Wrocław University of Technology

Decoherence-assisted optical polarization of localized hole spins in p-doped quantum wells

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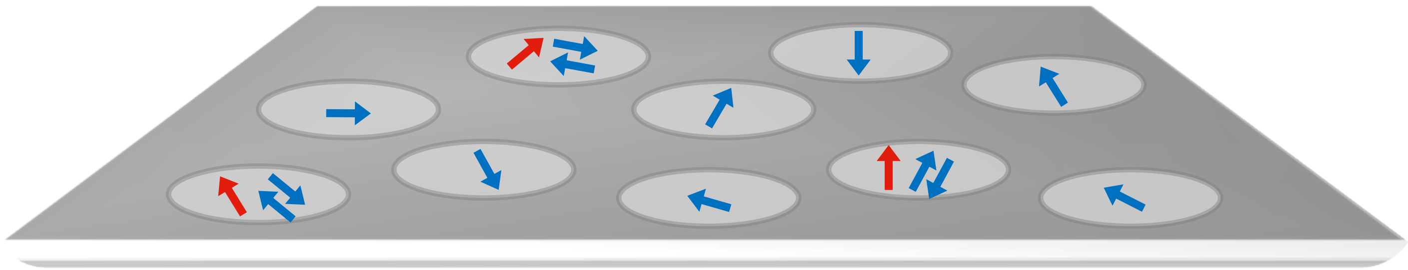
Contents

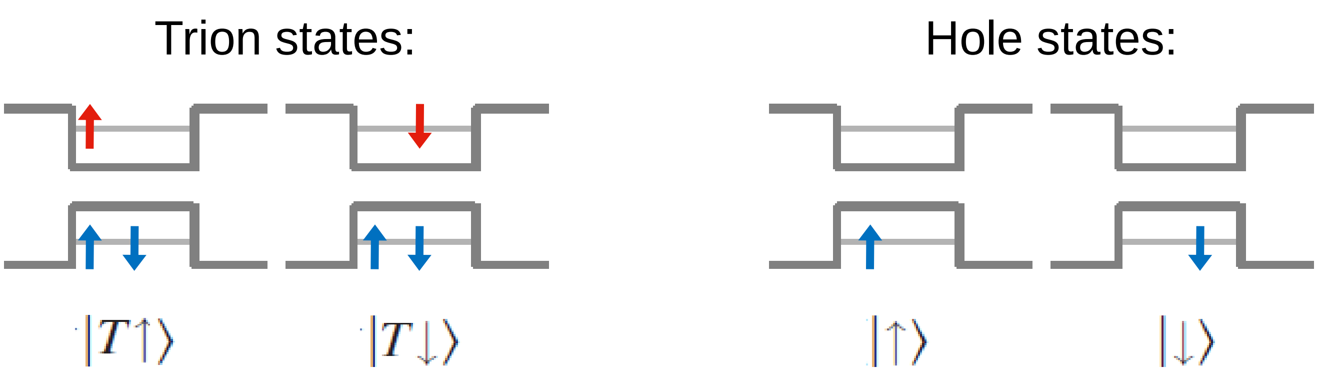
Motivation

- Spin dynamics and coherence is crucial for many applications in emerging technologies (spintronics)
- Time–resolved Kerr rotation is a very efficient method for the investigation of spin dynamics; interesting experiments have been performed quite recently
- Resonant spin amplification signal shows interesting, still unexplained behaviour for non-resonant excitation, including the formation of a zero-field peak
- Extended life times are observed in semiconductor nanostructures, especially for hole spin states (for which reduced hyperfine interaction makes the spin decoherence slower)

System and pump-probe configuration

- Holes in a 2DHG weakly bound at trapping centers (ensemble of independent hole-trion systems)
- Only heavy hole states are considered (heavy-light hole splitting large in confined systems)

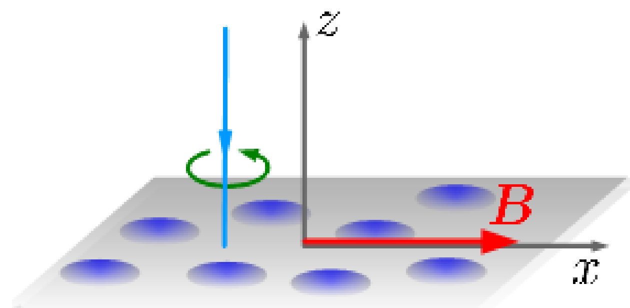


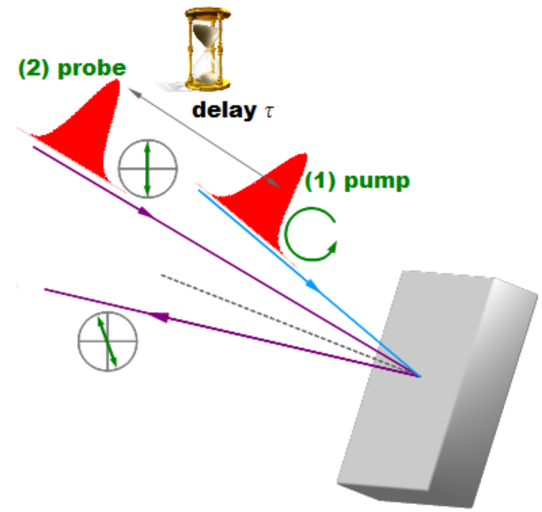


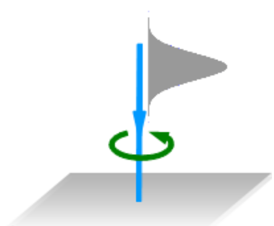
System and pump-probe configuration

- System pumped by circurarly polarized pump pulse and probed after delay time by linearly polarized probe pulse

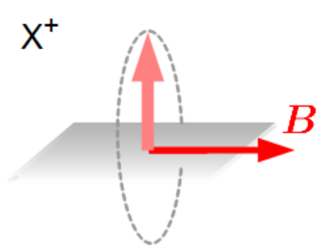
- Exact Voigt geometry



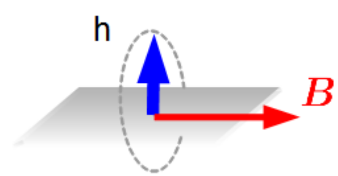




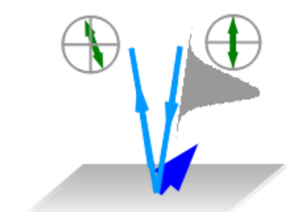
Pump pulse generates trion and hole spin polarization



