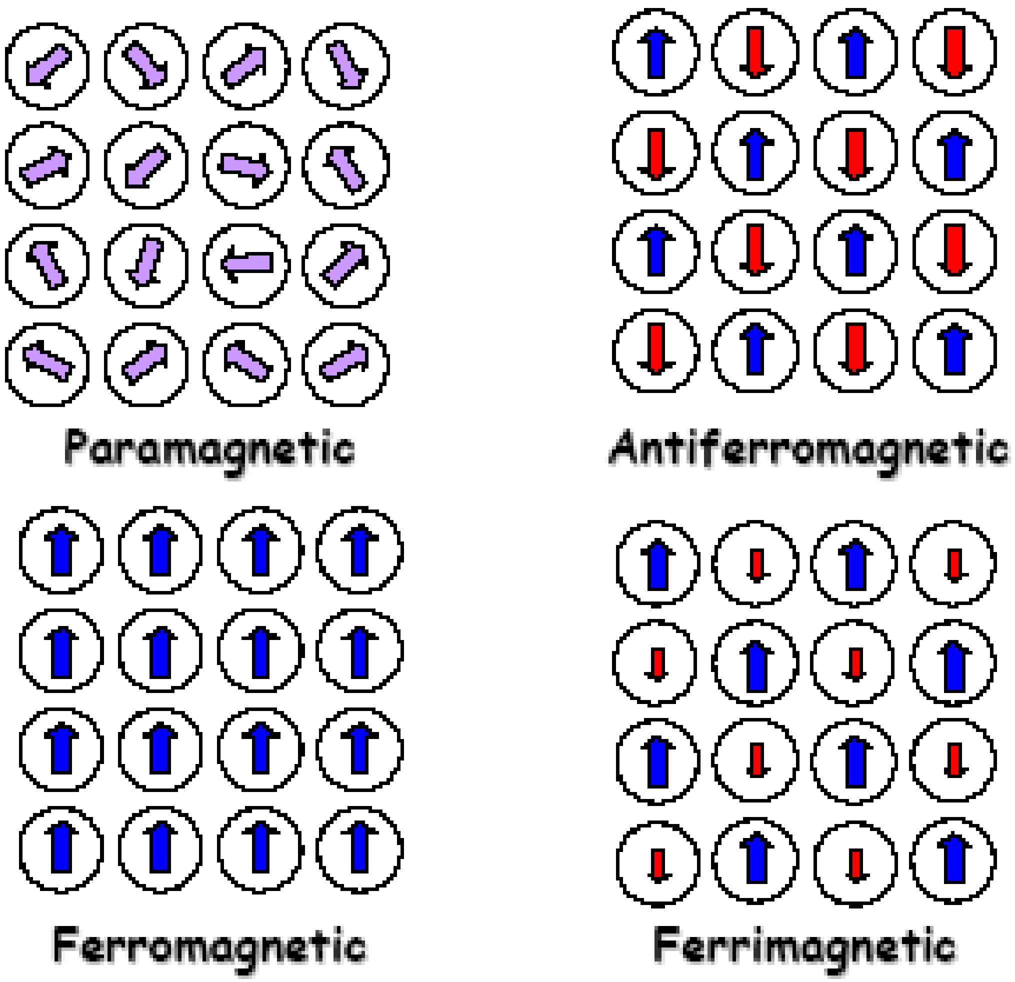
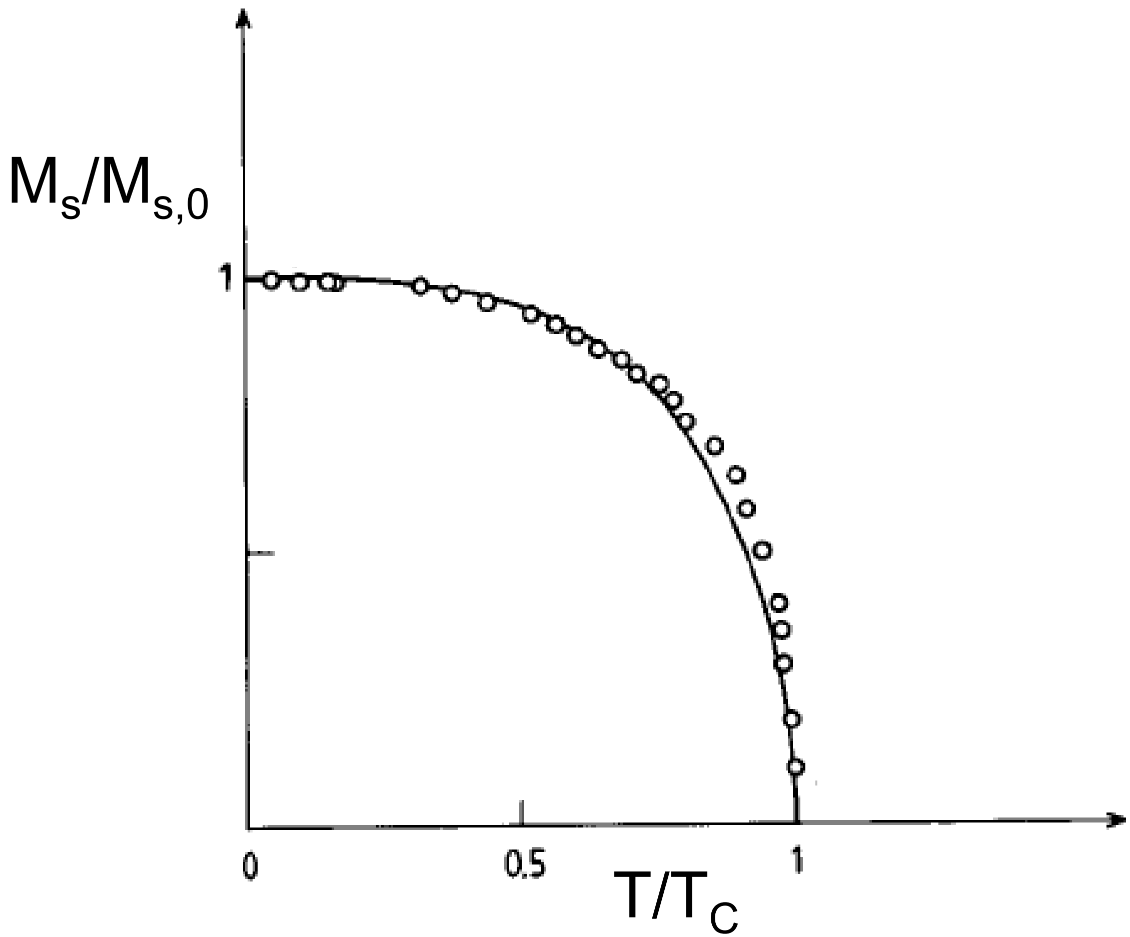
Magnetic order in low-dimensional systems

Magnetic order in solids





Ferromagnets

	T_C
Fe	1043 K
Co	1394 K
Ni	631 K
Gd	293 K

Antiferromagnets

	T_N
CoO	293 K
NiO	523 K

Localized Models: Heisenberg, Ising, …

point-like interacting magnetic moments

- X Non-integer magnetic moments in metals
- ✓ Modelization of thermal effects (spin waves), interpretation of T_C
- ✓ Modelization of spatial effects (magnetic domains)

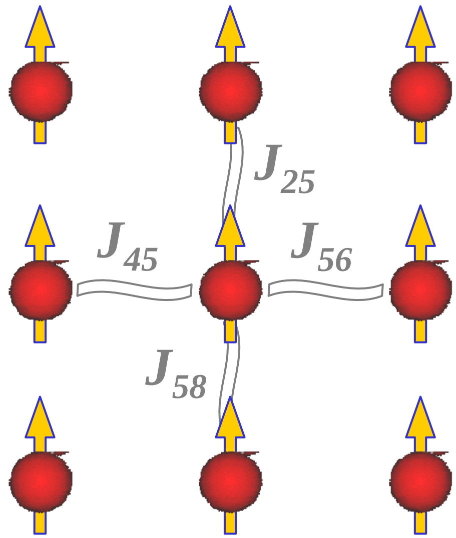
Itinerant Models:

Based on electronic band structure, delocalized electrons

- ✓ Non-integer magnetic moments in metals
- ✓ Prediction of ferromagnetism in Fe, Co, Ni; nonmagnetic 3*d*, 4*d*, 5*d* metals
- X Temperature dependence of *M*
- X Spatial dependence of *M* (e.g., due to magnetostatic interactions in homogeneous materials)

see also the lecture by E. Burzo

$$H = -\sum_{i \neq j} J_{\mathrm{ij}} \mathbf{S}_{\mathrm{i}} \cdot \mathbf{S}_{\mathrm{j}}$$ *Heisenberg model*

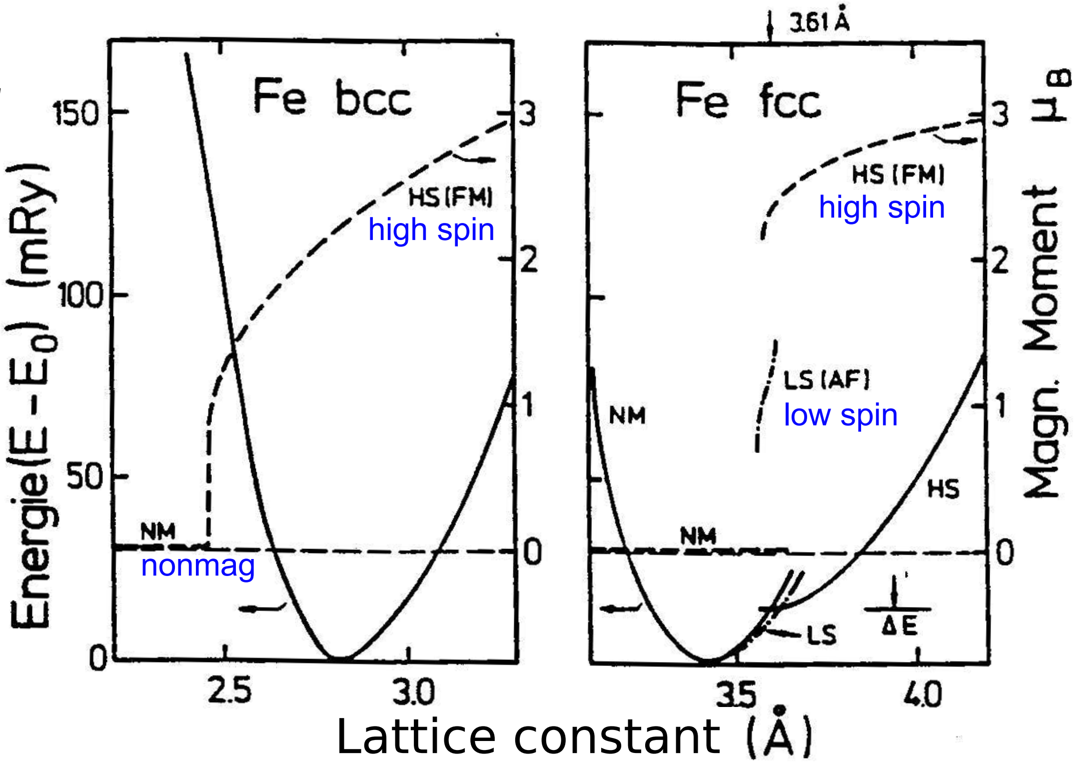


- There are many possible exchange-interaction Hamiltonians, e.g.:

$$H = -J_z \sum_{i \neq j} \mathrm{S}_{\mathrm{i}}^{\mathrm{z}} \mathrm{S}_{\mathrm{j}}^{\mathrm{z}} - J_{\perp} \sum_{i \neq j} \left(\mathrm{S}_{\mathrm{i}}^{\mathrm{x}} \mathrm{S}_{\mathrm{j}}^{\mathrm{x}} + \mathrm{S}_{\mathrm{i}}^{\mathrm{y}} \mathrm{S}_{\mathrm{j}}^{\mathrm{y}} \right)$$ *Anisotropic Heisenberg model and XY model (J_z=0)*

$$H = -J_z \sum_{i \neq j} \mathrm{S}_{\mathrm{i}}^{\mathrm{z}} \mathrm{S}_{\mathrm{j}}^{\mathrm{z}}$$ *Ising model*

