UNIVERSITÄT DORTMUND

Spin in semiconductor nanostructures

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Spin coherence of carriers in semiconductor quantum wells and quantum dots

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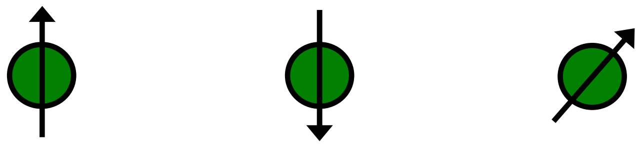
- **Introduction to carrier spin coherence**
- **Experimental techniques**
- **Spin coherence in quantum wells**
- **Spin coherence in quantum dots**
- **Mode-locking of spin coherences**

Motivation: Spin as a qu-bit

- classical information ⇒ bit: 0 or 1
- quantum information ⇒ quantum bit or 'qubit':

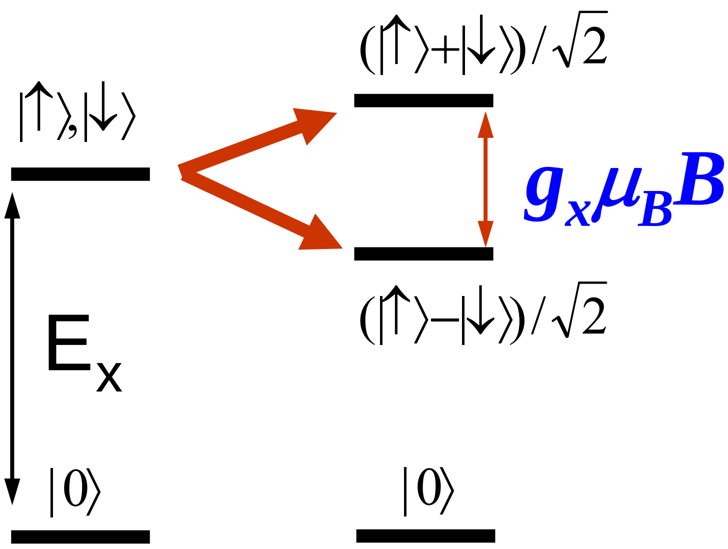
  0, 1 or superposition
- good candidate for 'qubit' is electron spin



$0 = |\uparrow\rangle$ $1 = |\downarrow\rangle$ $\alpha|\downarrow\rangle + \beta|\uparrow\rangle$

Loss and DiVincenzo PRA 57, 120 (1998)

electron spin in magnetic field

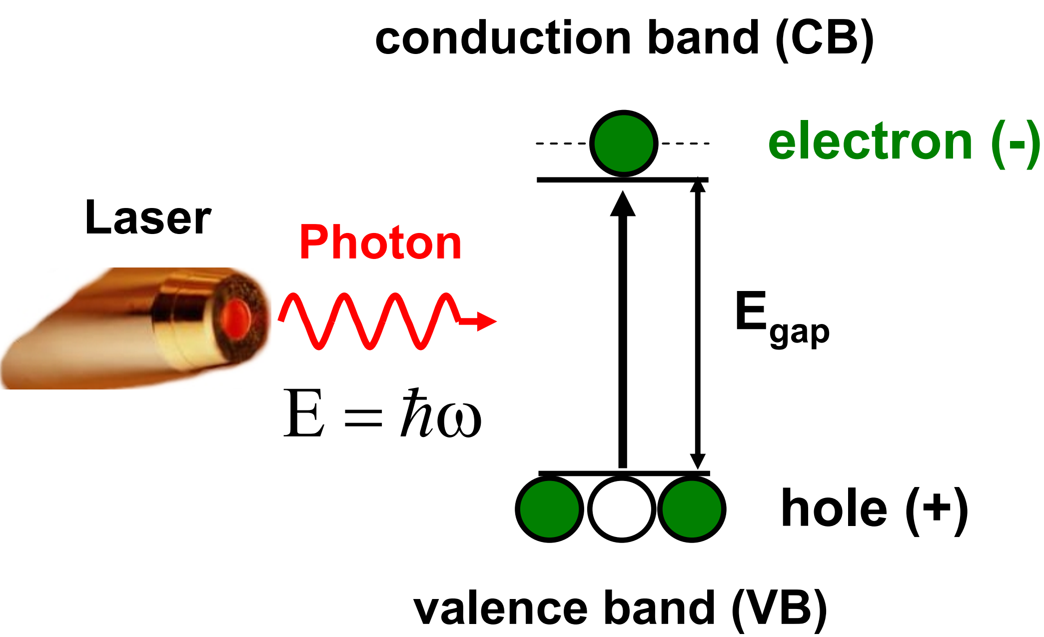


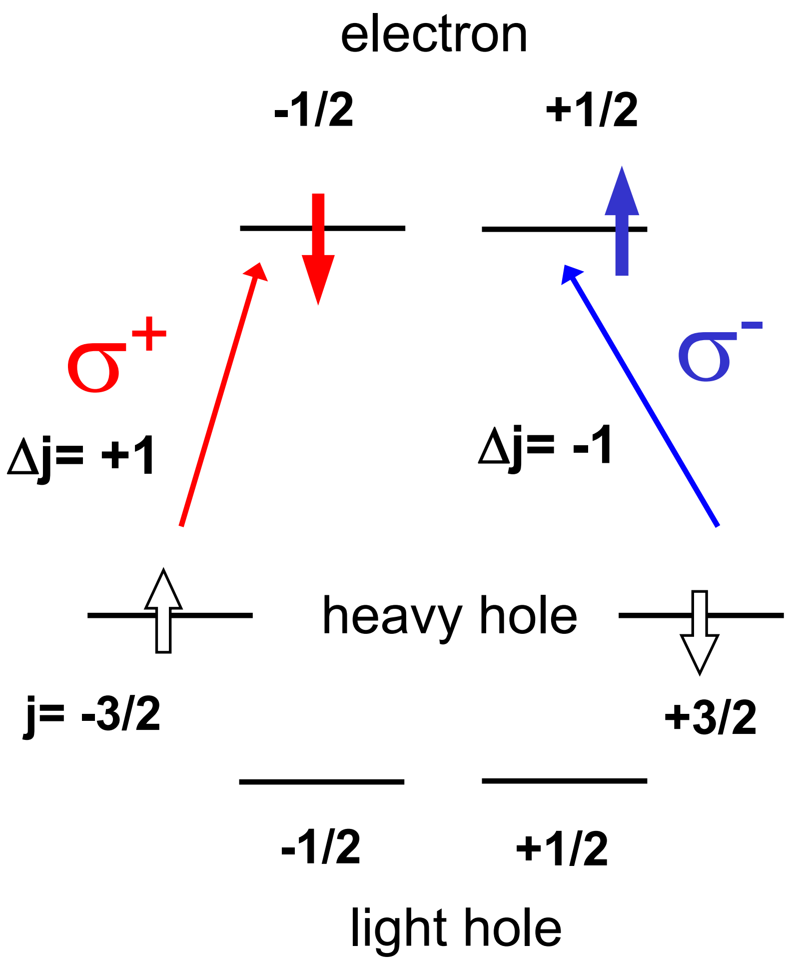
Goals:

- creation of spin
- readout of spin
- control of spin

Optical orientation of carrier spin

semiconductor energy gap, E_{gap}



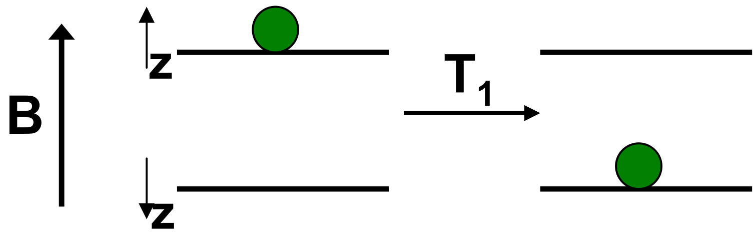


⇒ **electron spin is defined by laser polarization**

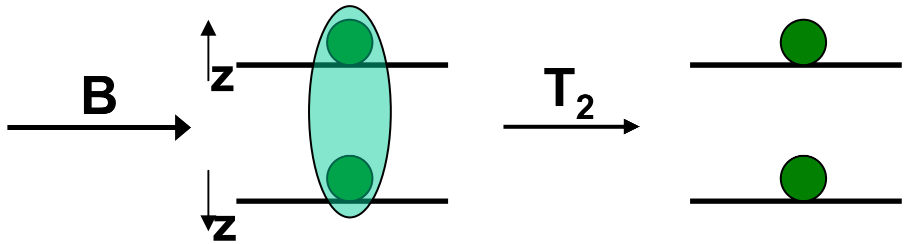
Spin relaxation times

times T_1 and T_2 (T_2^*) ?

energy relaxation, spin flip



loss of phase



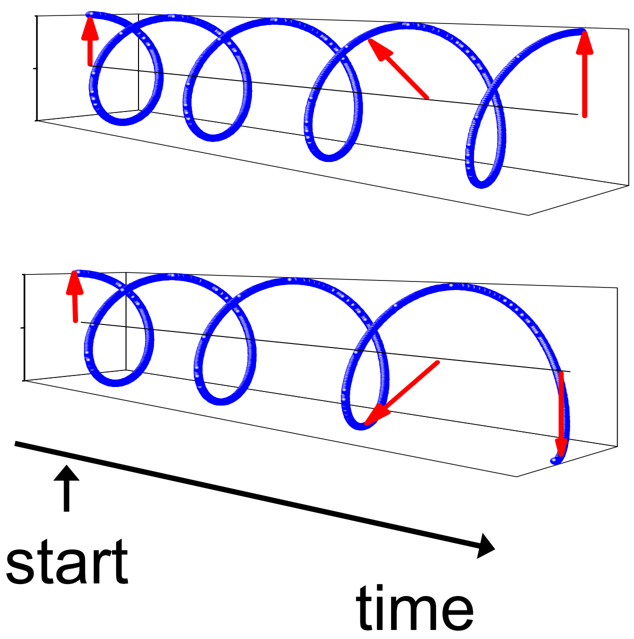
B > 0T

$$E = \hbar\omega = g_e \mu_B B$$

- **T_1 is the time it takes for longitudinal spin polarization to reach equilibrium; relaxation process requires energy transfer**

- **T_2 decoherence is a result of a loss of the phase relation between the two eigenstates; no energy transfer, no change in occupation (T_2^* is defined for ensemble)**

Lamor spin precession in magnetic field



$$\omega_L = \frac{\mu_B \, g \, B}{\hbar}$$

frequency dispersion

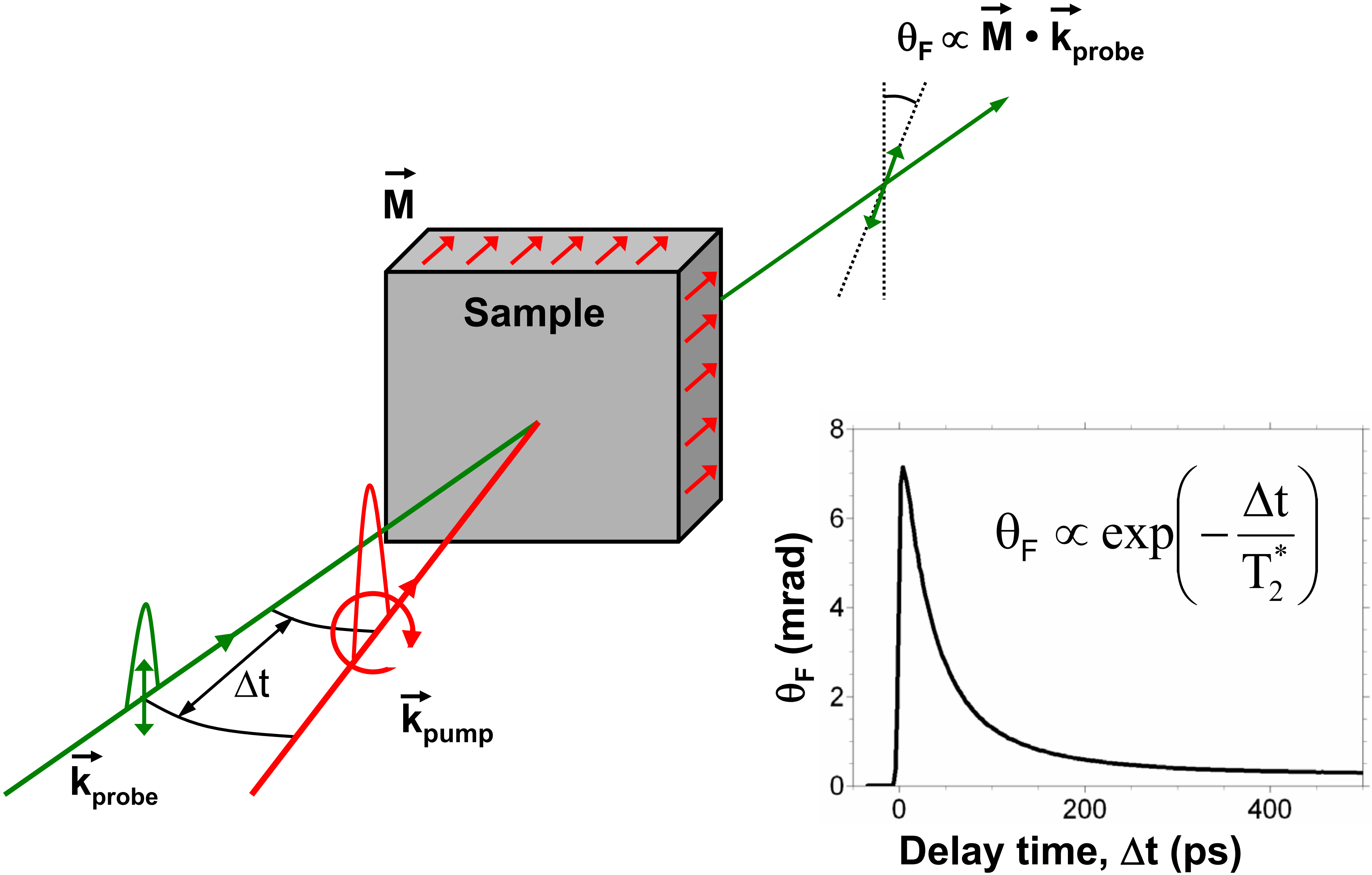
$$\Delta\omega_L = \frac{\mu_B \, \Delta g \, B}{\hbar}$$

Ensemble looses spin synhronisation much faster than

the coherence is lost by individual spins: $T_2^* \ll T_2$

Detection of spin dynamics

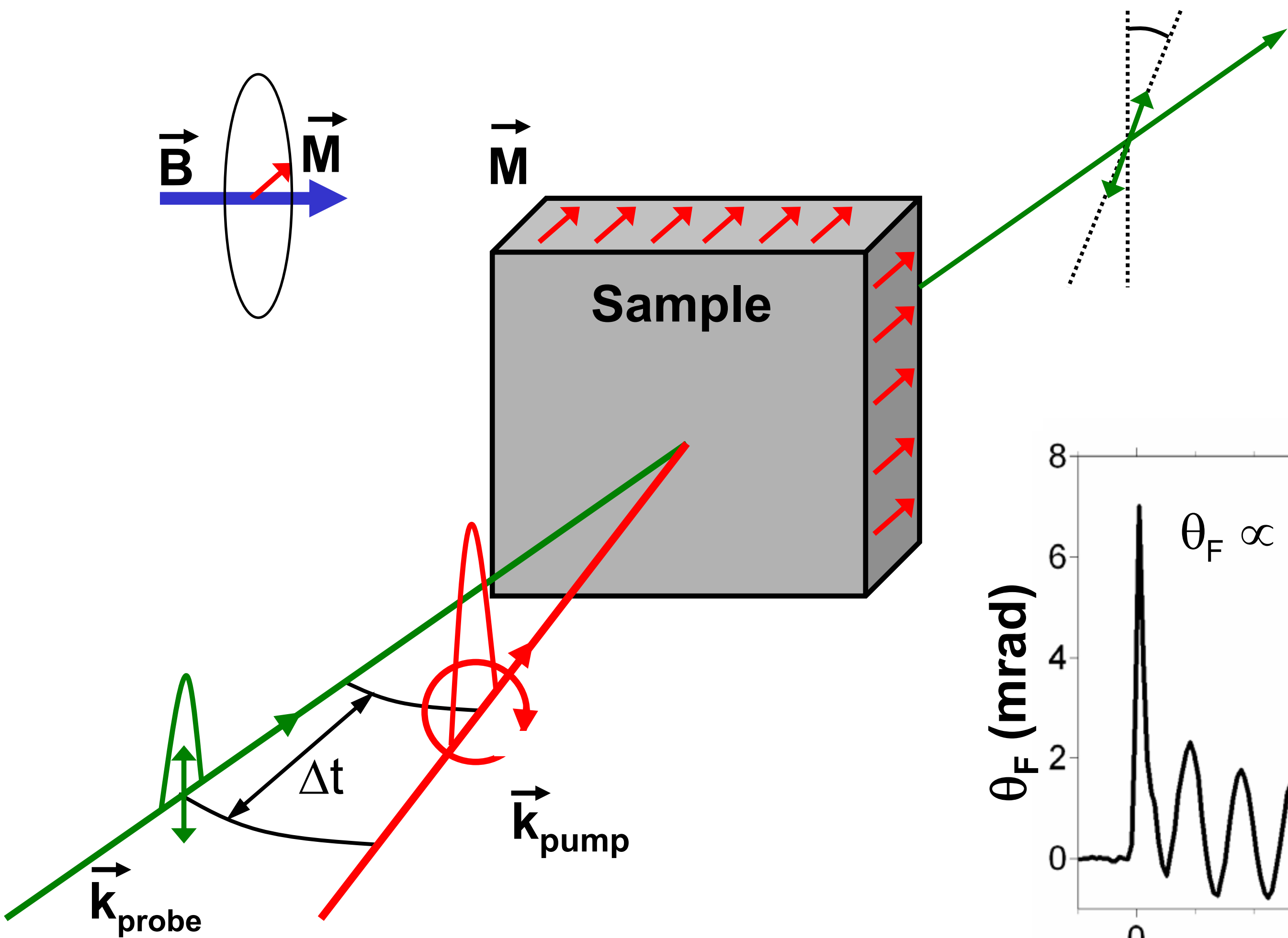
Pump - Probe Faraday rotation



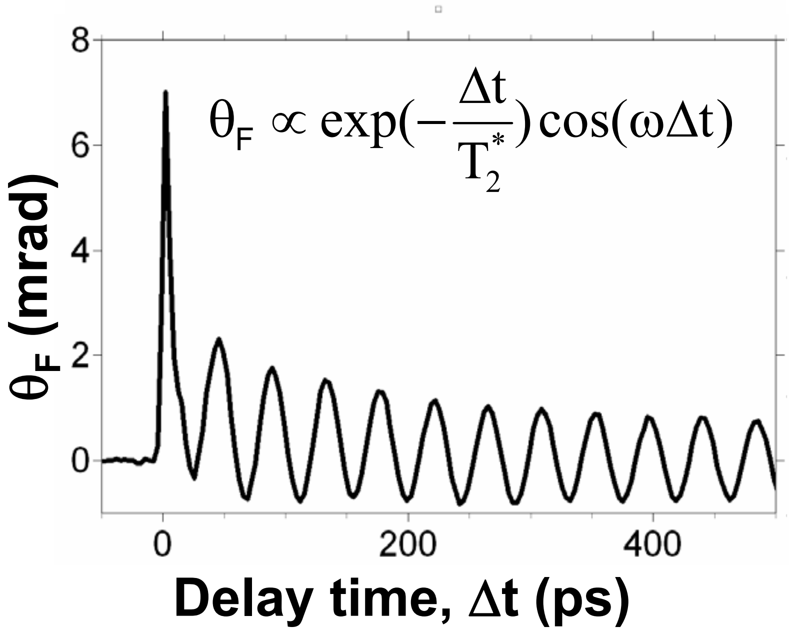
Detection of spin dynamics

Pump - Probe Faraday rotation

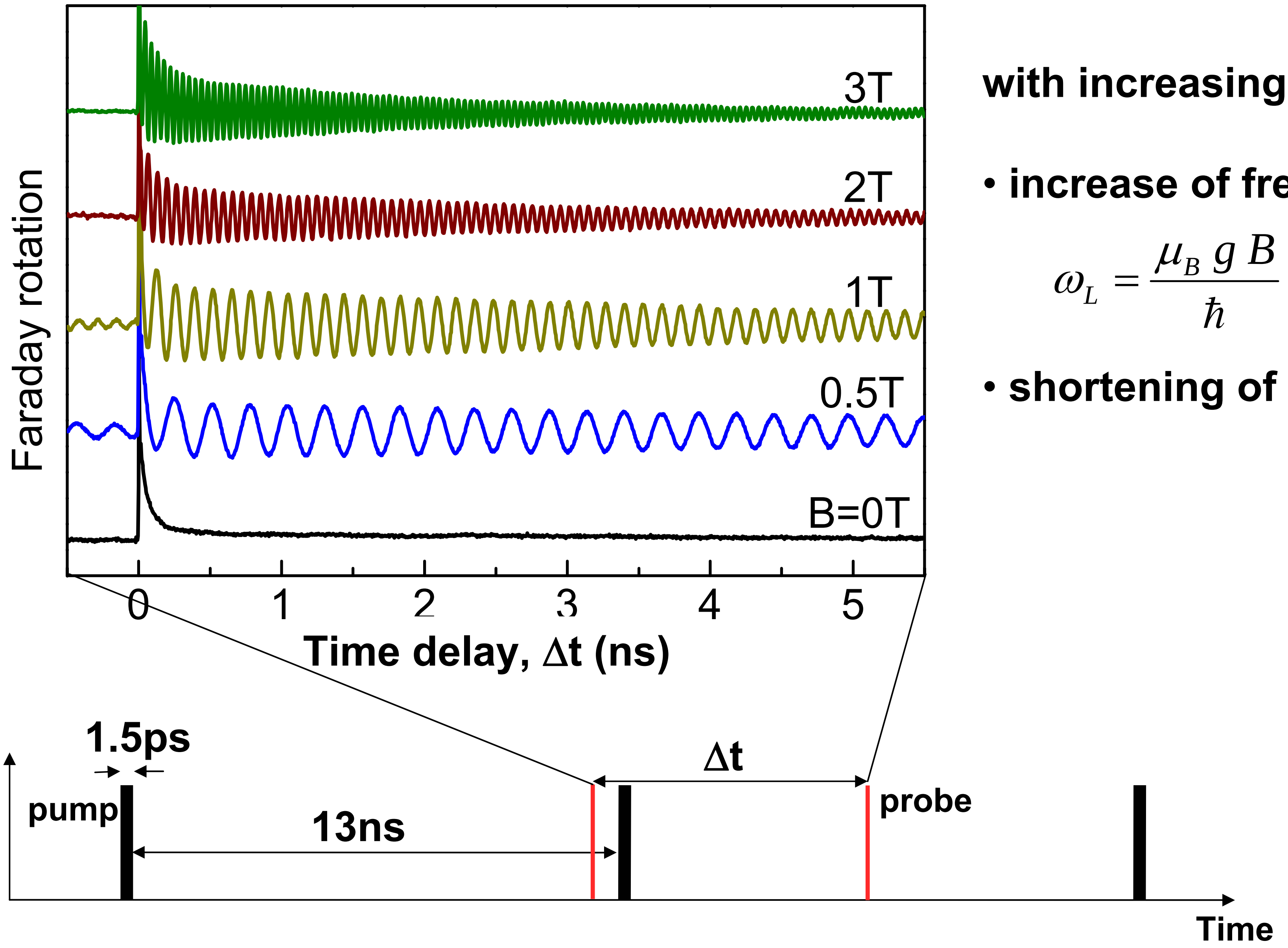
$\theta_F \propto \vec{M} \bullet \vec{k}_{probe}$



B= 3T



Spin coherence in InGaAs/GaAs QWs



with increasing of B:

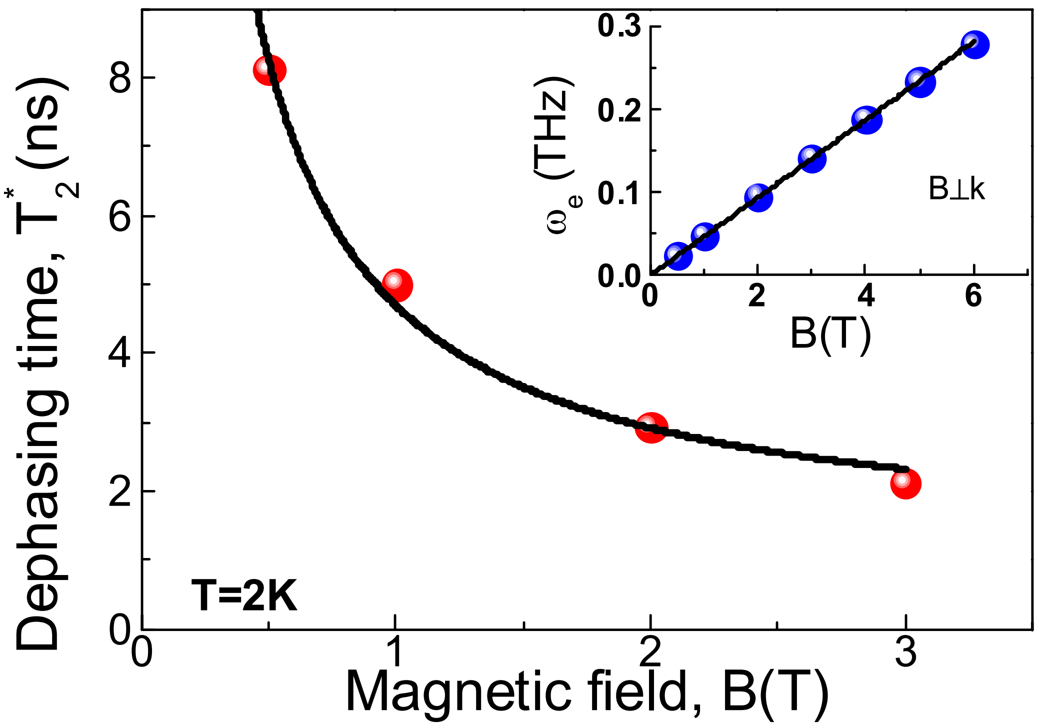
- **increase of frequency**

$$\omega_L = \frac{\mu_B\, g\, B}{\hbar}$$

- **shortening of T_2^***

Spin coherence in InGaAs/GaAs QWs

$$f(t) = f_0 \exp(-\Delta t / T_2^*) \cos(\omega_e \Delta t)$$



$$\hbar \Delta\omega_e = \Delta g_e \mu_B B$$

$$\Downarrow$$

dephasing of ensemble

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^{inh}(\Delta g)}$$

decoherence of single spin

$$T_{inh} = \frac{1}{\Delta\omega_L} = \frac{\hbar}{\Delta g \mu_B B}$$

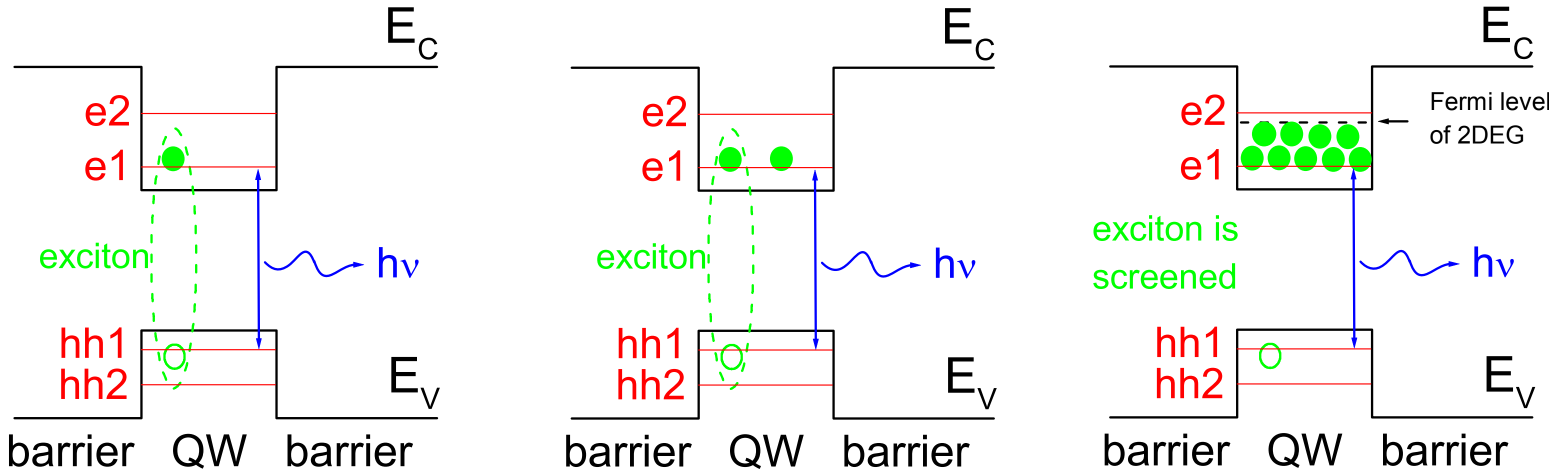
- $g_e = |0.54|, \quad \Delta g_e = 0.4\%$
- **T_2^* > 8 ns**

Spin coherence in quantum wells

- Regime of diluted carrier gas
- Radiative times of excitons and trions
- Long electron spin coherence
- Generation mechanism of spin coherence for resonant excitation of trions
- Spin coherence of holes

Low dimensional systems with diluted electron gas

single-body | few-body | many-body



“empty” QW, EXCITON

Few electrons charged excitons TRION

Many electrons dence 2DEG.

Important role of Coulombic interaction !

Let‘s study materials with strong Coulombic interactions

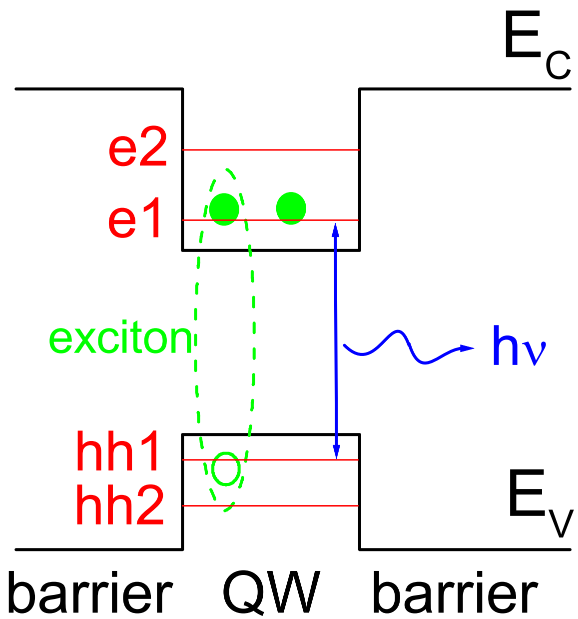
→ II-VI (CdTe, ZnSe, ZnO....)

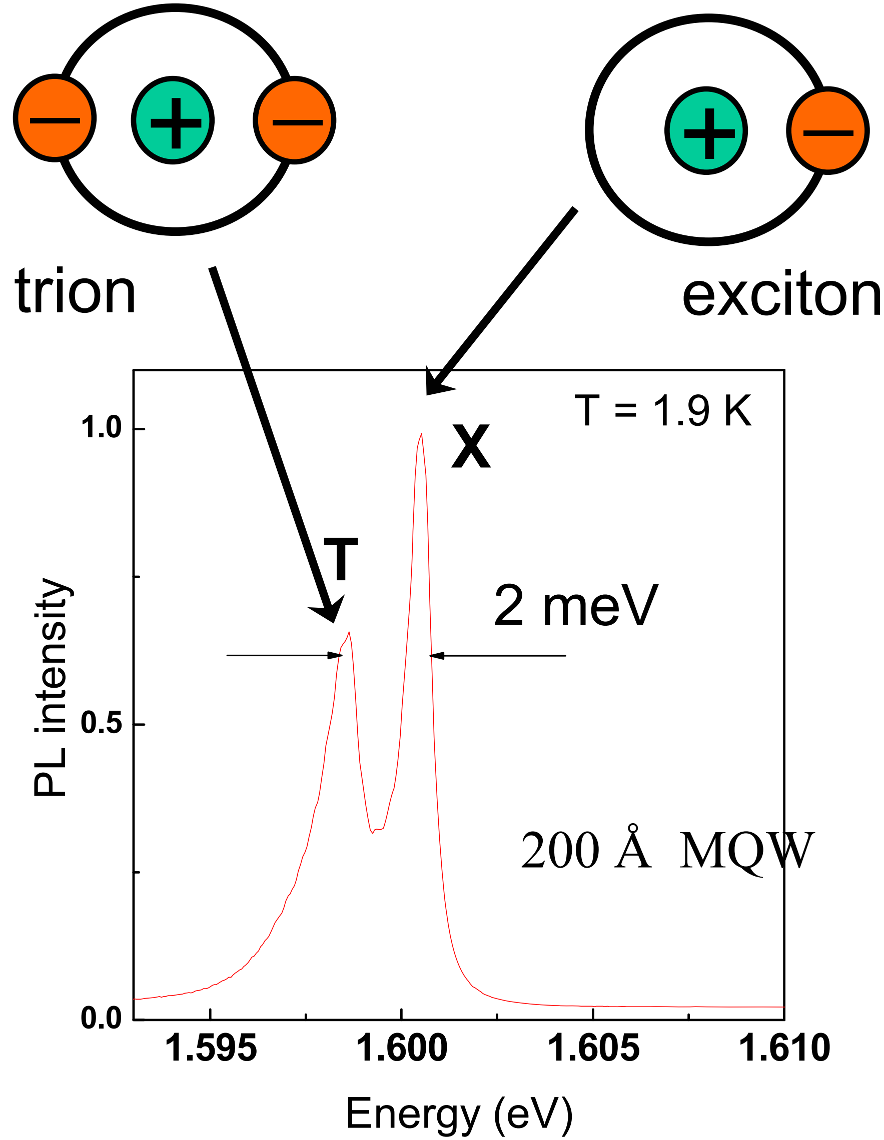
II-VI QWs with strong Coulomb interaction

CdTe/CdMgTe quantum wells

200 Å QWs, 5 periods

n_e = 5 - 8 x 10^9 cm^{-2}



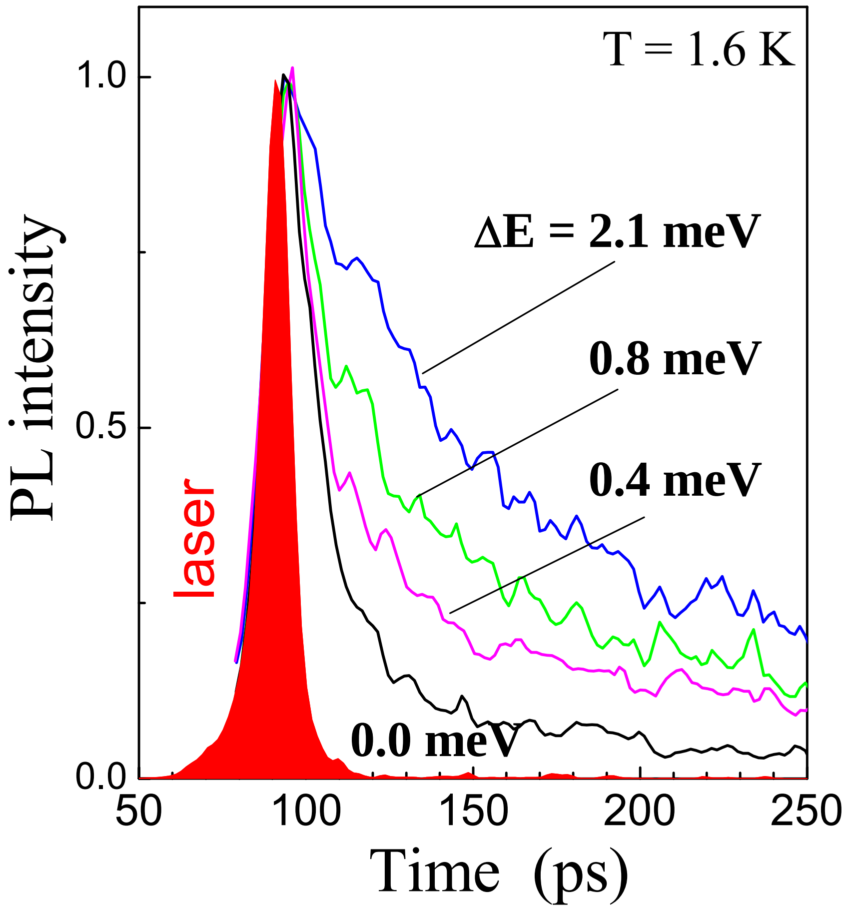


PHOTOLUMINESCENCE

Low-dense electron gas,
charged exciton, TRION

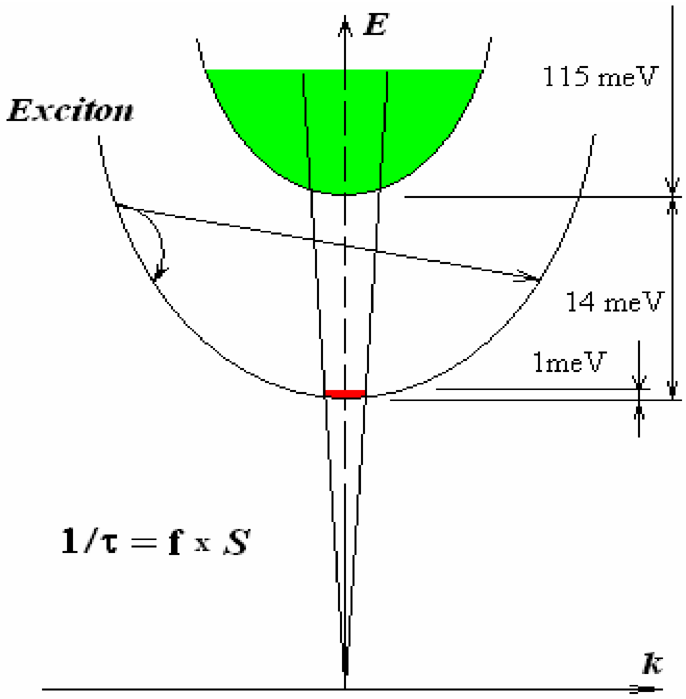
Kinetics of exciton and trion photoluminescence

Excitation 1.5-ps pulses,
detection with streak-camera



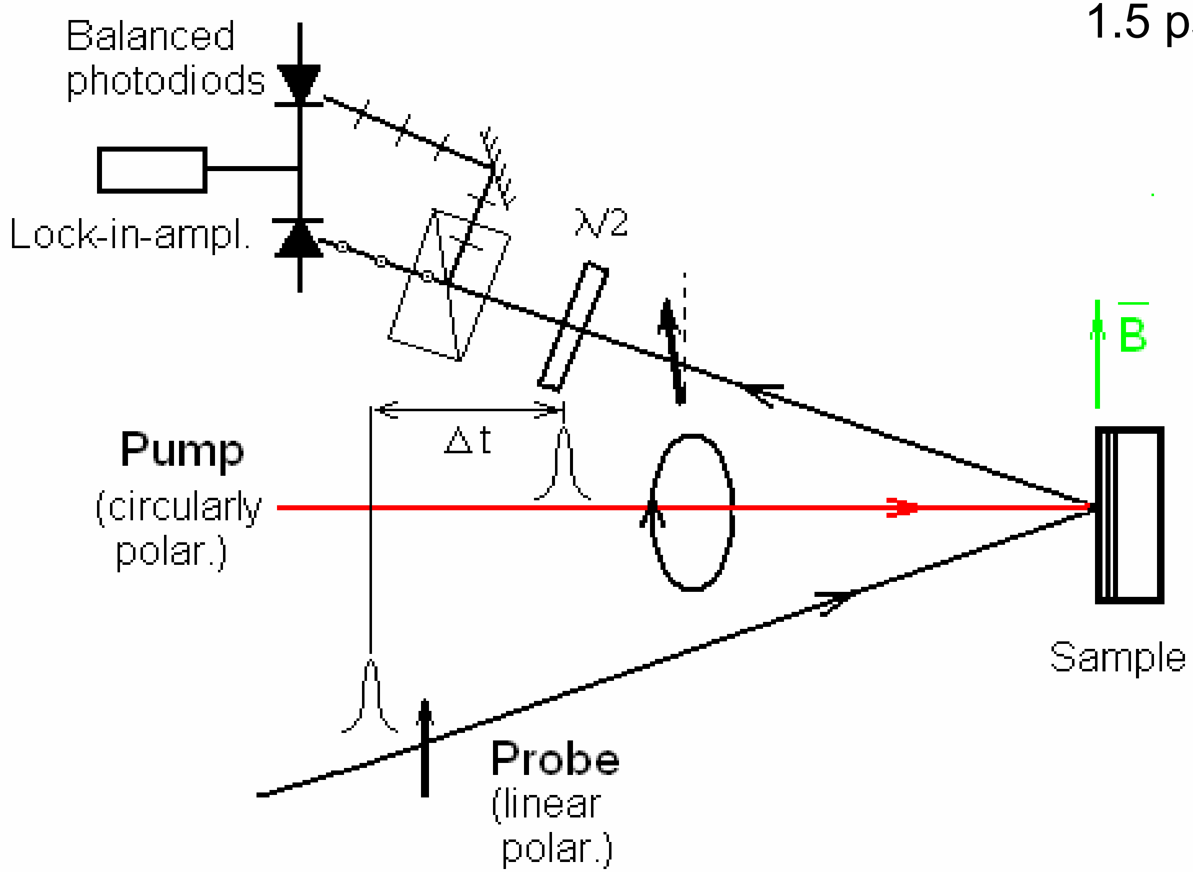
Fast decay of 20 ps is exciton radiative time.

Longer decay of 100 ps is due to exciton relaxation into radiative cone.



Pump-probe Kerr rotation with ps-pulses

1.5 ps pulses, 76 MHz



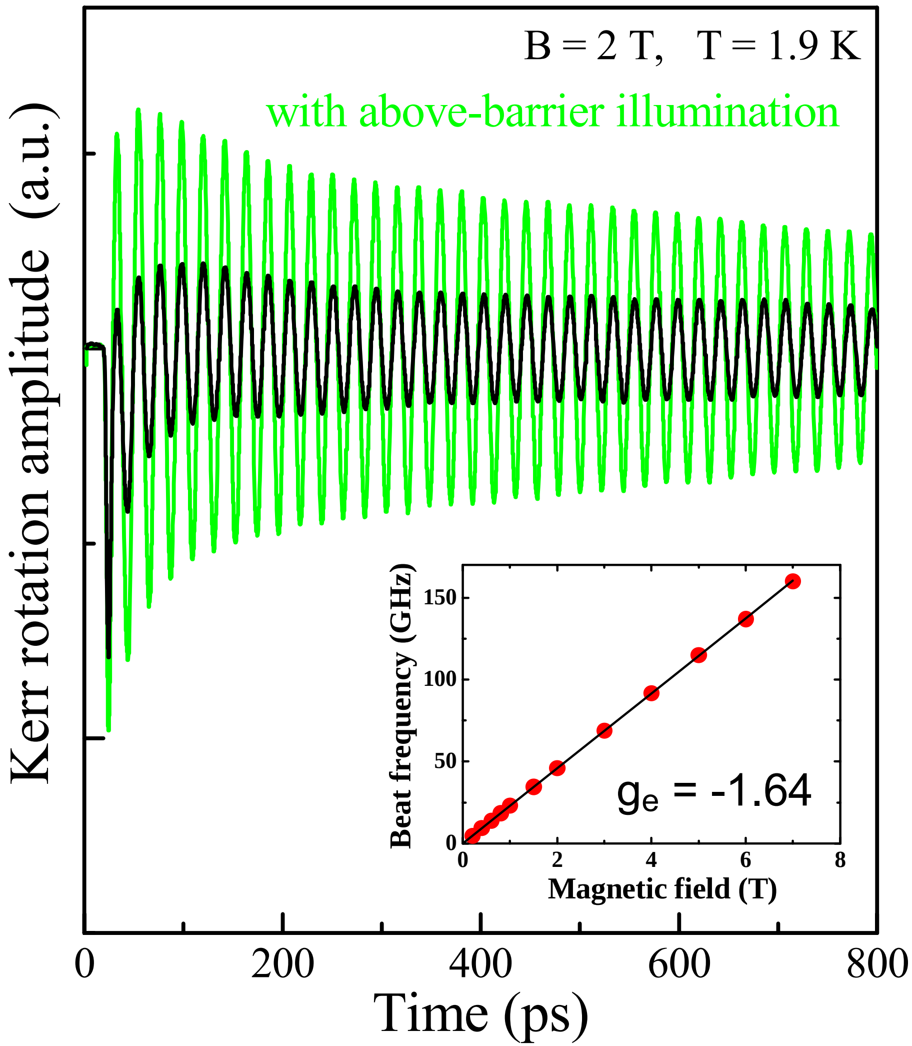
$$\Delta t \times \Delta E \propto \hbar$$

$$100 \text{ fs} \leftrightarrow 20 \text{ meV}$$
$$1 \text{ ps} \leftrightarrow 2 \text{ meV}$$

S.A.Crooker, D.D. Awschalom, N. Samarth
IEEE J. Quantum Electronic 1, 1082 (1995)

Resonant excitation in trion

200 Å MQW , $n_e = 5\text{-}8\times10^9$ cm^{-2}



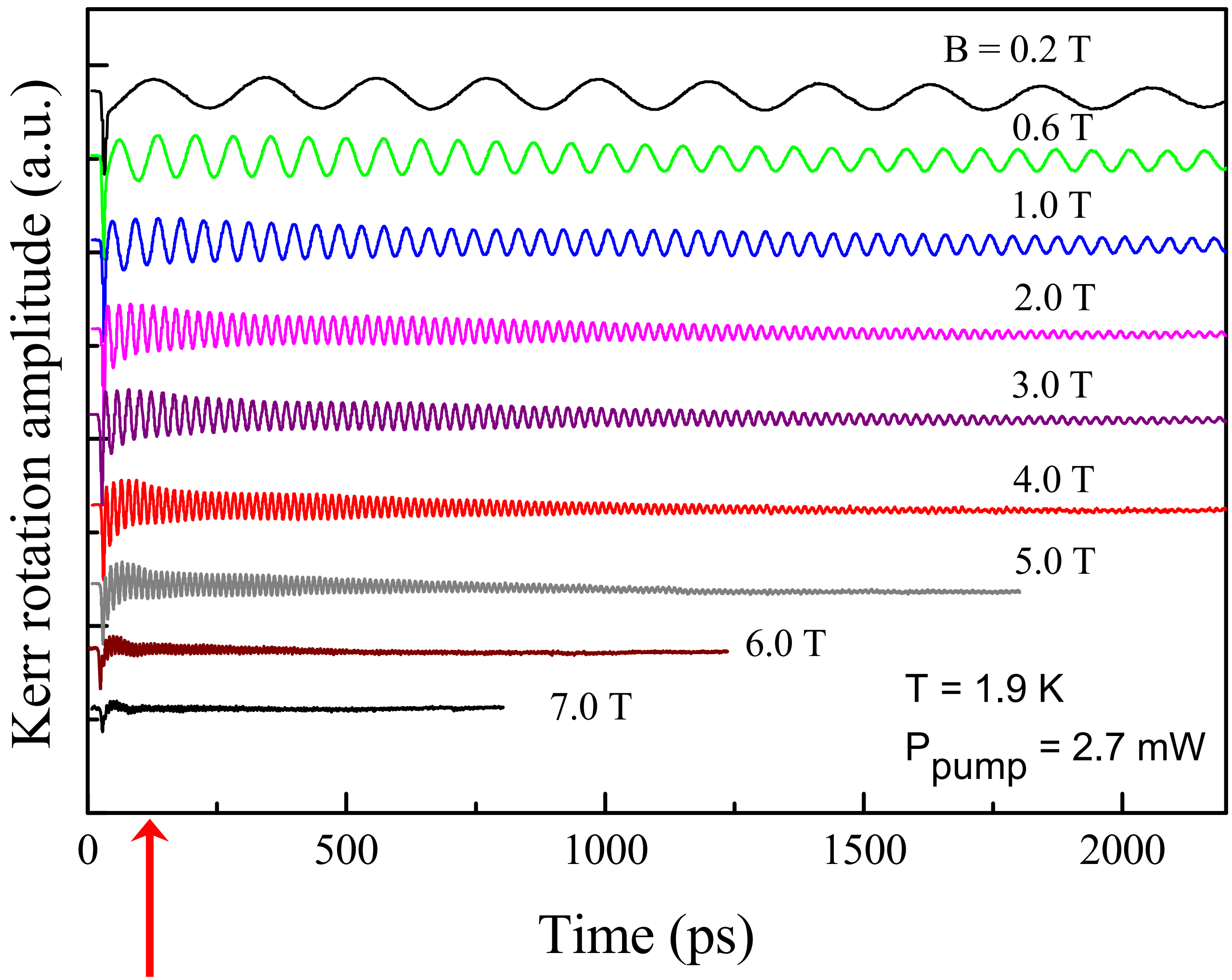
Above-barrier illumination increases 2DEG concentration.

