Theoretical modelling of magnetooptical experiments in p-doped nanostructures

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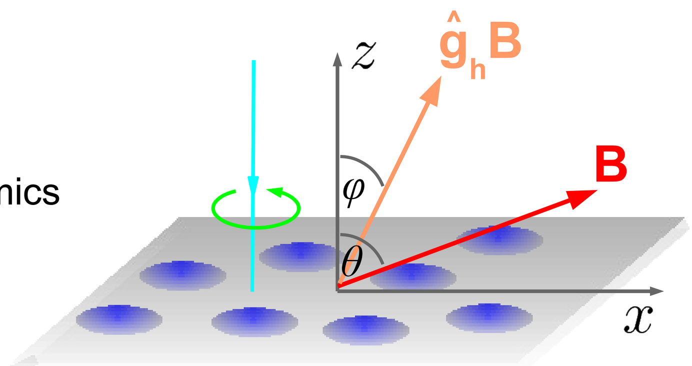
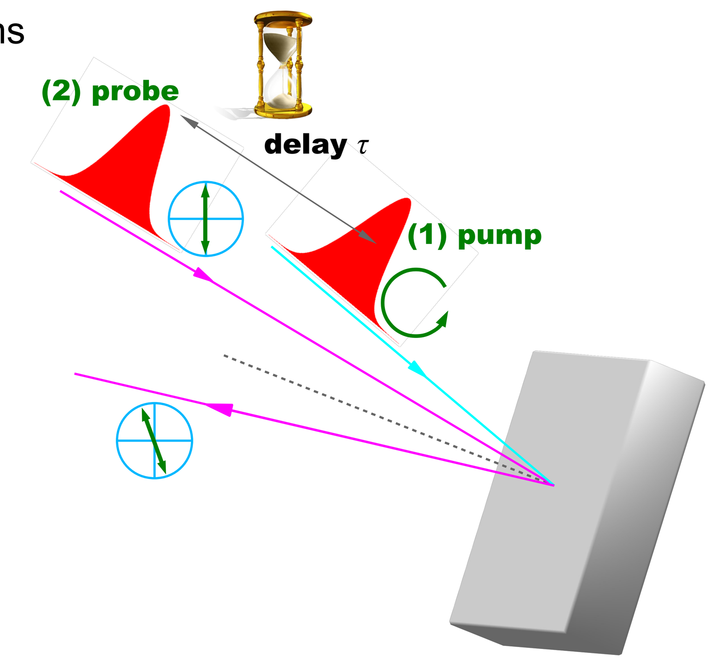
1. Motivation

- Spin dynamics and coherence is crucial for many applications in emerging technologies
- Time–resolved Kerr rotation is a very efficient method for the investigation of spin dynamics
- Anisotropy of the hole g-factor makes the evolution in tilted magnetic field nontrivial



2. System

- Holes weakly bound at trapping centers - ensemble of independent hole-trion systems
- Non-magnetic system
- Magnetic field tilted from the exact Voigt geometry
- Pump-probe configuration at normal incidence

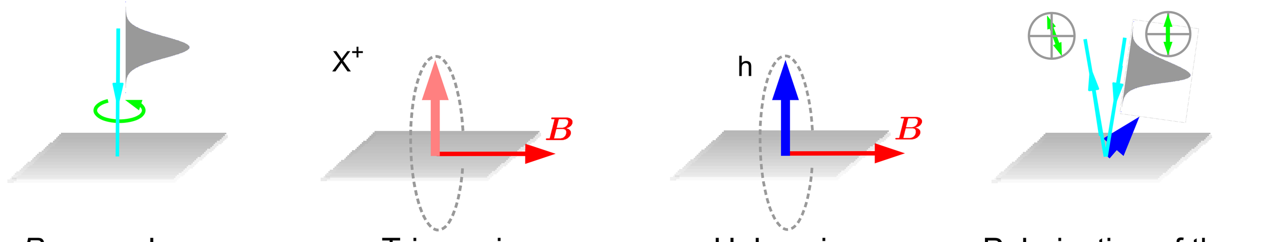


3. Model

- **Hole–trion system** described by a 4-dimensional density matrix[1]
- **Pump pulse** treated perturbatively – low power limit
- **System dynamics:** Zeeman splitting and precession in the magnetic field
- **System–reservoir interactions:**
  – Trion recombination described by a Lindblad generator
  – Hole spin decoherence described by a Lindblad generator (Markovian, weak coupling limit)
- **Detection:** homodyne formed by the reference signal reflected from the surface and the weak optical signal from the system.

