Magnetomechanical coupling and ferromagnetic resonance in magnetic nanoparticles

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Introduction

We address the theory of the coupled lattice and magnetization dynamics of freely suspended single-domain nanoparticles of spheroidal shape.

- motivation: investigation of the importance of the shape anisotropy and the Barnett/Einstein-de Haas effects on FMR spectra, going beyond previous work [2]
- theoretical approach: classical description of the dynamics of macrospin and macrolattice
- magnetomechanical coupling: Barnett field, magnetic anisotropy, and Gilbert damping

Main results

- blueshift of the high-frequency ferromagnetic resonance (FMR)
- new low-frequency satellite peaks with strongly reduced spectral broadening, magnetic and mechanical precessions are locked, thereby suppressing Gilbert damping
- the Barnett effect strongly influences the fine structure of FMR spectra

Outlook

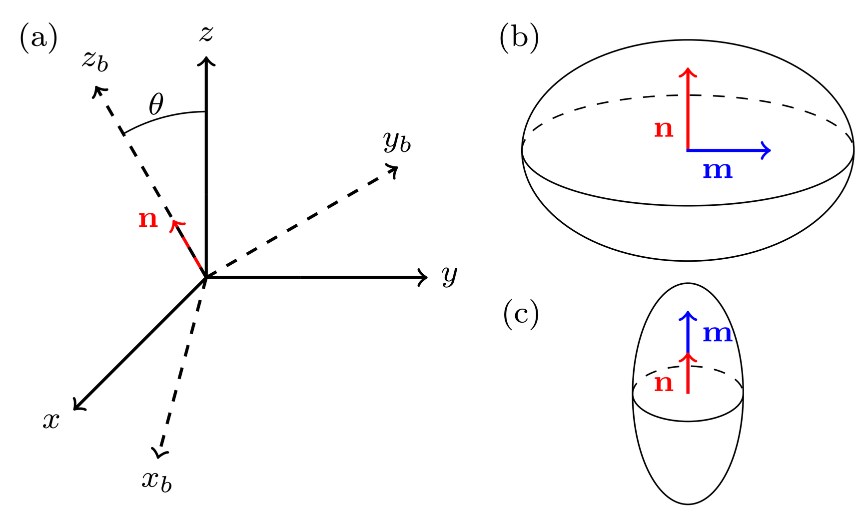
- coupling of the sharp low-frequency modes to rf cavity modes
- route to access non-linear, chaotic, or quantum dynamical regimes
- magnets with large dampings can be used instead of YIG

Macrolattice and macrospin approximations

- macrolattice approximation: no elastic deformations of the lattice
- macrospin approximation: $\mathbf{M} = M_s \mathbf{m}$ (position independent), with $|\mathbf{m}| = 1$
  valid for nm sized particles due to adiabatic decoupling of spin and lattice waves
- suppression of thermal fluctuations of the magnetization (numbers: Fe sphere, radius R)
  - with respect to the lattice: $T < T_B \sim K_A V/(25 k_B) = 11(R/\mathrm{nm})^3$ K
  - with respect to the static field $\mathbf{H}_0$: $(V M_s \mu_0 |\mathbf{H}_0|)/(k_B T) = 520 \left(\frac{R^3 \mu_0 |\mathbf{H}_0| T^{-1}}{\mathrm{nm^3\,T\,K^{-1}}}\right) \gg 1$

Coordinate systems and configurations

- lab frame: x, y, z
  body frame: x_b, y_b, z_b
- orientation of the spheroid: θ, ϕ, ψ
  main axis of the spheroid:
  $\mathbf{n} = \left(\sin\theta\sin\phi, -\sin\theta\cos\phi, \cos\theta\right)^{\mathrm{T}}$
- easy-axis: $\mathbf{m} \parallel \mathbf{n}$
  easy-plane: $\mathbf{m} \perp \mathbf{n}$



Energy of the nanomagnet

$$E = E_T + E_Z + E_K + E_D$$

$E_T = \frac{1}{2}\mathbf{\Omega}^T \mathcal{I} \mathbf{\Omega}$ = rotational kin. energy with angular frequency $\mathbf{\Omega}$ and inertia tensor $\mathcal{I}$

$E_Z = -\mu_0 V \mathbf{M}\cdot\mathbf{H}_{\mathrm{ext}}$ = Zeeman energy in external field $\mathbf{H}_{\mathrm{ext}} = \mathbf{H}_0 + \mathbf{h}_\perp(t)$, $\mathbf{h}_\perp \perp \mathbf{H}_0$

