Electromagnetically Induced Transparency (EIT) via Spin Coherences in Semiconductor

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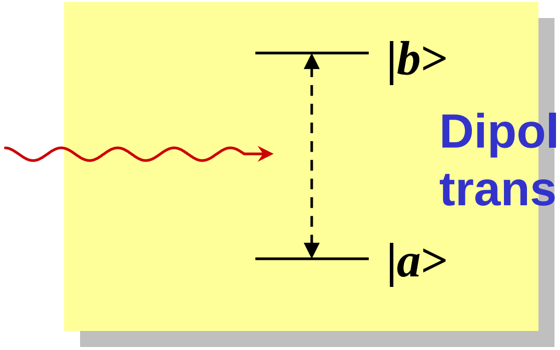
Outline

- **Introduction**
  - **EIT: Destructive interference via quantum coherence**
  - **Why we are interested in EIT?**
  - **Challenges for realizing EIT in semiconductors**
- **Experimental realization of EIT in semiconductors**
  - **Exciton spin coherence**
  - **Electron spin coherence**
- **Future work**

Quantum Coherence

- **Coherent superposition with well-defined relative phase between probability amplitudes**



Dipole optical transition

Two-level system:

$$|\psi> = C_a |a> + C_b |b>$$

e.g. atoms, spins

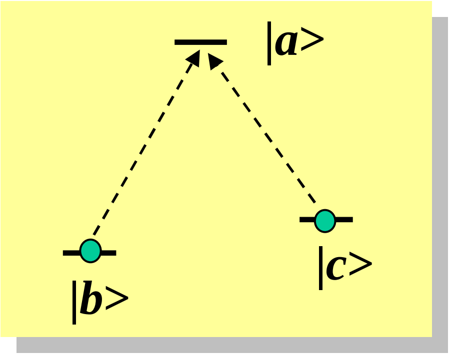
Quantum coherence can be induced and manipulated via optical processes.

Nonradiative Quantum Coherence

- **Nonradiative coherence:**

$$C_b\,|\,b> + C_c\,|\,c>$$

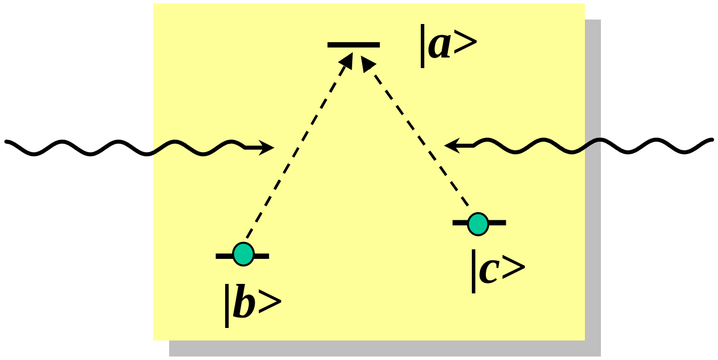
$|b>$ and $|c>$ are not directly coupled by a dipole optical transition.



- **Quantum interference:**

Total optical transition rate depends on the relative phase of the probability amplitudes.

Electromagnetically Induced Transparency (EIT)



$$|C_a|^2 = |C_{b\to a} + C_{c\to a}|^2 = 0$$

Harris, Physics Today **50** (7), 36 (1997);
Scully & Zubairy, *Quantum Optics*.

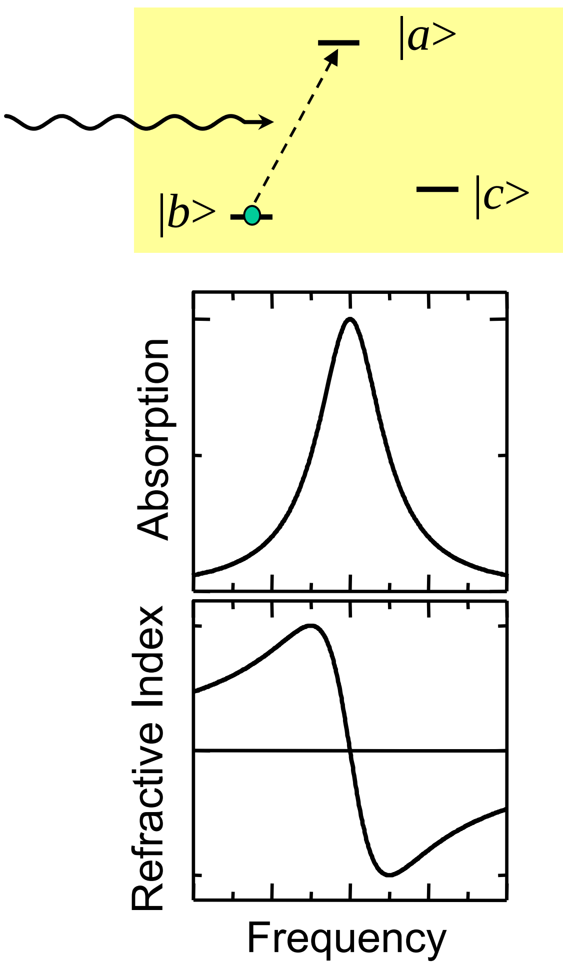
$$|\psi\rangle = C_b|b\rangle + C_c|c\rangle$$

- **Population trapped state:** **A special superposition state with**

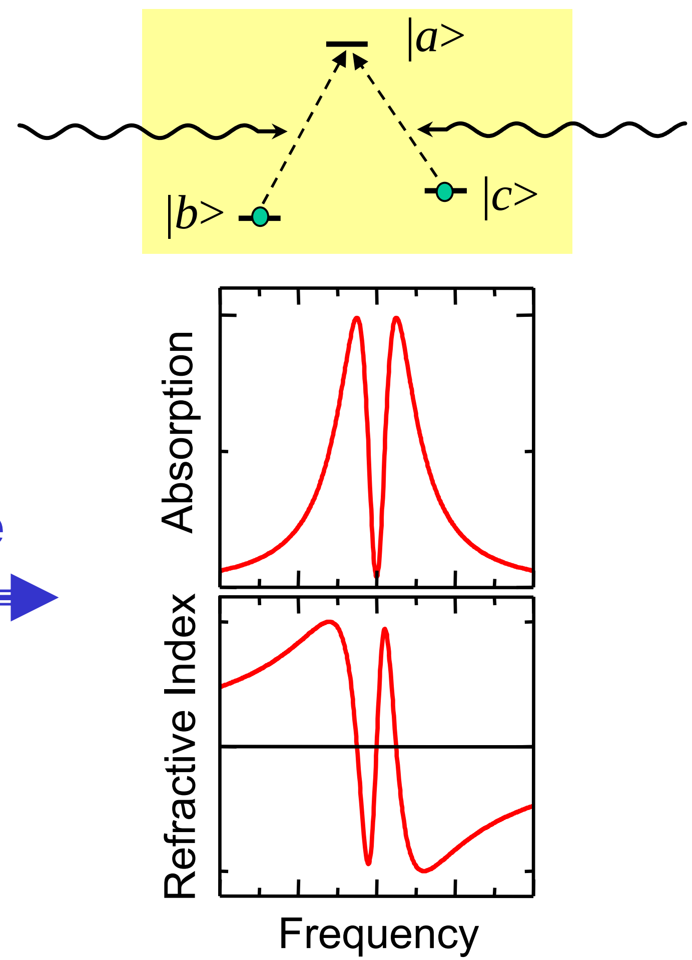
$$C_{b\to a} = -C_{c\to a}$$

- **EIT:** **Vanishing optical absorption due to complete destructive quantum interference**

EIT: Quantum Interference Induced Transparency



Destructive quantum interference



Manipulating Light with EIT

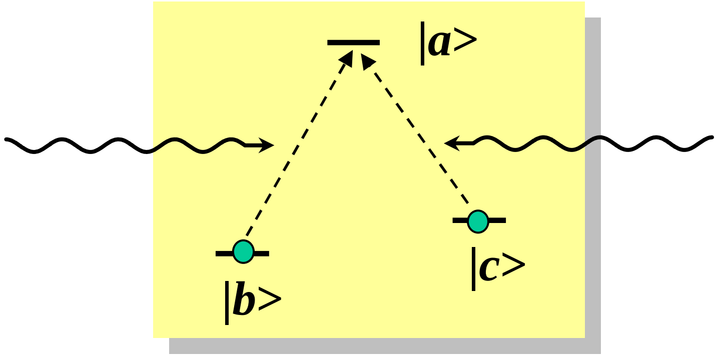
- Slow and stored light
- Entangled photon pairs
- Light-matter quantum interface

- Lasing without inversion
- Nonlinear optics with single photons
- Stimulated Raman adiabatic passage

For a review, see for example, Lukin, Rev. Mod. Phys. 75, 457 (2003).

Slow Light

$$v_g = \frac{d\omega}{dk} = \frac{c}{n + \omega \frac{dn}{d\omega}}$$

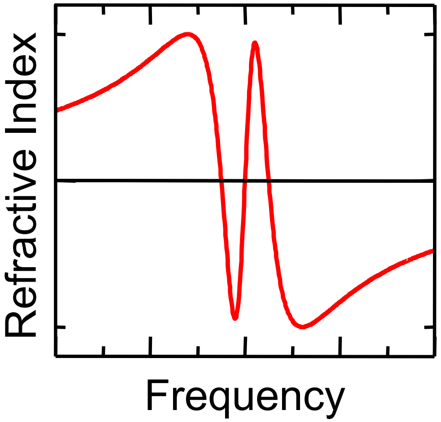


Group velocity ~ $c/10^7$

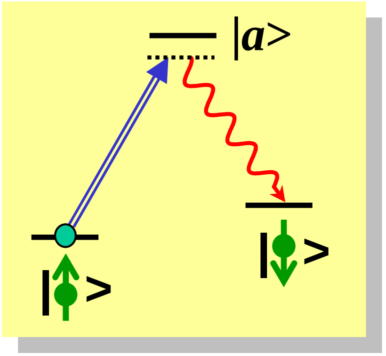
Hau *et al.*, Nature **397**, 594 (1999).
Kash *et al.*, Phys. Rev. Lett. **82**, 5229 (1999).
Budker *et al.*, Phys. Rev. Lett. **83**, 1767 (1999).

Application:

e.g., Optical buffers (Chang-Hasnain, UC Berkeley)



Spin-Photon Correlation



Duan *et al.*, Nature 414, 413 (2001).

- Emission of a photon via the spontaneous Raman transition is correlated with a spin flip.

