Ultrafast Coherent Electron Spin Flip in a 2D Electron Gas

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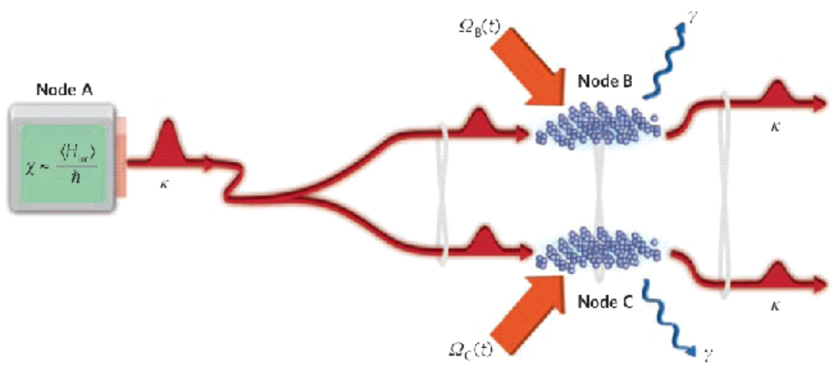
Supported by NSF and ARL

Electron Spins in Semiconductors

Ensemble spin Systems



Quantum memories and repeaters, spintronic devices

Duan *et al*., *Nature* **414** (2001).
Briegel *et al*., *PRL* **81** (1998).
For recent reviews, see for example,
Kimble, *Nature* **453**, 1023 (2008).

Two goals:

- Complete spin control.
- Protect electron spins from decoherence.

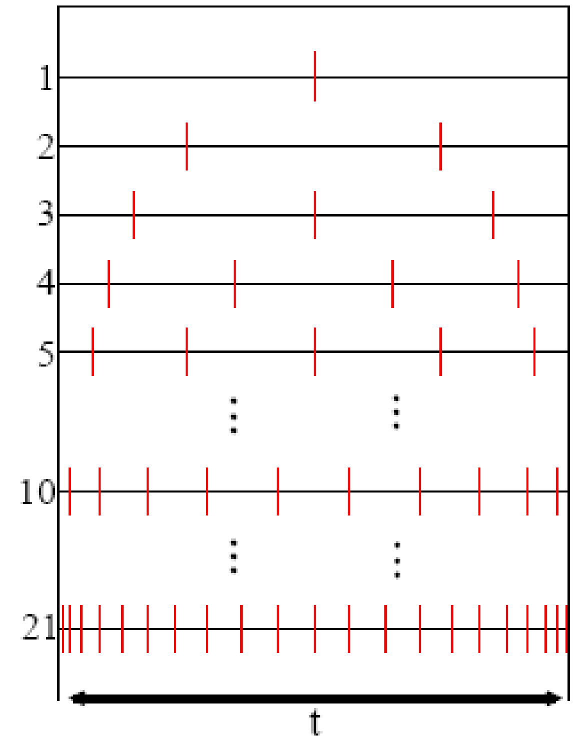
→ Key step: π-rotations

Dynamic Decoupling

- **Uhrig dynamic decoupling (UDD)**
  - Special sequence of π-pulses.
  - Reverses decoherence due to dynamical interactions with the environment.

$$t_j = \frac{T}{2}\left(1-\cos\frac{\pi j}{n+1}\right),\ j = 1, 2, \ldots n$$

n: number of pulses



- **UDD is "universal" and "magical."**
  - **Universal:** *Independent* of dephasing Hamiltonian.
  - **Magical:** The improvement in decoherence time scales *linearly,* instead of exponentially, with the number of pulses.

G. S. Uhrig, *Phys. Rev. Lett*. **98** (2007).

B. Lee, W.M. Witzel, S. Das Sarma, *Phys. Rev. Lett*. 100, 160505 (2008).

W. Yao, R.B. Liu, and L. J. Sham, *Phys. Rev. Lett*. **98**, 077602 (2007).

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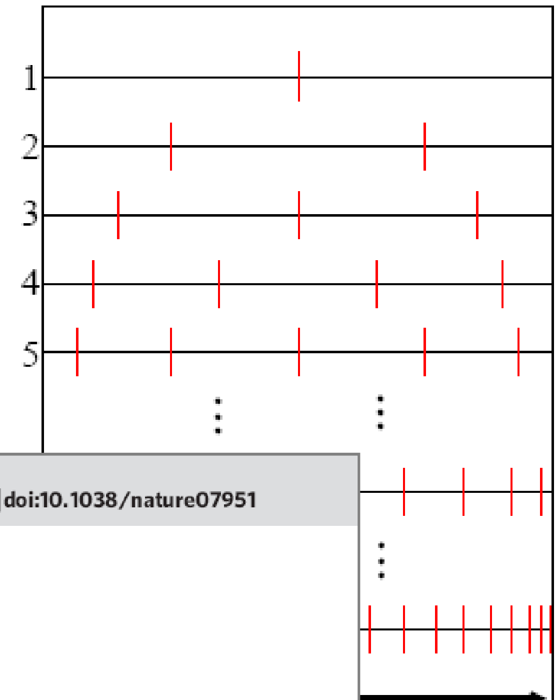


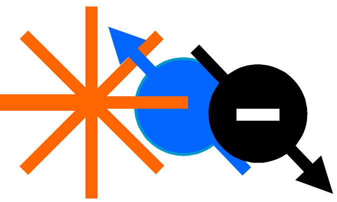
nature | Vol 458 | 23 April 2009 | doi:10.1038/nature07951

