Coherent spin dynamics in semiconductor low-dimensional systems

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Spin-related phenomena in mesoscopic transport

17th of September, 2012

Electron spin plays major role in various phenomena. Most importantly, the spin of electrons results in the Pauli exclusion principle, which in turn underlies the periodic table of chemical elements and makes our existence possible.

It is needless to explain in this audience the manifestations of spin in the electron transport. Hence, the aim of my talk is to demonstrate alternative, in particular, optical means to access electron spin in low-dimensional systems.

Pump-probe technique

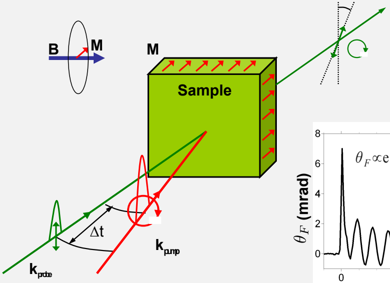
time-resolved, $t <> \tau_{\rm rad}$,
"non-destructive"

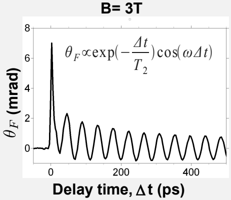
DICHROISM AND OPTICAL ANISOTROPY OF MEDIA WITH ORIENTED SPINS OF FREE ELECTRONS

A. G. Aronov and E. L. Ivchenko

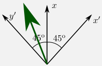
A. F. Ioffe Physicotechnical Institute,
Academy of Sciences of the USSR, Leningrad

Sov. Phys. Solid State (1973)

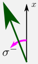




Faraday rotation



Ellipticity



Pump: circularly polarized pulse orients carrier spins

$$S_z \neq 0 \Rightarrow \begin{cases} n_+ \neq n_- \\ \alpha_+ \neq \alpha_- \end{cases}$$

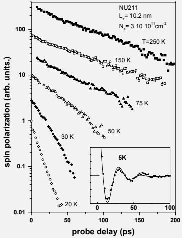
Faraday rotation

$$\Theta \propto S_z$$

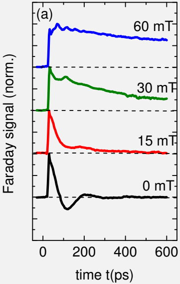
- $\mathcal{F}$araday Effect (polarization plane rotation)
- $\mathcal{E}$llipticity Effect (appearance of the circular polarization)
- $\mathcal{K}$err Effect (polarization plane rotation of reflected light)

Awschalom et al. (1985); Zheludev et al. (1994)

Quantum wells, free electrons

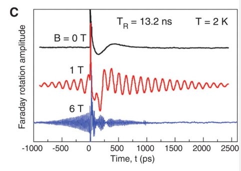


R.T. Harley et al. (2007)



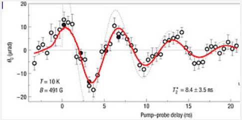
T. Korn et al. (2009)

Quantum dot ensembles



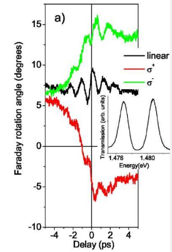
A. Greilich et al. (2006)

Single quantum dots



M.H. Mikkelsen et al. (2007)

Microcavities



A. Brunetti et al. (2006)

Pump-probe is a widespread technique to measure

relaxation times, precession frequencies

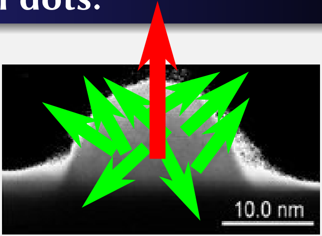
- What can we learn from "microscopics" of signals?
- What about signal amplitudes?

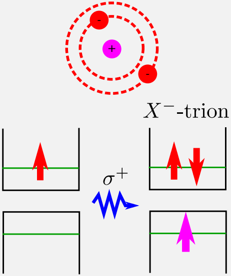
n-type **single quantum dots** and quantum dot arrays

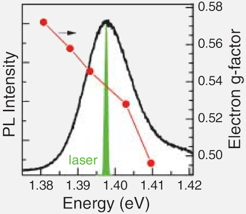
- Carrier localization leads to the spin relaxation slowdown
- Possibility to address resonantly singlet trion
- Hyperfine interaction of electron and nuclear spins is effective

Similar physics for quantum wires, wells and bulk materials with low, $n_d a_B^d \ll 1$, density electrons/holes

Other systems: Phys. Solid State **54**, 1 (2012)



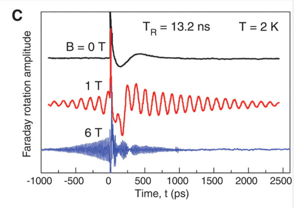




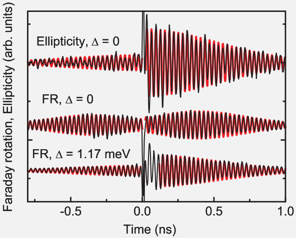
Element	^{27}Al	$^{69(71)}$Ga	^{75}As	^{115}In
Z	13	31	33	49
I	5/2	3/2	3/2	9/2

Spin pump-probe signals for InAs *n*-type quantum dots array

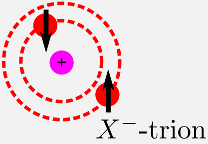
Experiments:



A. Greilich et al. (2006, 2007); S. Carter et al. (2009)



MMG et al. (2010)

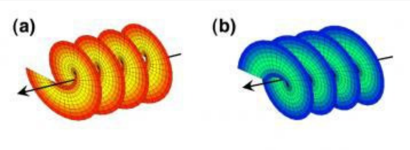


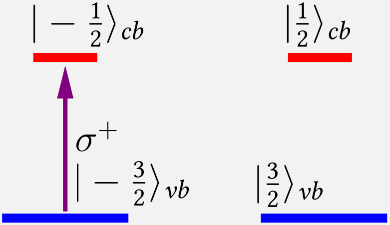
1. Origin of the long-living signal at singlet ($S = 0$) trion excitation?
2. Signals at negative delays, i.e. before the next pump pulse?
3. Growth of Faraday rotation signal with time?