Beat frequency corresponds to electron Zeeman splitting with g_e=|1.64|.

$$\omega_L = \frac{\mu_B g_e B}{\hbar}$$

Electron spin beats

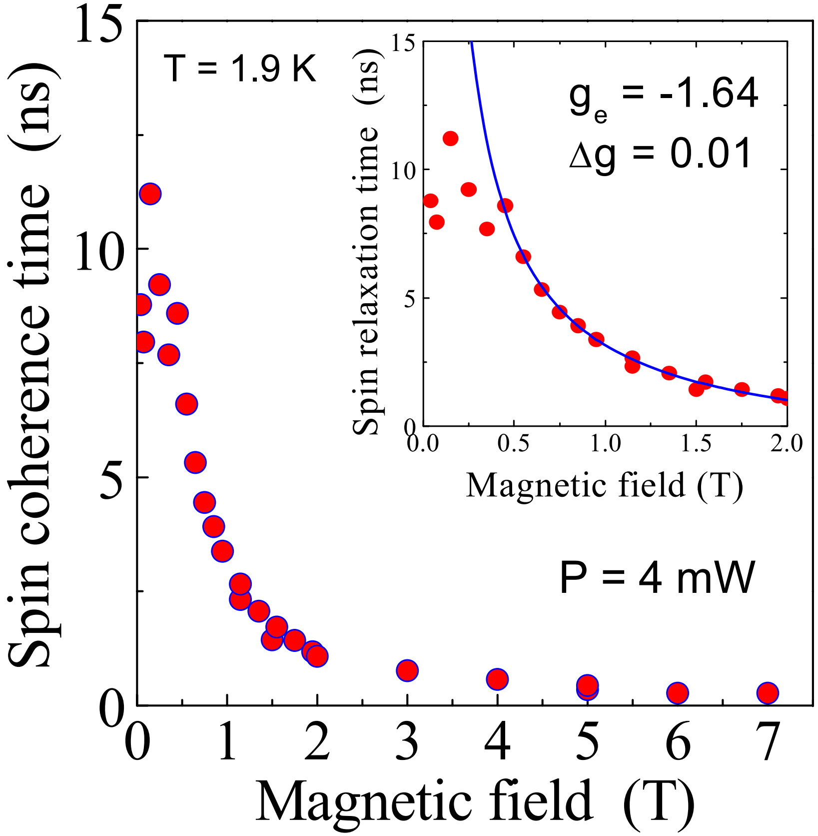
200 Å MQW CdTe/(Cd,Mg)Te $n_e = 5\times10^9$ cm^{-2}



Trion / exciton lifetime <100 ps

Spin beats come from 2DEG

Dephasing of spin coherence in magnetic fields



Spin coherence of spin ensemble

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_{inh}(\Delta g)}$$

Decoherence of individual spin

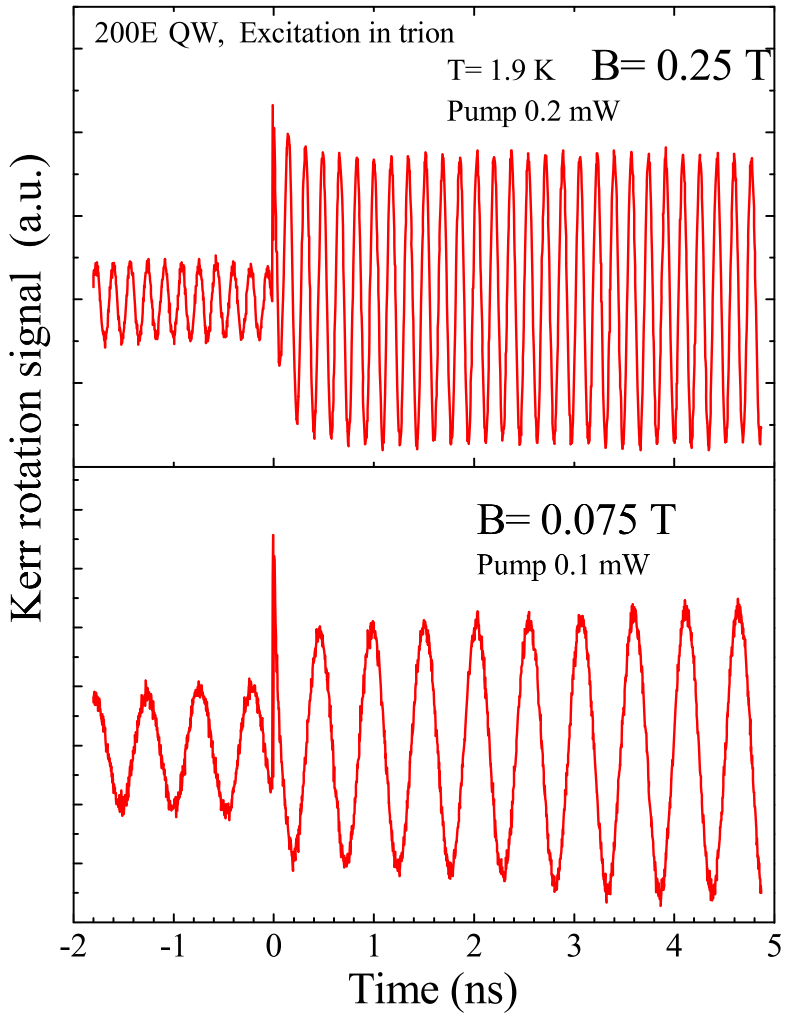
Dephasing of ensemble

$$T_{inh} = \frac{1}{\Delta\omega_L} = \frac{\hbar}{\Delta g \mu_B B}$$

Decay of spin beats in B > 0.5 T is due to dephasing of ensemble T_{inh}.
Single spin decoherence time T_2 = 10 ns is seen for B < 0.5 T.

Long-lived electron spin coherence

200 Å MQW $n_e = 5\times10^9$ cm^{-2}



Period between pump puses 13.2 ns (repetition rate 75.6 MHz)

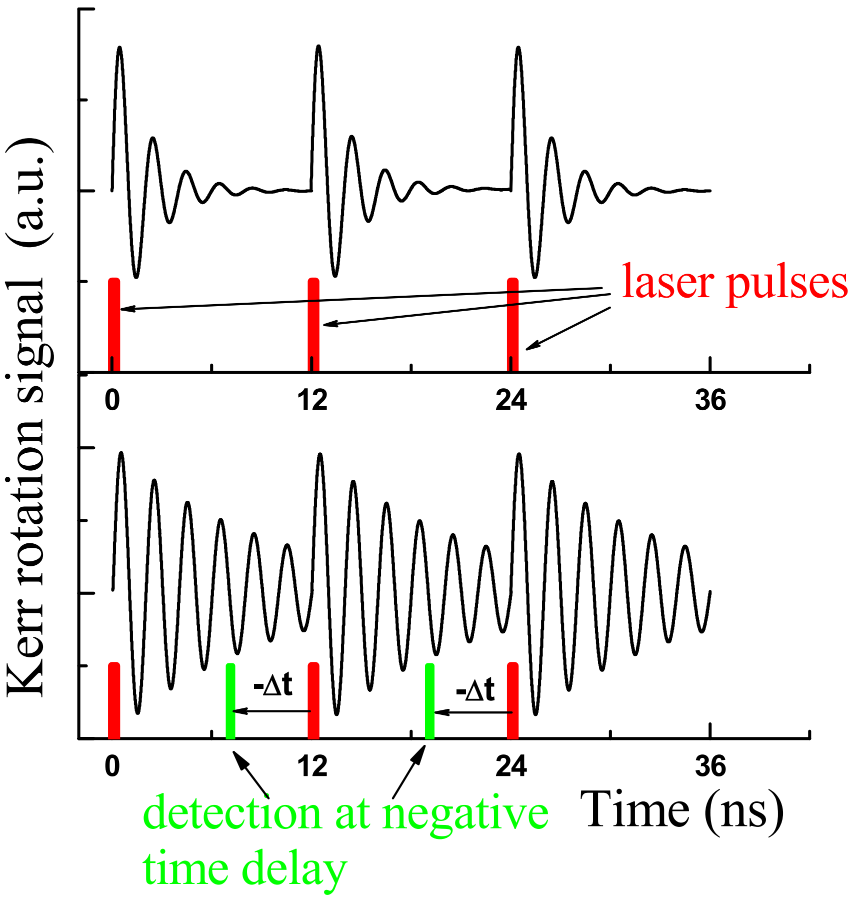
Electron spin coherence lives longer than 13.2 ns.

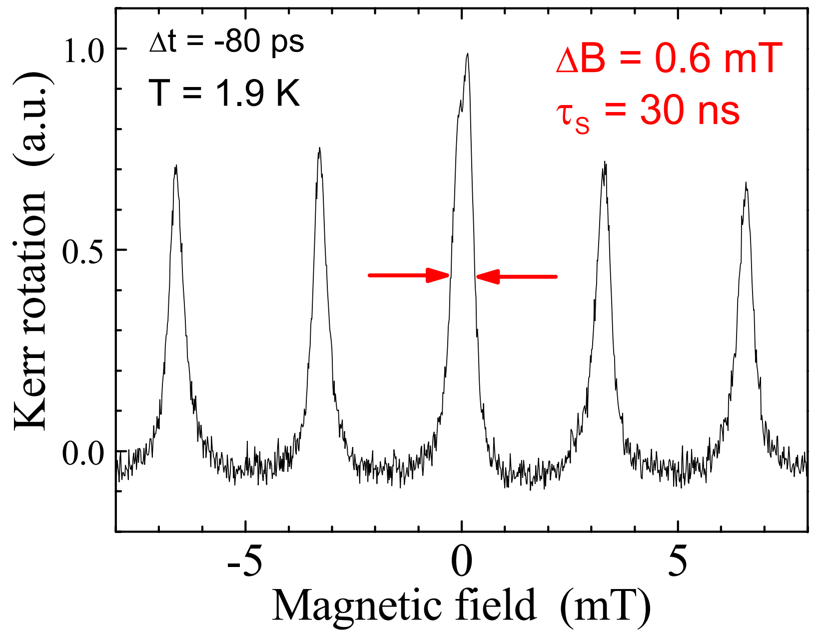
Other techniques are needed to measure spin coherence time:

Resonant Spin Amplification (RSA) technique.

Kikkawa and Awschalom, PRL 80, 4313 (1998).

Resonant Spin Amplification (RSA) technique





Very long electron spin coherence time T_2*=30 ns !!!

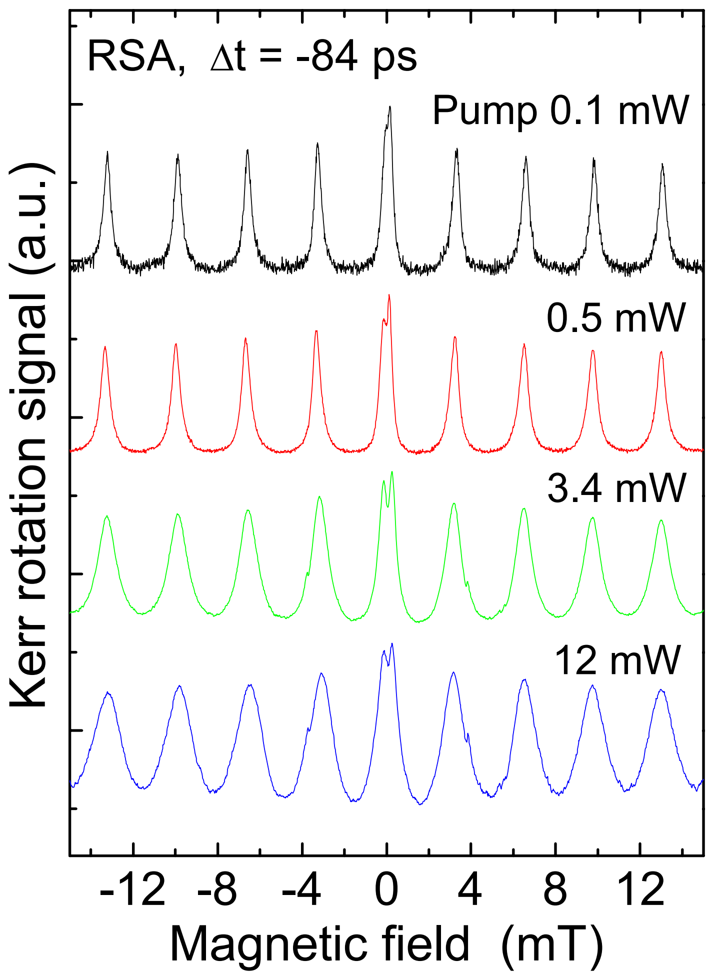
10 ns, GaAs QW, Dzhioev PRB 66 (2002).

300 ns, GaAs bulk, Dzhioev PRB 66 (2002).

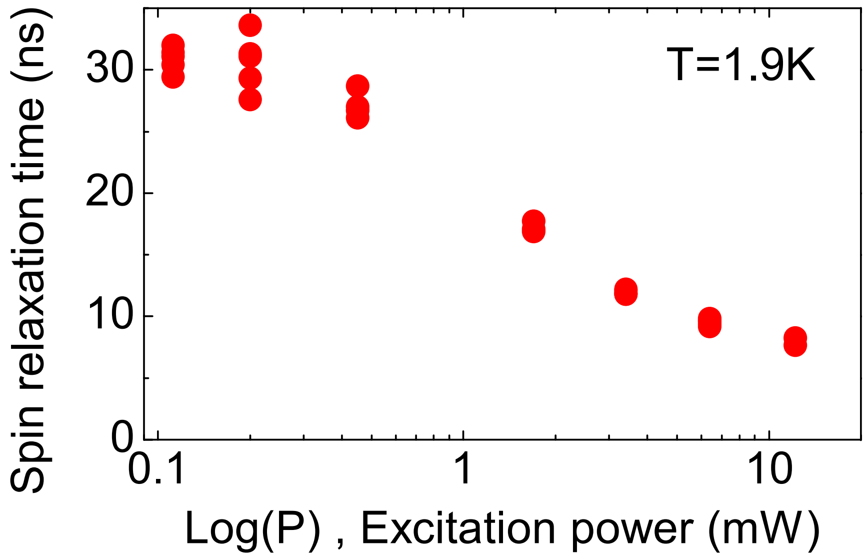
T = 1.6 – 5 K

B → 0 T

Spin relaxation time vs pump power

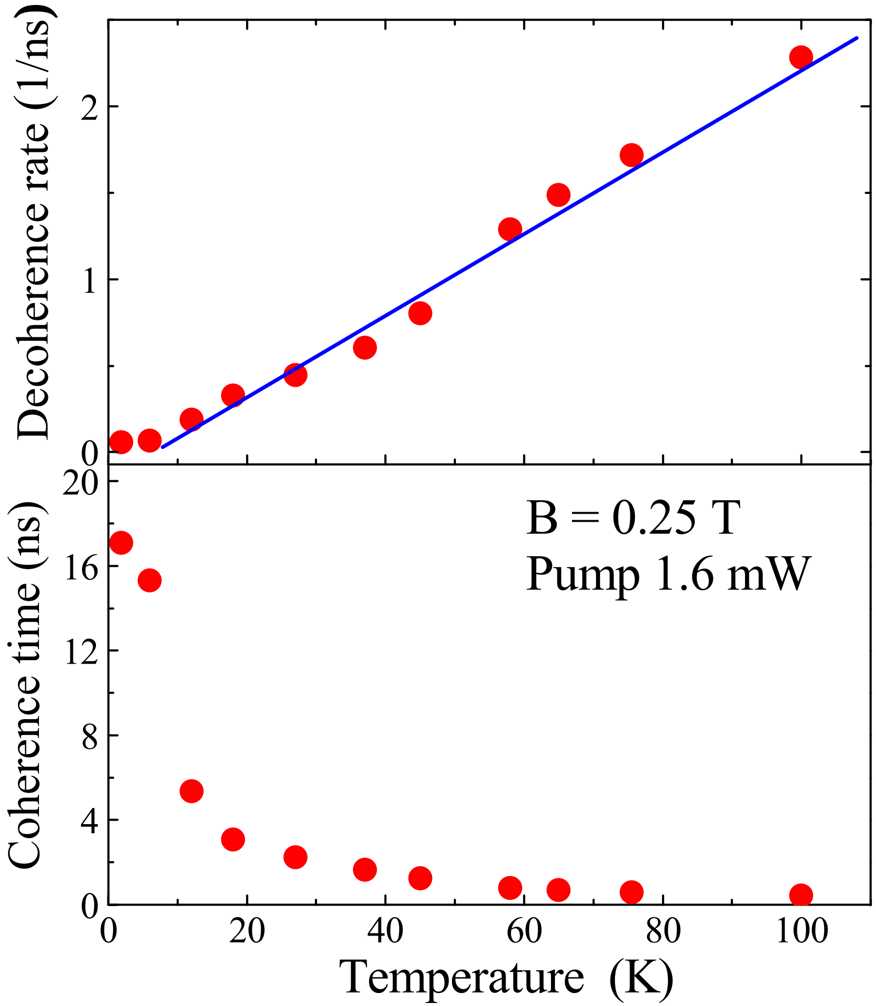


200 Å MQW $n_e = 5\times10^9$ cm^{-2}



Electron spin relaxation time depends on excitation power.
Electron delocalization due to heating.

Spin coherence time vs bath temperature



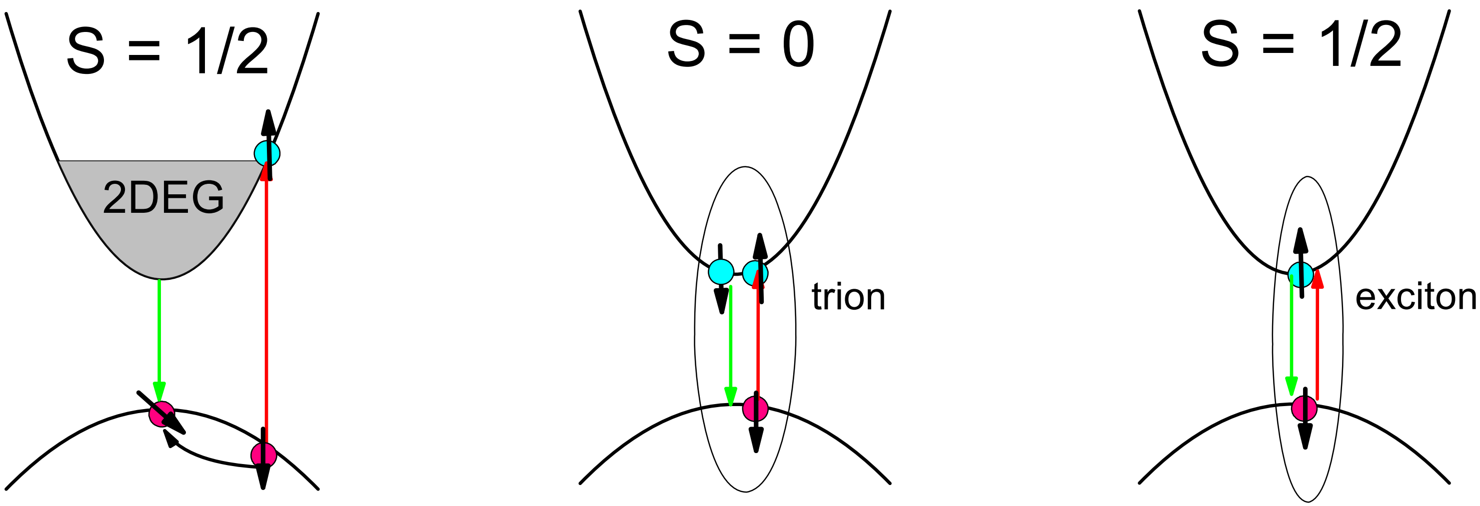
Dyakonov-Perel relaxation of electrons in QWs for T > 10 K.

$$\frac{1}{\tau_S} \propto T \times \tau_p(T)$$

At T < 10 K fluctuations of nuclei field contribute to spin relaxation of localized electrons.

Generation of spin coherence

High density 2DEG | Low density 2DEG | undoped



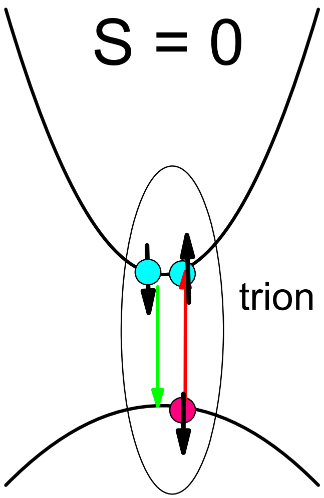
Long-lived spin beats of 2DEG

No beats

Beats of electron in exciton, $< 30\text{-}100$ ps

Problem: How the spin coherence is excited in low density 2DEG?

Which electrons are contributing to spin beats?



Free electrons of 2DEG with infinite lifetime.

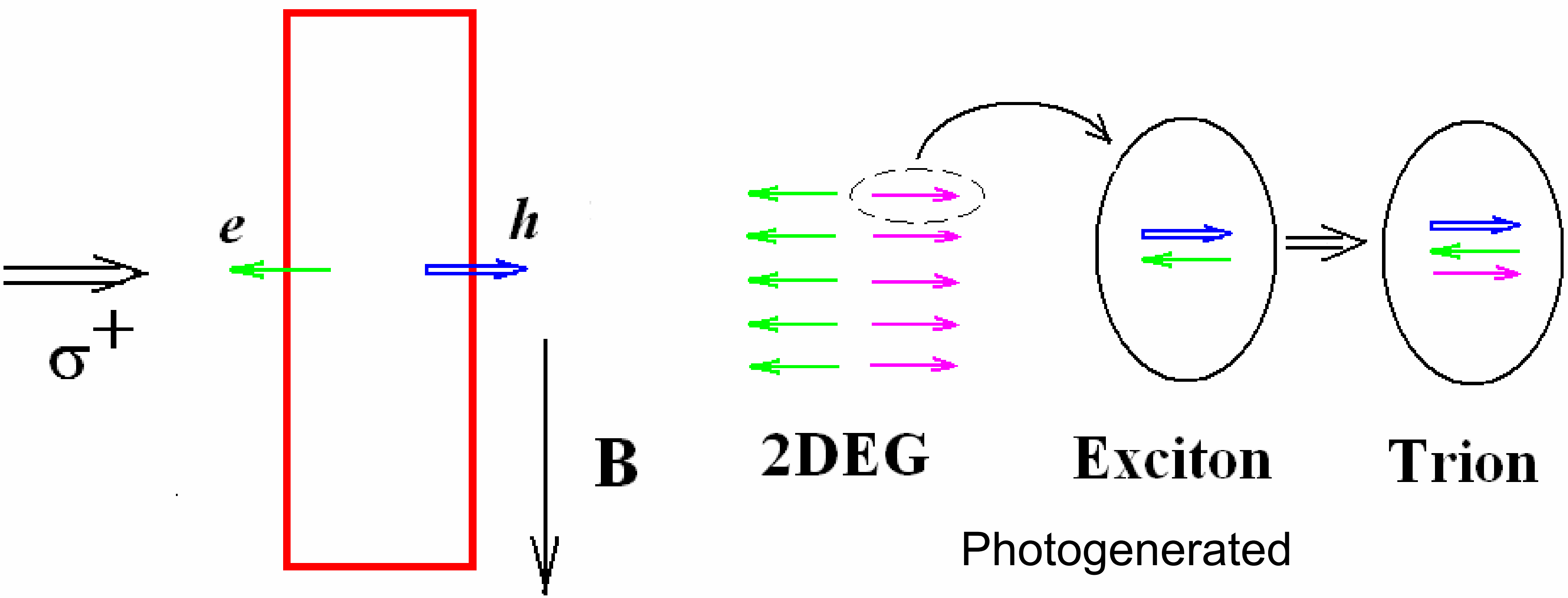
Electrons in excitons. - Beat decay is limited by exciton lifetime of 30-100 ps.

Electrons in trions. – Trion has singlet state with two antiprallel electron spins and S=0. No spin precession is possible.

