All optical control of electron spins in quantum dot ensembles

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Experimentelle Physik II

Technische Universität Dortmund

JST-DFG workshop, Aachen, 05.-07.03.2008

Acknowledgements

A. Greilich, S. Spatzek, I. Yugova, I. Akimov, D. Yakovlev,
Technische Universität Dortmund, Germany

A. Shabaev and A. Efros
Naval Research Laboratory, Washington DC, USA

D. Reuter and A. Wieck
Ruhr-University of Bochum, Germany

Acknowledgements

Bundesministerium für Bildung und Forschung

nanoQUIT

Research group:
„Quantum Optics in Semiconductor Nanostructures“

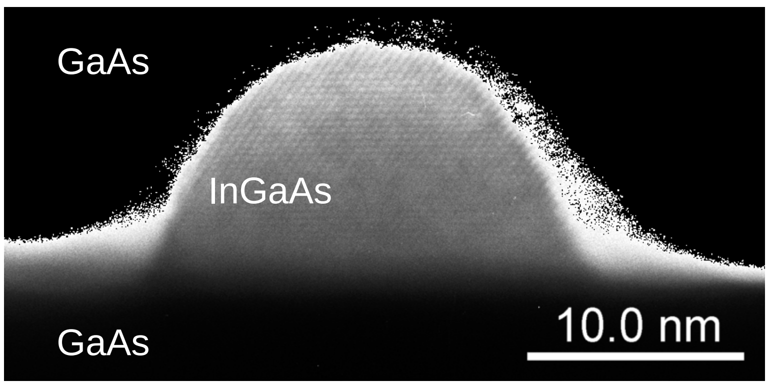
Deutsche Forschungsgemeinschaft
DFG

Borussia Dortmund
Fußball heißt das Spiel, Borussia seine Seele!

Quantum information processing

Potential of quantum information processing:

- **Increase of computational power**
- **Realization of new functionalities for communication**
- **Reduction of complexity**



Demand:

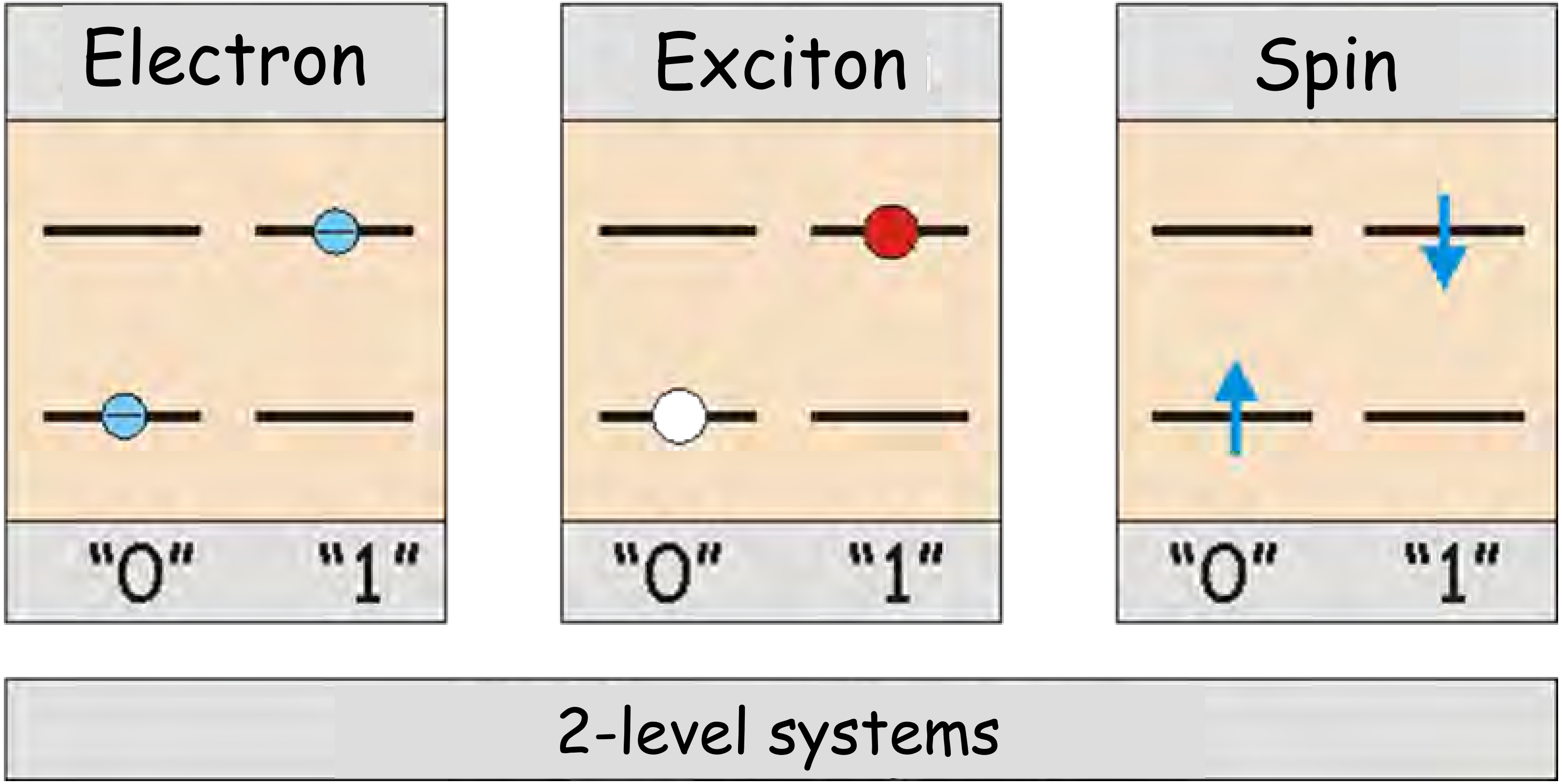
Long living coherence

$$\alpha|0\rangle + \beta|1\rangle \ \text{mit} \ \alpha, \beta = \text{const.}$$

Prerequisite

Availability of high quality quantum hardware: Quantum dots!

Qubit-candidates in QDs



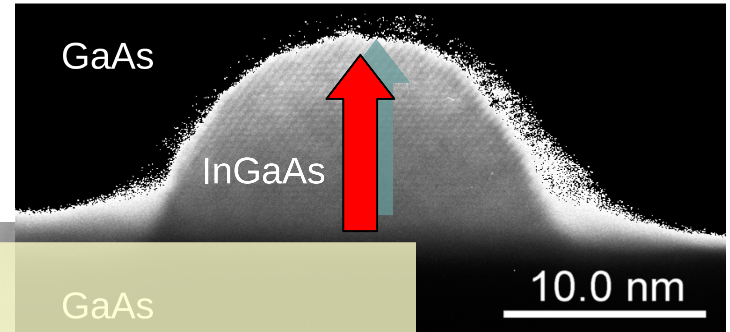
Spin is efficiently protected by confinement

against efficient relaxation mechanisms in higher-dim. systems.

Attractivity of QD electron spin qu-bits

Experiments on QD ensembles!!

Single electron per QD!



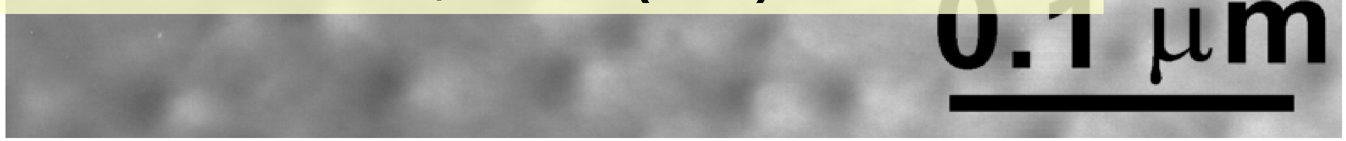
Relaxation times T_1

in high magnetic field:

TU Delft:	**gated QDs** **Nature 430, 431 (2004)**	T_1 **~ 10 ms**
TU Munich:	**self-assembled QDs** **Nature 432, 81 (2004)**	T_1 **~ 10 ms**

at zero magnetic field:

Dortmund:	**self-assembled QDs** **PRL 98, 107401 (2007)**	T_1 **~ 0.3 s**



Single spin vs spin ensembles

- **Single spin**

Pro:

avoid inhomogeneities

Con:

fragile

weak spectroscopic signal

- **Spin ensemble**

Pro:

robustness

strong spectroscopic signal

Con:

inhomogeneities

Outline

1. Introduction
2. Faraday rotation with time resolution
3. Generation of spin coherence
4. Mode-locking of spin coherence
5. Tailoring of mode-locking
6. Electron spin focussing by nuclei
7. Current work

Quantum dot samples

Self-assembled quantum dots

- **20 layers of InGaAs/GaAs QDs with density ~ 10^{10}cm^{-2} per layer**
- **n-doped 20nm below QD layer - dopant density ~ dot density**
- **thermal annealing (T>900°C for 30s) to use Si-based detectors**

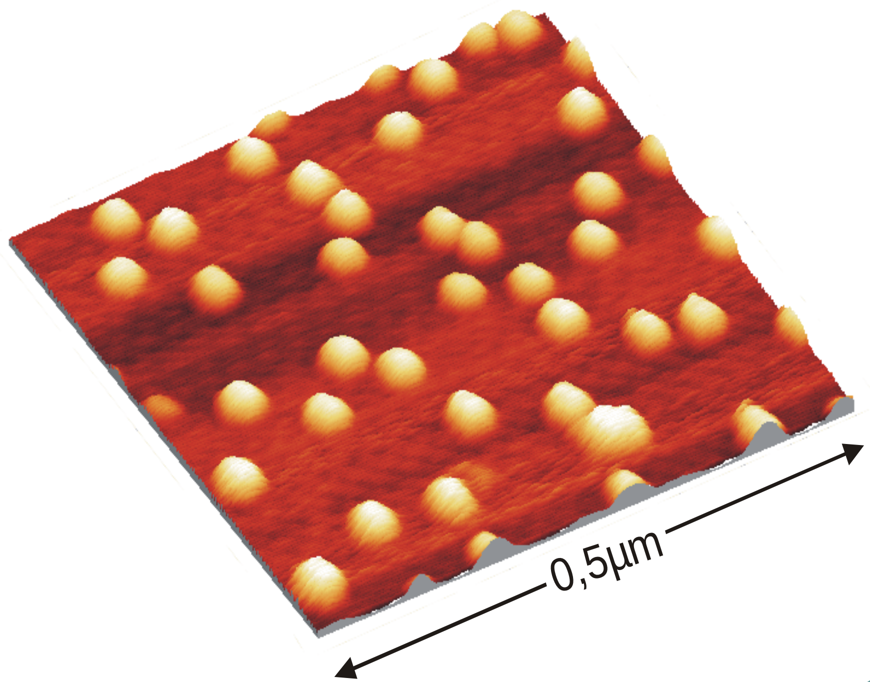
Non-annealed QD geometry:

dome-shaped

~ 25 nm diameter

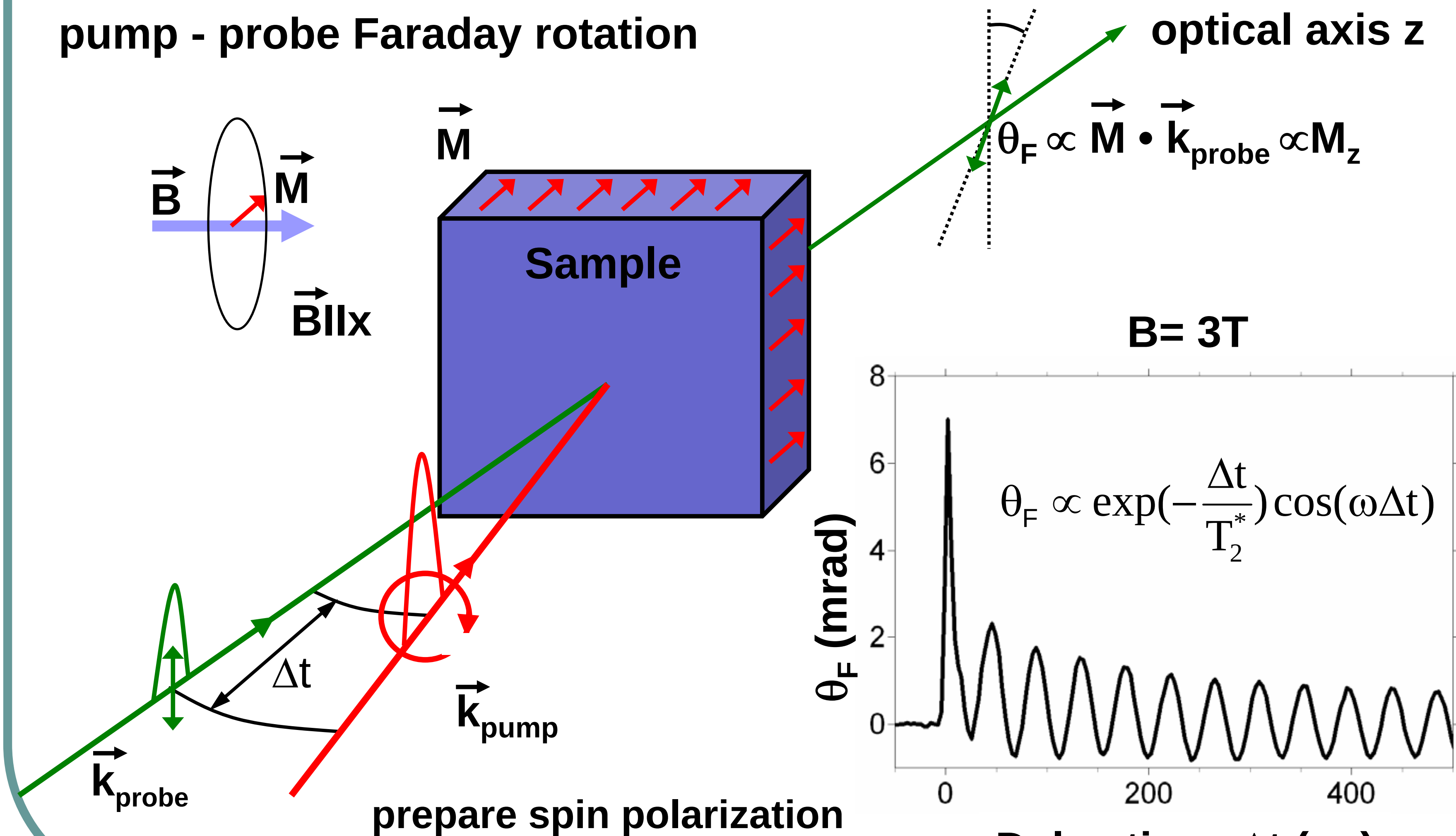
~ 5 nm height

large oscillator strength!



Experiment

pump - probe Faraday rotation



prepare spin polarization

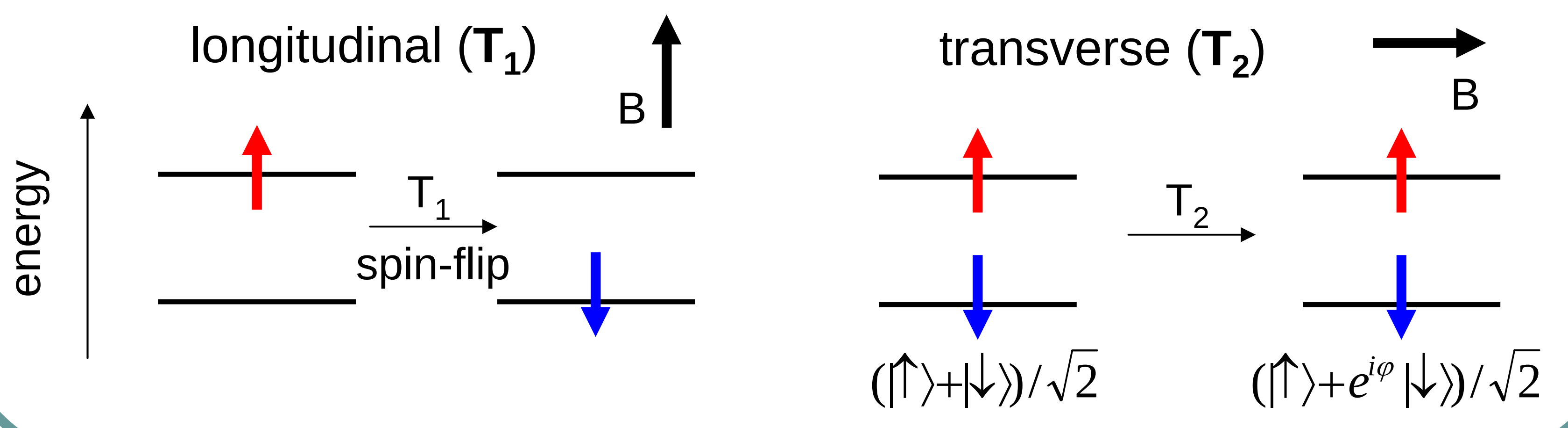
Spin relaxation

characteristic quantities:

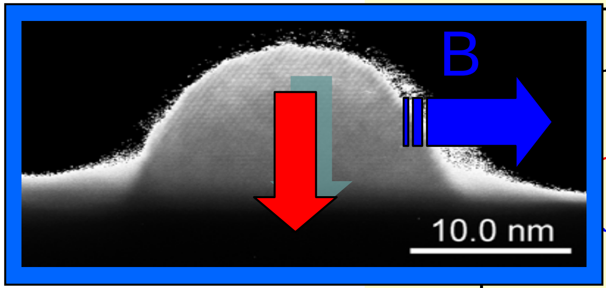
T_1	**relaxation**
	longitudinal relaxation time
T_2	**decoherence**
	transverse relaxation time

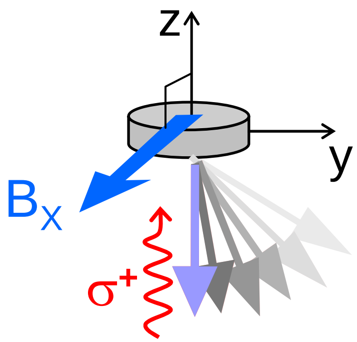
spin dynamics of electron

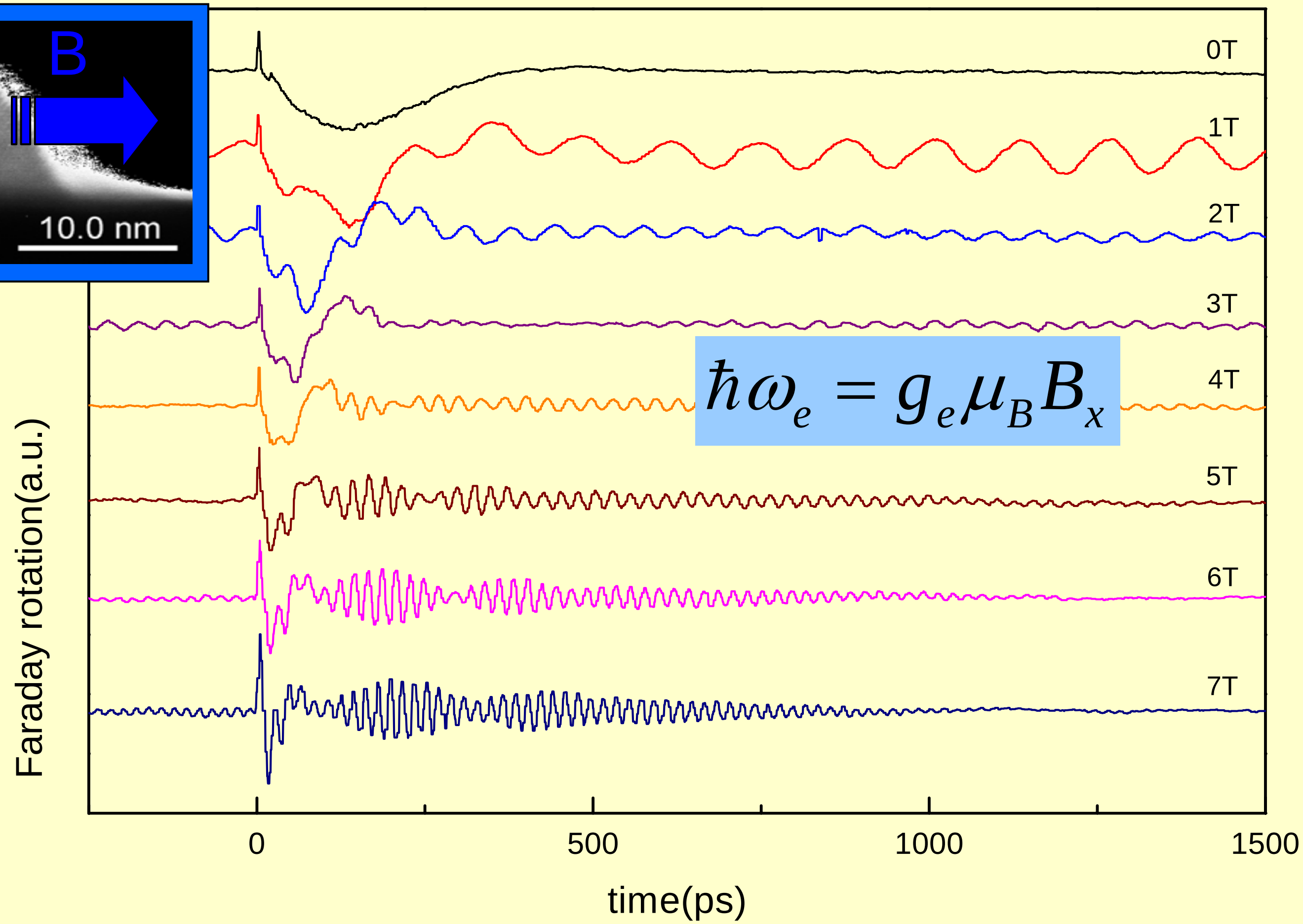
T_2^*	**dephasing**
	ensemble effects (inhomogeneities, measurement variations etc)



