UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

SPINTRONICS PHENOMENA IN THE CLASSICAL AND QUANTUM WORLDS

- Alexey A. Kovalev

Collaborators:

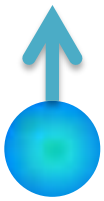
- Yaroslav Tserkovnyak (UCLA, USA)
- Gerrit E. W. Bauer (TU Delft, the Netherlands)
- Leonid P. Pryadko (University of California, Riverside)
- Lorien X. Hayden (University of Missouri, USA)
- and others…

Support

OUTLINE

- Introduction: the notion of *spin* and *spintronics*.
- Accumulation of *geometrical phase* (parallel transport) by spin and its implications for solids with magnetic textures and/or relativistic (spin-orbit) interactions.
- Review of my research in spintronics: *Aharonov-Casher* effect, *anomalous Hall* effect, thermoelectric and thermomagnonic *spin transfer* and *Peltier effects*.
- Going quantum with spintronics: *Magnetomechanical effects* at nanoscale and magnetization reversal.
- Macrospin tunneling and magnetopolaritons in the presence of *nanomechanical interference*.
- Future study directions.

FROM SPIN TO SPINTRONICS



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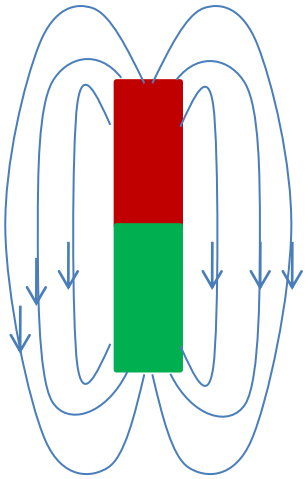
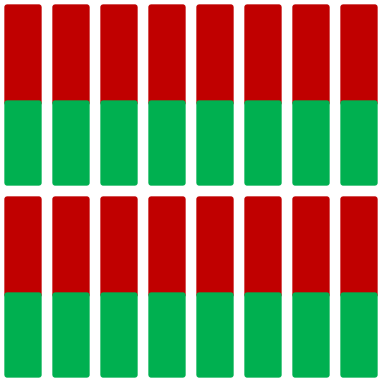
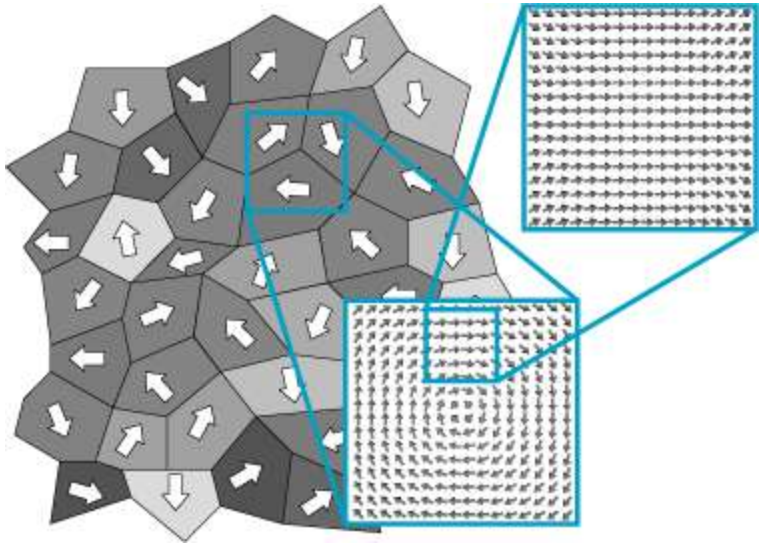




Electron possesses spin in addition to charge.

In ferromagnets all spins are aligned by exchange interactions.



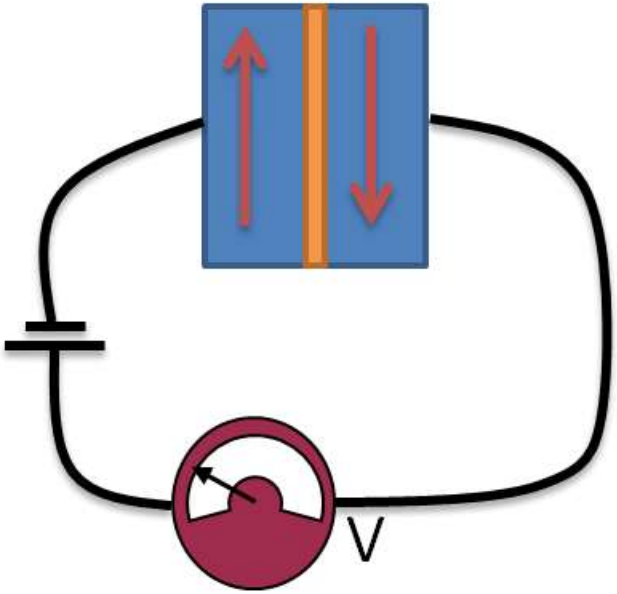
"Nanometer magnets," in AccessScience (2006)

The spin direction can slowly change in space – texture.

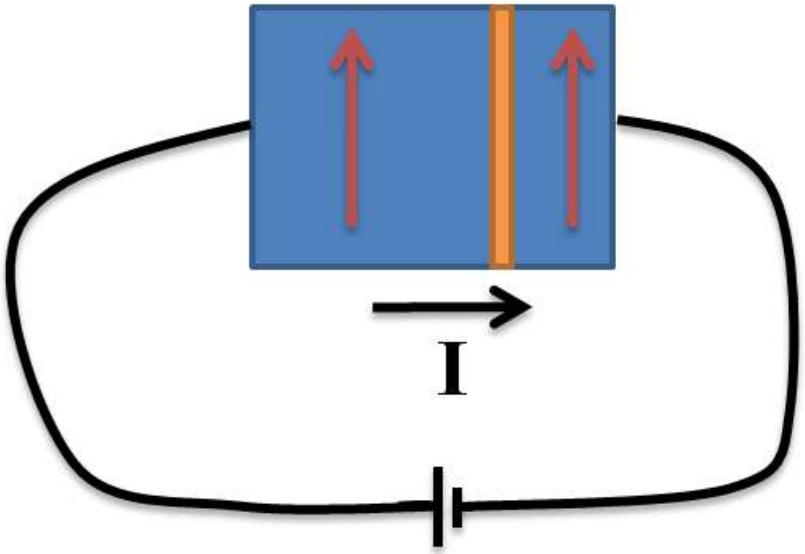
Torque is a force on a magnet (spin) by magnetic field or by passing current.

History of Spintronics: Where it all started

Albert Fert and Peter Grünberg discovered giant magnetoresistance effect in 1988, Nobel Prize 2007.

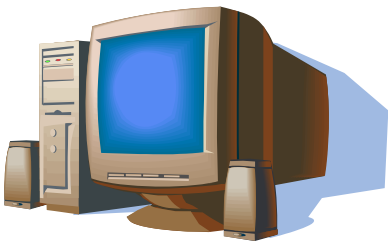


Opposite effect: current induced torque.

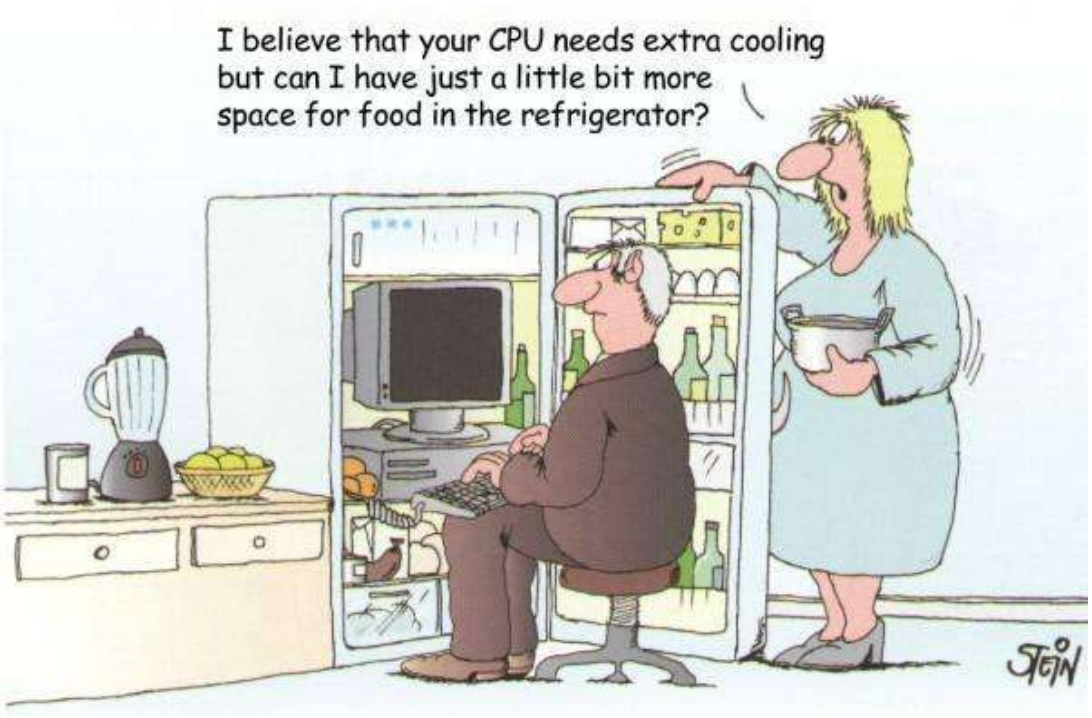


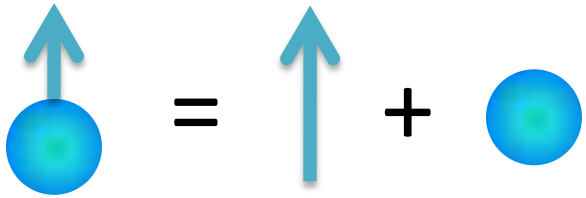
CAN SPINTRONICS IMPROVE OUR LIVES?

In every computer operation of hard disk relies on spintronics; however, information carrier is charge.



Shrinking of processor technology has stopped yielding exponential gains in power and performance!

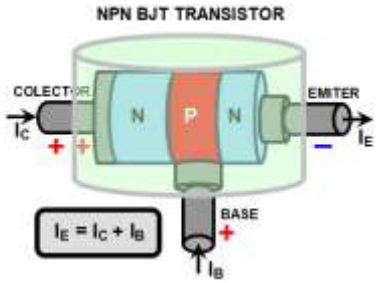




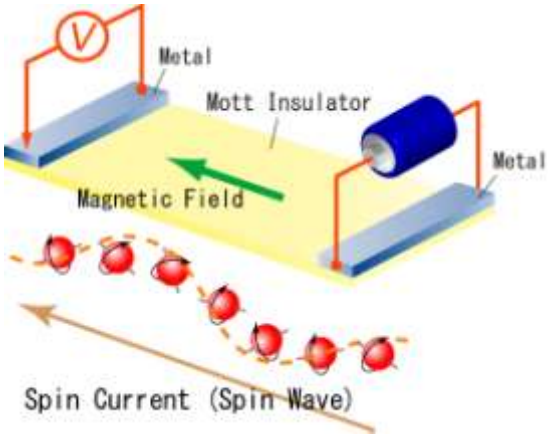
Idea: Improve devices relying on charge transport by employing the spin degree of freedom.

NEW WAY TO TRANSFER SIGNAL

First transistor invented by John Bardeen, William Shockley and Walter Brattain in 1947 relied on possibility that hole current can flow through bulk of semiconductor.

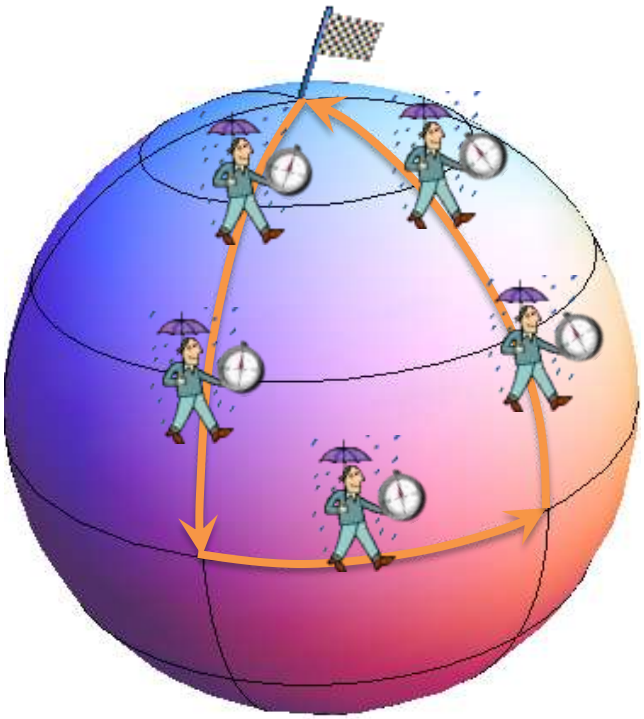


Recently, controllable spin flows through ferromagnetic insulators have been experimentally realized.



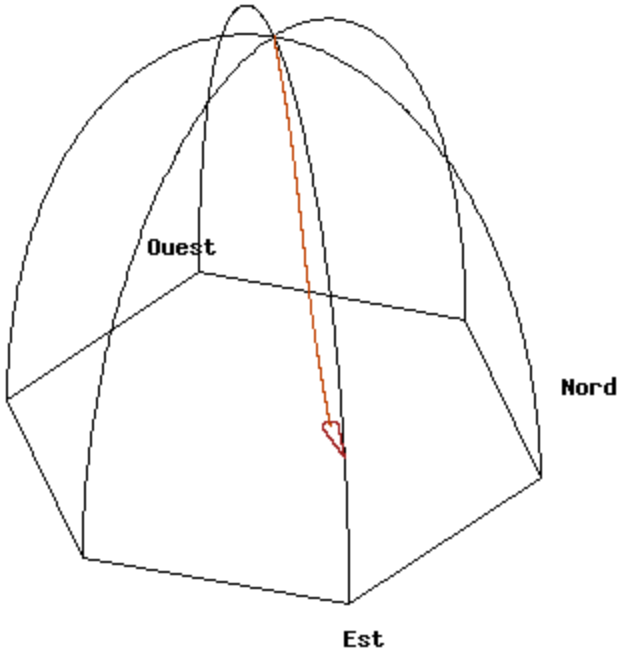
Y. Kajiwara, K. Harii, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi, S. Maekawa & E. Saitoh Nature **464**, 262 (2010)

GEOMETRIC PHASES AND PARALLEL TRANSPORT



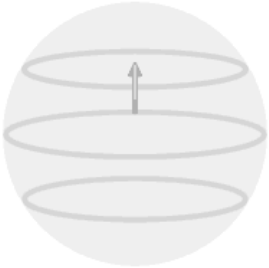
Example 1: Traveler with a compass;

- traveler with a compass starts from and returns to the North pole.
- compass arrow acquires an angle (phase).