- Application

  Quantum state transfer, entangled photon pairs, quantum repeaters, and long distance quantum communication

Quantum Control of Single Photons with EIT

Functional quantum nodes for entanglement distribution over scalable quantum networks, **Science 316, 1316 (2006).**
Kimble group

Generation of narrow-bandwidth paired photons: use of a single driving laser**, Phys. Rev. Lett. 97, 113602 (2006).**
Harris group

Storage and retrieval of single photons transmitted between remote quantum memories**, Nature 438, 833 (2005).**
Kuzmich group

Electromagnetically induced transparency with tunable single-photon pulses**, Nature 438, 837 (2005).**
Lukin group

Challenges for EIT in Semiconductors

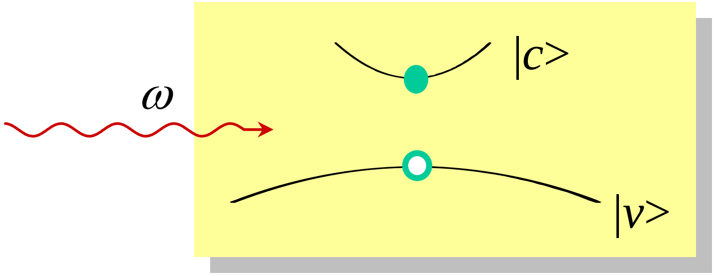
- **Short decoherence time**
  - **Solution 1: Pursuing quantum interference in a transient regime**
  - **Solution 1: Using robust quantum coherence.**

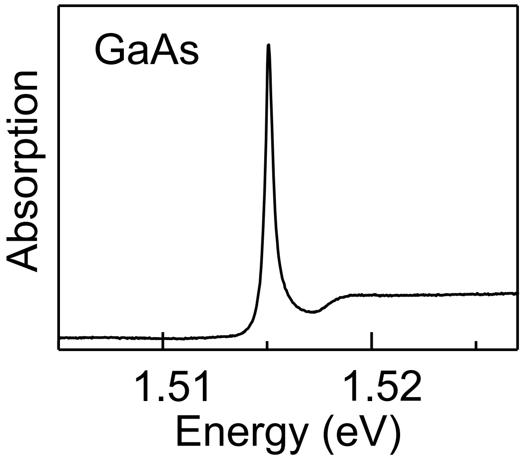
- **Manybody Coulomb interactions**

  Fundamentally affect optical processes in semiconductors.

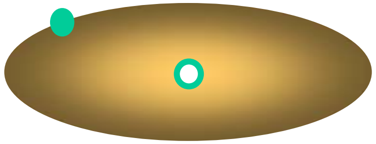
  - **Solution: Understand and harness manybody interactions for EIT.**

Optical Excitations in Semiconductors: Excitons





- **Excitons: Bound states of an e-h pair**

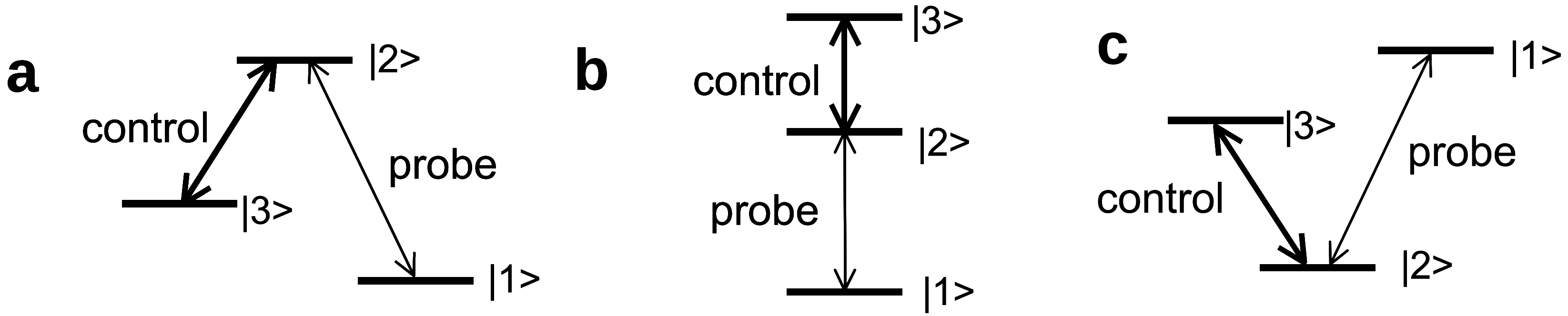


E_B ~ 10 meV
r_B ~ 10 nm

Very loosely bound e-h pairs!

- **Collective excitation of the crystal**
- **Manybody interactions between excitons**

Three Types of EIT Systems



Demonstrated EIT using analogous systems in semiconductors:

a) **Exciton spin coherence** [Phys. Rev. Lett. **89**, 186401 (2002)]
b) **Biexciton coherence** [Phys. Rev. Lett. **91**, 183602 (2003)]
c) **Electron spin coherence** [Phys. Rev. B **70**, 153307 (2004); Phys. Rev. B **72**, 035343 (2005); Opt. Lett. **32**, 569 (2007).]

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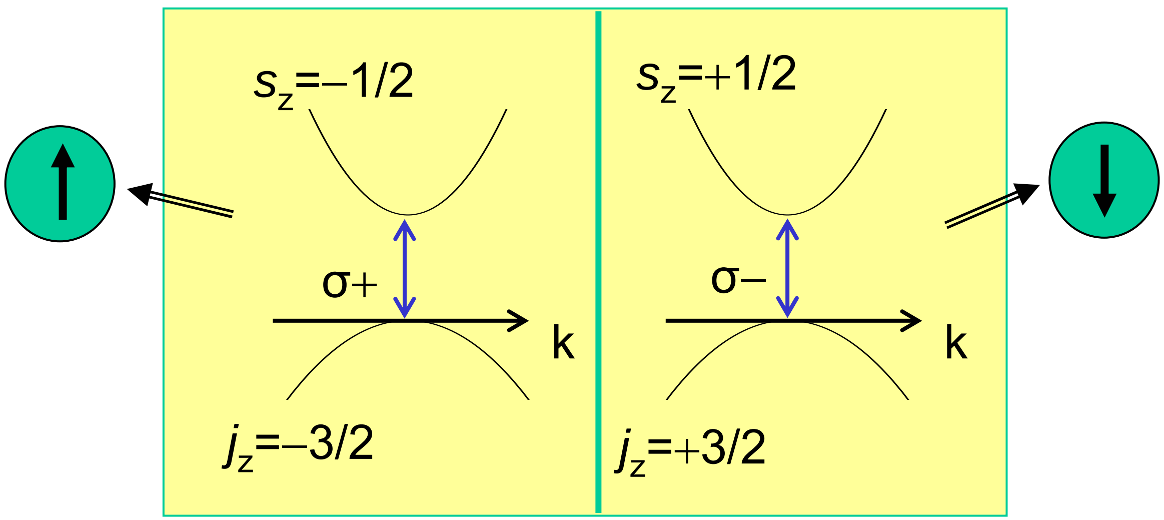
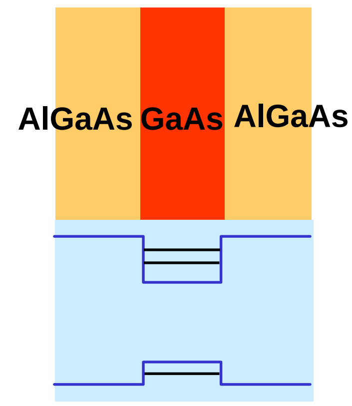
  - Electron spin coherence
- Summary

Exciton Spin Coherence





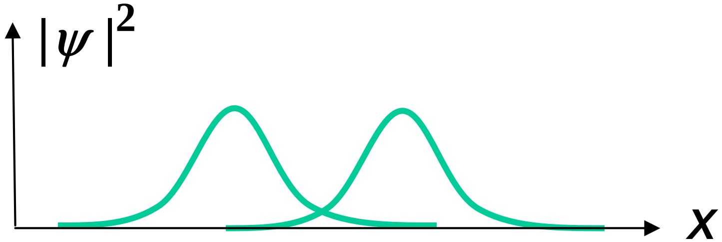
GaAs quantum well

- **Exciton spin coherence: coherent superposition of spin-up and spin-down exciton states**
  - **The two transitions share no common state.**
  - **No exciton spin coherence can be induced in a non-interacting exciton system.**

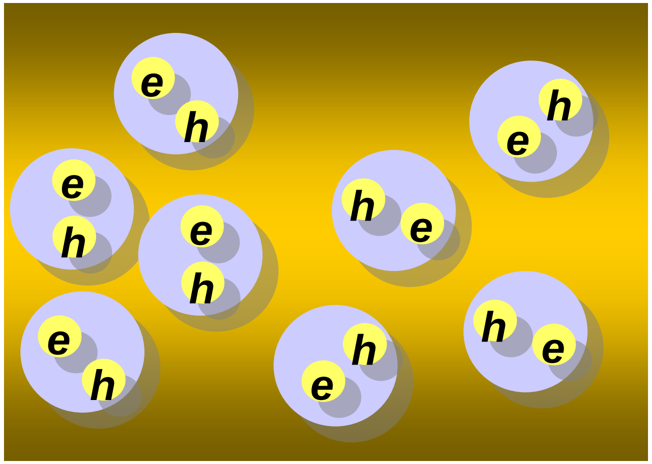
Excitons: A Interacting Many-Particle System

- **Exchange interaction:**

  Exciton wave-functions start to overlap at relatively low densities.



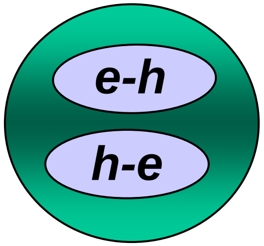
r_B ~ 10 nm



- **Coulomb correlation:**

  For nearby excitons, charge fluctuations are strongly correlated.