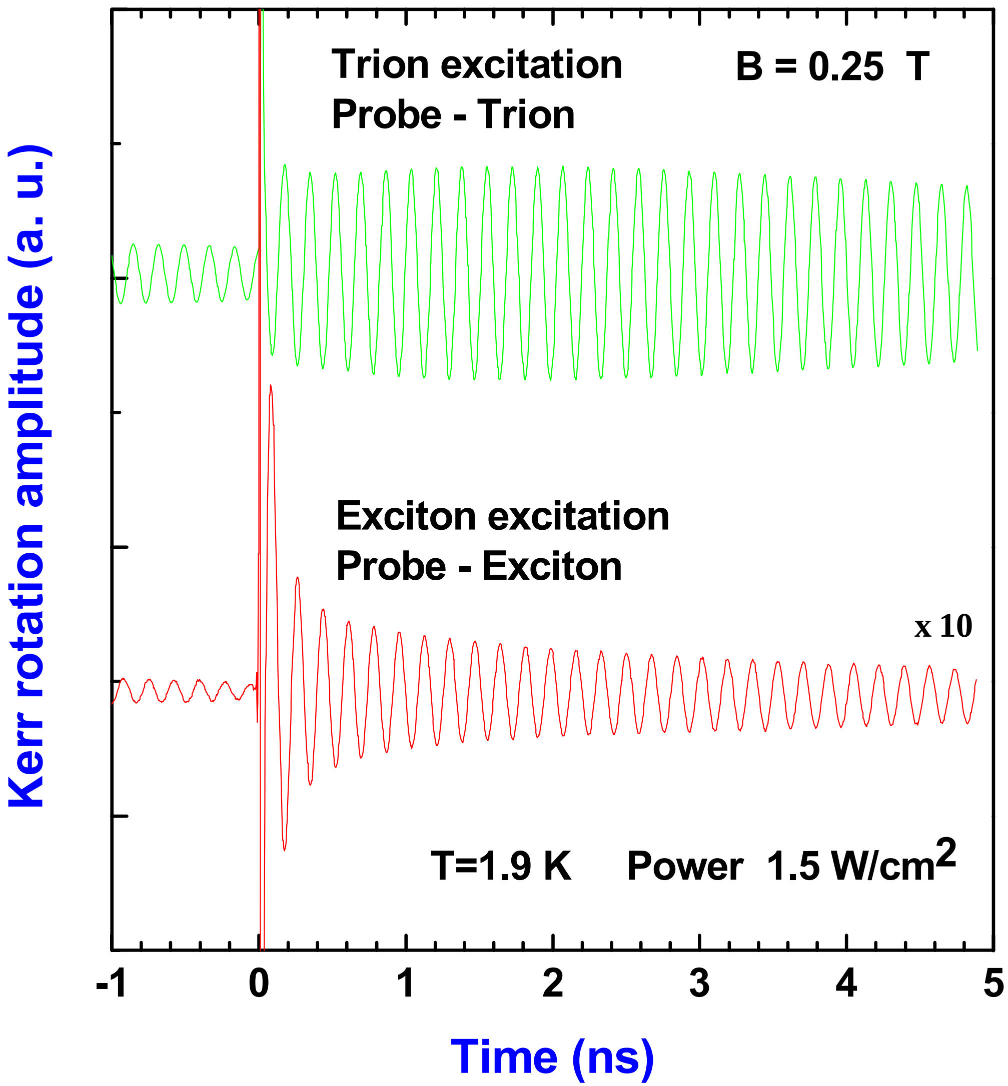
Conclusion: Long-lived beats can be from 2DEG only.

Problem: How the spin coherence in 2DEG is excited?

Mechanism of generation spin coherence in 2DEG via formation of trions



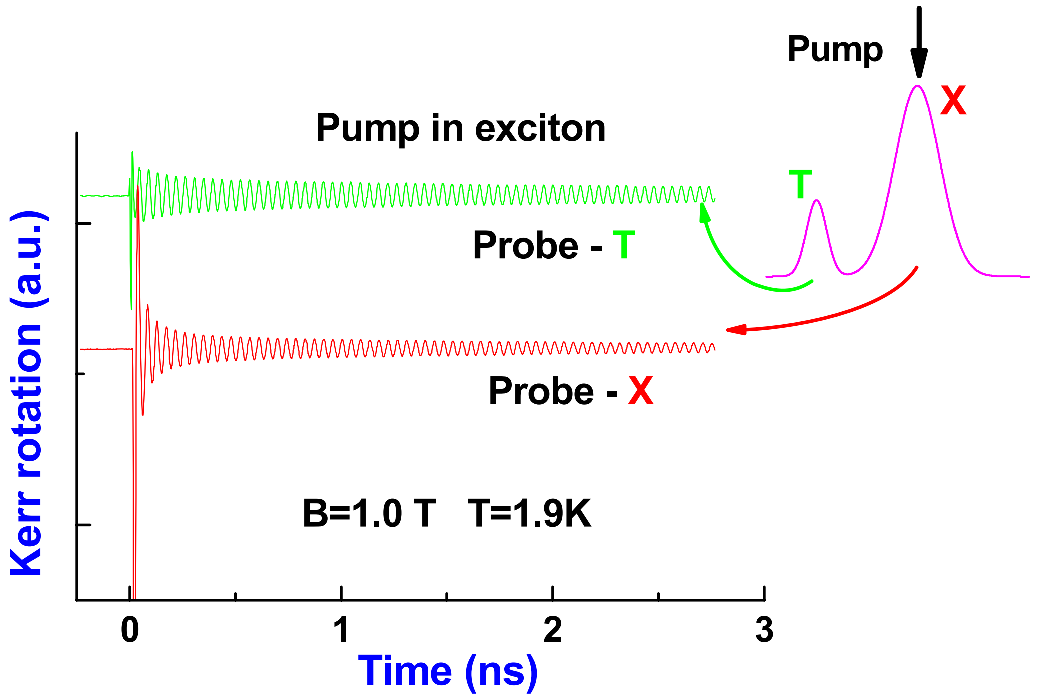
Degenerate pump-probe

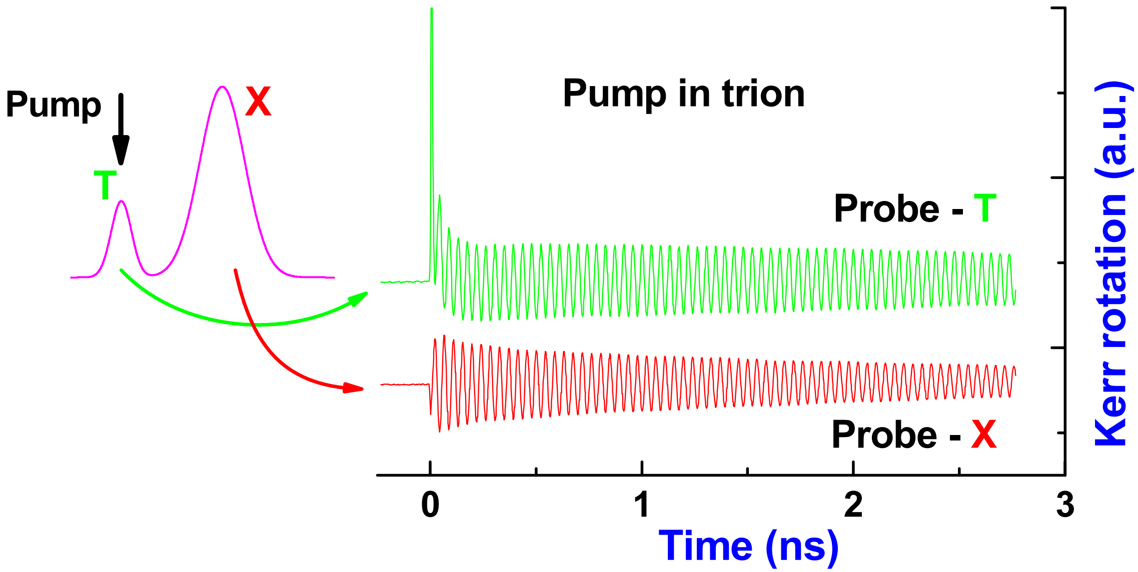


Only long-living decay of 2DEG.

Fast decay due to exciton recombination and long-living one of 2DEG.

Two-color pump-probe

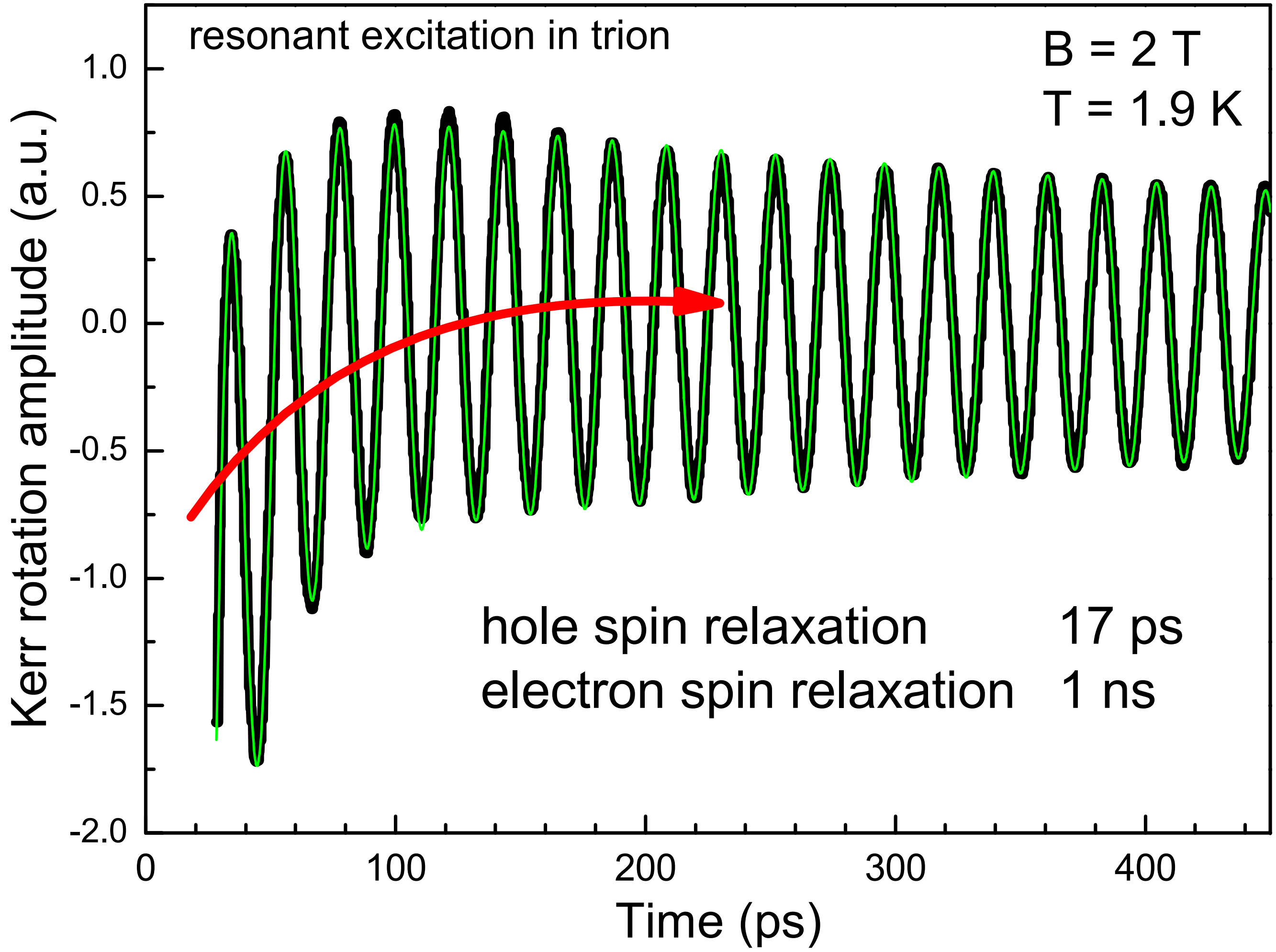




Hole spin relaxation

$$\omega_L = \frac{\mu_B\, g\, B}{\hbar}$$

200 Å MQW $n_e = 5\times10^9$ cm^{-2}



Summary to CdTe QWs

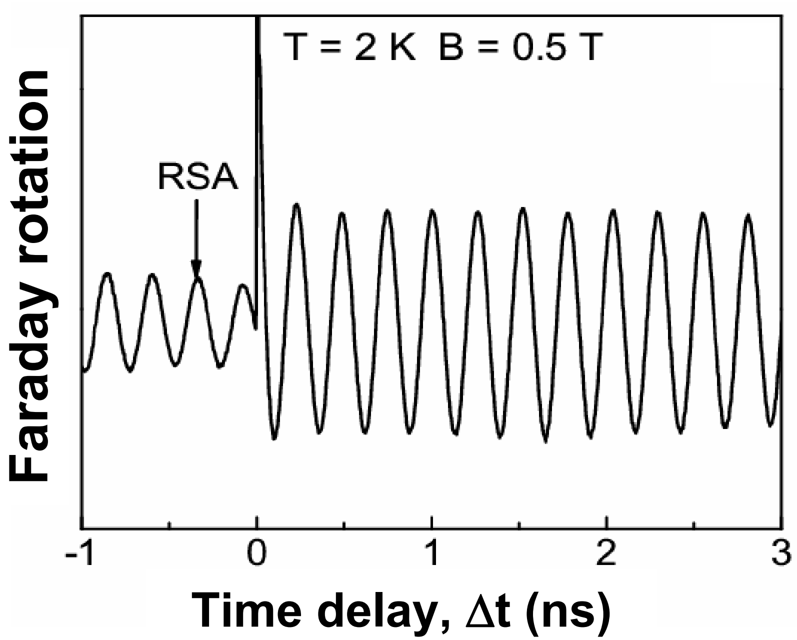
Spin coherence of 2DEG is generated via trion formation when trions or excitons are excited resonantly.

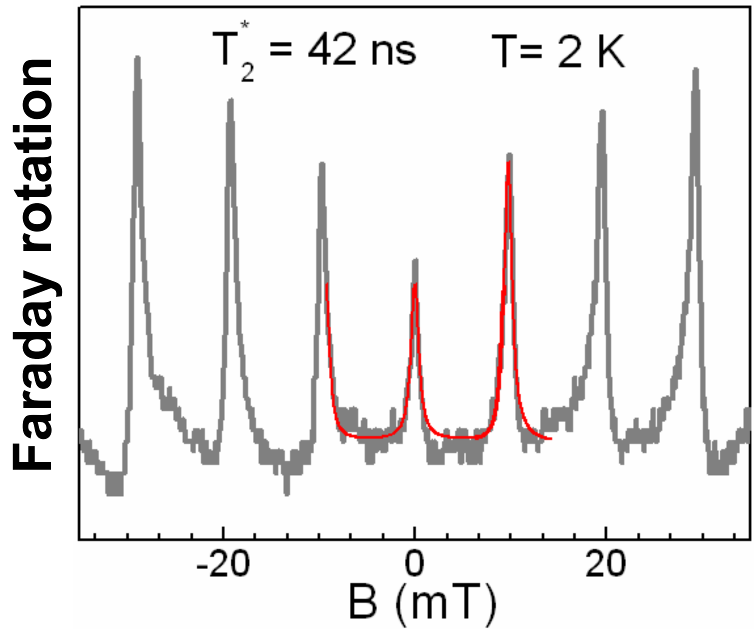
Long-lived electron spin coherence in CdTe QWs:

$T_2^* = 30$ ns, which means that $T_2 > 30$ ns.

Electron localization favors long spin coherence.

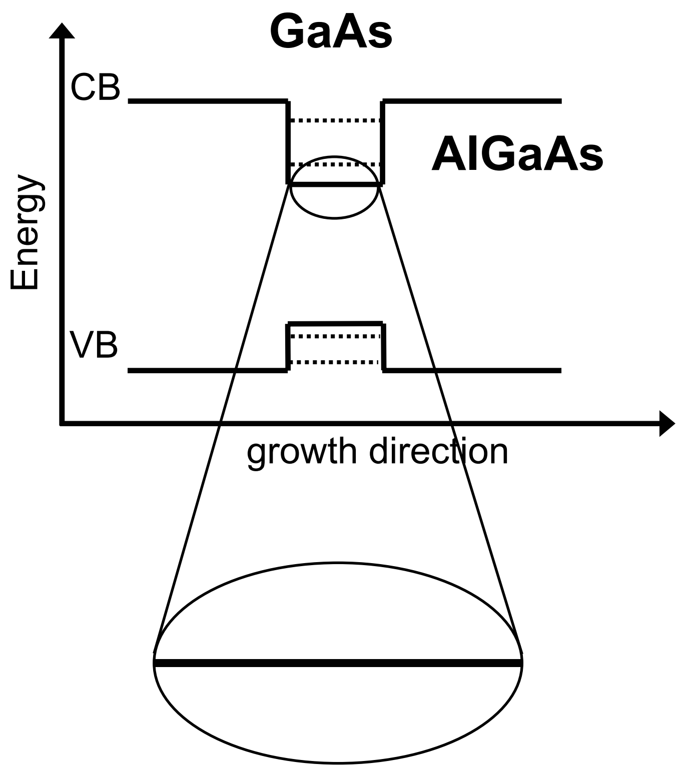
Spin coherence in InGaAs/GaAs QW

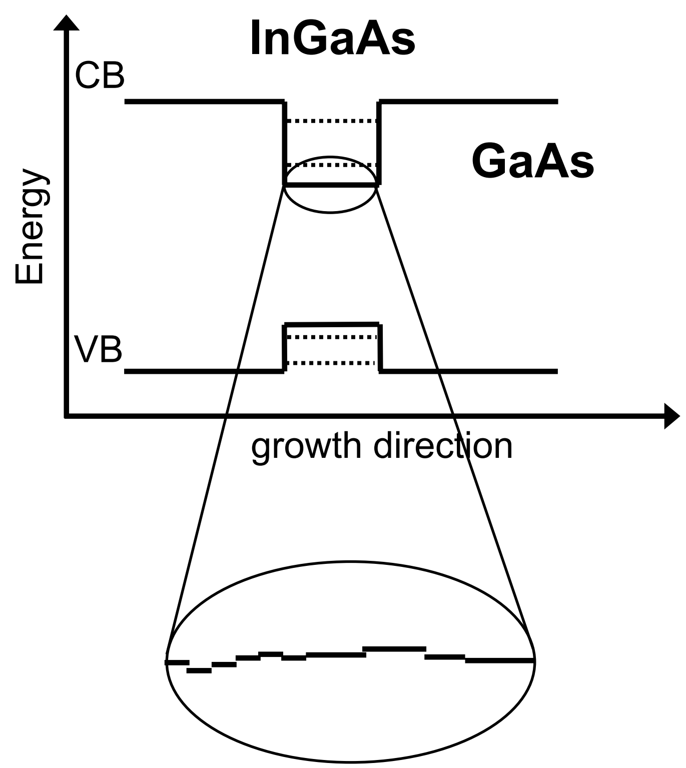




- Literature: T_2^* = 10 ns, GaAs QW
- T_2^* = 25 ns, GaAs QW
- **T_2^* = 42 ns**, InGaAs QW

Spin coherence in III-V QWs





- **no alloy fluctuations**
- **shorter T_2^***

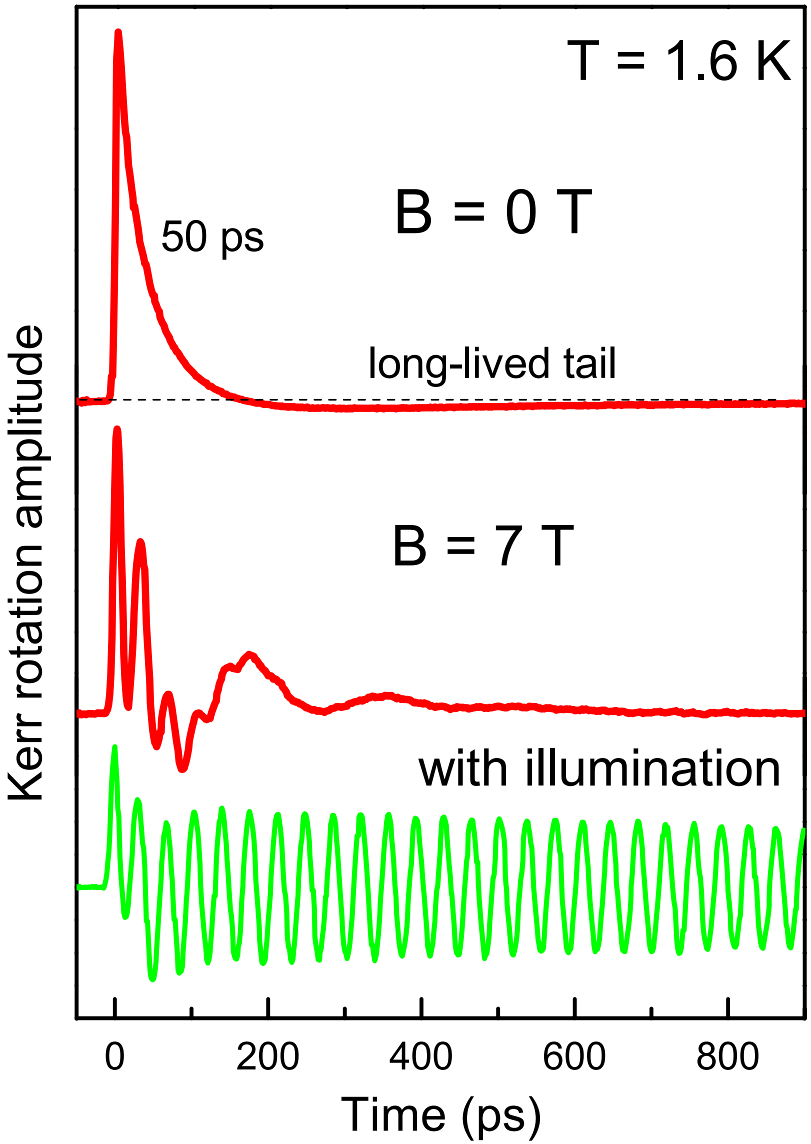
- **alloy fluctuations**

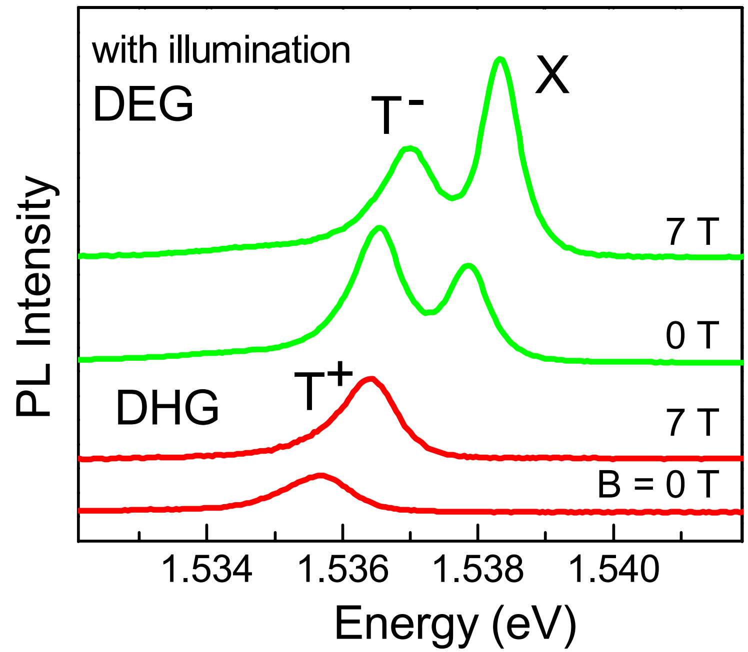
⇒in plane electron localization

longer T_2^*

Spin coherence of holes

p-doped GaAs/AlGaAs quantum well





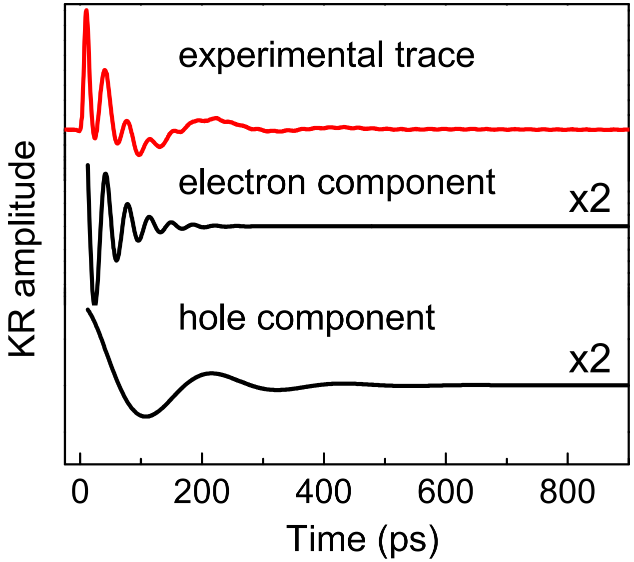
Carrier concentration is tuned

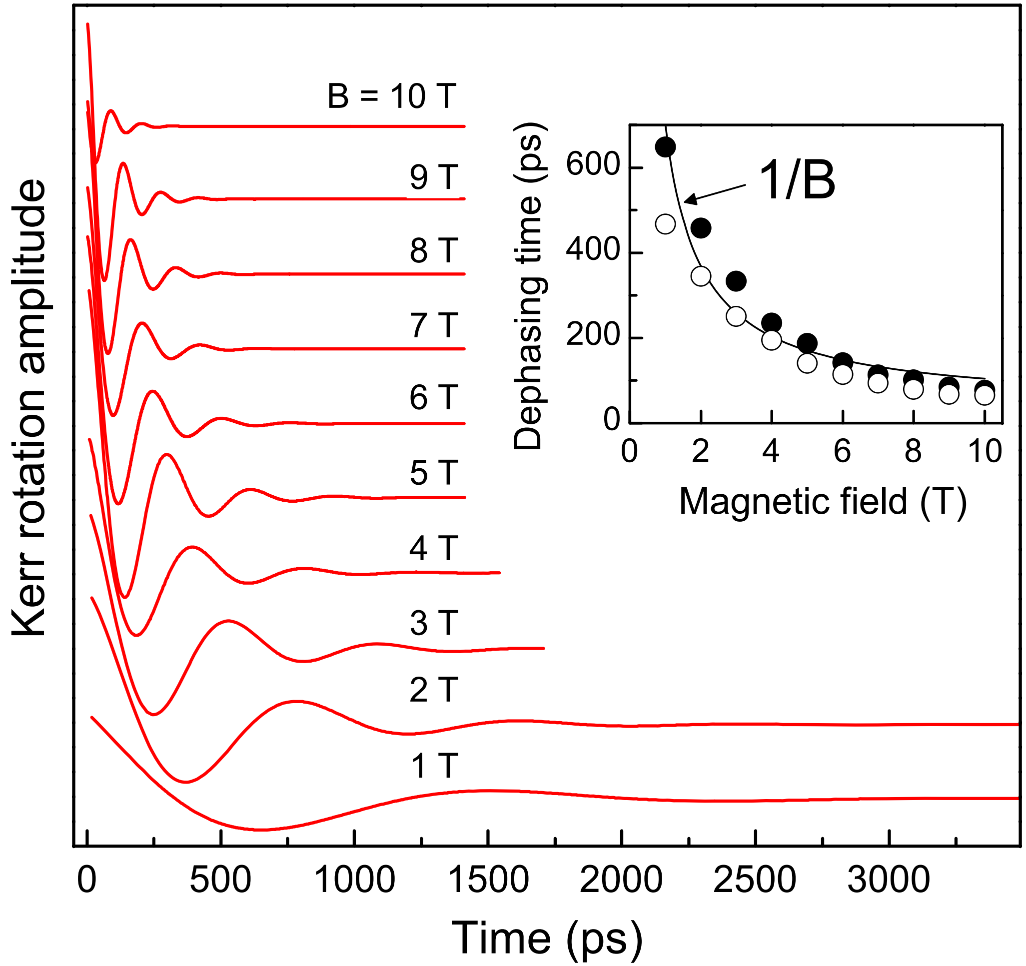
by above-barrier illumination.

