Супермагнетизм:

свойства и приложения.

I Суперпарамагнетизм.

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- Thermodynamic Formalism

  mean field approximation

  Noble &transitional metals
- **MAGNETIC Nano-Crystals**

  Transition metals if iron series

  Band Structure based shell model
- **FerroFluids**

  Lab on a Chip systems

Thermodynamic Formalism

Potential $\Omega = -T \cdot \ln \mathcal{Z},$

Particil function

$$\mathcal{Z} = \mathrm{Tr}(\exp\{-(\hat{\mathcal{H}} - \sum_{\mathrm{N}} \hat{N}_{\mathrm{N}} \lambda_{\mathrm{N}})/T\})$$

Magnetization

$$\mathcal{P} = M/V$$

$$M = -\left(\partial\Omega/\partial H\right)_{T,\lambda}.$$

Magnetic susceptibility

$$\chi = (1/V)\left(\partial M/\partial H\right)_{T,\lambda} = -(1/V)\left(\partial^2\Omega/\partial H^2\right)_{T,\lambda}$$

Number Density

$$N_{\mathrm{N}} = -\frac{\partial\Omega}{\partial\lambda_{\mathrm{N}}}$$

$$\mathcal{D}_{\mathrm{N}} = N_{\mathrm{N}}/V)$$

To Canonical ensemble

$$F \approx \sum_{\mathrm{N}} N_{\mathrm{N}}\lambda_{\mathrm{N}} + \Omega$$

Mean Field approximation

$$\hat{h}_{\mathrm{N}} = \frac{\hat{\mathbf{p}}_{\mathrm{N}}^2}{2m_{\mathrm{N}}} + V_{\mathrm{N}}(\mathbf{r}) + V_{\mathrm{so}}(\mathbf{r}) + \delta h_{\mathrm{N}}^{\mathbf{m}}$$

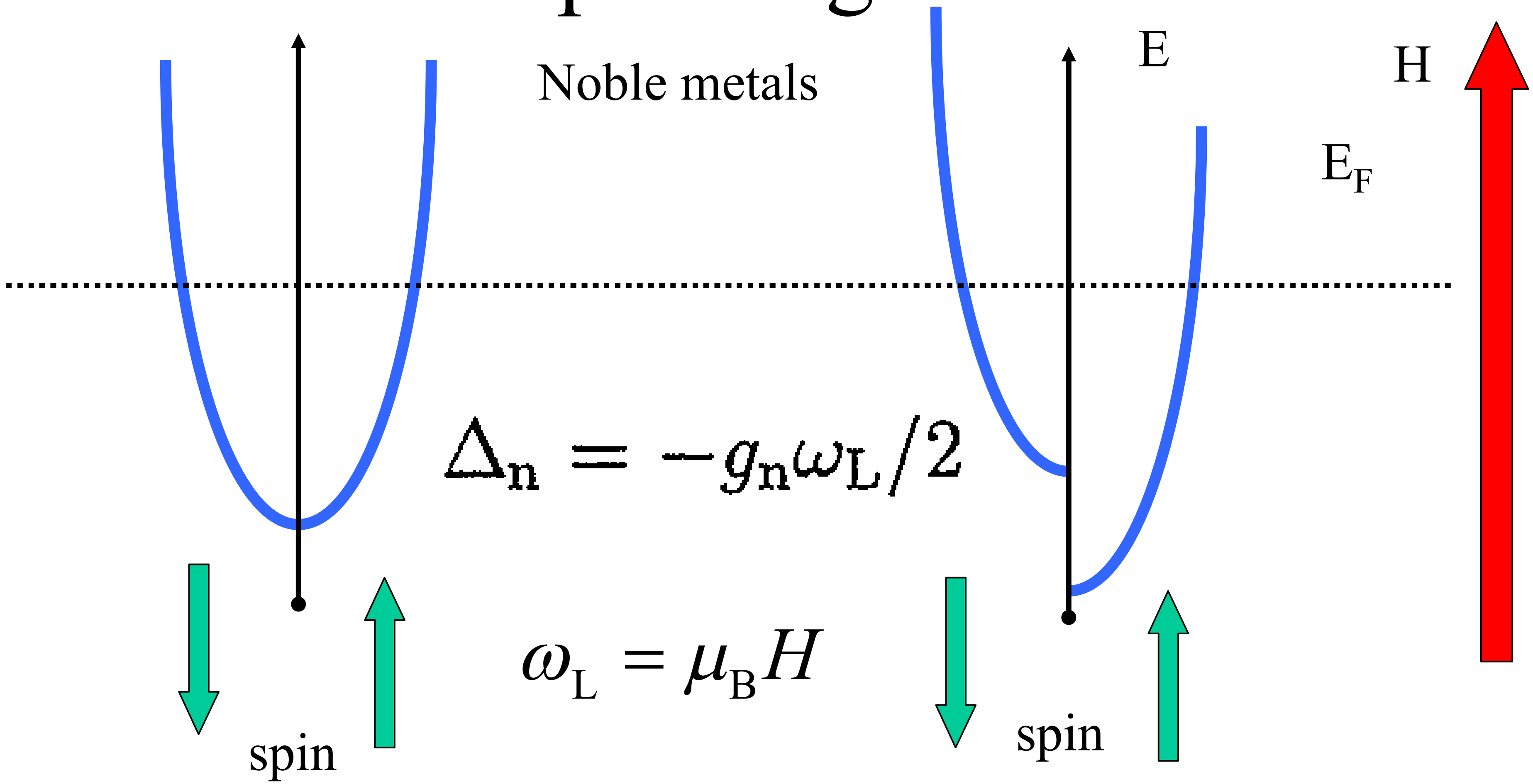
Magnetic field ***B***

$$\delta h_{\mathrm{N}}^{\mathbf{m}} = -\mathbf{B}\hat{\mathcal{M}}_{\mathrm{N}} + \delta h_{\mathrm{o}}^{\mathbf{m}},$$

Level deensity
$$\rho_{\mathrm{N}}(\epsilon) = \sum_{\zeta} \delta(\epsilon - \epsilon_{\zeta}^{\mathrm{N}})$$

$$\Omega_{\mathrm{N}} = -T\int_{-\infty}^{\infty} \mathrm{d}\epsilon\ \rho_{\mathrm{N}}(\epsilon) \cdot \ln[1 + \exp\{(\lambda_{\mathrm{N}} - \epsilon)/T\}].$$

Pauli spin magnetization



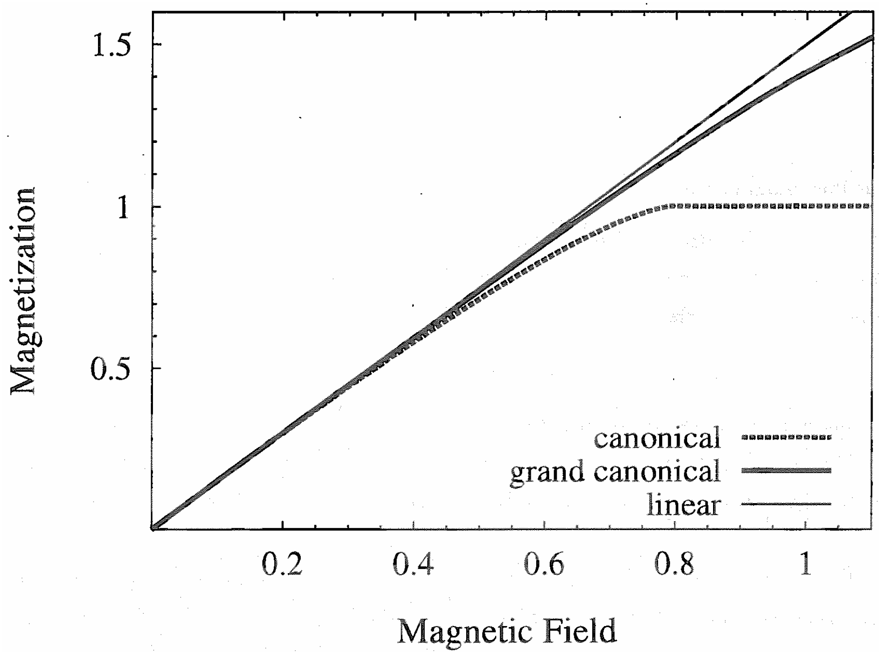
$$\Delta_{\mathbf{n}} = -g_{\mathbf{n}}\omega_{\mathrm{L}}/2$$