Example 2: Foucault pendulum;

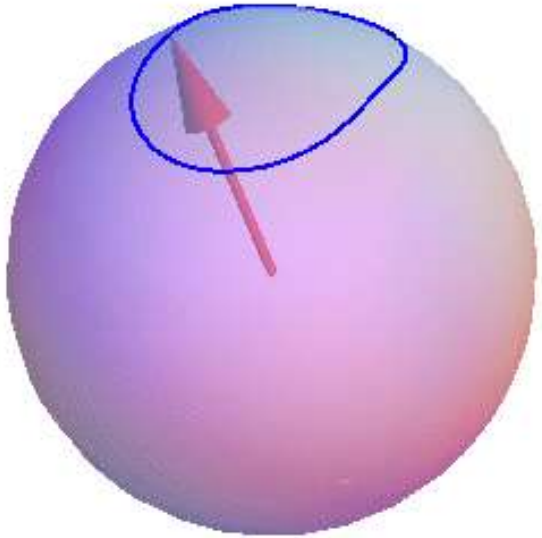
- as earth rotates pendulum acquires rotation
- projection of the angular velocity of Earth onto the normal direction to Earth determines precession.



(From wikipedia)

GEOMETRIC PHASE OF SPIN

$$\Phi = A * S$$

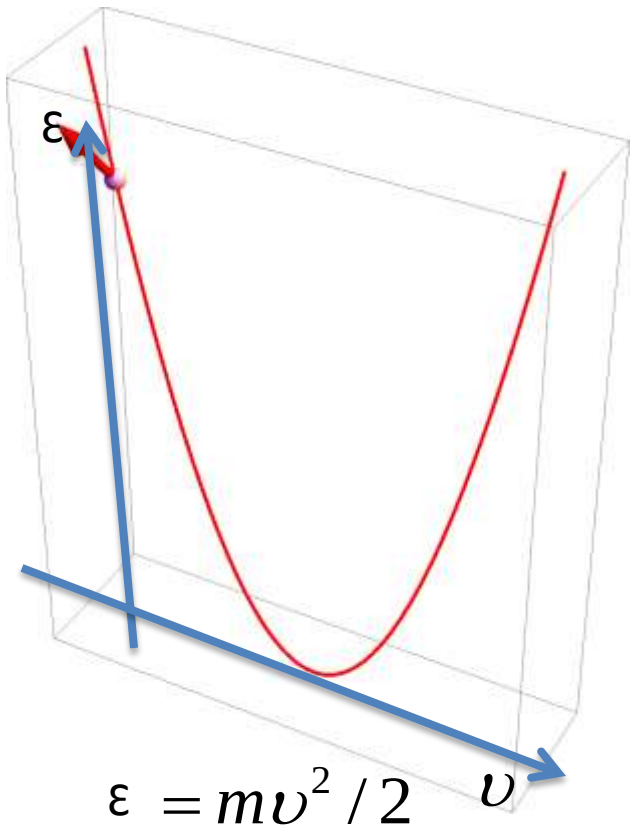


- Spin lives on a surface of a sphere.
- Spin returns to initial position and accumulates a Geometric phase – a product of encircled area and spin.

$|\boldsymbol{S}\rangle = e^{-i\hat{S}_z\phi} e^{-i\hat{S}_y\theta} e^{-i\hat{S}_z\chi} |\uparrow\rangle$ -- spin direction is defined by three Euler angles.

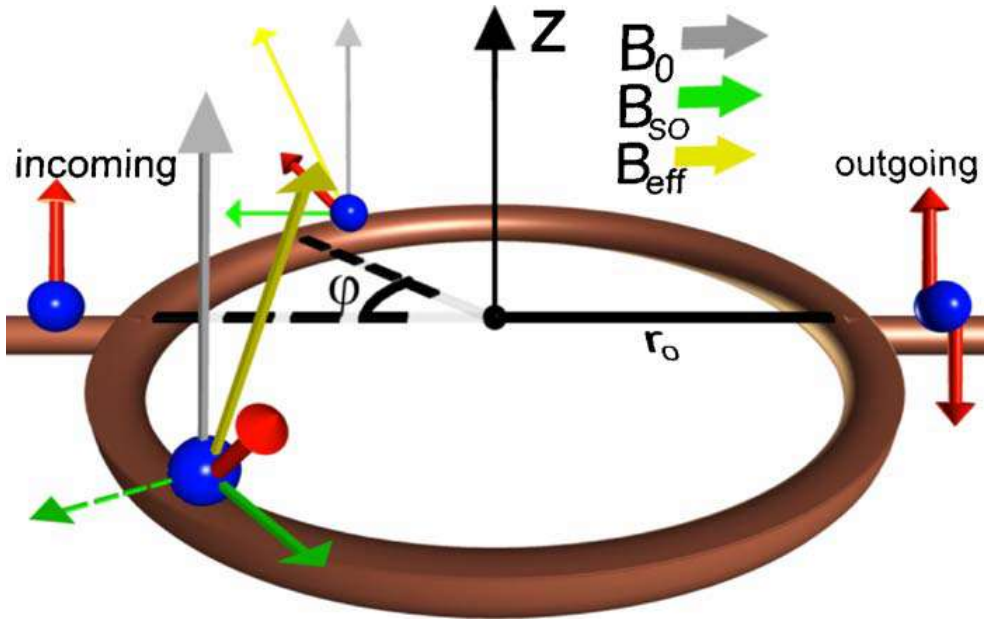
Geometric phase of spin -> $\boxed{\Phi = i \int_{R(0)}^{R(t)} \langle \boldsymbol{S}(R)| \nabla_R |\boldsymbol{S}(R)\rangle \, dR}$

RELATIVISTIC EFFECTS, AHARONOV-CASHER EFFECT



$$\varepsilon = m\upsilon^2/2$$

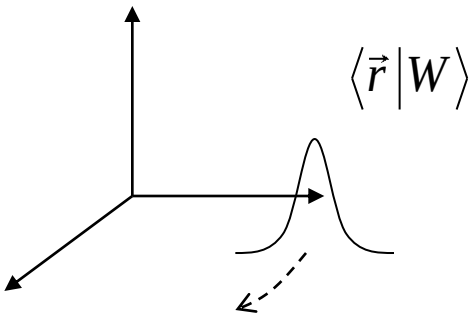
Velocity dependent magnetic field in the reference frame moving with electron.



M. Konig, A. Tschetschetkin, E. M. Hankiewicz, J. Sinova, V. Hock, V. Daumer, M. Schafer, C. R.Becker, H. Buhmann, and L. W. Molenkamp, PRL **96**, 076804 (2006); D. Frustaglia and K. Richter, PRB **69**, 235310 (2004); B. Molnar, F. M. Peeters, and P. Vasilopoulos, PRB **69**, 155335 (2004).

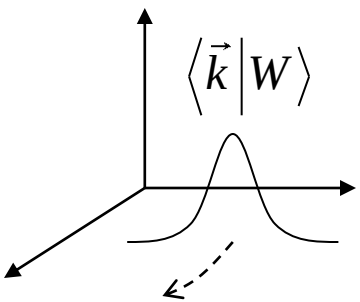
AC effect in a two dimensional hole ring, A.A. Kovalev, M. F. Borunda, T. Jungwirth, L. W. Molenkamp, J. Sinova, PRB **76**, 125307 (2007).

GEOMETRIC PHASES FROM WAVE PACKET APPROACH



1. The wave packet is localized in both the *r* and *k* spaces.

2. Effective Lagrangian obtained using the time-dependent variational principle.



$$L(\mathbf{r}_c, \mathbf{q}_c, \dot{\mathbf{r}}_c, \dot{\mathbf{q}}_c) = \langle W | i\hbar\partial_t - H | W \rangle$$
$$= -E + \mathbf{q}_c \cdot \dot{\mathbf{r}}_c + \dot{\mathbf{q}}_c \cdot \langle u | i\partial_{\mathbf{q}_c} u \rangle + \dot{\mathbf{r}}_c \cdot \langle u | i\partial_{\mathbf{r}_c} u \rangle + \langle u | i\partial_t u \rangle$$

$|u\rangle$ – Periodic part of the Bloch wave.

$$\dot{\mathbf{r}}_c = \partial_{\mathbf{q}_c} E - (\overleftrightarrow{\Omega}_{\mathbf{qr}} \cdot \dot{\mathbf{r}}_c + \overleftrightarrow{\Omega}_{\mathbf{qq}} \cdot \dot{\mathbf{q}}_c) + \Omega_{t\mathbf{q}}$$
$$\dot{\mathbf{q}}_c = -\partial_{\mathbf{r}_c} E + (\overleftrightarrow{\Omega}_{\mathbf{rr}} \cdot \dot{\mathbf{r}}_c + \overleftrightarrow{\Omega}_{\mathbf{rq}} \cdot \dot{\mathbf{q}}_c) - \Omega_{t\mathbf{r}}$$
$$\overleftrightarrow{\Omega}_{AB} = i\left(\langle \partial_A u | \partial_B u \rangle - \langle \partial_B u | \partial_A u \rangle\right)$$

$\overleftrightarrow{\Omega}_{\mathbf{rr}}$ – Effective band-dependent magnetic field

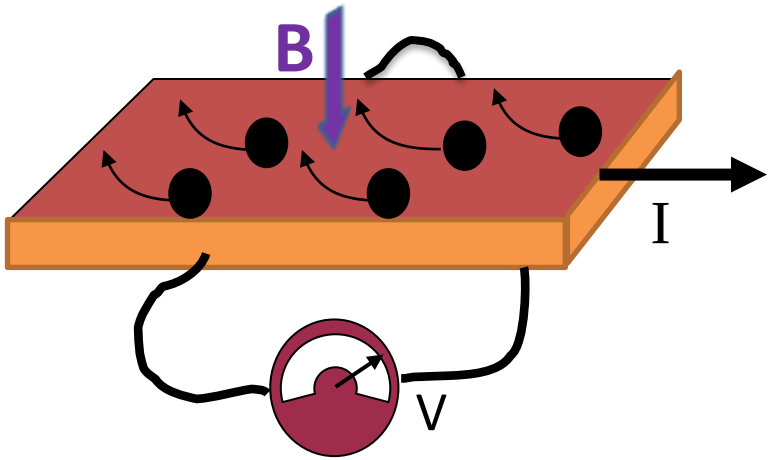
$\overleftrightarrow{\Omega}_{\mathbf{qq}}$ – Anomalous velocity

$\Omega_{t\mathbf{r}}$ – Electromotive force

These semiclassical equations contain the physics of the Geometric phases.

G. Sundaram and Q. Niu, PRB **59**, 14915 (1999)

MANIFESTATIONS: ANOMALOUS HALL EFFECT (AHE)



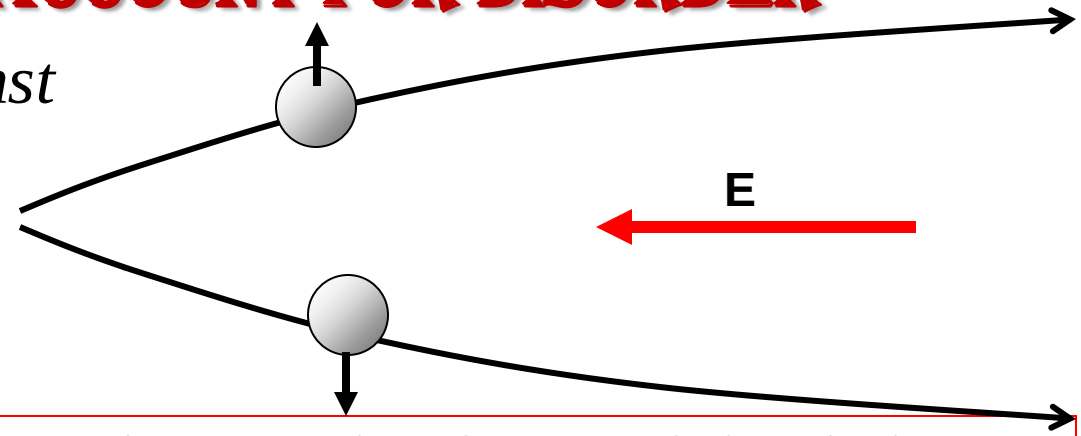
Anomalous Hall effect is a Hall effect without magnetic field.

The origin is in spin rotation and accumulation of Geometric phases.

R. Karplus and J. M. Luttinger, Phys. Rev. **95**, 1154 (1954); N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, N. P. Ong, Rev. Mod. Phys. **82**, 1539 (2010) and references therein; A. A. Kovalev et al. PRB **79**, 195129 (2009); S. Onoda, N. Sugimoto, and N. Nagaosa, PRB **77**, 165103 (2008); N. A. Sinitsyn et al. PRB **75**, 045315 (2007); T.S. Nunner et al., PRB **76**, 235312 (2007); A.A. Kovalev, K. Vyborny, and J. Sinova, PRB **78**, 041305(R) (2008); N.A. Sinitsyn, J. Phys. Condens. Matter **20**, 023201 (2008).