Precession about magnetic field



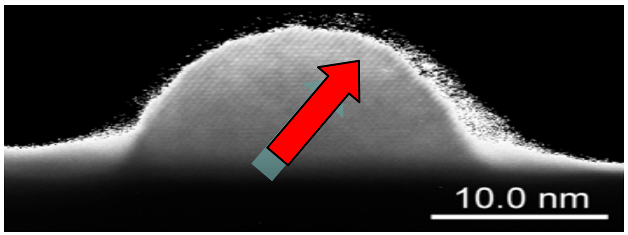


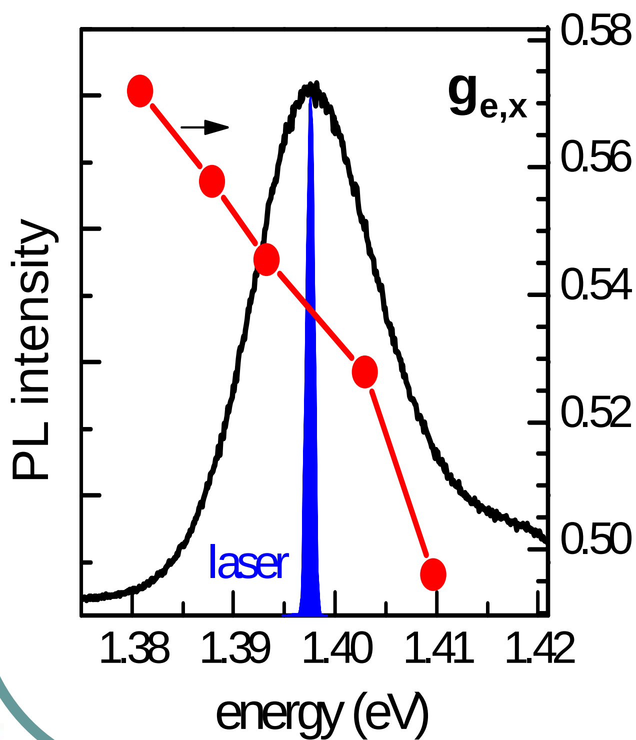


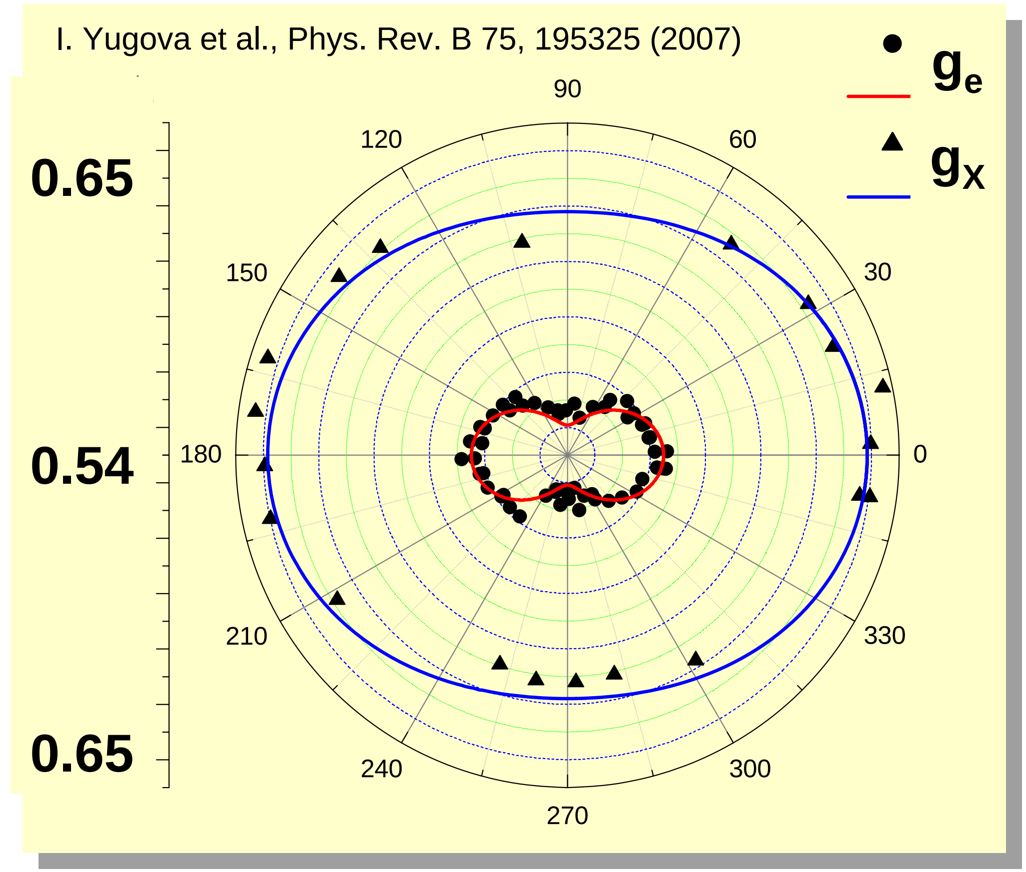
$$\hbar\omega_e = g_e \mu_B B_x$$

A. Greilich et al., Phys. Rev. Lett. 96, 227401 (2006)

Electron g-factor tensor



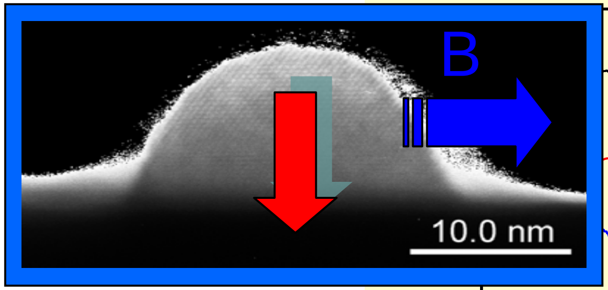


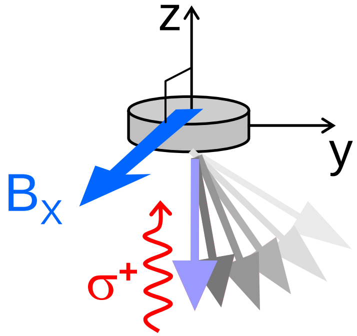


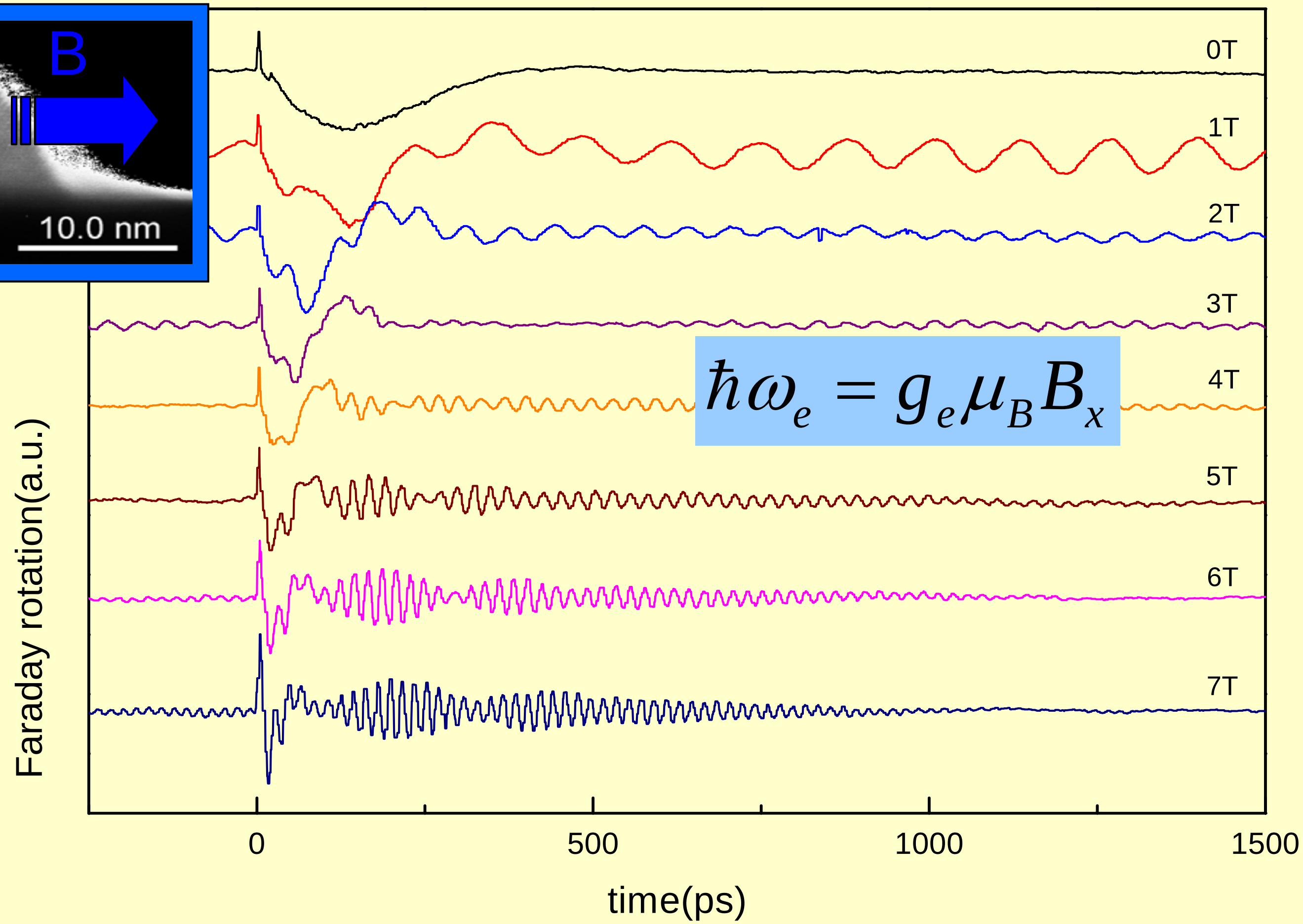
considerable variation of g-factor

I. Yugova et al., Phys. Rev. B 75, 195325 (2007)

Precession about magnetic field



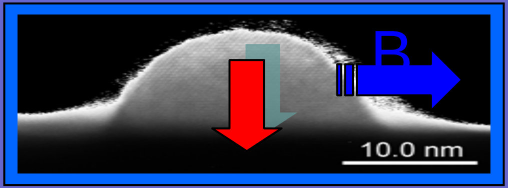


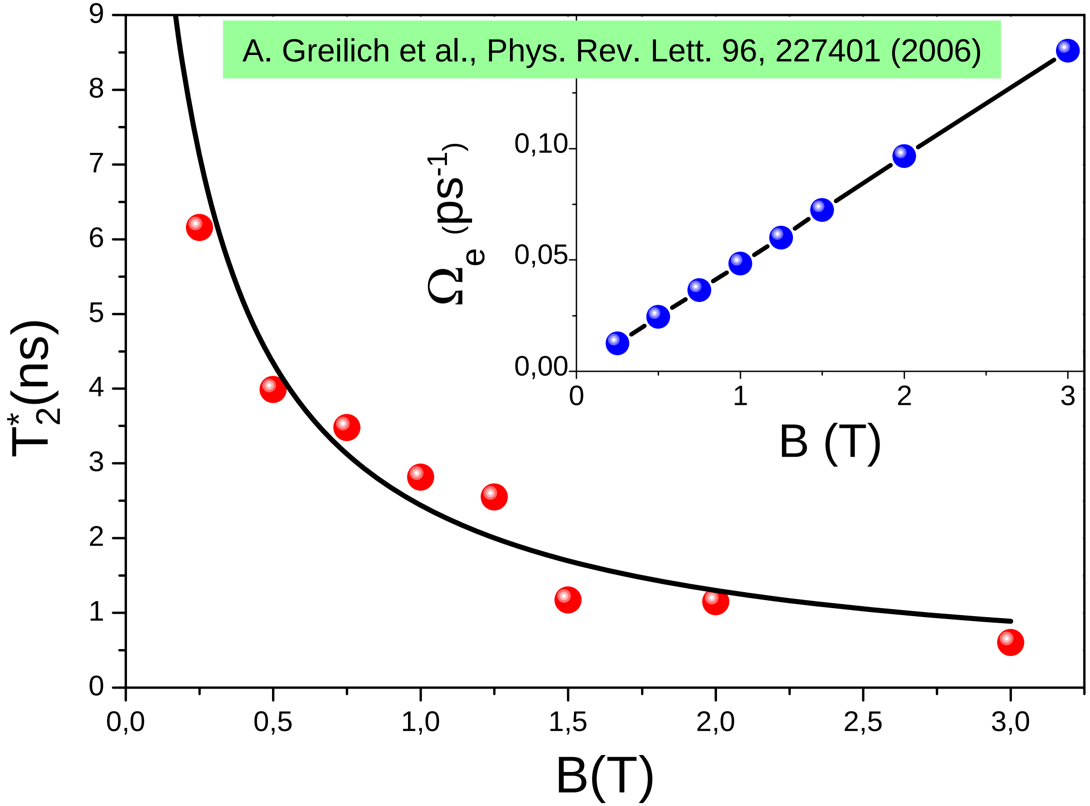


$$\hbar\omega_e = g_e \mu_B B_x$$

A. Greilich et al., Phys. Rev. Lett. 96, 227401 (2006)

Analysis of FR data





FR amplitude

$$\propto \exp\left(-\frac{t}{T_2^*}\right)\cdot\cos(\Omega_e t)$$

$$\hbar\Omega_e = g_e\mu_B B$$

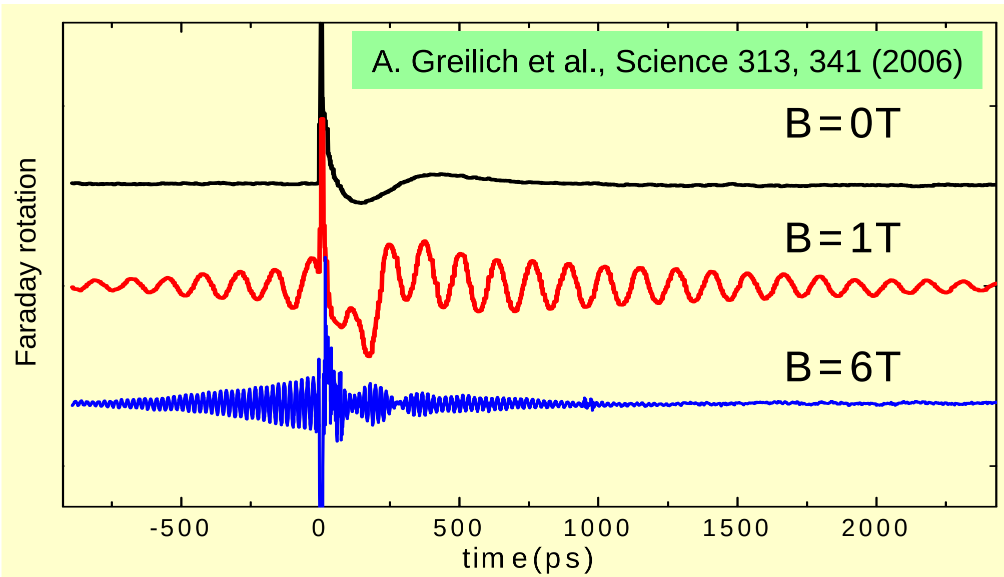
$$\Downarrow$$