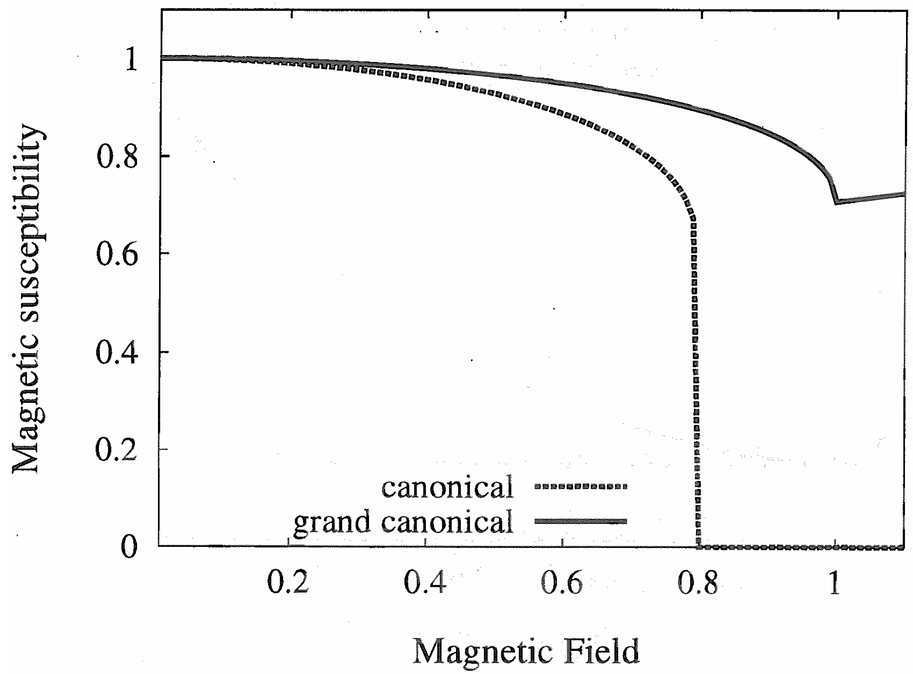
$$\omega_{\mathrm{L}} = \mu_{\mathrm{B}} H$$

$$M_{\mathbf{n}} = \frac{1}{2} g_{\mathbf{n}} \mu_{\mathrm{N}} \mathcal{N},$$

$$\mathcal{N} = N_{\mathbf{n}+} - N_{\mathbf{n}-}$$

Magnetization & susceptibility





Landau Diamagnetism

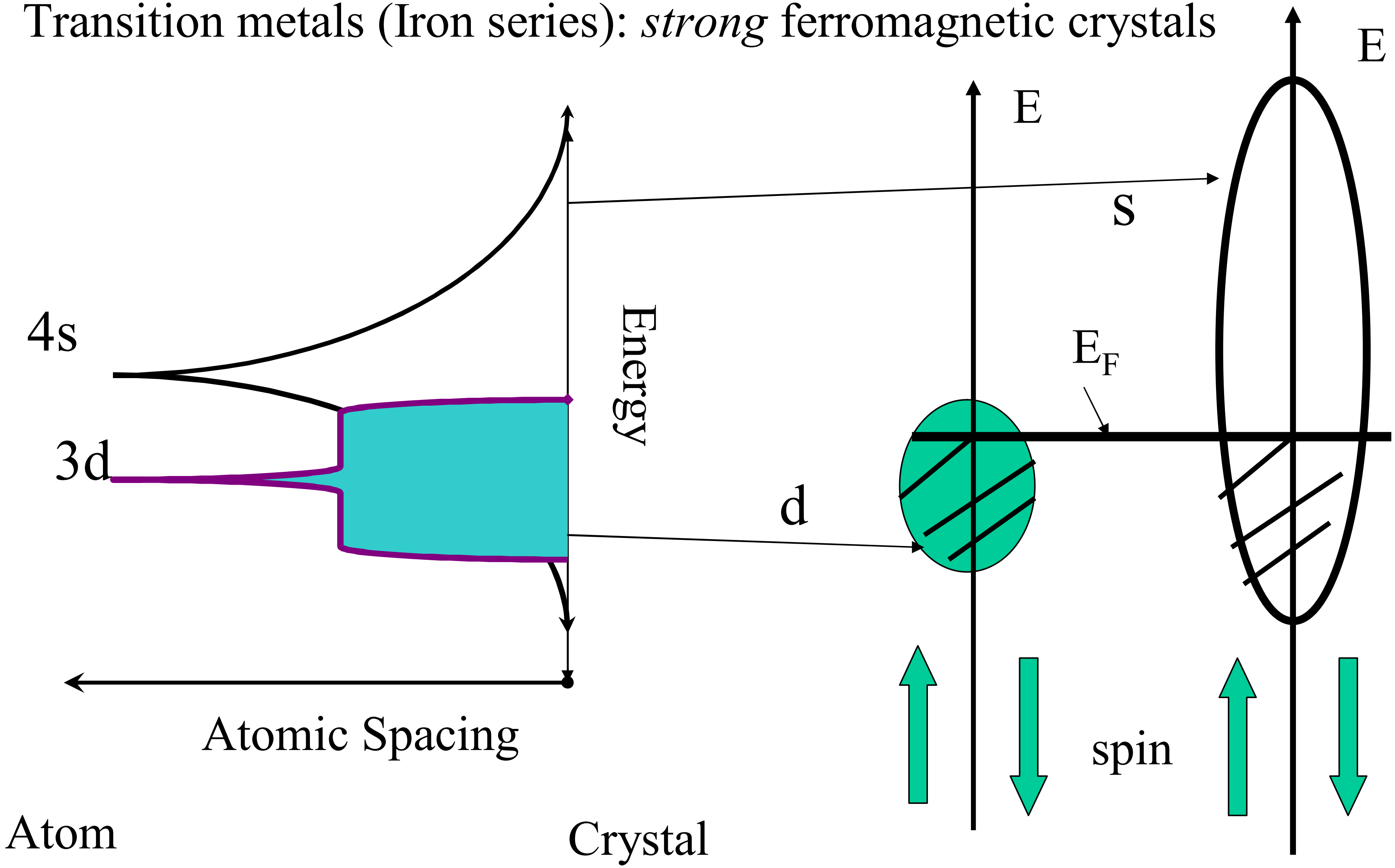
$$\epsilon_n \equiv (n + \tfrac{1}{2})\hbar\omega_c$$

Landau levels

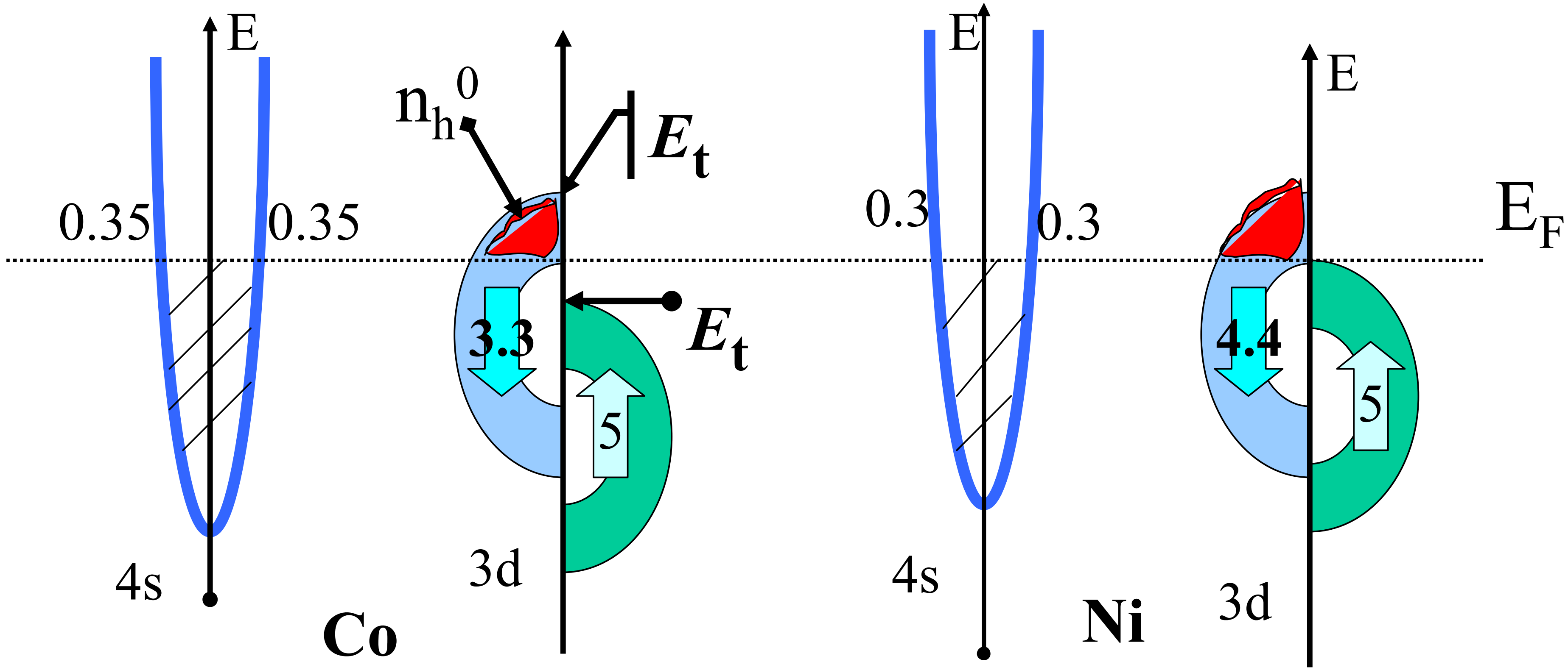
$$\Omega(H) = -k_B T \frac{Am}{\pi\hbar^2} \hbar\omega_c \sum_n \ln[1 + e^{\beta(\mu - \epsilon_n)}],$$

$$\chi_{dia}^{(3d)} = -\frac{e^2}{12\pi mc^2} \int_{-k_F}^{k_F} \frac{dk_z}{2\pi} = -\frac{e^2 k_F}{12\pi^2 mc^2}.$$