LETTERS

Optimized dynamical decoupling in a model quantum memory

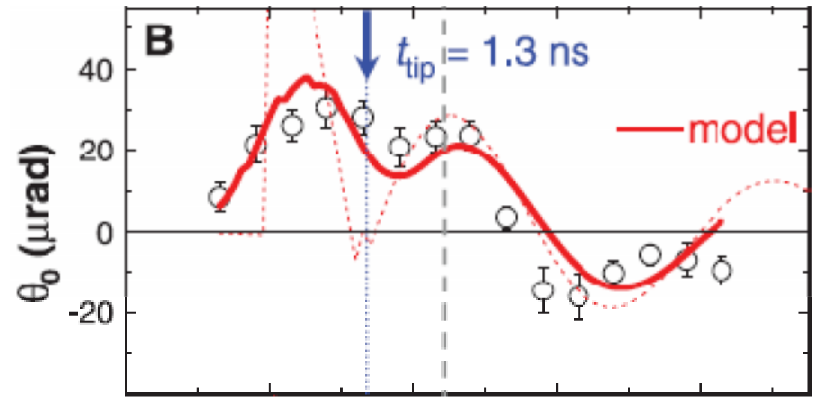
Michael J. Biercuk[1,2]*, Hermann Uys[1,3]*, Aaron P. VanDevender[1], Nobuyasu Shiga[1]†, Wayne M. Itano[1] & John J. Bollinger[1]

Single Quantum Dots

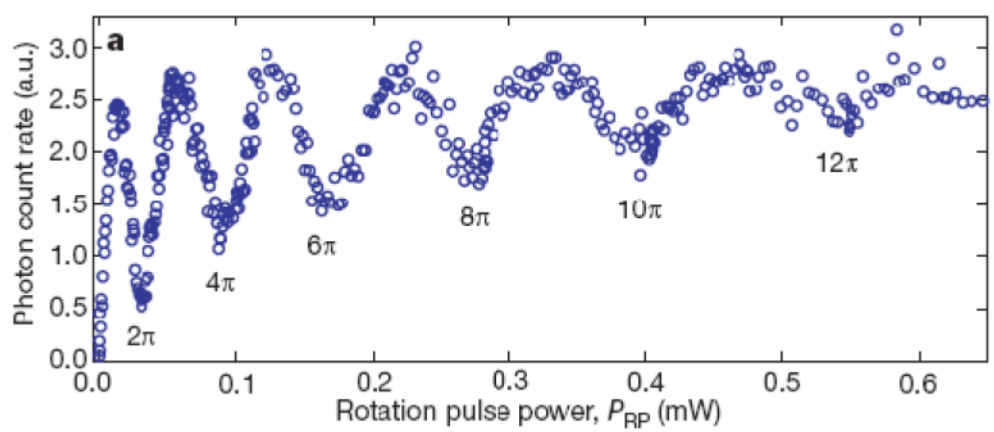


Complete spin control has been realized recently in single quantum dots:

J. Berezovsky *et al.*, *Science* **320,** 349 (2008)

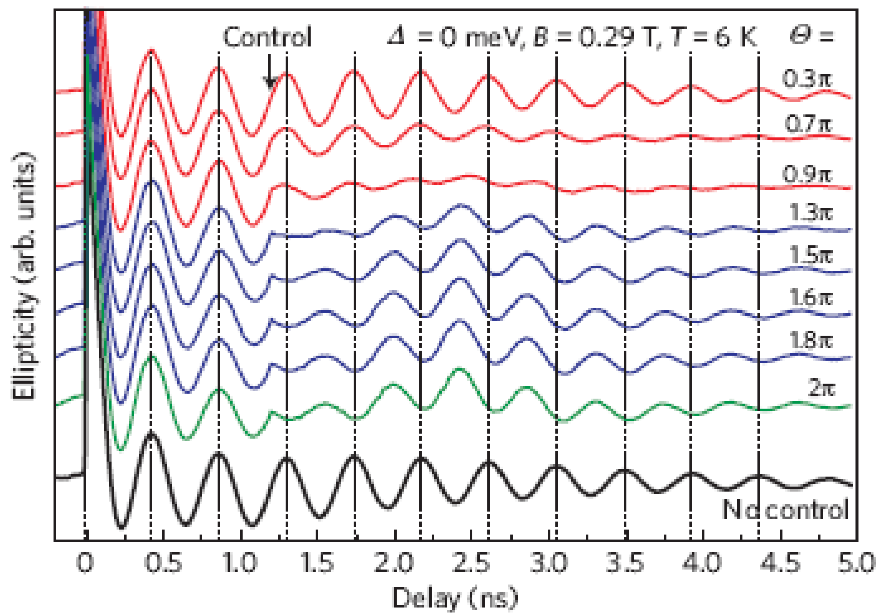


D. Press, T. D. Ladd, B. Zhang, and Y. Yamamoto, *Nature* **456** 218 (2008)



Quantum Dot Ensembles

A. Greilich *et al.*, *Nature Physics* **5**, 262 (2009)



Quantum dots feature atomic-like, sharp optical transitions. Complete spin control in these systems is easier to achieve than in a 2DEG.

Spin Ensembles: 2D Electron Gas

- **Difficulties and physics issues** for π-rotation in 2D electron gas:

  Inherent manybody interactions.

  Short dipole decoherence time.