$E_K = K_1 V (\mathbf{m}\times\mathbf{n})^2$ = magnetocrystalline anisotropy energy

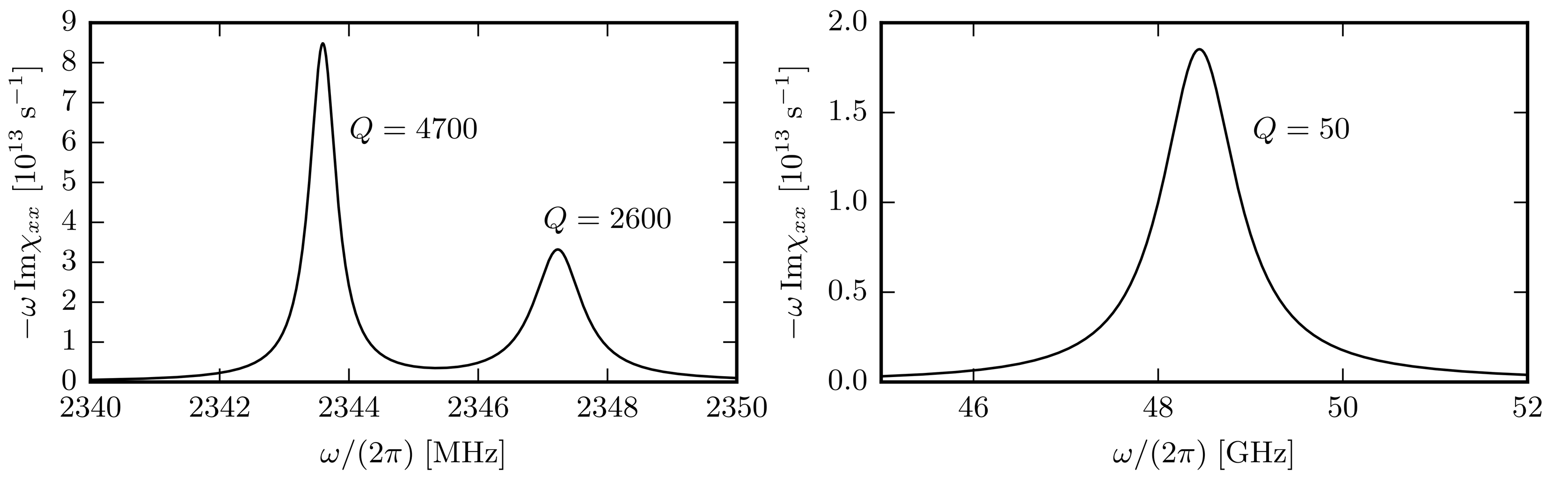
$E_D = \frac{1}{2}\mu_0 V \mathbf{M}^T \mathcal{D} \mathbf{M}$ = magnetostatic self-energy with demagnetizing tensor $\mathcal{D}$