Transition metals (Iron series): *strong* ferromagnetic crystals



strong ferromagnets: Bulk

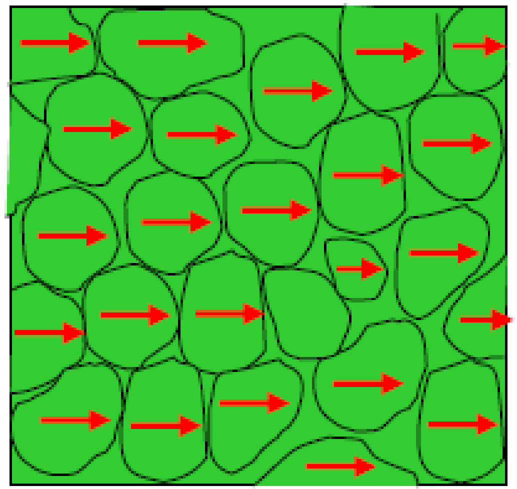


the *iron series* transition metals

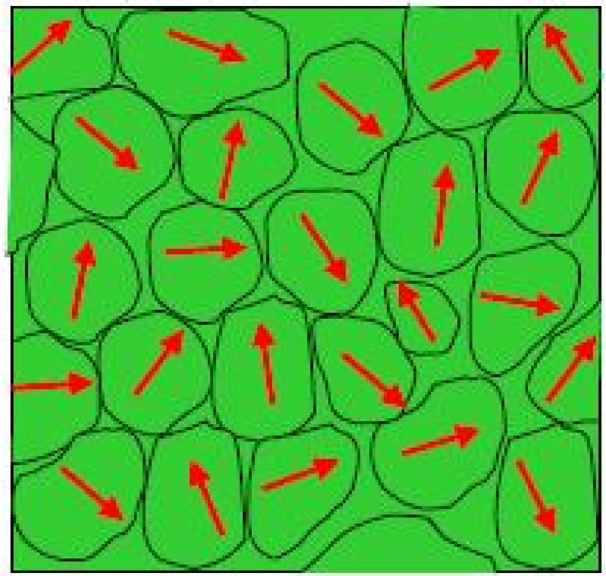
$$n_h^0 = 10 - n_v + n_s^0$$

Magnetization $M \sim \mu_B\, n_h^0$

Demagnetizing energy



$E \sim M^2$



Domain Radius

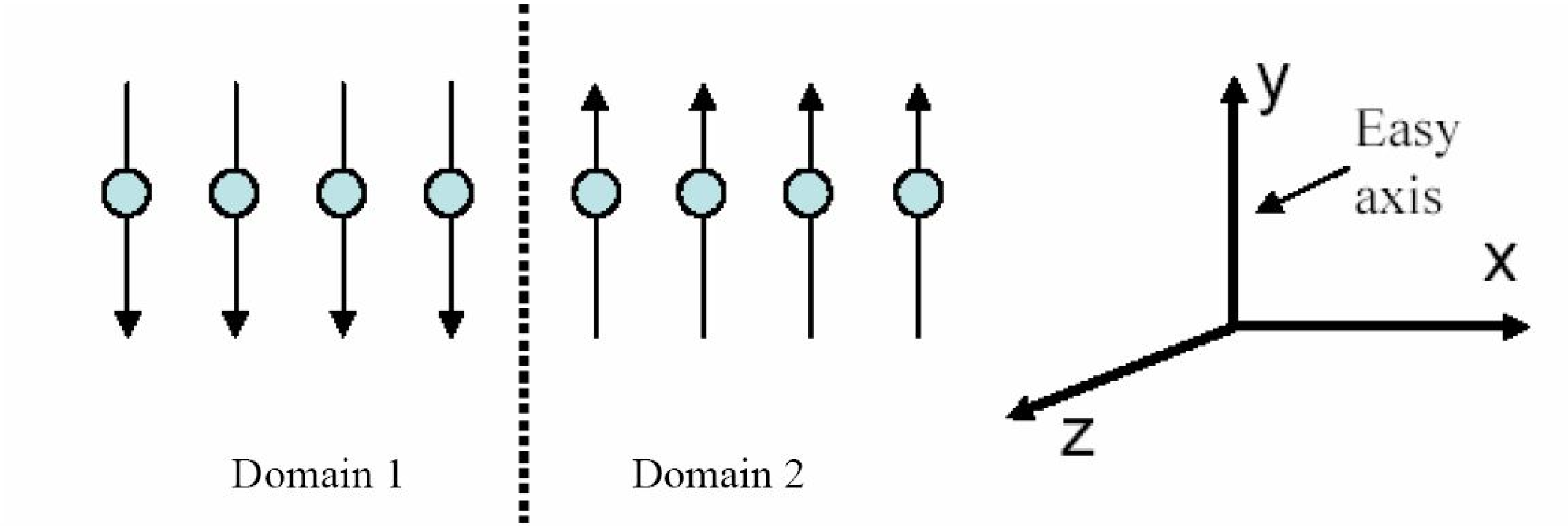
$$r_c \approx 9 \frac{(AK_u)^{1/2}}{\mu_0 M_s^2}$$ ~10 nm

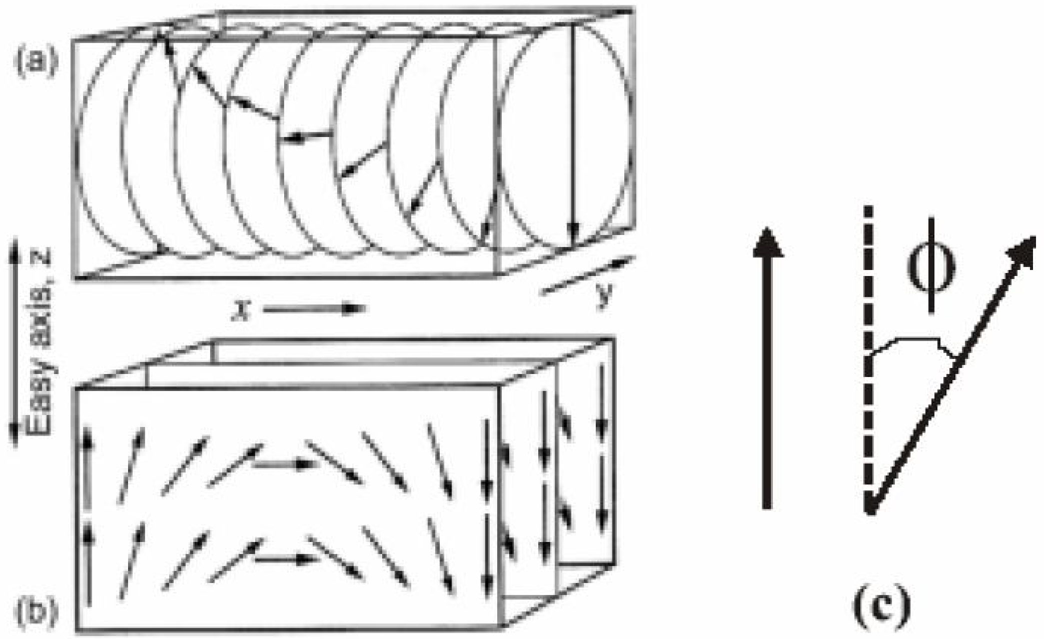
A is the exchange

$\boldsymbol{K_u}$ the uniaxial anisotropy constant

μ_0 the vacuum permeability ***Ms*** the saturation magnetization.