  Quantum dots ~ 100 ps.

  2D electron gas ~ 2 ps.

Earlier studies in 2DEGs have only achieved partial spin rotation.

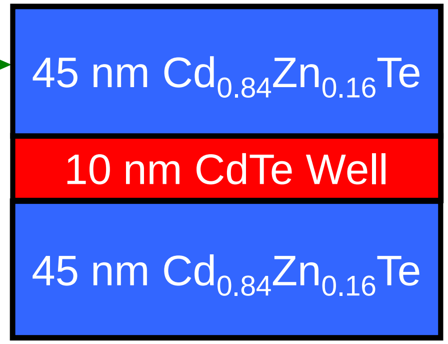
J. Gupta *et al., Science* **292** (2001).
Y. Shen *et al.*, *Phys. Rev. B* **75** (2007).
Y. Wu *et al.*, *Phys. Rev. Lett* **99** (2007).
K. Fu *et al.,Nature Phys.* **4** (2008).

Outline

- Mechanism for spin rotation
- Experimental design
- Experimental results
- Summary

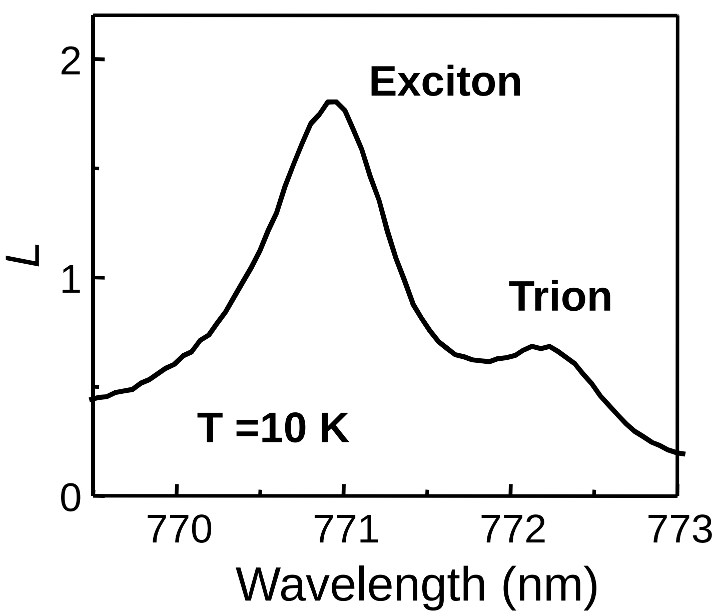
2D Electron Gas and Trions

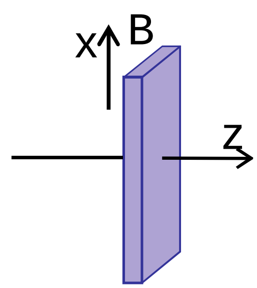
Indium doping
n~3x10^{10}/cm^2

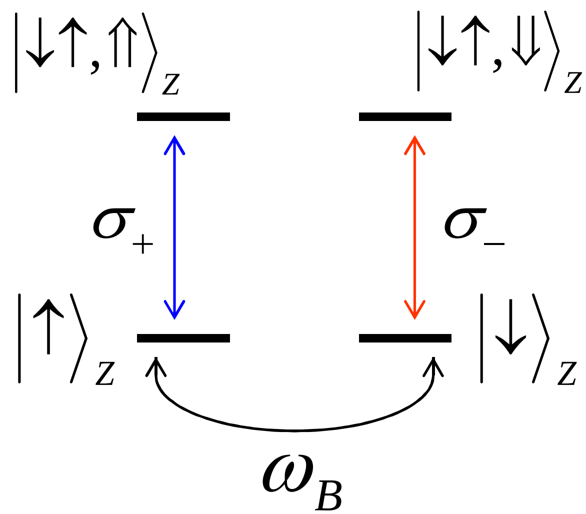


Sample from R. Cox, Grenoble, France

- Trions consist of two electrons of opposite spins bound to a hole.
- Trion absorption scales with electron doping density.



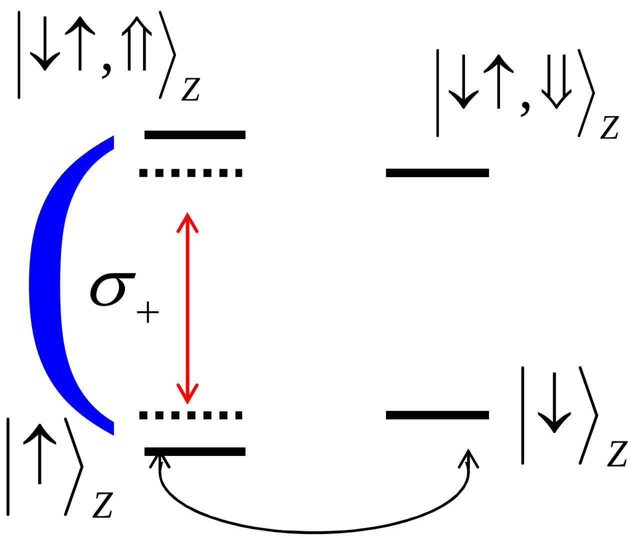


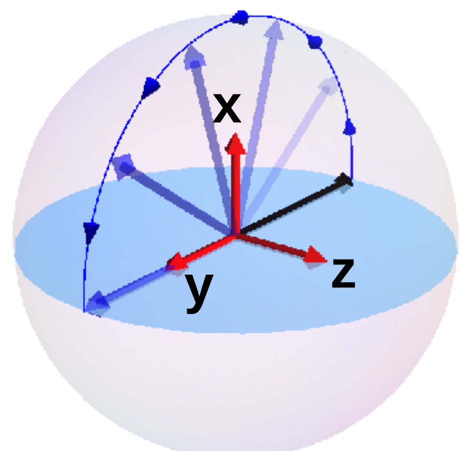


Magnetic field along x-direcion leads to spin precession in y,z-plane (.45 T).