Trion spin polarization precesses and decays due to recombination and spin decoherence



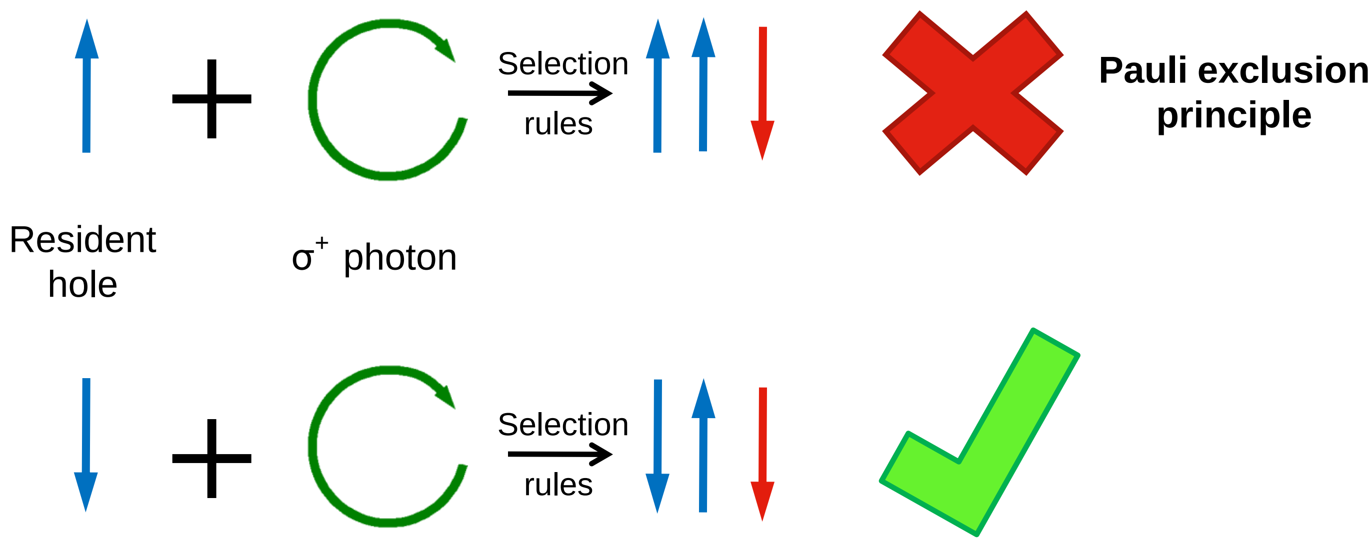
Hole spin polarization precesses and decays due to spin decoherence



Polarization of the probe pulse is rotated proportionally to the existing spin polarization

System and pump-probe configuration

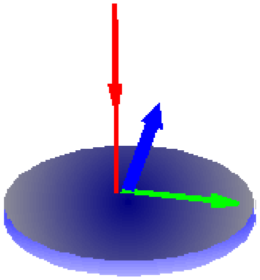
- The fundamental optical transition at each trapping center consists of an excitation of an electron-hole pair which, together with the resident hole, forms a bound trion (spin-polarized electron–hole pairs according to the optical selection rules and Pauli exclusion principle)

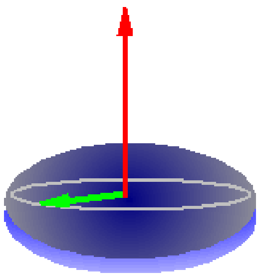


Angular momentum: $1 \quad = \quad \frac{3}{2} + \left(-\frac{1}{2}\right)$

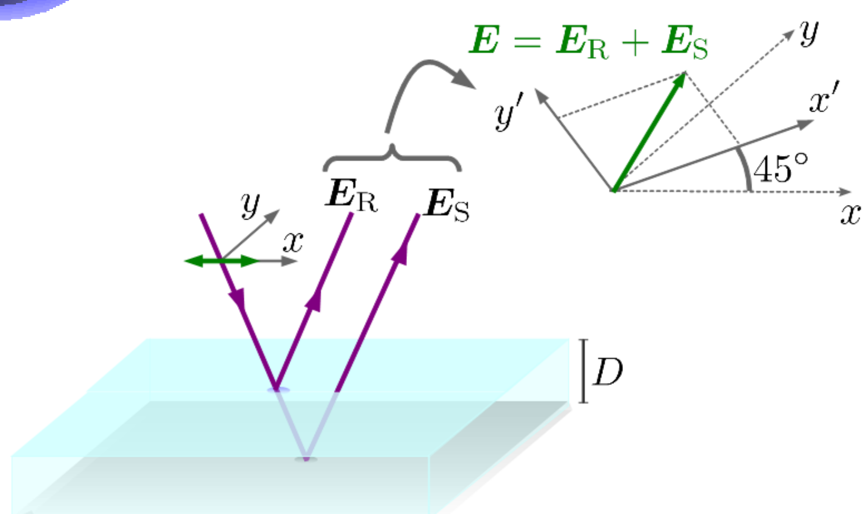
Homodyne detection

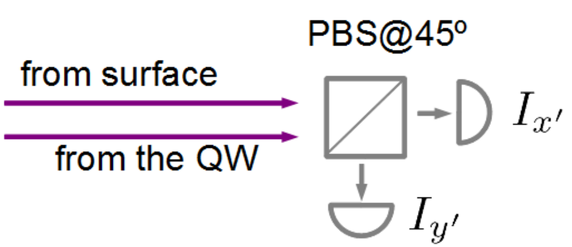
Probe pulse induces dipole moment that depends on the spin polarization (selection rules and Pauli exclusion)