[1] P. Machnikowski, T. Kuhn, Phys. Rev. B **81**, 115306 (2010)

Phenomenology – magnetooptical Kerr effect



Pump pulse generates trion and hole spin polarization | Trion spin polarization precesses and decays due to recombination and spin decoherence | Hole spin polarization precesses and decays due to spin decoherence | Polarization of the *probe* pulse is rotated proportionally to the existing spin polarization

Magnetization (spin polarization) dynamics on picosecond time scales

RSA signal

RSA signal obtained by finding the stationary point of the spin polarization transformation corresponding to one repetition of the pulsed laser:

$$\underbrace{\mathcal{L}_D}_{\text{Long time scale decoherence}} \{ \underbrace{\mathcal{L}_P}_{\text{Pump pulse}} \{ \underbrace{\mathbf{S}_{RSA}}_{\text{Initial spin state being transformed}} \} \} = \underbrace{\mathbf{S}_{RSA}}_{\text{Final spin state equal to initial one}}$$

Inhomogeneous broadening of the hole g-factors is model with the normal distribution.

4. Dynamics

- Pump pulse generates trion and hole spin polarization; the hole polarization survives recombination
- Optical selection rules with respect to the structure axis
- Analytical solution for the precession + decoherence
- **TRKR signal** proportional to the **spin polarization** at the arrival of the probe pulse
- **RSA signal** proportional to the spin polarization generated by subsequent laser pulses, peaks obtained for pulse repetition frequency in resonance with the precession frequency

5. Results – TRKR in tilted magnetic field

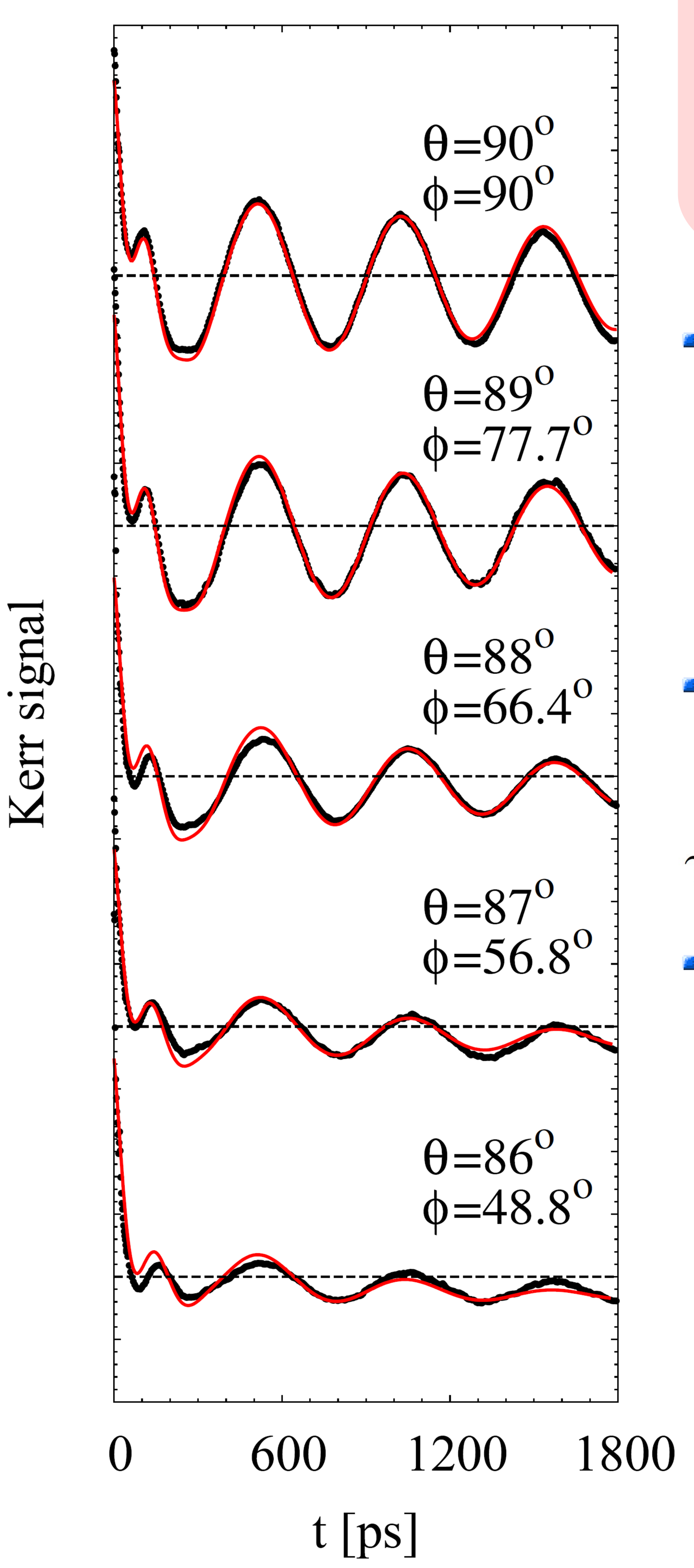
- Expression for Kerr signal in tilted magnetic field:

$$TRKR = \Sigma_h - \Sigma_t$$

$$\underbrace{\Sigma_t = \Sigma_t(0)e^{-\gamma_1 t}[\cos^2\theta + \sin^2\theta\cos\omega_t t]}_{\text{Depends on trion variables}}$$

$$\Sigma_h = \underbrace{A_1 e^{-\gamma_1 t} + A_2 e^{-(\gamma_1 + i\omega_t)t}}_{\text{Depends on trion variables}} + \underbrace{B_1 e^{-(\kappa_{1\perp}\sin^2\phi + \kappa_{1\parallel}\cos^2\phi)t} + B_2 e^{-(\kappa_{2\perp}\sin^2\phi + \kappa_{2\parallel}\cos^2\phi + i\omega_h)t}}_{\text{Depends on hole variables}} + c.c.$$

Fitting to the experimental results for Kerr rotation (T=1.2 K)



Trion Larmor frequency: ω_t
Radiative decay rate: γ_1
Prefactors follow the relations:

$$\theta = 0^0 : A_2 = 0$$
$$\theta = 90^0 : A_1 = 0$$

Hole Larmor frequency: ω_h
Hole decoherence rates:
$\kappa_{1\perp},\ \kappa_{1\parallel},\ \kappa_{2\perp},\ \kappa_{2\parallel}$

$$\phi = 0^0 : B_2 = 0$$
$$\phi = 90^0 : B_1 = 0$$

- In-plane and out-of-plane components of hole g-factor were measured in the RSA experiment. Hence, it was possible to keep the hole Larmor frequency constant for different tilt angles in TRKR experiment:

$$g_\parallel = 0.88 \quad ; \quad \omega_h = 1.23 \cdot 10^{10}\ \frac{1}{s}$$
$$g_\perp = 0.07$$

- Radiative decay rate and electron g-factor were measured independently and were assumed as known constants in the simulations:

$$\gamma_1 = 1.33 \cdot 10^{10}\ \frac{1}{s}\ ;\ g_e = 0.266\ ;\ \omega_t = 4.68 \cdot 10^{10}\ \frac{1}{s}$$