Spin Rotation via Optical Stark Effect

Pulse duration << Larmor precession period.



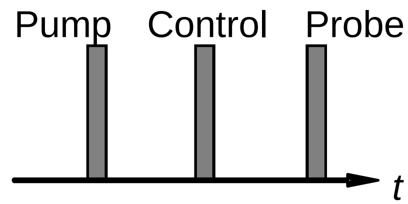


$$\phi = \int \delta\omega(t)dt$$

"Control" beam:
Induces a Stark shift, resulting in a rotation angle about the z-axis.
J.A. Gupta *et al*., *Science* **292** (2001)

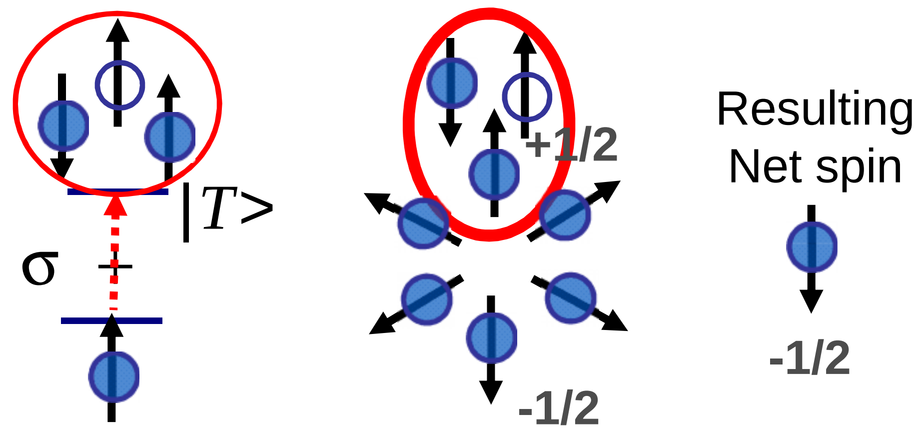
Experimental Setup

3 beam experiment



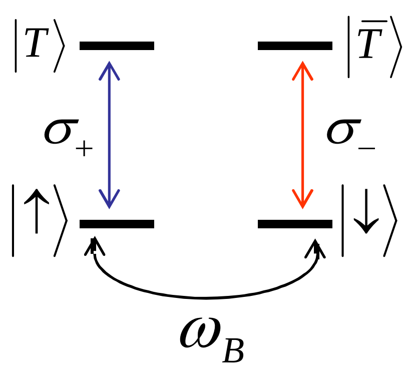
Spin initialization "Pump"

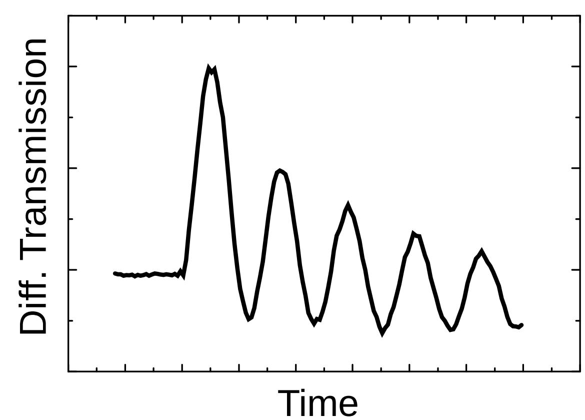
Trion excitation leads to a net spin polarization in the electron spin bath.



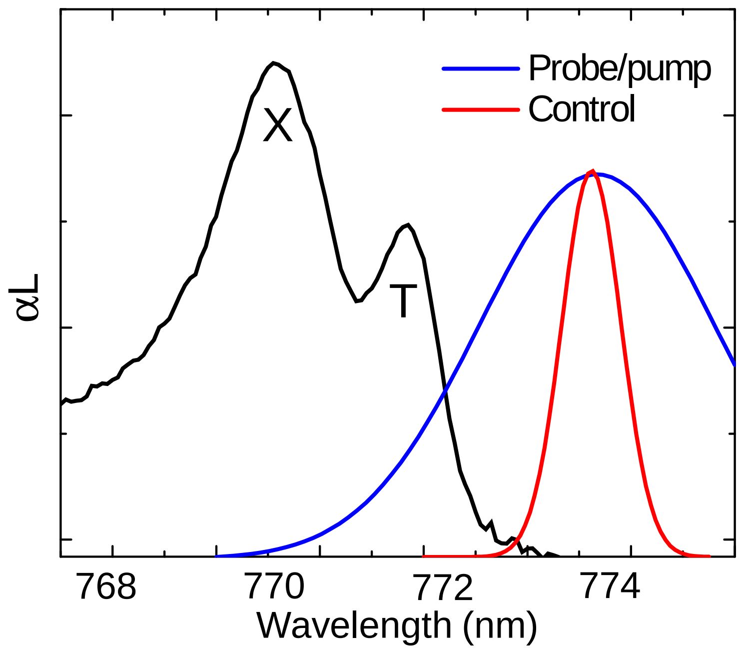
Measurement "Probe"

Transmission follows the resulting Larmor precession.