Lattice binding energy + magnetic energy

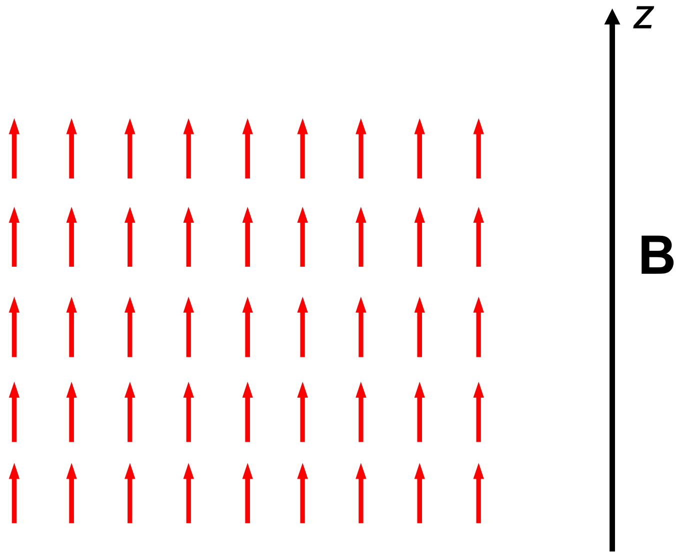


Moruzzi et al., Handbook of Mag. Materials Vol. 7

Heisenberg Hamiltonian in the presence of an external field

$$H_{Heisenberg} = -\frac{J}{2}\sum_{i,j}\mathbf{S}_\mathrm{i}\cdot\mathbf{S}_\mathrm{j} - \mathrm{g}\mu_\mathrm{B}\mathrm{B}\sum_i S_i^z$$

exchange Zeeman



Need for approximations: e.g., nearest neighbor interaction, mean-field

See lecture by C. Lacroix

$$\mathbf{S}_i = \left(\mathbf{S}_i - \langle \mathbf{S}_i \rangle\right) + \langle \mathbf{S}_i \rangle$$

$$\mathbf{S}_i \cdot \mathbf{S}_j = \underbrace{\left(\mathbf{S}_i - \langle \mathbf{S}_i \rangle\right) \cdot \left(\mathbf{S}_j - \langle \mathbf{S}_j \rangle\right)}_{} + \left(\mathbf{S}_i - \langle \mathbf{S}_i \rangle\right) \cdot \langle \mathbf{S}_j \rangle + \left(\mathbf{S}_j - \langle \mathbf{S}_j \rangle\right) \cdot \langle \mathbf{S}_i \rangle + \langle \mathbf{S}_i \rangle \cdot \langle \mathbf{S}_j \rangle$$

Fluctuations
(correlated deviations
from thermal average) → 0

$$\Rightarrow \mathbf{S}_i \cdot \mathbf{S}_j \approx 2\mathbf{S}_i \cdot \langle \mathbf{S}_j \rangle - \langle \mathbf{S}_i \rangle \cdot \langle \mathbf{S}_j \rangle$$

define $$\mathrm{m}(T) := \frac{\mathrm{M}(T)}{\mathrm{M}(0)} = \frac{\langle S_i^z \rangle}{S}$$

Temperature dependence of the magnetization in the mean field Heisenberg model

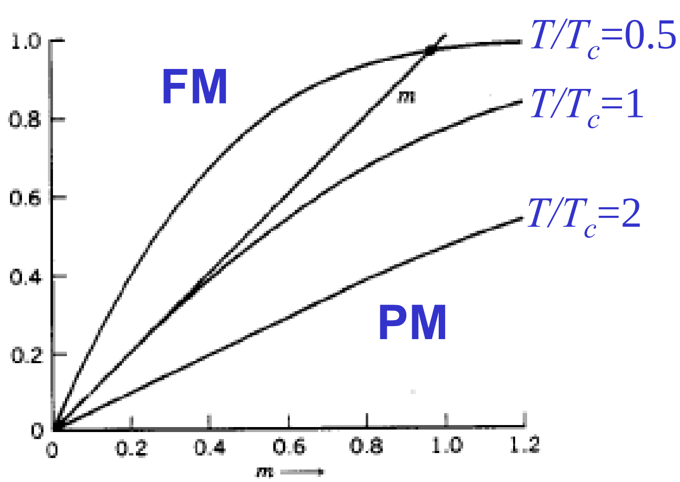
$$H = -\frac{J}{2}\sum_{i,j}\mathbf{S}_i\cdot\mathbf{S}_j - g\mu_B B\sum_i S_i^z \longrightarrow H \approx -\left(Jzm + g\mu_B B\right)\sum_i S_i^z + \frac{J}{2}Nzm^2$$

Number of neighbors

analogy with paramagnetic case

$$m = \mathfrak{B}_S\left(\frac{\mu_B g S B}{kT}\right) \longrightarrow m = \mathfrak{B}_S\left(\frac{Jzm + \mu_B g S B}{kT}\right)$$

Effective field (Weiss molecular field)



Graphical solution: intersection of $\mathfrak{B}_S\left(\frac{Jzm}{kT}\right)$ *vs.* m with line representing m

For small arguments $\mathfrak{B}_S(x) \approx \frac{S+1}{3S}x$

Limit intersection gives T_c

$$T_C = \frac{S+1}{3S}\frac{J_{exc}z}{k}$$

Temperature dependence of the magnetization in the FM Heisenberg model

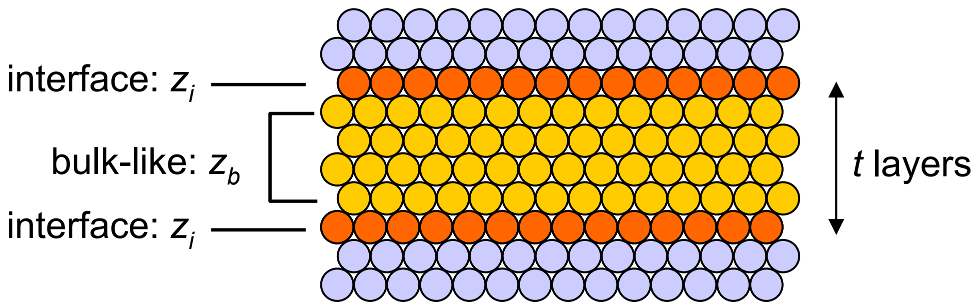
$$B_{\text{Weiss}} = \frac{J z m}{g \mu_B S}$$

The Heisenberg model provides an atomistic explanation of the Weiss field for a FM material

$$T_C = \frac{S+1}{3S} \frac{J_{exc} z}{k}$$

The Curie temperature depends on the number of nearest neighbors *z*.
E.g., for bcc Fe, $z = 8$, $T_c = 1040$ K, S ≈ 2, we get $J \approx 20$ meV.

⇒ **T_c nanostructures < T_c bulk**



The number of magnetic neighbors is reduced in a thin film

$$\bar{z} = \frac{t_b z_b + t_i z_i}{t_b + t_i} = z_b - 2\frac{z_b - z_i}{t}$$

1/*t* dependence

Experimental temperature dependence of the magnetization in thin films

$$T_C = \frac{S+1}{3S}\frac{J_{exc}z}{k} \quad \Rightarrow \quad \textbf{1/}t\textbf{ dependence}$$

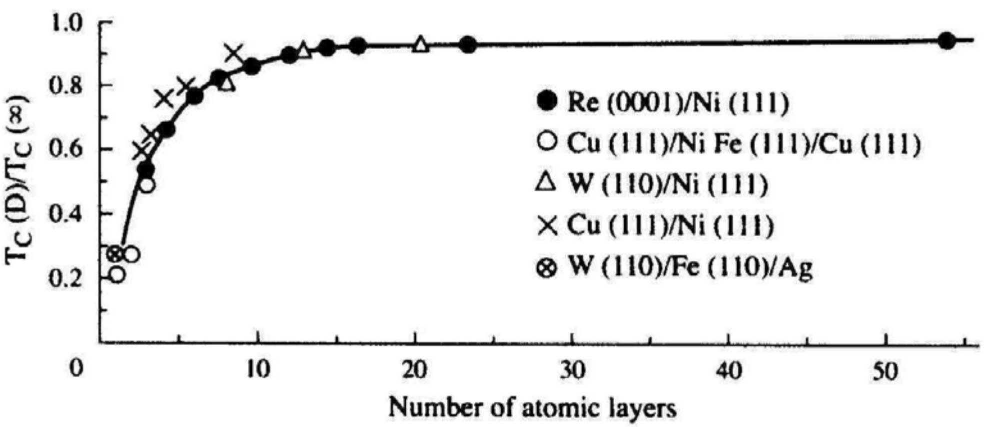
Critical Temperatures of Ising Lattice Films

G. A. T. Allan

Baker Laboratory, Cornell University, Ithaca, New York 14850

Phys. Rev. B 1, 352 (1970)

$$T_C(\infty) - T_C(t) \sim t^{-\lambda}, \quad \lambda = 1$$



Gradmann, Handbook of Mag. Materials Vol. 7

Experiment and finite-size scaling model:

$$\frac{T_C(\infty) - T_C(t)}{T_C(\infty)} = \left(\frac{t}{t_0}\right)^{-\lambda'}, \quad \lambda' = 1 - 1.4$$

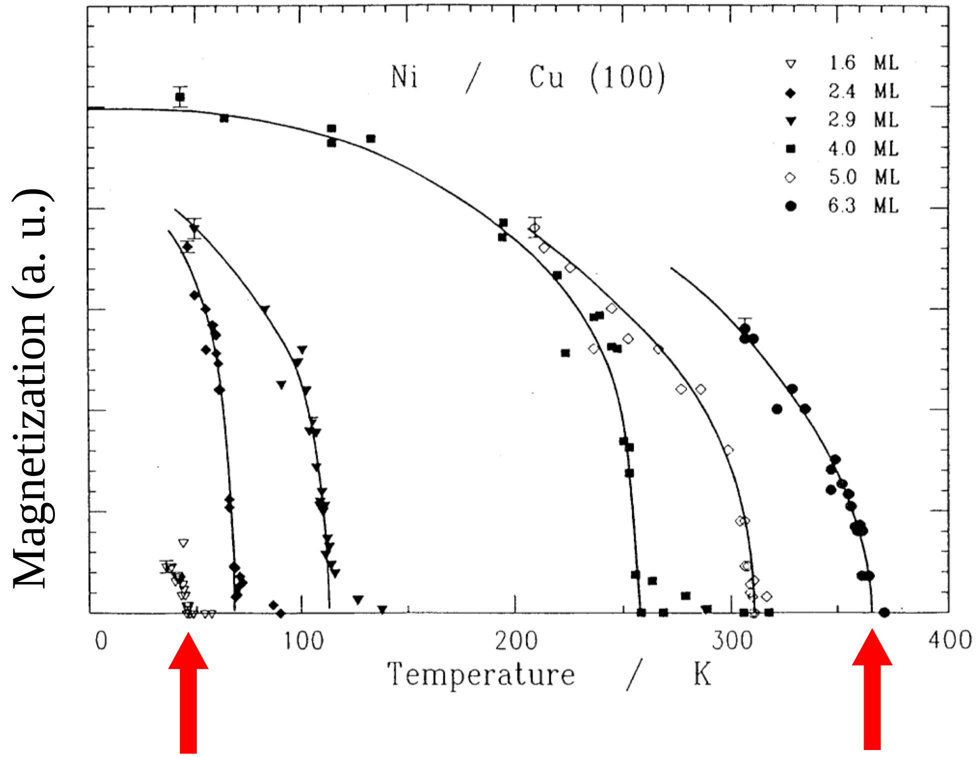
This model accounts for the decrease of T_C with t down to a critical thickness $t_0 \approx 4$ monolayers. Below t_0 ferromagnetic order can become unstable ($T_C = 0$) depending on the magnetic anisotropy.