$$|g_e| = 0.574$$

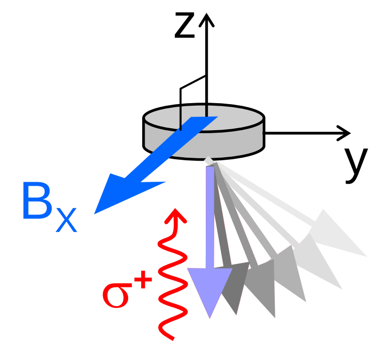
$$\Delta g_e \quad \Rightarrow \quad \hbar\Delta\Omega_e = \Delta g_e\mu_B B \quad \Rightarrow \quad \Delta g_e = 0.004 \equiv 0.7\%$$

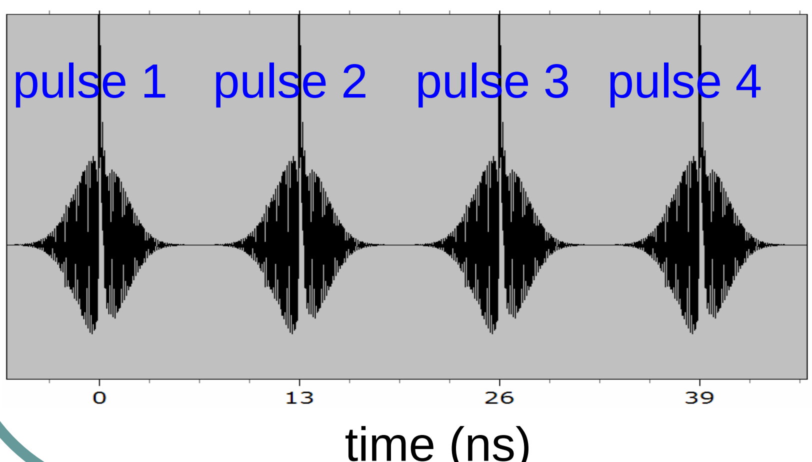
T_2*(B=0) > 6ns   dephasing in random nuclear magnetic field

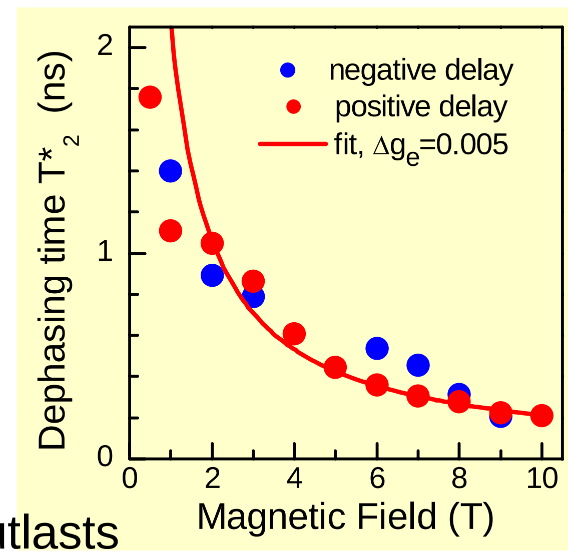
Long lasting spin coherence



$$T_2^* < 5ns$$

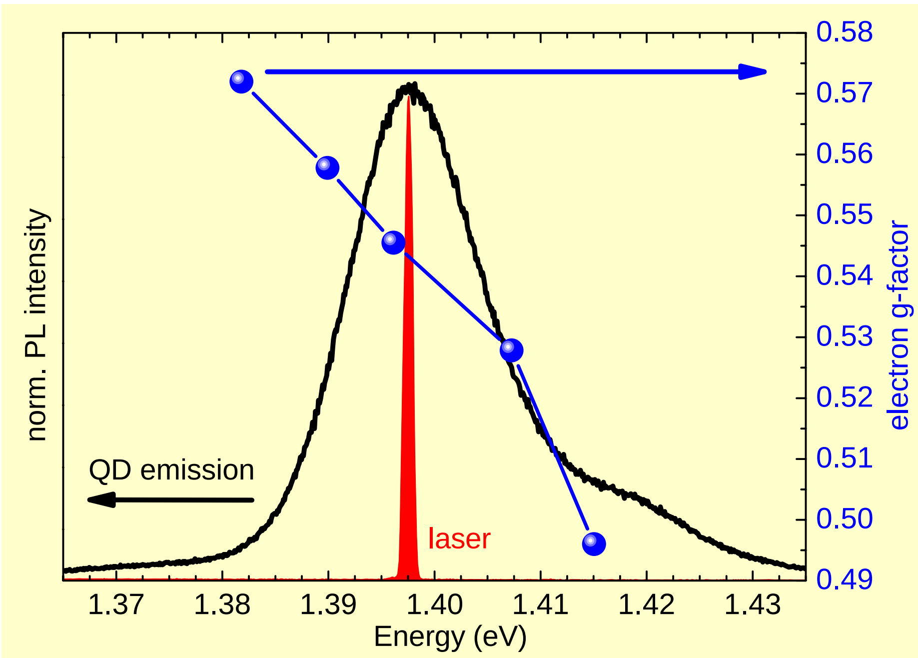


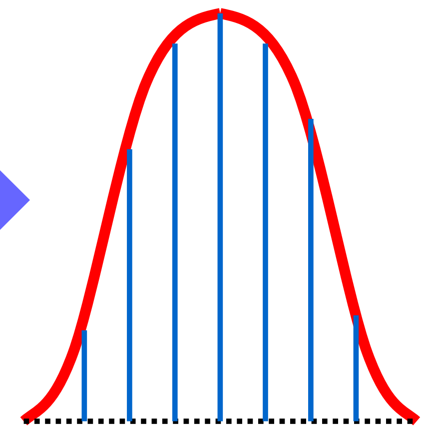




coherence outlasts
pulse repetition period
& dephasing time.

Spin mode locking





g-factor
precession frequency

QD ensemble offers broad distribution of g-factors

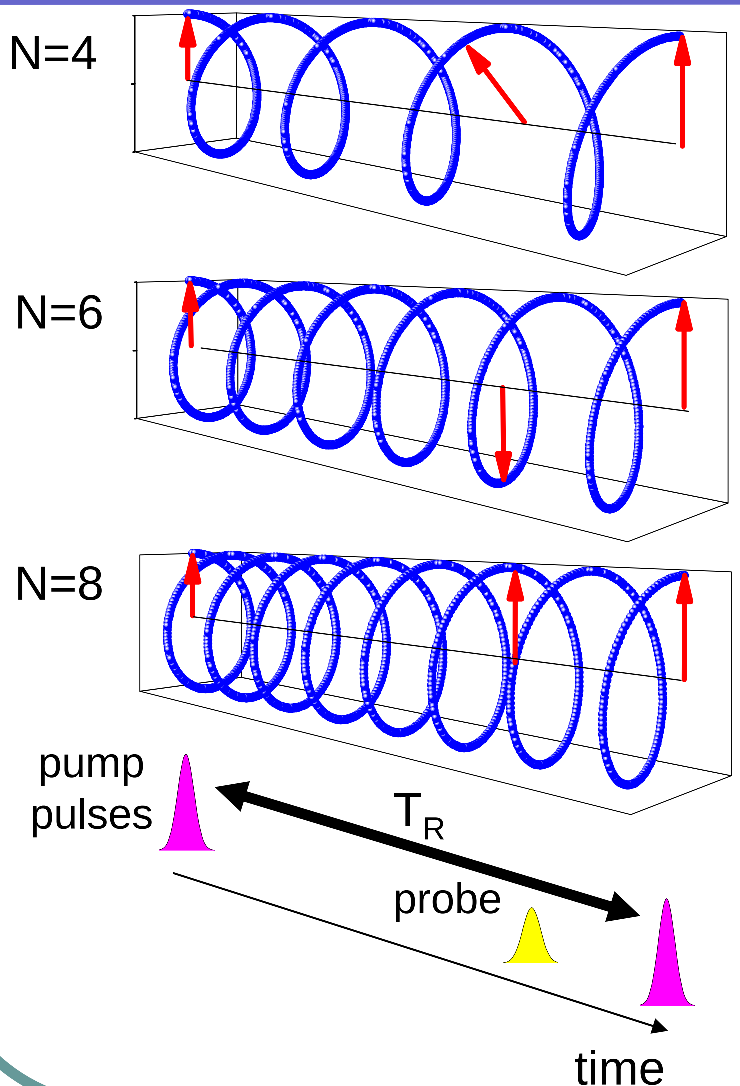
further selection:

$$\omega_e = \frac{g_e \mu_B B}{\hbar} = N \cdot \frac{2\pi}{T_R} = N \cdot \Omega_R$$

laser pulse separation:
T_R = 13.2ns

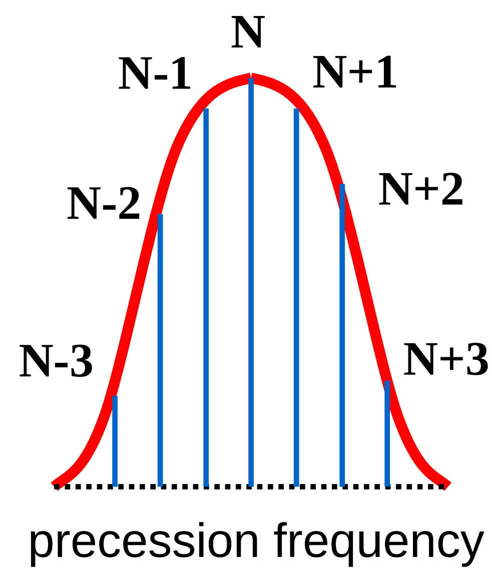
phase synchronization of spin subsets by laser