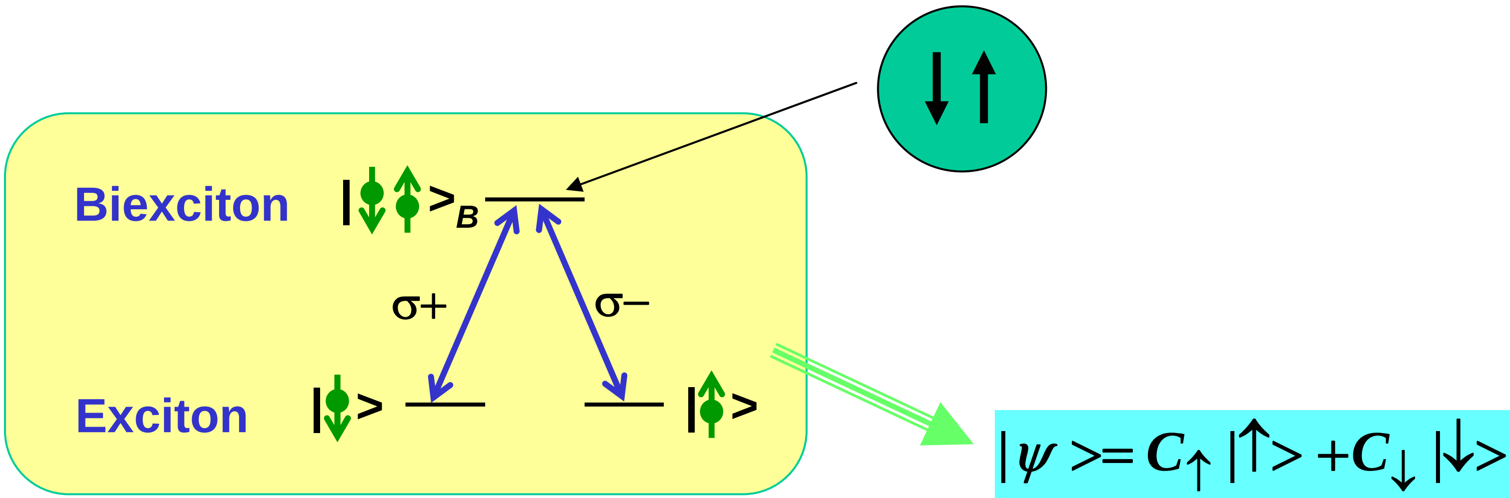
  Attractive correlations can lead to the formation of exciton molecules or biexcitons.



biexciton

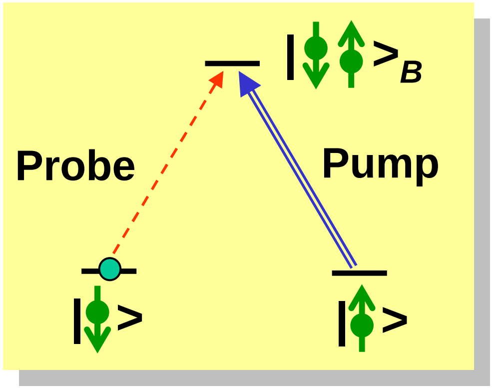
Exciton Spin Coherence via Biexcitons

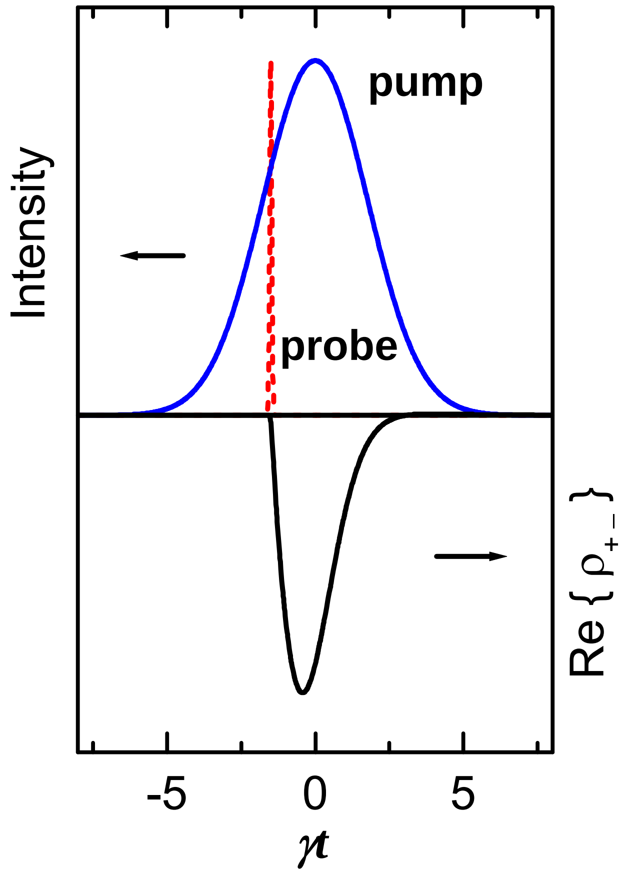
- **Coupling exciton spin states via biexcitonic transitions:**



Taking advantage of manybody interactions between excitons to induce quantum coherence and realize EIT.

EIT with Ultrafast Pulses



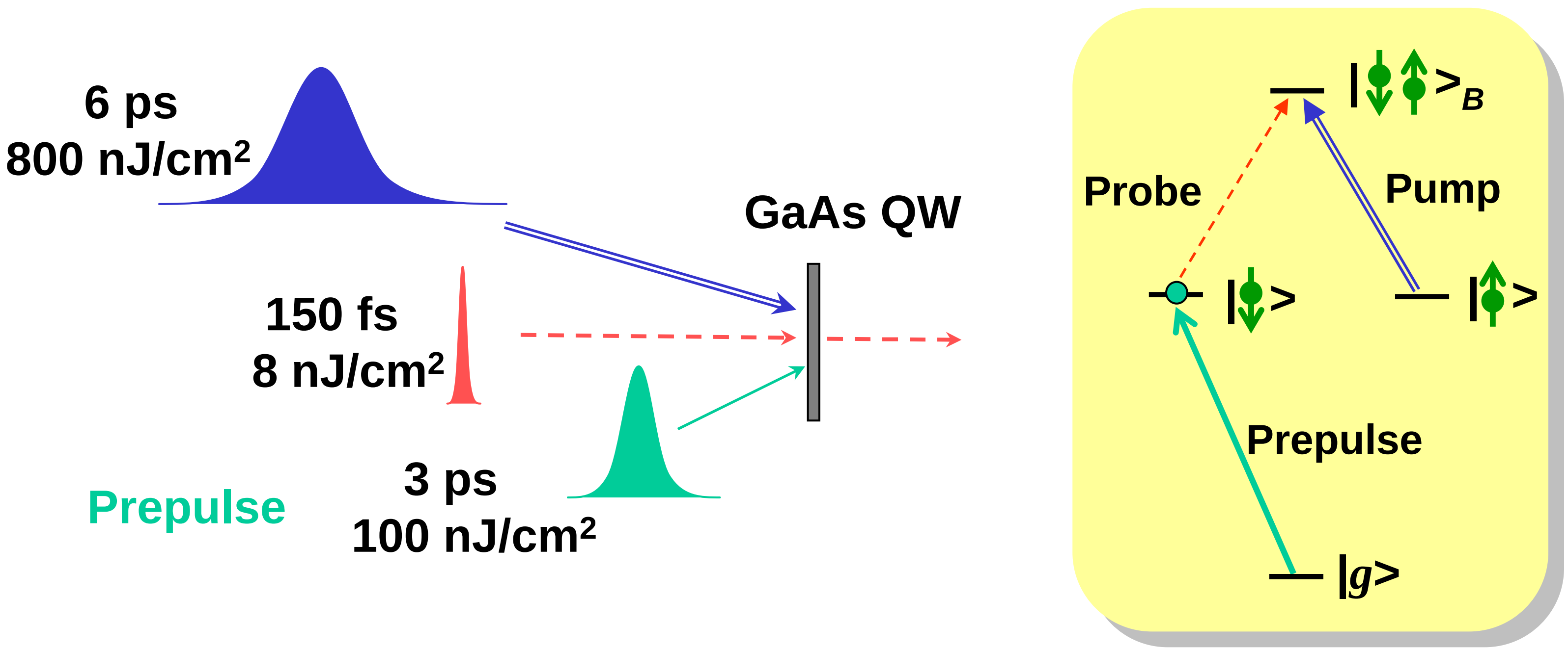


A long pump pulse and a short probe induce a spin coherence.

- **Spin coherence**

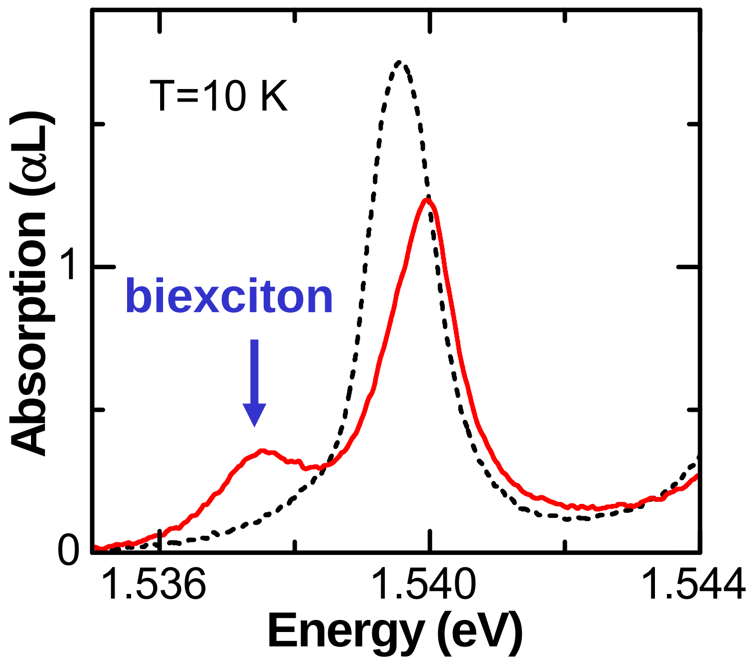
Re(ρ_{+-})<0: Phased for destructive interference.

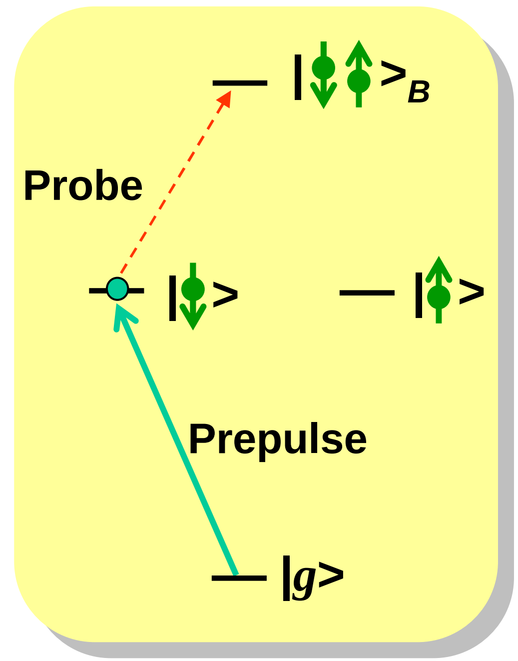
Experimental Configuration



The prepulse pulse arrives 10 ps before the pump to inject spin-down excitons.