p-type can be converted to n-type

Spin coherence of holes

p-doped GaAs/AlGaAs quantum well

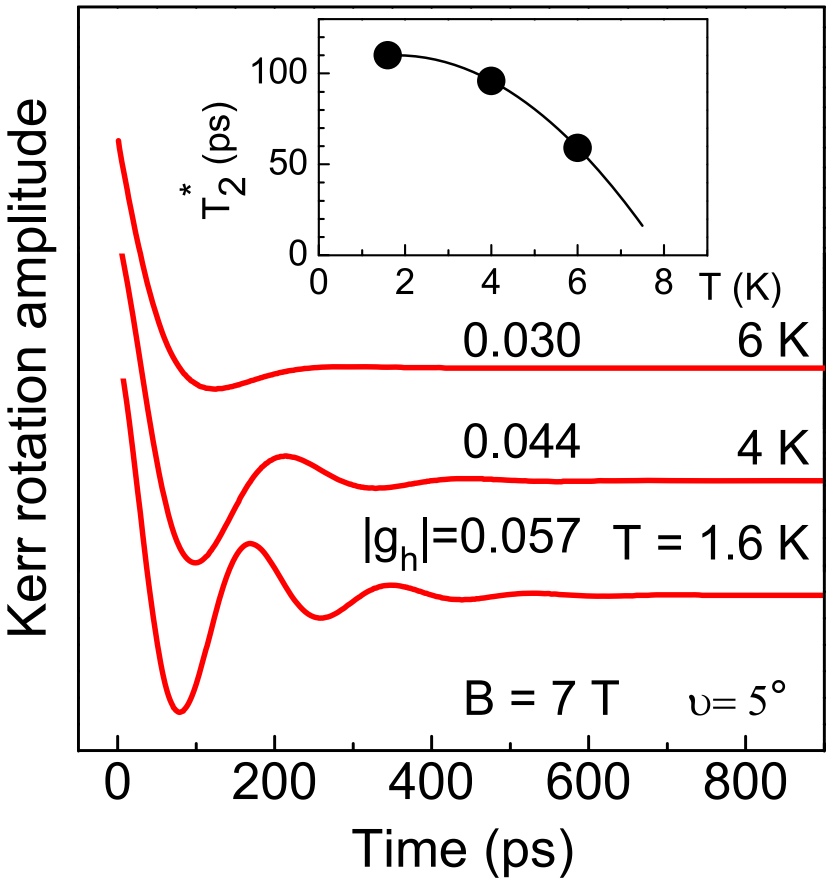




Spin dephasing time of holes T_2^* is longer than 650 ps.

Spin coherence of holes: temperature dependence

p-doped GaAs/AlGaAs quantum well

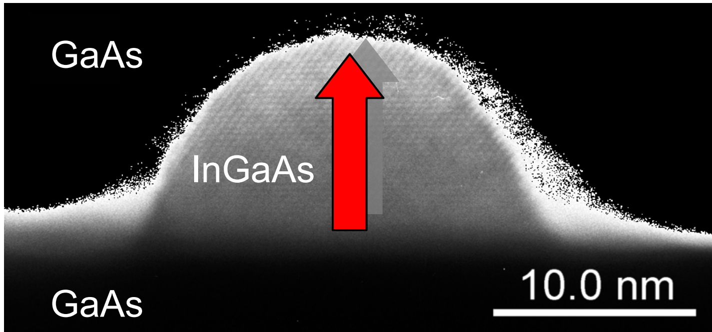


Similar to electrons localization favors long spin dephasing time for holes.

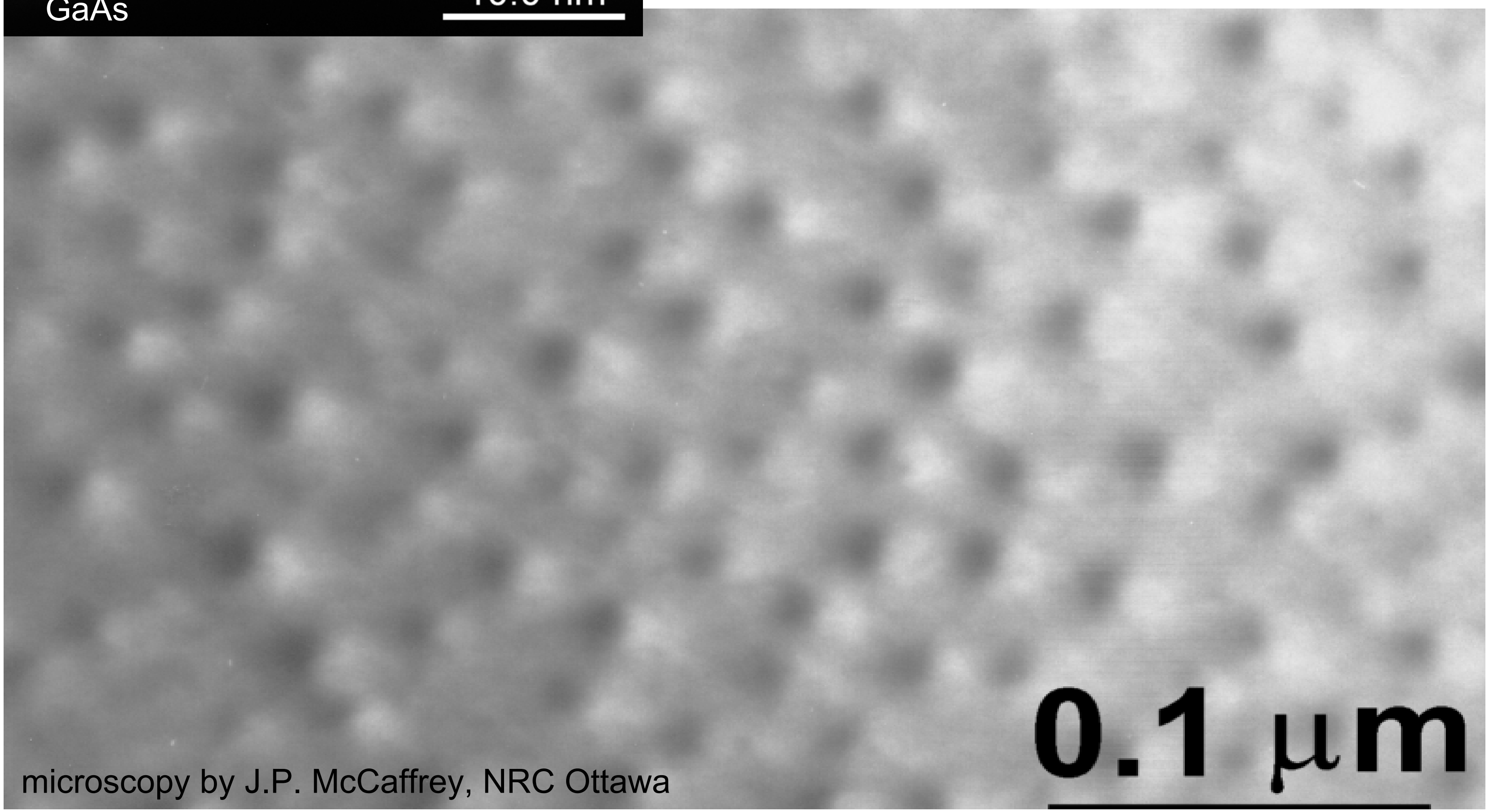
Spin coherence in quantum dots

- **Singly charged InGaAs quantum dots**
- **Spin beats of resident electrons**
- **Generation mechanism of spin coherence for resonant excitation of trions**

Self-organized quantum dots

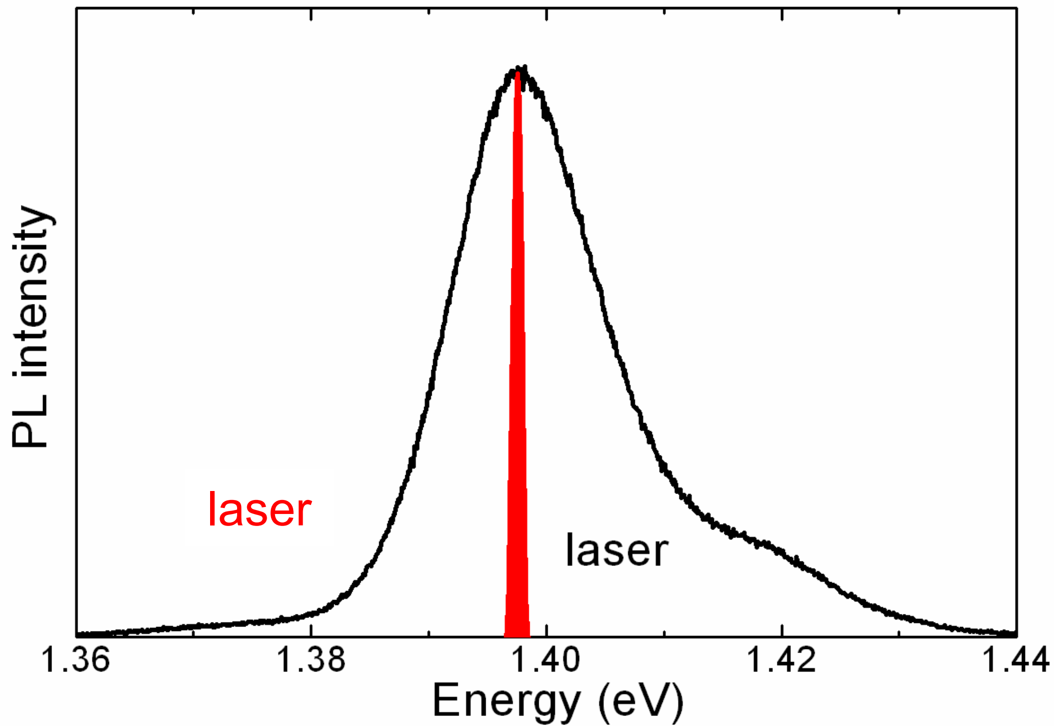


- InGaAs / GaAs quantum dots (QDs)
- strong localization



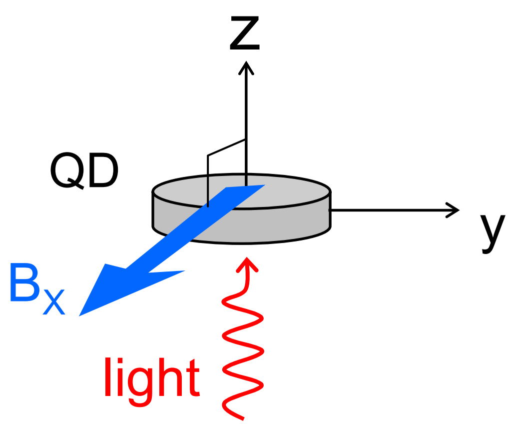
InGaAs quantum dots

Ensemble of singly charged QDs

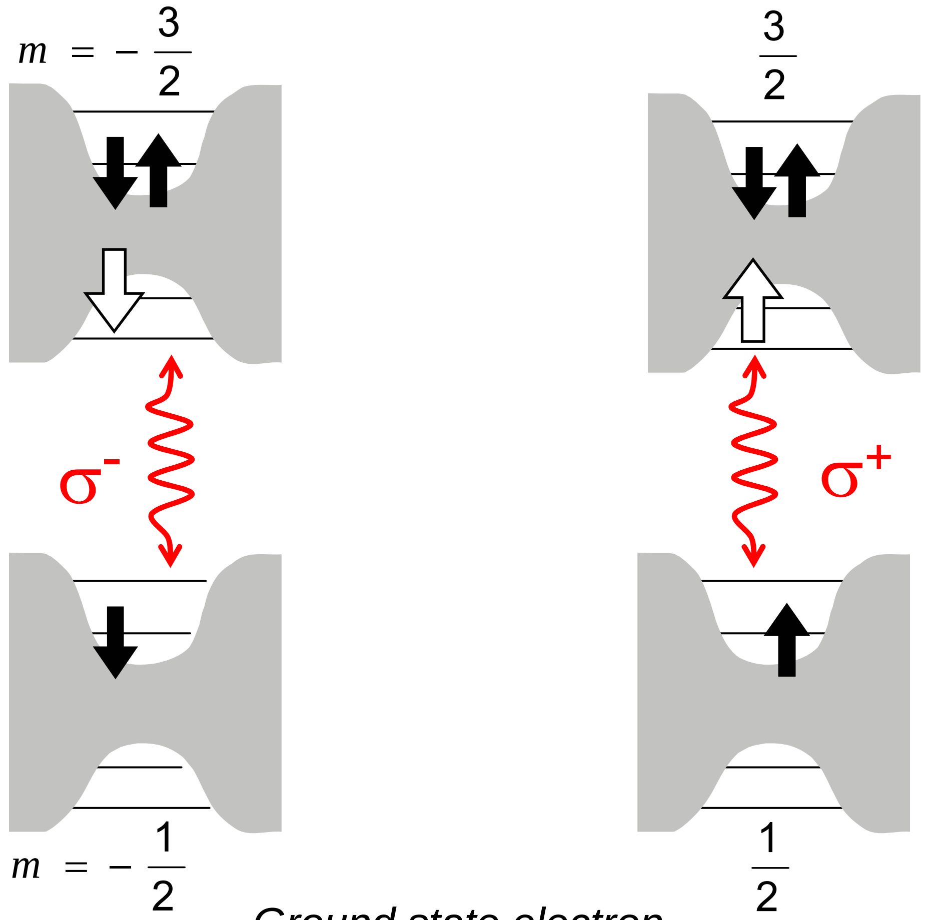


- **20 layers InGaAs/GaAs QDs**
- **dot density 10^{10} cm^{-2}**
- **n-doped with dopant density ~ dot density**

Resonant excitation of singly-charged dots

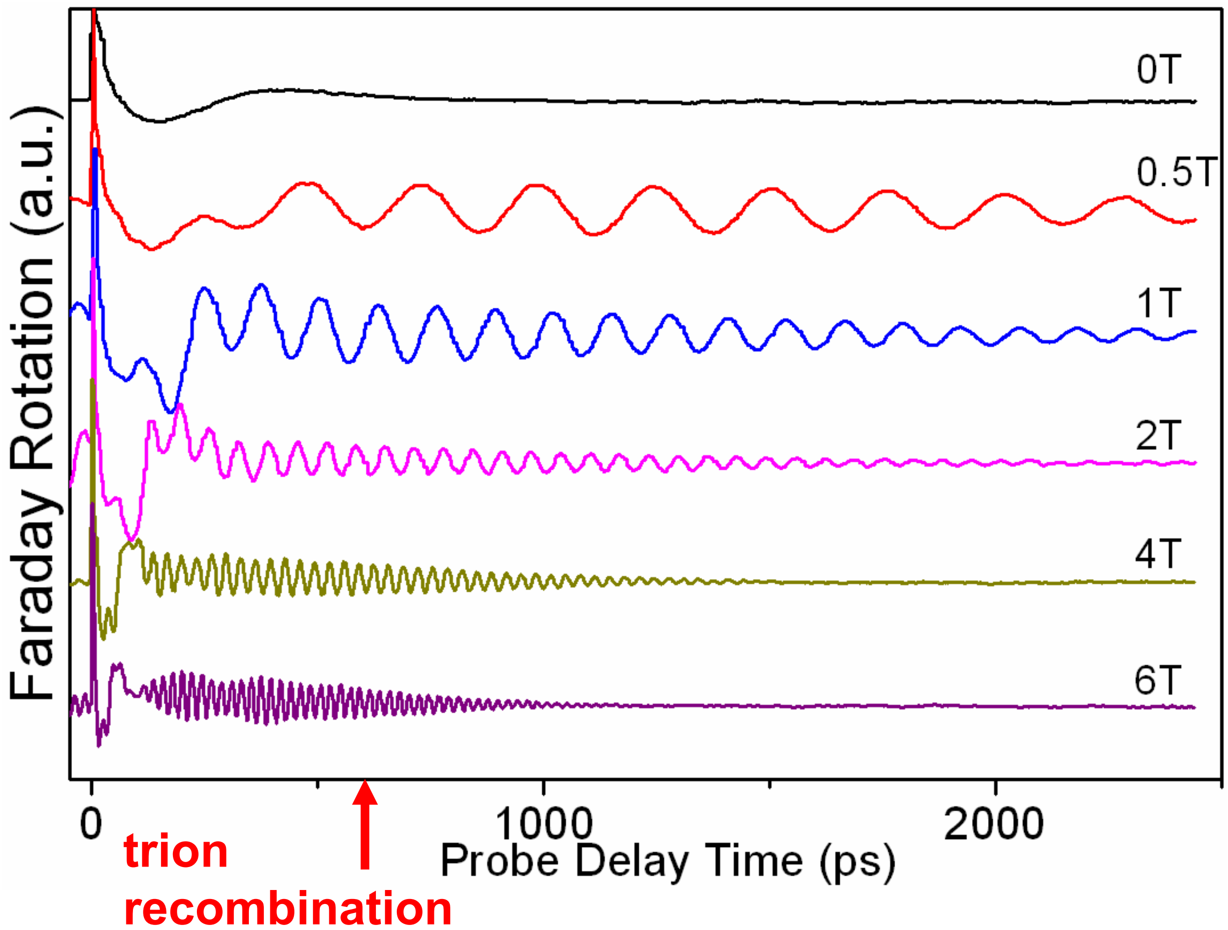


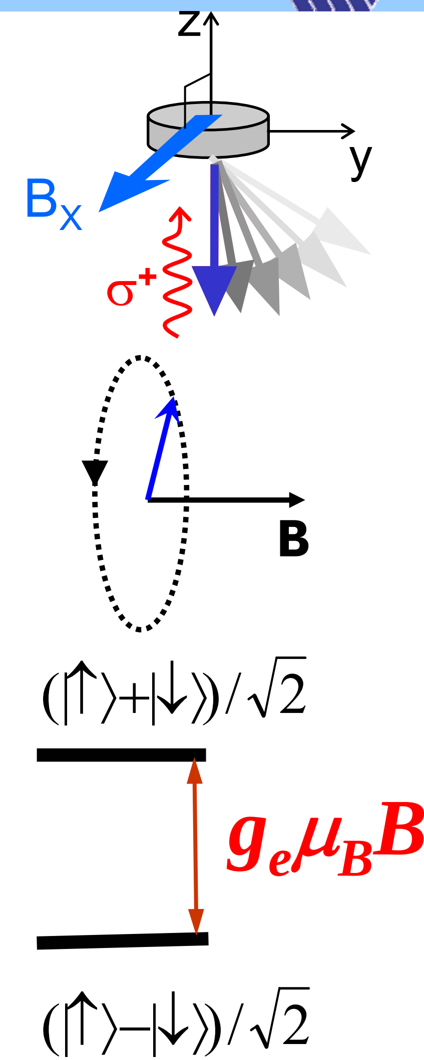
Charged exciton or "trion"

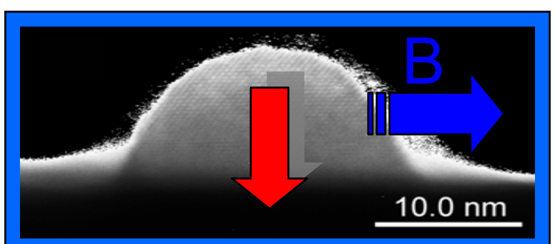


Ground state electron

Optical generation of spin coherence



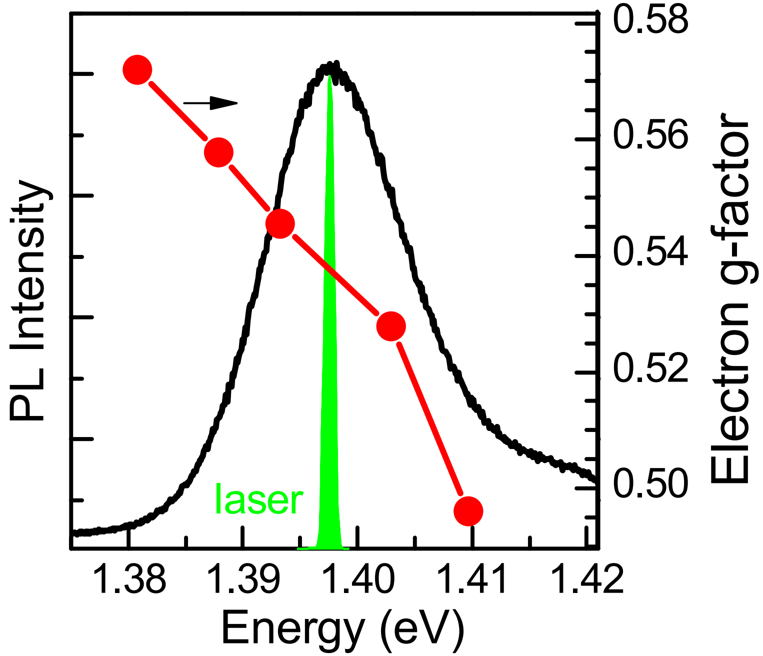




long-lasting electron spin beats

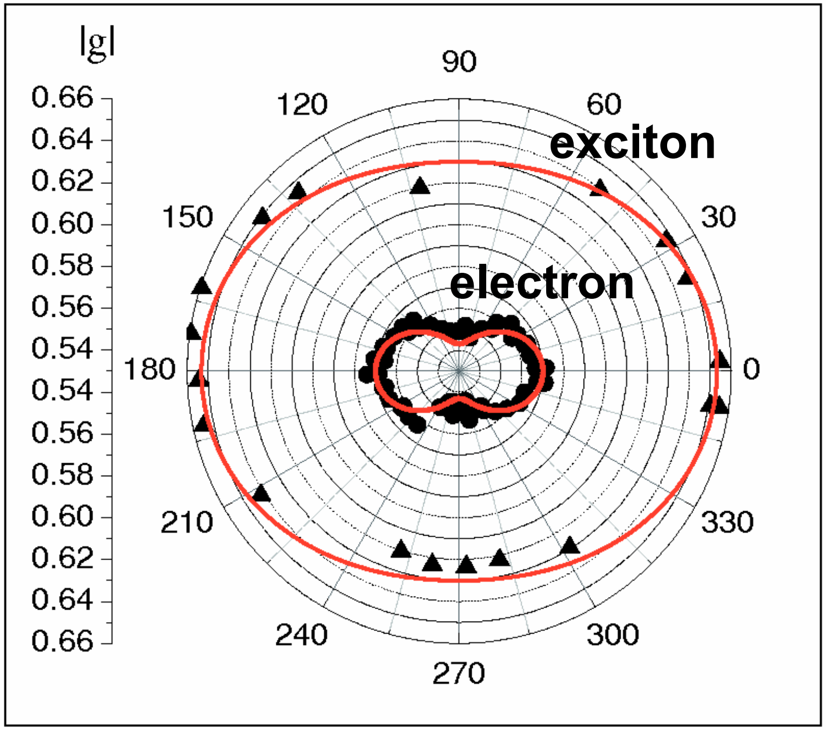
Greilich et al. PRL 96, 227401 (2006)