DIFFICULT TO ACCOUNT FOR DISORDER

a) Intrinsic deflection $\sigma_H \propto const$



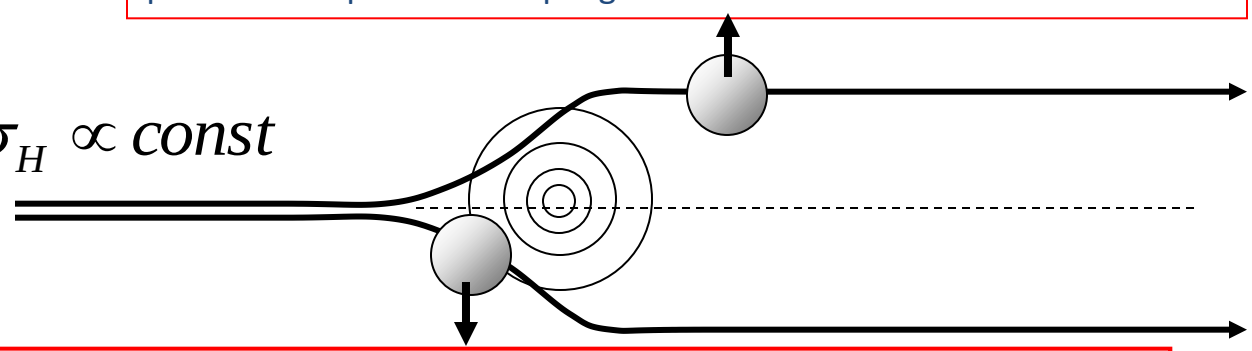
Electrons deflect to the right or to the left as they are accelerated by an electric field due to the spin-orbit coupling in the periodic potential (electronics structure).

$$\hbar \frac{d\vec{k}}{dt} = -e\vec{E} - \frac{e}{c}\dot{\vec{r}} \times \vec{B}$$

$$\frac{d\vec{r}}{dt} = \frac{1}{\hbar}\frac{\partial E}{\partial \vec{k}} - \dot{\vec{k}} \times \vec{\Omega}(\vec{k})$$

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry's phase curvature which is nonzero in the presence of spin-orbit coupling.

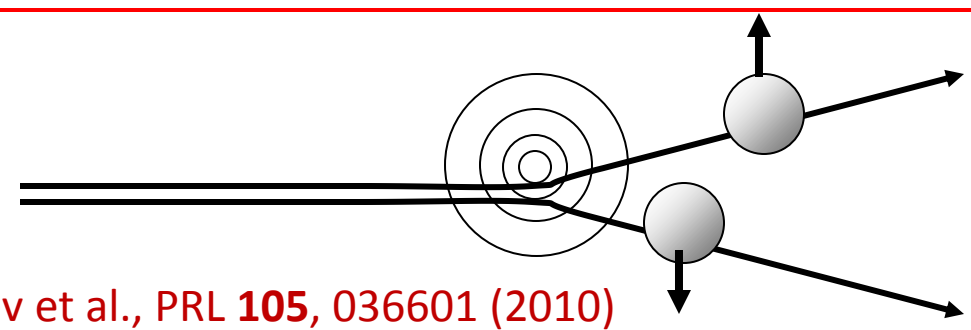
b) Side jump scattering $\sigma_H \propto const$



Electrons deflect first to one side due to the field created by the impurity and deflect back when they leave the impurity since the field is opposite resulting in a side step. This side-jump deflection is superimposed on the skew scattering deflection upon scattering.

c) Skew scattering $\sigma_H \propto \sigma_{xx}$

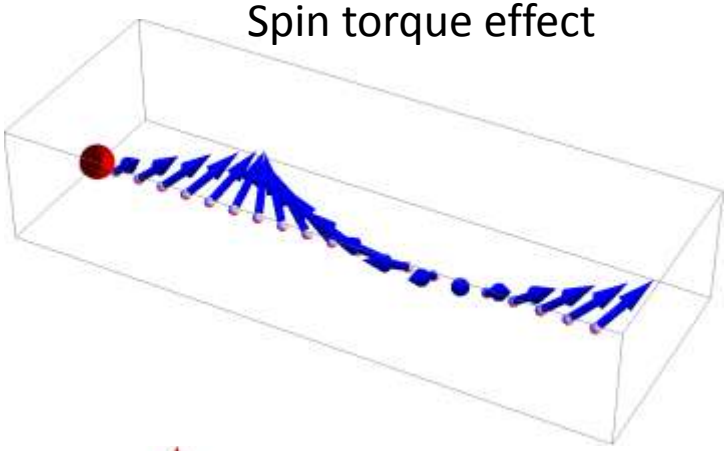
Asymmetric scattering is due to the effective spin-orbit coupling of the electron or the impurity.



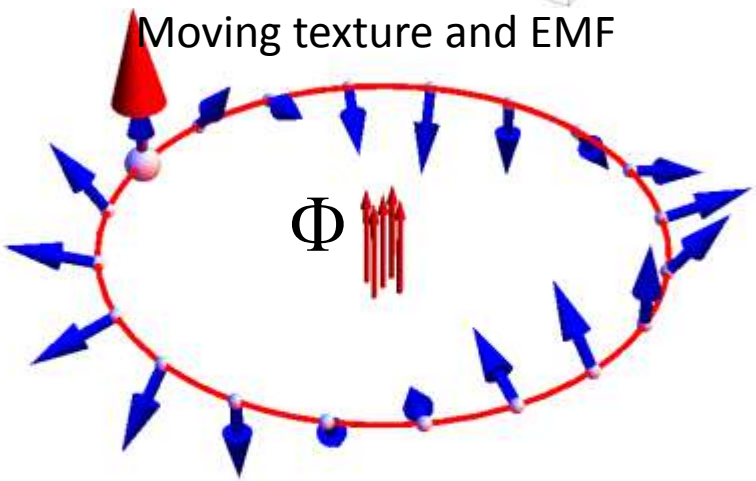
A.A. Kovalev et al., PRL **105**, 036601 (2010)

MAGNETIC TEXTURE INDUCED GEOMETRIC PHASES

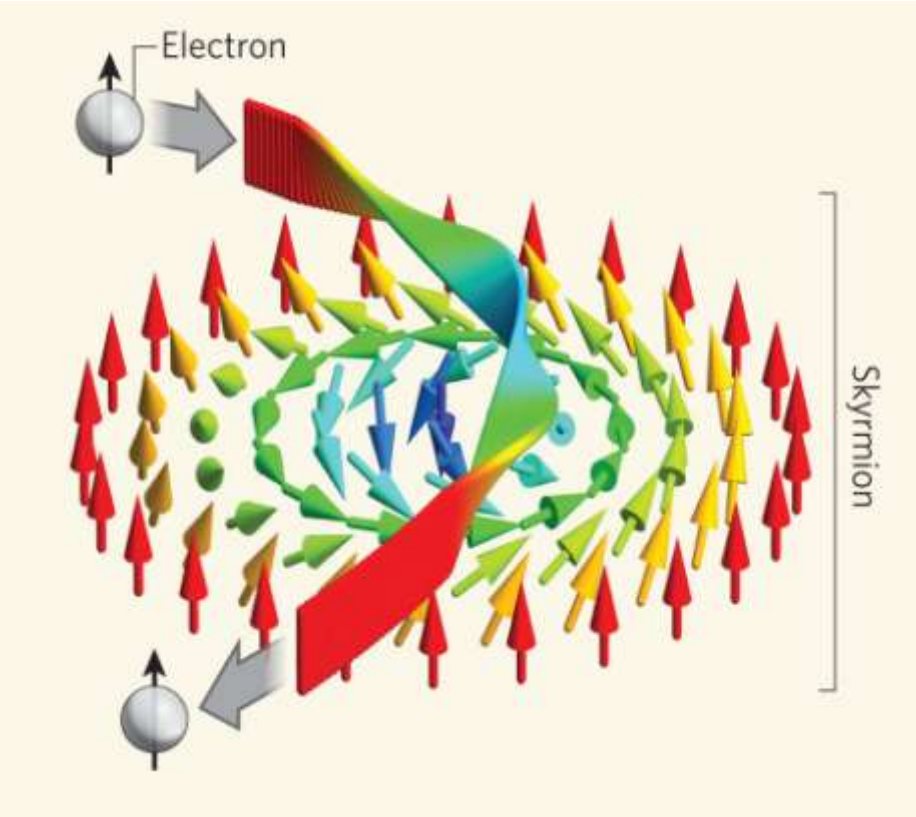
Spin torque effect



Moving texture and EMF



Fictitious magnetic field

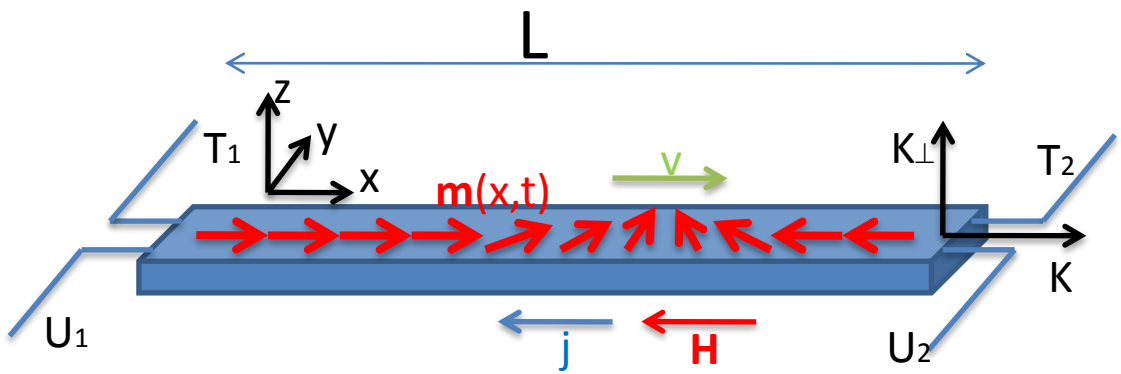


1. If magnetic field changes then by Faraday's law there is electro-motive force: $\mathcal{E} = -\partial_t \Phi$
2. Electron also accumulates additional phase Φ' due to magnetic texture. If the magnetic texture changes in time, by analogy to Faraday's law we have additional electromotive force: $\mathcal{E}' = -\partial_t \Phi'$

Magnetic texture induced fictitious magnetic field deflects the trajectory.

C. Pfleiderer, A. Rosch, Nature 465, 880 (2010)
X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa& Y. Tokura Nature 465, 901 (2010)

PHENOMENOLOGICAL EQUATIONS



Equation for the entropy production $$\frac{dS}{dt} = \frac{L}{T}\left[- j_q \frac{T_2 - T_1}{TL} - j\frac{\mu_2 - \mu_1}{L} - \dot{X}\frac{2MH}{L} \right]$$

$$\dot{X} = -\mathrm{O}_X \frac{2MH}{L} - \mathrm{O}_{X\mu} j - \mathrm{O}_{XT} j_q$$

$$\frac{T_2 - T_1}{TL} = -\mathrm{O}_T j_q + \mathrm{O}_{XT}\frac{2MH}{L} - \mathrm{O}_{T\mu} j$$

$$\frac{\mu_2 - \mu_1}{L} = -\mathrm{O}_\mu j + \mathrm{O}_{X\mu}\frac{2MH}{L} + \mathrm{O}_{T\mu} j_q$$

By Onsager reciprocity principle.

A. A. Kovalev and Y. Tserkovnyak, Solid State Commun. **150**, 500 (2010).

INTERPLAY BETWEEN CURRENTS AND TEXTURES

$$-\partial_i \mu = \Upsilon_{ik} j_k + \Pi_{ik} \frac{\partial_k T}{T} - p\,(\mathbf{m} \times \partial_i \mathbf{m} + \beta \partial_i \mathbf{m}) \cdot \dot{\mathbf{m}}$$ ⟸ Particle current

$$(j_q)_i = \Pi^T_{ik} j_k - \kappa_{ik} \partial_k T + p_1\,(\mathbf{m} \times \partial_i \mathbf{m} + \beta_1 \partial_i \mathbf{m}) \cdot \dot{\mathbf{m}}$$ ⟸ Heat current

$$s(1 + \alpha \mathbf{m}\times)\dot{\mathbf{m}} + s\mathbf{m} \times \mathbf{H}_{\text{eff}} = p\,[\partial_i \mathbf{m} + \beta(\mathbf{m} \times \partial_i \mathbf{m})]\, j_i - p_1\,[\partial_i \mathbf{m} + \beta_1(\mathbf{m} \times \partial_i \mathbf{m})] \cdot \partial_i T/T\,,$$ ⟸ LLG

A.A. Kovalev and Y. Tserkovnyak, Phys. Rev. B **80**, 100408(R) (2009); arXiv:1106.3135.

