Vortex formation in Permalloy 44 nanospheres in chains

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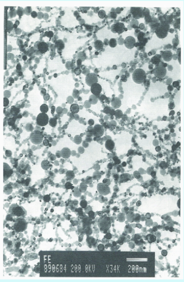
Cryogenic melting

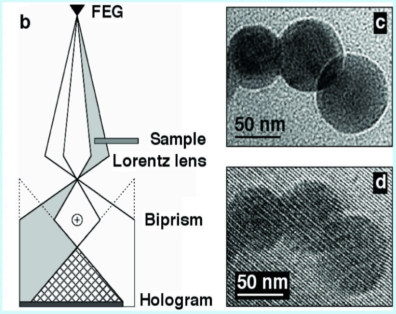
The metallic drp is levitated in the center of the RF inductor in liquid nitrogen.



Ingot composition: Fe50Ni50

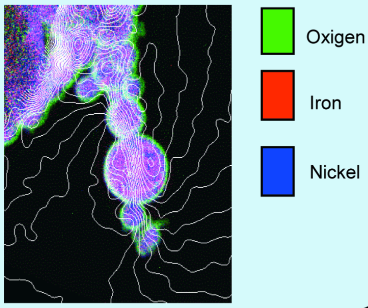
Particles composition: Fe56Ni44

Off-axis electron holography in transmission electron microscope

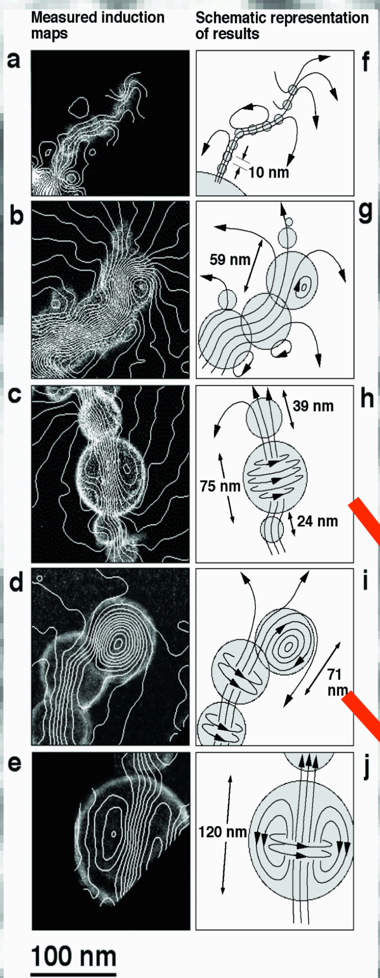


Chemical map of $Fe_{56}Ni_{44}$ particles

obtained by electron energy loss spectrometry (EELS) superimposed with magnetic field lines in the remnant state

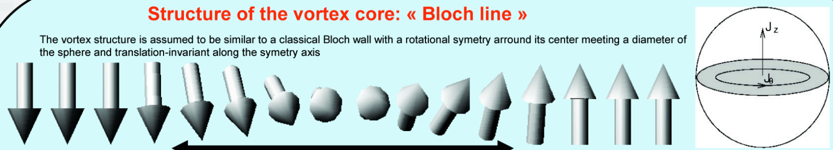


Exemples of spin structures for particles in chains having different diameters



Structure of the vortex core: « Bloch line »

The vortex structure is assumed to be similar to a classical Bloch wall with a rotational symetry arround its center meeting a diameter of the sphere and translation-invariant along the symetry axis

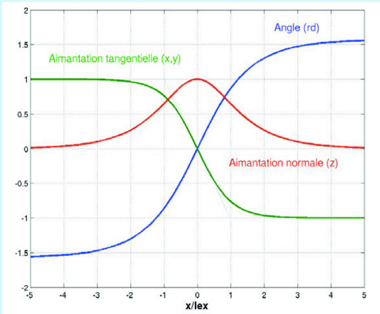


$$\delta = \pi \ell^*_{ex}$$

For a 2D object like a nano-island (circular layer thinner than exchange length) the « Bloch point » parameter is:

$$\ell^*_{ex} = \ell_{ex} = \sqrt{\frac{2\mu_0 A}{J_S^2}}$$

[A. Wachowiak et al., Science 298, 577 (2002)]

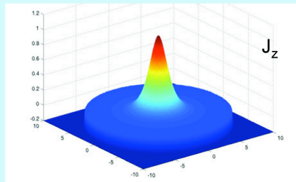


Distribution of spin angles according to z axis, in plane tangential component of the magnetization and axial component (out of plane) of the magnetization in a vortex. Horizontal axis is the radius reduced to the effective exchange length.