Electron g-factor in quantum dots



$$g_e = g_0 - \frac{4m_0P^2}{3\hbar^2}\frac{\Delta}{E_g\,(E_g+\Delta)}$$

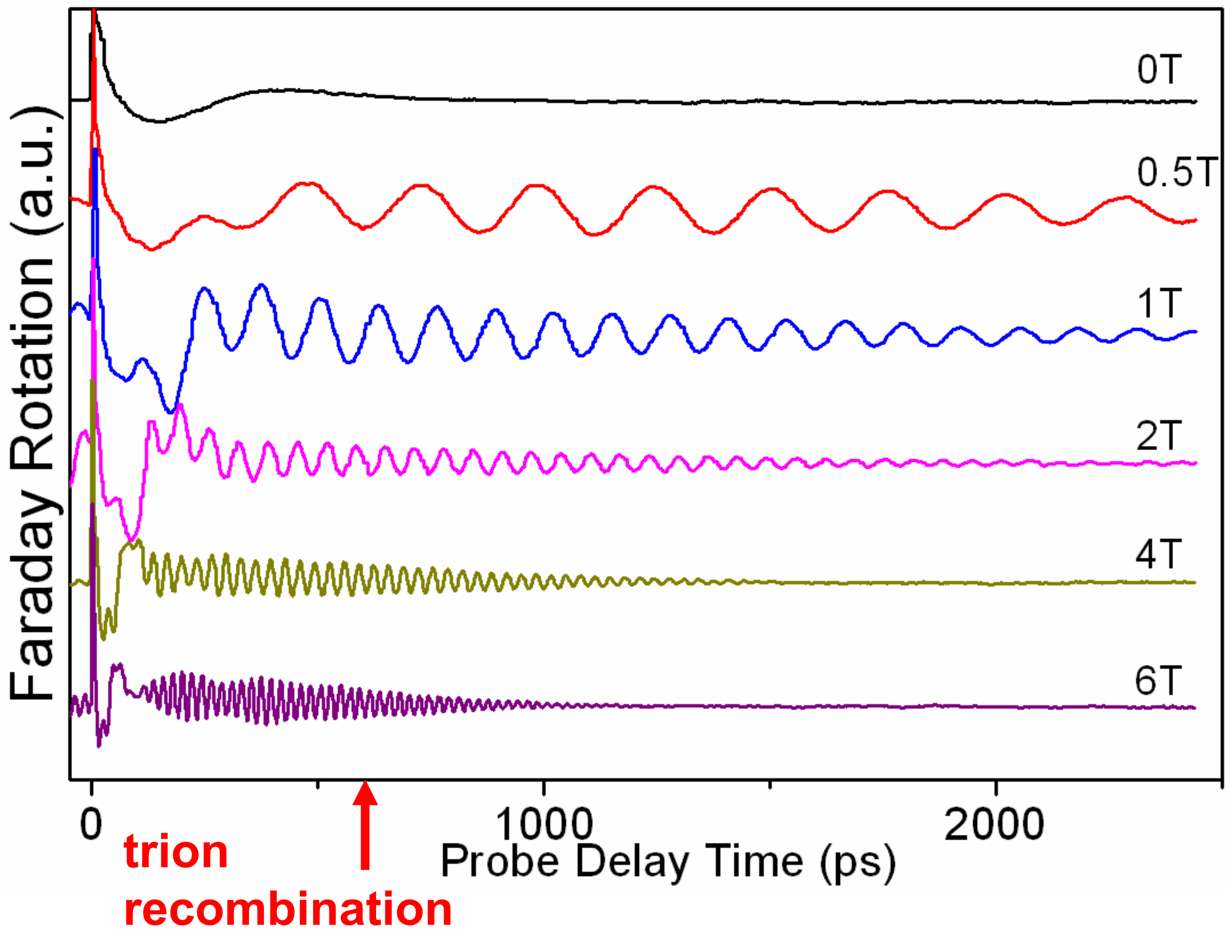
In-plane anisotropy



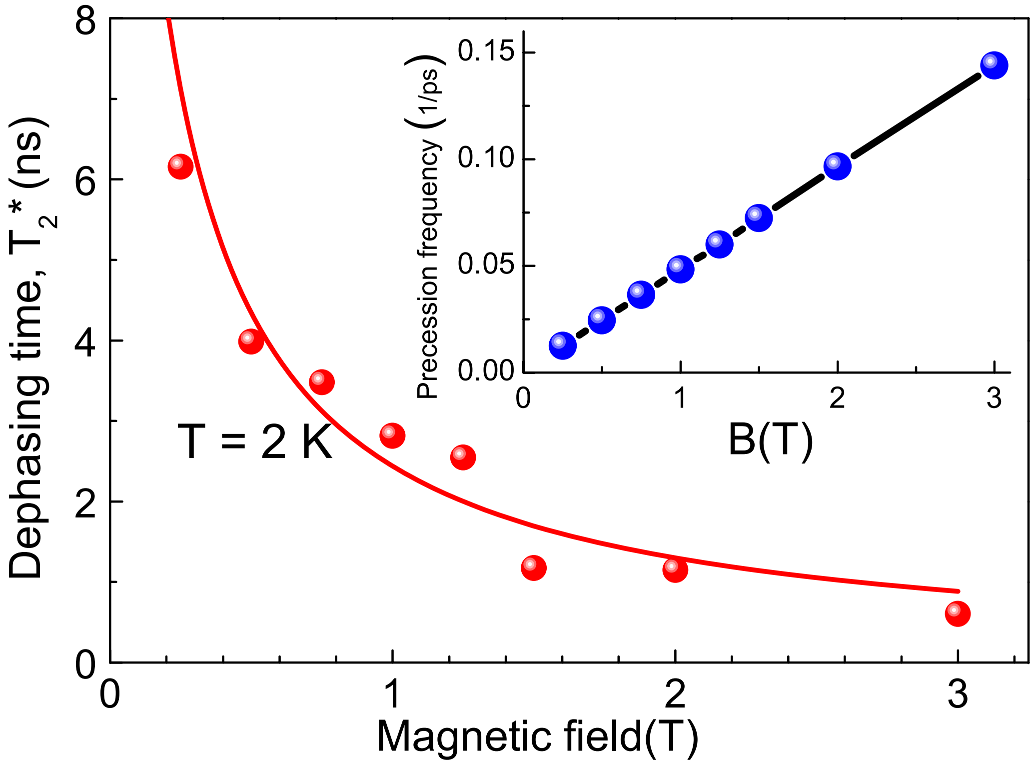
$g_x = -0.57$

$g_y = -0.54$

Optical generation of spin coherence



InGaAs quantum dots



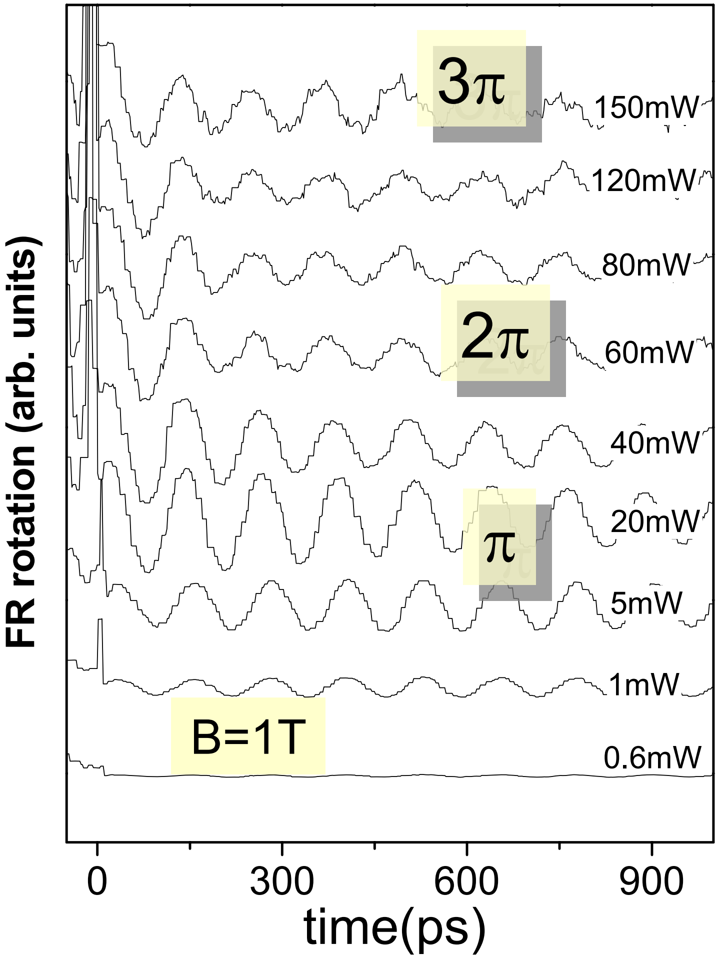
dephasing of ensemble

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^{inh}(\Delta g)}$$

decoherence of single spin

⇒	**Δg_e = 0.7%**	**g_e is rather insensitive to dot variations**
⇒	**T_2*(B=0) > 6ns**	**dephasing in random nuclear magnetic field**

Pump power dependence



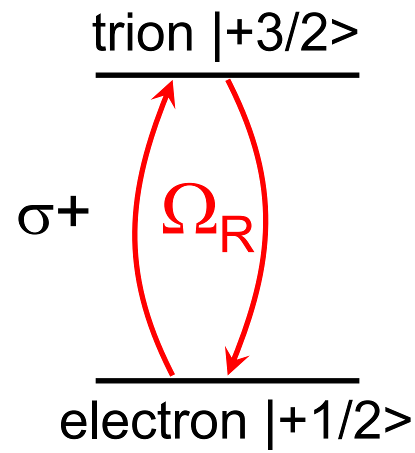
non-monotonic increase of amplitude with increasing excitation power

P. Borri et al, PRB 66, 081306 (2002)

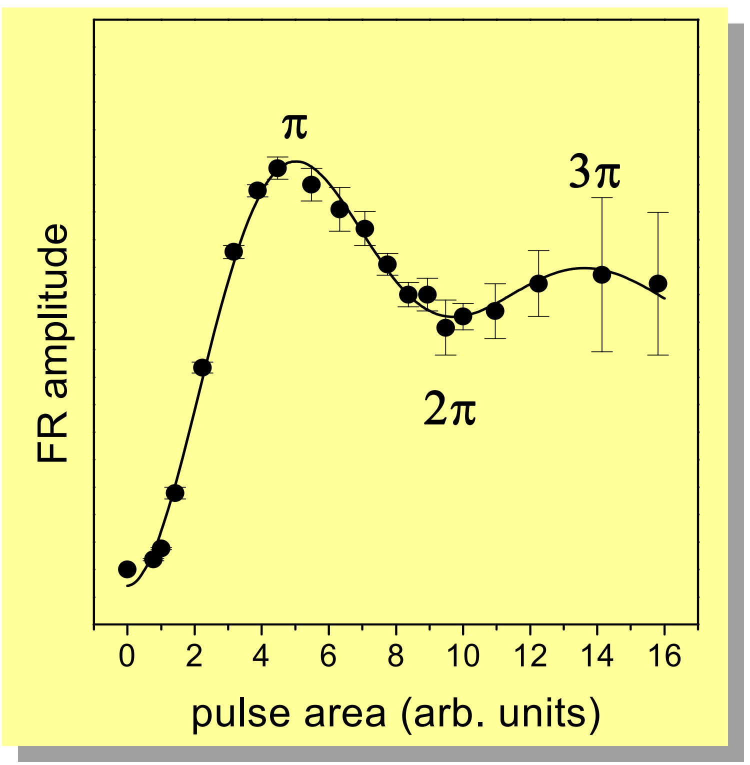
Rabi-oscillations

pulse area

$$\theta = \frac{1}{\hbar}\int_{-\infty}^{\infty} \vec{p}\vec{E}dt$$

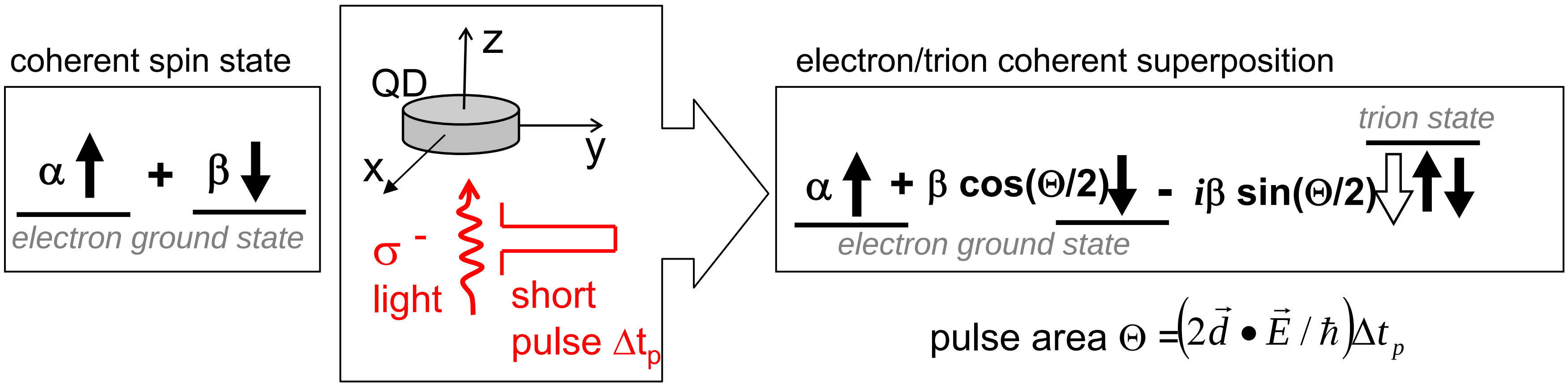


$\hbar$

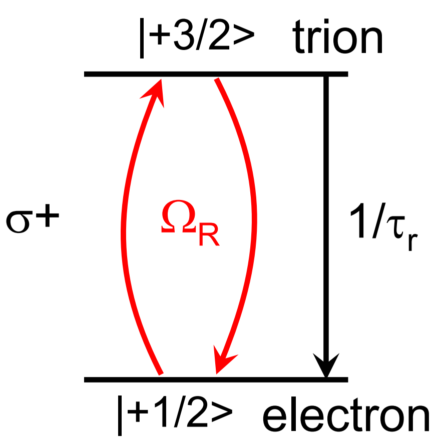


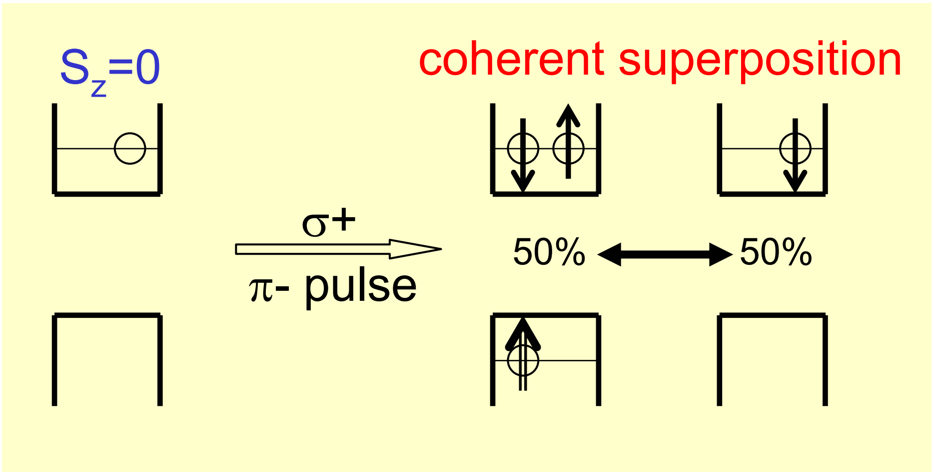
Generation of spin coherence

coherent spin superposition of electron and trion



pulse area $\Theta = \left(2\vec{d} \bullet \vec{E} / \hbar\right)\Delta t_p$

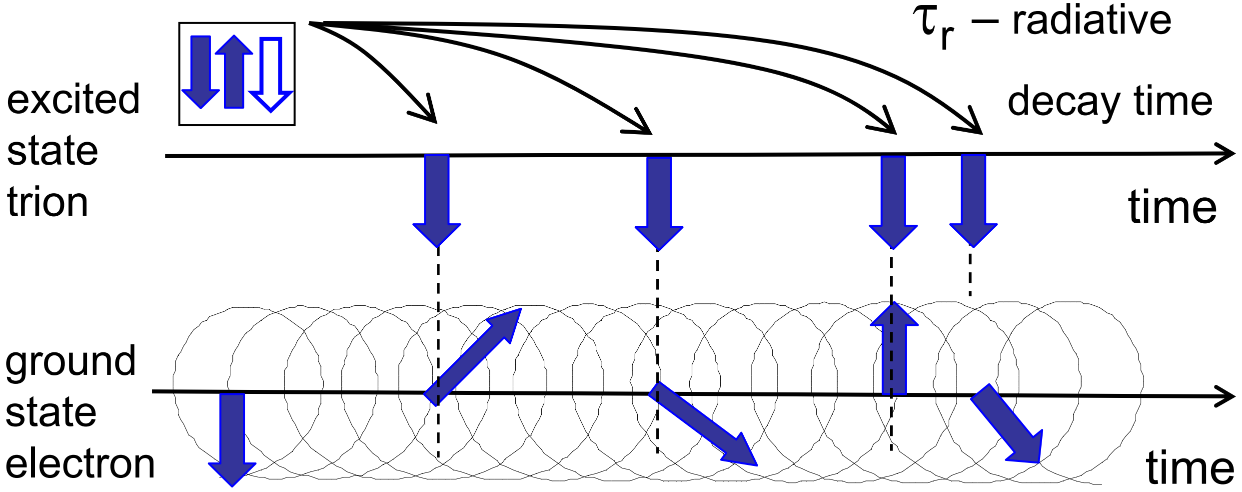




Shabaev, Efros PRB 68, 201305R (2003)
Greilich et al. PRL 96, 227401 (2006)

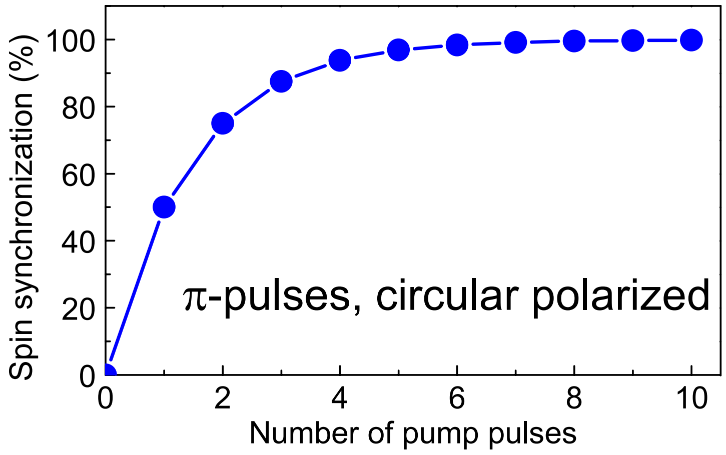
Generation of spin coherence

decay of trion



Spontaneous decay of trion does not affect spin coherence at $\omega_L \tau_r >> 1$

initialization of spin coherence

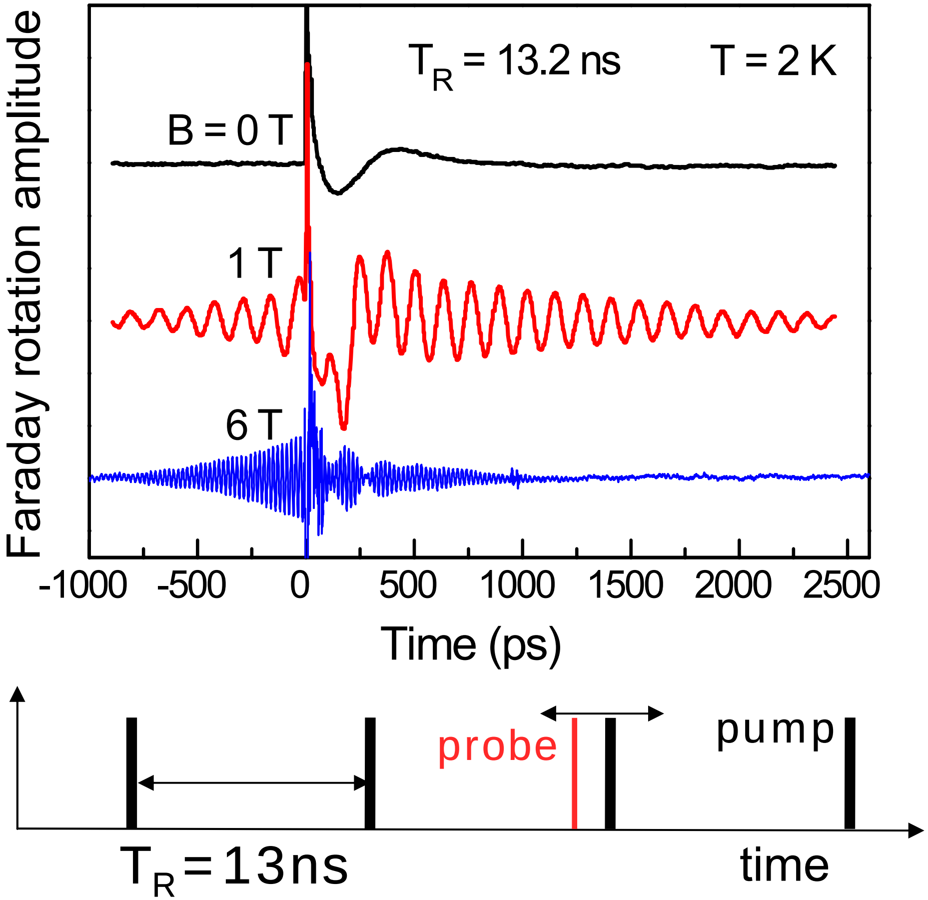


after a dozen of π-pulses:
99% electron spin polarization

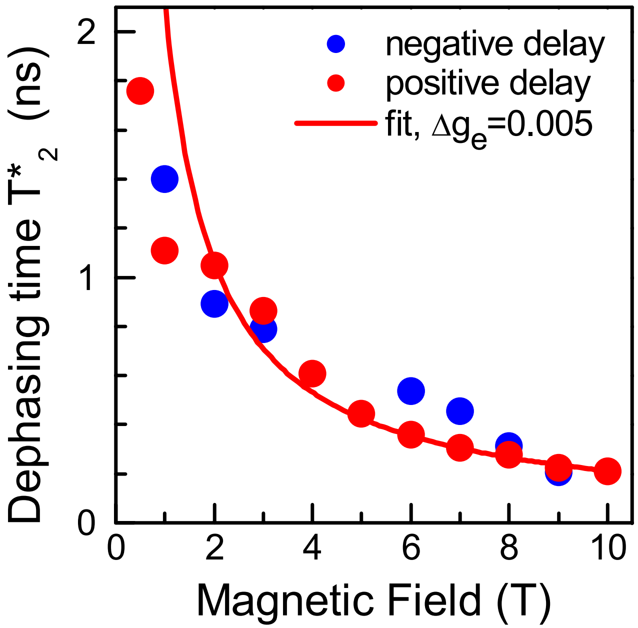
Mode-locking of electron spin coherence

- **Phase synchronization of spin precession**
- **Spin coherence time T_2 of electron in a dot**
- **Two-pulse control**
- **Robustness**
- **Polarization phase control**

Spin precession at negative time delay



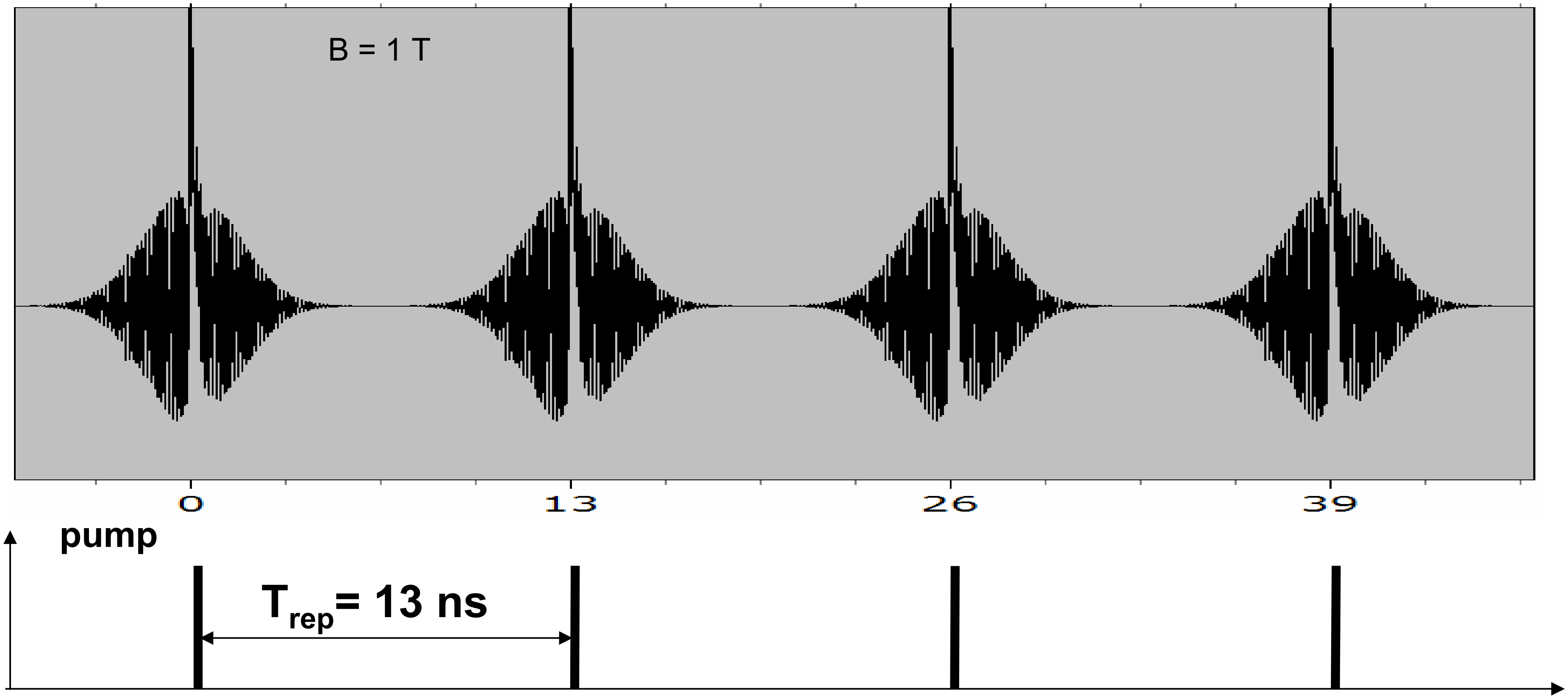
dephasing of spin ensemble



spin coherence in each dot lasts much longer than the pulse repetition period and dephasing time of ensemble (T_2*=2 ns).