Hall effect

Resistivity tensor $\Upsilon_{ik} = \delta_{ik}\left[\Upsilon + \eta_\Upsilon (\partial_l \mathbf{m})^2\right] + \eta'_\Upsilon \partial_i \mathbf{m} \cdot \partial_k \mathbf{m} + b_\Upsilon \mathbf{m} \cdot (\partial_i \mathbf{m} \times \partial_k \mathbf{m})$

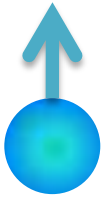
Nernst and Righi-Leduc effects

Peltier coeff. tensor $\Pi_{ik} = \delta_{ik}\left[\Pi + \eta_\Pi (\partial_l \mathbf{m})^2\right] + \eta'_\Pi \partial_i \mathbf{m} \cdot \partial_k \mathbf{m} + b_\Pi \mathbf{m} \cdot (\partial_i \mathbf{m} \times \partial_k \mathbf{m})$

Therm. conductivity tensor $\kappa_{ik} = \delta_{ik}\left[\kappa + \eta_\kappa (\partial_l \mathbf{m})^2\right] + \eta'_\kappa \partial_i \mathbf{m} \cdot \partial_k \mathbf{m} + b_\kappa \mathbf{m} \cdot (\partial_i \mathbf{m} \times \partial_k \mathbf{m})$

Going Quantum with Spintronics: Magnetomechanical Effects at Nanoscale and Magnetization Reversal

FROM SPINS TO MAGNETS



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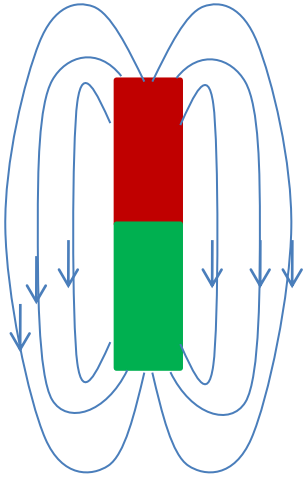
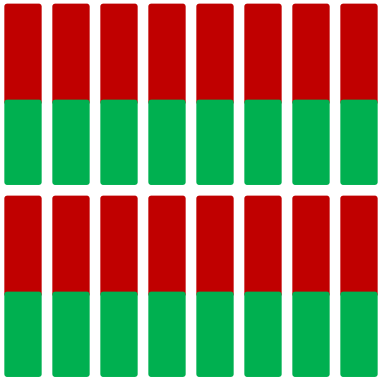
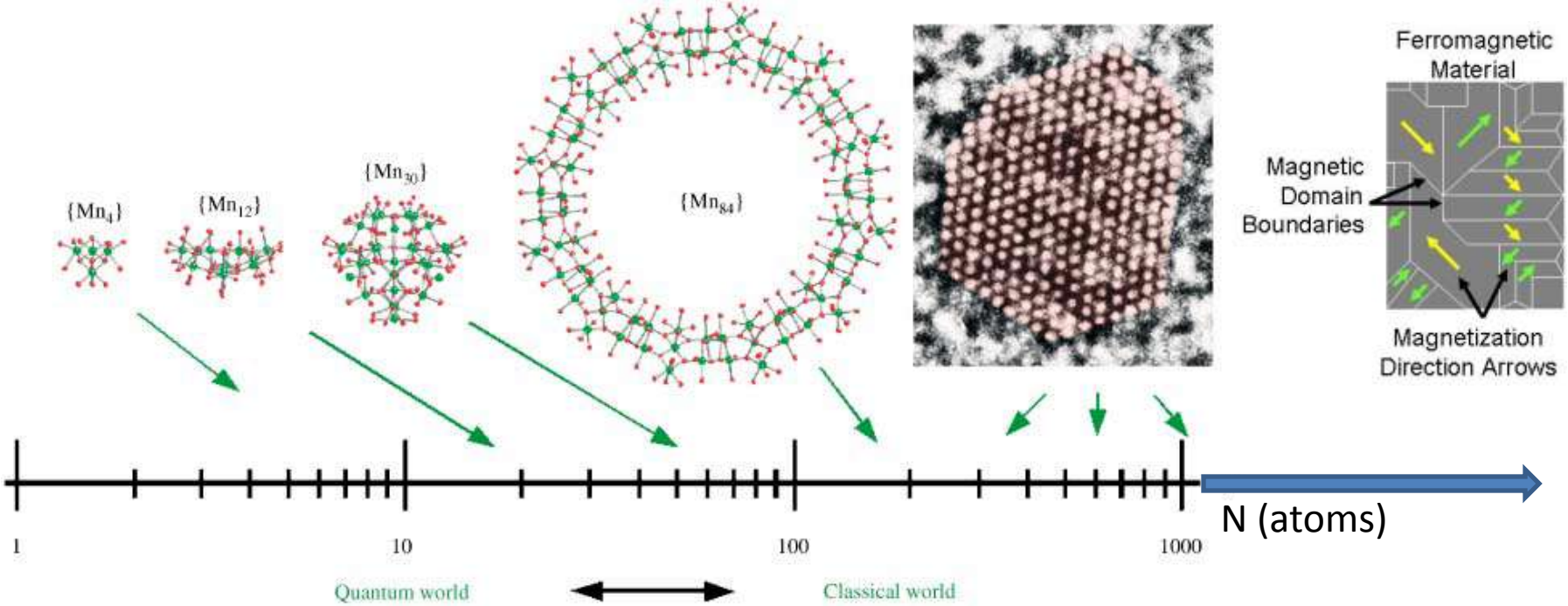




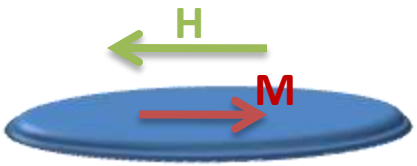
Electron processes spin in addition to charge.

In ferromagnets spins are aligned by exchange interactions.

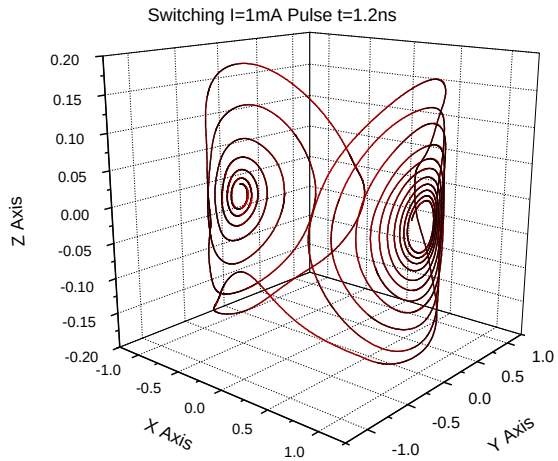
A.J. Tasiopoulos, A. Vinslava, W. Wernsdorfer, K.A. Abboud, G. Christou, Angew. Chem. Int. Ed. 43, 2117 (2004)

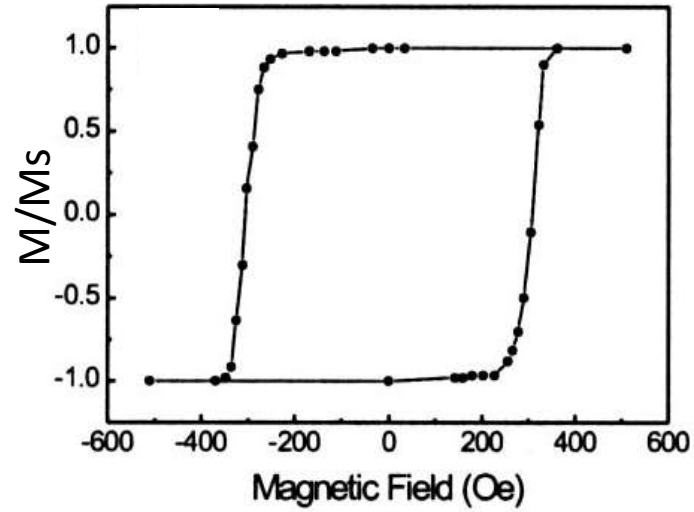


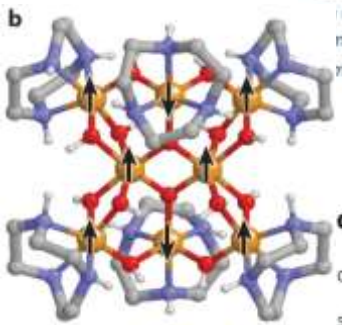
QUANTUM VS. CLASSICAL MAGNETIZATION REVERSAL



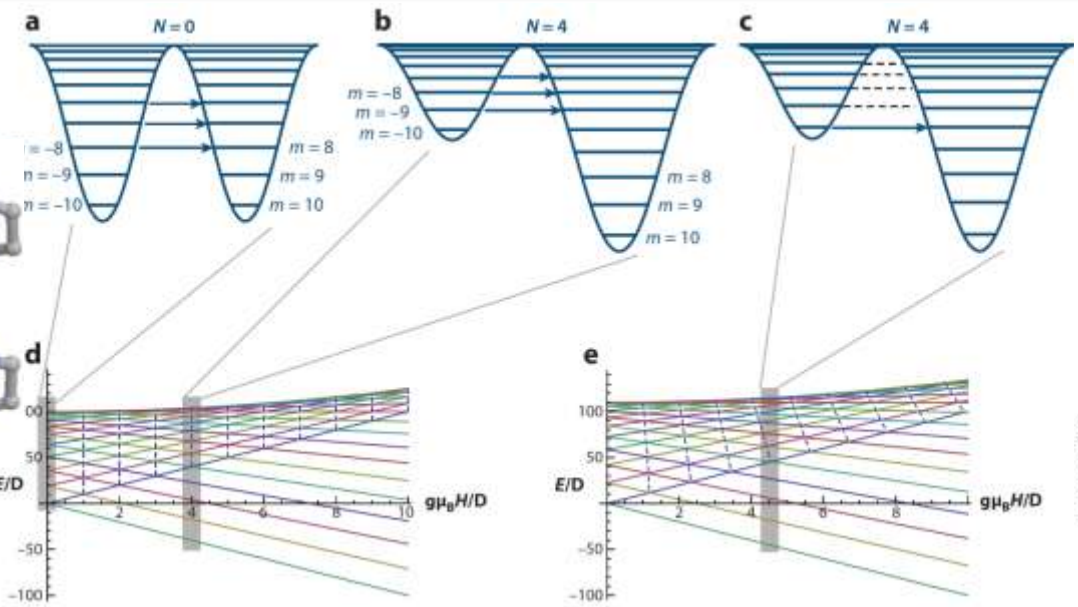
Single domain magnet or Stoner-Wohlfarth particle.

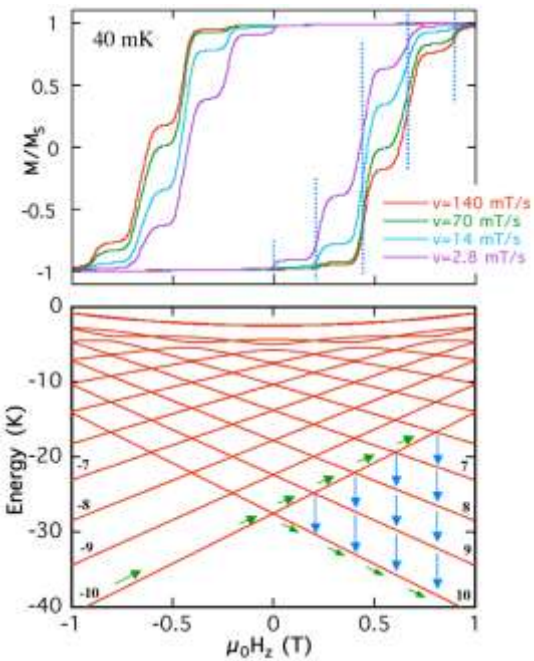






Fe8



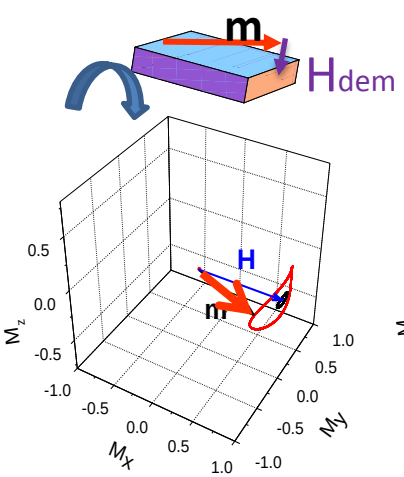


J. R. Friedman & M. P. Sarachik, Annual Review of Condensed Matter Physics (2010).

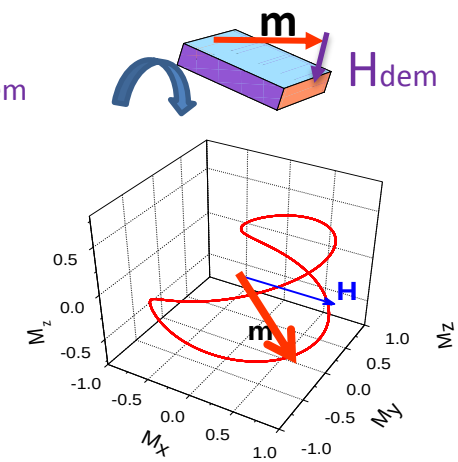
W. Wernsdorfer & R. Sessoli, Science (1999).

MECHANICAL DEGREE OF FREEDOM MATTERS AT NANOSCALE

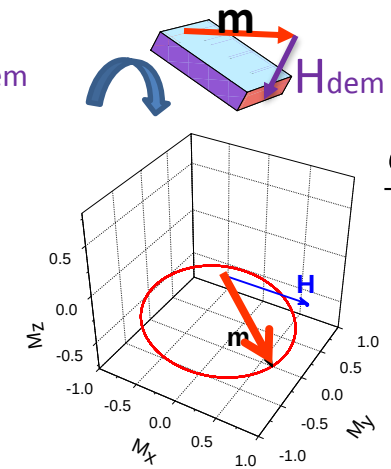
By applying a sharp mechanical pulse (rapid torsion) one can reverse magnetization in a thin magnetic film which is a result of demagnetizing field.