Experimental Design



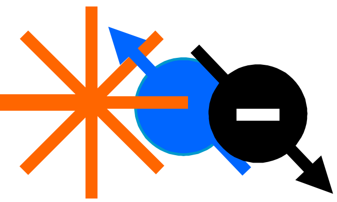
3 control pulse parameters:
Δ, τ, and Ω.

τ no more than ~ 2 ps.
Ω less than trion binding energy.
These requirements conflict with (3).
Compromise: choose τ = 2 ps and Δ small.

3 Goals
1.) Avoid dipole decoherence
2.) Avoid exciton excitation (many-body effects)
3.) $\phi = \int \delta\omega(t)dt \geq \pi$

Parameters used:
Δ = 2 nm, τ = 2 ps (5 nm bandwidth)

Stark Shift

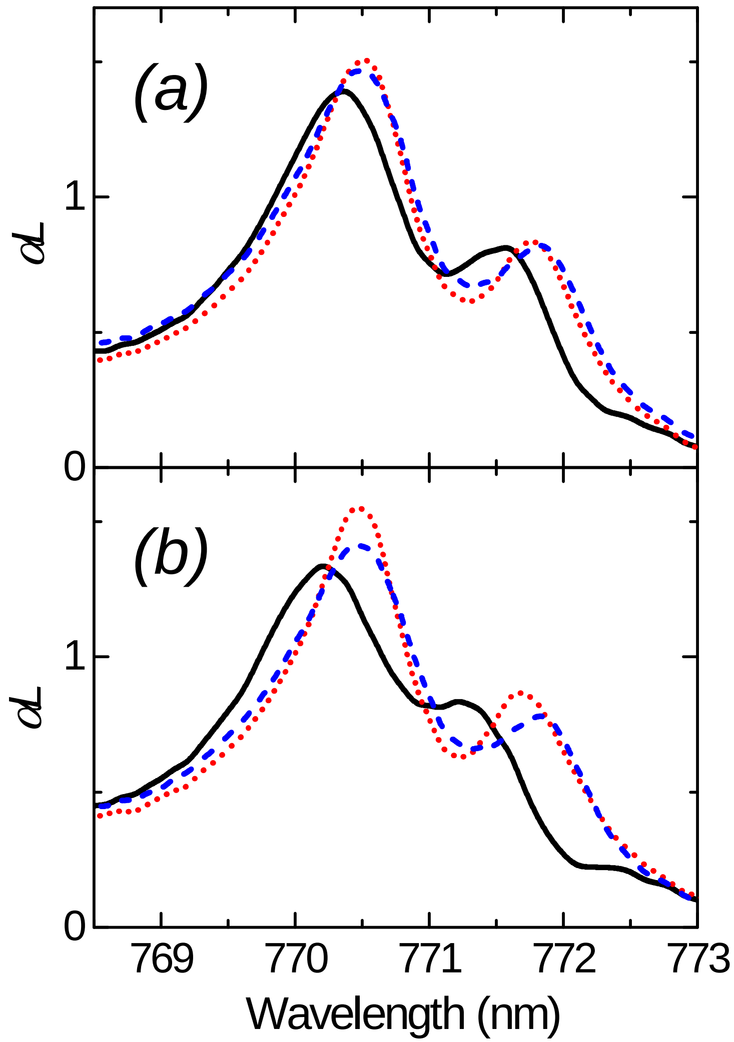


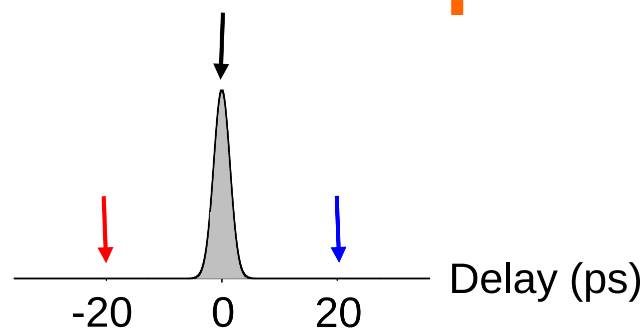
I_c = 10 mW

$\frac{\pi}{2}$ rotation

I_c = 20 mW

π rotation



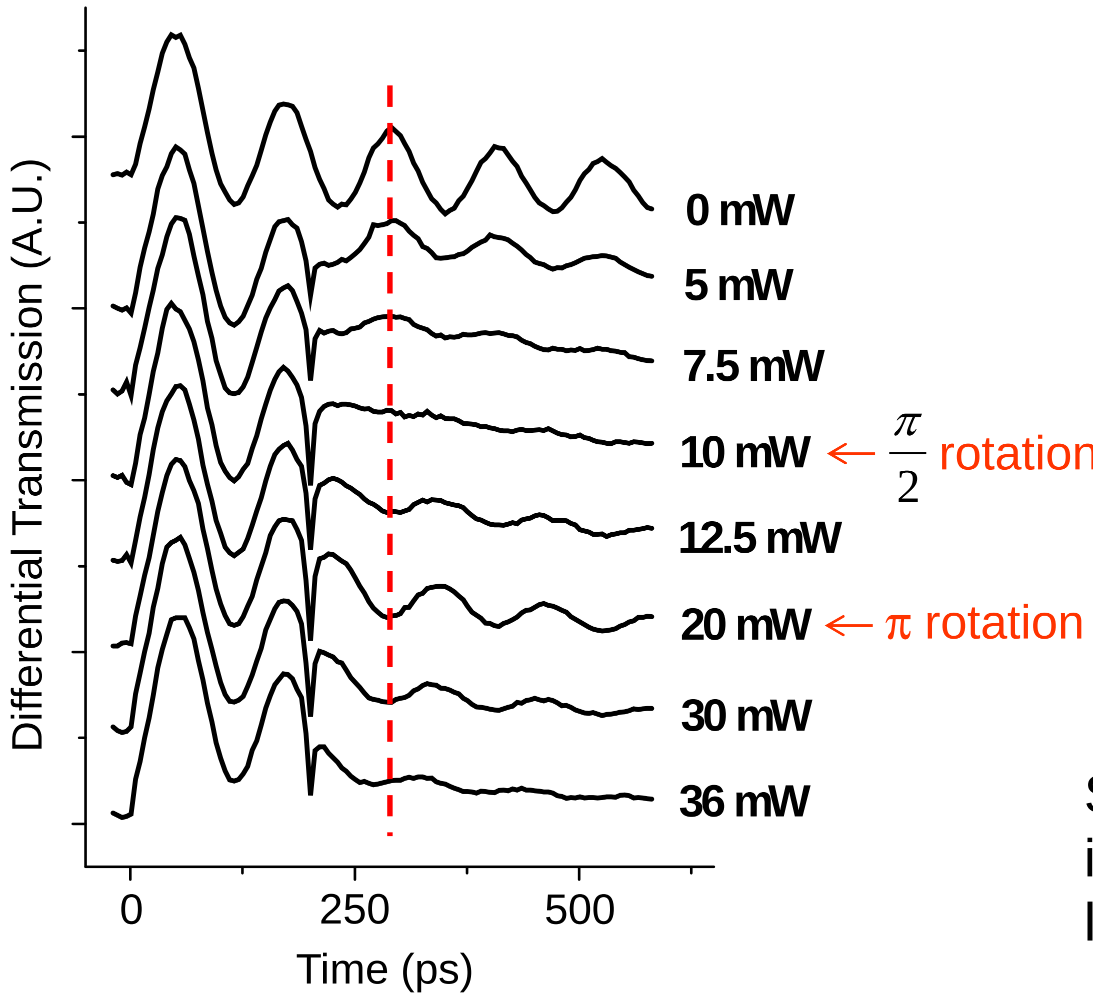


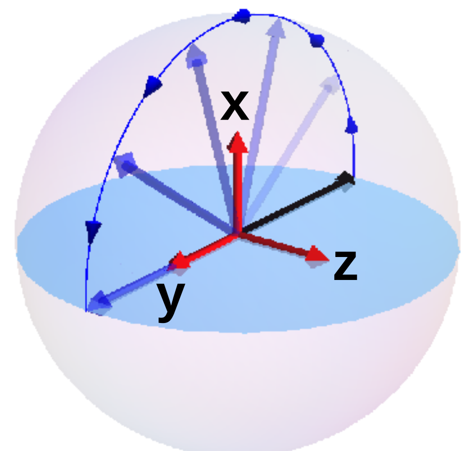
$$\phi = \int \delta\omega(t)dt$$

(a) System nearly completely recovers, leading to high fidelity rotation.

(b) Some bleaching prevents high fidelity rotation at high intensity.