Greilich et al., Science 313, 341 (2006)

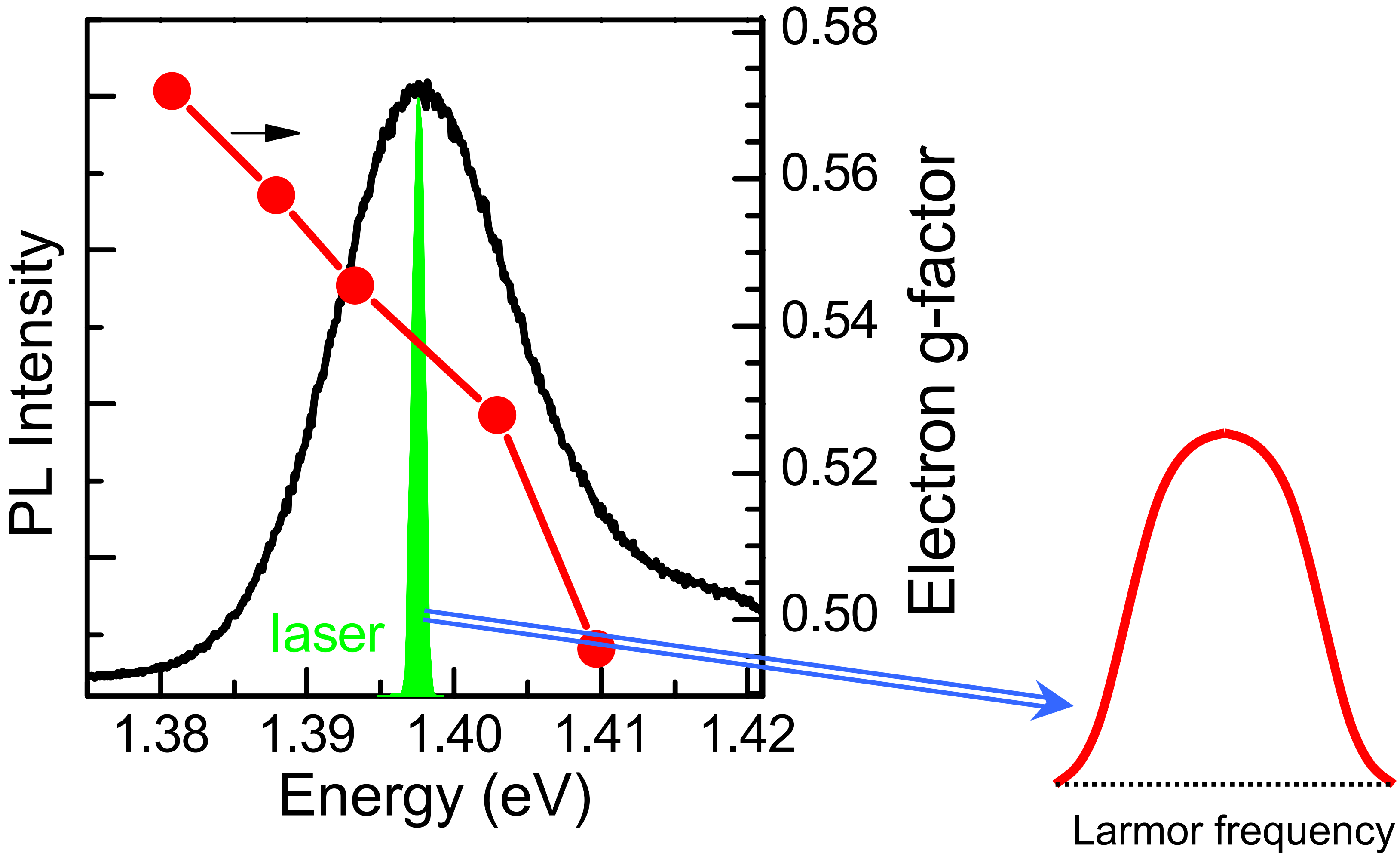
Spin coherence in QDs



• spin coherence of ensemble is short, $T_2^* < 10$ ns

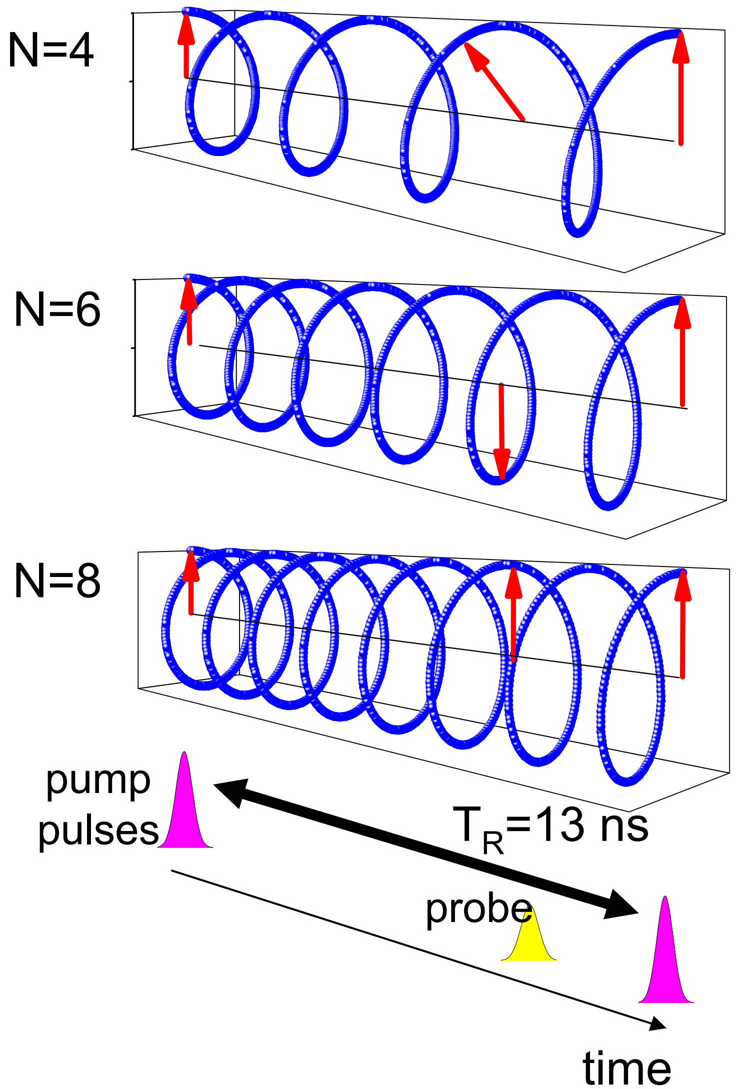
⇒ spin coherence in each dot is longer than T_{rep}

Dispersion of Larmor frequencies due to Δg_e

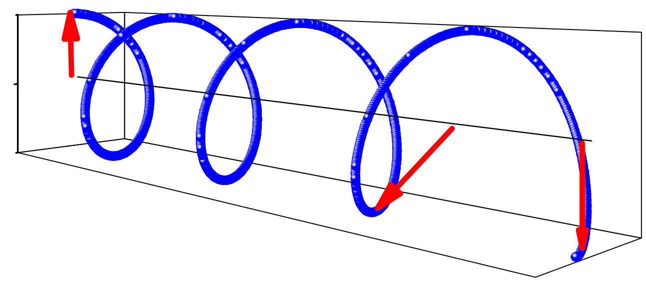


Phase-locked spin precession

spin precession synchronized by mode-locked pump laser

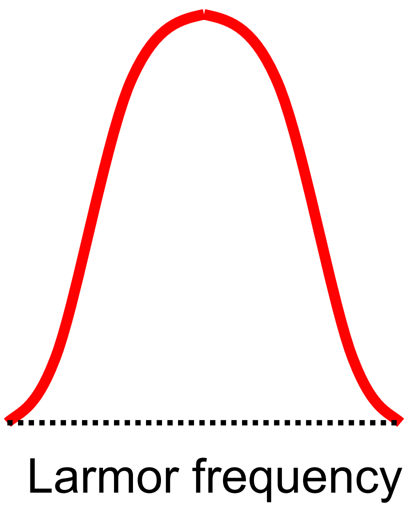


Out of phase mode

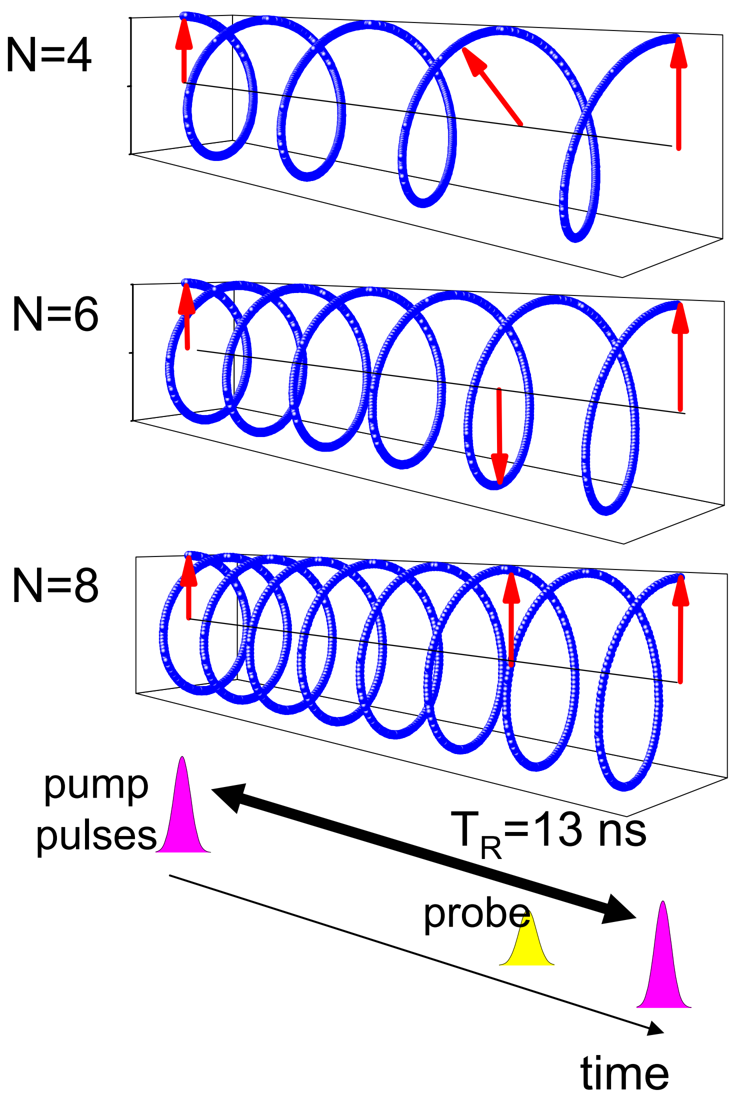


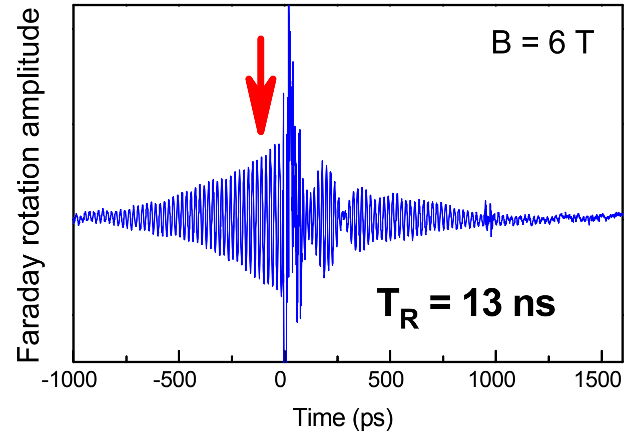
Phase synchronization condition

$$\omega_L = \frac{2\pi N}{T_R}$$



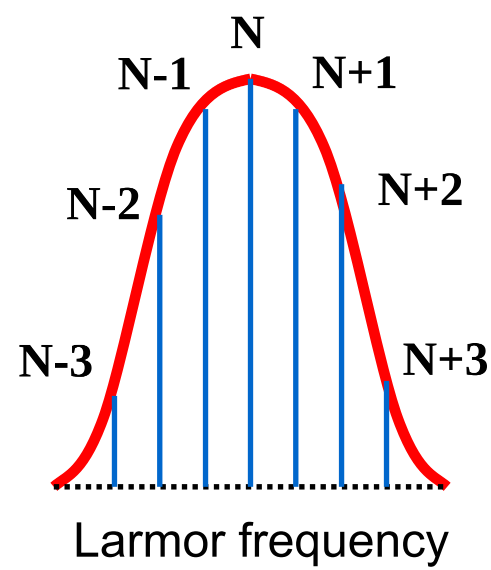
Phase-locked spin precession



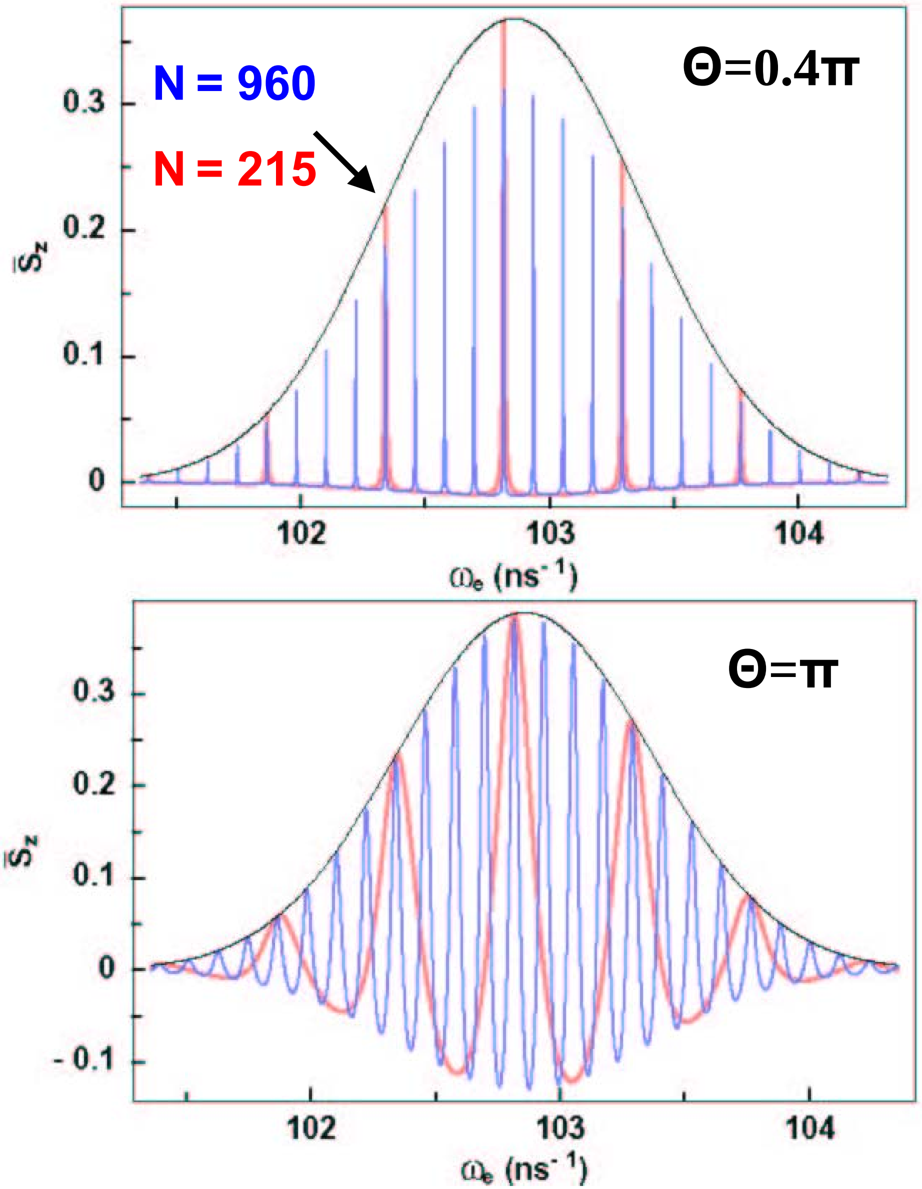


Phase synchronization condition

$$\omega_L = \frac{2\pi N}{T_R}$$



Spin coherence in QDs



Calculation of spin synchronization for different T_2 und T_R

T_R = 13.2ns

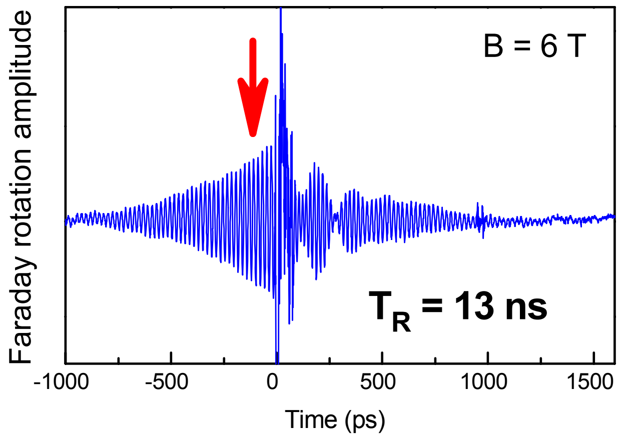
T_R = 52.8ns

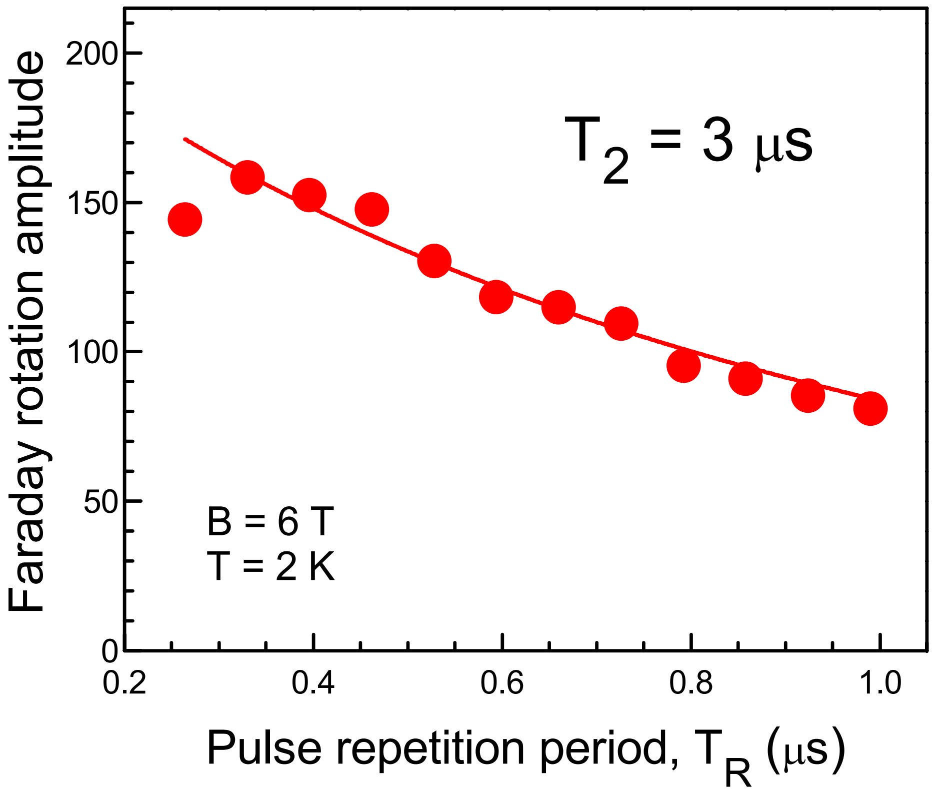
$$\omega_L = \frac{2\pi N}{T_R}$$

Spin coherence time T_2 of single electron

Repetition period T_R varied by pulse-picker from 13 to 1000 ns

FR amplitude $\propto \frac{T_2}{T_R}$



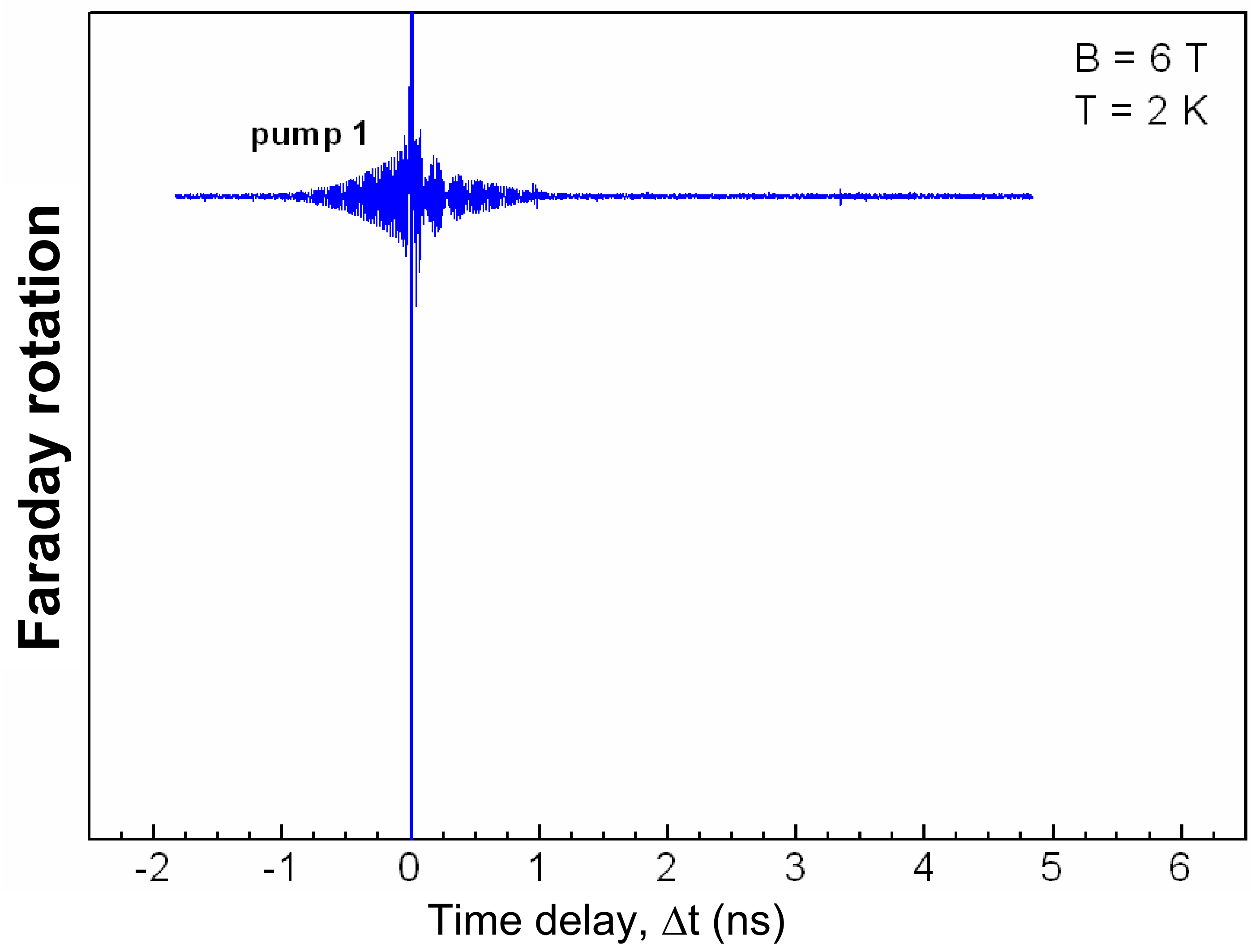


decay time is single dot coherence time T_2 = 3 μs

four orders of magnitude longer than ensemble dephasing T_2^* = 0.4 ns !