Weak pulse



Stronger pulse



Sufficient for reversal pulse

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_S} \vec{M} \times \left(\frac{d\vec{M}}{dt} \right)$$

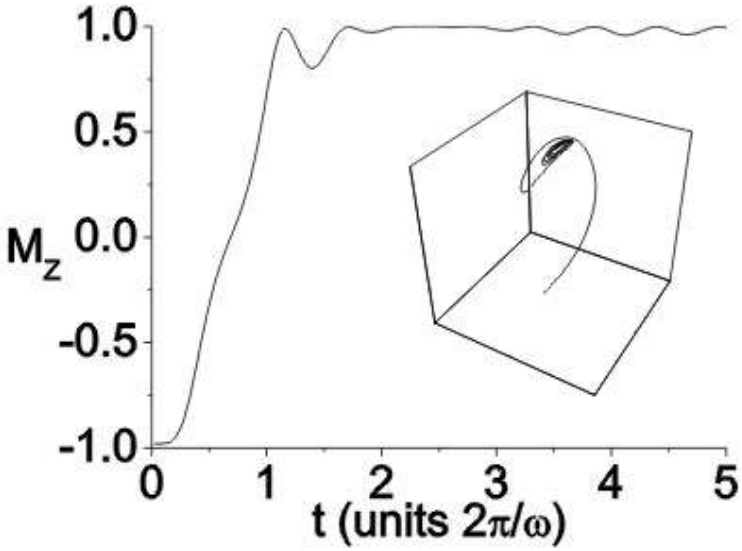
$$\vec{H}_{eff} = \frac{\delta F(\vec{M})}{\delta \vec{M}}$$

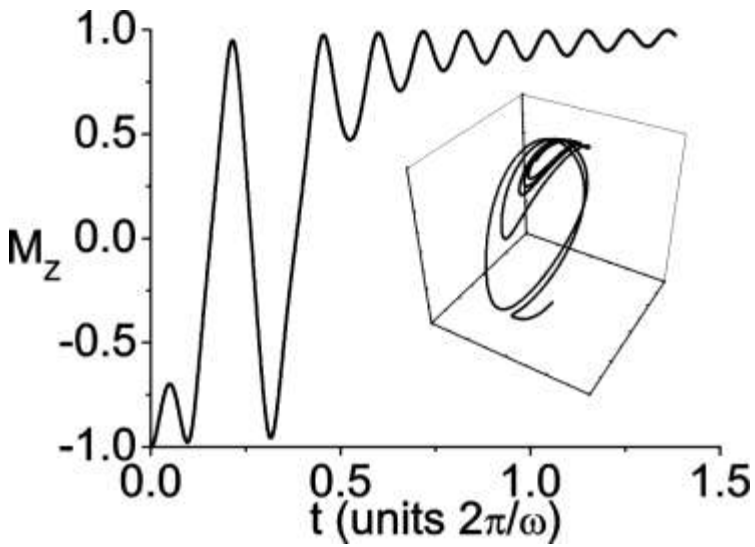
Description by LLG equation with effective field depending on torsion **Kovalev et al. PRL 94, 167201**

Similar to precessional magnetization reversal techniques relying on a sharp magnetic or electric (for current induced switching) pulse. **Back et al., PRL 81, 3251**

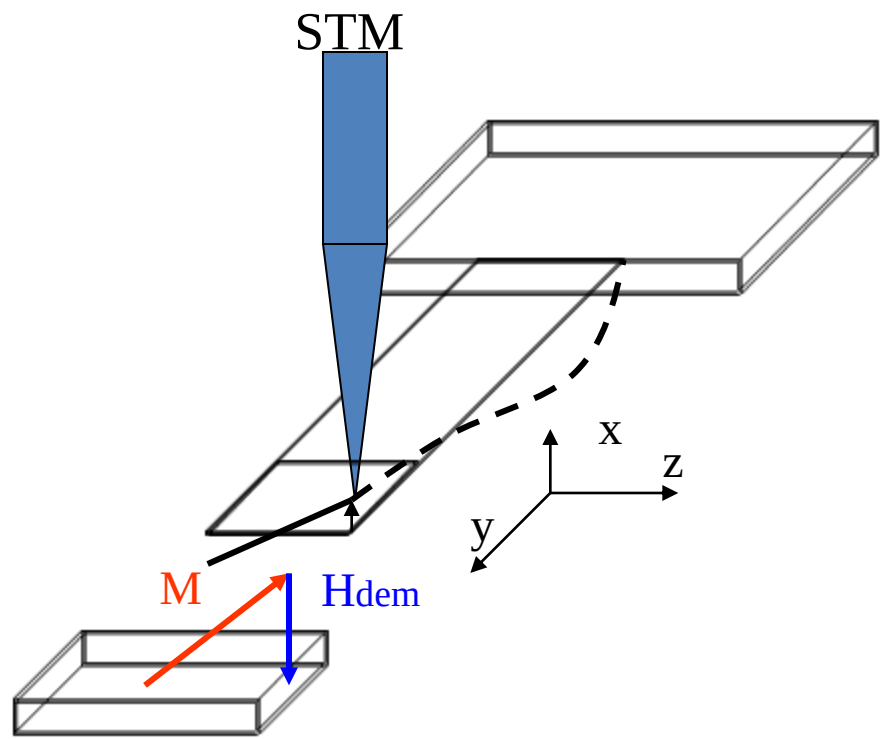
However, the mechanical actuation has to be fast ~ 1GHz!

PRECESSIONAL REVERSAL BY MECHANICAL ACTUATION





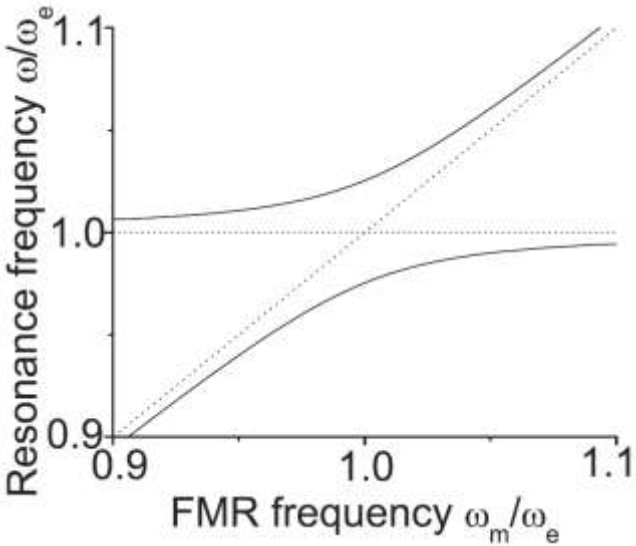
Sudden mechanical twist of a tip released by STM generates magnetic pulse given by effective field in the LLG. Thus, tilted magnetization is reversed by demagnetizing field.

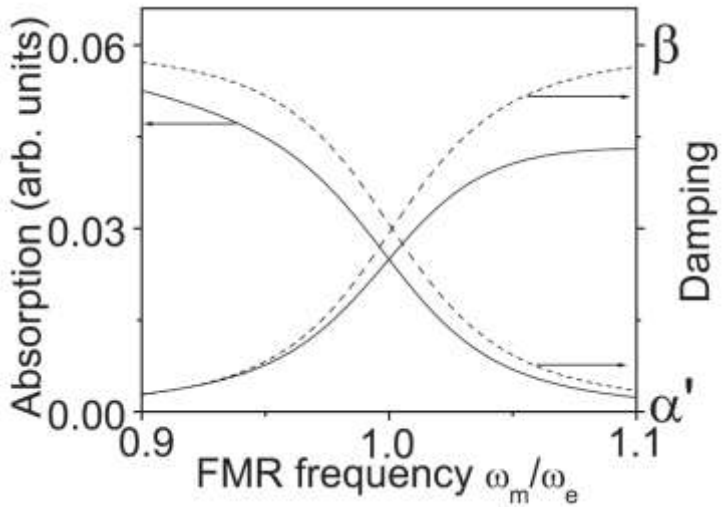


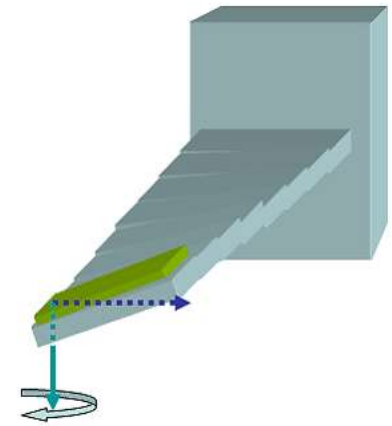
Related experiments by Mark Freeman, University of Alberta, Canada

Kovalev et al. PRL 94, 167201

MAGNETOVIBRATIONAL MODES EXCITED BY RF FIELDS

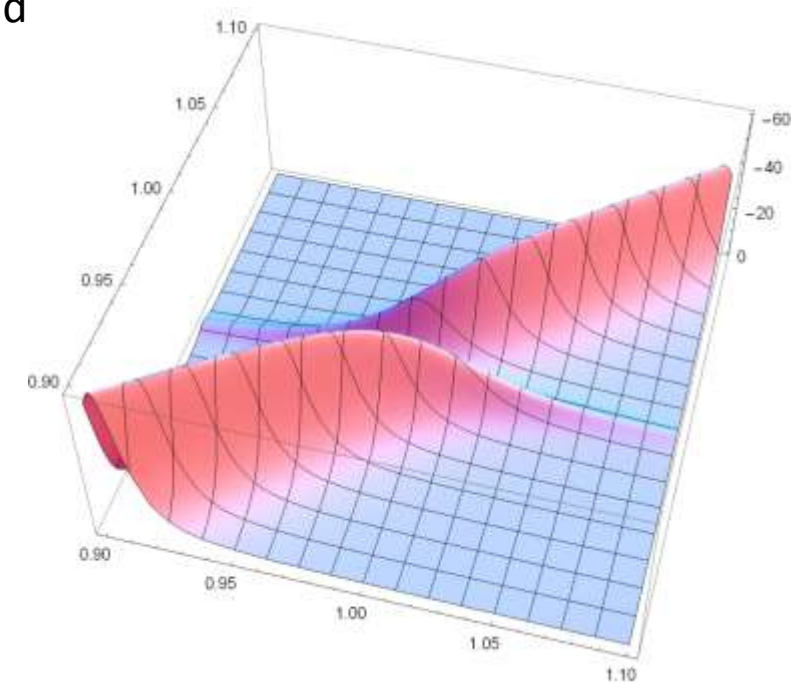






The resonance frequency of the coupled motion and the corresponding oscillator strength.

$$\frac{\Delta\omega}{\omega_e} = \left(\frac{H_k + H_{dem}}{H_k}\right)^{\frac{1}{4}} \sqrt{\frac{S\hbar}{I\omega_e}}$$



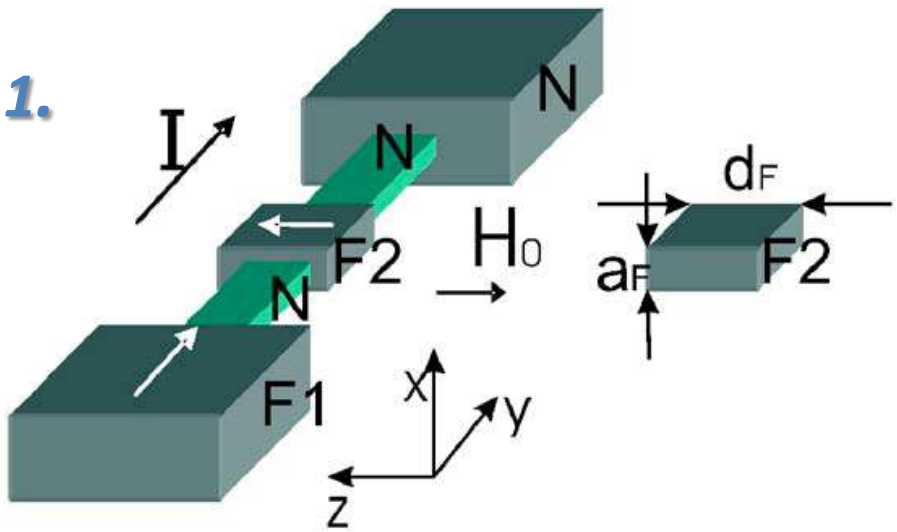
The splitting is defined by the ration of spin momentum to mechanical momentum,

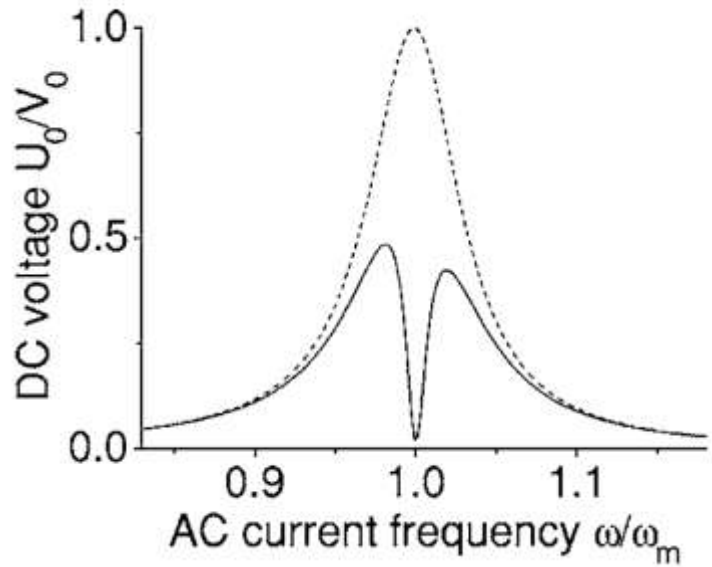
I - moment of inertia.

Kovalev et al. JJAP 45 3878; APL 83, 1584

MAGNETOVIBRATIONAL MODES EXCITED BY CURRENTS

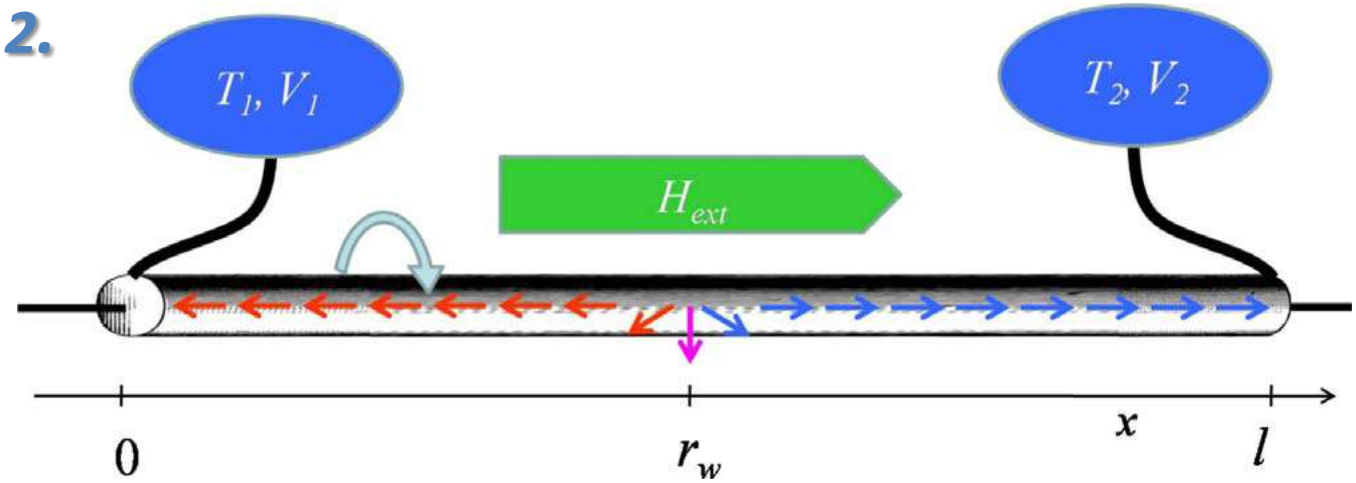
1.