Rotation vs. Intensity

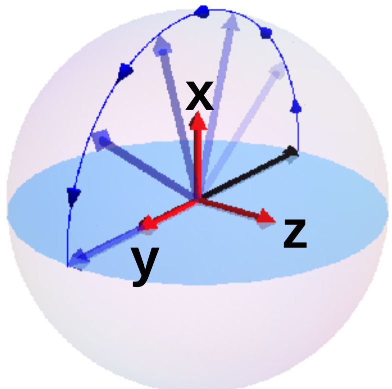




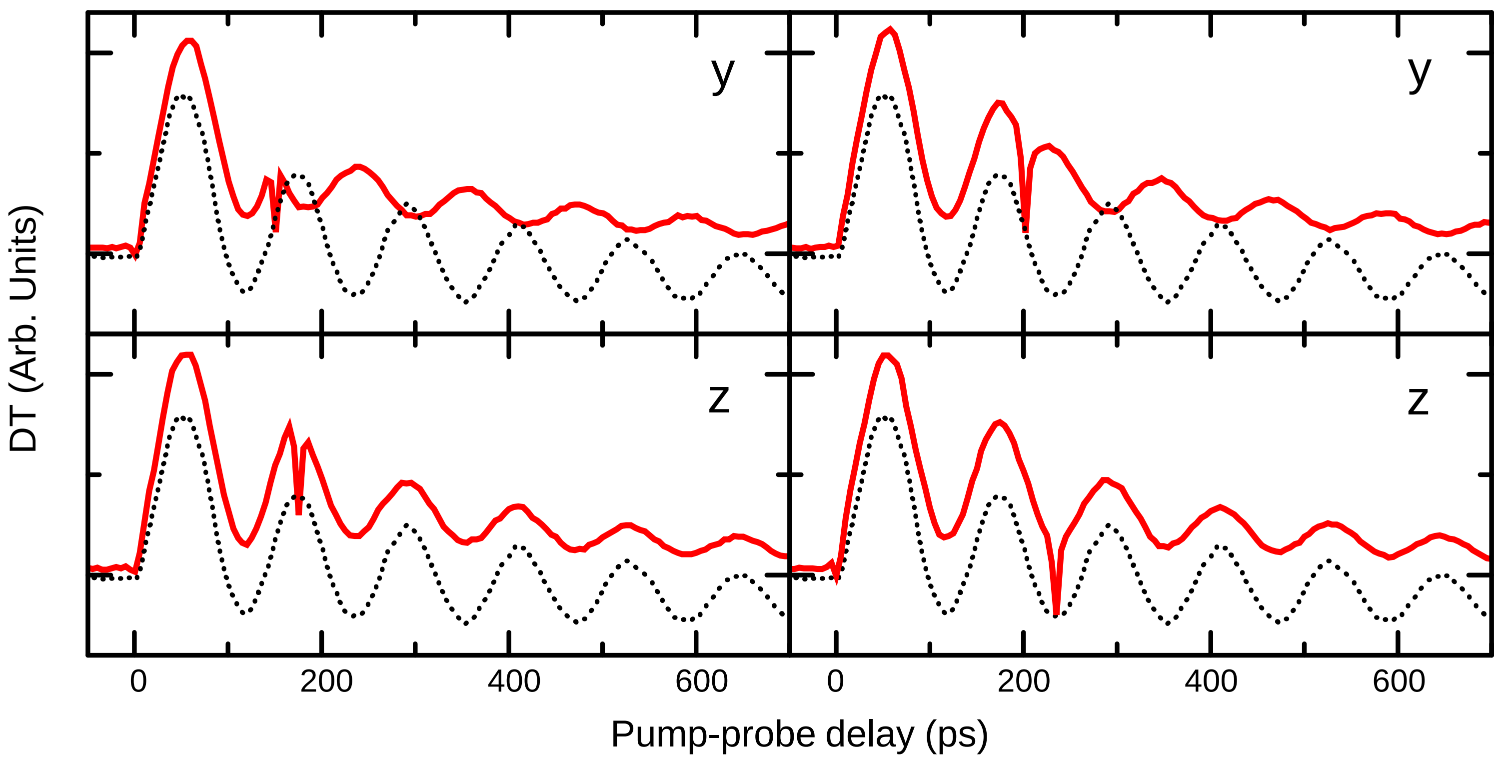
$$\delta\omega(t) \approx \frac{\Omega^2}{2\Delta}$$

Stark shift is linear for low intensity, but becomes non-linear at higher intensities.