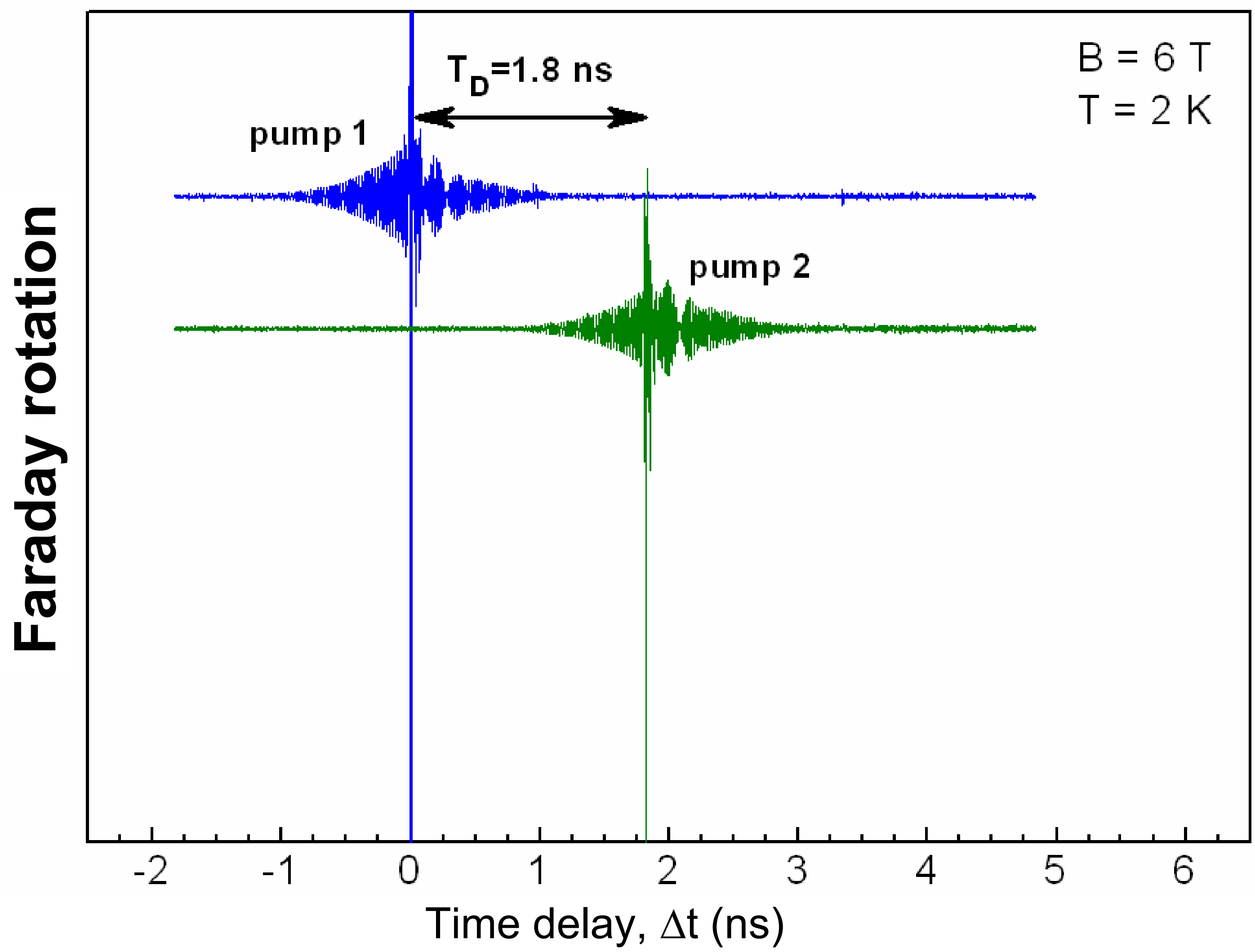
Petta et al., Science 309, 2180 (2005)

Two pump pulse control



Only pump 1 is on

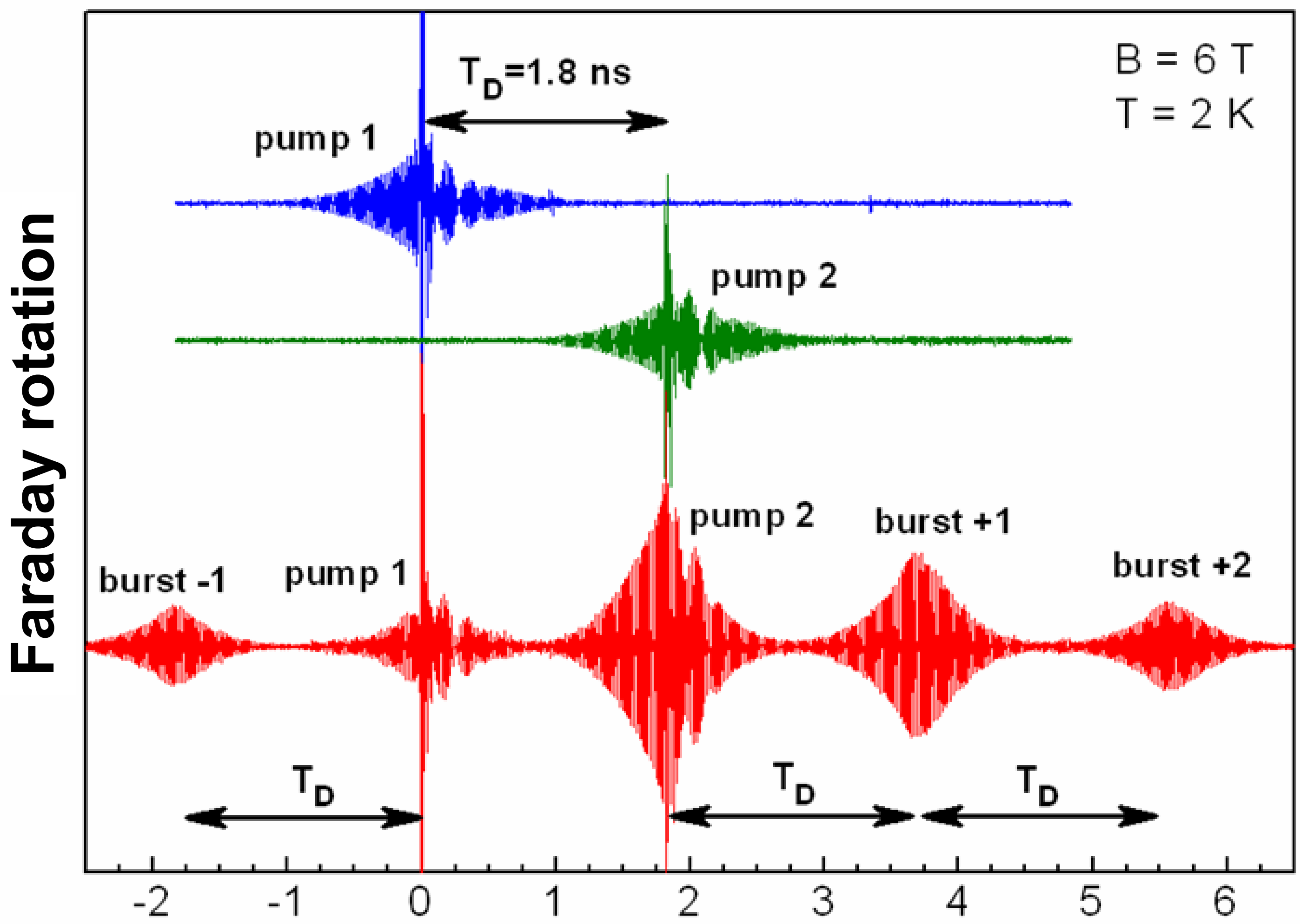
Two pump pulse control



Only pump 1 is on

Only pump 2 is on

Two pump pulse control



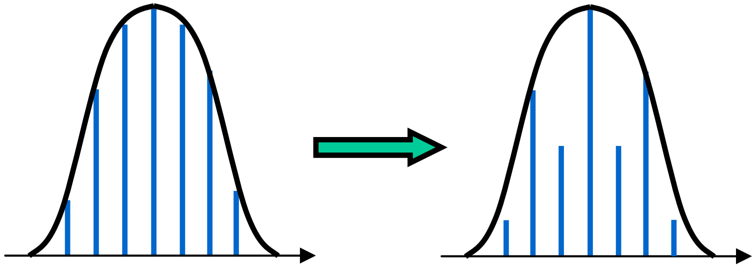
Only pump 1 is on

Only pump 2 is on

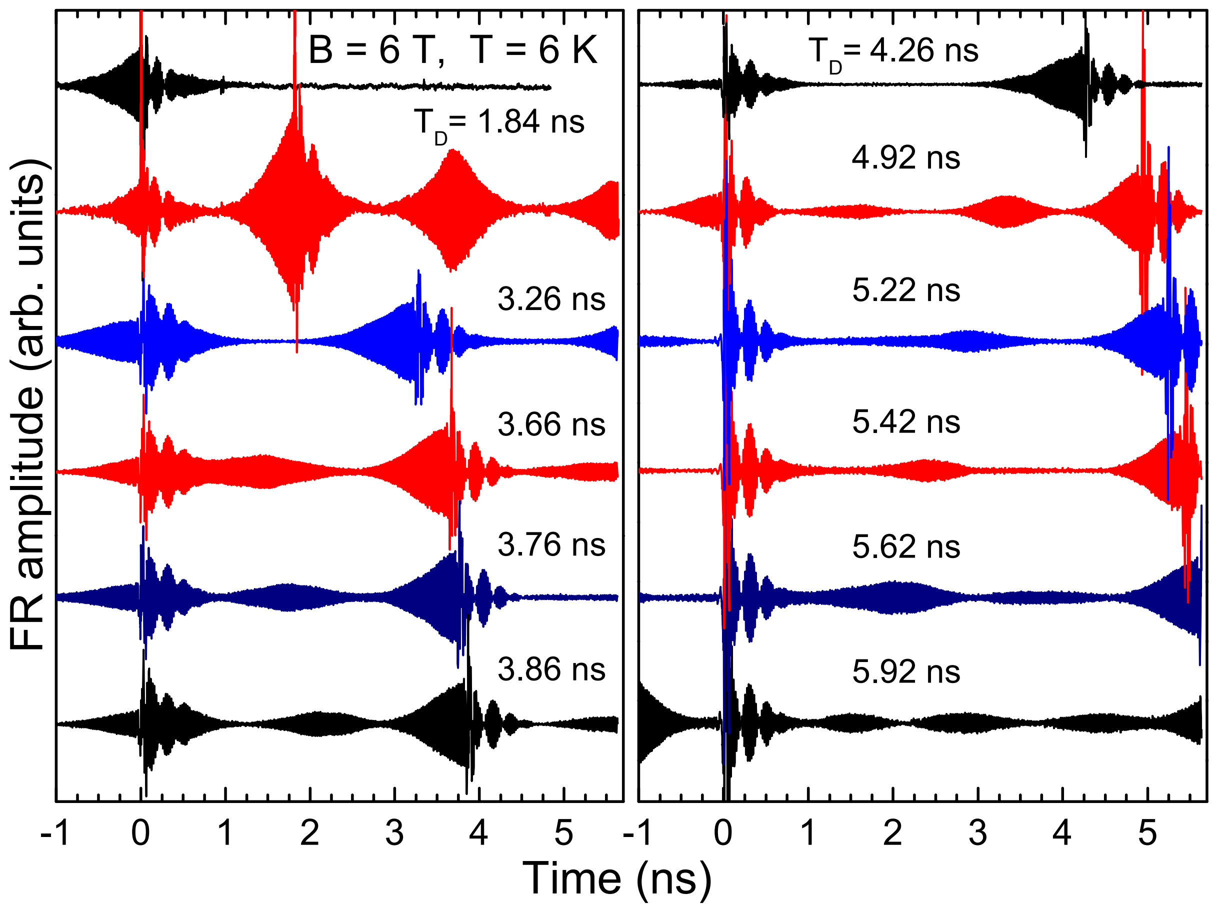
Both pumps are on

$T_D = T_{rep} / 7$

$$\omega_e = \frac{2\pi N}{T_{rep}} = \frac{2\pi M}{T_{rep} - T_D}$$



Two pump pulse control



Commensurability conditions:

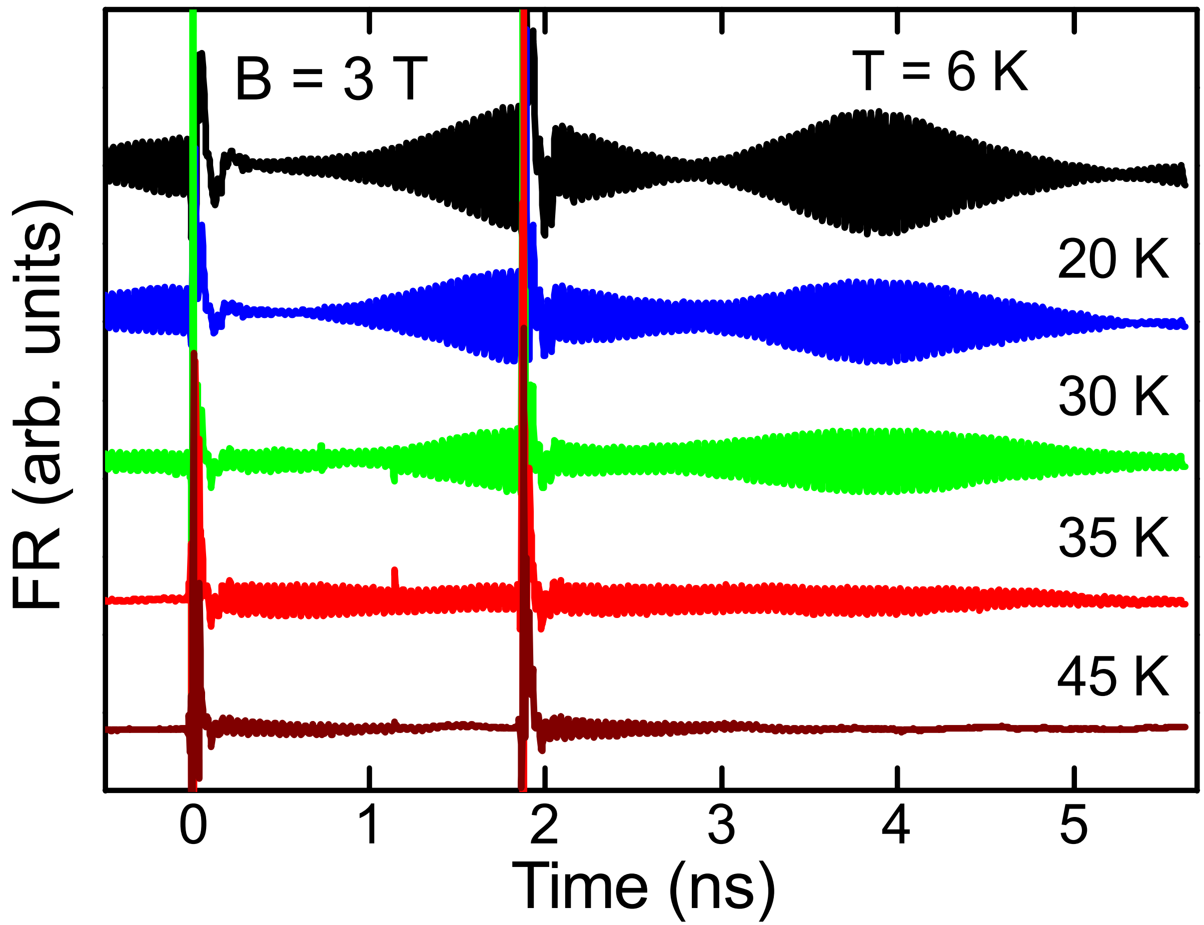
$T_D=T_R/7=1.84$ ns

$T_D=T_R/4=3.26$ ns

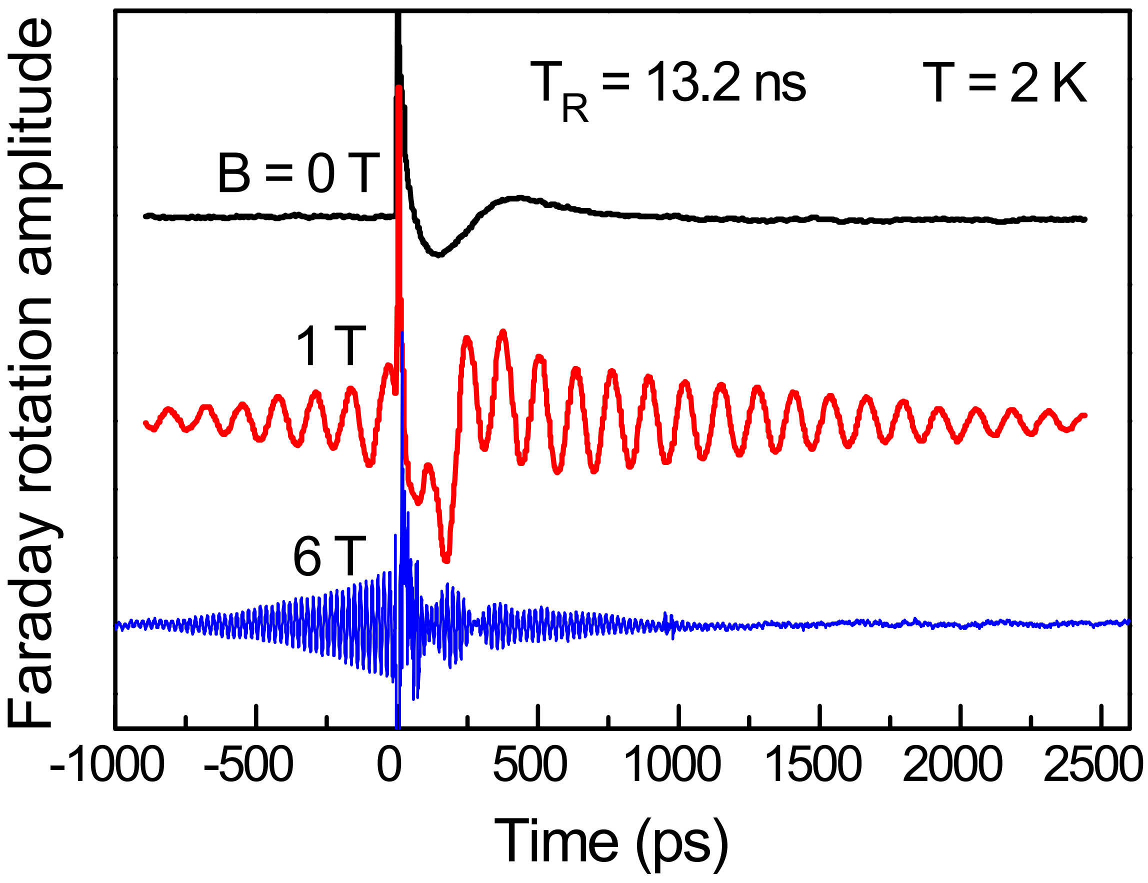
$T_D=T_R/3=4.26$ ns

Greilich et al., PRB 75, 233301 (2007)

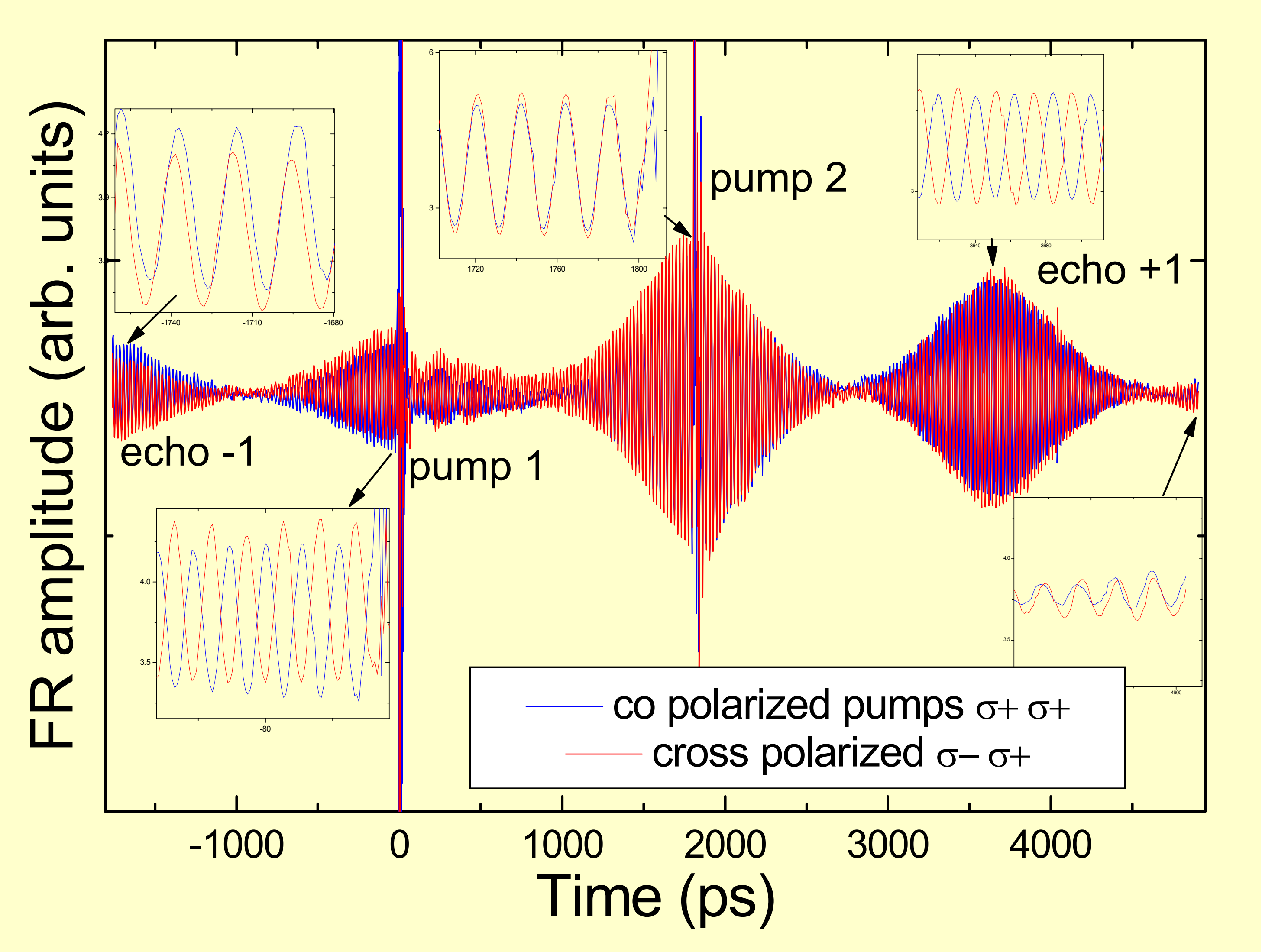
Temperature stability of mode-locking



Robustness against magnetic field



Phase control of spin precession



B = 6 T
T = 2 K

Greilich et al., PRB 75, 233301 (2007)

Mode-locking summary

Robustness of mode-locking:

- Wide range of Larmor frequencies, i.e. versus magnetic field
- Temperature range up to 40 K
- Ensemble of QDs with dispersion in energy and g-factor
- Spectrally broad laser line for generation and read out (1 meV)

Requirements for mode-locking:

- Ensemble of (localized) electron spins
- Coherence time of individual spin $T_2 >> T_R$
- Dispersion in Larmor precession frequencies

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