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Decoherence-driven mechanism for initialization of hole spins in a p-doped semiconductor quantum well

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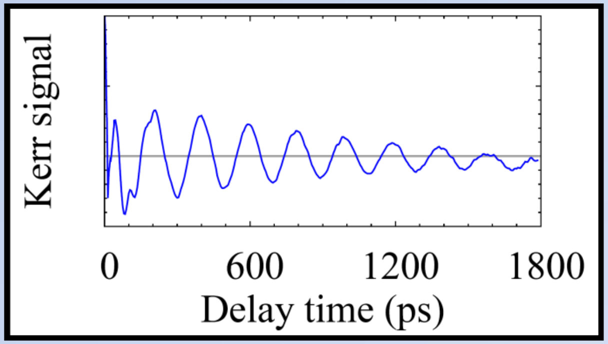
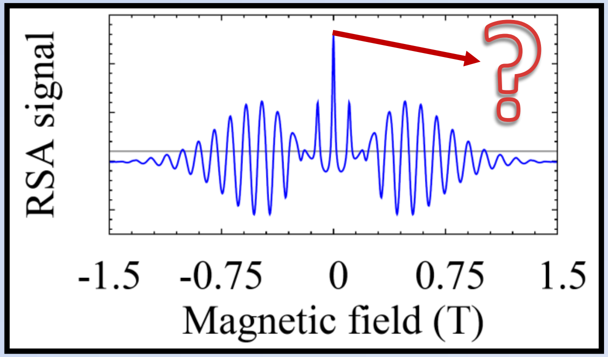
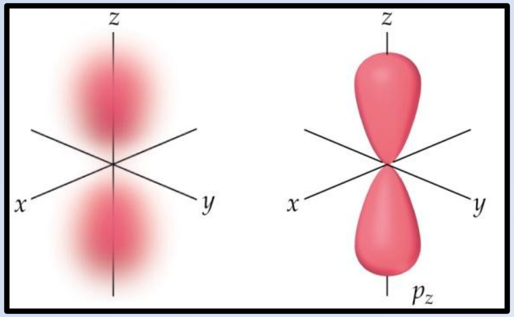
Contents

Motivation

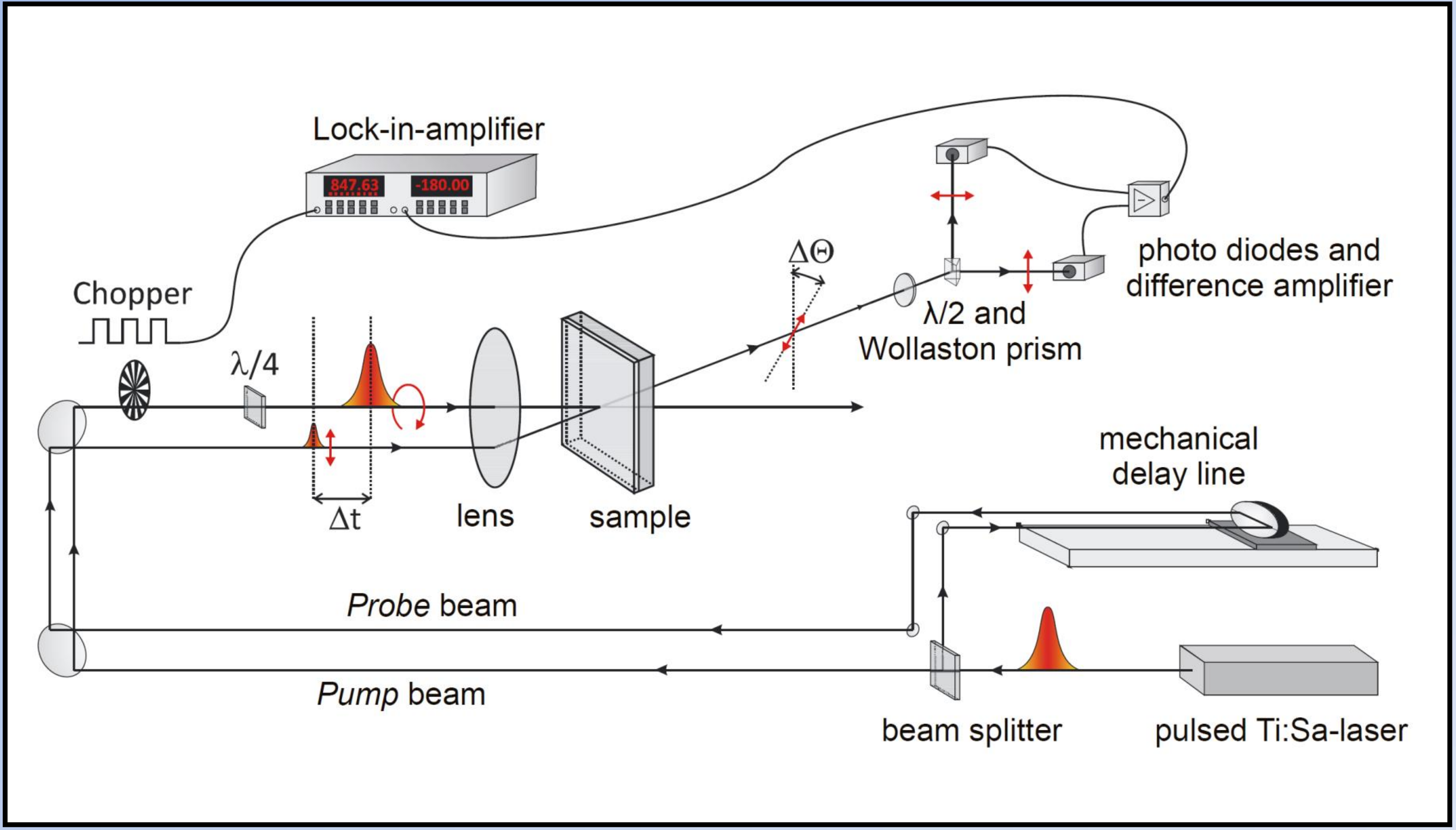
- Spin dynamics and coherence is crucial for many applications in emerging technologies (spintronics)
- Time–resolved Kerr rotation is a very efficient method for the investigation of spin dynamics; interesting experiments have been performed quite recently
- Resonant spin amplification signal shows interesting 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)