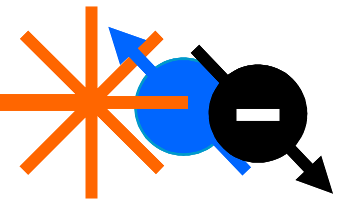
Rotation Timing

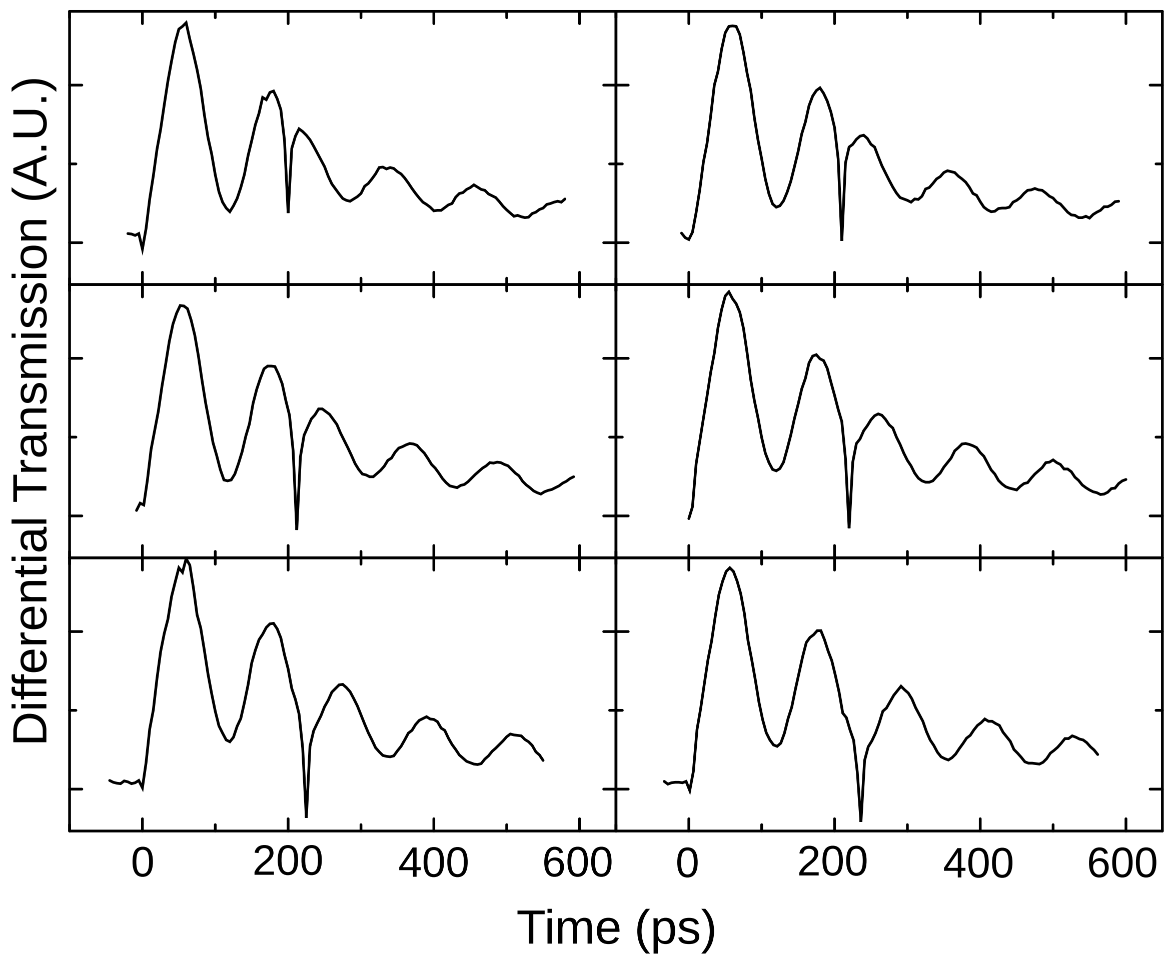


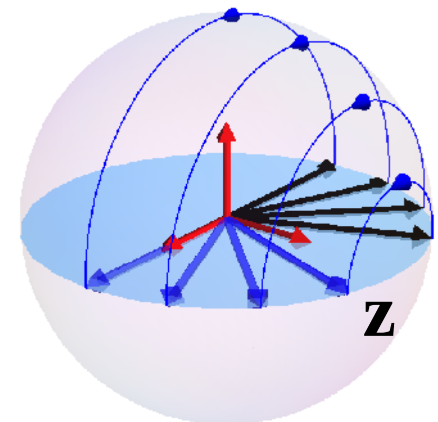
- Spins along the y-axis flip 180 degrees.
- Spins along z-axis do not rotate.



Arbitrary Timing

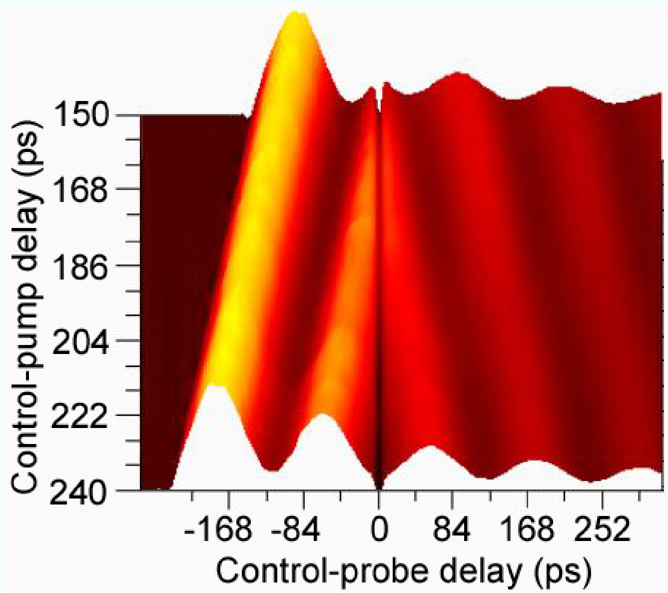


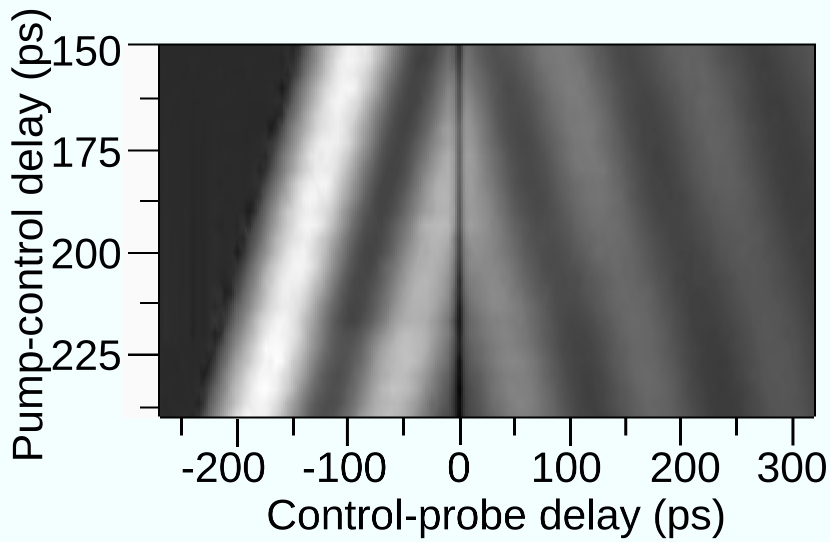




Beat peaks and troughs are symmetric w.r.t. control pulse.

Symmetrical Spin Precession





- For π rotations, phase of spin beats is symmetric w.r.t. control arrival, demonstrating complete spin flip.
- Dipole decoherence can lead to rotation asymmetry if pulse duration is too long.

Summary

- Demonstrated coherent spin flip in a 2D electron gas with an off-resonant ultrafast laser pulse, designed to induce optical Stark shifts and avoid excessive exciton excitation.

- Spin precessions are symmetric with respect to the timing of the control pulse, demonstrating the complete spin flip.

- Future work: further improvement in fidelity and decoupling of electron spins from their surroundings.