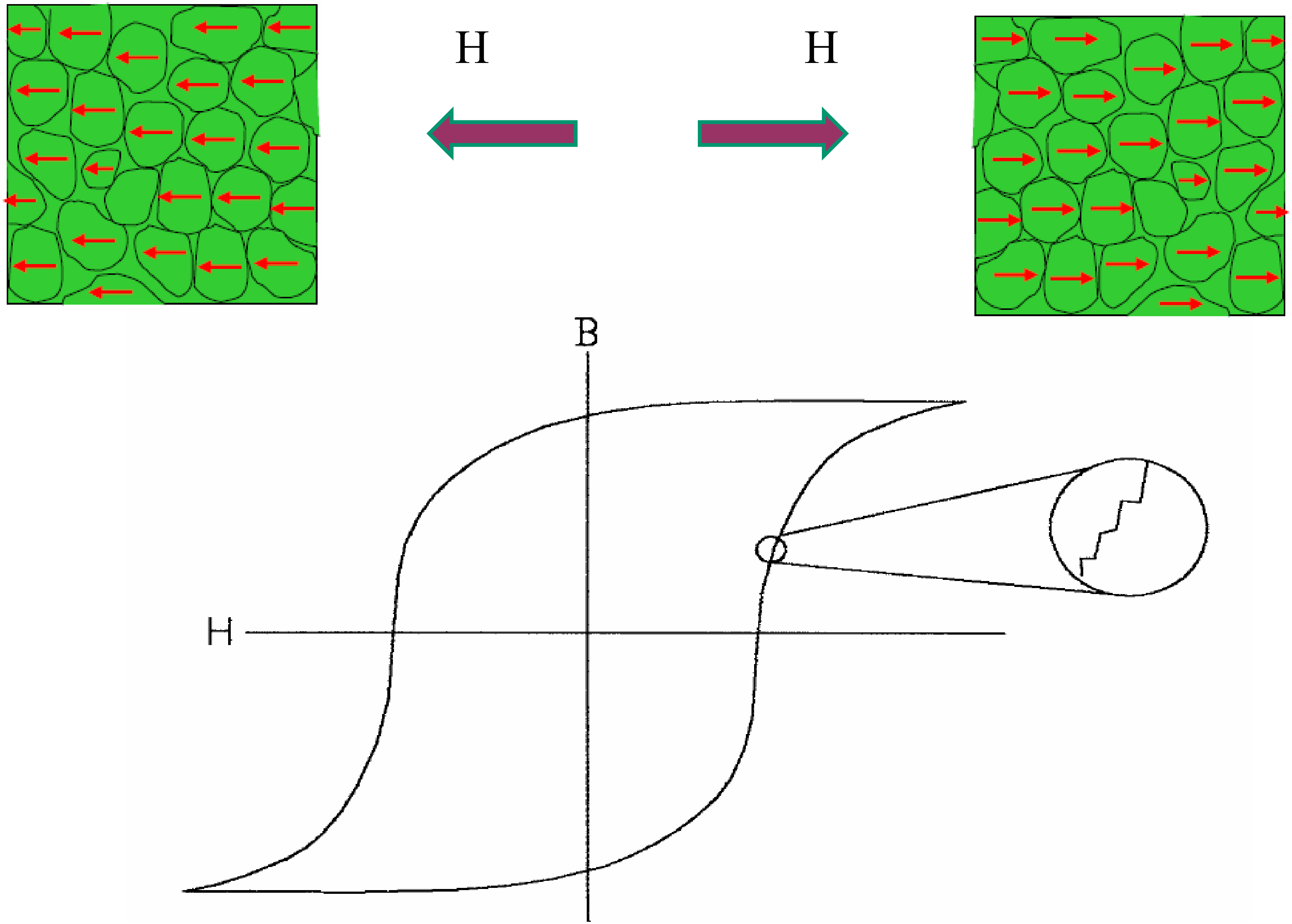
Domain walls



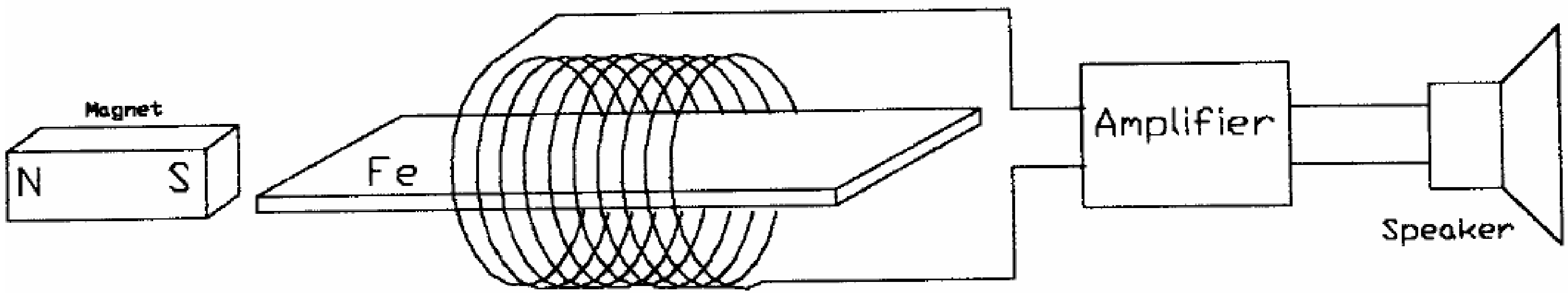


D~ 1 nm

Magnetization reversal hysteresis loop

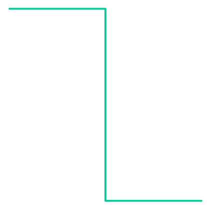


Barkhausen noise
originates from magnetization jumps



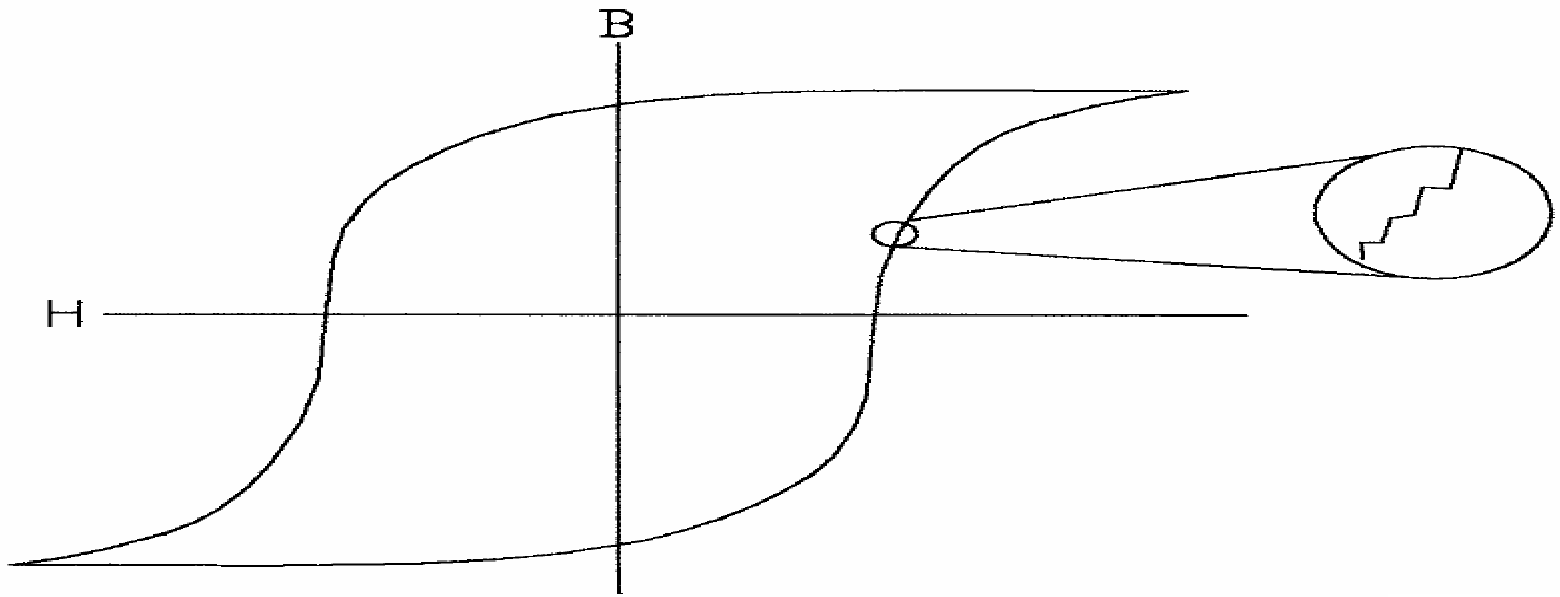
Simplified Barkhausen Noise Detection System