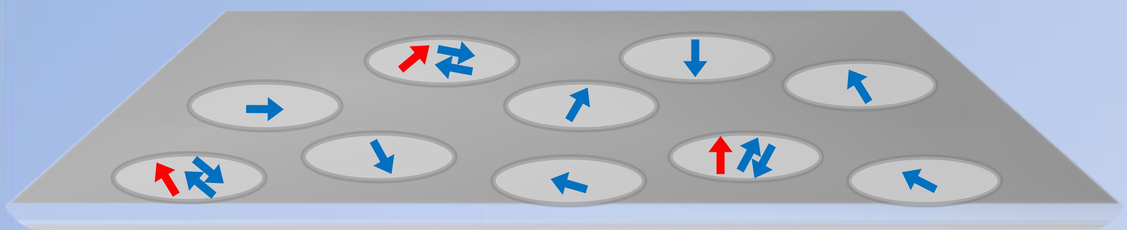
Experiment



Sample:

Single-side p-modulation-doped $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well, width: 4 nm, hole density: $1.1 \times 10^{11}\ cm^{-2}$, mobility: $1.3 \times 10^{4}\ cm^{2}/Vs$

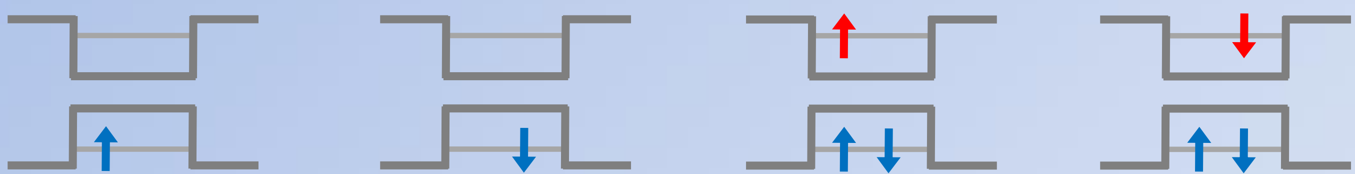
Model



Selection rules for σ^+ pump pulse

$|\downarrow\rangle \longleftrightarrow |\mathrm{T}\downarrow\rangle \qquad |\uparrow\rangle \not\longleftrightarrow |\mathrm{T}\downarrow\rangle$

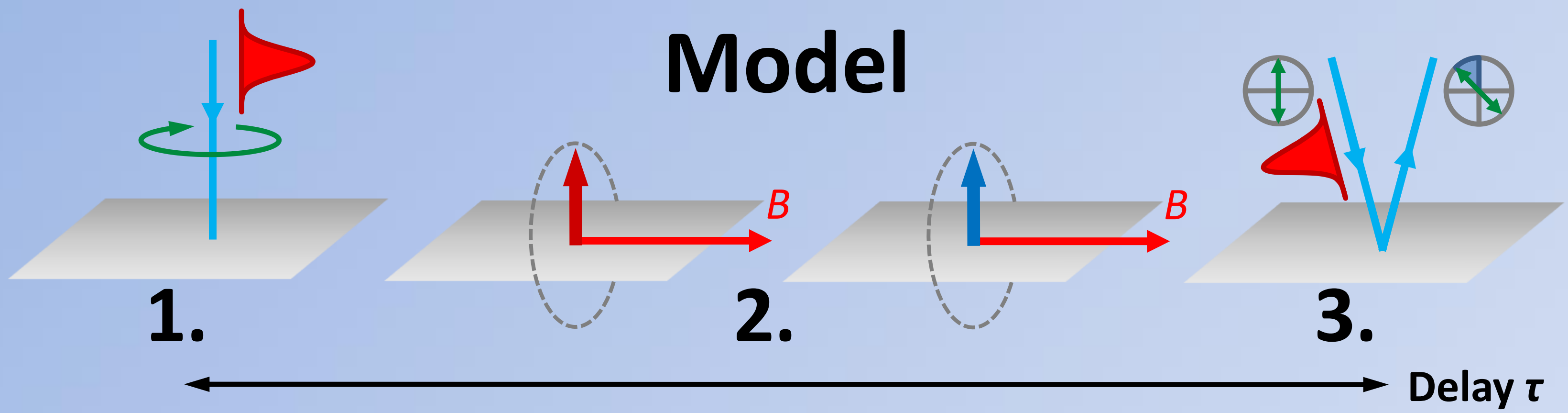
Hole states | Trion states



$|\uparrow\rangle \qquad |\downarrow\rangle \qquad |\mathrm{T}\uparrow\rangle \qquad |\mathrm{T}\downarrow\rangle$