Curie temperature vs. film thickness

$$M(T) = M(0)\left(1 - \frac{T}{T_C}\right)^{\beta}$$

2D films

Tischer et al., *Surf. Sci.* 1993



1.6 ML: T_C = 45 K

6.3 ML: T_C = 370 K

Critical exponents in 3D and 2D systems: zero field magnetization close to T_C

$$m \approx (T_C - T)^{\beta}$$

Mean Field	3D Ising	2D Ising	1D Ising
$\beta = 1/2$	$\beta = 0.33$	$\beta = 1/8$	-

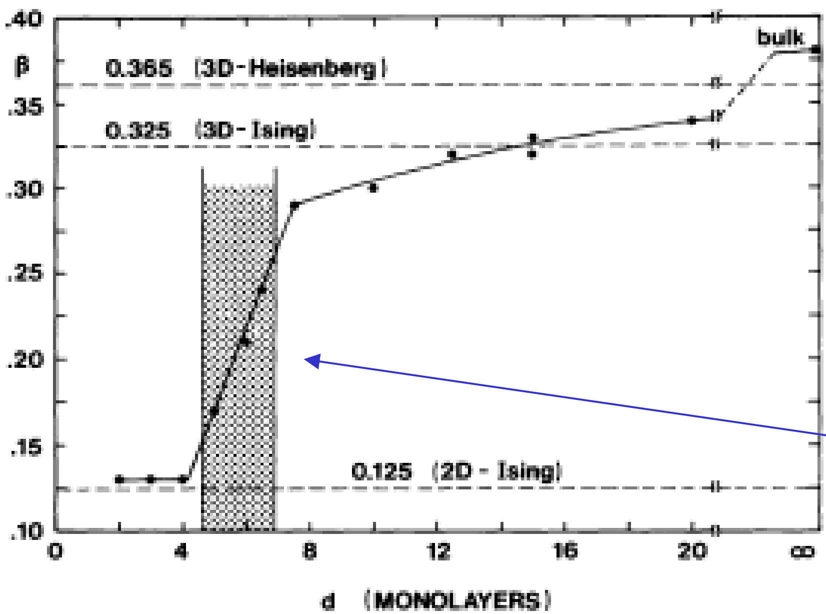


FIG. 2. Critical exponent β as a function of film thickness (error bars are given in Table I). The dashed lines show the theoretical values for a 3D Heisenberg, 3D Ising, and 2D Ising system. The shaded regime marks the crossover from 3D to 2D.

Ni films on W(110)

***t* = 2 - 20 monolayers**

Li and Babershcke, Phys. Rev. Lett. 68, 1208 (1992).

2D -3D crossover of magnetic behavior

For a review of critical parameters in magnetic materials see, e.g., Kadanoff Rev. Mod. Phys. 39, 395 (1967).

Limitations of Mean Field theory:

- It does not take into account spin waves and fluctuations
- T_C depends on the number of neighbors only, but in reality also on the lattice dimensionality and symmetry.

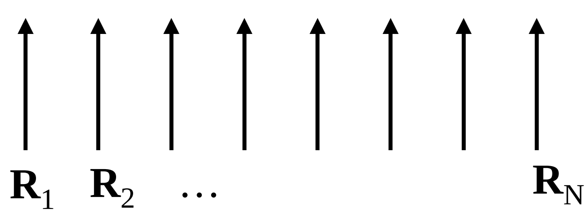
Excitated states of the Heisenberg Hamiltonian correspond to magnons

$$H = -\frac{J}{2}\sum_{i,j} \mathbf{S}_i \cdot \mathbf{S}_j$$

Ground state, $T = 0$

$$|0\rangle = |S\rangle_{\mathbf{R}_1} |S\rangle_{\mathbf{R}_2} \ldots |S\rangle_{\mathbf{R}_N}$$

$$E_0 = -NJzS^2$$



Excited states, $T > 0$

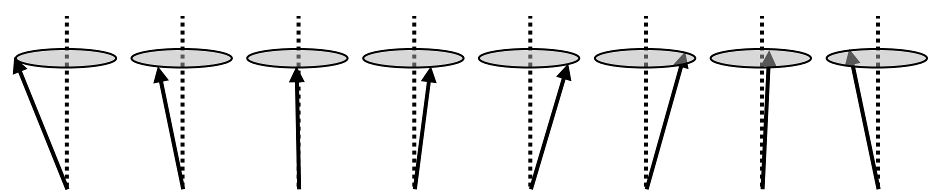
$$|\mathbf{R}_i\rangle = \frac{1}{\sqrt{2S}} \mathbf{S}_-(\mathbf{R}_i)|0\rangle = |S\rangle_{\mathbf{R}_1} |S\rangle_{\mathbf{R}_2} \ldots |S-1\rangle_{\mathbf{R}_i} \ldots |S\rangle_{\mathbf{R}_N}$$

$$|\mathbf{q}\rangle = \sum_{\mathbf{R}_i} e^{i\mathbf{q}\cdot\mathbf{R}_i} |\mathbf{R}_i\rangle$$

$$H = E_0 - \sum_{\mathbf{q}} \hbar\omega(\mathbf{q}) a^\dagger_{\mathbf{q}} a_{\mathbf{q}}$$

$$\hbar\omega(\mathbf{q}) \sim 2JSa^2q^2 = Dq^2$$

spin wave stiffness



Hamiltonian
$$H = E_0 - \sum_q \hbar\omega(\mathbf{q}) a_q^\dagger a_q$$

Avg. number of magnons in state **q**
$$\langle n_q \rangle = \frac{1}{e^{\hbar\omega(q)/kT} - 1}$$

Magnetization at finite *T*
$$M(T) = M(0) - \mu_B S \frac{1}{V} \sum_q \langle n_q \rangle,$$

$$\Rightarrow M(0)\text{-}M(T) \to \mu_B S \frac{1}{(2\pi)^3} \int_{B.Z.} \frac{d\mathbf{q}}{e^{\hbar\omega(\mathbf{q})/kT} - 1} \approx \mu_B S \frac{1}{(2\pi)^3} \int_{-\infty}^{-\infty} \frac{d\mathbf{q}}{e^{D\mathbf{q}^2/kT} - 1}$$

In 3D, Bloch $T^{3/2}$ dependence:

Substitution and integration on solid angle
$$\frac{Dq^2}{kT} \to x \quad \Rightarrow \quad M(0)\text{-}M(T) \approx \mu_B S \frac{1}{4\pi^2} \left(\frac{kT}{D}\right)^{3/2} \int_0^\infty \frac{\sqrt{x}}{e^x - 1} dx$$

Small wavevector, finite *T* approximation:
$$\int_{-\infty}^{-\infty} \frac{d\mathbf{q}}{e^{D\mathbf{q}^2/kT} - 1} \approx \int_{-\infty}^{-\infty} \frac{d\mathbf{q}}{1 + D\mathbf{q}^2/kT - 1} \propto \int_{-\infty}^{-\infty} \frac{d\mathbf{q}}{\mathbf{q}^2}$$

Diverges in less than 3D

Absence of magnetic order in 2D and 1D at *T* > 0

F. Bloch, Z. Phys. 61, 206 (1930); N.D. Mermin and H. Wagner, Phys. Rev. Lett. 17, 1183 (1966).

VOLUME 17, NUMBER 22 PHYSICAL REVIEW LETTERS 28 NOVEMBER 1966

ABSENCE OF FERROMAGNETISM OR ANTIFERROMAGNETISM IN ONE- OR TWO-DIMENSIONAL ISOTROPIC HEISENBERG MODELS*

N. D. Mermin† and H. Wagner‡
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York
(Received 17 October 1966)

It is rigorously proved that at any nonzero temperature, a one- or two-dimensional isotropic spin-S Heisenberg model with finite-range exchange interaction can be neither ferromagnetic nor antiferromagnetic. The method of proof is capable of excluding a variety of types of ordering in one and two dimensions.

VOLUME 87, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 2001

Absence of Spontaneous Magnetic Order at Nonzero Temperature in One- and Two-Dimensional Heisenberg and *XY* Systems with Long-Range Interactions

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(Received 6 May 2001; published 7 September 2001)

The Mermin-Wagner theorem is strengthened so as to rule out magnetic long-range order at $T > 0$ in one- or two-dimensional Heisenberg and XY systems with *long-range* interactions decreasing as $R^{-\alpha}$ with a sufficiently large exponent α. For *oscillatory* interactions, ferromagnetic long-range order at $T > 0$ is ruled out if $\alpha \geq 1 (D = 1)$ or $\alpha > 5/2 (D = 2)$. For systems with *monotonically decreasing* interactions, ferro- or antiferromagnetic long-range order at $T > 0$ is ruled out if $\alpha \geq 2D$.

Magnetic order in anisotropic 2D systems

Heisenberg model: low-T spin wave excitations -> collapse of magnetic order in 2D and 1D

Model assumes ideal isotropic spins

In a real magnetic material, the presence of an effective magnetic anisotropy field

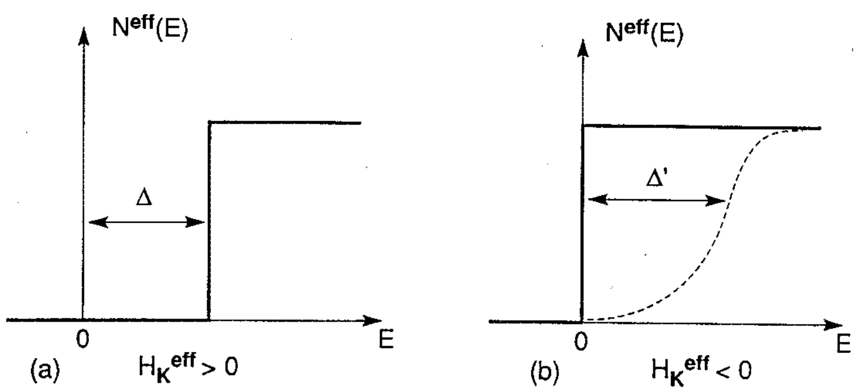
$$H_K^{eff} = \frac{2H_K}{n} - 4\pi M_s$$

anisotropy field (H_K); number of atomic planes (n); dipolar anisotropy ($4\pi M_s$)

opens a gap at the bottom of the spin-wave excitation spectrum of width

$$\Delta = 2\mu_B H_K^{eff}$$ Out-of-plane

$$\Delta' = 2\mu_B \frac{H_{dip}}{8}\sqrt{\frac{2\mu_B H_K^{eff}}{2JS}}$$ In-plane



The presence of magnetic anisotropy allows for ferromagnetic order to set in

$$\Rightarrow \text{finite Curie Temperature}$$

$$T_C = \frac{4\pi(S+1)}{3} \frac{2JS}{\ln\left(8\pi JS/\Delta\right)}$$

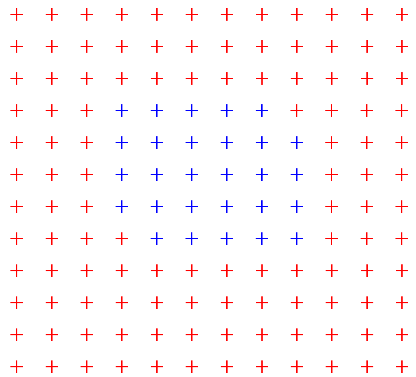
N.B. 1: T_C depends logarithmically on the magnetocrystalline (out-of-plane case) or dipolar (in-plane case) anisotropy, but linearly on the number of n.n. and exchange. T_C is only weakly influenced by the magnetic anisotropy.