Splittings in the current induced FMR spectra. **Kovalev et al., PRB 75, 014430**

2.



Yu et al., JAP 102, 066101; Bauer et al., PRB 81, 024427

ROTATING FRAME AND BARNETT EFFECT

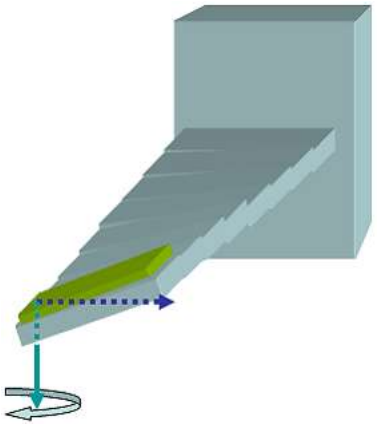
- **In the rotating frame, the rotation is equivalent to magnetic field.**

Bretzel et al., APL 95, 122504

- **Mechanical torsional oscillations are equivalent to AC magnetic field.**

FMR $\xrightarrow{\text{coupling}}$ Coupled magnetomechanical polaritonic modes

Kovalev et al. JJAP 45 3878; APL 83, 1584



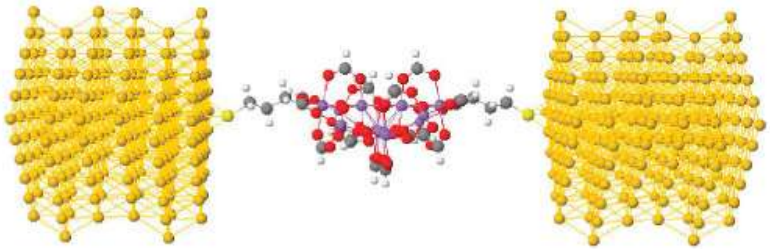
EPR $\xrightarrow{\text{coupling}}$ Coupled mechanical mode and quantum oscillations of spin (level anti-crossing) Landau-Zener transitions.
Jaafar et al., EPL 89, 27001 (2010)

Barraza-Lopez et al., PRL 102, 246801

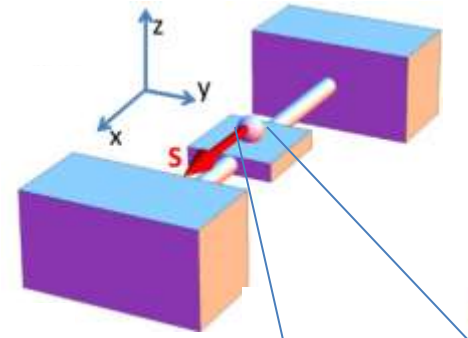
In both cases the coupling can be traced back to the effective field in the rotating frame (Barnett effect).

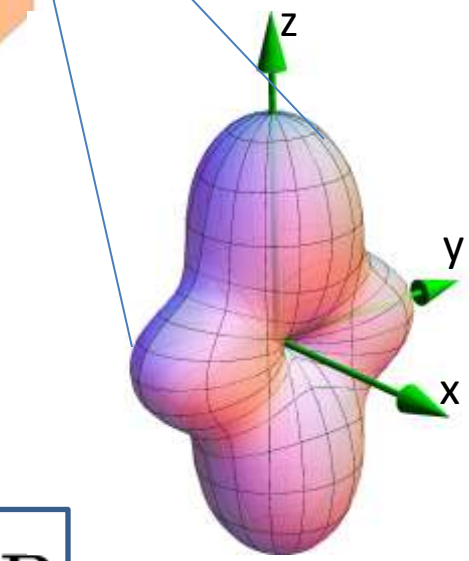
See also: M. Matsuo, J. Ieda, E. Saitoh, S. Maekawa, PRL **106**, 076601 (2011)

HAMILTONIAN AND FORMULATION OF THE PROBLEM



Idealized system





$$\hat{H}_A = -D\hat{S}_x^2 + E(\hat{S}_y^2 - \hat{S}_z^2) + C(\hat{S}_-^4 + \hat{S}_+^4)$$

The typical Hamiltonian describing the magnetic anisotropy of the molecule leads to two energy minima along the y axis. Tunneling can be described by instanton paths between the minima.

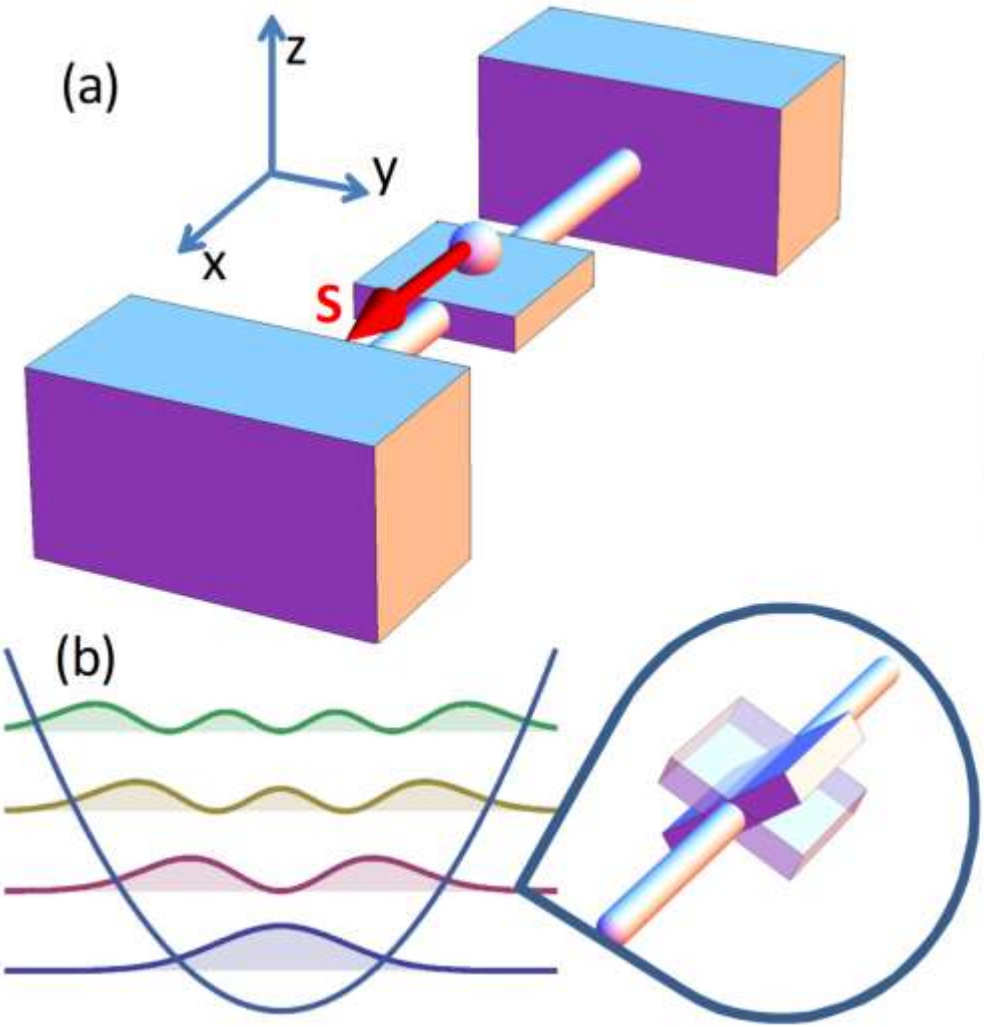
$$\boxed{\hat{H} = \hbar\omega_r(\hat{a}^\dagger\hat{a} + 1/2) + e^{-i\hat{S}_x\hat{\varphi}}\hat{H}_A e^{i\hat{S}_x\hat{\varphi}} + \gamma\hbar\hat{\mathbf{S}}\mathbf{B}}$$

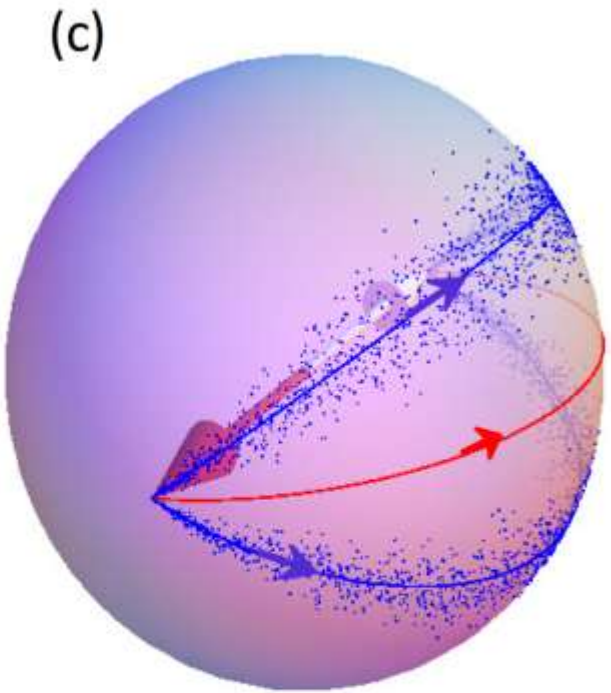
$\hat{\varphi} = (\alpha\hat{a}^\dagger + \alpha^*\hat{a})/2S;\ \alpha = \sqrt{2S^2\hbar/I_x\omega_r}$

I_x is the moment of inertia and ω_r is the resonant frequency.

α - is a constant describing spin-mechanical coupling.

BACK OF THE ENVELOPE CALCULATION





(a) Coupled macrospin and a resonator, coupling via magnetic anisotropies.
(b) Lowest energy states of the resonator.
(c) Splitting of the trajectories for the first excited state.

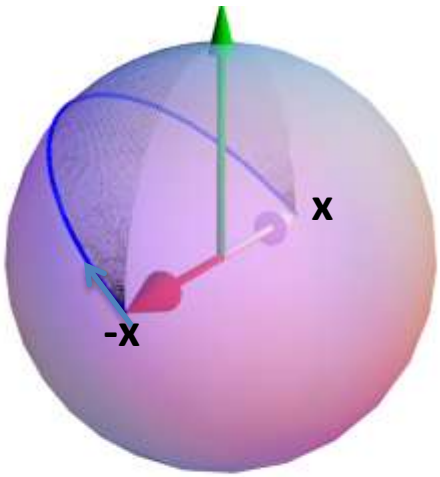
Phase difference for the trajectories in (c) is area times spin $\sim 4S\sqrt{\hbar/I_x\omega_r}$

Condition for suppression of tunneling: $4S\sqrt{\hbar/I_x\omega_r} = \pi$

PATH INTEGRAL FORMULATION

Unitary transformed Hamiltonian:

$$\hat{H} = \hbar\omega_r \left[(\hat{a}^\dagger + i\hat{S}_x\lambda/2s)(\hat{a} - i\hat{S}_x\lambda/2s) + 1/2 \right] + \hat{H}_A$$



We construct a coherent state from a Fock state n and spin state along the y axis

$$|\mathbf{\Omega}, z\rangle = e^{z\hat{a}^\dagger - z^*\hat{a}} e^{-i\hat{S}_z\phi} e^{-i\hat{S}_y\theta} e^{-i\hat{S}_z\chi} |s, n\rangle$$

$$\int d\mathbf{\Omega} dz \, |\mathbf{\Omega}, z\rangle \langle \mathbf{\Omega}, z| \sim \mathcal{I}$$

By inserting identity operator at ends of each time interval we Arrive at path integral formulation:

$$\left\langle -\mathbf{x}, -i\alpha/2 \left| e^{-i\int dt \hat{H}} \right| \mathbf{x}, i\alpha/2 \right\rangle = \int \mathcal{D}\Omega e^{i(\mathcal{S}_k + \mathcal{S}_E)/\hbar}$$ -- Integration over all paths

$$\mathcal{D}\Omega \sim \prod_t d\phi_t d(\cos\theta_t) dz_t dz_t^*, \; \mathcal{S}_k = \hbar \int dt \left[(\dot{z}_r z_i - \dot{z}_i z_r) - S\dot{\phi}(1 - \cos\theta) \right]$$

$$\mathcal{S}_E = -\int dt \tilde{E}, \text{ where } \tilde{E} = \hbar\omega_r \left[n + 1/2 + (z - is_x\alpha/2)(z^* + is_x\alpha/2) \right] + E(\theta, \phi)$$

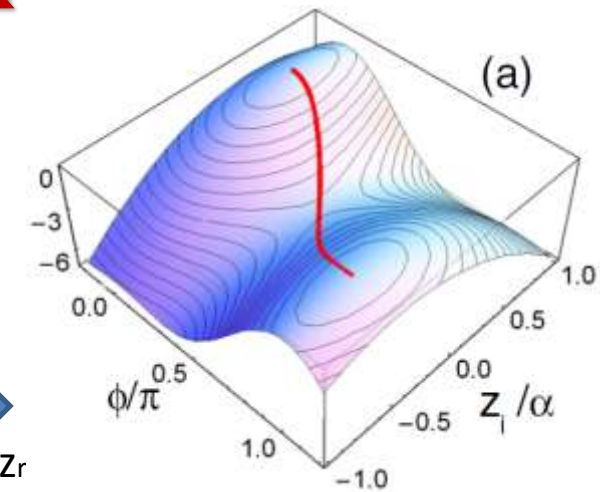
INSTANTON APPROACH

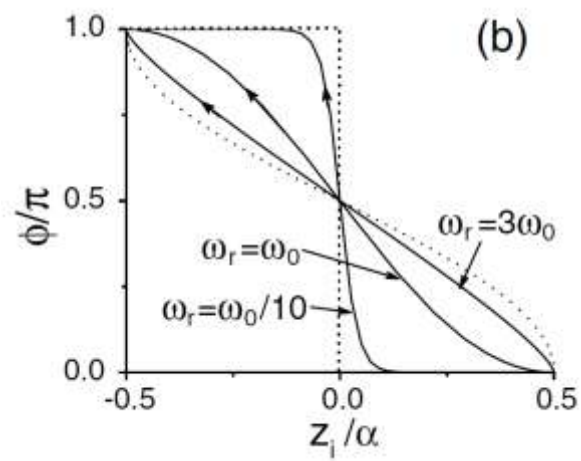
Equations of motion that minimize action:

$$\begin{cases} \dot{z}_i = -\omega_r z_r\,, \quad \dot{z}_r = \omega_r z_i - (\alpha\omega_r/2)\cos\phi\sin\theta \\ S\dot{\theta}\sin\theta = \partial\tilde{E}/\partial\phi\,, \quad S\dot{\phi}\sin\theta = -\partial\tilde{E}/\partial\theta \end{cases}$$

In imaginary time these equations lead to instanton solutions depicted on the right (z_r is eliminated).