$$\rho(t) = \begin{pmatrix} \frac{1-N_\mathrm{t}(t)+\Sigma_\mathrm{h}(t)}{2} & \frac{1}{2}X_\mathrm{h}(t) - \frac{i}{2}Y_\mathrm{h}(t) & 0 & 0 \\ \frac{1}{2}X_\mathrm{h}(t) + \frac{i}{2}Y_\mathrm{h}(t) & \frac{1-N_\mathrm{t}(t)-\Sigma_\mathrm{h}(t)}{2} & 0 & 0 \\ 0 & 0 & \frac{N_\mathrm{t}(t)+\Sigma_\mathrm{t}(t)}{2} & \frac{1}{2}X_\mathrm{t}(t) - \frac{i}{2}Y_\mathrm{t}(t) \\ 0 & 0 & \frac{1}{2}X_\mathrm{t}(t) + \frac{i}{2}Y_\mathrm{t}(t) & \frac{N_\mathrm{t}(t)-\Sigma_\mathrm{t}(t)}{2} \end{pmatrix}$$

Model



1. The electric field couples to the interband transitions via a dipole moment:

$$\boxed{H_{\mathrm{p}} = \frac{1}{2} f(t) e^{i\Delta t - i\psi} |\uparrow\rangle\langle T\uparrow| + \mathrm{H.c.}}$$

$$\boxed{f(t) = -\boldsymbol{d}\cdot\boldsymbol{\mathcal{E}}_0^*(1+r)\eta\,(t/\tau_{\mathrm{p}})}$$

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

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

$$\boxed{H_0 = -\frac{1}{2}\mu_{\mathrm{B}}\boldsymbol{B}\hat{g}_{\mathrm{h}}\boldsymbol{\sigma}_{\mathrm{h}} - \frac{1}{2}g_{\mathrm{t}}\mu_{\mathrm{B}}\boldsymbol{B}\cdot\boldsymbol{\sigma}_{\mathrm{t}}}$$

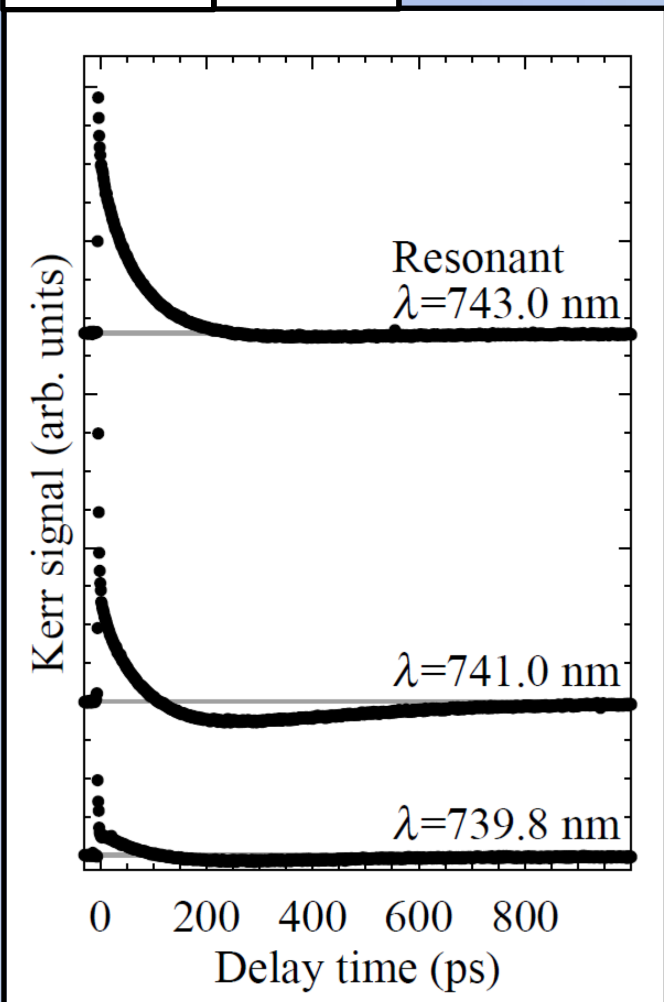
3. The optical response, that is, the rotation of the polarization plane of the reflected or transmitted probe pulse, is proportional to*:

$$\boxed{\mathrm{TRKR} = \Sigma_{\mathrm{t}} - \Sigma_{\mathrm{h}}}$$

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

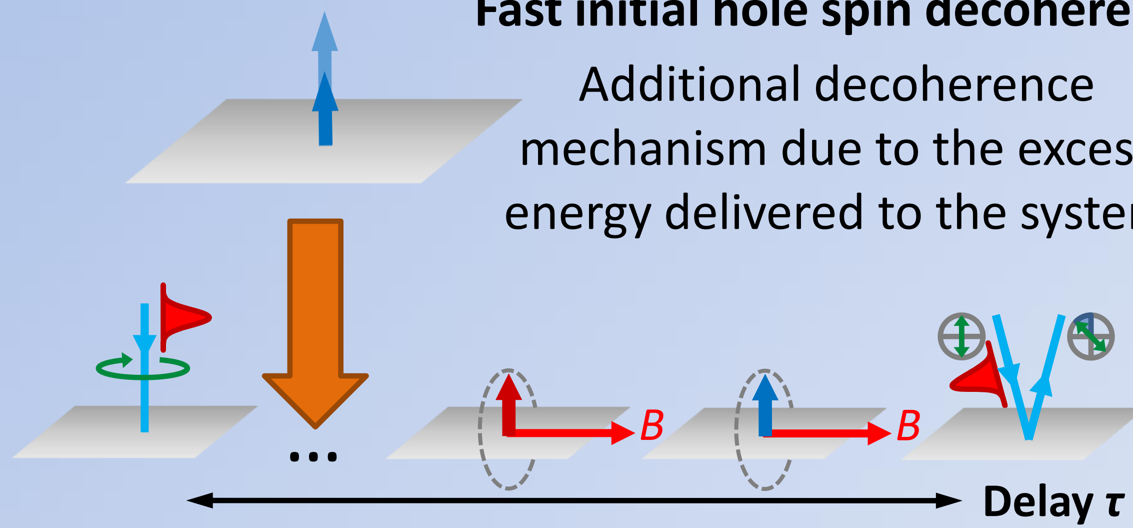
Kerr signal for non-resonant excitation

T = 15 K | B = 0 T



Fast initial hole spin decoherence

Additional decoherence mechanism due to the excess energy delivered to the system



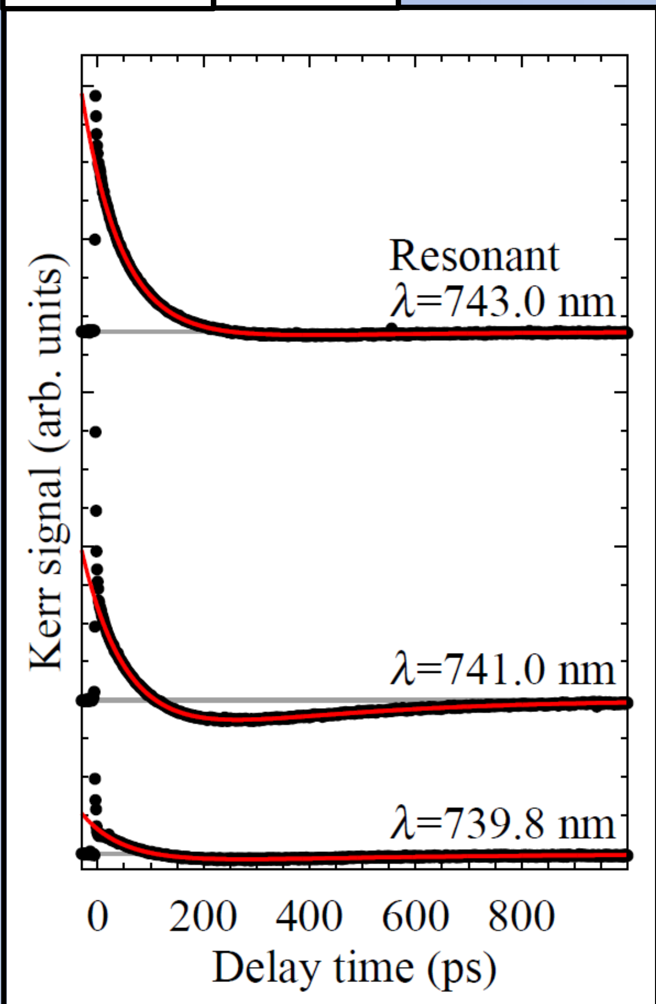
Described by occupation relaxation parameter *u* and pure dephasing parameter *w:*

$$
\begin{aligned}
\langle\downarrow|\rho_2|\uparrow\rangle &= \langle\downarrow|\rho_1|\uparrow\rangle e^{-u/2-w},\\
\langle\uparrow|\rho_2|\downarrow\rangle &= \langle\uparrow|\rho_1|\downarrow\rangle e^{-u/2-w},\\
\langle\uparrow|\rho_2|\uparrow\rangle &= \tfrac{1}{2}\langle\uparrow|\rho_1|\uparrow\rangle\left(1+e^{-u}\right)+\tfrac{1}{2}\langle\downarrow|\rho_1|\downarrow\rangle\left(1-e^{-u}\right),\\
\langle\downarrow|\rho_2|\downarrow\rangle &= \tfrac{1}{2}\langle\downarrow|\rho_1|\downarrow\rangle\left(1-e^{-u}\right)+\tfrac{1}{2}\langle\downarrow|\rho_1|\downarrow\rangle\left(1+e^{-u}\right).
\end{aligned}
$$

MoP60: ***Phonon-Assisted Dynamical Hole Spin Dephasing in p-doped Semiconductor Quantum Wells***

Kerr signal for non-resonant excitation

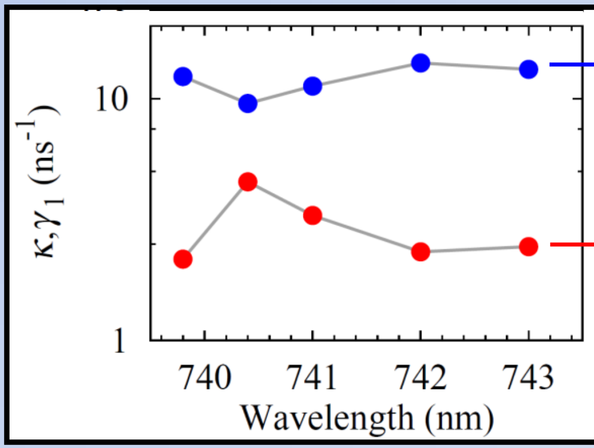
T = 15 K | B = 0 T



$$\mathrm{TRKR} = a e^{-\gamma_1 t} - b e^{-\kappa t}$$

$$a = \left(\frac{\gamma_1}{\gamma_1 - \kappa} + 1\right) \Sigma_{\mathrm{t}}^{(0)}$$

$$b = \left(\frac{\gamma_1}{\gamma_1 - \kappa} - e^{-u}\right) \Sigma_{\mathrm{t}}^{(0)}$$