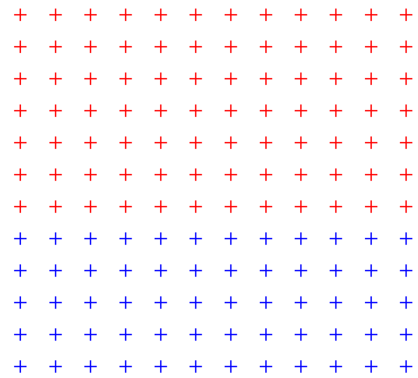
N.B. 2: $\Delta > \Delta' \Rightarrow T_C^{\perp} > T_C^{\parallel}$

P. Bruno, Phys. Rev. B 43, 6015 (1991);
P. Bruno, Mater. Res. Soc. Symp. Proc. 231, 299 (1992);
M. Bander and D. L. Mills, Phys. Rev. B 38, 12015 (1988).

ferromagnetic order in anisotropic 2D systems: Ising model

*N*x*N* localized moments





Energy cost of this excited state: 2NJ;

There are N such states, entropy = k lnN

change in free energy:
$\Delta F = 2NJ - kT\ln(N)$

Disorder is favored for

$$kT > \frac{2NJ}{\ln N}$$

exact solution (due to Onsager) : long-range magnetic order prevails for $kT < \dfrac{2J}{\ln\left(1+\sqrt{2}\right)}$

A 2D Ising system is less sensitive to thermal fluctuations with respect to the 1D case.
A finite Curie teperature exists, given by

$$T_c = \frac{2J}{k\ln\left(1+\sqrt{2}\right)}$$

"DEAD" LAYERS IN FERROMAGNETIC TRANSITION METALS*

L. Liebermann and J. Clinton
University of California, La Jolla, California 92037

and

D. M. Edwards and J. Mathon†
Imperial College, London, S. W. 7, England

(Received 1 June 1970)

"Magnetically "dead" layers […] are observed in nickel. From the temperature dependence of this effect it is deduced that two dead layers persist at T = 0, independent on the film thickness. […] The existence of dead layers at T = 0 is attributed to a transfer of electrons from the s band to the d band in the neighborhood of a surface."

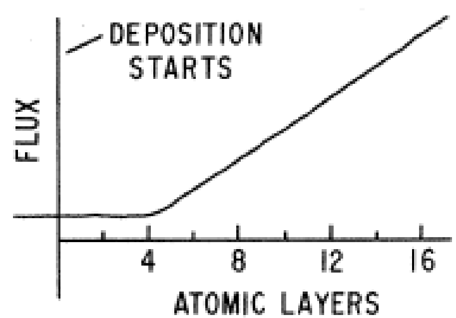


FIG. 1. Recording of the saturation flux as the thickness of a nickel film is continuously increased by electrolytic deposition. Four dead layers (or their equivalent) remain dead as the film thickness continues to grow.

PHYSICAL REVIEW B VOLUME 9, NUMBER 10 15 MAY 1974

Hot-electron scattering length by measurement of spin polarization

D. T. Pierce and H. C. Siegmann
Laboratorium für Festkörperphysik, Eidgenossische Technische Hochschule, CH-8049 Zürich, Switzerland

[…] A nonzero electron spin-polarization is observed in very thin Ni films showing that ferromagnetism occurs already in films of one or two layers average thickness.

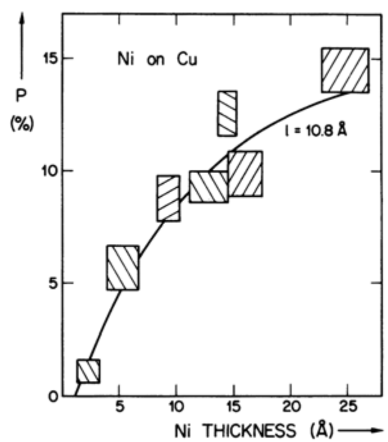


FIG. 1. Polarization P as a function of Ni film thickness is given by the rectangular fields where the vertical dimension represents the statistical uncertainty (one standard deviation) and the horizontal dimension represents the estimated uncertainty of the average film thickness. Fields with the same cross hatching are for films successively evaporated on the same Cu substrate. The solid curve is a least-squares fit of an exponential (see text) to the points.

$$P = P_{Ni}\left(1 - e^{(x-x_0)/t}\right)$$

$$P_{Ni} \approx 15\%$$

$$x_0 \approx 1.2 \pm 1\ \text{Å}$$

Estimated thickness of dead layer

VOLUME 59, NUMBER 10 PHYSICAL REVIEW LETTERS 7 SEPTEMBER 1987

Ferromagnetic Order in a Fe(110) Monolayer on W(110) by Mössbauer Spectroscopy

M. Przybylski[(a)] and U. Gradmann
Physikalisches Institut, Technische Universität Clausthal, D-3392 Clausthal-Zellerfeld, Federal Republic of Germany
(Received 22 June 1987)

"As strong crystalline anisotropies are present in monolayers, the physical problem is magnetic order in an anisotropic monolayer, not in the isotropic one."

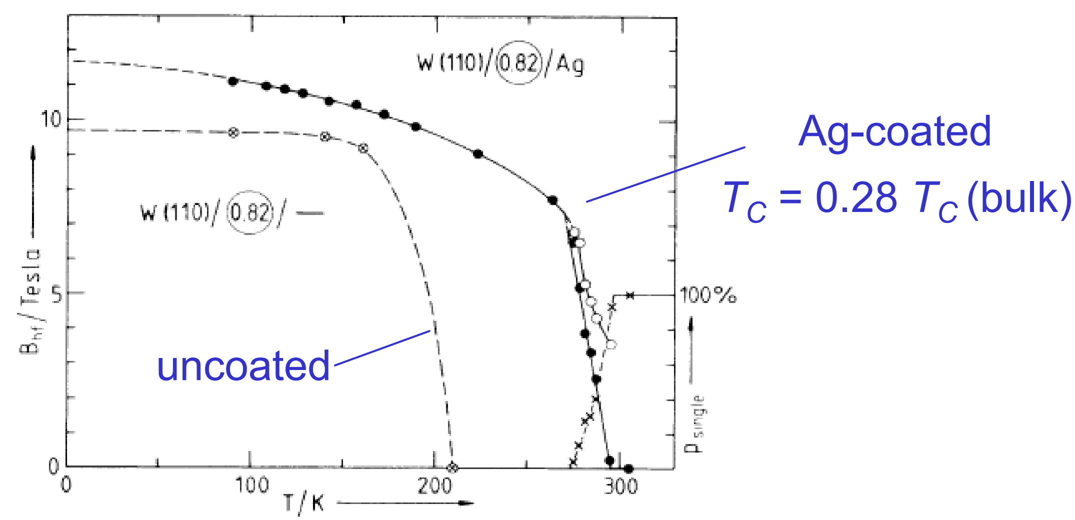


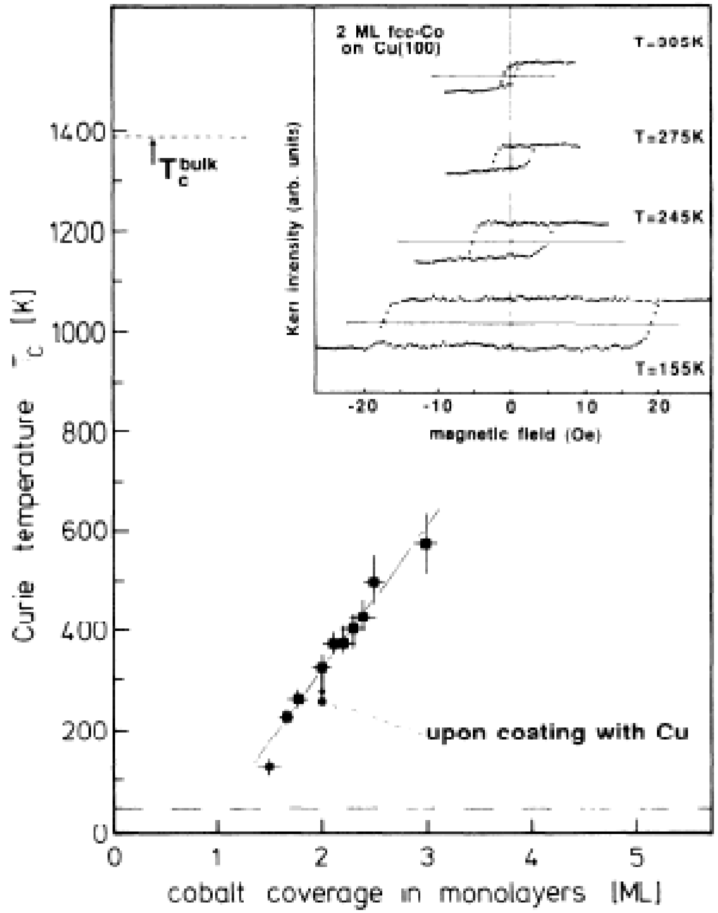
FIG. 3. Magnetic hyperfine fields $B_{hf}(T)$ vs temperature for pseudomorphic Fe(110) monolayers on W(110). Mean values B_{hf} (filled circles) and B_{hf} for the magnetic component (open circles) for the Ag-coated layer [W(110)/Fe(0.82 ML)/Ag]. B_{hf} from extrapolation and $T_C(1)$ from thermal scan for the uncoated monolayer (circled crosses).

Experiments: magnetic order is present in 2D monolayer systems

1 ML Fe/Au(100), Cu(100) - S.D. Bader and E.R. Moog, J. Appl. Phys. 61, 3729 (1987)

1 ML Fe/Au(111) with $T_C \approx 315$ K - W. Dürr et al., Phys. Rev. Lett. 62, 206 - 209 (1989)

1 ML Co/Cu(100) with $T_C \approx 50$ K - C.M. Schneider et al., Phys. Rev. Lett. 64, 1059 (1990).



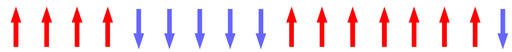
fcc Co/Cu(100)

Schneider et al.

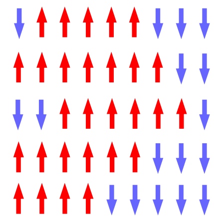
Ferromagnetic order in 1D atomic chains: theoretical models

- **Heisenberg model: at *T* > 0, no FM state in 1D and 2D**

  Mermin & Wagner, PRL 1966; Bruno, PRL 2001.



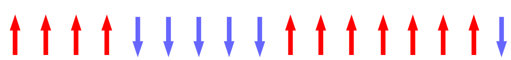
1D



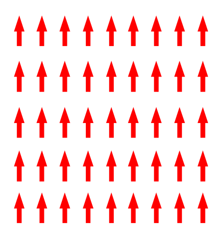
2D

- **Anisotropic Heisenberg model and Ising model: FM state in 2D not in 1D**

  Ising, Z. Phys. 1925; Bander & Mills, PRB 1989



1D

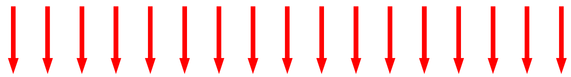


2D

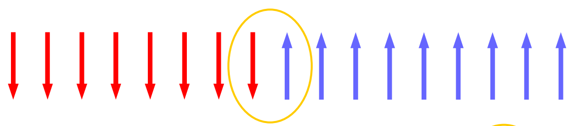
ferromagnetic order in finite 1D systems: Ising model

ISING-LIKE MODEL

• Finite system (N localized moments):



ground state: $E=E_0$



lowest excited state: $E=E_0 + 2J$
(N-1 such states)

change in free energy: $\Delta F = \Delta E - T\,\Delta S = 2J - kT\ln(N-1)$

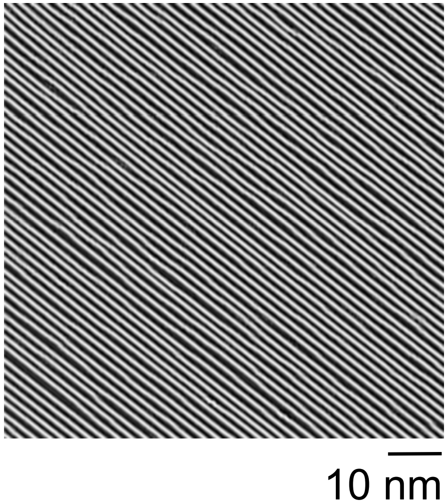
$\Delta F<0$ ⇨ no ferromagnetism for $N > exp(2J/kT)$