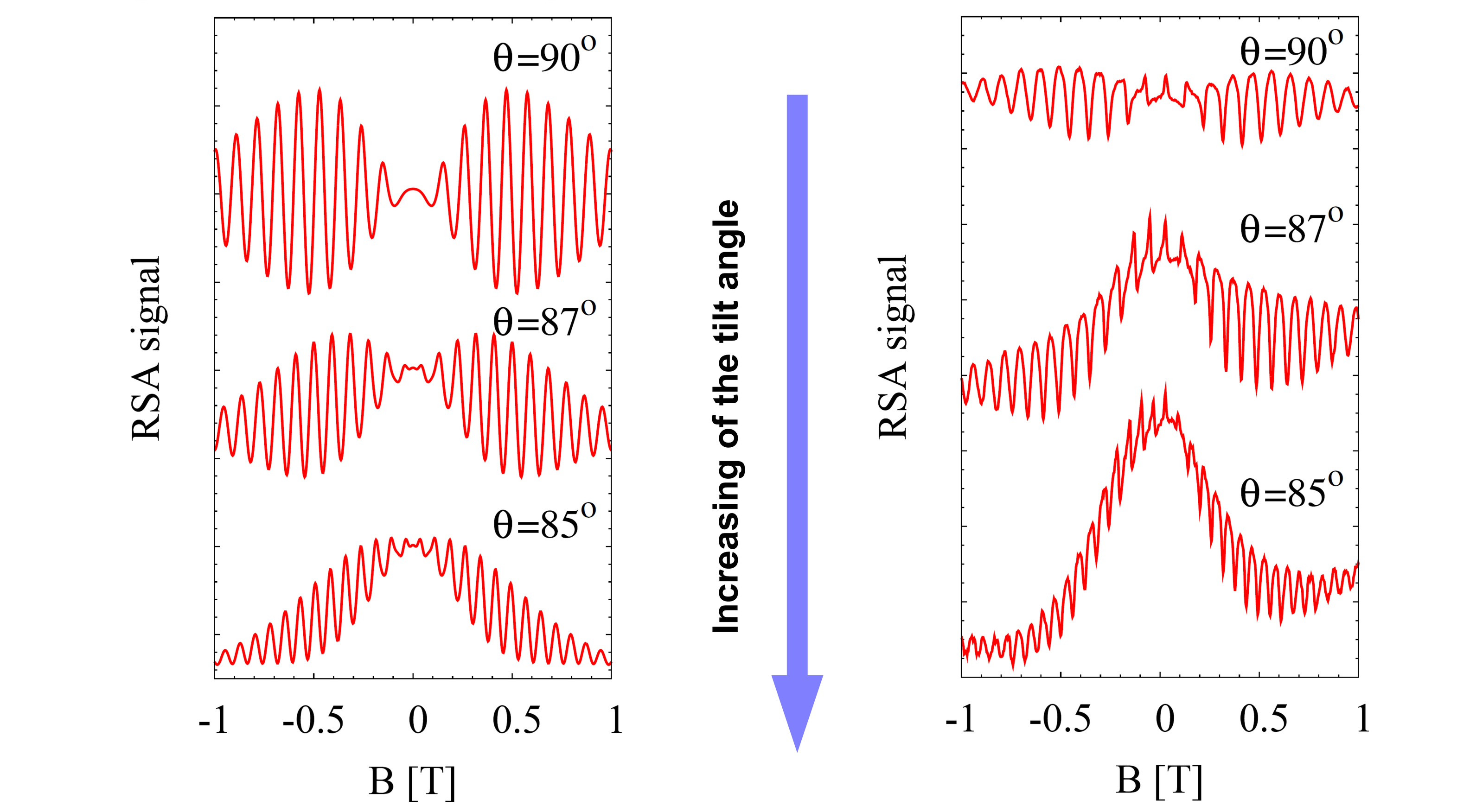
- Due to fixed Larmor frequency the reservoir is probed at different angles, but at the same frequency. Therefore the decoherence rates for different angles can be compared. By fitting to experimental data we obtained the values of hole decoherence rates and their dependence on the tilt angle. The anisotropy of the decoherence rates was found to be comparable with the anisotropy of the hole g-factor (one order of magnitude difference between in-plane and out-of-plane components):

$$\kappa_{1\perp} = 5.85 \cdot 10^8\ \frac{1}{s} \qquad \kappa_{2\perp} = 3.43 \cdot 10^8\ \frac{1}{s}$$
$$\kappa_{1\parallel} = 3.22 \cdot 10^9\ \frac{1}{s} \qquad \kappa_{2\parallel} = 2.92 \cdot 10^9\ \frac{1}{s}$$

6. Results - RSA

- General behaviour of the RSA signal shape in tilted magnetic field:

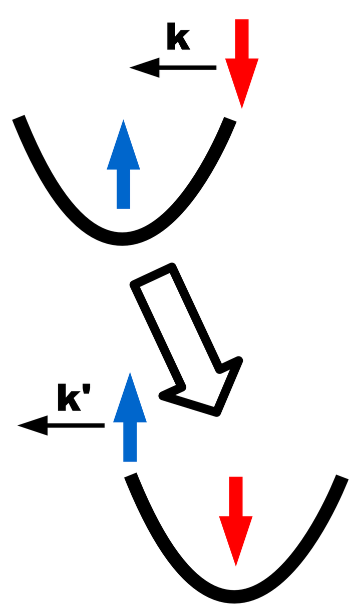
RSA signal obtained from analytical formula | **RSA measurements in T=1.2 K**