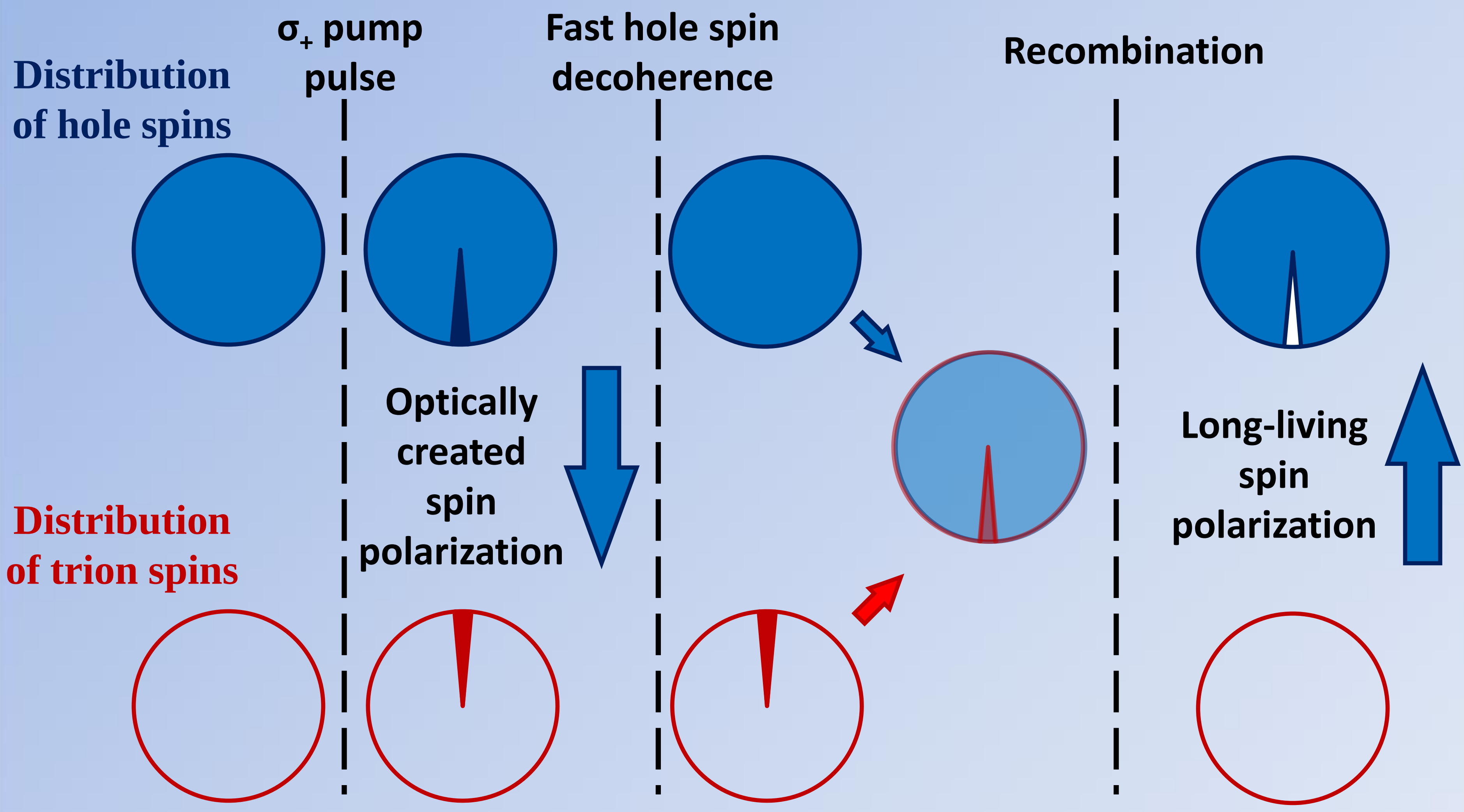


Hole spin decoherence rate

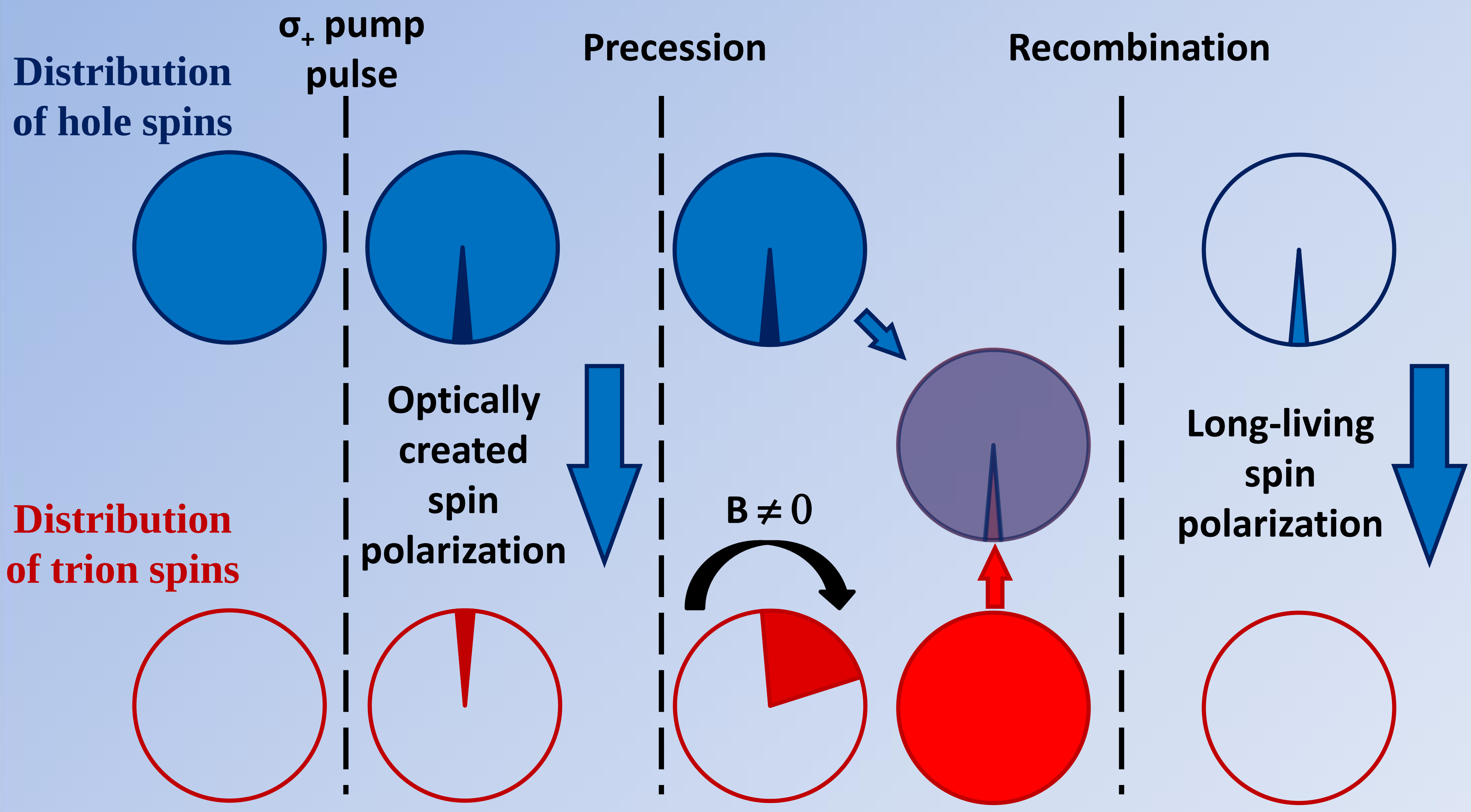
Recombination rate

Hole spin coherence time T_2 = **10 ns**