Interatomic exchange energy $2J \approx 15$ meV

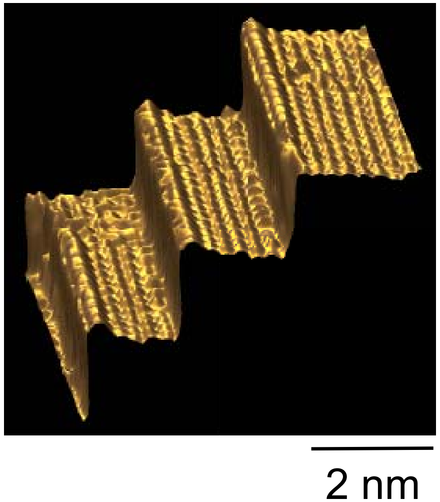
→ ferromagnetism is allowed only for

$N < 50$ atoms at $T = 50$ K

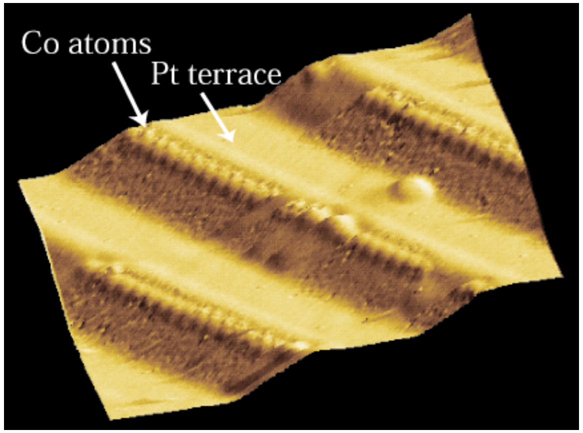
Self-assembly of one-dimensional metal chains



Deposition template:
stepped platinum surface



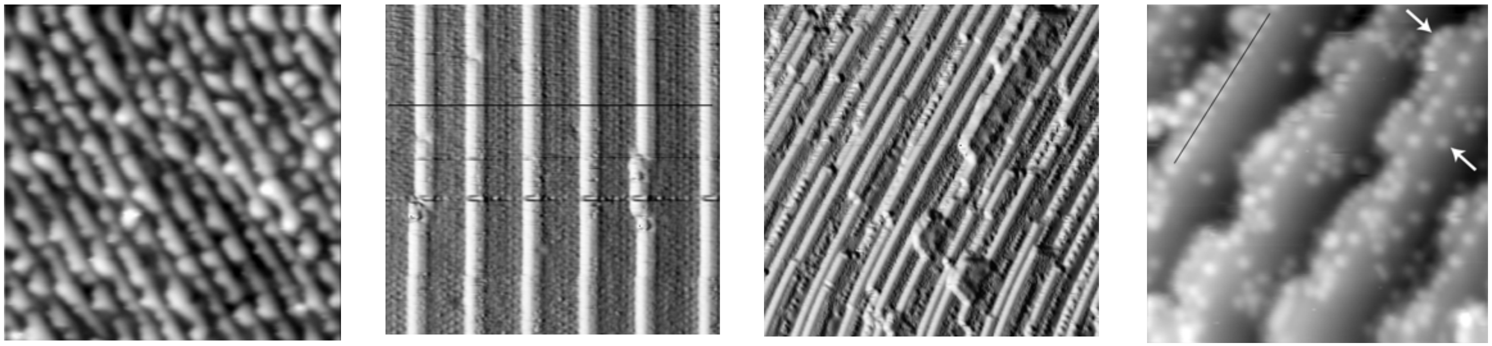
Detail of Pt steps



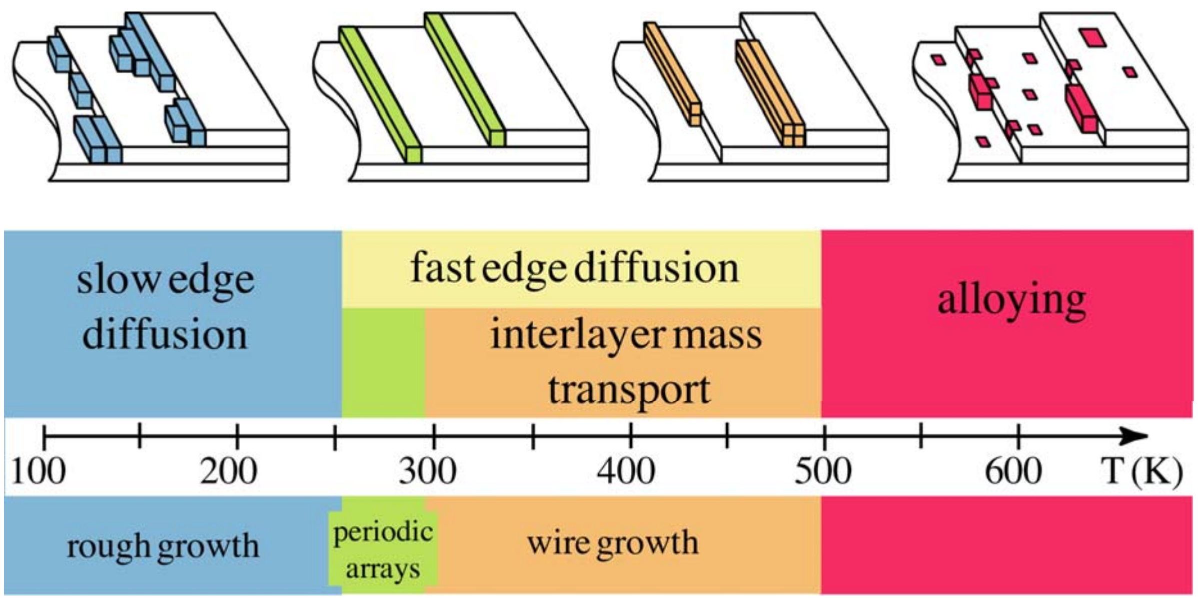
Array of parallel monatomic Co chains

P. Gambardella *et al., Phys. Rev.* B 61, 2254 (2000); *Surf. Sci*. 449, 93 (2000)

Epitaxial growth of 1D atomic chains

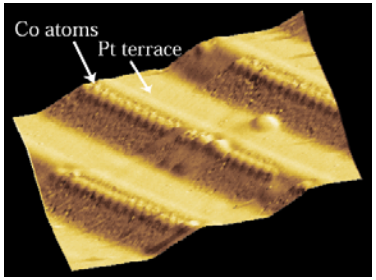


Ni/Pt(997)
1 x 2 alloy
T = 200 K

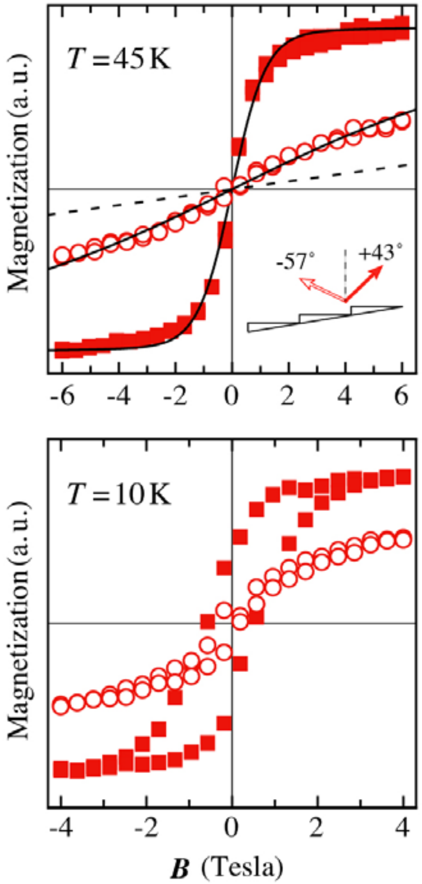


P. Gambardella, J. Phys.: Condens. Matter **15**, S2533 (2003).

Ferromagnetic order in 1D atomic chains: experiment



Monatomic Co chains



Magnetization curve: segments of about 15 atoms are ferromagnetically coupled

→ short-range FM order

Easy/hard axis magnetization: strong magnetic anisotropy (2.1 meV/atom)

↓

Metastable FM state stabilized by large anisotropy barriers

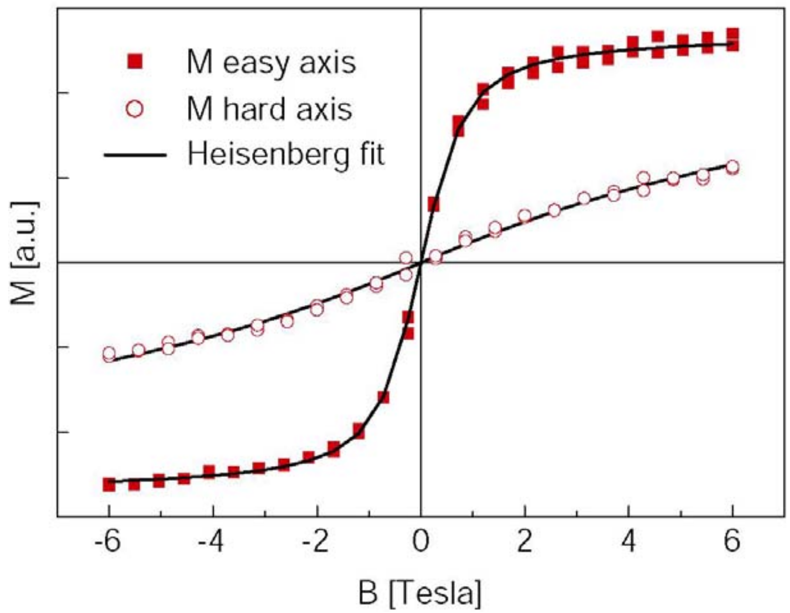
→ long-range FM order

Nature **416**, 301 (2002).

1D Heisenberg model of a chain of *N* Co atoms with open boundary conditions

$$H = -\sum_{i=1}^{N-1} J\,\vec{S}_i \cdot \vec{S}_{i+1} - \sum_{i=1}^{N}\left[K\,(S_i^z)^2 + g_{Co-Pt}\,\mu_B \vec{B}\cdot\vec{S}_i\right]$$

$$M^\alpha = \frac{g_{Co-Pt}}{N}\sum_{i=1}^{N}\left\langle S_i^\alpha \right\rangle$$



fixed parameters:

N = 80
T = 45 K
$g_{Co\text{-}Pt}$ = 3.8, $||S_i||$ = 1

fitting parameters:

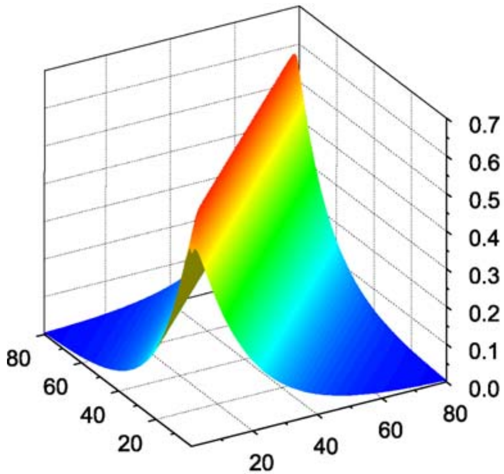
J = 20 meV
K = 3.3 meV

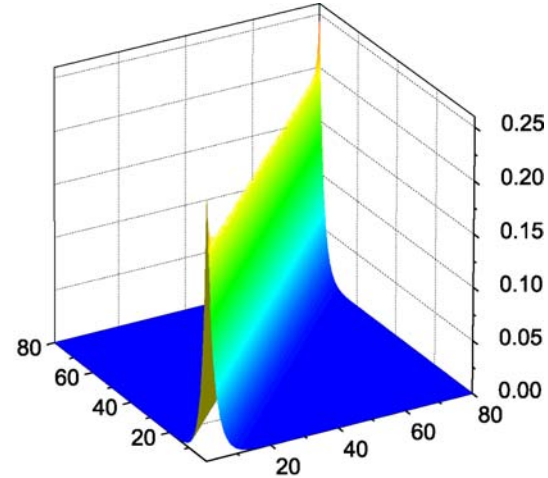
A. Vindigni, A. Rettori, M.G. Pini, C. Carbone, P. Gambardella, *Appl. Phys. A* ***82****, 385 (2006).*