7. Microscopic mechanism of spin decoherence

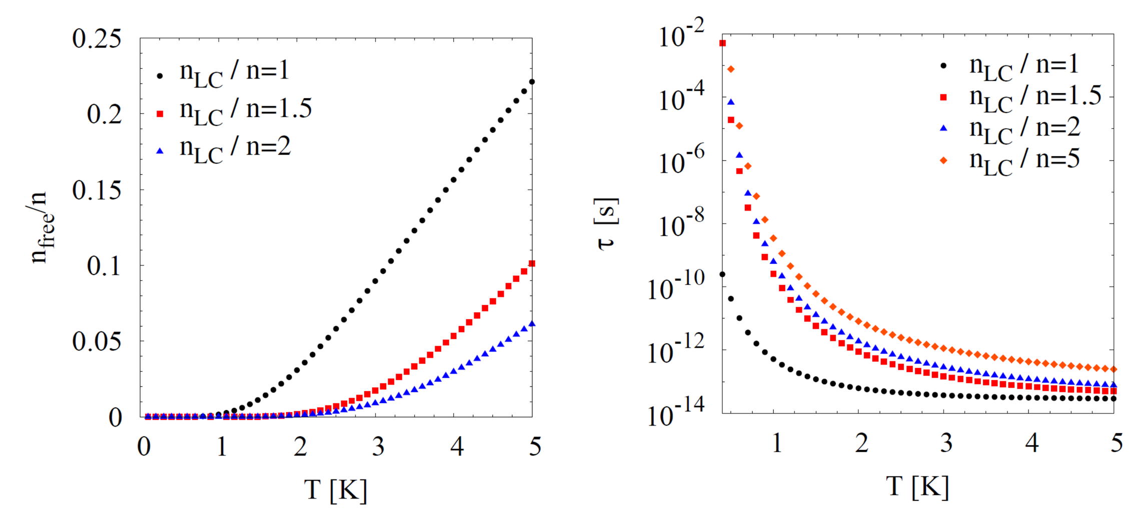
- Ensemble of localized and thermally released free holes (2D hole gas). The chemical potential of the system found from the fermionic grand partition function with Gaussian distribution of the energies of localized states $\mathcal{N}(E_0, \sigma_E)$.
- Due to very efficient Dyakonov-Perel spin relaxation mechanism the free holes do not contribute to the Kerr signal. However, simple calculations show that for temperatures, where no signal is observed, the majority of carriers are still localized. Therefore we propose the exchange scattering of free on localized holes to be the main decoherence mechanism.
- The in-plane wavefunctions are assumed to be Gaussians (localized states) and plane waves (free states). Due to confinement the wavefunction along *z* direction is approximated by a Gaussian:

$$\Phi(\vec{r}) = \frac{1}{\sqrt{\pi}\sigma} e^{-\frac{\vec{\rho}^2}{2\sigma^2}} \cdot \frac{1}{(\sqrt{\pi}\sigma_z)^{\frac{1}{2}}} e^{-\frac{z^2}{2\sigma_z^2}} \quad ; \quad \Psi_{\vec{k}}(\vec{r}) = \frac{1}{\sqrt{S}} e^{i\vec{k}\cdot\vec{\rho}} \cdot \frac{1}{(\sqrt{\pi}\sigma_z)^{\frac{1}{2}}} e^{-\frac{z^2}{2\sigma_z^2}}$$



- Using the Fermi's Golden Rule we get the transition probabilities from the state with localized spin-up hole and free spin-down hole with wavevector **k** to any of the allowed states with localized spin-down hole.

Ratio of free to all carriers dependence on temperature | **Localized spin lifetime dependence on temperature**



Parameters (QW width - 4nm):

Concentration of carriers:
$n = 1.1 \cdot 10^{11}\ \mathrm{cm}^{-2}$

Size of localized wavefunction:
$\sigma = 5\,\mathrm{nm} \quad ; \quad \sigma_z = 1.8\,\mathrm{nm}$

Depth of localization centers:
$E_0 = 1\,\mathrm{meV} \quad ; \quad \sigma_E = 0.1\,\mathrm{meV}$

Concentration of localization centers:
n_{LC}

8. Conclusions

- The Kerr signal in tilted magnetic field consists of two parts: dependent on hole and trion dynamical variables, each containing damped oscillation and decay terms (due to radiative recombination and hole decoherence).
- By fitting to experimental data we found strong anisotropy of the hole decoherence rates, which may result from the inhomogeneous broadening of the anisotropic g-factors.
- Thermal release of holes from localization centers may be indirectly responsible for extinction of Kerr signal in higher temperatures through exchange scattering of released carriers on localized ones.

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