Decoherence-driven mechanism

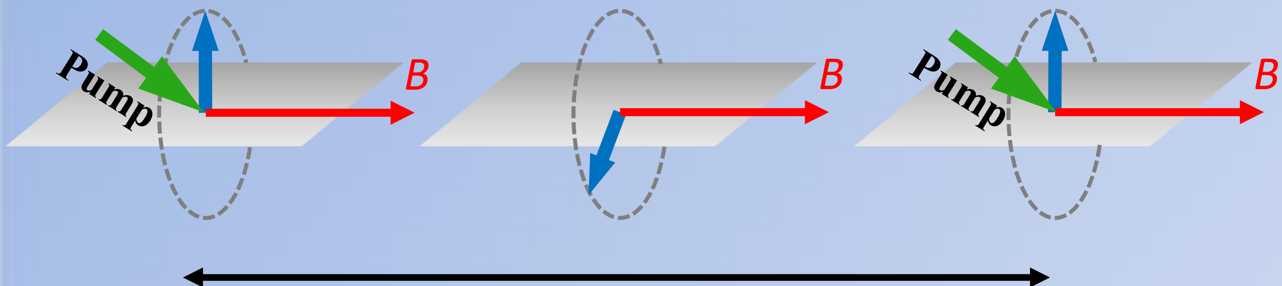


Precession-driven mechanism



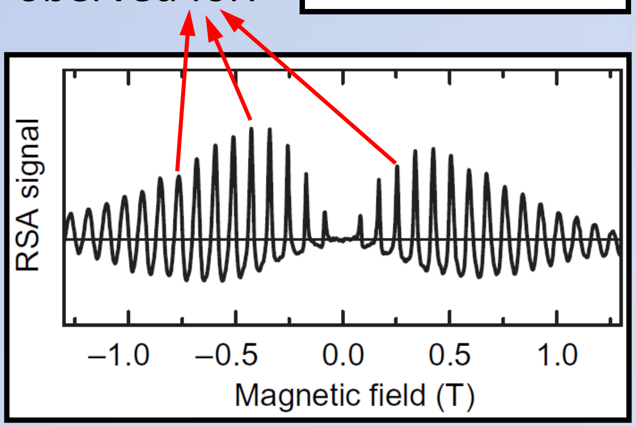
M.Syperek *et al.*, Phys.Rev.Lett. **99,** 187401(2007)

