Spintronics Phenomena in the Classical and Quantum Worlds

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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.
Electron possesses spin in addition to charge.

In ferromagnets all spins are aligned by exchange interactions.

The spin direction can slowly change in space – texture. Torque is a force on a magnet (spin) by magnetic field or by passing current.


Opposite effect: current induced torque.
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!

I believe that your CPU needs extra cooling but can I have just a little bit more space for food in the refrigerator?

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

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

\[ \Phi = A \ast S \]

- 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.

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

Geometric phase of spin -> \[ \Phi = i \int_{R(0)}^{R(t)} \langle S(R) | \nabla_R | S(R) \rangle \, dR \]
Relativistic effects, Aharonov-Casher effect

\[ \varepsilon = \frac{1}{2} m \nu^2 \]

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


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

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

$$L(r_c, q_c, \dot{r}_c, \dot{q}_c) = \langle W | i\hbar \partial_t - H | W \rangle$$

$$= -E + q_c \cdot \dot{r}_c + \dot{q}_c \cdot \langle u | i\partial_{q_c} u \rangle + \dot{r}_c \cdot \langle u | i\partial_{r_c} u \rangle + \langle u | i\partial_t u \rangle$$

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

\[ \dot{r}_c = \partial_{q_c} E - (\tilde{\Omega}_{qr} \cdot \dot{r}_c + \tilde{\Omega}_{qq} \cdot \dot{q}_c) + \Omega_{rq} \]

\[ \dot{q}_c = -\partial_{r_c} E + (\tilde{\Omega}_{rr} \cdot \dot{r}_c + \tilde{\Omega}_{rq} \cdot \dot{q}_c) - \Omega_{tr} \]

\[ \tilde{\Omega}_{AB} = i(\langle \partial_A u | \partial_B u \rangle - \langle \partial_B u | \partial_A u \rangle) \]

$\tilde{\Omega}_{rr}$ — Effective band-dependent magnetic field

$\tilde{\Omega}_{qq}$ — Anomalous velocity

$\Omega_{tr}$ — 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.

a) Intrinsic deflection

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).

\[
\begin{align*}
\dot{E} \frac{dk}{dt} &= -e\overrightarrow{E} - \frac{e}{c} \dot{r} \times \overrightarrow{B} \\
\frac{d\vec{r}}{dt} &= \frac{1}{\hbar} \frac{\partial E}{\partial \vec{k}} (\vec{k} \times \Omega(\vec{k}))
\end{align*}
\]

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

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

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)
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 $\Phi'$ 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.

X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa& Y. Tokura
Equation for the entropy production

\[
\frac{dS}{dt} = \frac{L}{T} \left[ -j q \frac{T_2 - T_1}{TL} - j \frac{\mu_2 - \mu_1}{L} - \dot{X} \frac{2MH}{L} \right]
\]

\[
\dot{X} = -O_x \frac{2MH}{L} - O_{x\mu} j - O_{xt} \dot{j}_q
\]

\[
\frac{T_2 - T_1}{TL} = -O_{Tj} \dot{j}_q + O_{xt} \frac{2MH}{L} - O_{T\mu} j
\]

\[
\frac{\mu_2 - \mu_1}{L} = -O_{\mu} j + O_{x\mu} \frac{2MH}{L} + O_{T\mu} \dot{j}_q
\]

By Onsager reciprocity principle.

Interplay between currents and textures

\[ -\partial_i \mu = \gamma_{ik} j_k + \Pi_{ik} \frac{\partial_k T}{T} - p (m \times \partial_i m + \beta \partial_i m) \cdot \dot{m} \]

\[ (j_q)_i = \Pi_{ik}^T j_k - \kappa_{ik} \partial_k T + p_1 (m \times \partial_i m + \beta_1 \partial_i m) \cdot \dot{m} \]

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

\[ \text{Resistivity tensor} \quad \gamma_{ik} = \delta_{ik} \left[ \gamma + \eta_\gamma (\partial_l m)^2 \right] + \eta'_\gamma \partial_i m \cdot \partial_k m + b_{\gamma} m \cdot (\partial_i m \times \partial_k m) \]

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

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


Hall effect

Nernst and Righi-Leduc effects
GOING QUANTUM WITH SPINTRONICS:
MAGNETOMECHANICAL EFFECTS AT NANOSCALE AND
MAGNETIZATION REVERSAL
From spins to magnets

Electron processes spin in addition to charge.

QUANTUM VS. CLASSICAL MAGNETIZATION REVERSAL

Single domain magnet or Stoner-Wohlfarth particle.

Fe8

J. R. Friedman & M. P. Sarachik,

W. Wernsdorfer & R. Sessoli,
**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.

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

\[ \vec{H}_{\text{eff}} = \frac{\delta F(\vec{M})}{\delta \vec{M}} \]

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.

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

The splitting is defined by the ratio 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. Splitting in the current induced FMR spectra.