Outline

Optical orientation in nanosystems

Optical orientation *is a transformation of the photon angular momentum to* ***the system of electron spins***





(normal light incidence)

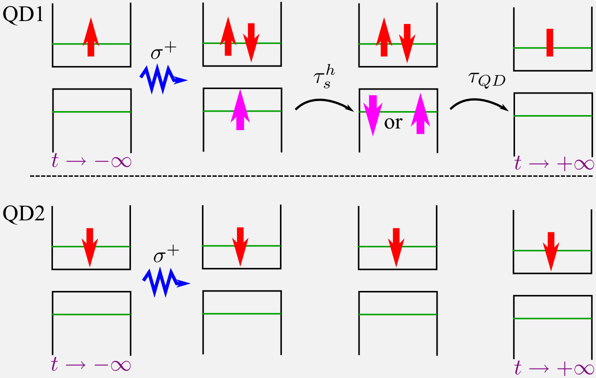
Semiconductor quantum well or self-organized quantum dot:

- at σ^+ pump $-\frac{3}{2} + 1 = -\frac{1}{2}$ i.e. $(e, hh) = (-1/2, 3/2)$
- at σ^- pump $\frac{3}{2} + (-1) = \frac{1}{2}$ i.e. $(e, hh) = (1/2, -3/2)$

Absorption of circularly polarized light

generates spin-polarized electrons and holes

Long-living electron spin polarization



σ^+ pump $\Rightarrow (-1/2_e, 3/2_h)$

The carriers with the spins opposite to those of photocreated electrons are picked out

Hole spin relaxation/fast spin precession (@ $\boldsymbol{B} \neq 0$) $\Rightarrow$ spin of returning electron is negligible

Resident electrons become spin polarized after recombination

Shabaev, Efros, Gammon, Merkulov (2003); Greilich et al (2006); Zhukov, Yakovlev, Bayer, MMG, Ivchenko, Karczewski, Kossut (2007)

Only QDs with a **certain spin projection** interact with the **circularly polarized light**

Technical details:

- Short pump pulse: $\tau_p \ll \tau_{QD}, 2\pi/\Omega_L$
- Four level model: two ground states $\psi_{\pm 1/2}$, two excited states $\psi_{\pm 3/2}$
- Returning electron is depolarized

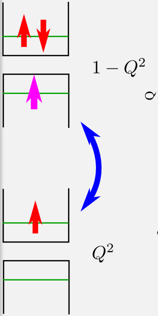
Under σ^+ pump the wave function transforms as

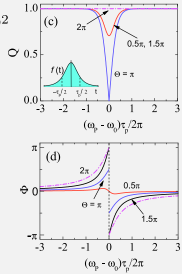
$$\psi_{1/2}(t \to +\infty) = Qe^{i\Phi}\psi_{1/2}(t \to -\infty)$$

$$\psi_{-1/2}(t \to +\infty) = \psi_{-1/2}(t \to -\infty)$$

Transformation of the wave function means transformation of the spin

Similar to N. Rosen & C. Zener (1932)





Parameters Q and Φ are determined by the pump pulse shape, area, and detuning from resonance

Spin pumping in quantum dots

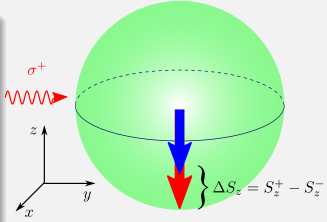
Only QDs with a **certain spin projection** interact with the **circularly polarized light**

Electron spin $\boldsymbol{S} = \frac{1}{2}\langle\psi|\boldsymbol{\sigma}|\psi\rangle$

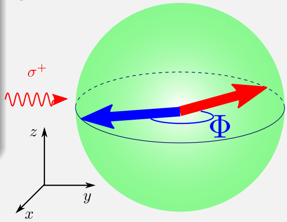
$$
\begin{aligned}
S_z^+ &= \frac{Q^2+1}{2} S_z^- + \frac{Q^2-1}{4} \\
S_y^+ &= Q\cos\Phi S_y^- - Q\sin\Phi S_x^- \\
S_x^+ &= Q\cos\Phi S_x^- + Q\sin\Phi S_y^-
\end{aligned}
$$

- Before pump pulse $\boldsymbol{S}^-$, after $\boldsymbol{S}^+$
- An increase of spin z-component
- In-plane components rotation

Spin orientation $\sim \frac{Q^2-1}{4}$

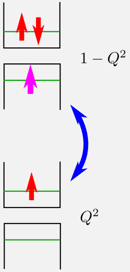


Spin rotation $\sim \Phi$



Yugova, MMG, Ivchenko, Efros (2009)

Spin rotation by optical pulse



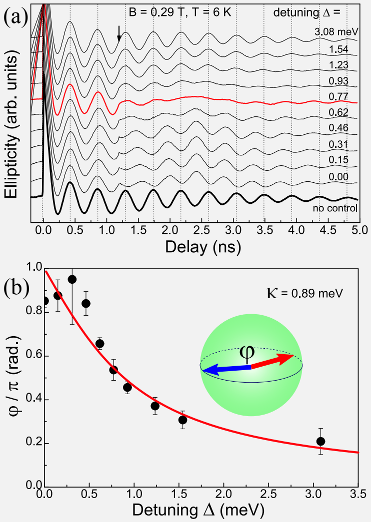
Circular pulse

- generates spin coherence (optical orientation)
- rotates spin (inverse Faraday effect)

$$S_z^+ = \frac{Q^2+1}{2} S_z^- + \frac{Q^2-1}{4}$$
$$S_y^+ = Q\cos\Phi S_y^- - Q\sin\Phi S_x^-$$
$$S_x^+ = Q\cos\Phi S_x^- + Q\sin\Phi S_y^-$$

Phys. Rev. B **80**, 104436 (2009)