Resonant spin amplification

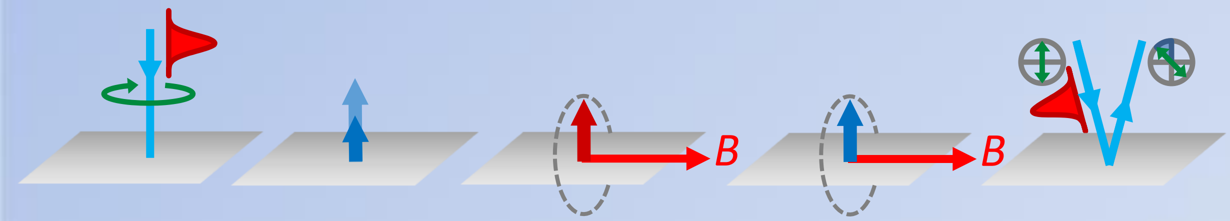


Pump pulse train with repetition time t_{rep}

Maxima oberved for: $\boxed{2\pi n = \Omega t_{rep}}$



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



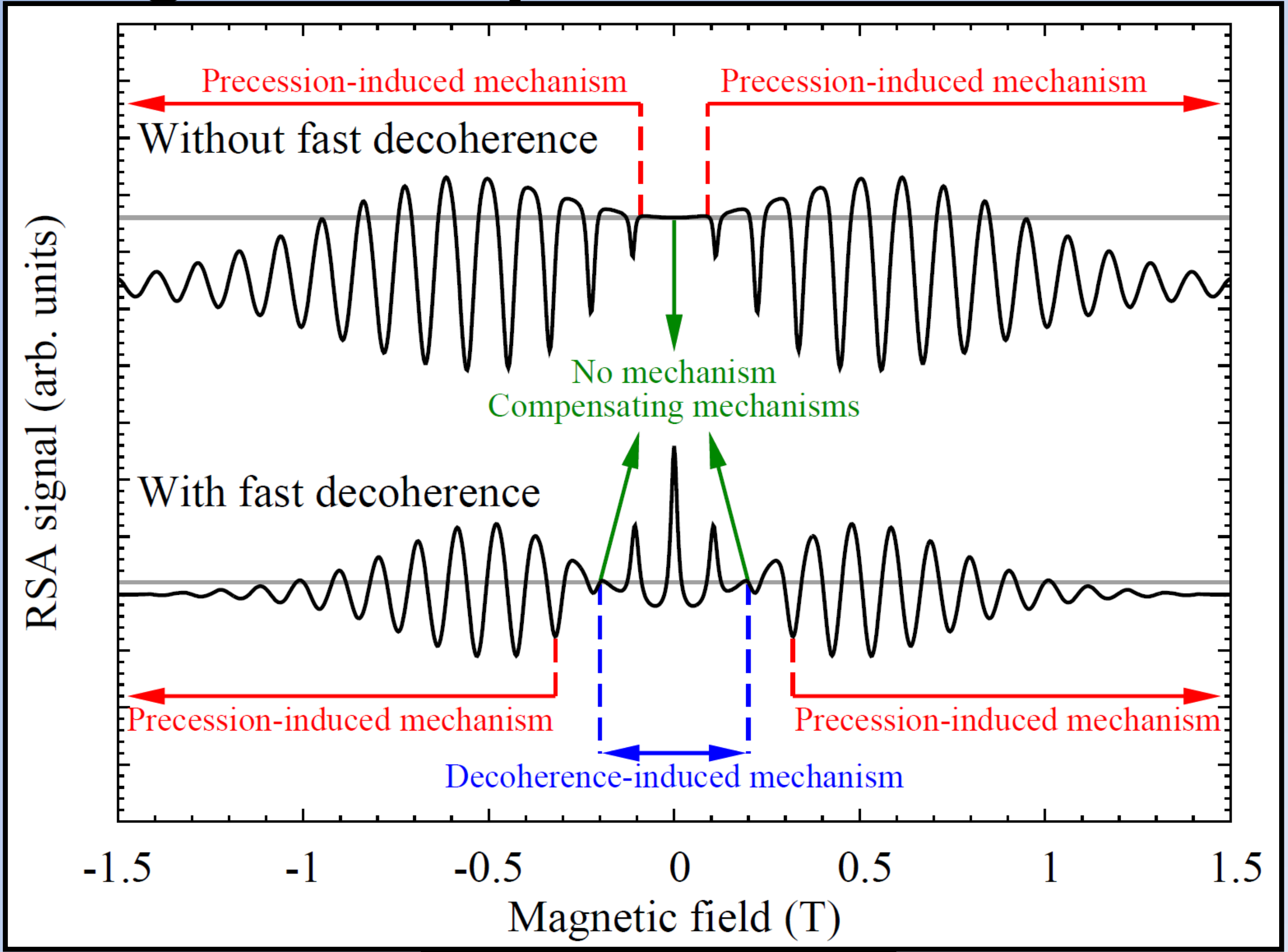
Response from an **inhomogeneous ensemble** of hole spins obtained by averaging the result according to a **Gaussian distribution** of hole g-factors

Analytical expression for RSA signal

$$\boxed{\mathrm{RSA} \sim f\frac{P}{Q}}$$

$$\boxed{f = 1 - e^{-u} - \frac{\omega_{\mathrm{t}}^2}{\gamma_{\mathrm{R}}^2 + \omega_{\mathrm{t}}^2}}$$