Biexciton Resonance

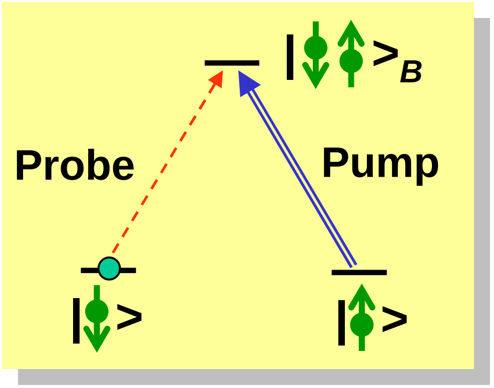




10 nm GaAs/AlGaAs QW

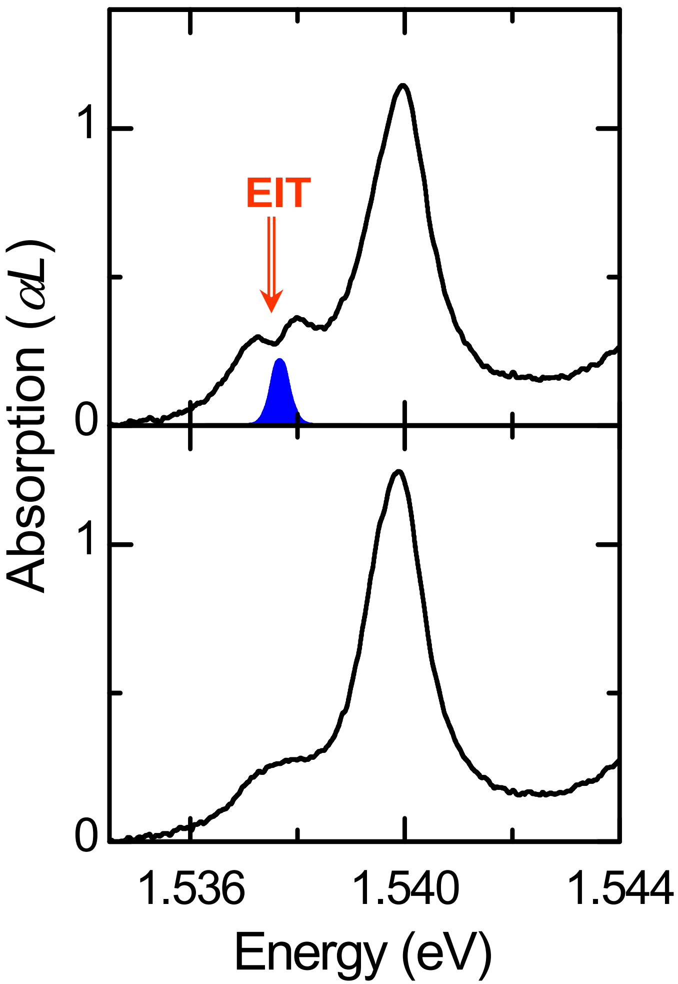
Dashed curve: Absorption spectrum without prepulse.
Solid curve: Absorption spectrum with prepulse.

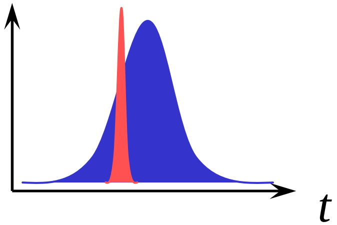
EIT from Exciton Spin Coherence

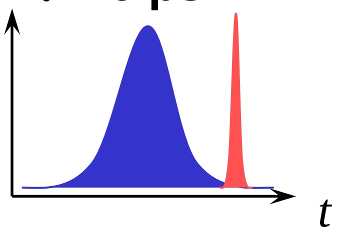


10 nm GaAs QW
T=10 K

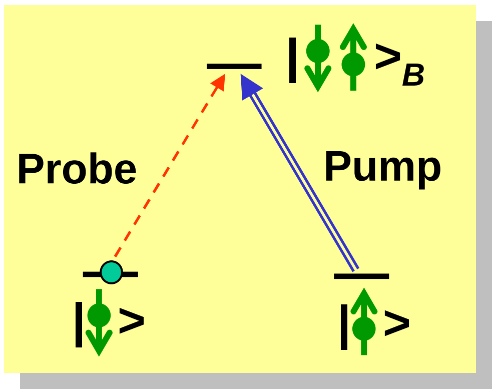
Phys. Rev. Lett. 89, 186401 (2002).

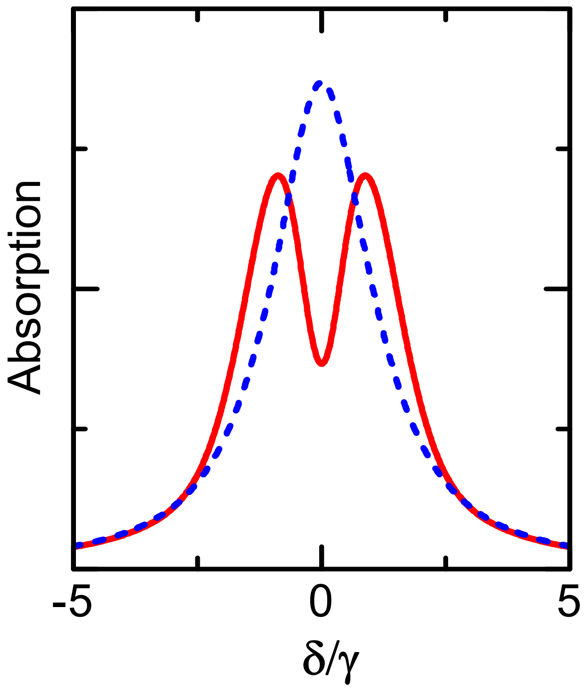






EIT from Spin Coherence

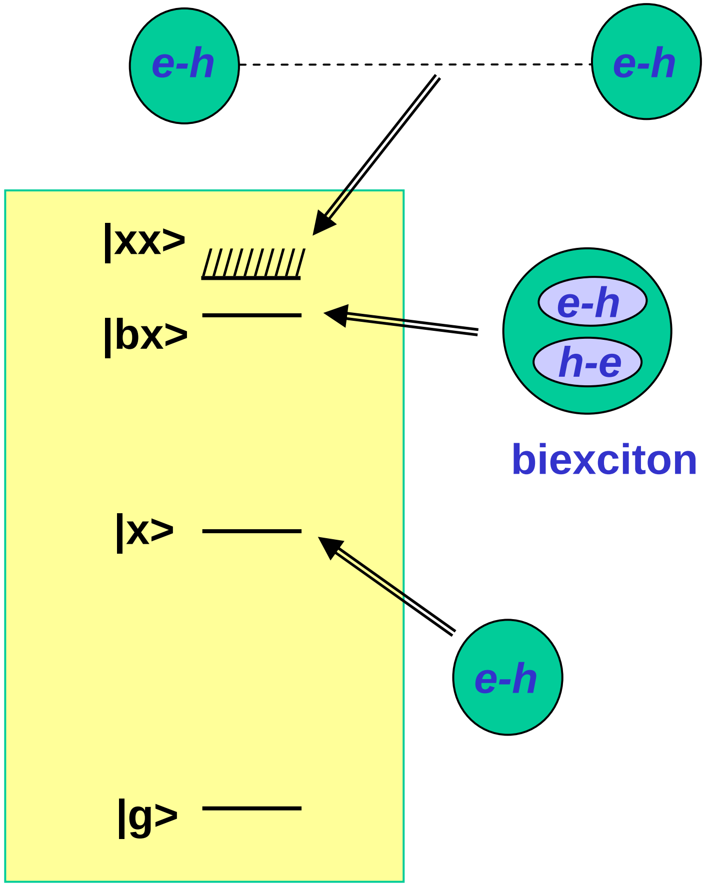




Theoretical calculation based on a 3-level model.

Dashed line: Absorption spectrum when the spin coherence is artificially turned off.

Two-Exciton States

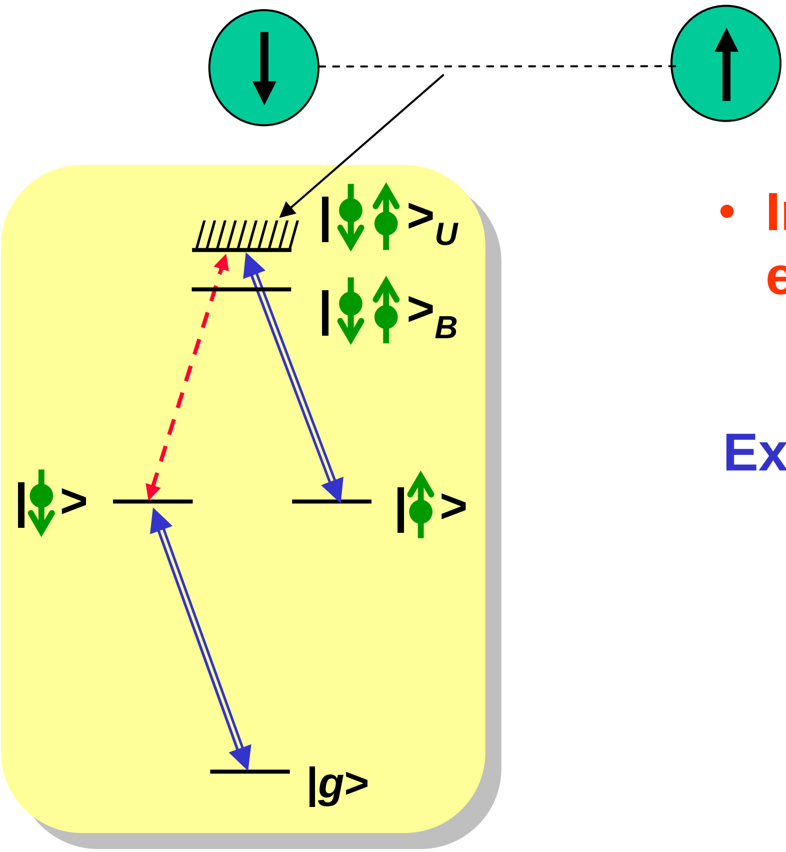


Axt and Stahl, Z. Phys. B **93**, 195 (1994).
Östreich *et al*., Phys. Rev. Lett. **74**, 4698 (1995).
Kner *et al*., Phys. Rev. Lett. **81**, 5386 (1998).
Sieh *et al*., Phys. Rev. Lett. **82**, 3112 (1999).

The two-exciton states play an essential role in coherent optical processes in semiconductors.

Only 1s exciton states are inlcuded.

Spin Coherence via Two-Exciton Scattering States



- Inducing spin coherence via two-exciton scattering states?