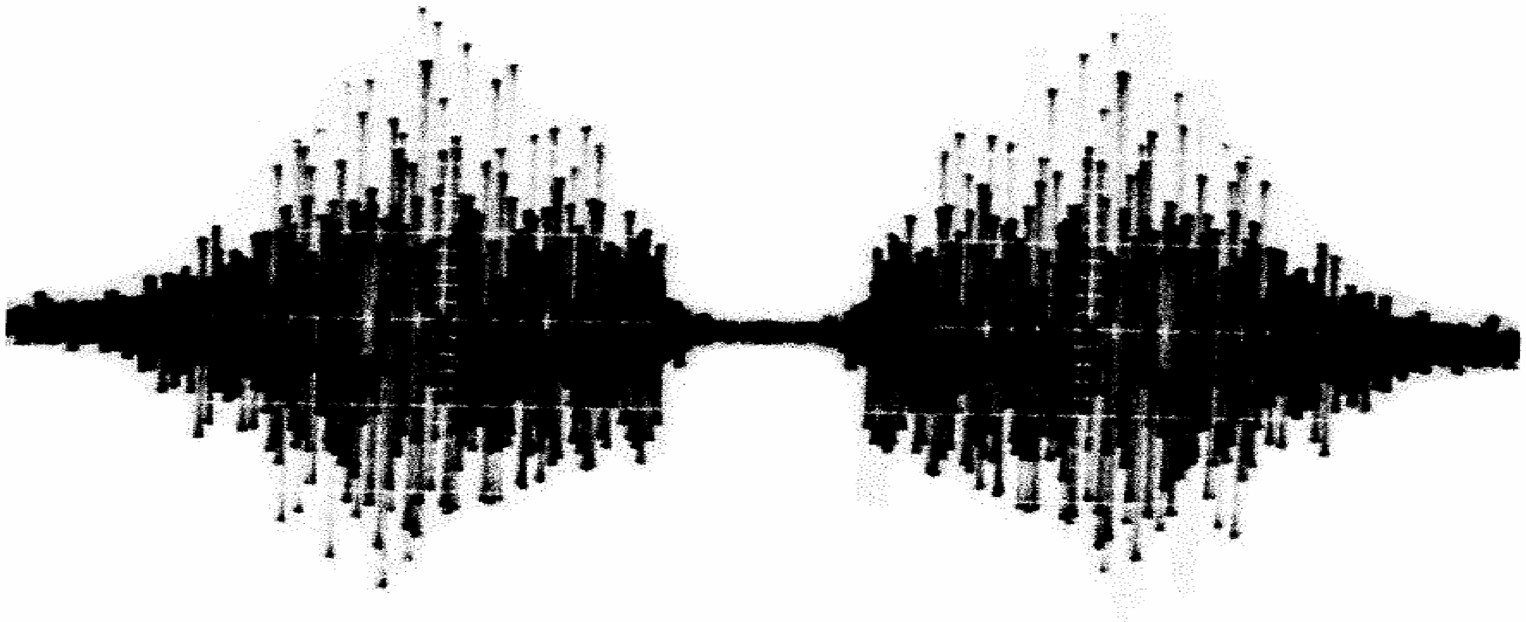
Field jump



Coil Current flux

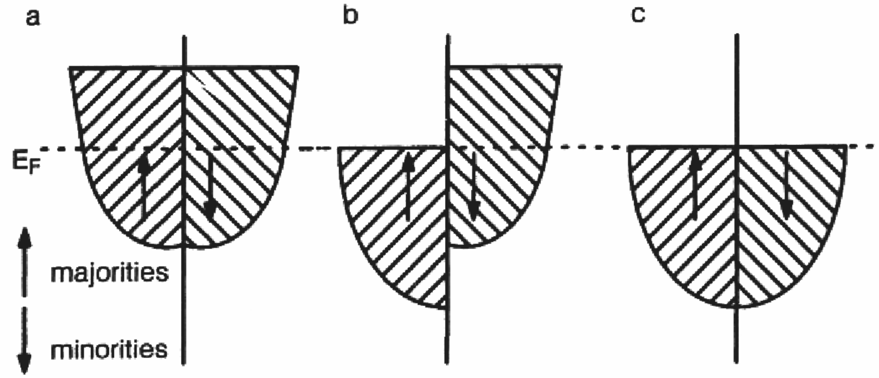
Speaker noise



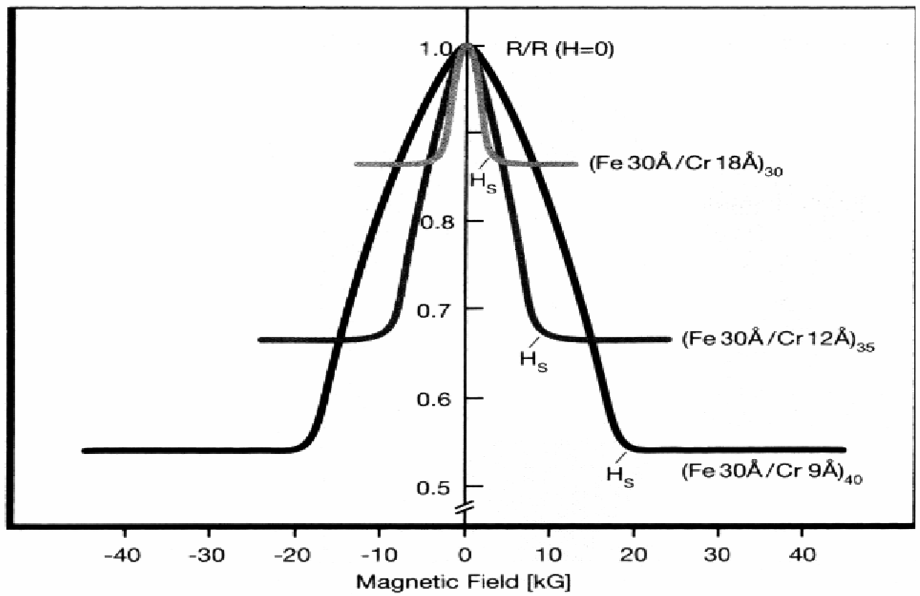


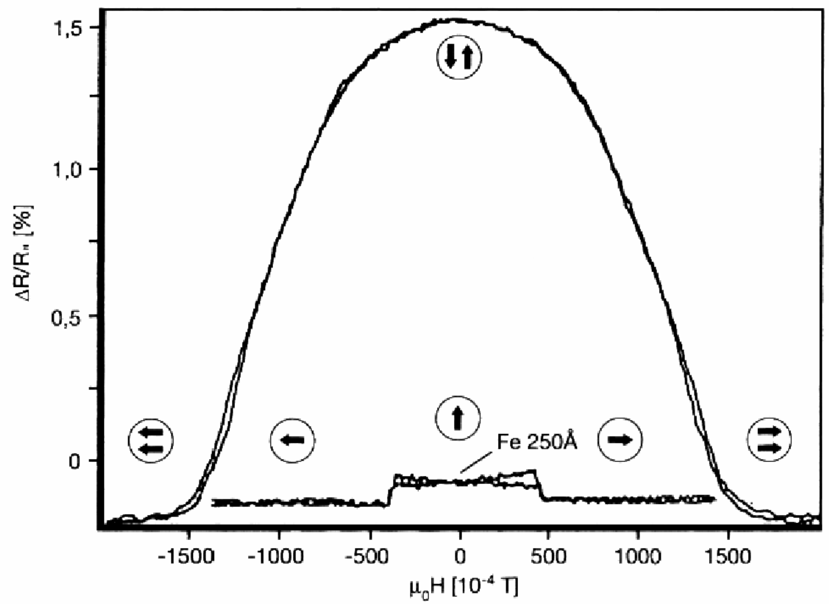
Photographic Scan of Barkhausen Emission Pulse