Time-dependent dipole moment is the source of coherent radiation





$$\mathrm{TRKR} = \frac{I_{x'} - I_{y'}}{I_{x'} + I_{y'}}$$

Model – resonant excitation

- Description restricted to the lowest hole and trion states: 4x4 density matrix. Due to short lifetime of trions initial density matrix has no trion part:

$$\rho_0 = \begin{pmatrix} \frac{1+\Sigma}{2} & \frac{1}{2}X - \frac{i}{2}Y & 0 & 0 \\ \frac{1}{2}X + \frac{i}{2}Y & \frac{1-\Sigma}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- A single trapped hole-trion system is described by the Hamiltonian:

$$H_0 = -\frac{1}{2}\mu_{\mathrm{B}}\boldsymbol{B}\hat{g}_h\boldsymbol{\sigma}_h - \frac{1}{2}g_t\mu_{\mathrm{B}}\boldsymbol{B}\cdot\boldsymbol{\sigma}_t$$

- The electric field couples to the interband transitions via a dipole moment *d:*

$$H_{\mathrm{las}} = \frac{A_1}{2}\eta\left(\frac{t}{\tau_p}\right)e^{i\psi_1}|\uparrow\rangle\langle T\uparrow| + \mathrm{H.c.}$$

where: $A_i = d|E_i|(1+r)$, $r = (1-n)/(1+n)$

Model – resonant excitation

- The system evolution (Larmor precession, recombination and spin decoherence) is modeled in terms of the Markovian Master equation:

$$\dot{\rho} = -\frac{i}{\hbar}[H_0, \rho] + \mathcal{L}_{\mathrm{h}}[\rho] + \mathcal{L}_{\mathrm{t}}[\rho] + \mathcal{L}_{\mathrm{r}}[\rho]$$

- The hole/trion spin dissipator is obtained within the weak-coupling approach from the hole/trion spin-environment Hamiltonian. The evolution equation for the spin is derived in the Markov limit

- Using C_{4v} symmetry the expressions for the spectral densities for the hole/trion reservoir are simplified

- We assume that the reservoirs coupled to electron (trion) and hole spins are uncorrelated

- The last term is the standard spontaneous emission generator that accounts for the radiative recombination of the trion

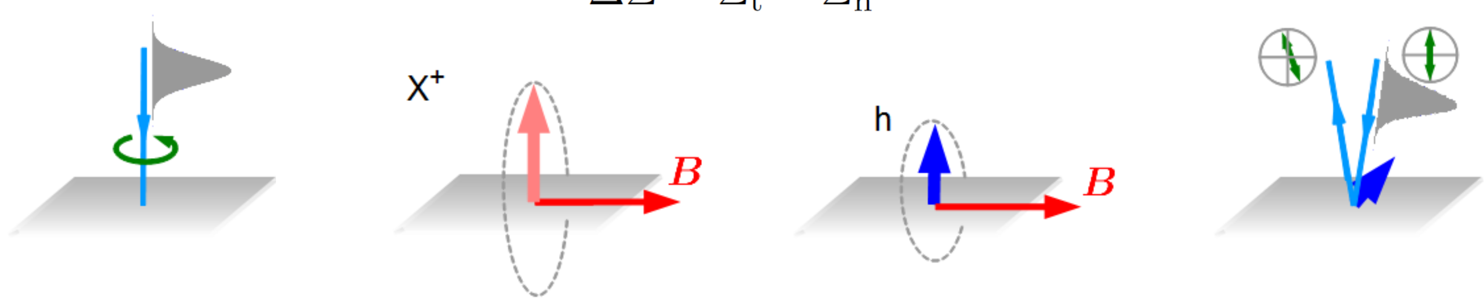
Model – resonant excitation

- The Markovian Master equation can be rewritten in terms of components of hole/trion spin polarization:

$$
\begin{aligned}
\dot{X}_{\mathrm{h}} &= -\left(\kappa_z+\kappa_x\right) X_{\mathrm{h}} + (\kappa'_x+\kappa'_z) N_{\mathrm{h}}, &\quad \dot{X}_{\mathrm{t}} &= -\left(\mu_z+\mu_x\right) X_{\mathrm{t}} + (\mu'_x+\mu'_z) N_{\mathrm{t}} - \gamma_{\mathrm{R}} X_{\mathrm{t}}, \\
\dot{Y}_{\mathrm{h}} &= \omega_{\mathrm{h}} \Sigma_{\mathrm{h}} - \left(\kappa_{x0}+\kappa_z\right) Y_{\mathrm{h}}, & \dot{Y}_{\mathrm{t}} &= \omega_{\mathrm{t}} \Sigma_{\mathrm{t}} - \left(\mu_{x0}+\mu_z\right) Y_{\mathrm{t}} - \gamma_{\mathrm{R}} Y_{\mathrm{t}}, \\
\dot{\Sigma}_{\mathrm{h}} &= -\omega_{\mathrm{h}} Y_{\mathrm{h}} - \left(\kappa_x+\kappa_{x0}\right) \Sigma_{\mathrm{h}} + \gamma_{\mathrm{R}} \Sigma_{\mathrm{t}}, & \dot{\Sigma}_{\mathrm{t}} &= -\omega_{\mathrm{t}} Y_{\mathrm{t}} - \left(\mu_x+\mu_{x0}\right) \Sigma_{\mathrm{t}} - \gamma_{\mathrm{R}} \Sigma_{\mathrm{t}}
\end{aligned}
$$

- The optical response, that is, the rotation of the polarization plane of the reflected or transmitted probe pulse, is proportional to*:

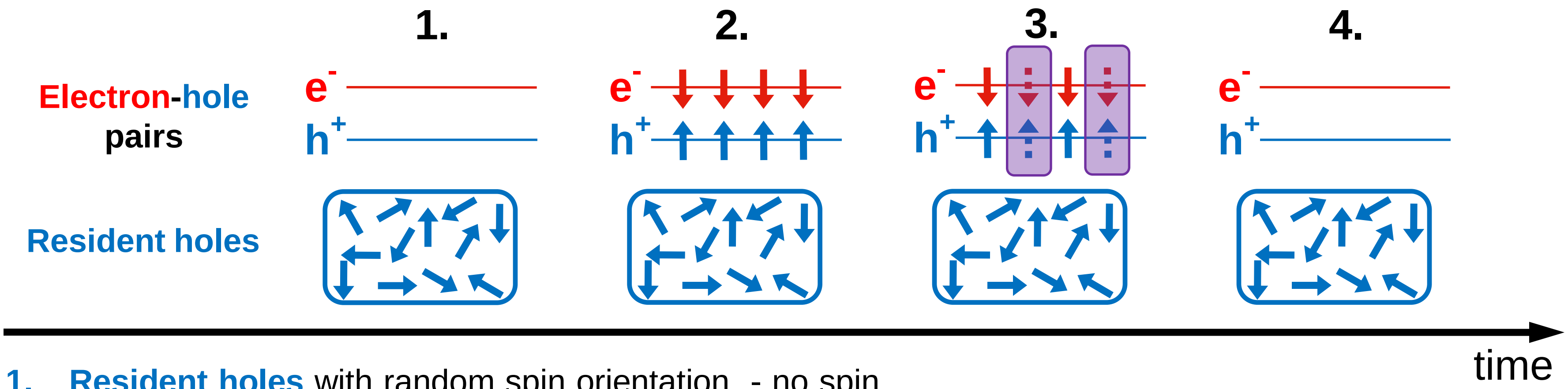
$$\Delta\Sigma = \Sigma_{\mathrm{t}} - \Sigma_{\mathrm{h}}$$



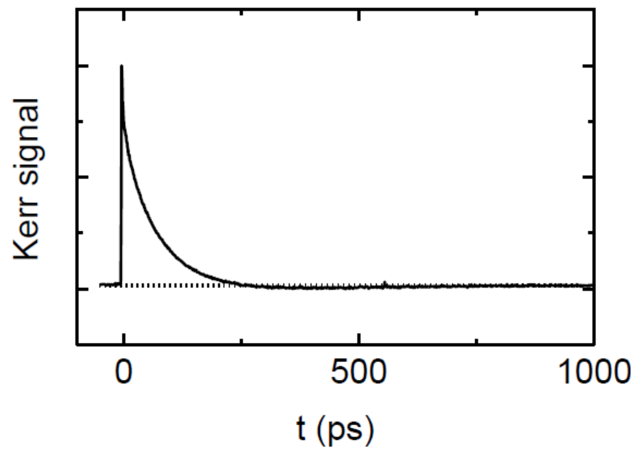
*P. Machnikowski and T. Kuhn, Phys. Rev. B **81**, 115306 (2010); I. A. Yugova *et al.* Phys. Rev. B **80**, 104436 (2009)

TRKR for resonant excitation

No magnetic field



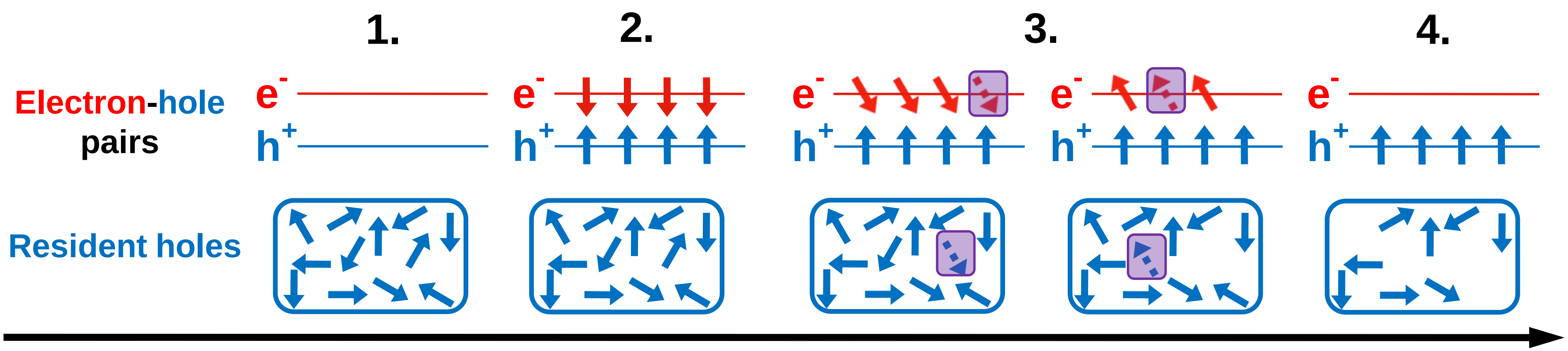
1. **Resident holes** with random spin orientation - no spin polarization
2. **Pump pulse (σ^+)** creates optically oriented **electron-hole** pairs
3. **Recombination**: electrons and holes with matching spin orientation
4. At the arrival of **probe pulse** no spin polarization in the system



Note: During evolution electron and hole spins also undergo decoherence processes (not shown in the picture)

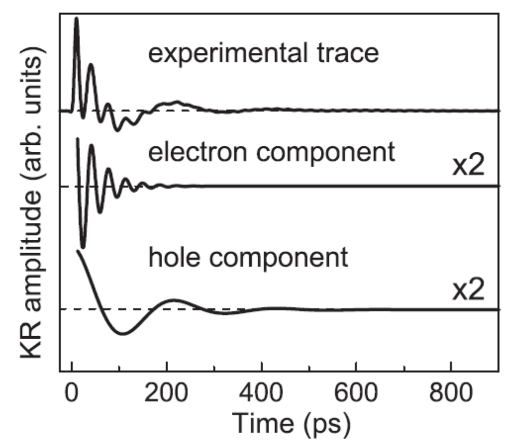
TRKR for resonant excitation

In-plane magnetic field



1. **Resident holes** with random spin orientation - no spin polarization
2. **Pump pulse (σ^+)** creates optically oriented **electron-hole** pairs
3. **Precession** and **recombination**: electron g-factor much bigger than the hole one, electrons recombine with resident holes
4. At the arrival of **probe pulse** spin polarization in the system