Parameters Q and Φ are determined by the pump pulse intensity, duration and detuning from the resonance (Φ)



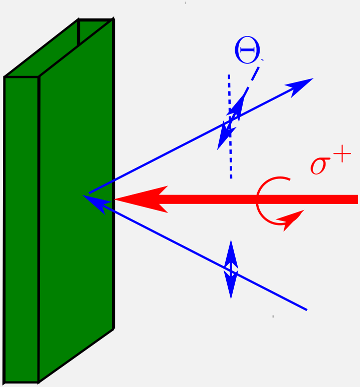
A. Greilich et al. (2009): InGaAs QDs
C. Phelps et al. (2009): CdTe QWs

Electron spin coherence generation & control

Circularly polarized pulses being resonant with the singlet trion transition orient electron spins in quantum dots

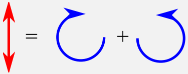
Slightly off-resonant pulse rotates spins

QW or ensemble of QDs, …



Probe: transmission/reflection of weak linearly-polarized pulse

weak=does not affect spin coherence



$r_+ \neq r_- \Rightarrow$ rotation of the linear polarization plane of the probe pulse and appearance of its ellipticity

Resonance trion, exciton, …

$$r_\pm(\omega) = \frac{\mathrm{i}\Gamma_{0,\pm}}{\omega_{0,\pm} - \omega - \mathrm{i}(\Gamma_{0,\pm} + \Gamma_\pm)}$$

$$t_\pm = 1 + r_\pm$$

Ellipticity and Faraday rotation

$$\mathcal{E} + \mathrm{i}\mathcal{F} \propto r_+ - r_-$$

Zhukov, Yakovlev, Bayer, MMG, Ivchenko, et al. (2007)

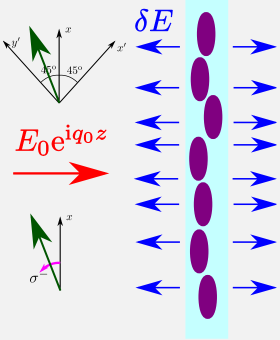
Probing the electron spins

- Faraday Effect (polarization plane rotation)

$$\mathcal{F} = \lim_{z\to+\infty} \int_{-\infty}^{\infty} \left[|E_{x'}^{(t)}(z,t)|^2 - |E_{y'}^{(t)}(z,t)|^2 \right] \mathrm{d}t$$

- Ellipticity Effect (appearance of the circular polarization)

$$\mathcal{E} = \lim_{z\to+\infty} \int_{-\infty}^{\infty} \left[|E_{\sigma^-}^{(t)}(z,t)|^2 - |E_{\sigma^+}^{(t)}(z,t)|^2 \right] \mathrm{d}t$$



Probe induced field

$$\delta \boldsymbol{E}(t) = -4\pi \left(\frac{\omega_{\mathrm{pr}}}{c}\right)^2 \frac{\mathrm{i}e^{\mathrm{i}q|z|}}{2q} N_{QD}^{2d} \boldsymbol{\Pi}(t)$$

$$\Pi_x \propto (n_e - n_{tr}) E_x^{probe}$$

$$\Pi_y \propto (S_z - J_z) E_x^{probe}$$

Spectral function

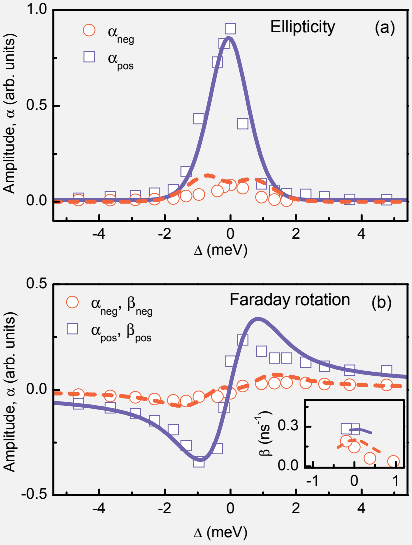
$$\mathcal{E} + \mathrm{i}\mathcal{F} \propto$$

$$\int_{-\infty}^{\infty} \mathrm{d}t \int_{-\infty}^{t} \mathrm{d}t' f(t) f(t') e^{\mathrm{i}\Delta(t-t')}$$

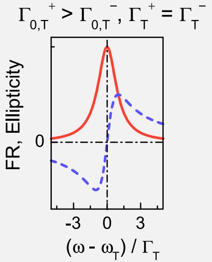
$$\Delta = \omega_{\mathrm{pr}} - \omega_0;\ \boldsymbol{E}_{\mathrm{pr}} \propto f(t) e^{-\mathrm{i}\omega t}$$

Yugova, MMG, Ivchenko, Efros (2009)

Electron spin coherence detection



MMG et al. (2010)

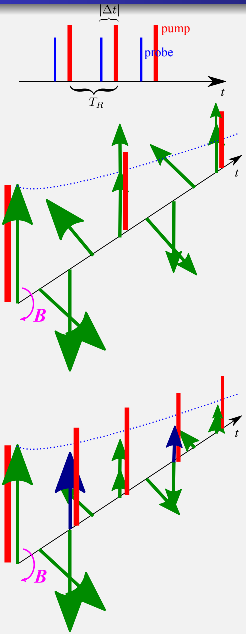


Linearly polarized pulse can readout spin polarization

Correct description is based on reflection/transmission rather than on dielectric constant

Outline

Resonant spin amplification and mode-locking



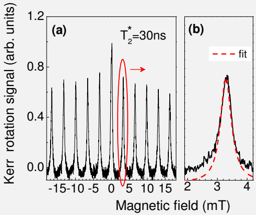
Signal dependence on $\boldsymbol{B}$ at a fixed delay Δt

Resonant spin amplification is

determined by commensurability of spin precession and pump repetition periods

$$\Omega_{\rm L} T_{\rm rep} = 2\pi$$

Kikkawa, Awschalom (1998)



$$\Omega_{\rm L} T_{\rm rep} = \pi$$

Astakhov, MMG, Yakovlev, Zhukov, Ossau, Molenkamp, Bayer (2008)