Giant magnetoresistance



Schematic representation of the matching of the d bands of the magnetic



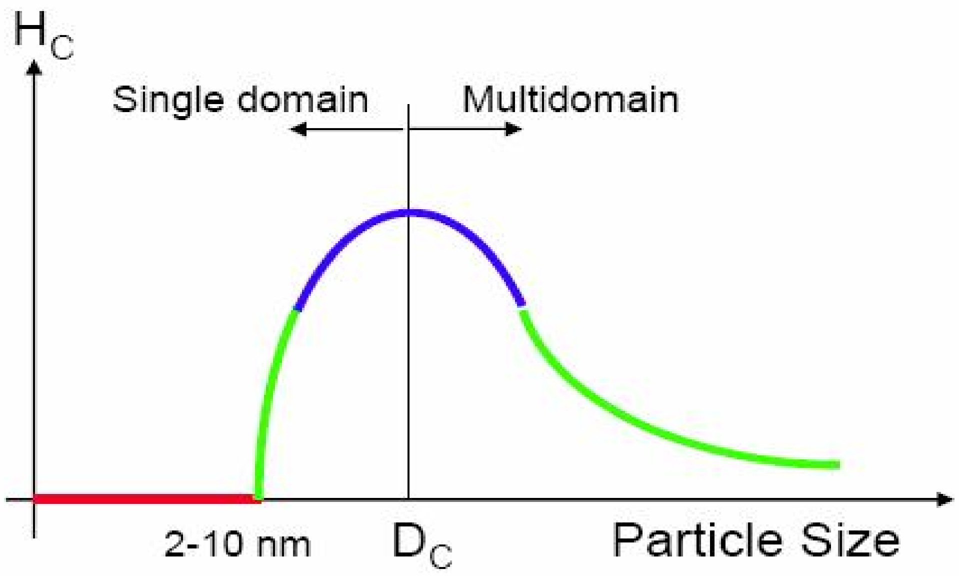


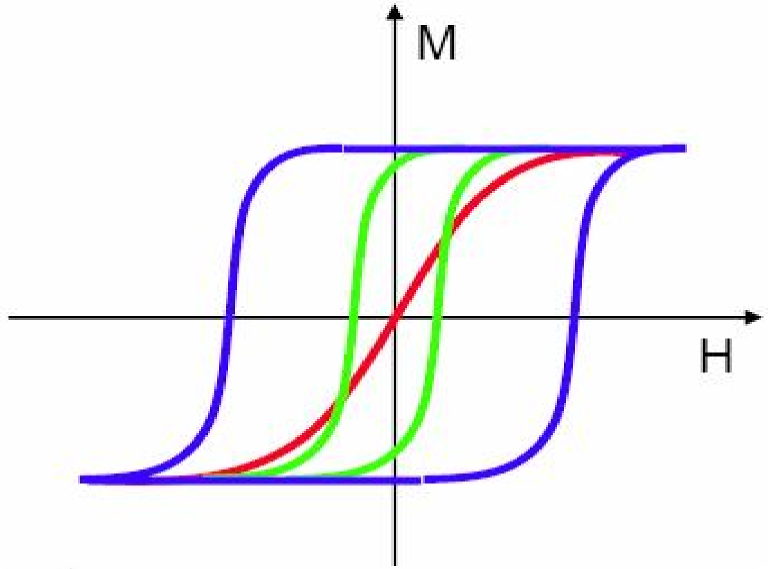
Resistivity versus applied field for Fe/Cr multilayers

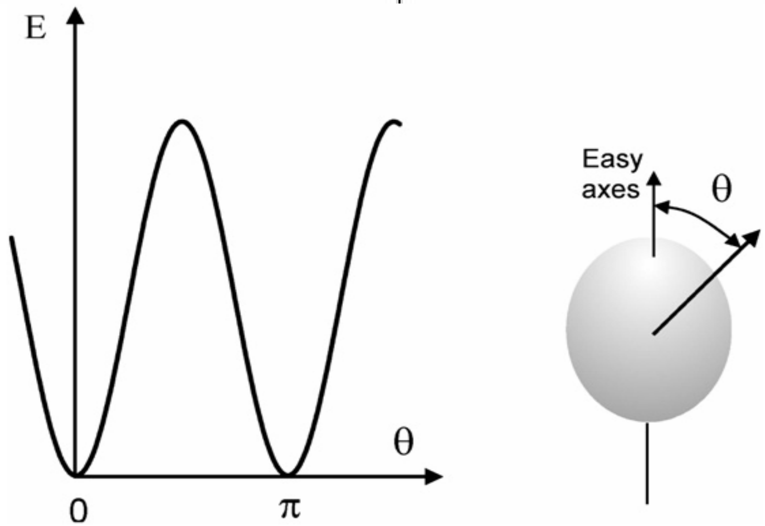
Relative resistance change as a function of the external magnetic field for Fe/Cr/Fe and 250A thick Fe film

SUPERPARAMAGNETISM - A SIZE EFFECT

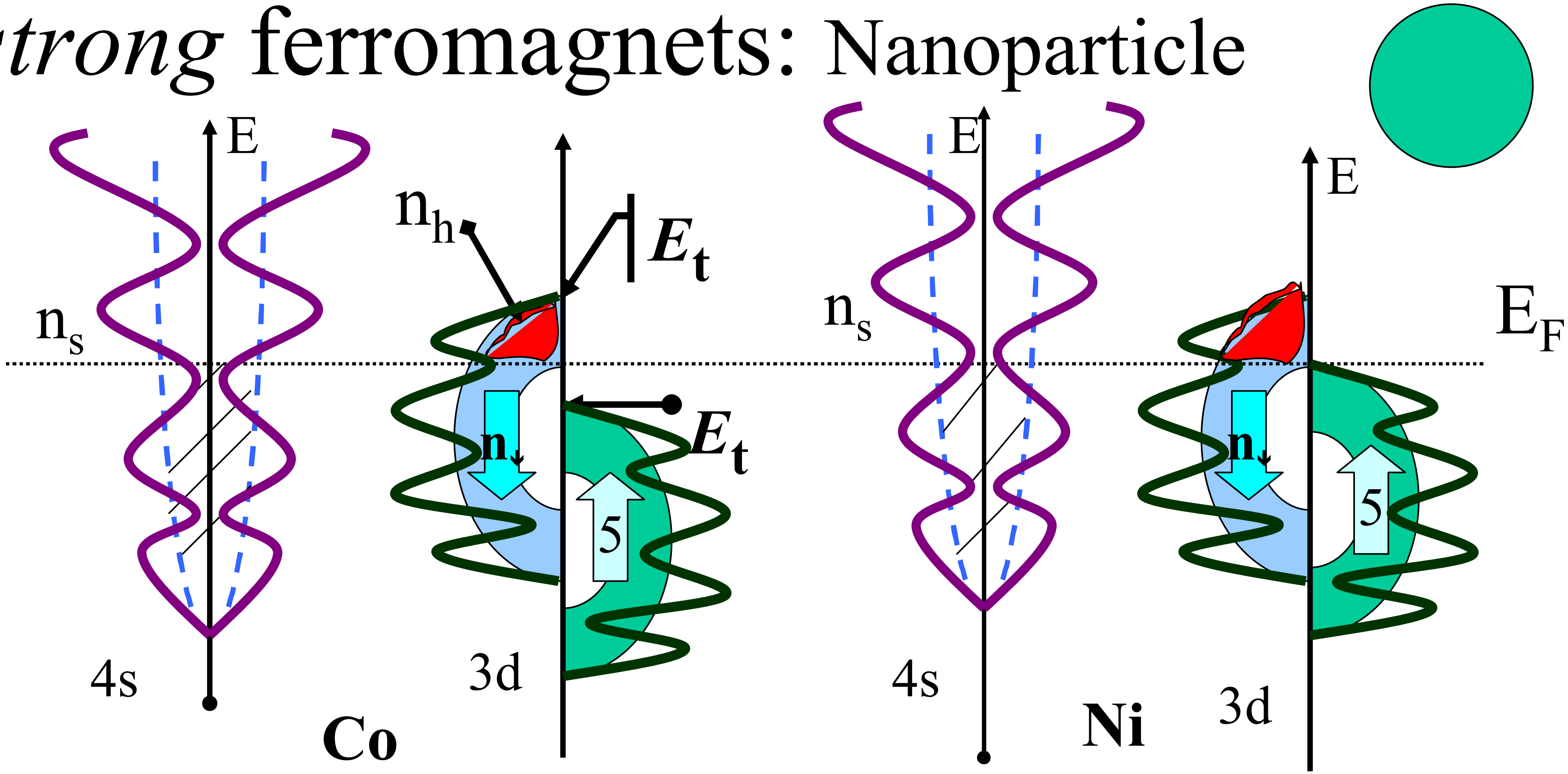
Magnetic Properties of Nanostructured Materials:







strong ferromagnets: Nanoparticle



the *iron series* transition metals

$$n_h = n_h^0 - \delta n_s^D$$

Superparamagnetic state

$$M \sim \mu_B \, n_h$$

VNK, H.O.Lutz, PRL **81** (1998) 4508

Shell **Effects**
at *Strong Magnetic Fields*

$$n_s(\mu) = \int d\varepsilon \rho_s(\varepsilon) f(\varepsilon - \mu)$$

Electrons

$$f(x) - \left[1 + \exp\{x / k_B T\}\right]^{-1}$$

Level density

$$\rho = \sum_n \delta(\varepsilon - \varepsilon_n) = \rho^{sm} + \rho^{sh}$$

With Single particle levels ε_n ***filled up to the Fermi energy*** ε_F

the **Hartree** self-consistent mean field approach in magnetic field : h

- Single particle Hamiltonian
- $\mathbf{H = H_{MF}}$ + *(Magnetic terms)*
- Landau–orbital (l) → **- M (hl)**