Spin-spin correlation matrix in zero field

easy axis | **hard axis**

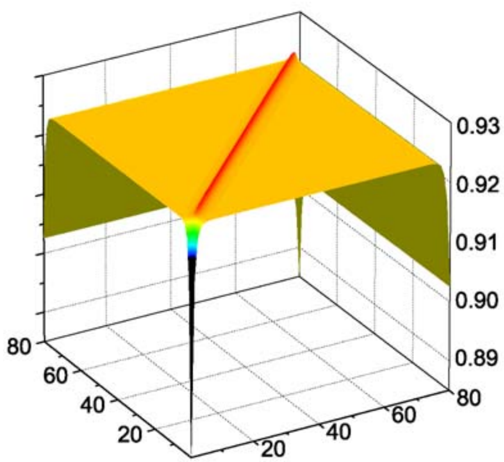
$\langle S_i^z S_j^z \rangle$ $T = 45$ K

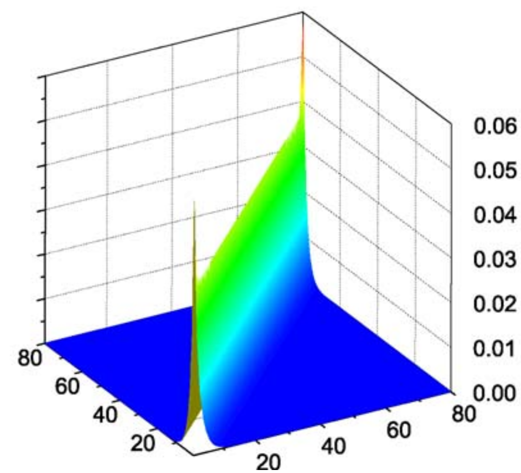




$\langle S_i^x S_j^x \rangle$ $T = 45$ K

$\langle S_i^z S_j^z \rangle$ $T = 10$ K

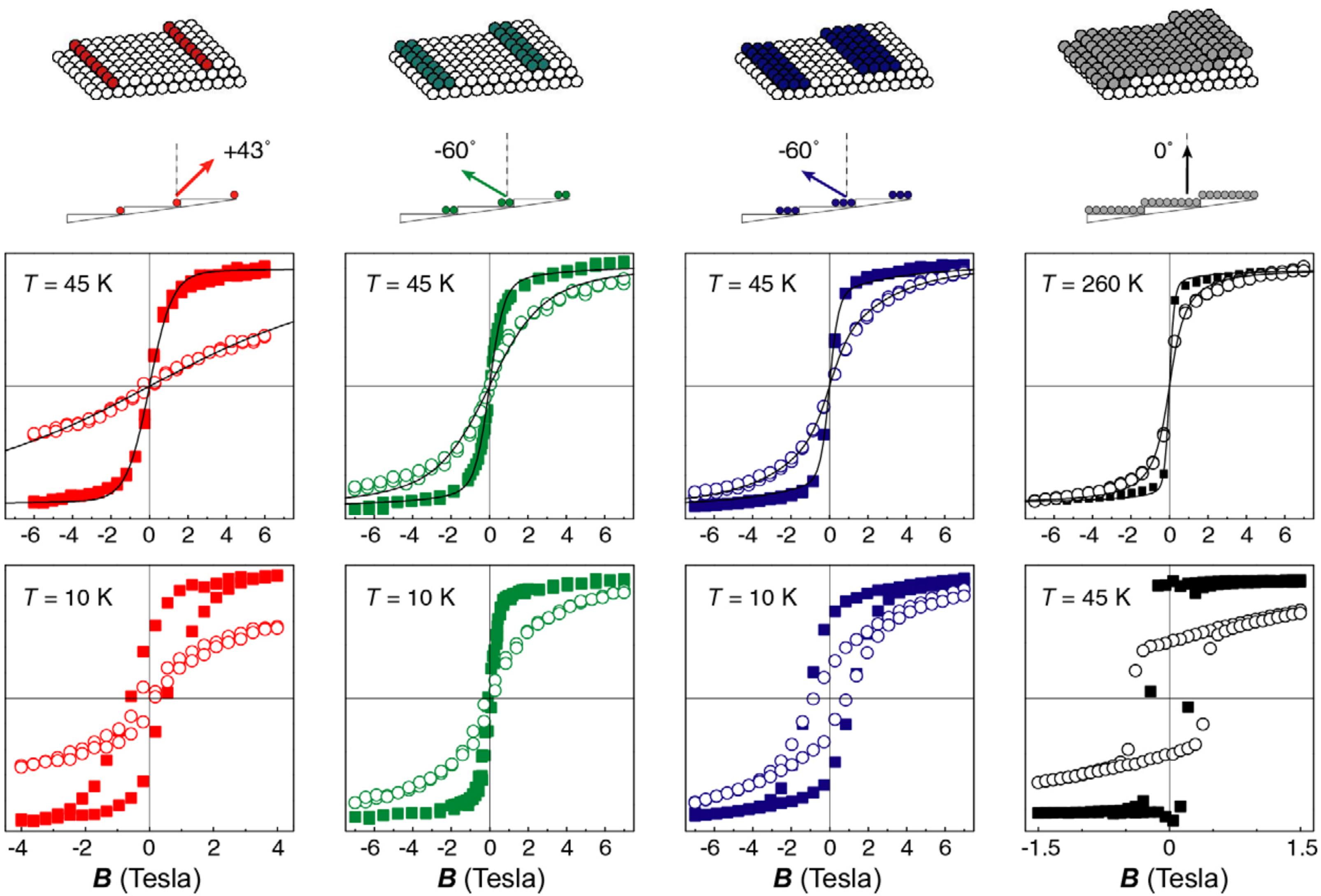




$\langle S_i^x S_j^x \rangle$ $T = 10$ K

A. Vindigni, A. Rettori, M.G. Pini, C. Carbone, P. Gambardella, *Appl. Phys. A* ***82****, 385 (2006).*

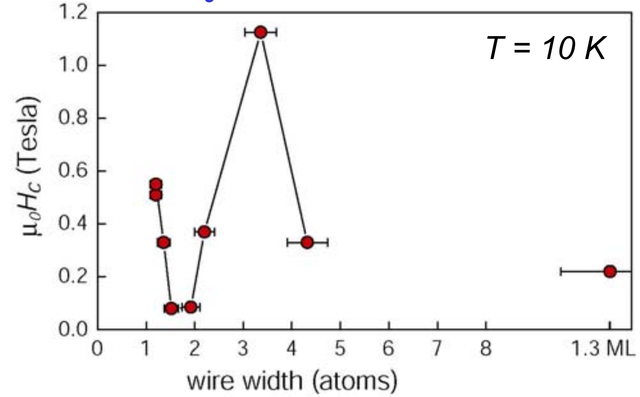
Influence of magnetic anisotropy on the FM properties of 1D atomic chains



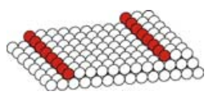
K = 2.1 meV/atom	**K = 0.34 meV/atom**	**K = 0.47 meV/atom**	**K = 0.13 meV/atom**
m_L = 0.68 μ_B	**m_L =0.37 μ_B**	**m_L =0.33 μ_B**	**m_L =0.31 μ_B**

P. Gambardella et al., *Phys. Rev. Lett.* **93**, 077203 (2004).

H_c parallel to easy axis

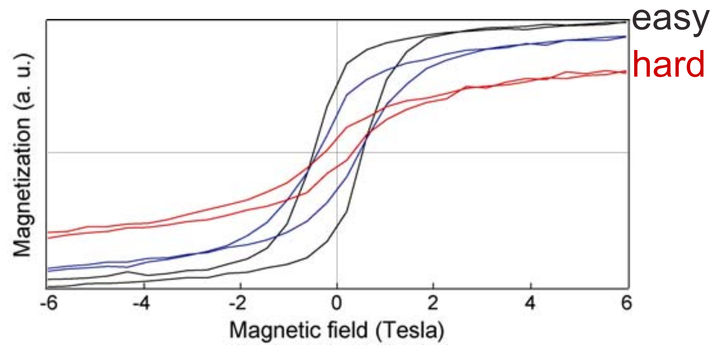


H_c oscillations vs. chain width reflect K changes

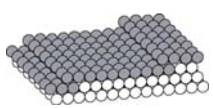


H_c easy > H_c hard

Stoner-Wohlfart like

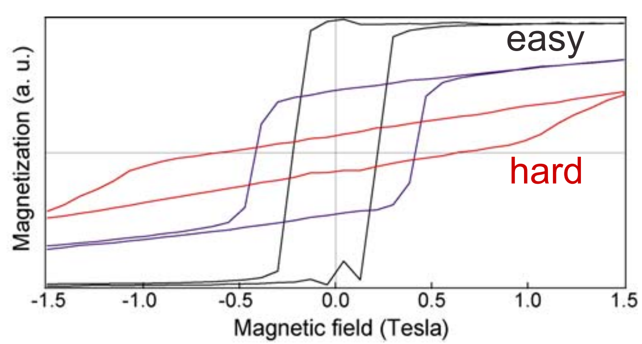


H_c angular dependence reflects the mechanism of magnetization reversal



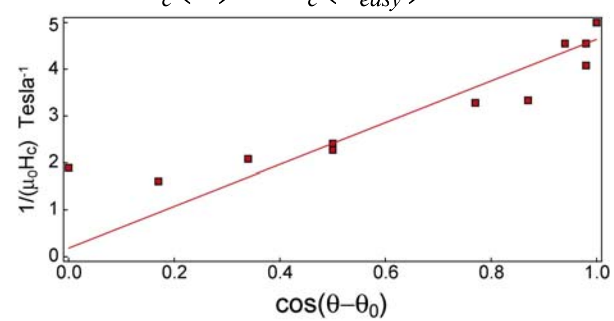
H_c easy < H_c hard

nucleation and growth of reverse domains



Kondorsky relation:

$$H_c(\vartheta) = H_c(\vartheta_{easy}) / \cos\vartheta$$



Decrease of T_N with decreasing AFM thickness

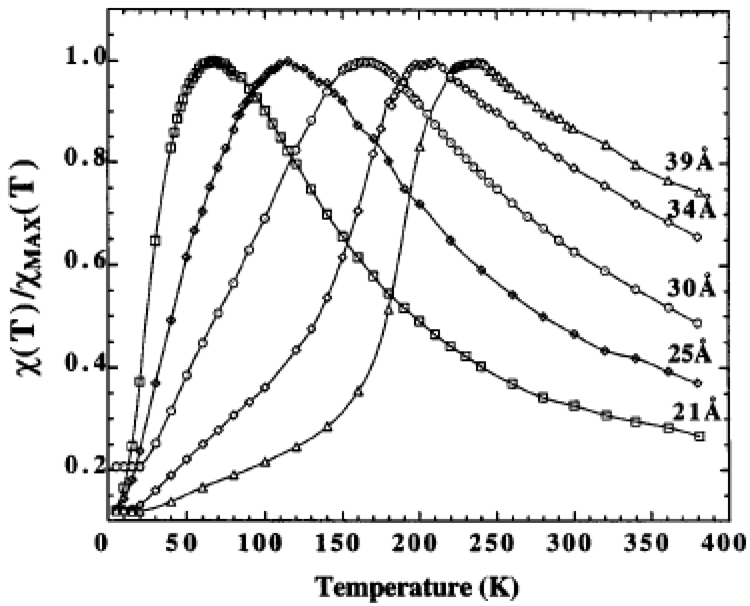
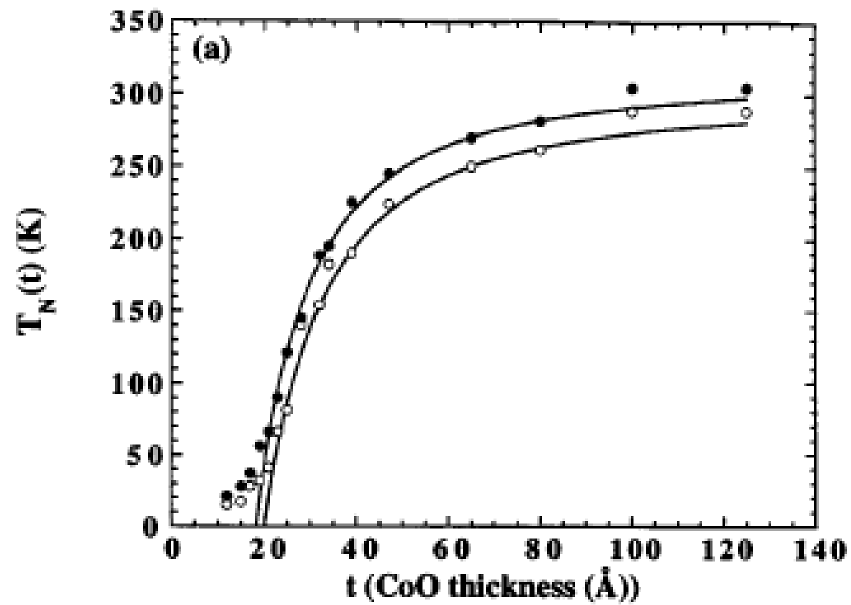


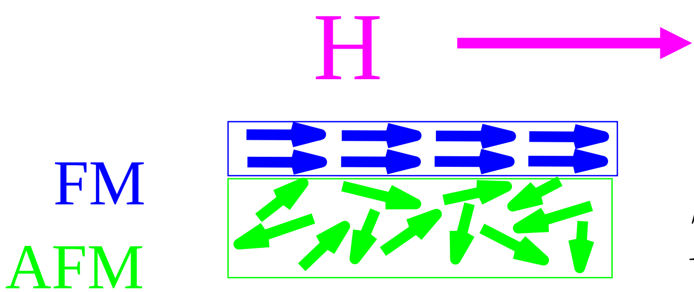
FIG. 2. Temperature dependence of dc susceptibility at H = 100 Oe of representative multilayer samples of CoO/SiO_2 with a fixed SiO_2 layer thickness of 50 Å and various CoO layer thicknesses of t = 21, 25, 30, 34, and 39 Å. For clarity, the results are normalized to the maximum susceptibility.