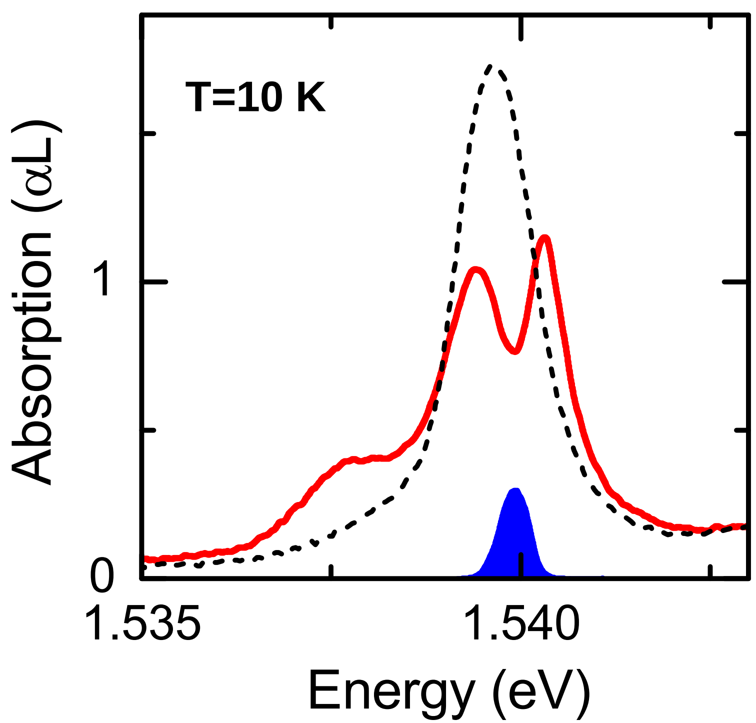
Experiment:

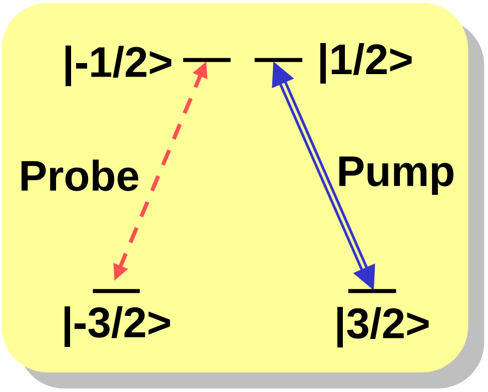
The pump pulse excites excitons directly: no prepulse is needed.

EIT occurs at the energy of the exciton resonance.

EIT via Exciton spin Coherence

Phys. Rev. Lett. 89, 186401 (2002).





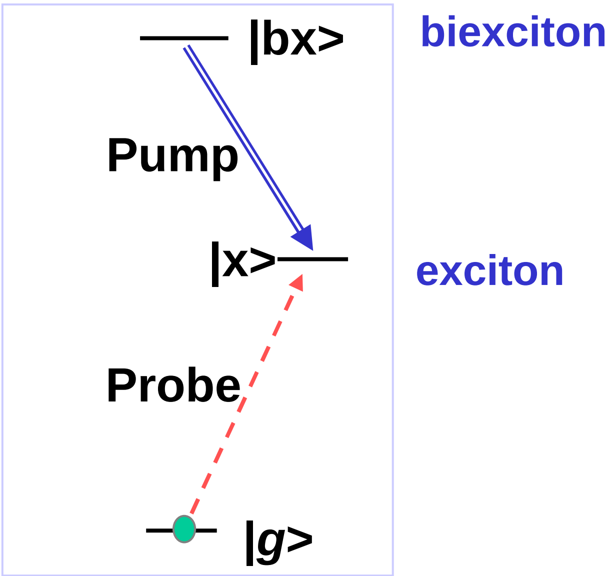
10 nm GaAs QW

The pump and probe couple to transitions that share no common states.

Exciton spin coherence induced via two-exciton continuum states can also lead to EIT.

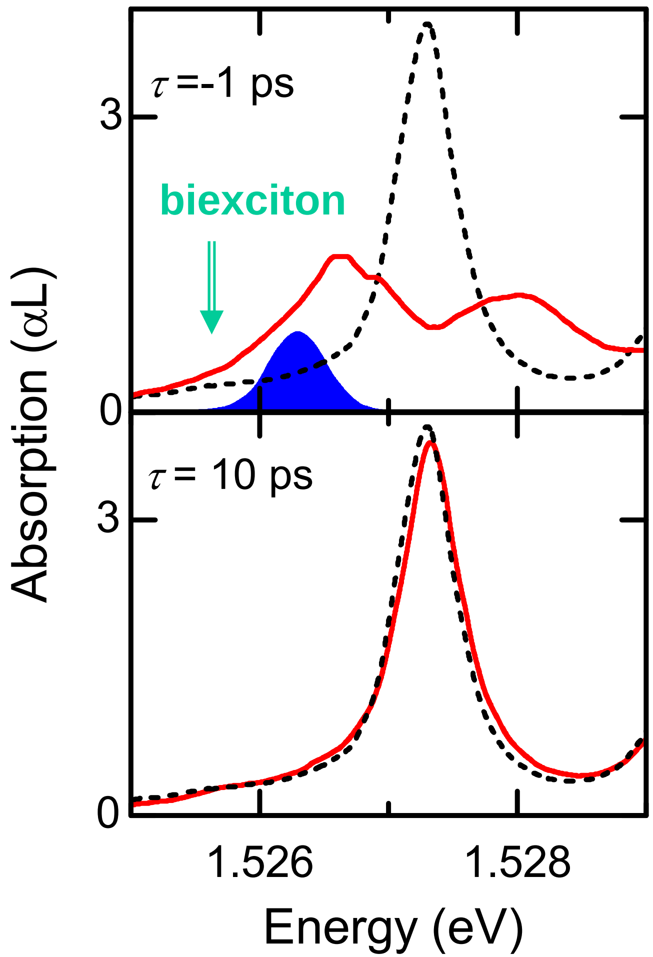
EIT from Biexciton Coherence

Two pathways to drive the system to state |x>: |*g*> to |x> & |bx> to |x>



- Biexciton coherence: Coherent superposition of |*g*> and |x>.
- The probe and pump couple to the exciton and biexciton transitions, respectively.
- The EIT dip occurs at the exciton absorption resonance.

EIT from Biexciton Coherence



- **The pump is tuned slightly above the biexciton resonance.**
- **The absorption dip occurs at the exciton resonance.**
- **Delay dependence shows the coherent nature of the dip.**

Phys. Rev. Lett. 91, 183602 (2003).

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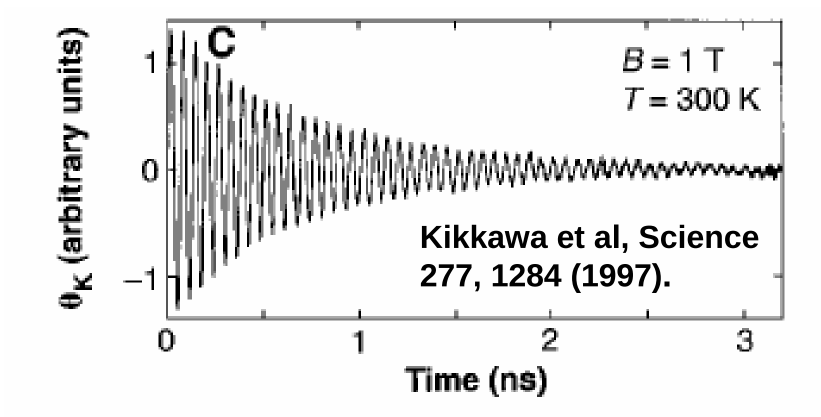
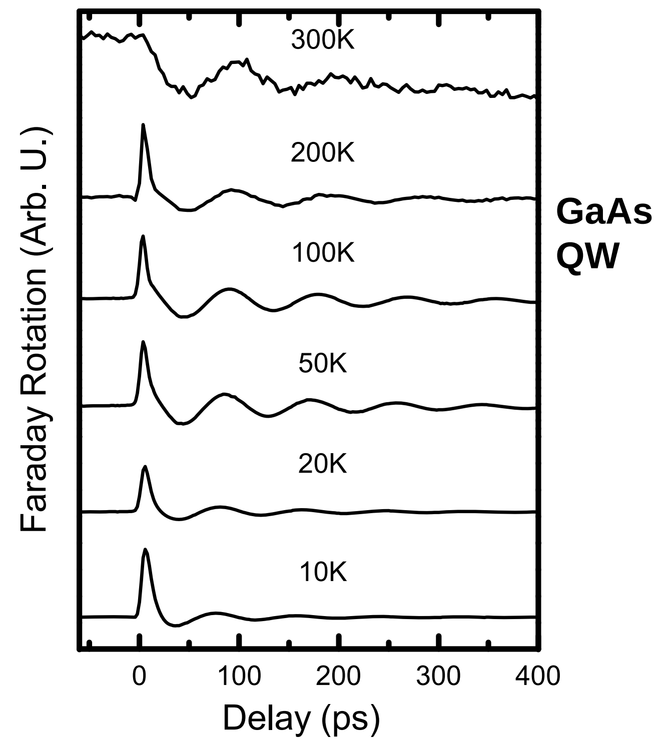
Electron Spin Coherence in Semiconductors

- Electron spin coherence is exceptionally robust.

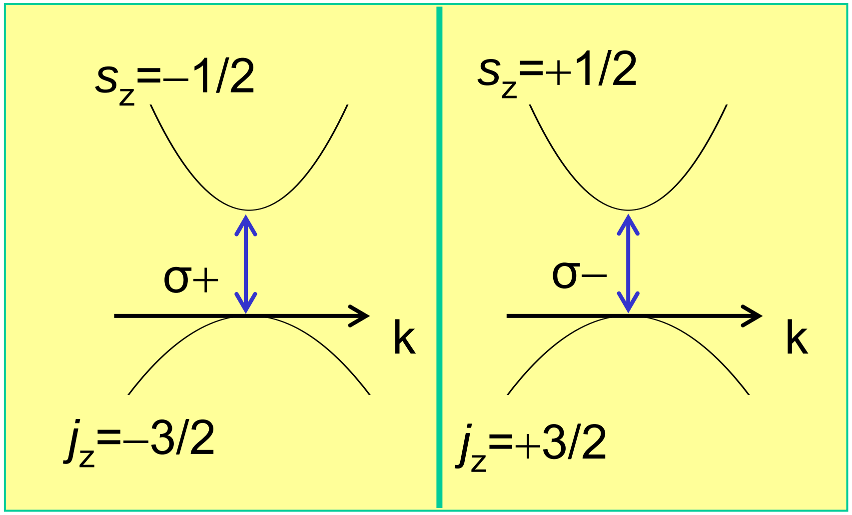
  can last as long as 0.1 μs and remain robust at room temperature.

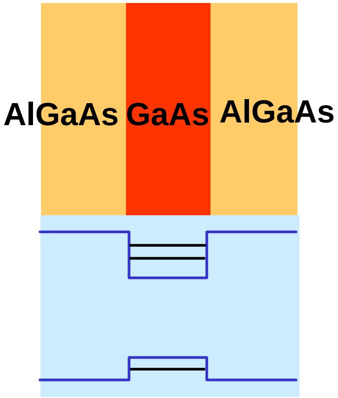




- Suitable three-level systems?