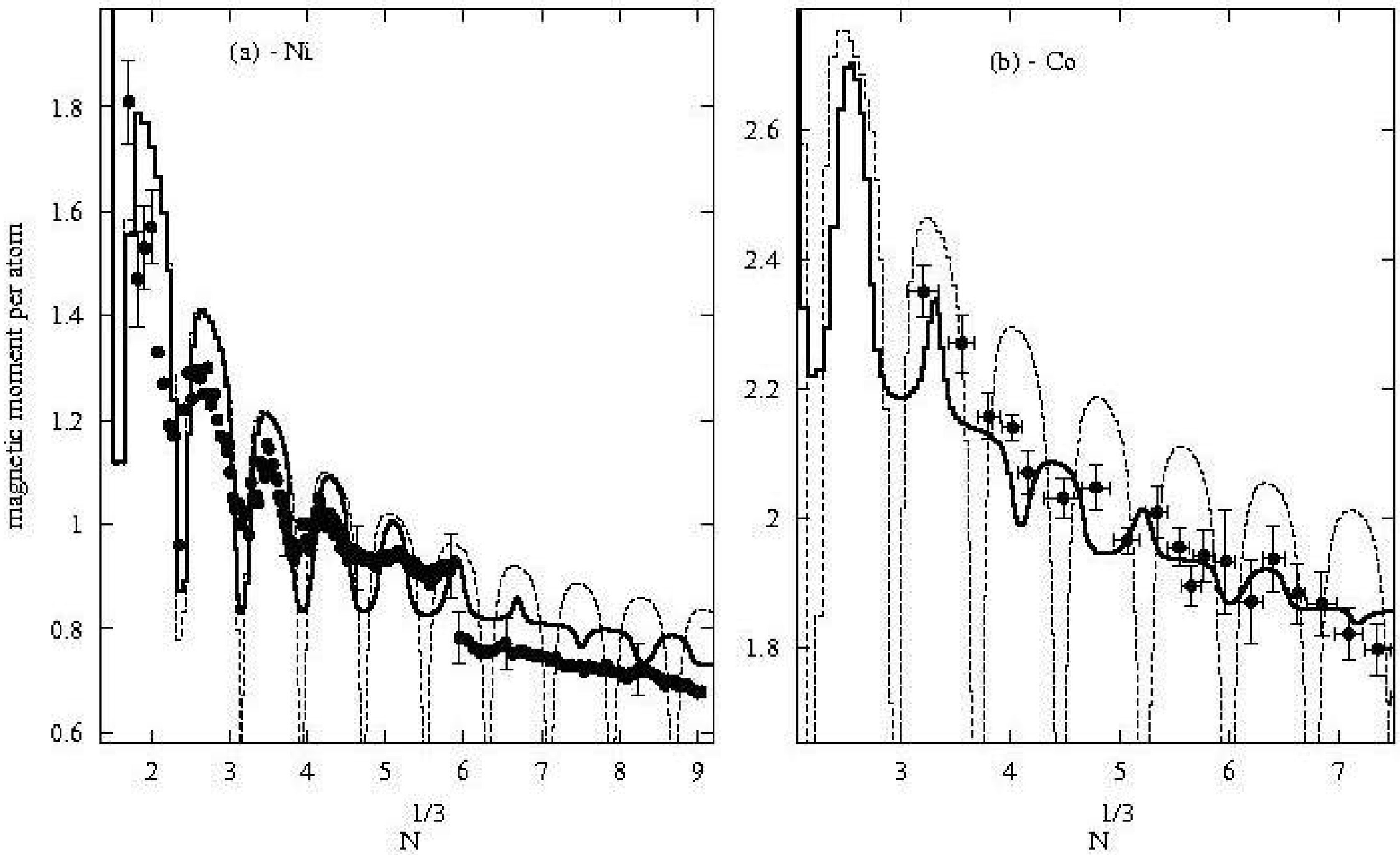
HO level density: $\mathbf{H_{MF} = H_{HO}}$

$$\rho^{sh} = \sum_{k=1} \cos\left(2\pi k\varepsilon / \omega\right) j_0\left(2\pi\eta k\varepsilon / \omega\right) \quad \times q^k$$

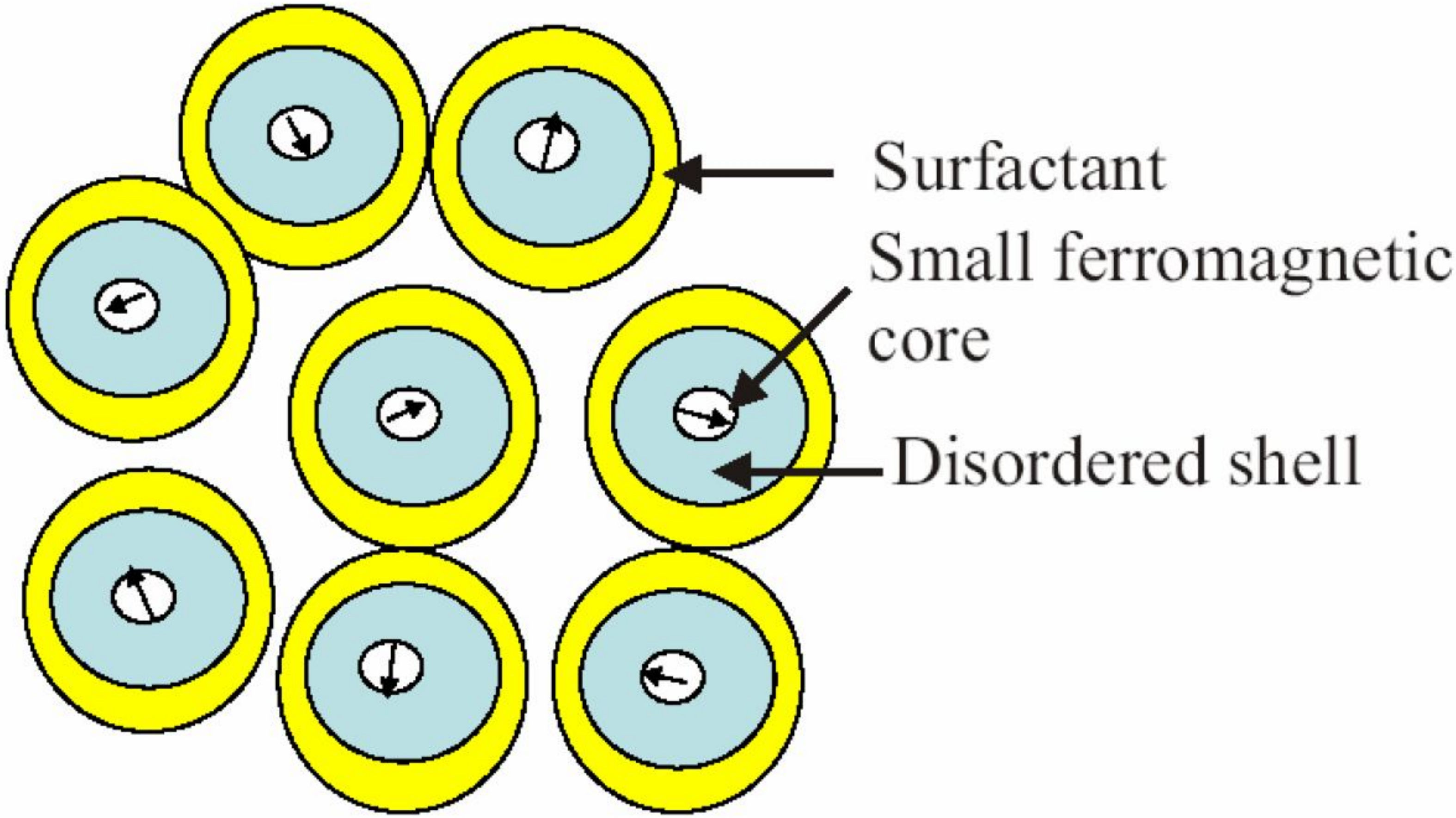
$$\eta = \omega_{\mathrm{L}} / \omega \qquad \omega_{\mathrm{L}} = \mu_{\mathrm{B}} H$$

Size dependence of cluster magnetic moment per atom (measured in μ_B)