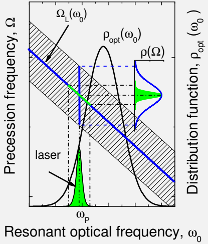
In inhomogeneous systems

certain electrons become polarized stronger than others (mode-locking)

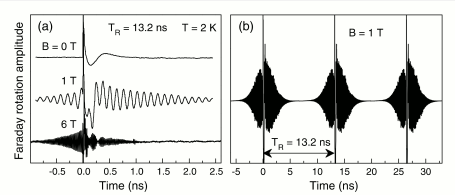
Electron spin precession mode-locking

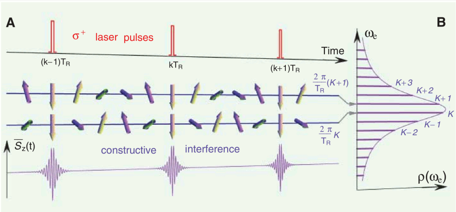
Train of pump and probe pulses, T_R is the repetition period

- Large spread of electron g-factors ⇒ fast dephasing
- Signal reappears before the next pump pulse arrival



$\hbar/\tau_p \sim 1$ meV





$\Omega T_R = 2\pi K$

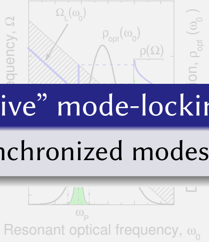
Constructive interference

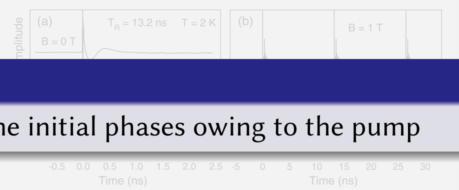
exp.: $K \sim 10^2$

Greilich, Yakovlev, Shabaev, Efros, Yugova, Oulton, Stavarache, Reuter, Wieck, Bayer (2006)

Train of pump and probe pulses, T_R is the repetition period

- Large spread of electron g-factors $\Rightarrow$ fast dephasing
- Signal reappears before the next pump pulse arrival





"Passive" mode-locking:

all synchronized modes have same initial phases owing to the pump

$\hbar/\tau_p \sim 1$ meV

$\Omega T_R = 2\pi K$

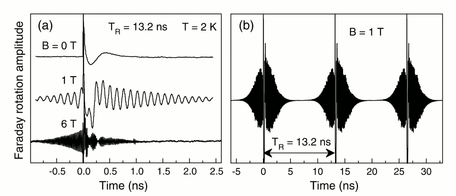
Constructive interference

exp.: $K \sim 10^2$

Greilich, Yakovlev, Shabaev, Efros, Yugova, Oulton, Stavarache, Reuter, Wieck, Bayer (2006)

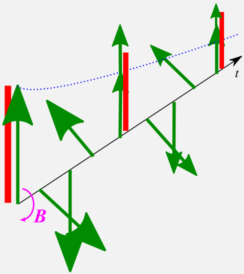
Mode-locking is much stronger than expected:

Where are other spins with precession frequecies $\Omega \neq \frac{2\pi K}{T_R}$?



Nuclear effects: experimental evidence

Very high amplitude at negative delays

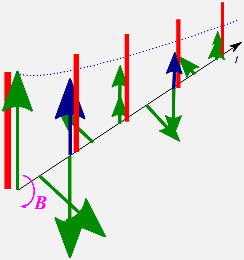


$$\Omega_{\text{eff}} T_R = 2\pi$$

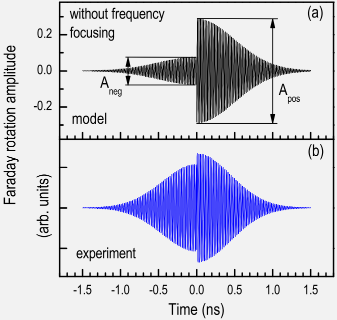
⇑

Nuclei-induced frequency focusing

⇑



$$\Omega_{\text{eff}} T_R = \pi$$

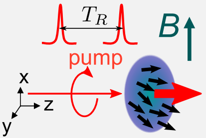


$$\boldsymbol{\Omega}_{\text{eff}} = \boldsymbol{\Omega}_{\text{L}} + \boldsymbol{\Omega}_{\text{nucl}}$$

Feedback of nuclei is necessary

Nuclei-induced frequency focusing takes place

Greilich, Shabaev, Yakovlev, Efros, Yugova, Reuter, Wieck, Bayer (2007)



Nuclear spin polarization

$$\boldsymbol{m} = \sum_i \boldsymbol{I}_i$$

Spin precession between the pulses

$$\frac{d\boldsymbol{m}}{dt} = [\alpha \boldsymbol{S}(t) \times \boldsymbol{m}(t)] + [\boldsymbol{\omega} \times \boldsymbol{m}(t)],$$

$$\frac{d\boldsymbol{S}}{dt} = [\alpha \boldsymbol{m}(t) \times \boldsymbol{S}(t)] + [\boldsymbol{\Omega} \times \boldsymbol{S}(t)],$$

$$(n-1)T_R < t < nT_R$$

Pump pulse action: $\boldsymbol{m}^+ = \boldsymbol{m}^-$

$$S_z^+ = \frac{Q^2+1}{2} S_z^- + \frac{Q^2-1}{4}$$

$$S_y^+ = Q S_y^-, \quad S_x^+ = Q S_x^-$$

Time scales @ $B = 1$ T

1. Electron spin precession
   $$\frac{2\pi}{\Omega} \lesssim 0.1 \text{ ns}$$
2. Precession in nuclear field
   $$\frac{2\pi}{\alpha m} \sim 10 \text{ ns}$$
3. Pulse repetition period
   $$T_R \sim 10 \text{ ns}$$
4. Nuclear spin precession
   $$\frac{2\pi}{\omega} \lesssim 100 \text{ ns}$$
5. Precession in electron field
   $$\frac{2\pi}{\alpha S} \gtrsim 10^3 \text{ ns}$$