Spin synchronization scheme

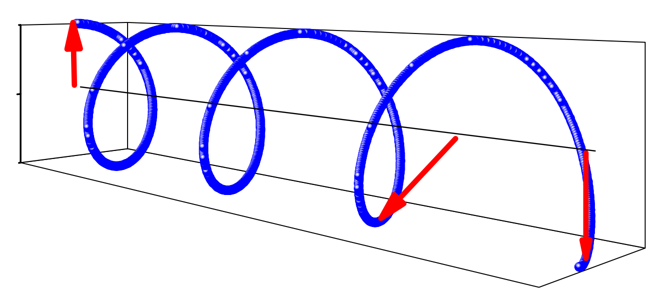


phase synchronization condition

$$\omega_e = N \cdot \frac{2\pi}{T_R}$$

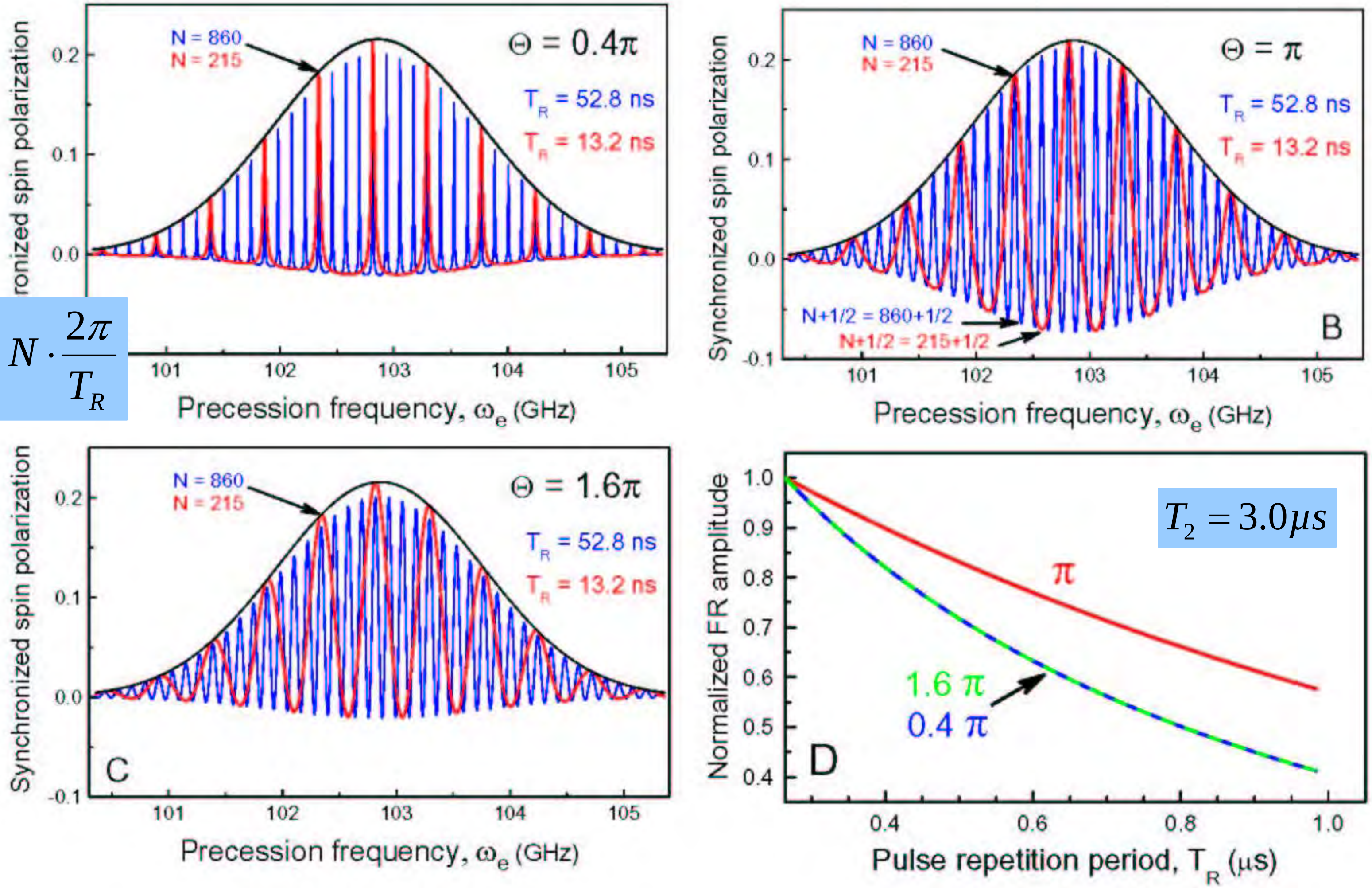


mode out of phase



Spin mode locking

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

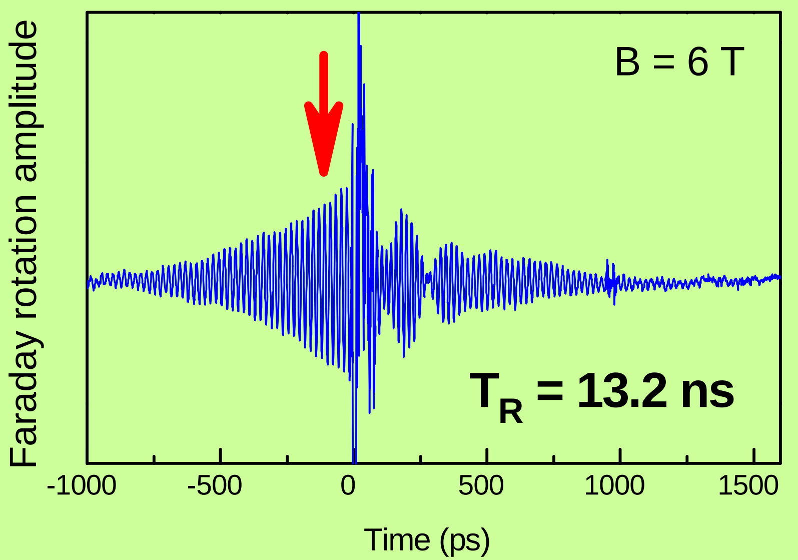


$$\omega_e = N \cdot \frac{2\pi}{T_R}$$

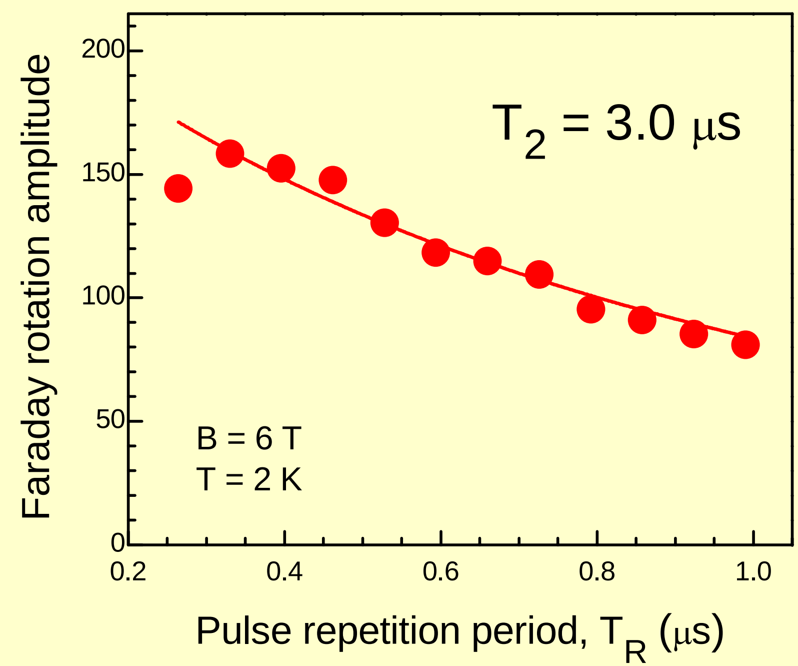
$$T_2 = 3.0\mu s$$

Transverse spin relaxation time

laser repetition period T_R varied by pulse-picker from 13.2 to 990 ns



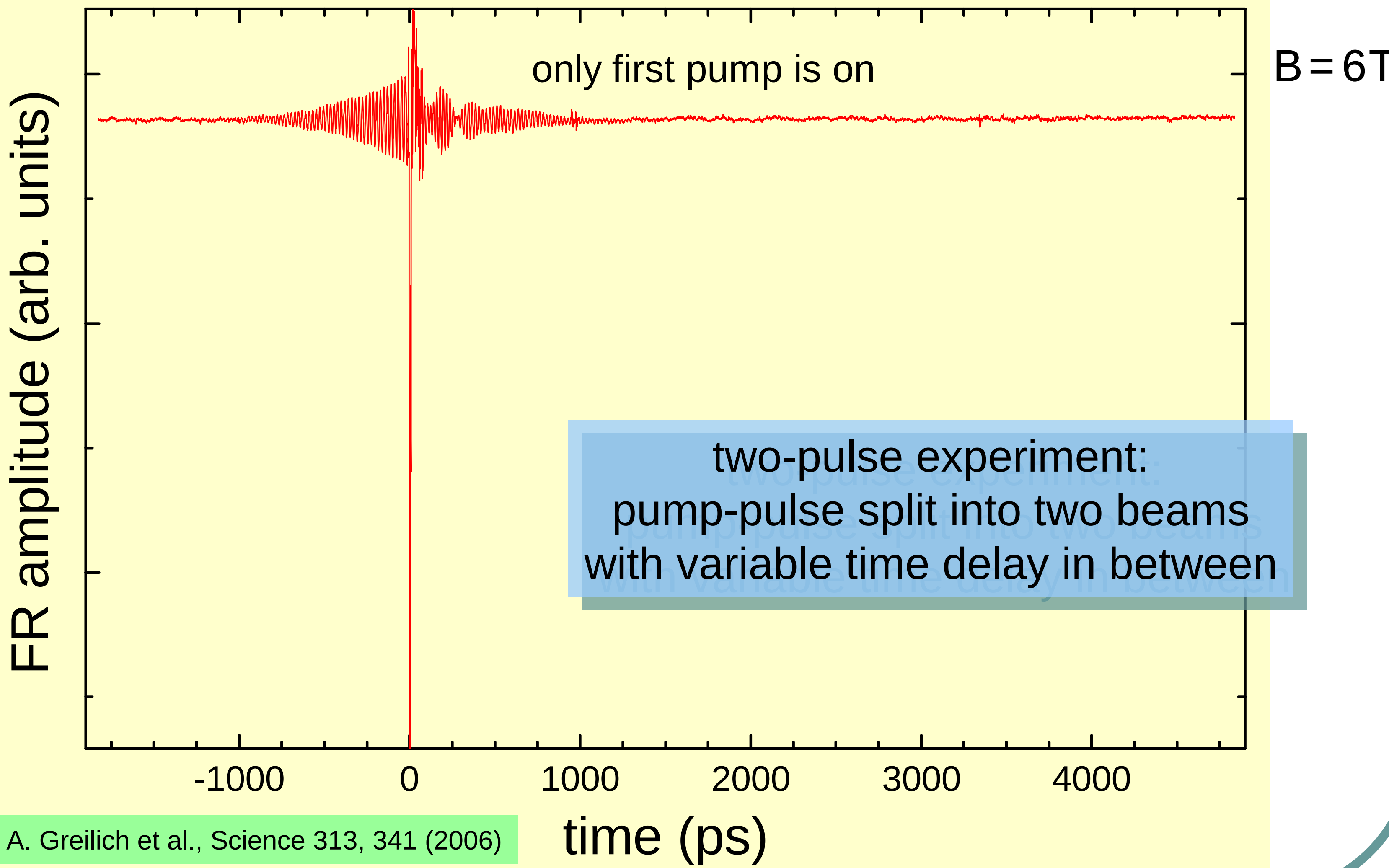
A. Greilich et al., Science 313, 341 (2006)



decay time gives single dot coherence time T_2 = 3.0 μs

four orders of magnitude longer than ensemble dephasing T_2^*=0.4ns at B=6T!