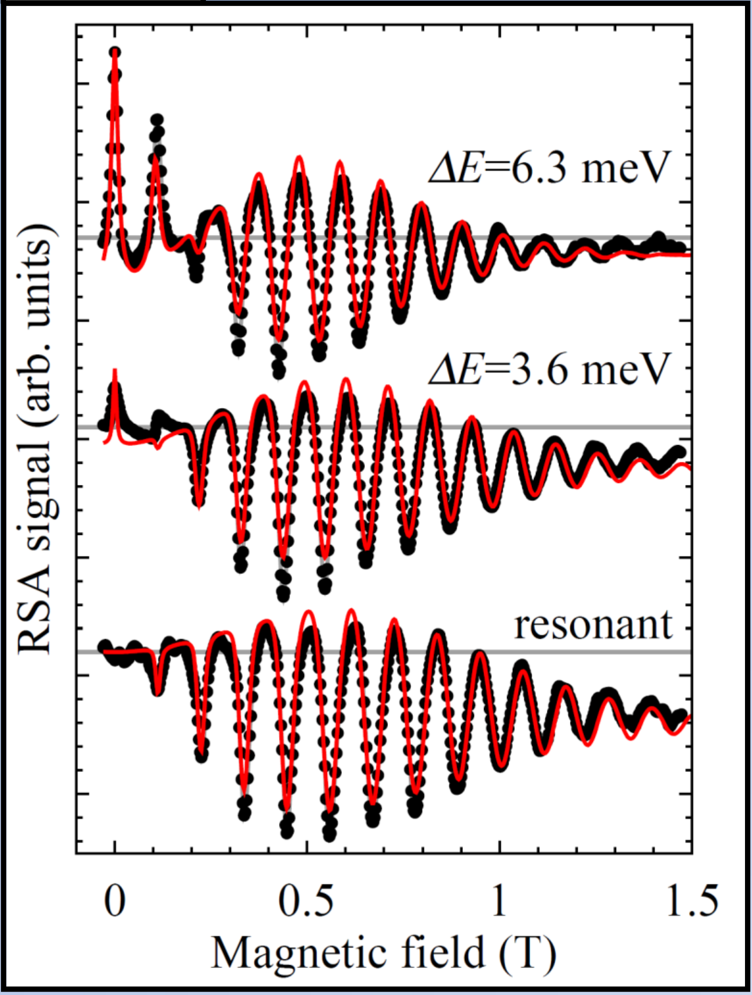
RSA signal: competition of mechanisms



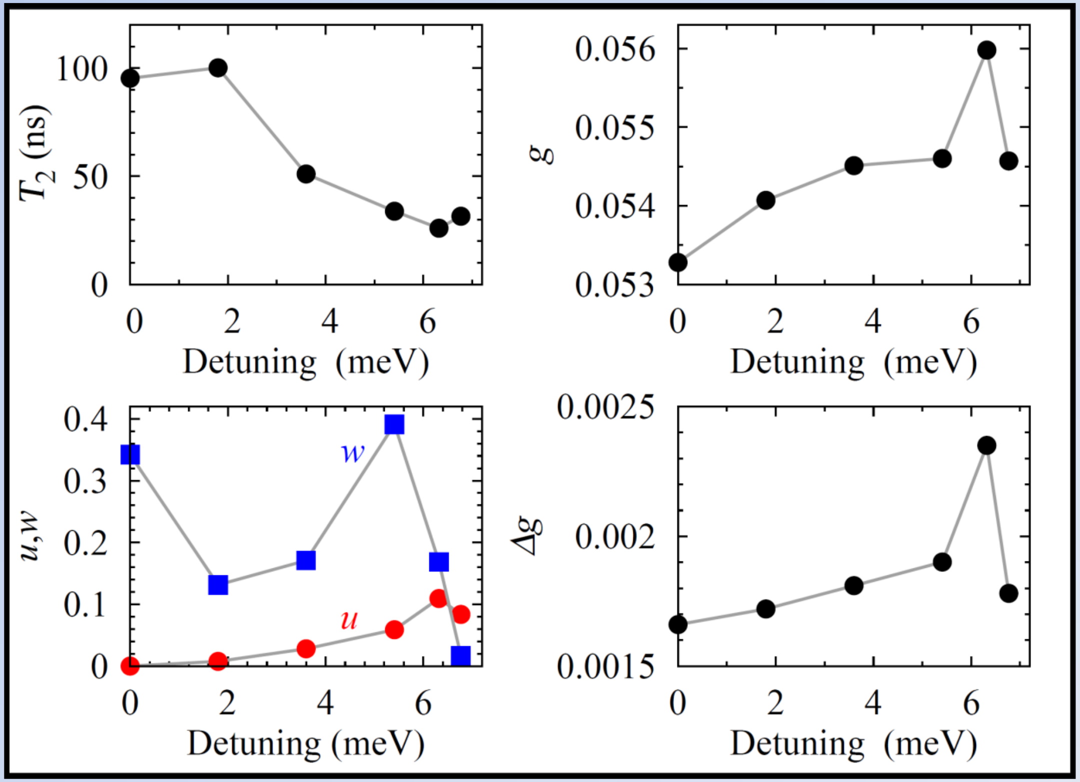
$$f = 1 - e^{-u} - \frac{\omega_{\mathrm{t}}^2}{\gamma_{\mathrm{R}}^2 + \omega_{\mathrm{t}}^2}$$

RSA for non-resonant excitation

T=1.2 K



Intrinsic hole spin coherence time
T_2 reaching **100 ns**



Conclusions

- 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
- 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
- It is possible to control the sign and magnitude of long-living spin polarization through the interplay of decoherence- and precession-induced mechanisms
- Hole spin coherence time in zero magnetic field (intrinsic) was experimentally observed to reach 100 ns

[Phys. Rev. B **84**, 085327 (2011)]

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