Band Structure



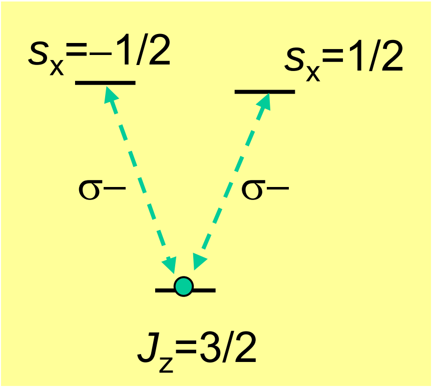


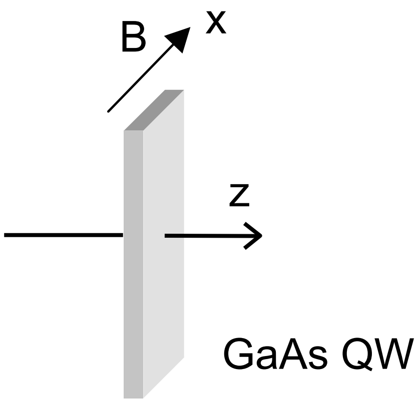
GaAs quantum well

- **The lowest energy interband transitions in a GaAs QW are characterized by two heavy-hole (HH) transitions.**
  - **The two transitions share no common state.**
  - **No electron spin coherence can be induced.**

V-System in an External Magnetic Field

Inducing spin coherence: **Coupling electron spin states to a common valence band state via dipole transitions.**

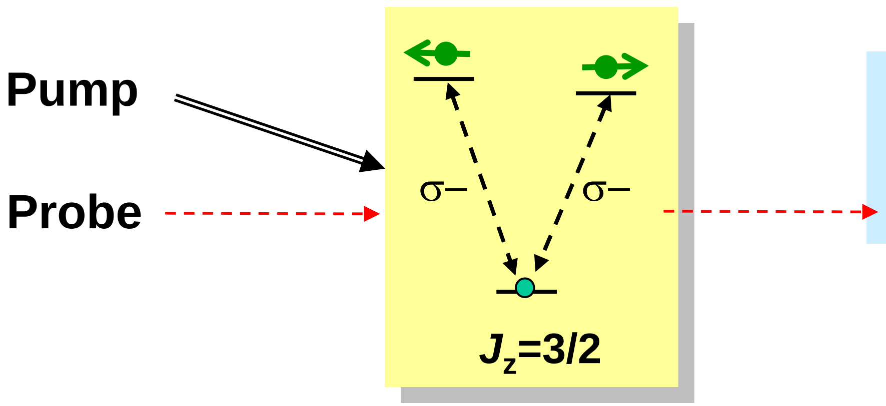




Voigt configuration

- **Electron spins are aligned with the external magnetic field.**
- **In a weak magnetic field, J_z remains approximately a good quantum number for the holes.**

CW EIT Experiments

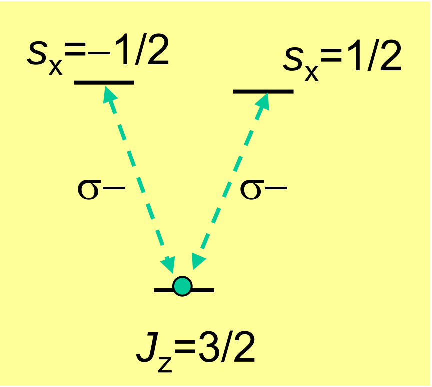


Differential transmission:

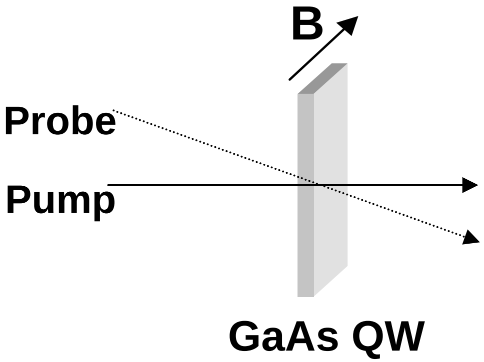
$\Delta T = T\,(pump\text{-}on) - T\,(pump\text{-}off)$

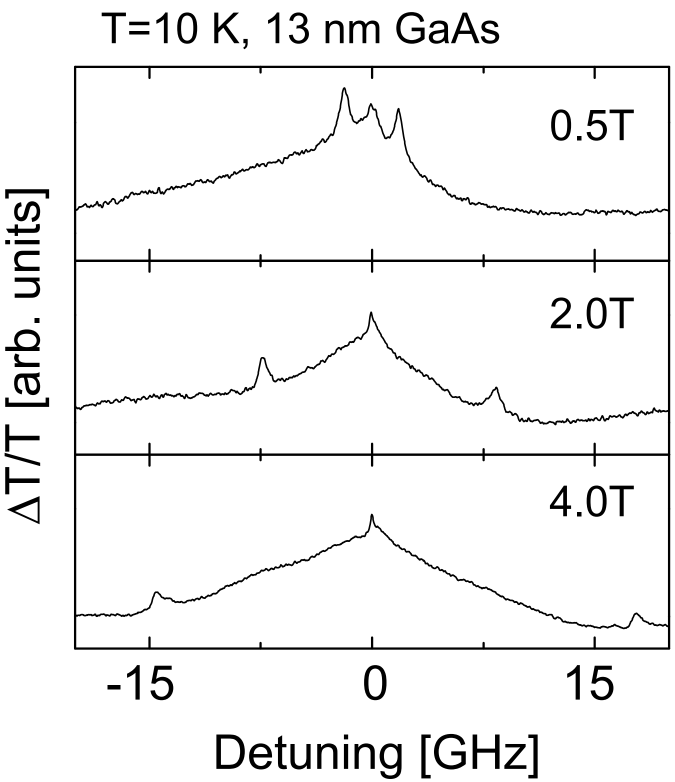
- **The pump and probe excite an electron spin coherence.**
- **Destructive interference induced by the spin coherence can lead to:**
  - **Induced resonance in transmission (dip in the absorption).**

Coherent Zeeman Resonance



$$\Delta T = T_{Pump-on} - T_{pump-off}$$

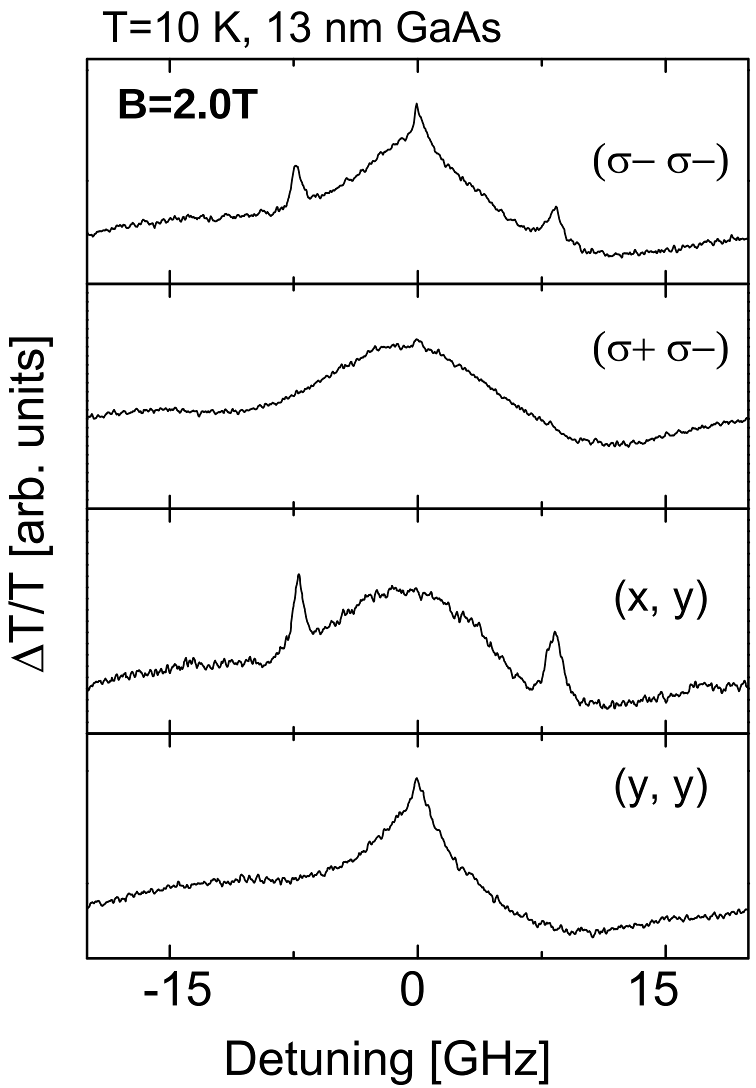


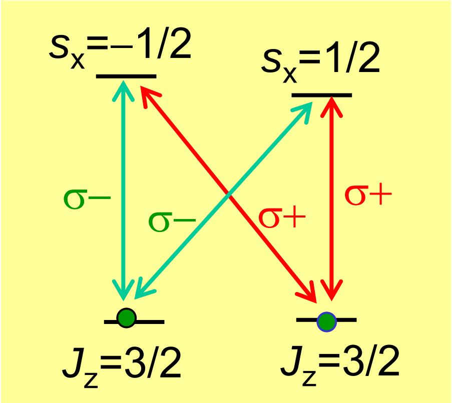


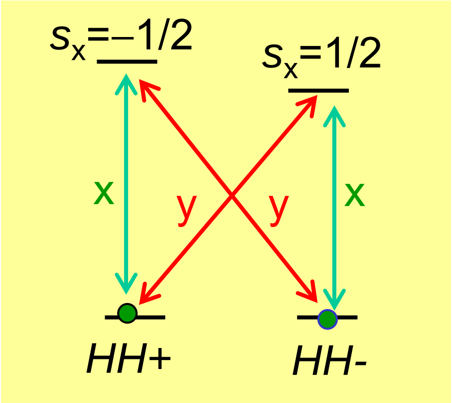
The sharp Zeeman resonance arises from destructive interference induced by the electron spin coherence.

Phys. Rev. B **70**, 153307 (2004).

Polarization Dependence

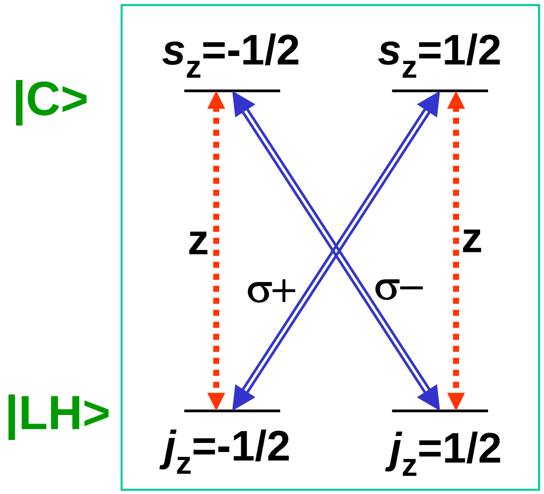




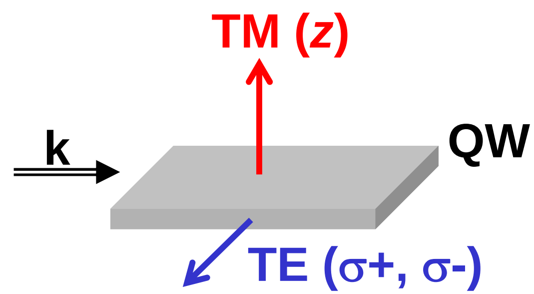


Coherent Zeeman resonance in the cross-linear configuration can be viewed as EIT from the electron spin coherence.