Eliminate z_r





Instantons do not overlap as long as $\omega_r \gg \Delta$

The tunnel splitting changes from $e^{-\alpha^2/2}\Delta$ to Δ as we increase ω_r

Alternatively we can eliminate z_i

$$\mathcal{L} = I\dot{\varphi}^2/2 - K\varphi^2/2 + S\hbar\dot{\phi}\cos\theta + S\hbar\dot{\varphi}\sin\theta\cos\varphi - E(\theta,\phi)$$

M. F. O'Keeffe, E. M. Chudnovsky Phys. Rev. B 83, 092402 (2011)

Connection with Rabi and Jaynes and Cummings models

A unitary transformed Hamiltonian:

$$\hat{H} = \hbar\omega_r \left[(\hat{a}^\dagger + \hat{S}_y \alpha/2S)(\hat{a} + \hat{S}_y \alpha^*/2S) + 1/2 \right] + \hat{H}_A - \gamma\hbar SB$$

Projection onto the two lowest levels

$$\hat{H}_{eff} = \begin{bmatrix} \hbar\omega_r[(\hat{a}^\dagger + \alpha/2)(\hat{a} + \alpha^*/2) + 1/2] + \gamma\hbar SB & -\frac{\Delta}{2} \\ -\frac{\Delta}{2} & \hbar\omega_r[(\hat{a}^\dagger - \alpha/2)(\hat{a} - \alpha^*/2) + 1/2] - \gamma\hbar SB \end{bmatrix}$$

Rabi model, I. I. Rabi, Phys. Rev. **49**, 324 (1936); **51**, 652 (1937);
Analytical solution, D. Braak, PRL **107**, 100401 (2011).

By using the rotating wave approximation one can arrive at Jaynes and Cummings model:

$$\hat{H} = \hbar\omega_r(\hat{a}^\dagger \hat{a} + 1/2) + g(\sigma^+ \hat{a} + \sigma^- \hat{a}^\dagger) + \Delta\sigma^z/2$$

Jaynes and Cummings model (**Proc. IEEE 51, 89 (1963)**)

PERTURBATIVE APPROACH AND PROJECTION

First we project the spin Hamiltonian on to the degenerate states of the original Hamiltonian corresponding to the *y* anisotropy direction $|\psi_{\pm S}\rangle$.

$$\boxed{\hat{H} = \hbar\omega_r(\hat{a}^\dagger\hat{a} + 1/2) + e^{-i\hat{S}_x\hat{\varphi}}\hat{H}_A e^{i\hat{S}_x\hat{\varphi}} + \gamma\hbar\hat{S}_y B}$$

$$\langle\psi_{\pm S}|\hat{H}_A|\psi_{\pm S}\rangle = 0, \quad \langle\psi_{-S}|\hat{H}_A|\psi_S\rangle = -\Delta/2$$

$$\langle\psi_{\pm S}|\hat{H}|\psi_{\pm S}\rangle = \pm\gamma\hbar SB, \quad \langle\psi_{\mp S}|\hat{H}|\psi_{\pm S}\rangle = -\frac{\Delta}{2}e^{\pm 2iS\hat{\varphi}}$$

The projected Hamiltonian becomes:

$$\boxed{\hat{H}_{eff} = \begin{bmatrix} \hbar\omega_r(\hat{a}^\dagger\hat{a} + 1/2) + \gamma\hbar SB & -\frac{\Delta}{2}e^{-2iS\hat{\varphi}} \\ -\frac{\Delta}{2}e^{2iS\hat{\varphi}} & \hbar\omega_r(\hat{a}^\dagger\hat{a} + 1/2) - \gamma\hbar SB \end{bmatrix}}$$

Jaafar et al., EPL 89, 27001 (2010)

SOLUTIONS OUTSIDE THE NEAR-RESONANCE ASSUMPTIONS

For the Rabi Hamiltonian solution are given via displaced states.
At the degeneracy points the splittings are given by:

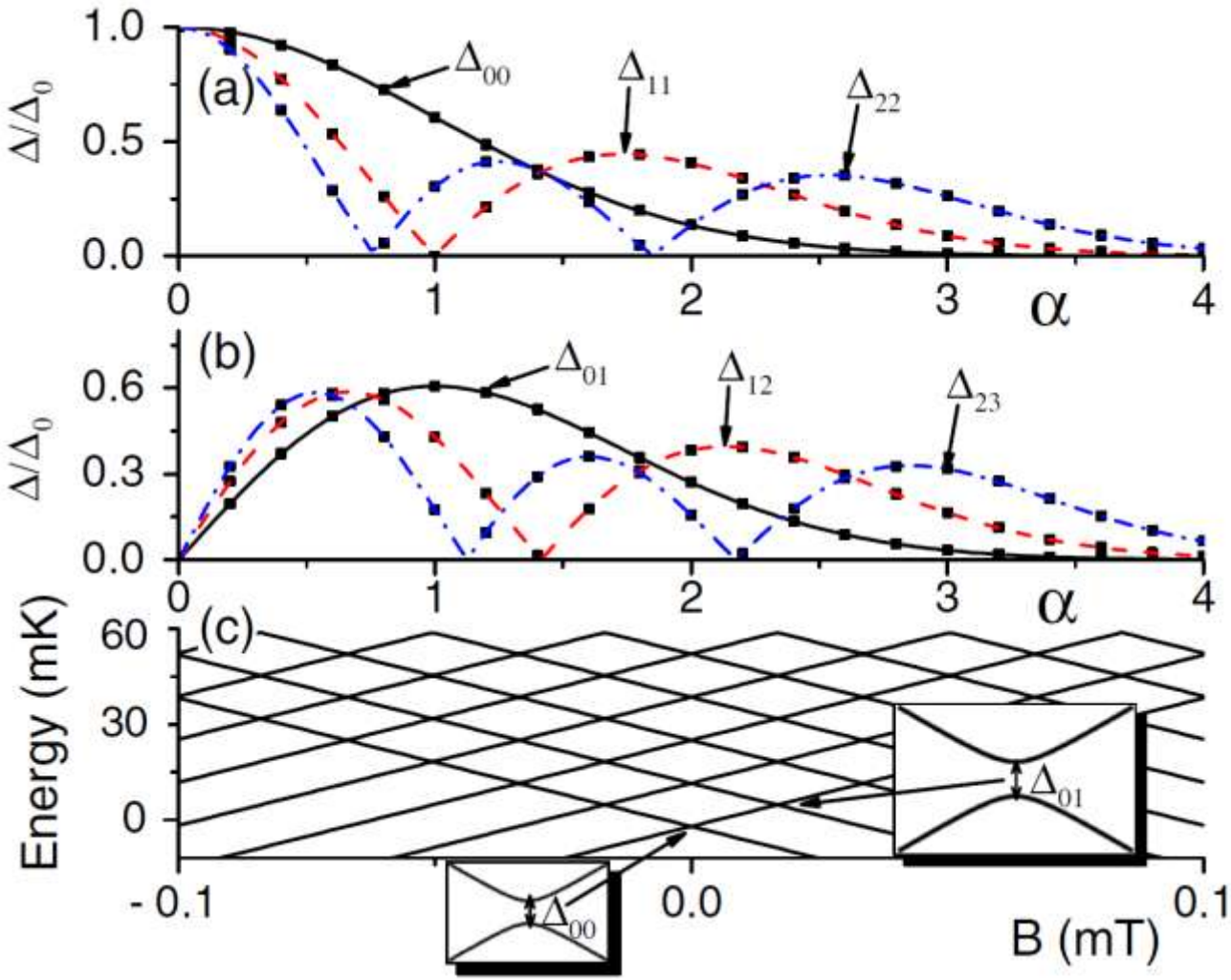
$$\boxed{\Delta_{nm} = \Delta \left| \left\langle n \left| e^{i2S\hat{\varphi}} \right| m \right\rangle \right|}$$

Laguerre polynomial

$$\left\langle n \left| e^{i2S\hat{\varphi}} \right| m \right\rangle = e^{-\alpha^2/2} (\alpha)^{n-m} \sqrt{\frac{m!}{n!}} L_m^{n-m}(\alpha^2)$$

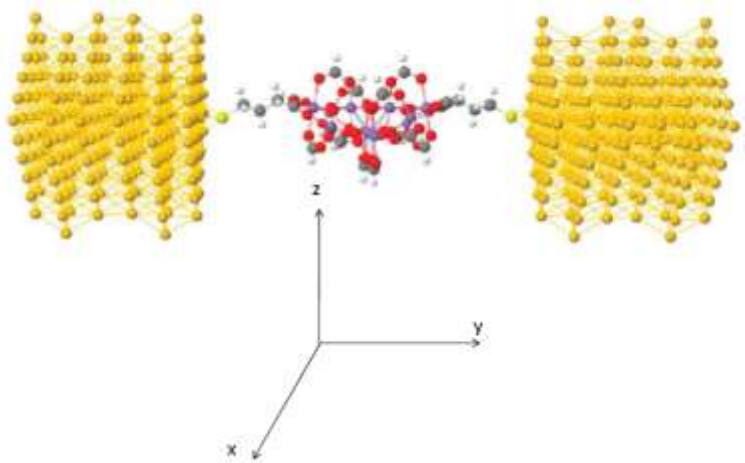
The coupling can be arbitrary large.

SUMMARY OF THE RESULTS



(a) Tunnel splittings as a function of the macrospin-resonator coupling for the first three excited states of the resonator. The curves show analytical results, while the squares are based on the numerical diagonalization of the Hamiltonian corresponding to an Fe8 SMM. (b) Analogous plot for tunnel splittings of the magnetopolaritonic modes corresponding to the Fock states differing by one phonon. (c) Lowest-energy levels of the Fe8 SMM coupled to a mechanical resonator.

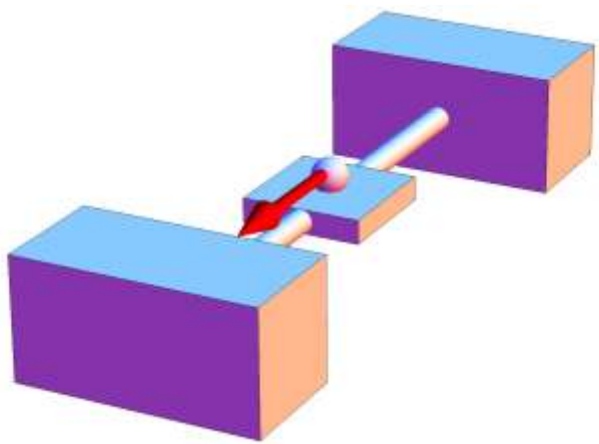
EXPERIMENTAL OBSERVATION OF PROPOSED EFFECTS



We estimate for a Mn_{12} molecule bridged between two leads:

$$\alpha = \sqrt{2S^2\hbar/I_x\omega_r} \sim 1.5$$

$$\omega_r = 10^9 s^{-1},\ S = 10,\ I_x = 10^{-41}\mathrm{kg\ m}^2$$



We estimate for a Mn_{17} molecule attached to a metallic paddle on a nanotube:

$$\alpha = \sqrt{2S^2\hbar/I_x\omega_r} \sim 0.02$$

$$\omega_r = 10^9 s^{-1},\ S = 37,\ I_x = 10^{-36}\mathrm{kg\ m}^2$$

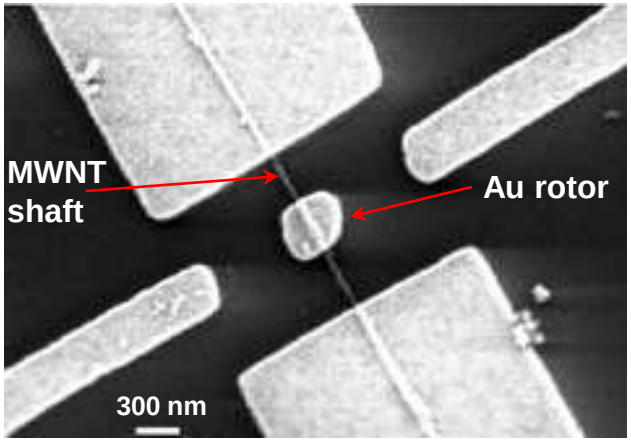
$$K_\phi = 10^{-10}\mathrm{Nm}$$

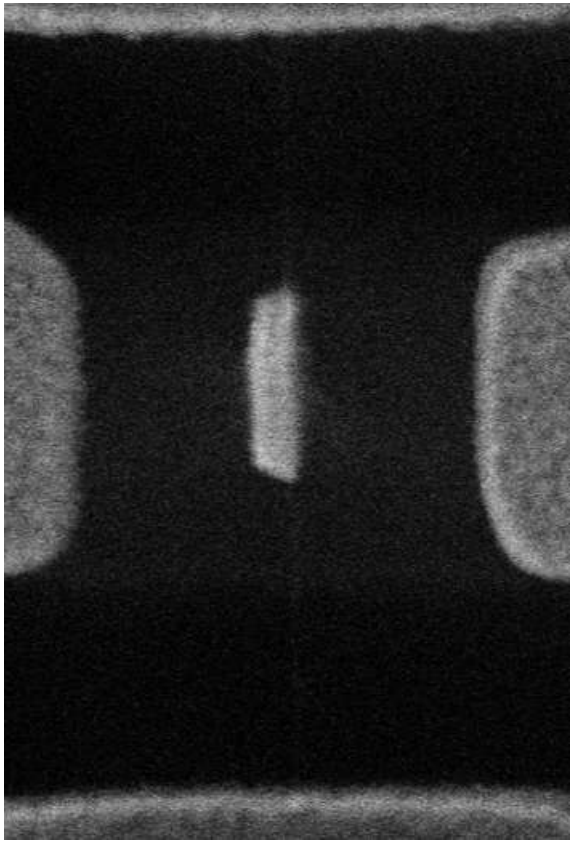
Nanotube can be tuned electrostatically.