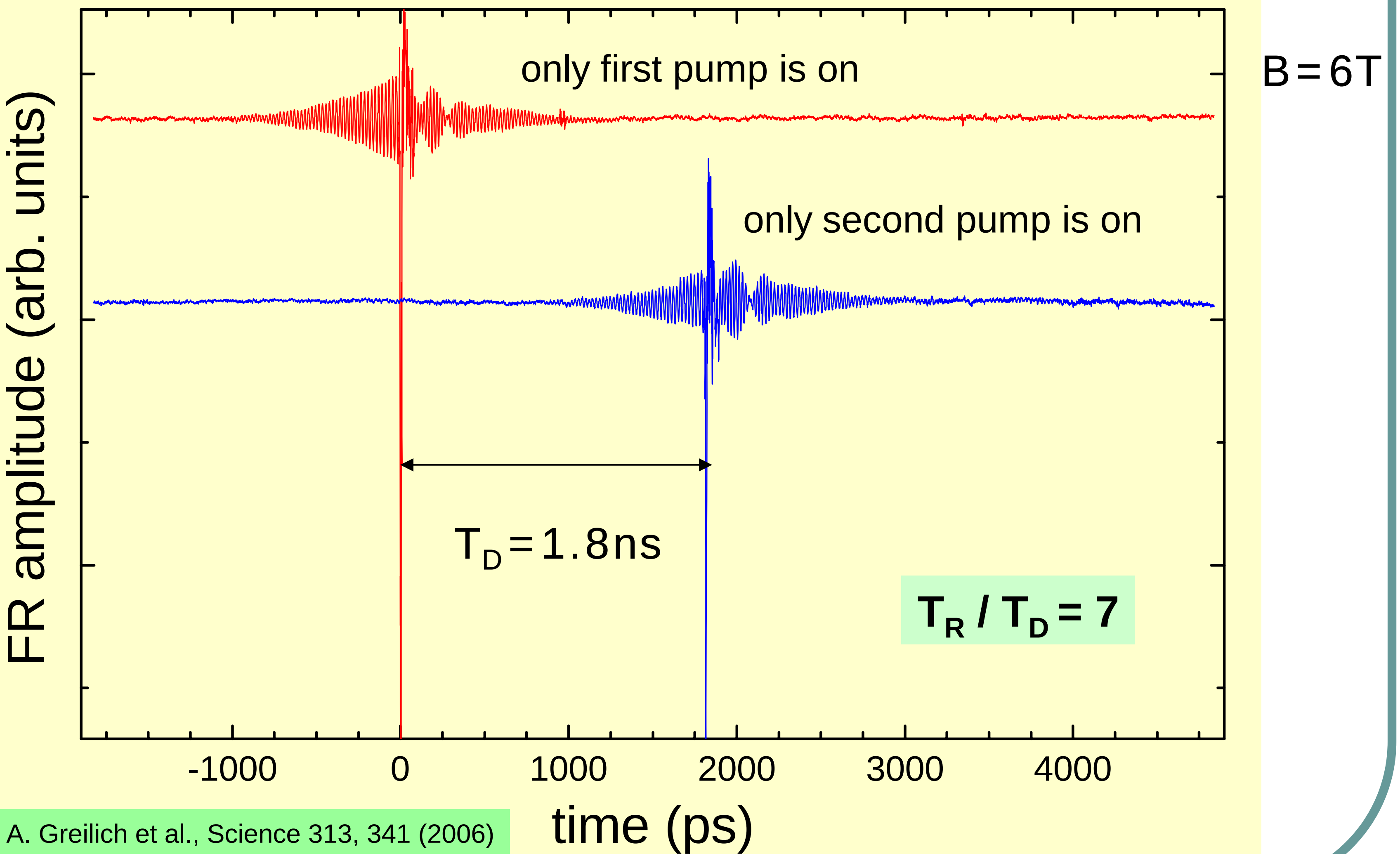
Clocking of spin modes



two-pulse experiment:
pump-pulse split into two beams
with variable time delay in between

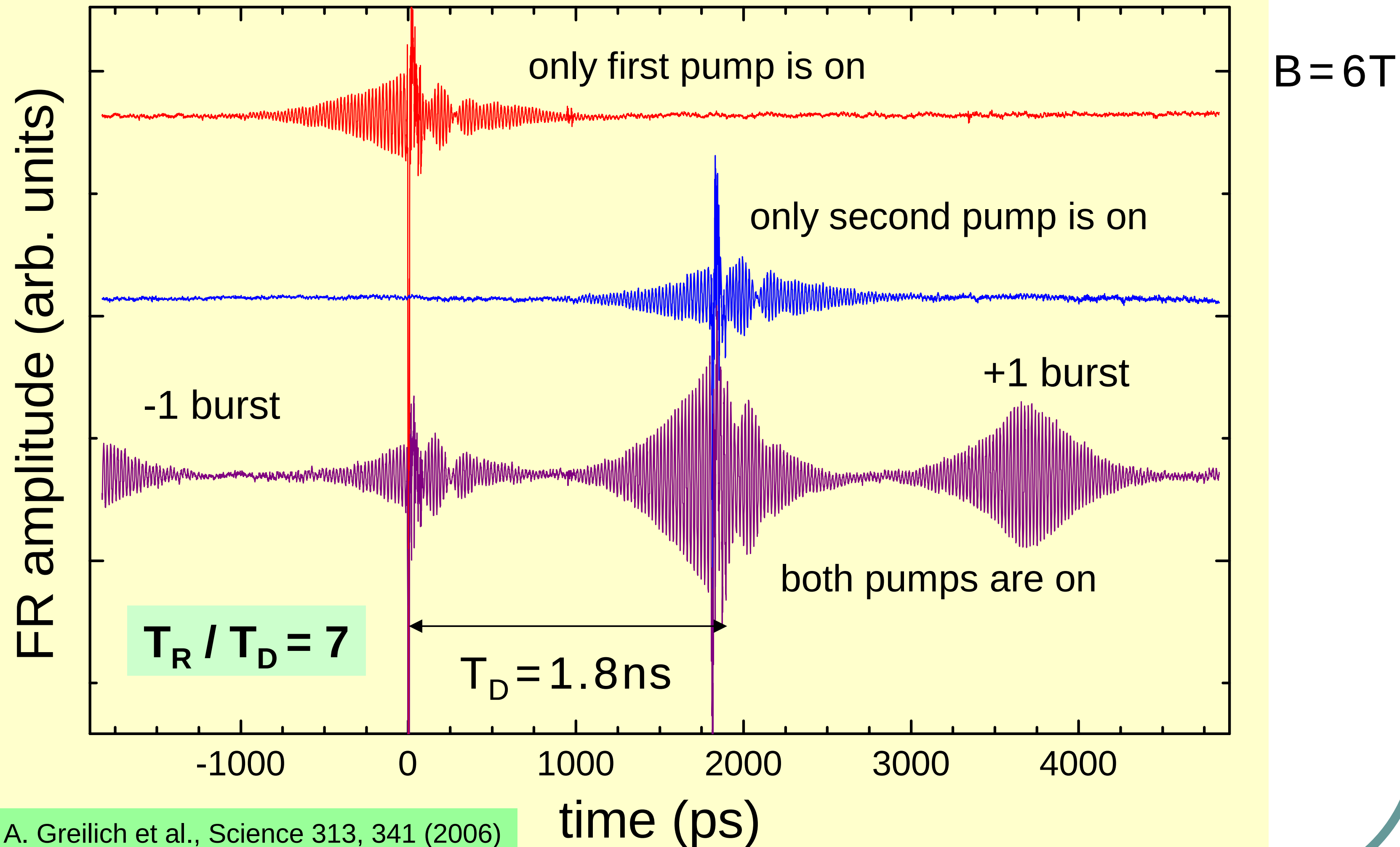
A. Greilich et al., Science 313, 341 (2006)

Clocking of spin modes



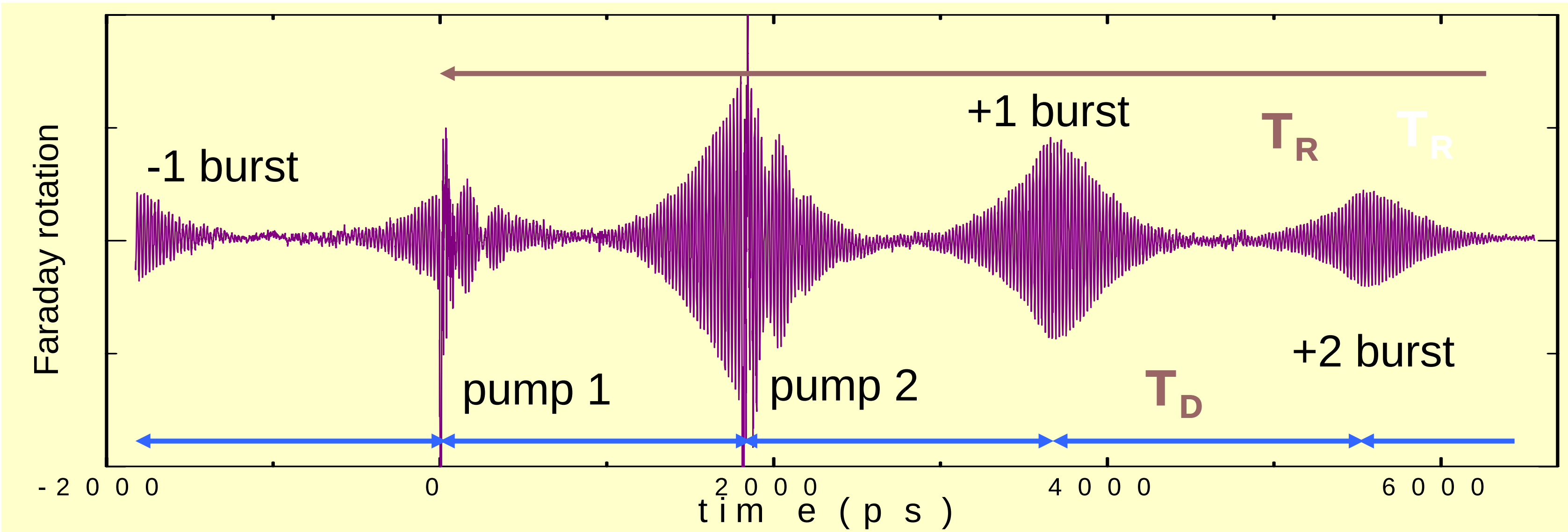
A. Greilich et al., Science 313, 341 (2006)