MMG, Yugova, Efros (2012)

Classical origin of the focusing

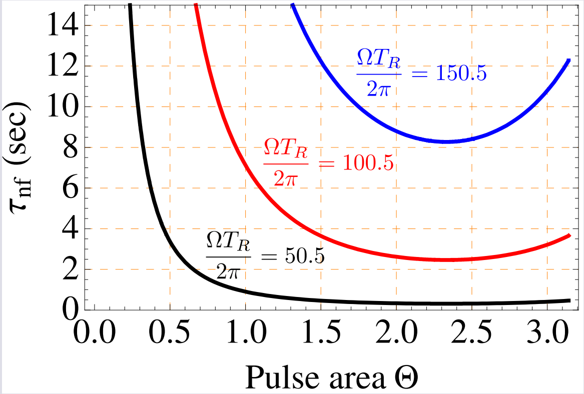
Nuclear spin polarization

$$\frac{m_x(t)}{m} \approx \frac{t}{\tau_{\rm nf}}, \qquad \frac{1}{\tau_{\rm nf}} = \frac{\alpha^3 m T_R}{\omega \Omega^2} f(\Omega T_R, \Theta)$$

Spin precession between the pulses

Pump pulse

Precession in nuclear field



Nuclear spin polarization

$$\boldsymbol{m} = \sum_i \boldsymbol{I}_i$$

Spin precession between the pulses

$$\frac{\mathrm{d}\boldsymbol{m}}{\mathrm{d}t} = [\alpha \boldsymbol{S}(t) \times \boldsymbol{m}(t)] + [\boldsymbol{\omega} \times \boldsymbol{m}(t)],$$

$$(n-1)T_R < t < nT_R$$

Pump pulse action: $\boldsymbol{m}^+ = \boldsymbol{m}^-$

$$S_z^+ = \frac{Q^2+1}{2} S_z^- + \frac{Q^2-1}{4}$$

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Time scales @ $B = 1$ T

1. Electron spin precession
   $$\frac{2\pi}{\Omega} \lesssim 0.1 \text{ ns}$$
2. Precession in nuclear field
   $$\frac{2\pi}{\ldots} \sim 10 \text{ ns}$$
4. Nuclear spin precession
   $$\frac{2\pi}{\omega} \lesssim 100 \text{ ns}$$
5. Precession in electron field
   $$\frac{2\pi}{\alpha S} \gtrsim 10^3 \text{ ns}$$

MMG, Yugova, Efros (2012)

"Active" mode-locking:

spin precession frequencies are synchronized in all dots thanks to nuclei

Alternatives

Random nuclear spin dynamics
A. Greilich et al (2006)

Random nuclear spin flips driven by precessing electron spin:

$$\frac{1}{\tau_n} = \frac{\alpha^2 \tau_c}{1 + (\Omega \tau_c)^2} \sim \frac{\alpha^2}{\Omega^2 \tau_c}$$

M.I. Dyakonov and V.I. Perel' (1973)

Phenomenological electron correlation time $\tau_c \propto 1/W_{tr}$, where W_{tr} is the trion creation probability. At PSC nuclear spin flips stop.

✓Our approach shows that the nuclear dynamics is **directed**!

Dynamical nuclear polarization
V. Korenev (2010)

Equilibrium approach/detuned pump: $$\frac{dm_x}{dt} = -\frac{m_x - qS_x(m_x)}{T_{1e}} - \frac{m_x}{T_1}$$

A.W. Overhauser (1953)

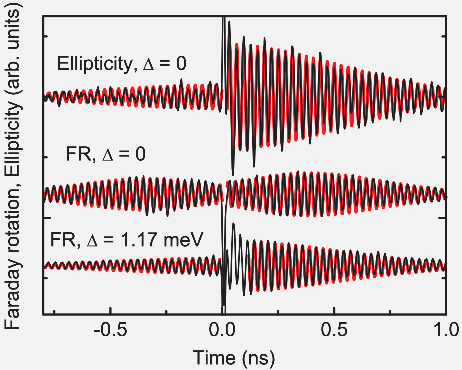
PSC is generally not stable!?

✓**Nonequilibrium** regime for the **pump-probe** conditions!

✓Tuning is possible for **resonant pump**!

Puzzle of spin-Faraday effect

Nuclei induce effective tuning of electron spin precession frequencies to the synchronous with pump repetition period values

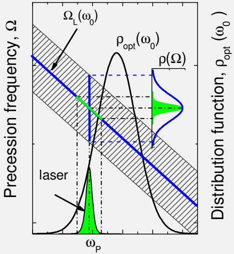


MMG et al. (2010)

Why does spin Faraday signal amplitude grow with time?

Inhomogenous array:

- Spread of resonant frequencies
- Related spread of g-factors
- Random nuclear fields



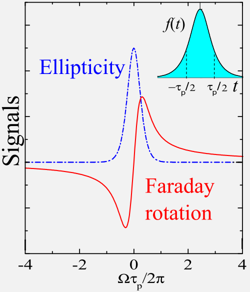
Pump-probe signal calculation

QDs array, correlated distribution of resonant frequencies, ω_0, and g-factors, $p(\omega_0, g)$:

$$\mathcal{S}(\Delta t) \propto \int d\omega_0 dg\, p(\omega_0, g) S_z(\omega_0, g, \Delta t) \times \left\{ \begin{array}{c} \mathcal{F}(\omega_0 - \omega_{pr}) \\ \mathcal{E}(\omega_0 - \omega_{pr}) \end{array} \right\}$$

$$g \approx 2 - \frac{4|p_{cv}|^2}{3m_0} \frac{\Delta}{E_g^{QD}(E_g^{QD} + \Delta)}$$

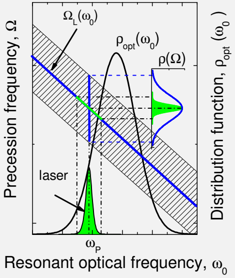
L. Roth (1964); E.L. Ivchenko, A.A. Kiselev (1992)