Equations of motion

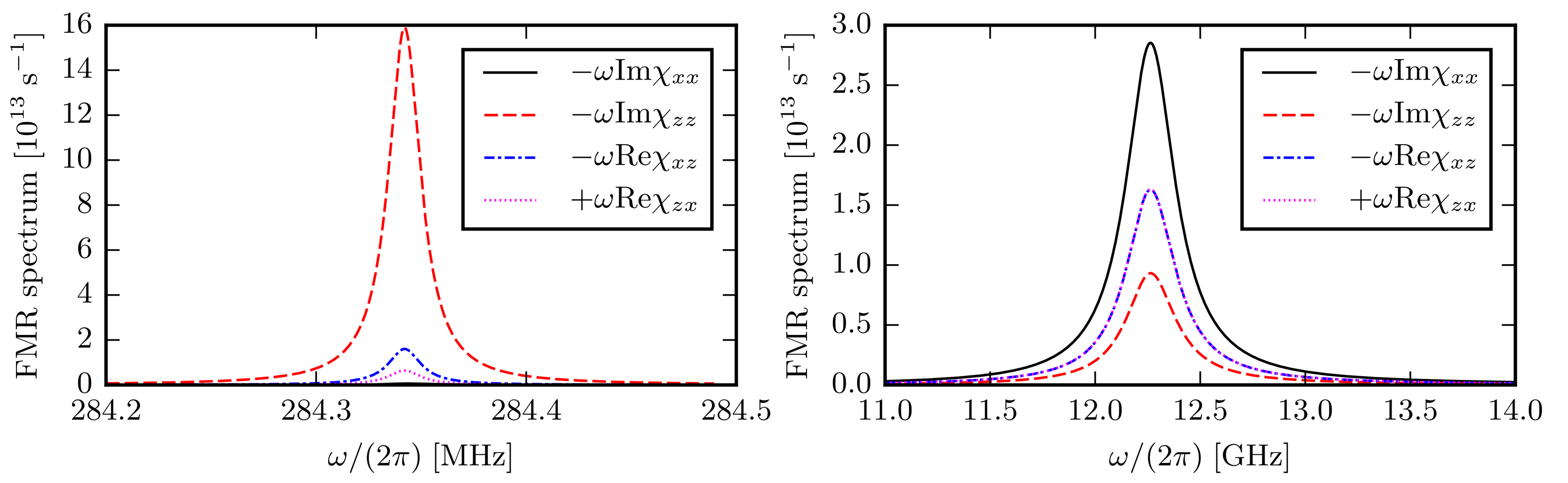
- Landau-Lifshitz-Gilbert equation: $\dot{\mathbf{m}} = -\gamma\mu_0 \mathbf{m}\times\mathbf{H}_{\mathrm{eff}} + \boldsymbol{\tau}_m^{(\alpha)}$
  effective magnetic field: $\mathbf{H}_{\mathrm{eff}} = -\frac{1}{\mu_0 V M_s}\nabla_{\mathbf{m}} E = \mathbf{H}_B + \mathbf{H}_{\mathrm{ext}} + \mathbf{H}_K + \mathbf{H}_D$
  Barnett field: $\mu_0 \mathbf{H}_B = -\mathbf{\Omega}/\gamma$, due to the Barnett effect (contained in E_T)
  Gilbert damping torque: $\boldsymbol{\tau}_m^{(\alpha)} = \alpha\left[\mathbf{m}\times\dot{\mathbf{m}} + \mathbf{m}\times(\mathbf{m}\times\mathbf{\Omega})\right]$
- mechanical torque: $\dot{\mathbf{L}} = \frac{V M_s}{\gamma}\dot{\mathbf{m}} + \mu_0 V M_s \mathbf{m}\times\mathbf{H}_{\mathrm{ex}}$
  total angular momentum: $\mathbf{J} = \mathbf{L} - V M_s \mathbf{m}/\gamma$
  torque on the total angular momentum: $\dot{\mathbf{J}} = \mu_0 V M_s \mathbf{m}\times\mathbf{H}_{\mathrm{ex}}$

Microwave absorption spectra

- nanomagnet in a monochromatic ac field $\mathbf{h}_\perp(t) \propto e^{i\omega t}$
- analytic calculation of magnetic susceptibility $\chi(\omega)$ in linear response to $\mathbf{h}_\perp(t)$
  normal modes: peaks in $\chi(\omega)$
  absorbed microwave power: $P = -\frac{\mu_0 V}{2}\omega \mathrm{Im}\left(\mathbf{h}_\perp^{*\mathrm{T}}\chi\mathbf{h}_\perp\right)$
- example 1: iron nanosphere of 2 nm diameter in a static magnetic field $\mu_0\mathbf{H}_0 = 0.65$ T
  with Gilbert damping constant $\alpha = 0.01$, easy-axis configuration $(\mathbf{m} \parallel \mathbf{n})$



- example 2: iron nanodisk (2×15 nm) in a static magnetic field $\mu_0\mathbf{H}_0 = 0.25$ T
  with Gilbert damping constant $\alpha = 0.01$, easy-plane configuration $(\mathbf{m}\perp\mathbf{n})$



Characterization of the normal modes

- high-frequency FMR: counterclockwise precession of $\mathbf{m}$
  blueshift $\sim \omega_c = M_s V/(\gamma I_\perp) = 492(\mathrm{nm}/R)^2$ MHz, for Fe sphere
- low-frequency modes: lattice orientation $\mathbf{n}$ and magnetization $\mathbf{m}$ are locked
  easy-axis $(\mathbf{m}\parallel\mathbf{n})$: clockwise and counterclockwise precession
  easy-plane $(\mathbf{m}\perp\mathbf{n})$: oscillation about the axis perpendicular to the $\mathbf{m}$,$\mathbf{n}$-plane
- Barnett effect: increase of the blueshift of the FMR by a factor of ~ 2
  change of the position of the low-frequency modes

References

[1] H. Keshtgar, S. Streib, A. Kamra, Y. M. Blanter, G. E. W. Bauer, arXiv:1610.01072.
[2] N. Usov and B. Y. Liubimov, J. Magn. Magn. Mater. **385**, 339 (2015).