Clocking of spin modes



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

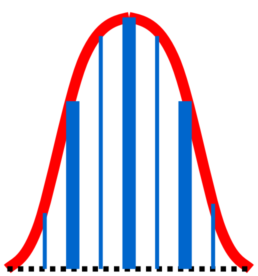
Clocking of spin modes



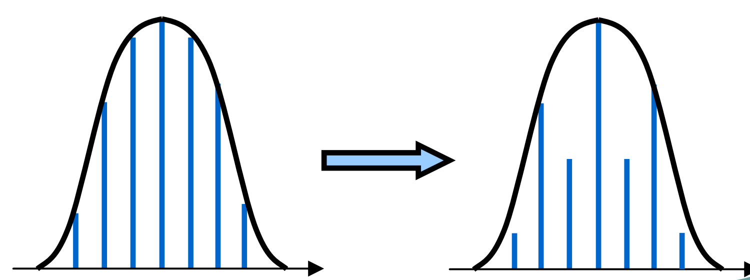
$$\omega_e = N \cdot K \cdot \frac{2\pi}{T_D}$$

$$\omega_e = N \cdot L \cdot \frac{2\pi}{T_R - T_D}$$

$\Rightarrow$ spins echoes every T_D

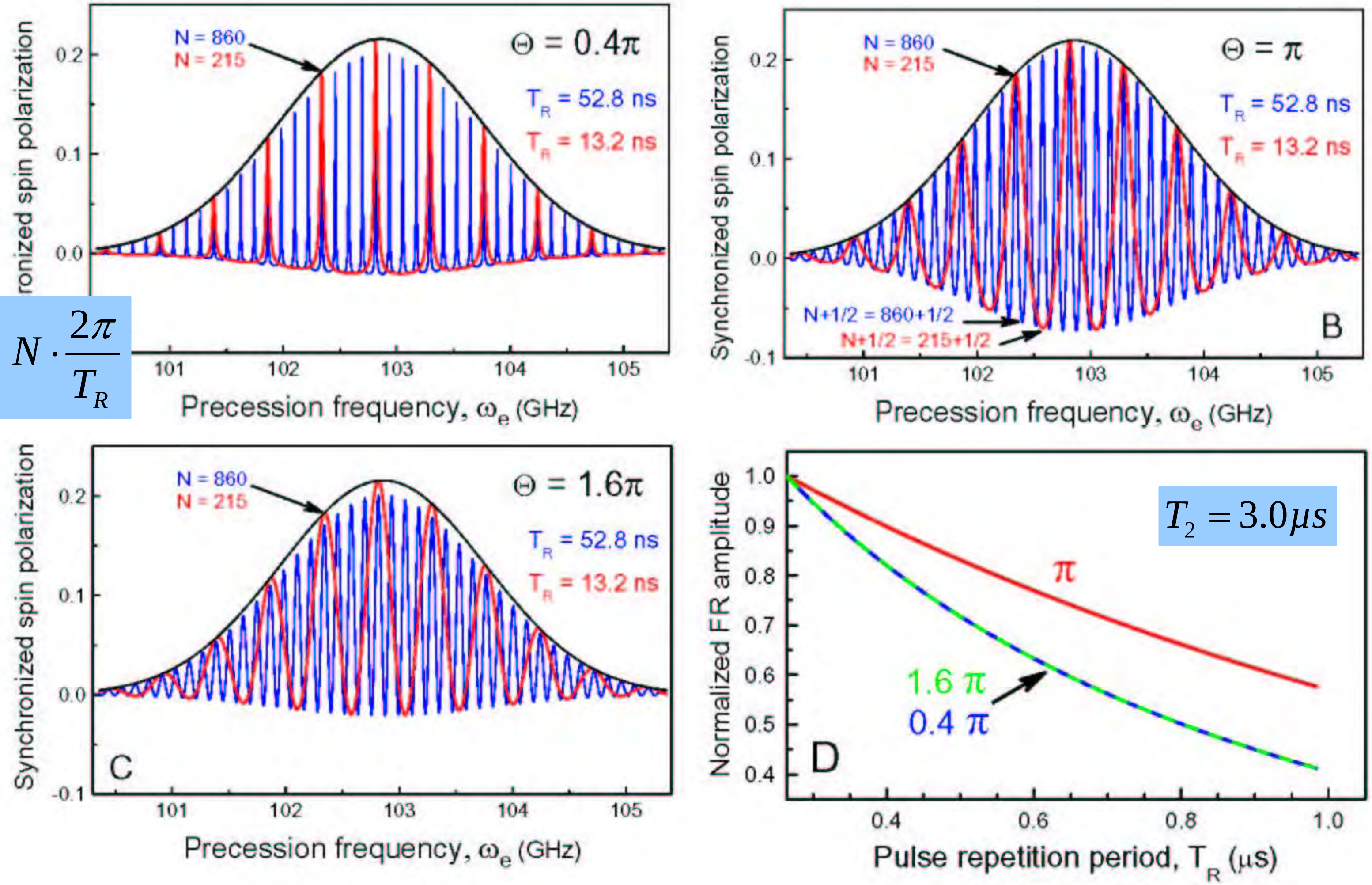


redistribution
of
precession frequencies



Spin mode locking

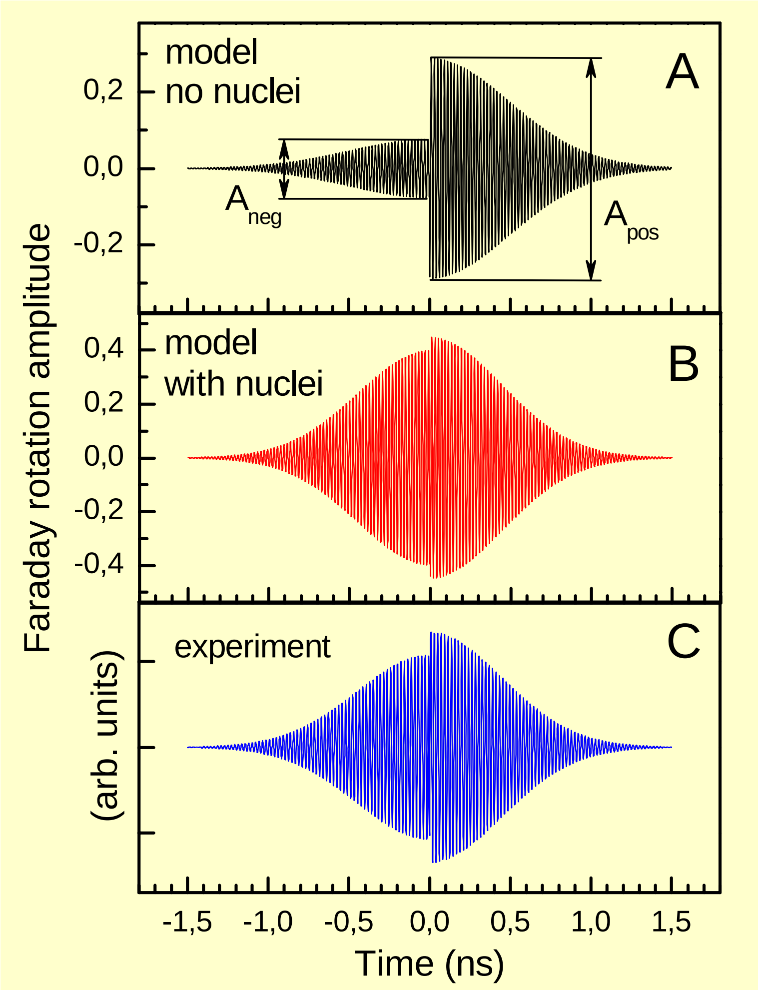
A. Greilich et al., Science 313, 341 (2006)



$$\omega_e = N \cdot \frac{2\pi}{T_R}$$

$$T_2 = 3.0\mu s$$

Negative delay FR amplitude



explanation for similar FR amplitudes before and after pump pulse arrival

$$\omega_e = \frac{2\pi N}{T_R} = g_e \mu_B (B + B_N)/\hbar$$

nuclei create magnetic field such that all electron spins in the ensemble contribute to mode-locking

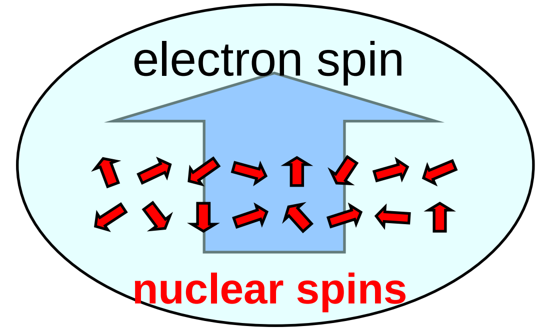
A. Greilich et al., Science 317, 1896 (2007)

Electron-nuclei spin flip-flop

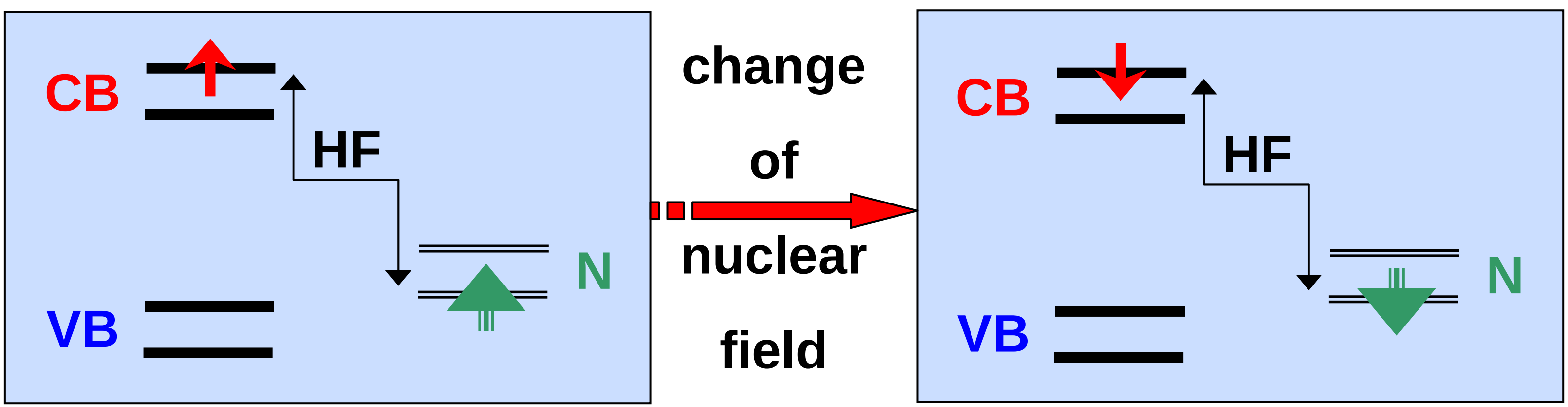
how do electrons and nuclei communicate?

hyperfine interaction

$$V^{\alpha} = v_0 A_{\alpha} \left(\vec{I}_{\alpha} \cdot \vec{S} \right) \left| \phi \left(\vec{R}_{\alpha} \right) \right|^2$$



~ 100.000 nuclei per QD



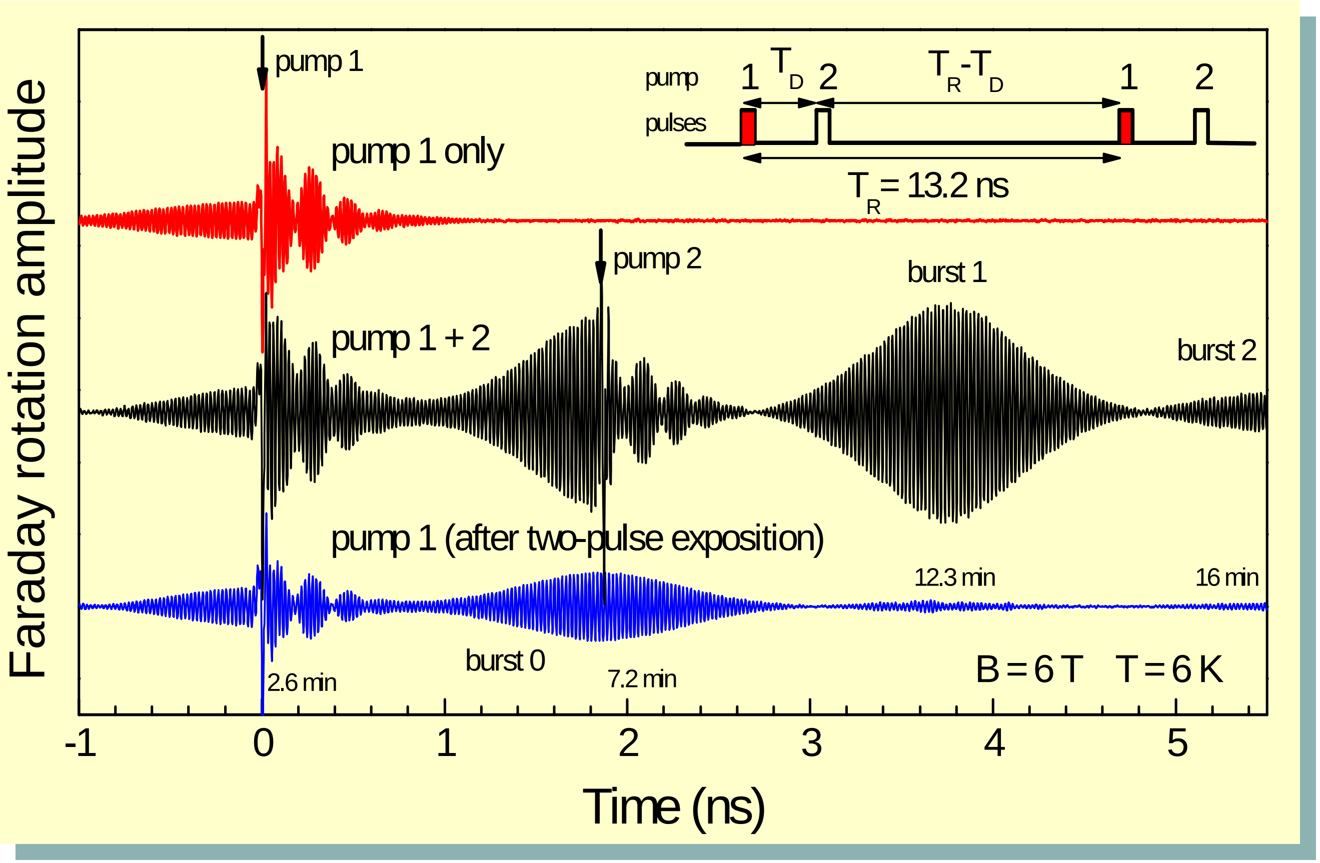
Random walk

until mode-locking is fulfilled!