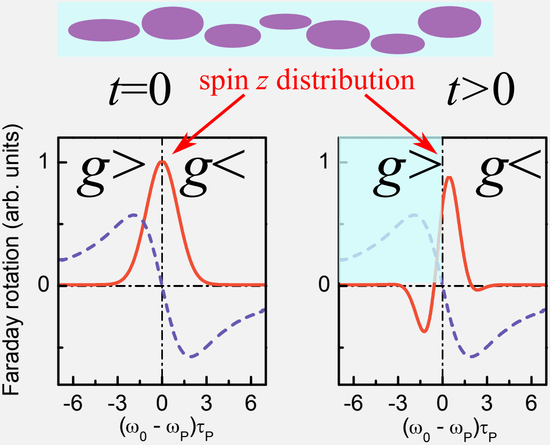


Emergence of Faraday rotation

Inhomogenous array:

- Spread of resonant frequencies
- Related spread of g-factors
- Random nuclear fields



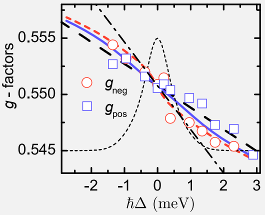


No Faraday rotation signal at $t = 0$

Faraday rotation signal appears at $t \neq 0$

Inhomogenous array:

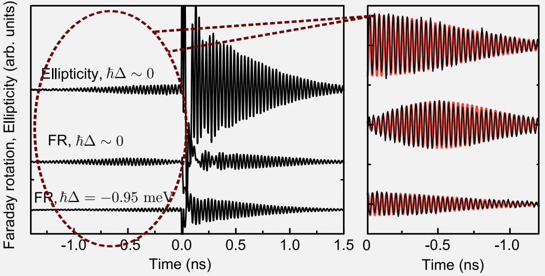
- Spread of resonant frequencies
- Related spread of g-factors
- Random nuclear fields



Simple model

$$\mathcal{F}(t) = \frac{1}{2}\sqrt{\frac{\pi}{2\tau_p^2}} \exp\left[\frac{-\Delta^2\tau_p^2/2 - (\Omega' t)^2}{8\tau_p^2}\right] \times$$
$$\left[2\Delta\tau_p \cos\left(\tilde{\Omega}_0 t\right) + \frac{\Omega' t}{\tau_p} \sin\left(\tilde{\Omega}_0 t\right)\right]$$

Experiment



Faraday rotation does not reflect “averaged” spin dynamics of electron ensemble!

MMG et al., (2010)

Inhomogenous array:

- Spread of

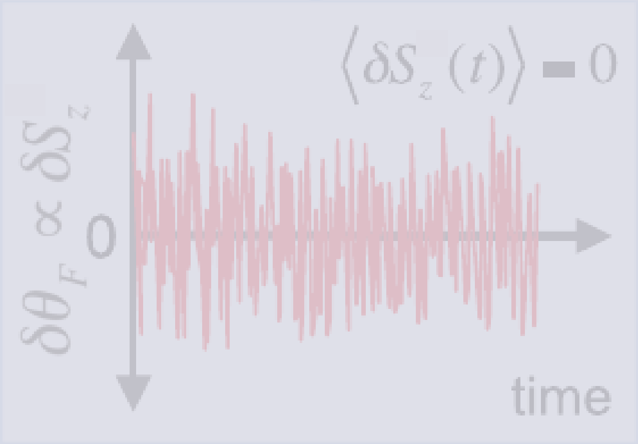
Faraday and ellipticity are formed by different ensembles of spins

- Different temporal behavior
- Faraday rotation does not reflect "averaged" spin dynamics of electron ensemble

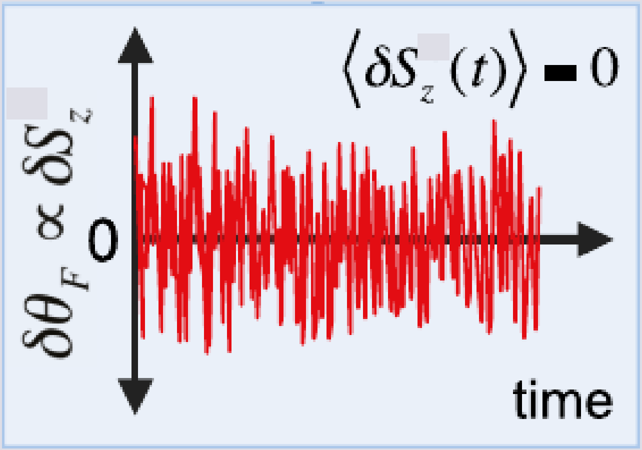
- Random nuclear fields

Outline

What would happen, if one measures Faraday or Kerr effect in the absence of pump?



What would happen, if one measures Faraday or Kerr effect in the absence of pump?



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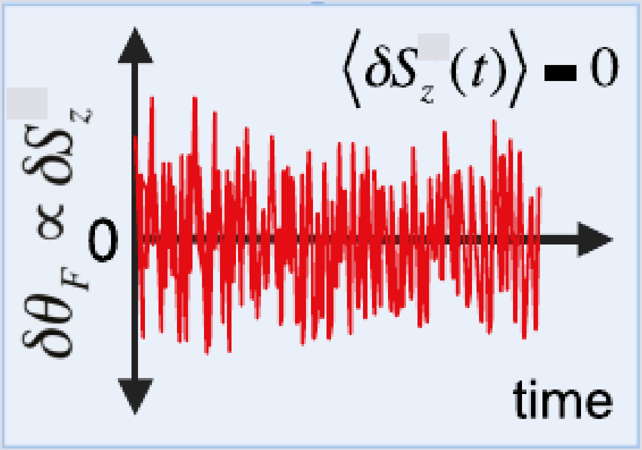


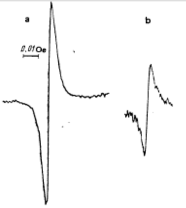
Just noise? Spin noise!