V-System without External Magnetic Fields



Using light hole transitions in a waveguide.

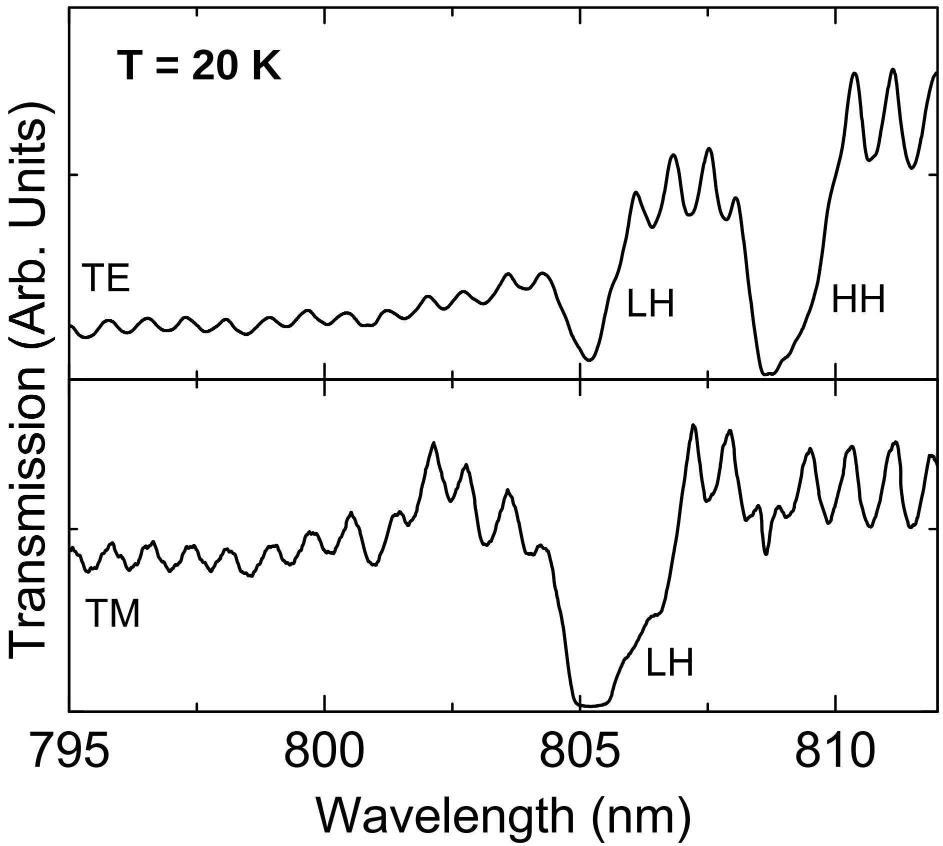


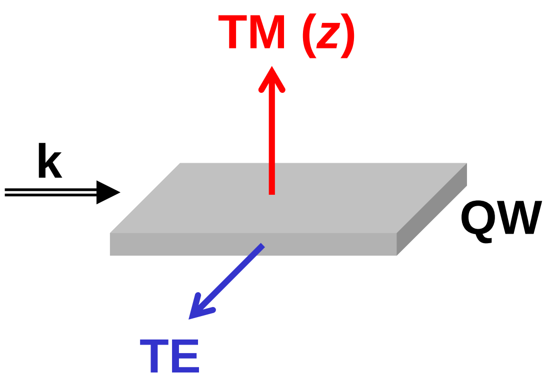
$$| j_z = 1/2 >= \frac{1}{\sqrt{3}} | Y_{11} >|\downarrow> + \sqrt{\frac{2}{3}} | Y_{10} >|\uparrow>$$

Key features:

- Spin-orbit coupling mixes the spin-up and spin-down states for the light-hole (LH) band: double-V system.
- Inducing electron spin coherence in the absence of an external magnetic field.
- The waveguide geometry enables long interaction length.

GaAs/AlGaAs QW Waveguide

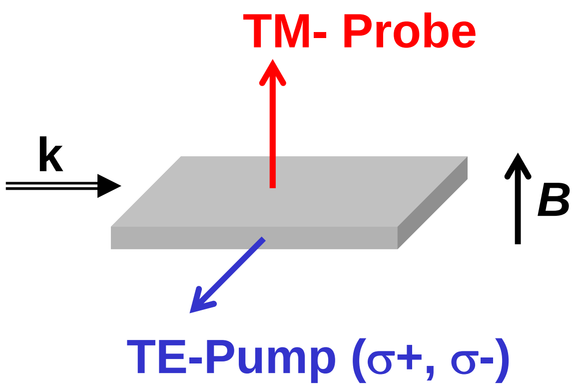




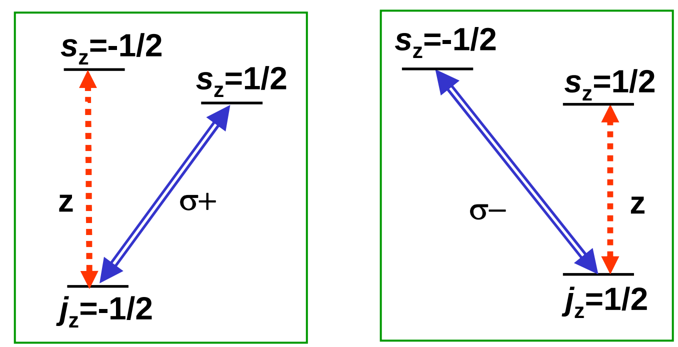
Sample:
Single 17.5 nm GaAs
QW AlGaAs Cladding
Length ~ 100 μm

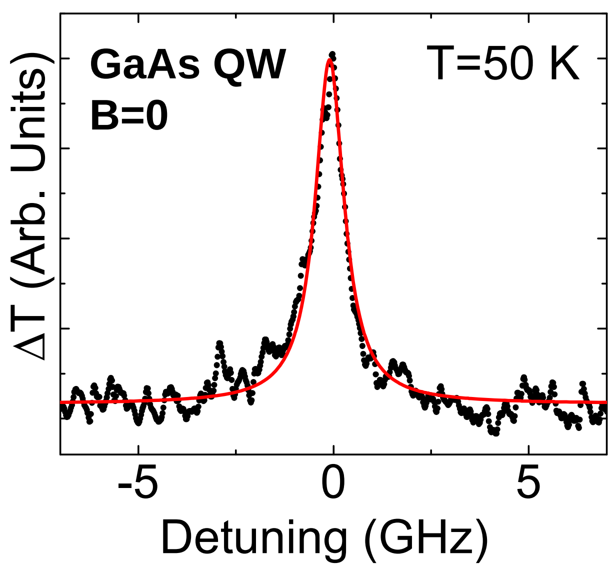
For TM polarization, HH exciton resonance is nearly negligible, as expected from optical selection rules.

EIT in a QW Waveguide

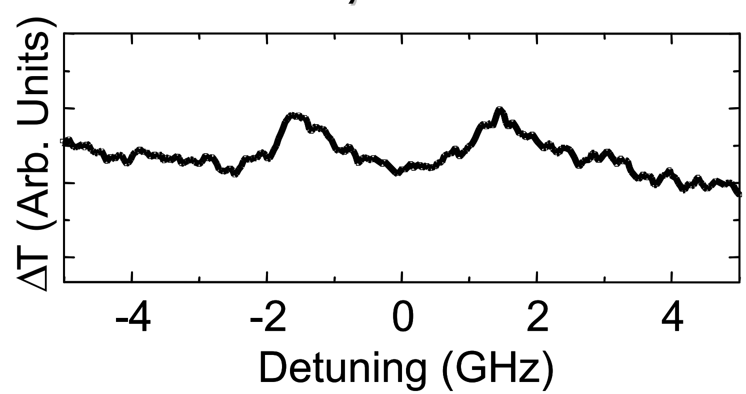


Light-Hole exciton transition



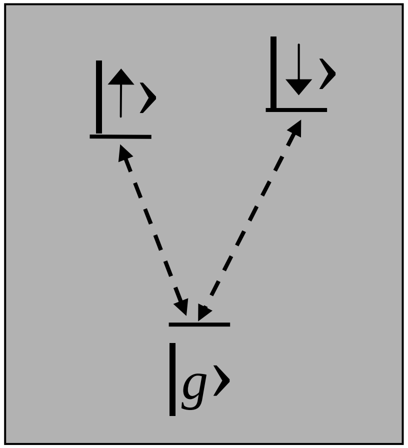


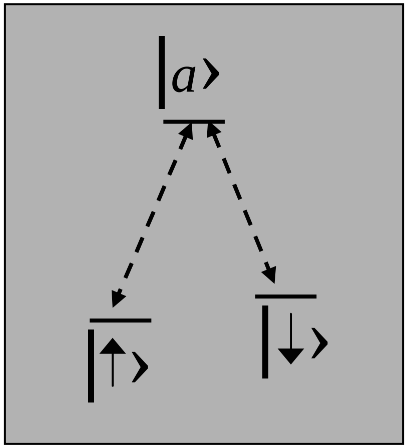
T = 50 K, B = 0.25 T



Phys. Rev. B **72**, 035343 (2005)

V-Type vs Λ-type Three-Level Systems





- **V-System**

  Spin decoherence is limited by radiative decay.

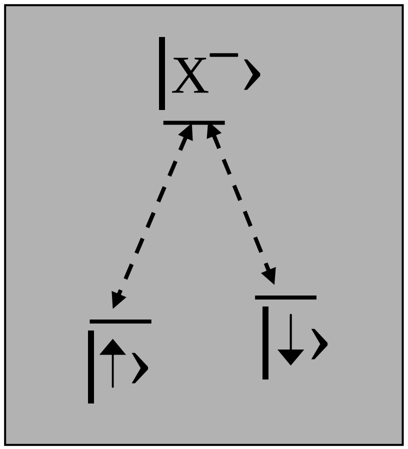
  Degree of transparency is limited.

- **Λ-System**

  Spin states are the ground states.

  Nearly complete transparency can be achieved.