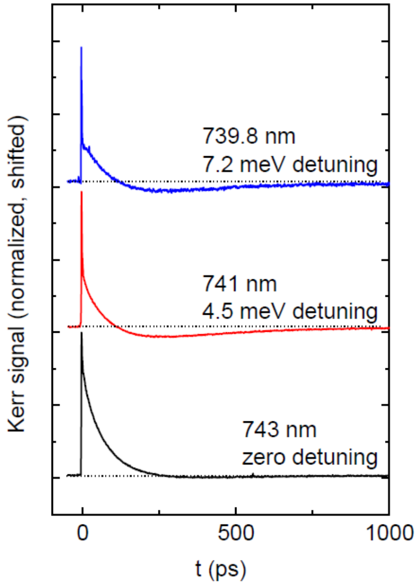
Note: During evolution electron and hole spins also undergo decoherence processes (not shown in the picture)



M. Syperek, D. R. Yakovlev, A. Greilich, J. Misiewicz, M. Bayer, D. Reuter,A. D. Wieck,Phys. Rev. Lett. **99,** 187401 (2007)

Kerr signal for non-resonant excitation

No magnetic field



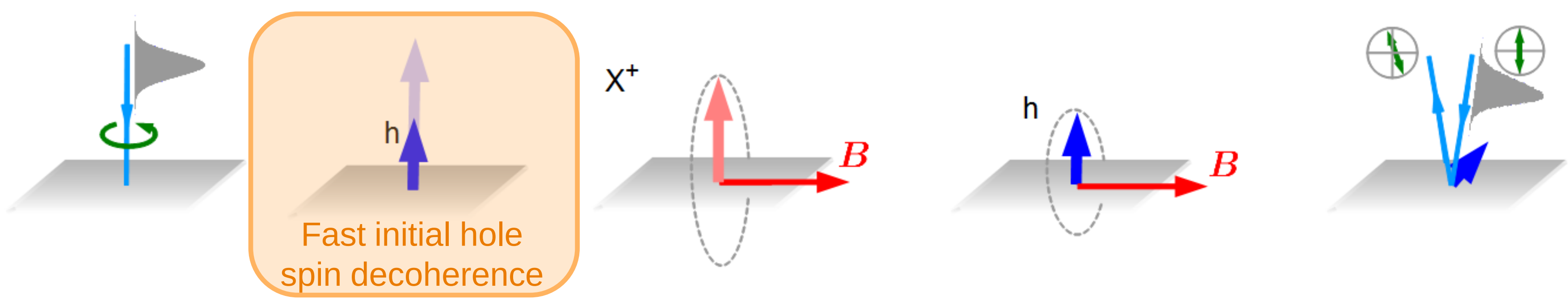
- Different pump pulse part of the hamiltonian for non-resonant excitation:

$$H_p(t) = \frac{1}{2} f(t)(|\uparrow\rangle \langle T\uparrow| e^{i\Delta t} + |T\uparrow\rangle \langle\uparrow| e^{-i\Delta t})$$

- Transformation of the density matrix by the pump pulse calculated perturbatively:

$$\rho_{fin} = \rho_0 - \frac{i}{\hbar}\int_{-\infty}^{\infty} dt[H_p(t), \rho_0] - \frac{1}{\hbar^2}\int_{-\infty}^{\infty} dt \int_{-\infty}^{t} dt' [H_p(t), [H_p(t'), \rho_0]] + \dots$$

- In the low-power limit detuning does not directly contribute to the Kerr signal. We therefore propose that the role of the detuning is to provide excess energy that increases the initial dephasing.



Kerr signal for non-resonant excitation

- Fast initial hole spin decoherence is described by two parameters:
  - *u* - decoherence rate (instantous) for longitudal component
  - *u/2+w* - decoherence rate for transverse components

- Kerr signal in the absence of magnetic field:

$$\Delta\Sigma = ae^{-\gamma_{\mathrm{t}} t} - be^{-\gamma_{\mathrm{h}} t} \quad ; \quad a = \left[1 + \frac{\gamma_{\mathrm{R}}}{\gamma_{\mathrm{t}} - \gamma_{\mathrm{h}}}\right] \Sigma_{\mathrm{t}}^{(0)}, \quad b = \left[\Sigma_{\mathrm{h}}^{(0)} + \frac{\gamma_{\mathrm{R}}}{\gamma_{\mathrm{t}} - \gamma_{\mathrm{h}}} \Sigma_{\mathrm{t}}^{(0)}\right]$$

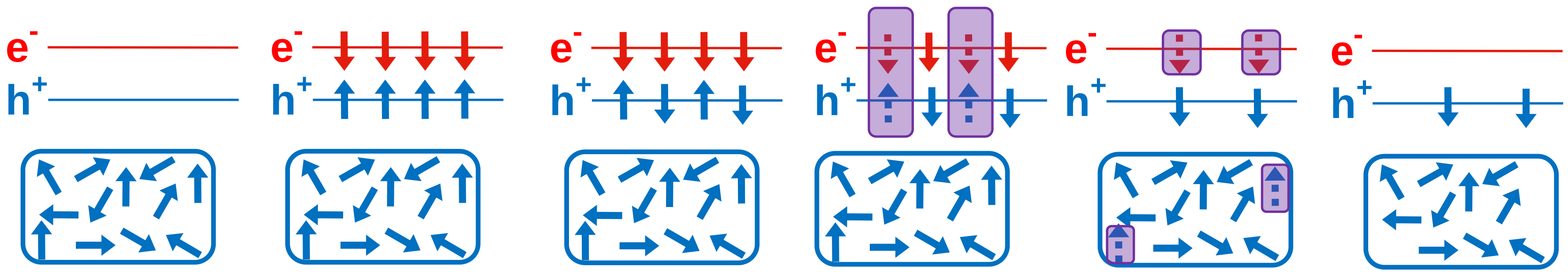
$\Sigma_{\mathrm{h}}^{(0)}$ - Initial (after the fast decoherence) hole spin polarization

$\Sigma_{\mathrm{t}}^{(0)}$ - Initial trion spin polarization

γ_h - Hole spin dephasing rate

γ_{t} - Sum of the trion spin decoherence rate and the radiative decay rate: $\gamma_{\mathrm{t}} = \mu + \gamma_{\mathrm{R}}$

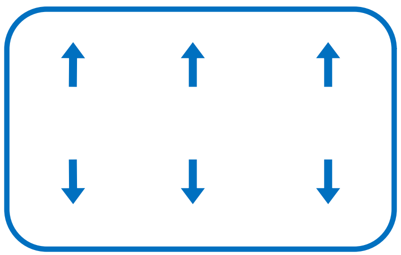
- Mechanism of the negative spin polarization buildup:



Kerr signal for non-resonant excitation

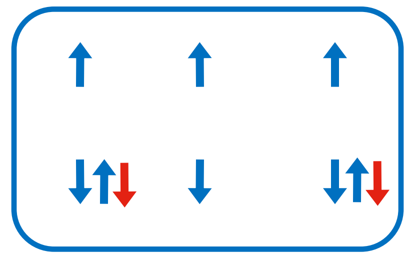
- More precise description of mechanism of the negative spin polarization buildup including trions:

1.