Magnetic resonance in the Faraday-rotation noise spectrum

E. B. Aleksandrov and V. S. Zapasskiĭ

(Submitted 23 January 1981)
Zh. Eksp. Teor. Fiz. 81, 132–138 (July 1981)

A maximum at the magnetic resonance frequency of sodium atoms in the ground state is observed near the 5896 Å absorption line in the fluctuation spectrum of the azimuth of the polarization plane of light crossing a magnetic field in sodium vapor. The experiment is a demonstration of a new EPR method which does not require in principle magnetic polarization of the investigated medium, nor the use of high-frequency or microwave fields to induce the resonance.



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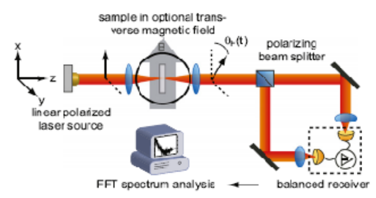
Invited review

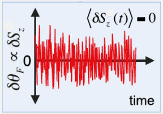
Semiconductor spin noise spectroscopy: Fundamentals, accomplishments, and challenges

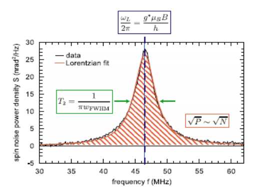
Georg M. Müller, Michael Oestreich, Michael Römer, Jens Hübner *
Institut für Festkörperphysik, Leibniz Universität Hannover, Appelstraße 2, D-30167 Hannover, Germany

$$\langle \vartheta_{\mathcal{F}}(t)\vartheta_{\mathcal{F}}(t')\rangle,$$

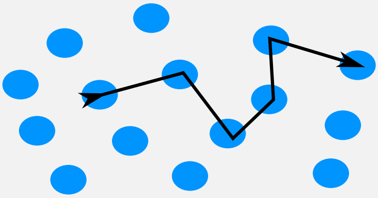
$$\langle \vartheta_{\mathcal{K}}(t)\vartheta_{\mathcal{K}}(t')\rangle \propto \langle S_z(t)S_z(t')\rangle$$







Transport $\delta \boldsymbol{v}(t) = \delta \boldsymbol{v}(0) e^{-t/\tau_p}$



Electron velocity noise:

$$\langle v_x(t) v_x(0) \rangle = \frac{v_F^2}{2} e^{-t/\tau_p}$$

Diffusion coefficient

$$D = \int_0^\infty \langle v_x(t) v_x(0) \rangle \mathrm{d}t = \frac{v_F^2 \tau_p}{2}$$

Spin $\delta \boldsymbol{s}(t) = \delta \boldsymbol{s}(0) e^{-t/\tau_s}$

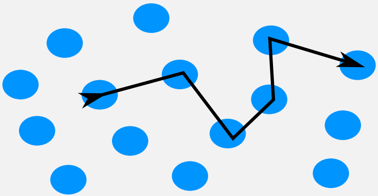
Electron spin noise:

$$\langle s_z(t) s_z(0) \rangle = \langle s_z^2 \rangle e^{-t/\tau_s}$$

Magnetic susceptibility

$$\mu_{zz}(\omega) \propto \int_0^\infty \langle s_z(t) s_z(0) \rangle e^{i\omega t} \mathrm{d}t$$

Transport $\delta \boldsymbol{v}(t) = \delta \boldsymbol{v}(0) e^{-t/\tau_p}$



Electron velocity noise:

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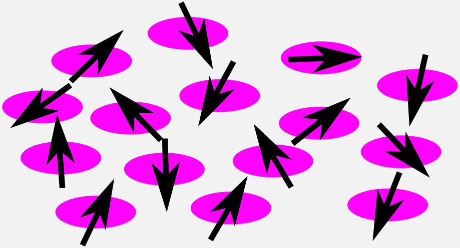

Electron spin noise:

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Magnetic susceptibility

$$\mu_{zz}(\omega) \propto \int_0^\infty \langle s_z(t) s_z(0) \rangle e^{\mathrm{i}\omega t} \mathrm{d}t$$

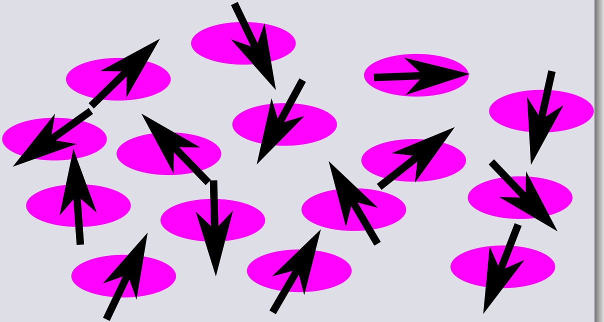
Spin noise in electron ensembles

Single spin

$$\langle s_x \rangle = \langle s_y \rangle = \langle s_z \rangle = 0 \quad \text{but} \quad \langle s_x^2 \rangle = \langle s_y^2 \rangle = \langle s_z^2 \rangle = \frac{1}{3} \times \frac{1}{2}\left(1 + \frac{1}{2}\right)$$

Spin ensemble

$$\sqrt{\langle S_i^2 \rangle} = \sqrt{N}\sqrt{\langle s_i^2 \rangle} = \frac{\sqrt{N}}{2}$$

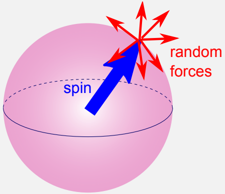


Spin fluctuation $\delta \boldsymbol{s}$ in a dot

$$\frac{\partial \delta \boldsymbol{s}(t)}{\partial t} + \frac{\delta \boldsymbol{s}(t)}{\tau_s} + \delta \boldsymbol{s}(t) \times (\boldsymbol{\Omega_B} + \boldsymbol{\Omega}_N) = \boldsymbol{\xi}(t)$$

Random (Langevin) forces

$$\langle \xi_\alpha(t')\xi_\beta(t)\rangle = \frac{1}{2\tau_s}\delta_{\alpha\beta}\delta(t'-t)$$