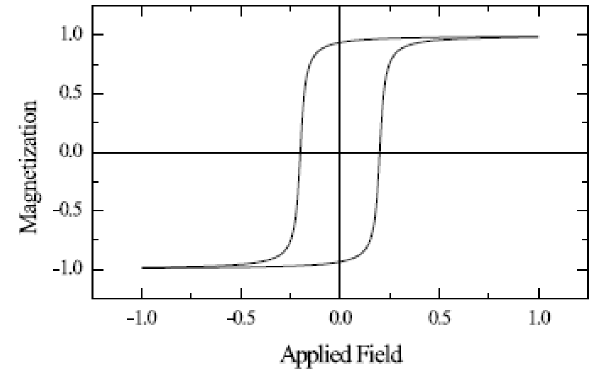
CoO - T. Ambrose and C. L. Chien, Phys. Rev. Lett. 76, 1743 (1996).

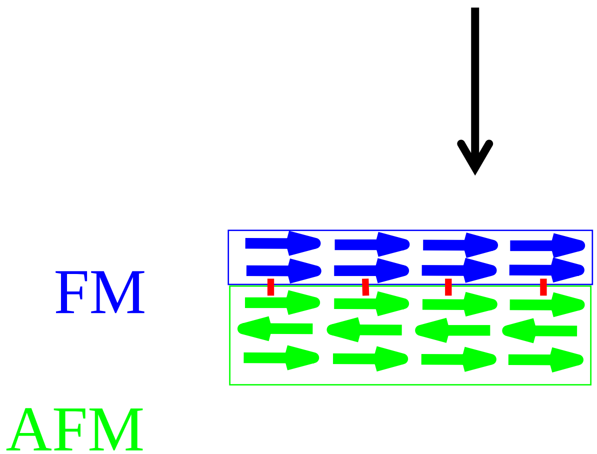
FeF_2 - D. Lederman, C. A. Ramos, V. Jaccarino, and J. L. Cardy, Phys. Rev. B 48, 8365 (1993)

Exchange biased films



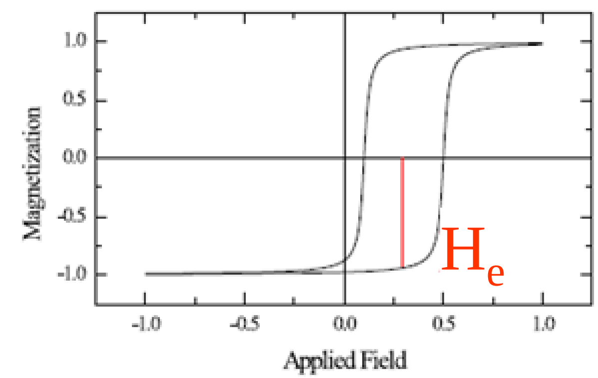
$$T_C > T > T_B\,,\ T_N$$





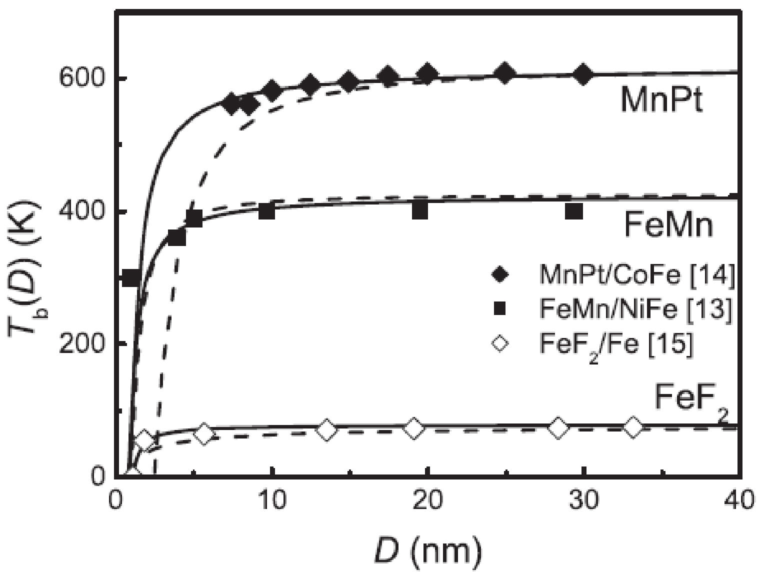
Field Cooling

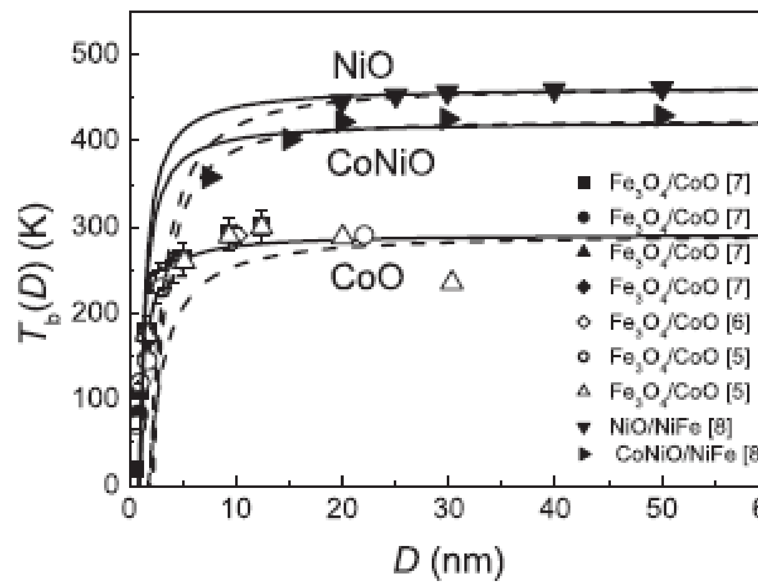
$$T < T_B\,,\ T_N$$



Usually, but not always, $T_B < T_N$, see Nogues et al., Phys. Rep. 422, 65 (2005) and refs. therein.

T_B vs AFM film thickness in polycrystalline materials





$$\frac{T_B(D)}{T_B(\infty)} = 1 - \left(\frac{J_{FM/AFM}}{2raK_{AFM}D}\right)^{\delta}$$

δ — 0.6-1.5

r: grain size; a: lattice const.; K_{AFM}: anisotropy energy

Lang et al., Nanotechnology 18, 155701 (2007).

AFM vs FM magnetic order in 2D films

VOLUME 38, NUMBER 8 PHYSICAL REVIEW LETTERS 21 FEBRUARY 1977

Existence of Phase Transitions for Anisotropic Heisenberg Models

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(Received 21 December 1976)

The two-dimensional anisotropic, nearest-neighbor Heisenberg model on a square lattice, both quantum and classical, has been shown rigorously to have a phase transition in the sense that the spontaneous magnetization is positive at low temperatures. This is so for all anisotropies. An analogous result (staggered polarization) holds for the antiferromagnet in the classical case; in the quantum case it holds if the anisotropy is large enough (depending on the single-site spin). *i.e., if* $|S| \geq 1$

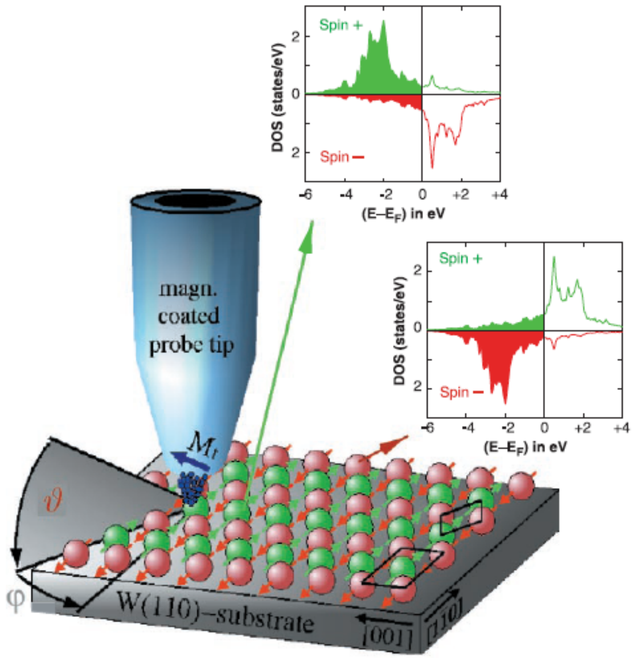
$$H = J\sum_{i,j} \mathrm{S}_i \cdot \mathrm{S}_j - K\sum_i \left(S_i^z\right)^2$$

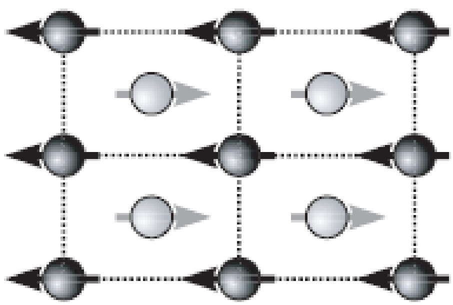
$$= J\sum_{i,j} S_i^z S_j^z + J\underbrace{\sum_{i,j}\left(S_i^+ S_j^- + S_i^- S_j^+\right)} - K\sum_i \left(S_i^z\right)^2$$

If $J < 0$ (FM) this term is zero since $|S_i|$ = max ar favored

If $J > 0$ (AFM) this term mixes different spin configurations
Hence the classical AFM ordered state is not an eigenstate of the Hamiltonian

AFM magnetic order in 2D systems with S>1

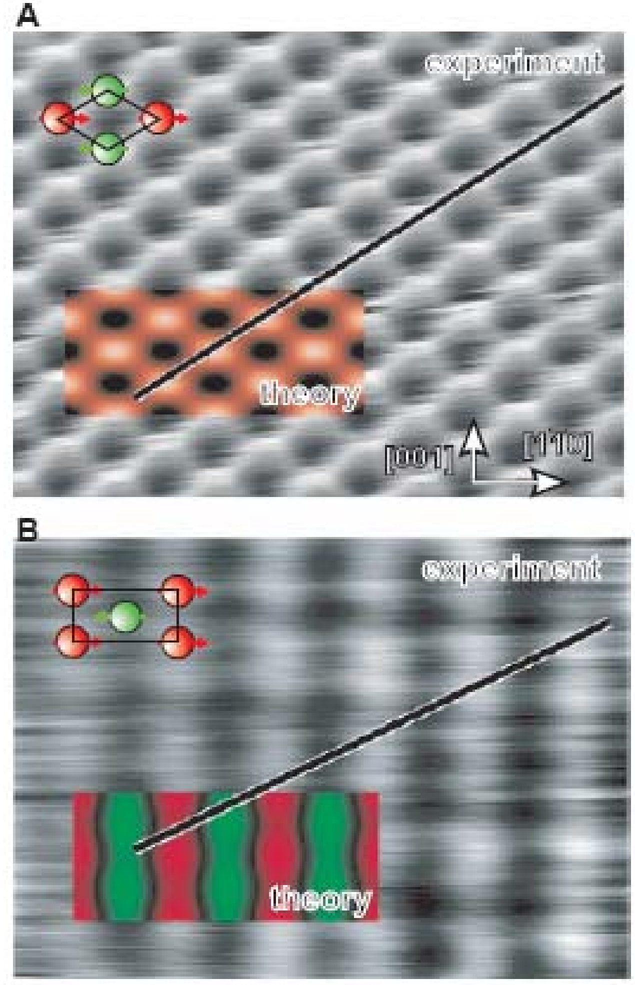




1 monolayer Mn/W(110)