Kovalev et al., PRB 75, 014430

2. $T_1, V_1$ vs $T_2, V_2$

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

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

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

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.

\[ \hat{H} = \hbar \omega_r (\hat{a}^\dagger \hat{a} + 1/2) + e^{-i\hat{S}_x \hat{\varphi}} \hat{H}_A e^{i\hat{S}_x \hat{\varphi}} + \gamma \hbar \hat{S}_B \]

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

\( I_x \) is the moment of inertia and \( \omega_r \) is the resonant frequency.

\( \alpha \) - is a constant describing spin-mechanical coupling.
(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: $4S \sqrt{\hbar / I_x \omega_r} = \pi$
Unitary transformed Hamiltonian:

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

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

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

\[ \int d\Omega dz |\Omega, z\rangle \langle \Omega, z| \sim \mathcal{I} \]

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

\[ \left\langle -x, -i\alpha/2 \left| e^{-i \int dt \hat{H}} \right| x, i\alpha/2 \right\rangle = \int \mathcal{D}\Omega e^{i(S_k + S_E)/\hbar} \]

-- Integration over all paths

\[ \mathcal{D}\Omega \sim \prod_t d\phi_t d(cos \theta_t) dz_t dz_t^* \]

\[ S_k = \hbar \int dt \left[ (\dot{z}_r z_i - \dot{z}_i z_r) - S \phi (1 - \cos \theta) \right] \]

\[ S_E = -\int dt \tilde{E} \]

where \( \tilde{E} = \hbar \omega_r [n + 1/2 + (z - is_x \alpha/2)(z^* + is_x \alpha/2)] + E(\theta, \phi) \)
Equations of motion that minimize action:

\[
\begin{align*}
\dot{z}_i &= -\omega_r z_r, \\
\dot{z}_r &= \omega_r z_i - (\alpha \omega_r/2) \cos \phi \sin \theta \\
S \dot{\theta} \sin \theta &= \partial \tilde{E} / \partial \phi, \\
S \dot{\phi} \sin \theta &= -\partial \tilde{E} / \partial \theta
\end{align*}
\]

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

Instantons do not overlap as long as \(\omega_r \gg \Delta\)

The tunnel splitting changes from \(e^{-\alpha^2/2} \Delta\) to \(\Delta\) as we increase \(\omega_r\)

Alternatively we can eliminate \(z_i\)

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

A unitary transformed Hamiltonian:

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

Projection onto the two lowest levels

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


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

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

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

\[
\langle \psi_{\pm S} | \hat{H} | \psi_{\pm S} \rangle = \pm \gamma \hbar S B, \quad \langle \psi_{\mp S} | \hat{H} | \psi_{\pm S} \rangle = -\frac{\Delta}{2} e^{\pm 2i S \hat{\phi}}
\]

The projected Hamiltonian becomes:

\[
\hat{H}_{\text{eff}} = \begin{bmatrix}
\hbar \omega_r (\hat{a}^{\dagger} \hat{a} + 1/2) + \gamma \hbar S B & -\frac{\Delta}{2} e^{-2i S \hat{\phi}} \\
-\frac{\Delta}{2} e^{2i S \hat{\phi}} & \hbar \omega_r (\hat{a}^{\dagger} \hat{a} + 1/2) - \gamma \hbar S B
\end{bmatrix}
\]

Jaafar et al., EPL 89, 27001 (2010)
For the Rabi Hamiltonian solution are given via displaced states. At the degeneracy points the splittings are given by:

\[ \Delta_{nm} = \Delta \left| \left\langle n \left| e^{i2S\hat{\phi}} \right| m \right\rangle \right| \]

\[ \left\langle n \left| e^{i2S\hat{\phi}} \right| m \right\rangle = e^{-\alpha^2/2} (\alpha)^{n-m} \sqrt{\frac{m!}{n!}} L_{n-m}^m (\alpha^2) \]

The coupling can be arbitrary large.
(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.

Summary of the Results
Experimental Observation of Proposed Effects

We estimate for a $\text{Mn}_{12}$ molecule bridged between two leads:

$$\alpha = \sqrt{\frac{2S^2\hbar}{I_x\omega_r}} \sim 1.5$$
$$\omega_r = 10^9 \text{s}^{-1}, \ S = 10, \ I_x = 10^{-41} \text{kg m}^2$$

We estimate for a $\text{Mn}_{17}$ molecule attached to a metallic paddle on a nanotube:

$$\alpha = \sqrt{\frac{2S^2\hbar}{I_x\omega_r}} \sim 0.02$$
$$\omega_r = 10^9 \text{s}^{-1}, \ S = 37, \ I_x = 10^{-36} \text{kg m}^2$$
$$K_\phi = 10^{-10} \text{Nm}$$

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

1. Quantum optical techniques for detection.

2. Detection by studying Landau-Zener transitions.

O'Connell et al., Nature 464, 697
Phonon mediated spin-spin interactions in NEMS

Takis Kontos, Physics 4, 28 (2011).


Macrospin molecules interacting via phonon mode.

Ions interacting via phonon mode.

FIG. 1. (a) $N$ ions in a linear trap interacting with $N$ different laser beams; (b) atomic level scheme.
Magnetomechanical effects scale favorably in the nano-world

Importance of magnetomechanical effects.