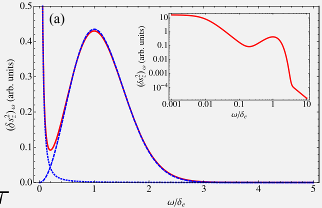
$$(\delta s_\alpha \delta s_\beta)_\omega = \int_{-\infty}^{+\infty} \langle \delta s_\alpha(t+\tau)\delta s_\beta(t)\rangle e^{i\omega\tau}\, d\tau$$

MMG, Ivchenko (2012)

Zero field

Nuclei fluctuations

$$(\delta s_\alpha^2)_\omega = \frac{\pi}{6}\{\Delta(\omega) + \int_0^\infty d\Omega_N\, F(\Omega_N) [\Delta(\omega-\Omega_N)+\Delta(\omega+\Omega_N)]\}$$



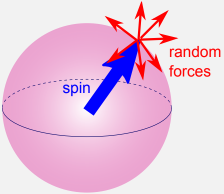
- Zero field peak
- Peak at $\Omega \sim \langle\sqrt{\Omega_N^2}\rangle$

Spin fluctuation $\delta \boldsymbol{s}$ in a dot

$$\frac{\partial \delta \boldsymbol{s}(t)}{\partial t} + \frac{\delta \boldsymbol{s}(t)}{\tau_s} + \delta \boldsymbol{s}(t) \times (\boldsymbol{\Omega_B} + \boldsymbol{\Omega}_N) = \boldsymbol{\xi}(t)$$

Random (Langevin) forces

$$\langle \xi_\alpha(t') \xi_\beta(t) \rangle = \frac{1}{2\tau_s} \delta_{\alpha\beta} \delta(t' - t)$$

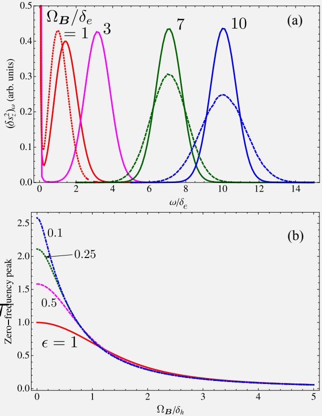


$$(\delta s_\alpha \delta s_\beta)_\omega = \int_{-\infty}^{+\infty} \langle \delta s_\alpha(t+\tau) \delta s_\beta(t) \rangle e^{i\omega\tau} d\tau$$

MMG, Ivchenko (2012)

Transverse field

- Zero field peak is reduced
- Main peak shifts $\sim \Omega_{\boldsymbol{B}}$

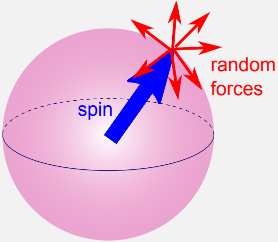


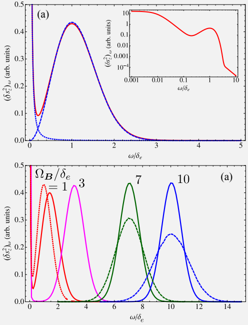
Spin noise theory & experiment

$$\frac{\partial \delta \mathbf{s}(t)}{\partial t} + \frac{\delta \mathbf{s}(t)}{\tau_s} + \delta \mathbf{s}(t) \times (\boldsymbol{\Omega}_{\boldsymbol{B}} + \boldsymbol{\Omega}_N) = \boldsymbol{\xi}(t)$$

Random (Langevin) forces

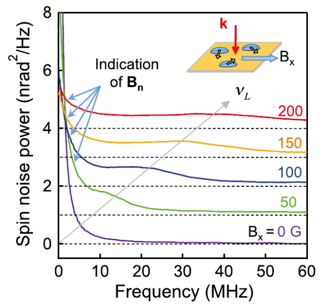
$$\langle \xi_\alpha(t')\xi_\beta(t)\rangle = \frac{1}{2\tau_s}\delta_{\alpha\beta}\delta(t'-t)$$





MMG, Ivchenko (2012)

Experiment

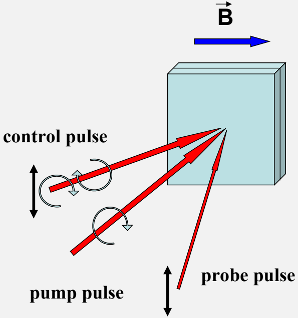


Yan Li, Sinitsyn, Smith, Reuter, Wieck, Yakovlev, Bayer, Crooker (2012)

Spin noise spectroscopy

provides information about spin precession and dephasing in close-to-equilibrium conditions

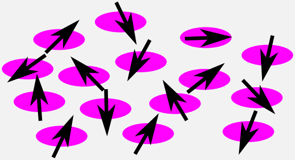
Spin control



3 pulse technique

Chen, et al. (2004)
Economou, Sham, Wu, Steel (2006)

Spin noise spectroscopy



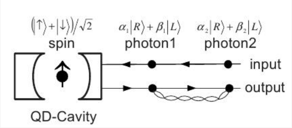
$$\langle S_i^2\rangle = N\langle s_i^2\rangle$$

monitoring Faraday/Kerr/Ellipticity fluctuations (in an absence of a pump)

Aleksandrov, Zapasskii (1981)

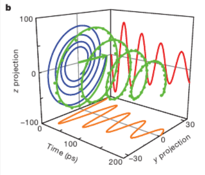
Spins in cavities

entanglement via spin

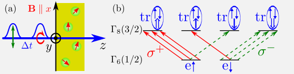


Hu, Munro, Rarity (2008)

3D spin tomography



Kosaka et al. (2009)



Smirnov, MMG (2012)

Conclusions

Faraday effect and ellipticity provide complementary information about dynamics of electron and nuclear spins in QDs

Coherent spin dynamics of electrons and excitons in nanostructures (a review)
Phys. Solid State 54, 1 (2012)

Plan

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SOLAB