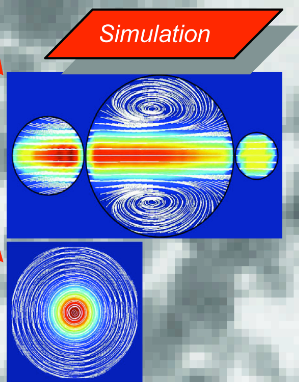
For a 3D object like a nano-sphere the « Bloch point » parameter ℓ^*_{ex} is larger than ℓ_{ex}

$$B_z(x) = J_S \cos\left(\arctan\left(e^{-x/\ell^*_{ex}}\right)\right)$$

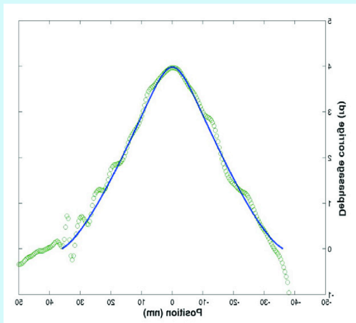
$$B_\theta(x) = J_S \sin\left(\arctan\left(e^{-x/\ell^*_{ex}}\right)\right)$$



Simulation



Direct measurement exchange length by fitting phase profile using Bloch line model



The theoretical magnetization Bloch profile is integrated along the symetry axis to recover the experimental phase profile

$$\varphi_\theta(x) = \frac{e}{\hbar}\iint J_S \sin\left(\arctan\left(e^{-x/\ell^*_{ex}}\right)\right)\cdot dxdz$$

71 nm particle (Fig. e)

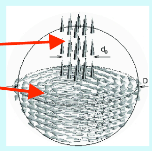
$$\ell^*_{ex} = 4.3\ \text{nm} \geq \ell_{ex} = 3.2\ \text{nm}$$

$$\delta = \pi \ell^*_{ex} = 13.5\ \text{nm}$$

In theory the experimental curve should be below the modelized curve near the edge of the particle because the magnetization slightly turns back in order to minimize the the demagnetizing energy of the vortex core. However the accuracy of the measurements does not allows to observe clearly thiseffect.

Comparaison between exchange length measurement, micromagnétic simulation and analytical model

The analytical model is based on the minimisation of exchange + demagnetizing energy using simple approximations. The sphere is devided into a uniformly magnetized cylindrical core and a shell with in-plane curling spins.
A Zeeman term is added in order to take into account the turning back of the shell spins which lower the demagnetizing energy of the core.



Critical size for single domain to vortex transition

$$d_{SD} = 2\sqrt{\frac{9\mu_0 A}{J_S^2(1-3\mu_0 H/J_S)}\left[\ln\left(\frac{d_{SD}}{d_{nn}}\right)-1\right]}$$

$$F_{ex} = 2\pi\left[\ln\frac{d_C/D}{1-\cos\alpha} - \cos\alpha\right] \quad \text{with} \quad \alpha = \arcsin d_C/D$$ In the vortex shell and zero in the core

$$F_{ms} = N_z \frac{J_S^2}{2\mu_0}V_C \quad \text{with} \quad V_C = \frac{\pi D^3}{6}\left[1-\frac{1}{4}\cos(3\alpha)+\frac{3}{4}\cos\alpha\right]$$ Demagnetizing energy associated to vortex core

$$F_Z = -J_S H_{CS} V_C \quad \text{with} \quad H_{CS} \propto J_S$$ Zeeman energy associated to core-shell interaction

$$\min(F_{ex}+F_{ms}+F_Z) \Rightarrow d_C$$

The best fit yields $\mu_0 H_{CS} \approx 0.1\,\text{T} \approx J_S/16$