$$\omega_e = \frac{2\pi N}{T_R} = g_e \mu_B (B + B_N) / \hbar$$

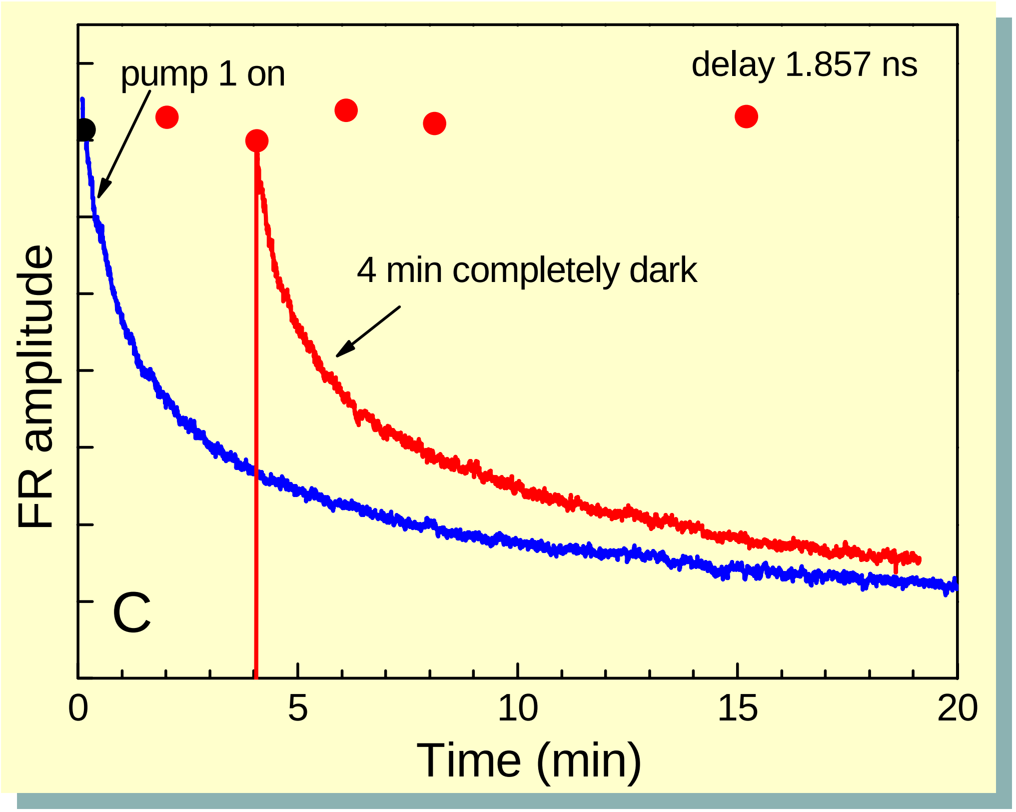
Ultralong memory

Do the long-living nuclear spins show up in the FR studies?



A. Greilich et al., Science 317, 1896 (2007)

Optically induced relaxation

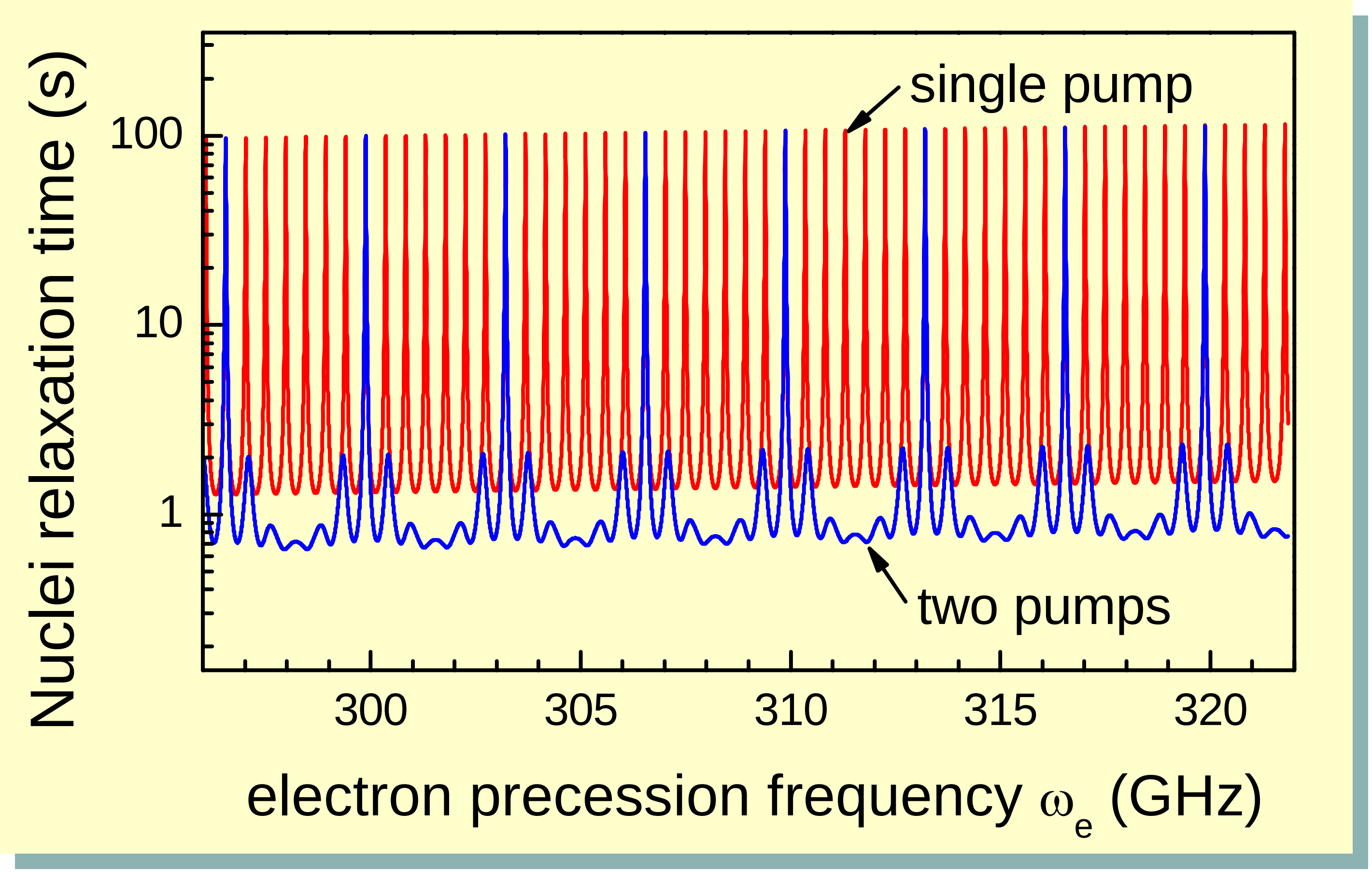


FR decay only for system under illumination!

A. Greilich et al., Science 317, 1896 (2007)

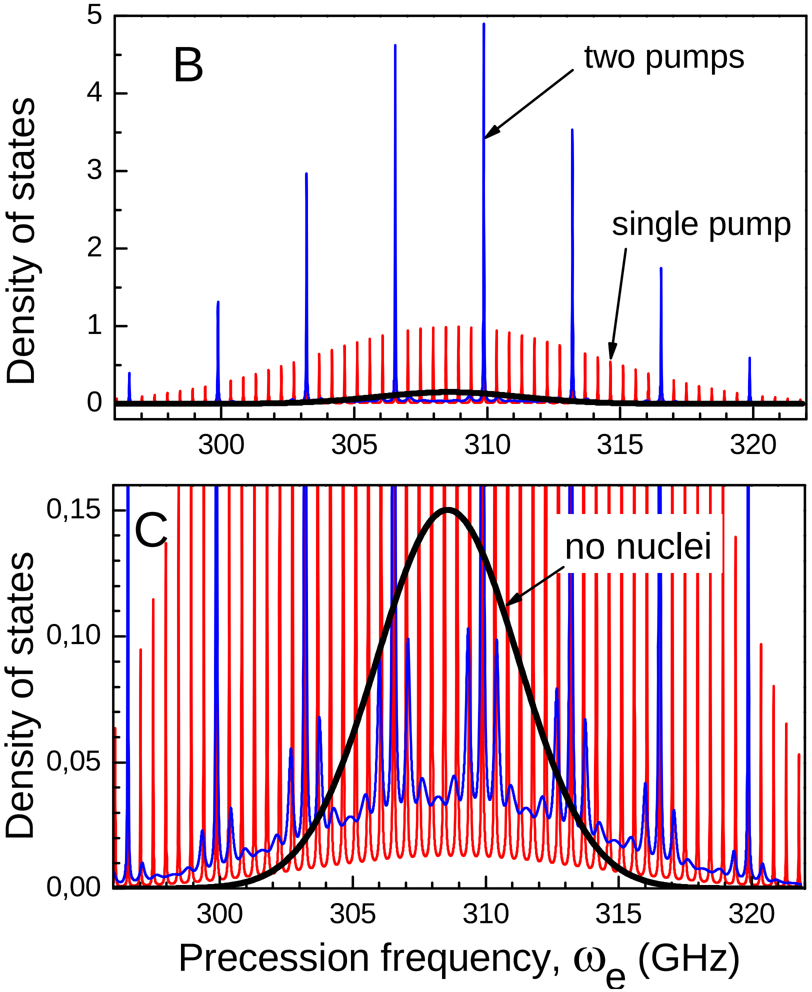
FR amplitude constant over an hour time scale, when system is held in darkness!

Nuclear spin relaxation times



A. Greilich et al., Science 317, 1896 (2007)

Spin precession density



A. Greilich et al., Science 317, 1896 (2007)

background of unlocked dots is removed!

broad spin precession distribution is transferred to comb-like distribution!

important:

change of precession frequency

comparable to

mode locking spacing

Current work

- Optical spin rotation
- Ensemble single mode spin precession
  - ~million inhomogeneous electrons focussed on single precession mode
- Application to EIT, slow light?

Conclusions

Quantum effects will play a key role in the next generation of information technologies!

EXCITONS

coherence time: ~ns

manipulation time: ~ps

sufficient for quantum communication!

ELECTRON SPINS

coherence time: ~µs

(manipulation time: ~ps)

sufficient for simple processors!

Publications

- A. Greilich et al., Phys. Rev. Lett. 96, 227401 (2006)
- A. Greilich et al., Science 313, 341 (2006)
- R. Oulton et al., Phys. Rev. Lett. 98, 107401 (2007)
- I. Yugova et al., Phys. Rev. B 75, 195325 (2007)
- A. Greilich et al., Phys. Rev. B 75, 233301 (2007)
- A. Greilich et al., Science 317, 1896 (2007)
- Further submitted papers