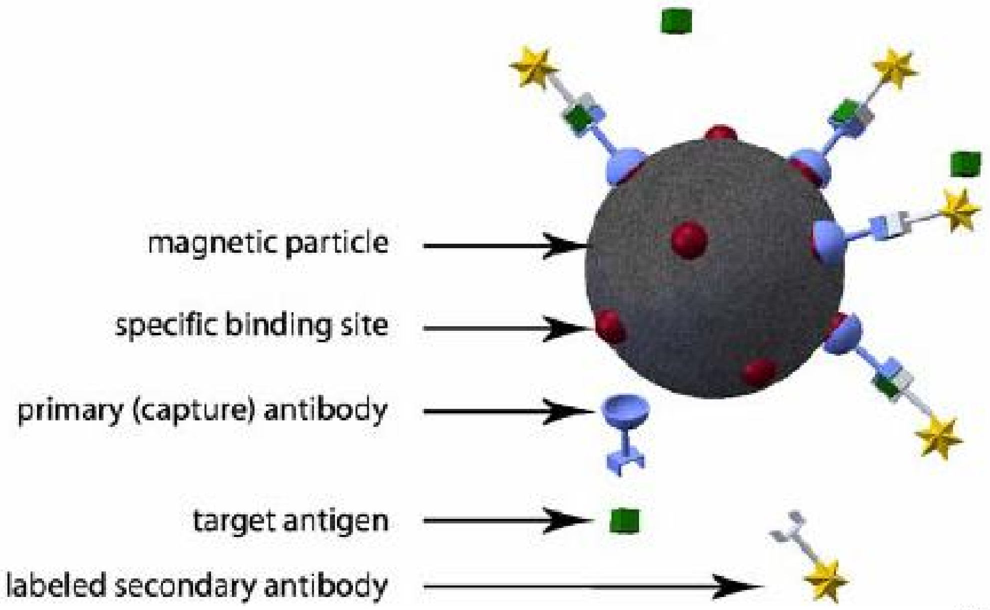
VNK, H.O.Lutz, PRL **81** (1998) 4508

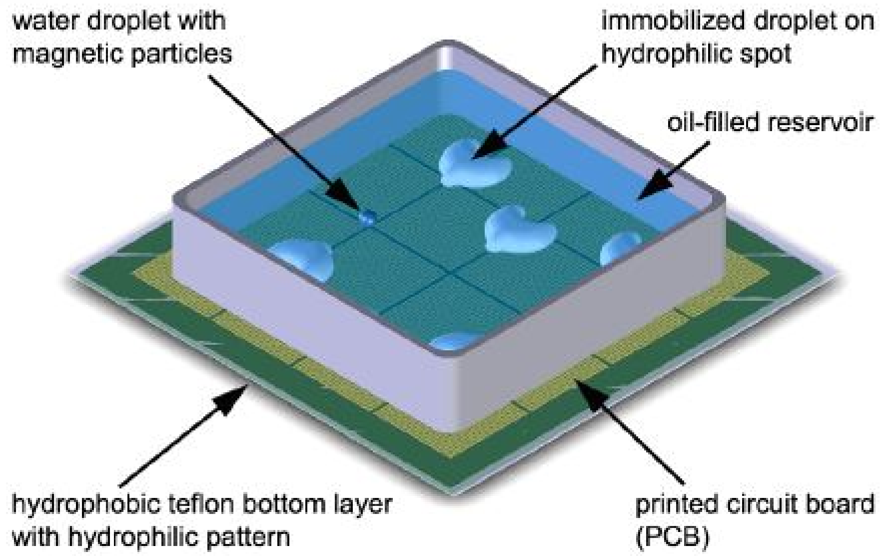


FerroFluid



Lab on a chip Systems





APPLICATIONS OF SUPERPARAMAGNETISM

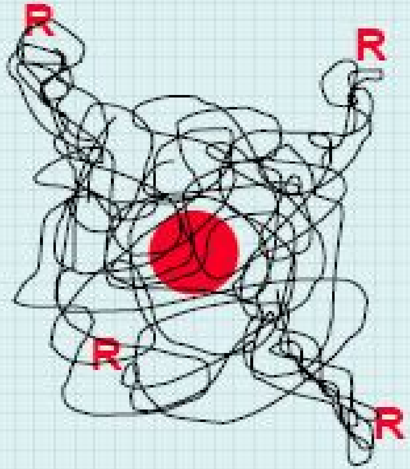
Biomedical applications

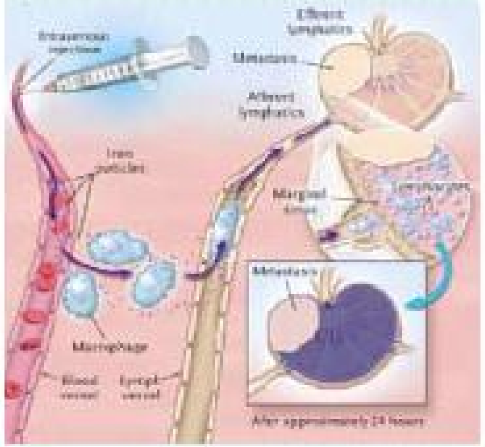
- **Detection**: MRI Magnetic Resonance Imaging
- **Separation**: Cell-, DNA-, protein- separation, RNA fishing
- **Treatment**: Drug delivery, hyperthermia, magnetofaction

Other applications:

- **Ferrofluid:** Tunable viscosity
- **Sensors**: high sensitivity (GMR, BARCIII)
- Self - Assambling

Drug Delivery:





Particles with attached drug can be injected and guided through the body by application of an external field.

??? WHY SUPERPARAMAGNETIC PARTICLES ???

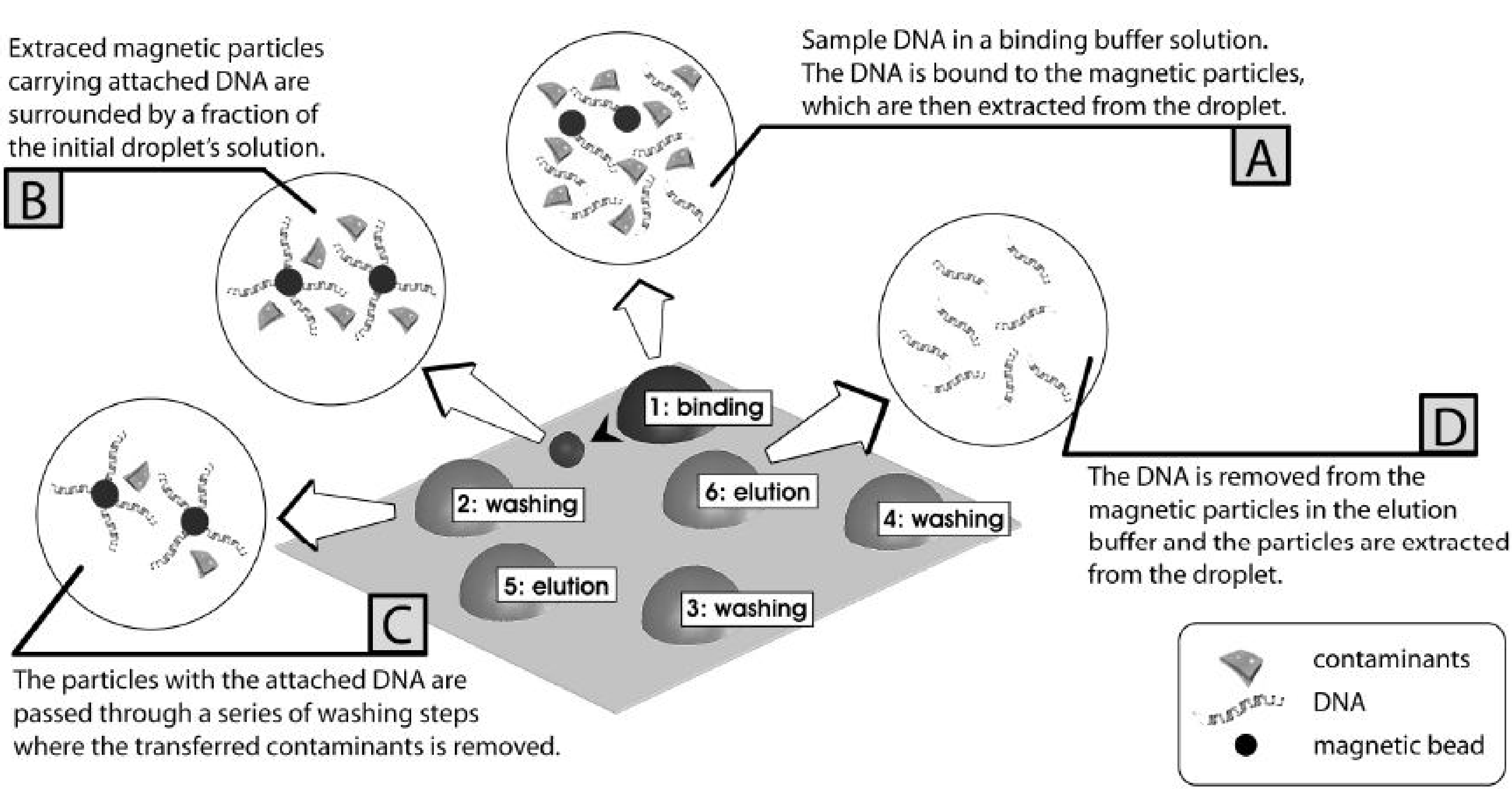
Size of the superparamagnetic particle:

Magnetic active core = 2-3 nm
Coating (polymer, proteins, functional rest groups R) ~ 10 nm

Size of cell = 10 – 100 µm
virus = 20 – 450 nm
protein = 5 – 50 nm
gene = 2* (10 - 100) nm^2

Design of the particle:

- **Attachment of R -> Particles entre the cells**
  Particles can be recognized by the organism
  Drugs can be attached to the particle
  R influences the toxicity for the organism



Schematic principle of the on-chip DNA purification protocol.
The sample in the binding buffer solution is injected onto the chip and mixed with a droplet of magnetic particles. These are extracted and wash in three stages, before the DNA is again eluted in the steps 5 and 6