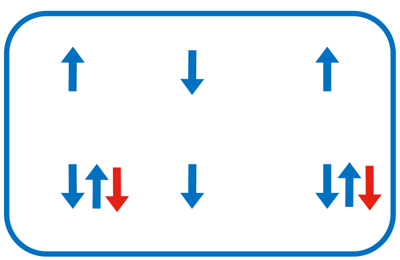
Resident holes with random spin orientation

2.



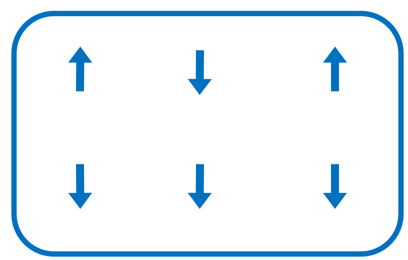
Pump pulse (σ^+) creates trions according to selection rules and Pauli exclusion principle

3.



Fast initial decoherence of resident holes

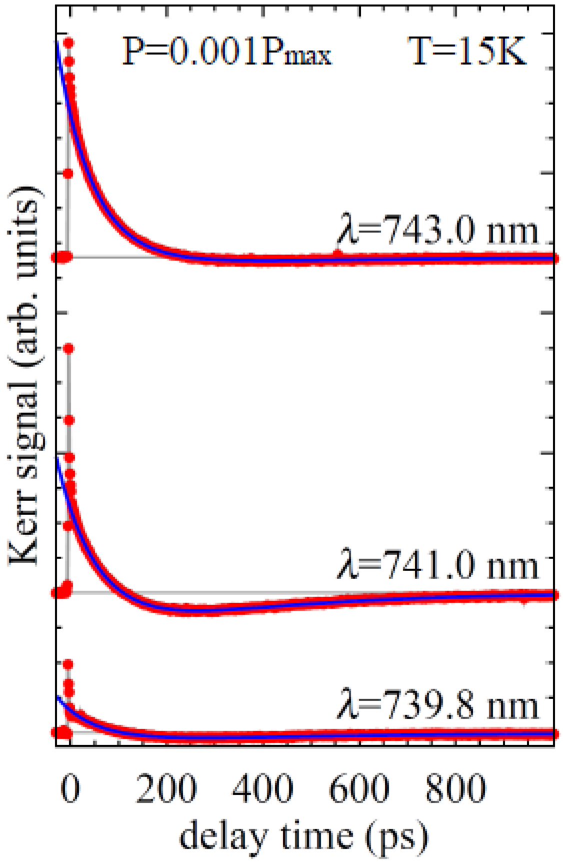
4.



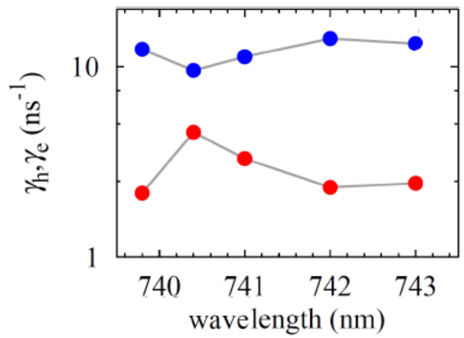
Spin polarization left in the system after recombination

Kerr signal for non-resonant excitation - results

Fitting to the experimental results for Kerr rotation

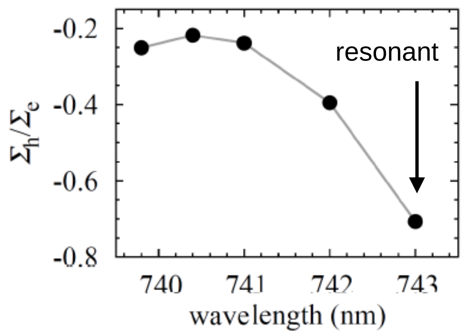


Dependence of decay rates



One of the decay rates (blue) is close to the recombination rate, so we link it with the trion and the red one is connected with the hole.

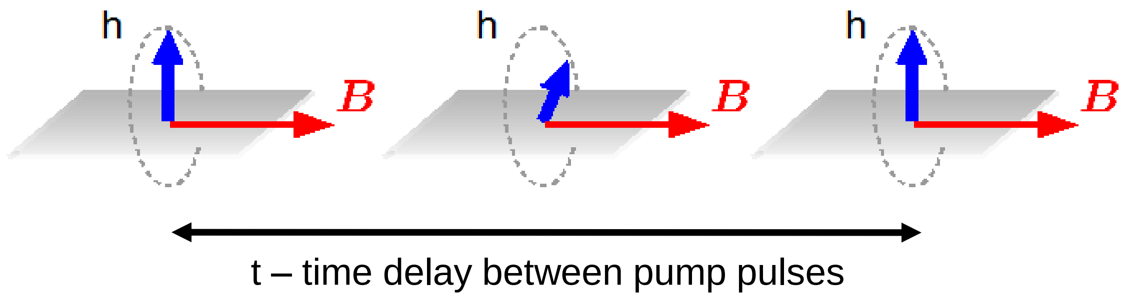
The ration of the hole-to-trion spin polarization just after the fast initial decay



The absolute value of the ratio drops down for more detuned pulses, which leads to a negative total spin polarization