By studying Landau-Zener transitions, one can measure the splitting.

Related experiments by Enrique del Barco, University of Central Florida

TECHNOLOGY TO TUNE SPRING CONSTANT

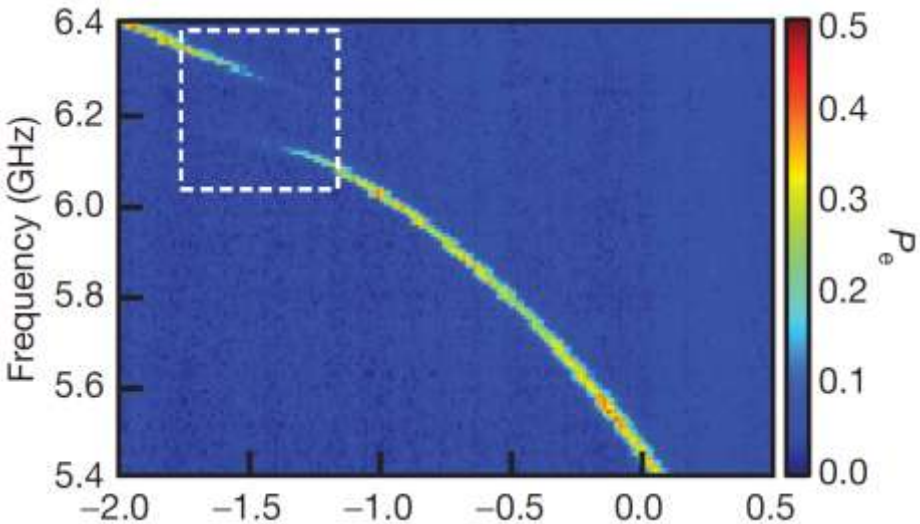


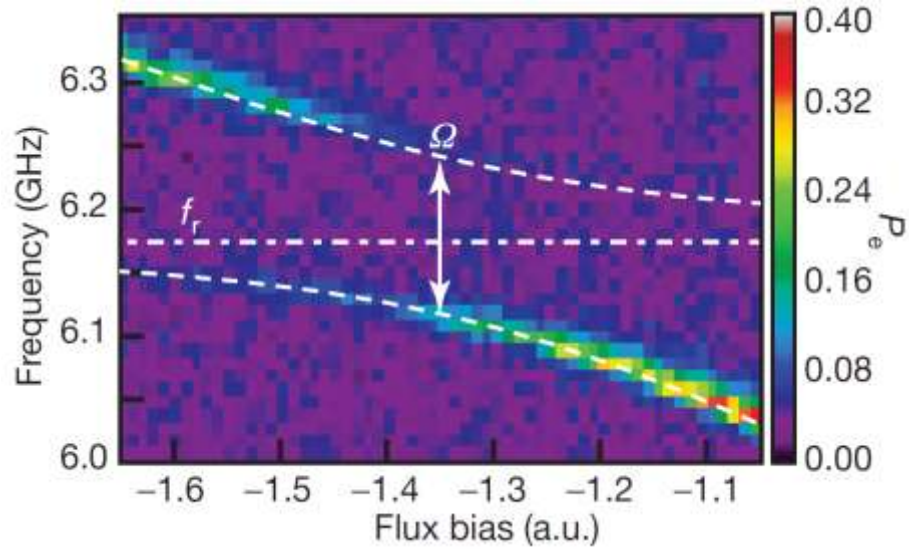


Electrostatic forces can excite fast rotation of a golden particle attached to MWNT.

A. M. Fennimore *et al*, Nature **424**, 408 (2003).

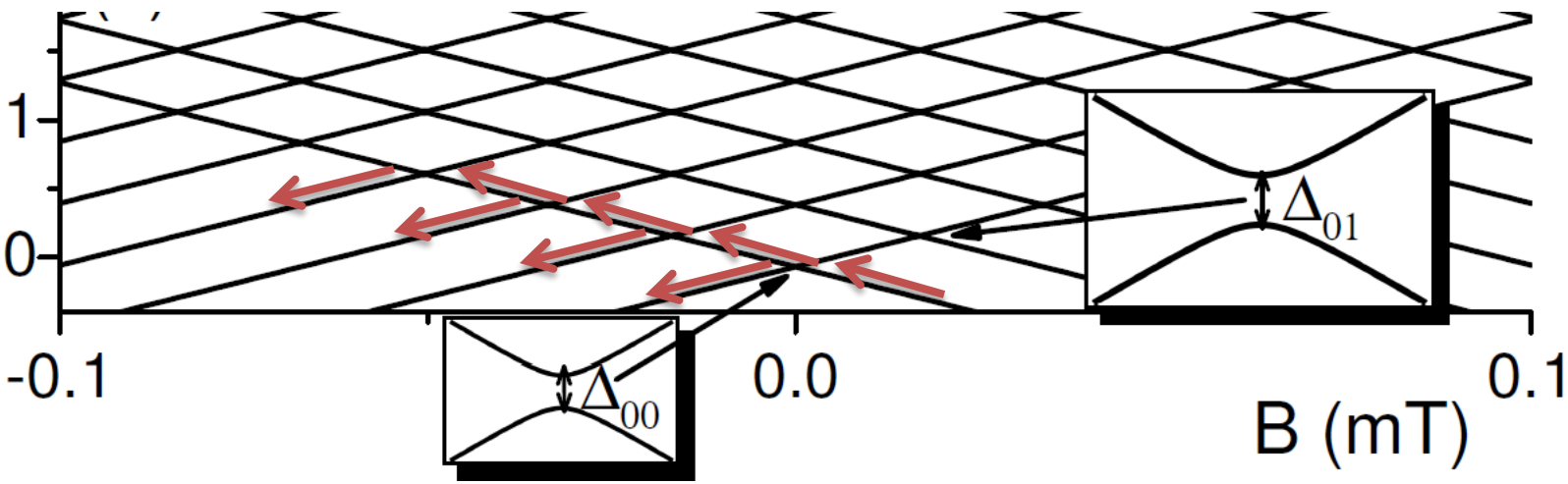
QUANTUM CONTROL ON A SINGLE PHONON LEVEL





1. Quantum optical techniques for detection.

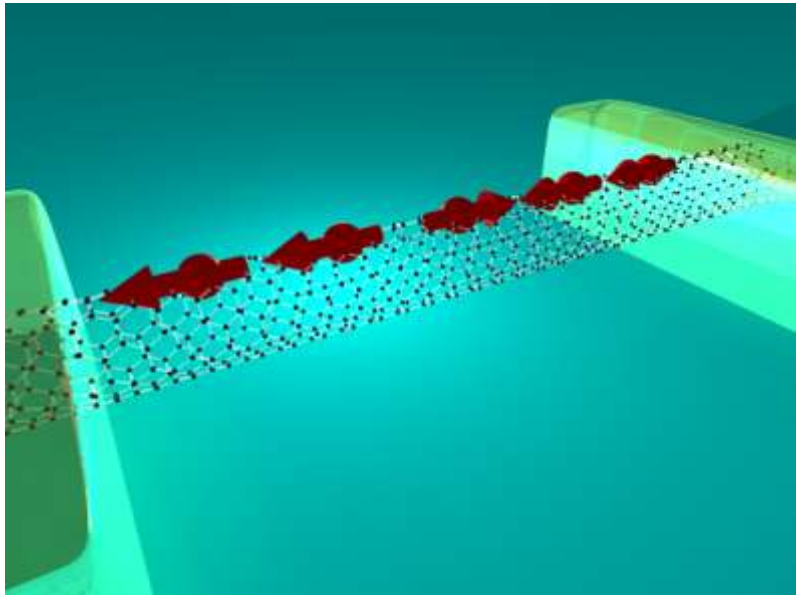
O'Connell et al., Nature 464, 697



2. Detection by studying Landau-Zener transitions.

PHONON MEDIATED SPIN-SPIN INTERACTIONS IN NEMS

Macrospin molecules interacting via phonon mode.



Takis Kontos, Physics **4**, 28 (2011).

Ions interacting via phonon mode.

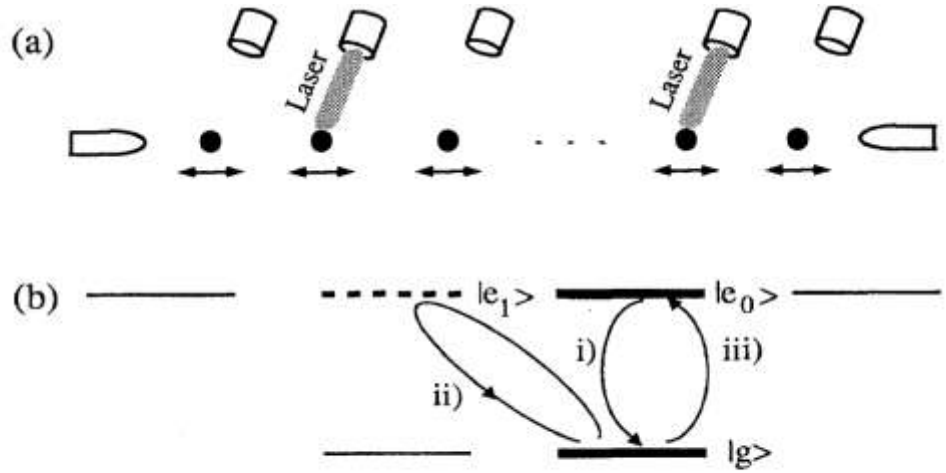
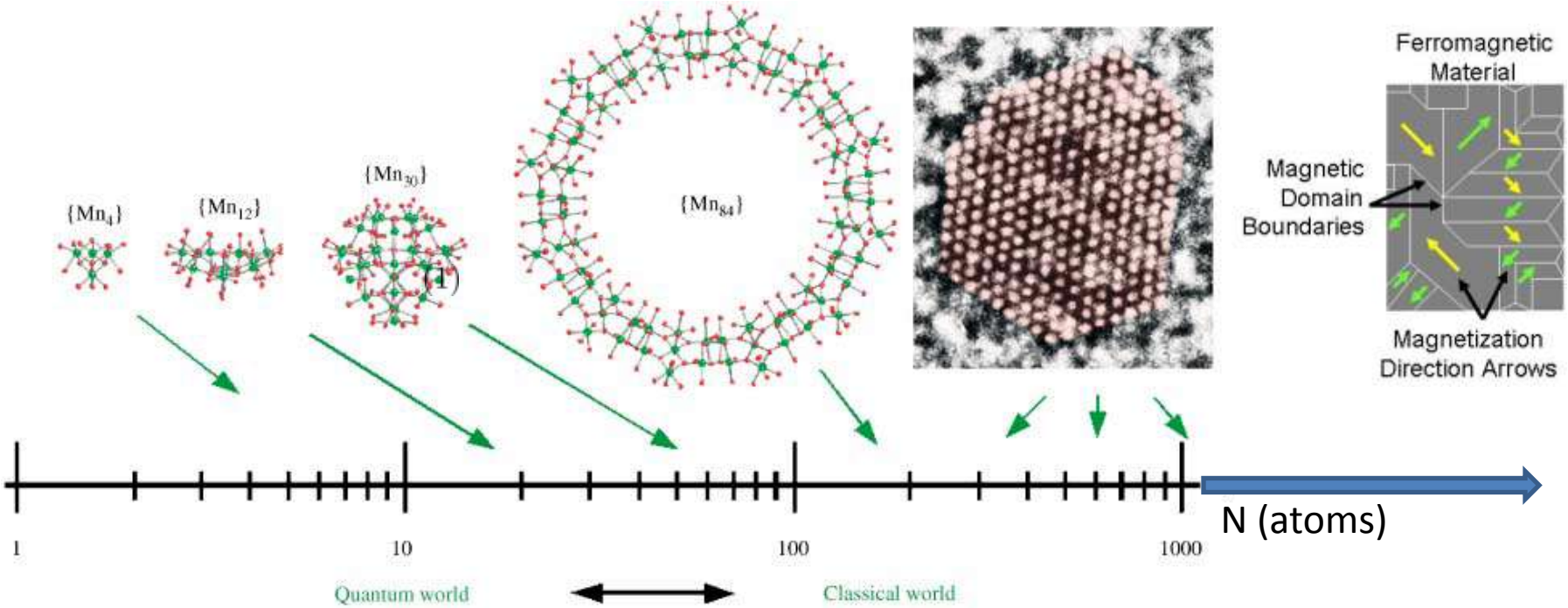


FIG. 1. (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme.

J. I. Cirac and P. Zoller, PRL **74**, 4091 (1995).

Magnetomechanical effects scale favorably in the nano-world



$$\alpha = \sqrt{2S^2\hbar/I_x\omega_r}$$

Importance of magnetomechanical effects.