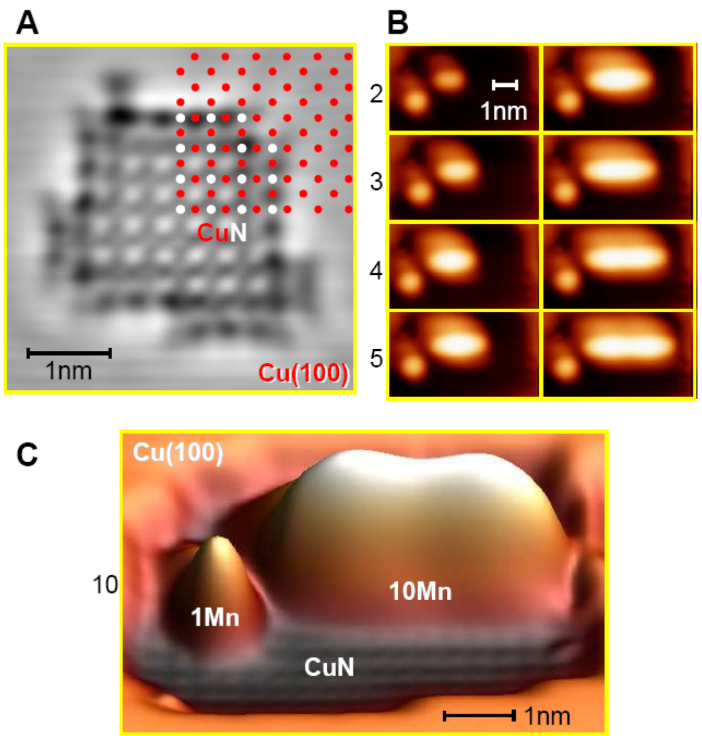
1x1 unit cell

c 2x2 magnetic unit cell

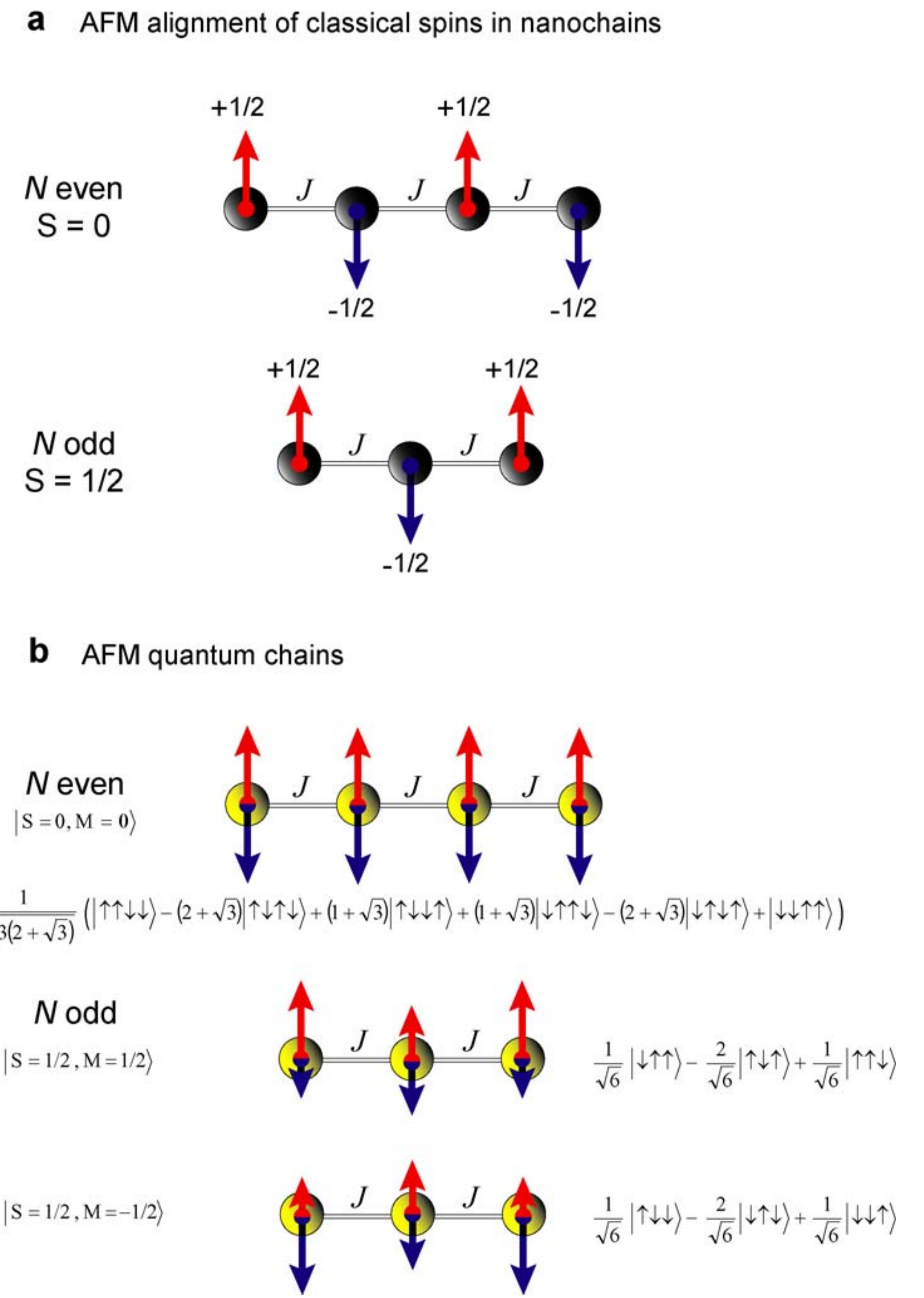


S. Heinze et al., Science 288, 1808 (2000)

AFM order in one-dimensional chains



C. Hirjibehedin et al.,
Science 312, 1021 (2006)



$$\frac{1}{2\sqrt{3(2+\sqrt{3})}}\left(|\uparrow\uparrow\downarrow\downarrow\rangle-(2+\sqrt{3})|\uparrow\downarrow\uparrow\downarrow\rangle+(1+\sqrt{3})|\uparrow\downarrow\downarrow\uparrow\rangle+(1+\sqrt{3})|\downarrow\uparrow\uparrow\downarrow\rangle-(2+\sqrt{3})|\downarrow\uparrow\downarrow\uparrow\rangle+|\downarrow\downarrow\uparrow\uparrow\rangle\right)$$

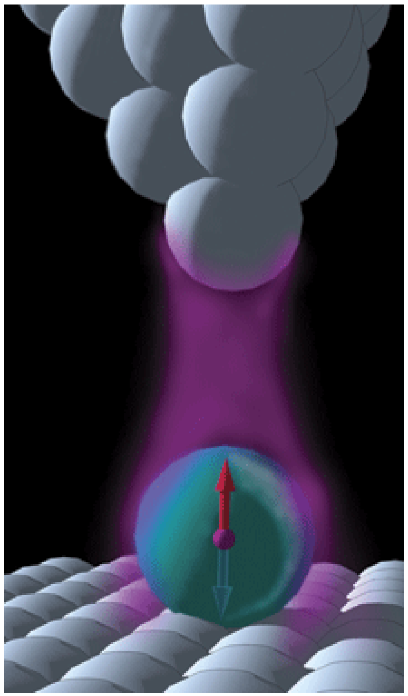
$$\frac{1}{\sqrt{6}}|\downarrow\uparrow\uparrow\rangle-\frac{2}{\sqrt{6}}|\uparrow\downarrow\uparrow\rangle+\frac{1}{\sqrt{6}}|\uparrow\uparrow\downarrow\rangle$$

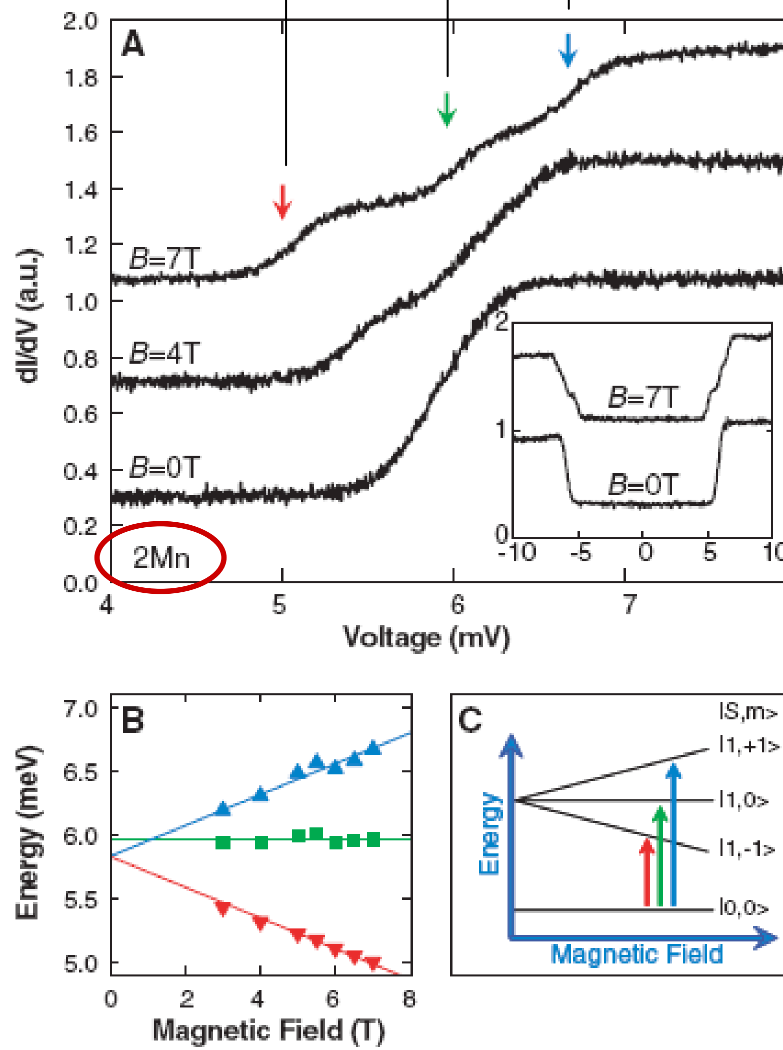
$$\frac{1}{\sqrt{6}}|\uparrow\downarrow\downarrow\rangle-\frac{2}{\sqrt{6}}|\downarrow\uparrow\downarrow\rangle+\frac{1}{\sqrt{6}}|\downarrow\downarrow\uparrow\rangle$$

P. Gambardella, Nat. Mater. 5, 432 (2006)

Inelastic spin-flip spectroscopy performed by STM reveals excited states of AFM

energy eigenvalues of Heisenberg Hamiltonian
With J = 6 meV/Mn atom as a function of applied field





Heinrich et al., Science 306, 466 (2004),
Science 312, 1021 (2006).

SUMMARY 1.

Magnetic order in low-dimensional metal systems

- Spin lattice models
- Mean field approximation
- Mermin-Wagner theorem
- Role of magnetic anisotropy
- Experimental observation of magnetic order in 2D films and 1D chains
- Magnetic order in AFMs
- Experimental observation of AFM ground state in 2D and 1D systems