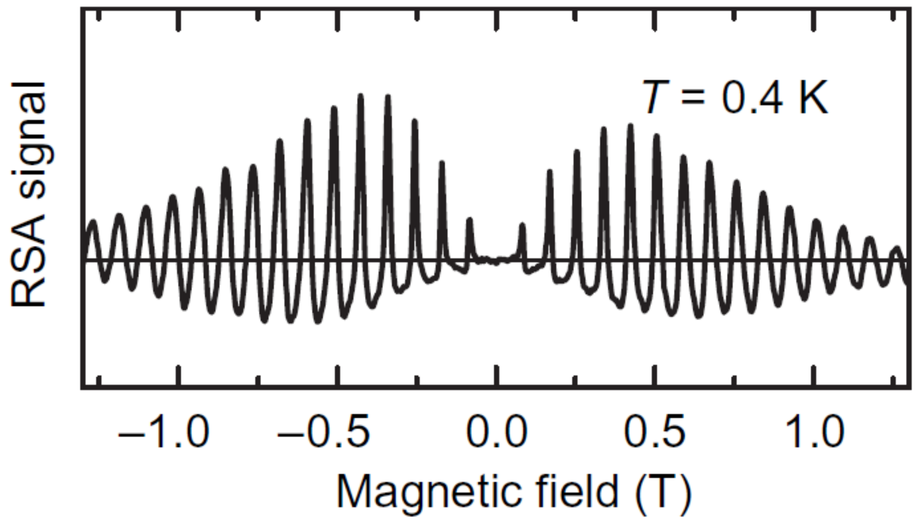
RSA experiment

RSA is based on the constructive interference of spin polarizations created by subsequent laser pulses in a time-resolved Kerr rotation measurement:



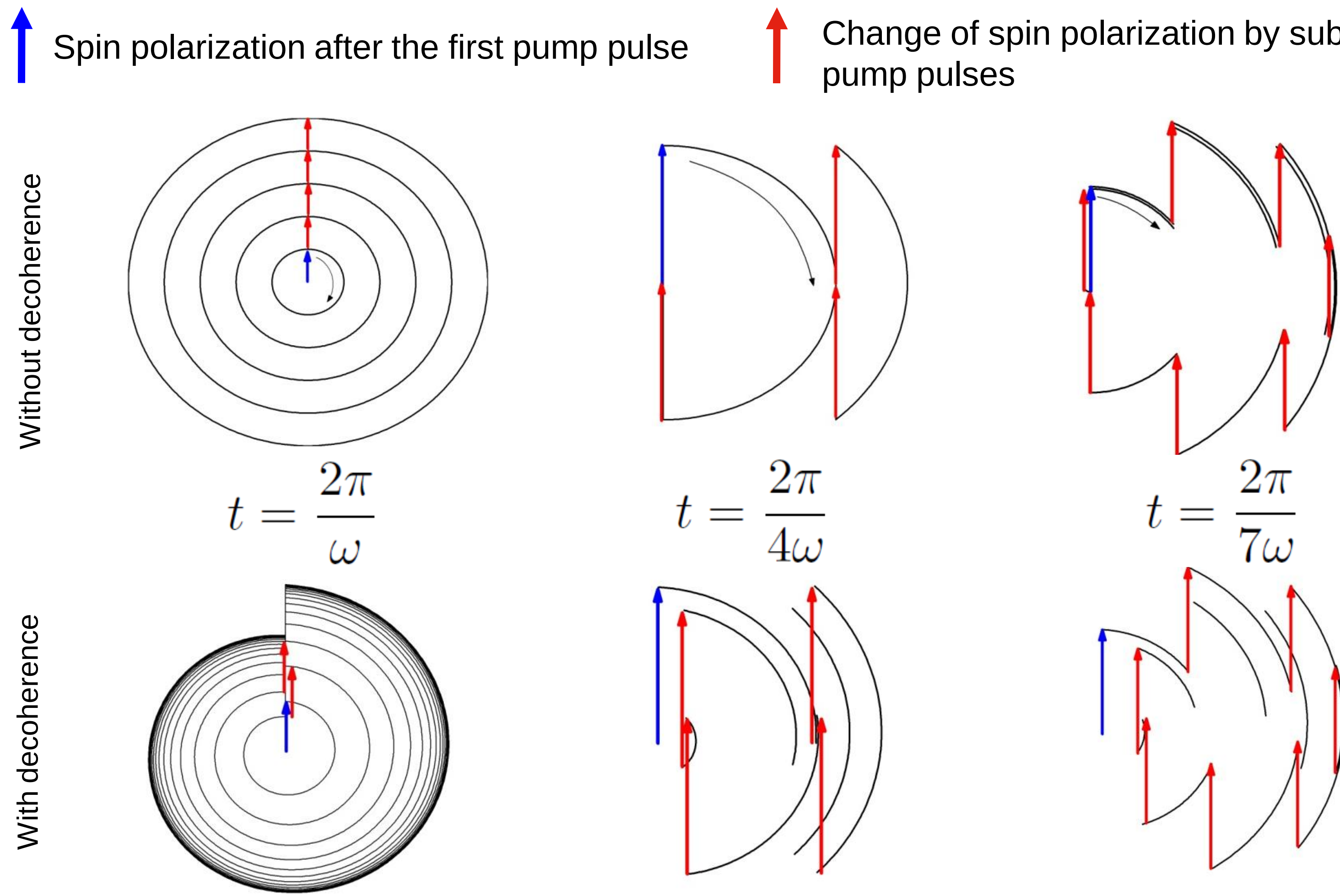
Maxima observed for:

$$2\pi n = \omega t$$

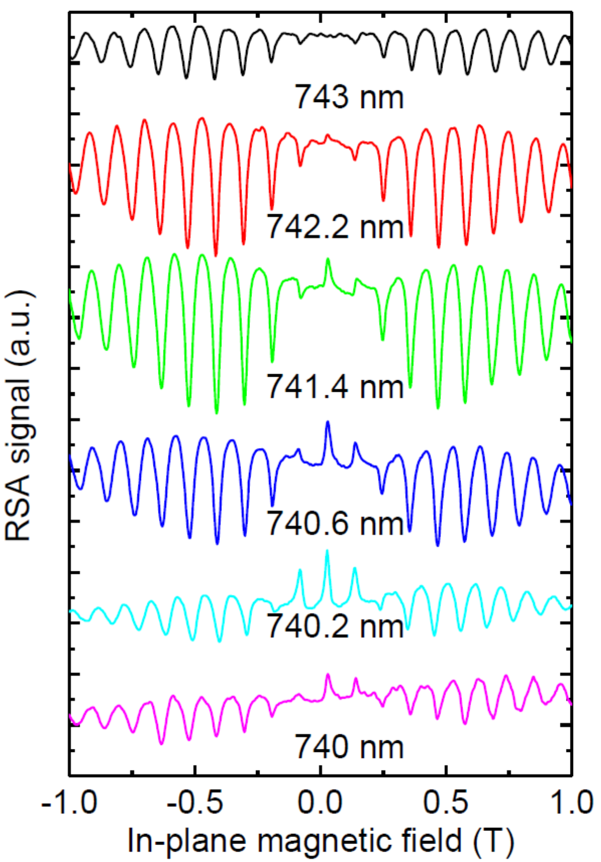


The spacing of the maxima yields the g-factor and the spin dephasing time can be determined from the their half-width

Formation of RSA signal



RSA for non-resonant excitation



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

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

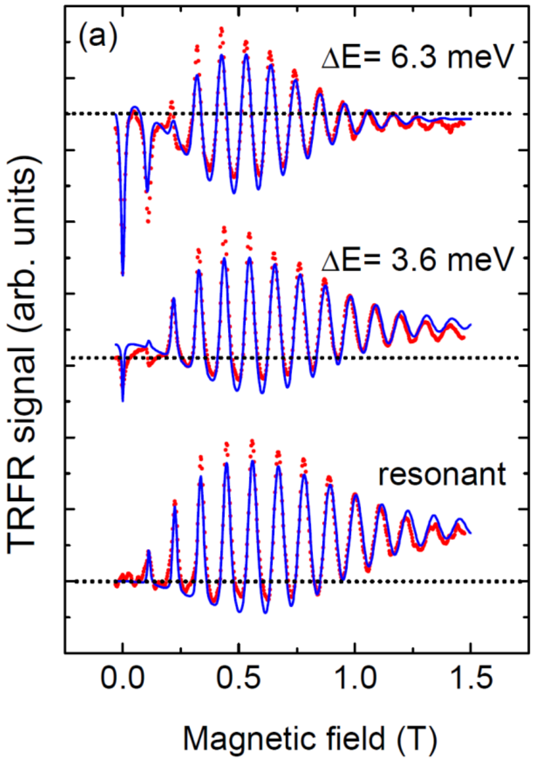
- We simplify our expressions by assuming that the trion radiative decay rate is much larger than the hole spin dephasing rates and get:

$$\Delta\Sigma^{(\mathrm{RSA})} \sim f\frac{P}{Q}, \quad f = 1 - e^{-u} - \frac{\omega_{\mathrm{t}}^2}{\gamma_{\mathrm{R}}^2 + \omega_{\mathrm{t}}^2}$$

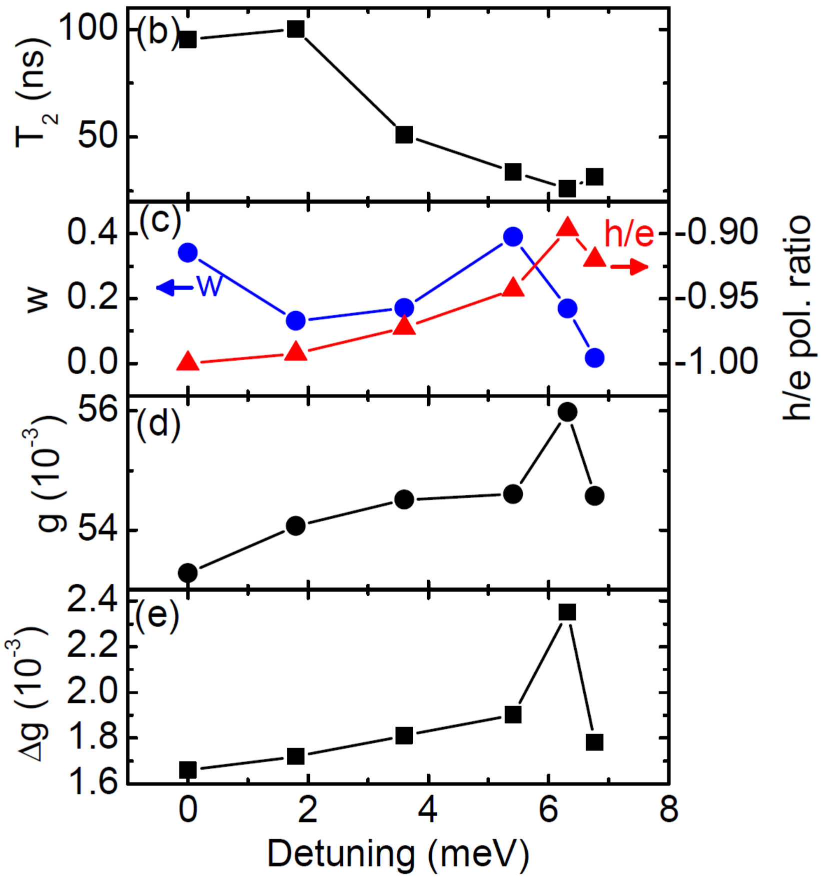
- We also include the inhomogenous broadening of the hole g-factors (gaussian distribution)

RSA - results

Experimental RSA traces and best fits for selected values of the detuning



Parameter values extracted from the fitting



Conclusions

- The Kerr signal decay in the absence of magnetic field consists of two parts: trion radiative decay and hole spin decoherence
- The negative Kerr signal observed in the experiment for nonresonant excitation is linked to the ratio of the hole-to-trion polarization after the fast initial decay
- The initial hole-trion spin imbalance (due to fast decoherence) may lead to the formation of the zero-field peak in RSA signal
- Detuning does not directly contribute to the RSA signal. Its role in the appearance of the zero-field peak may be to provide excess energy that increases the initial dephasing
- arXiv:1105.1338v1 [cond-mat.mes-hall]

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