Λ-type Three-Level System via Trions



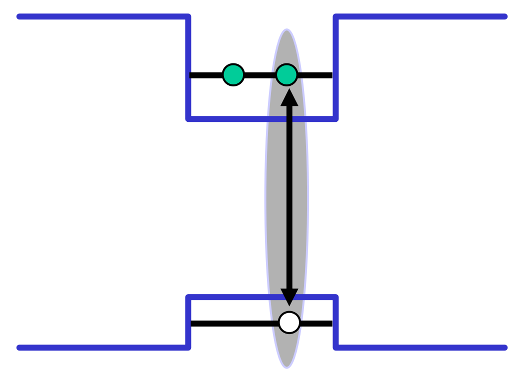
- **Trion:**

  An exciton bound to an electron (negatively charged exciton).

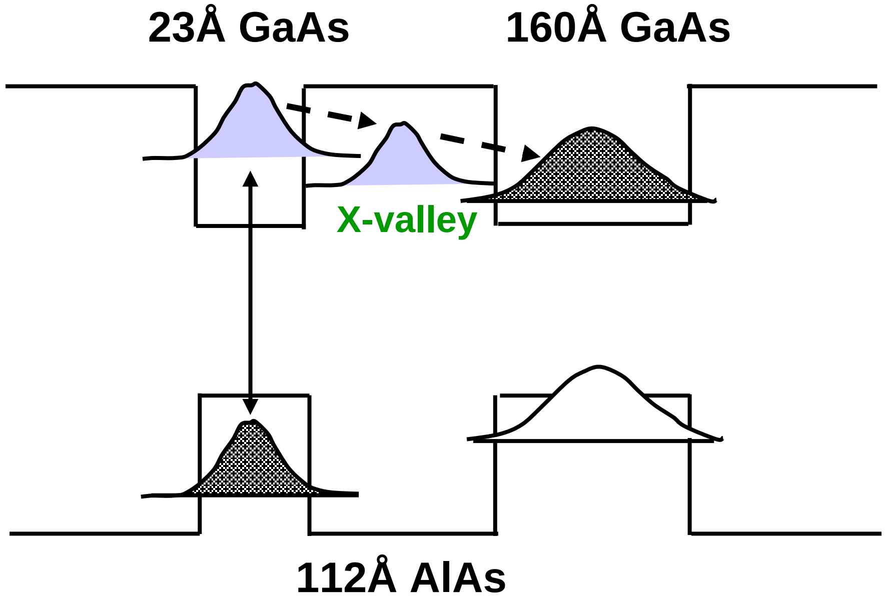
  Involves two electrons and one hole.

  Kheng *et al*., PRL 71, 1752 (1993).

- **The formation of the Λ-system requires an excess electron population in the conduction band.**



Mixed Type Quantum Well Structures



- Mixed type QW:

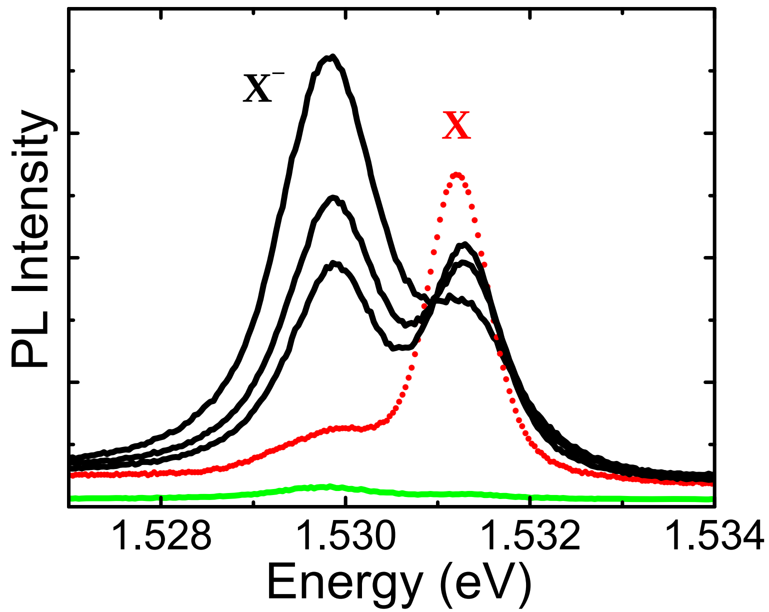
  The bottom of the conduction band in the narrow QW is higher than the X-valley in the AlAs barrier.

  Narrow well: type II
  Wide well: type I

  Galbraith et al., Phys. Rev. B 45, 013499 (1992).

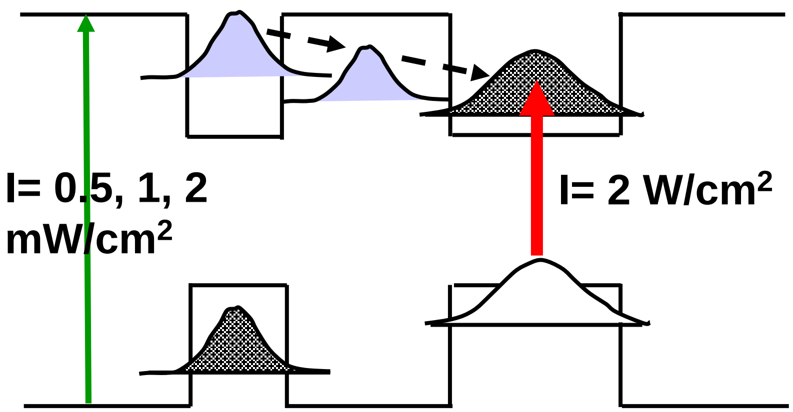
- Electrons in narrow QW transfer via X-valley in the barrier to wide QW. Holes remain confined in the narrow QW.
- Advantage: Using optical injection to control the electron density in the wide QW.

Formation of Trions in a Mixed-Type QW

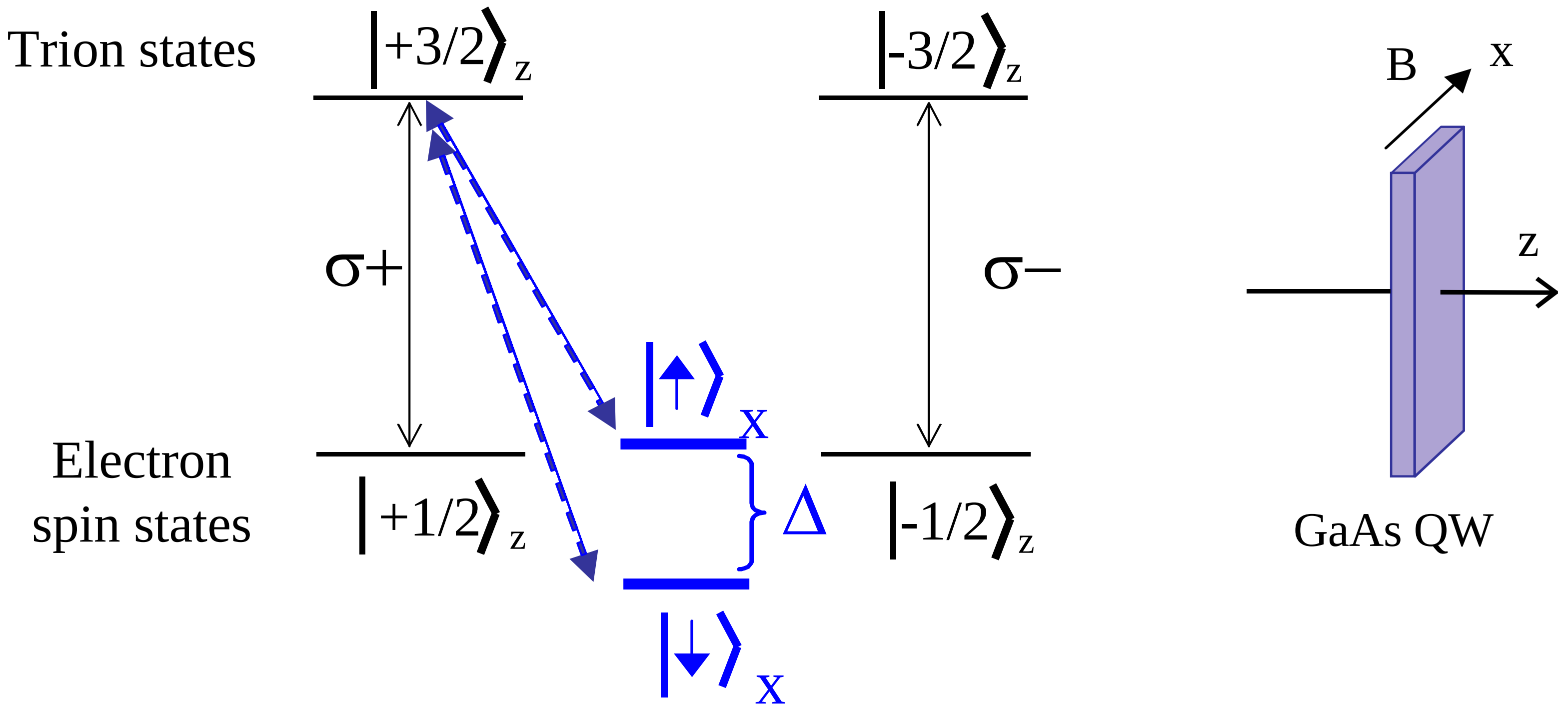


- **With increasing number of electrons in the wide well, more excitons are converted into trions.**
- **Trion binding energy: 1.6 meV**

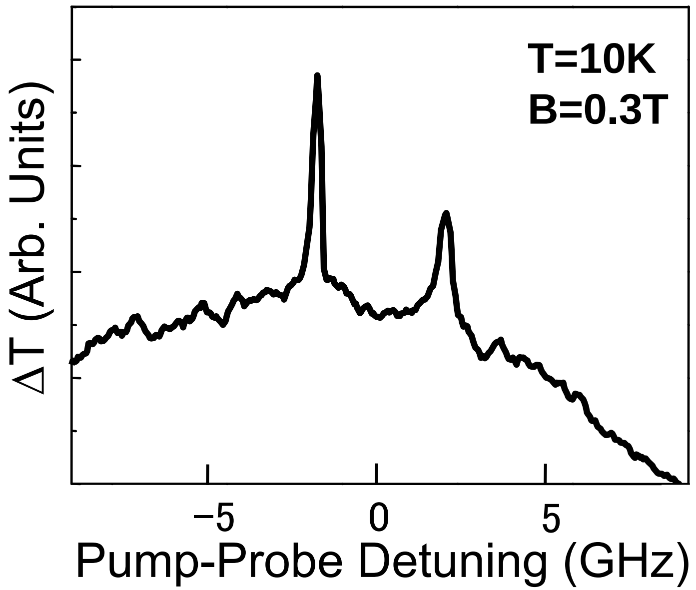
- **For black lines, the sample is excited by both the red and green laser beams.**

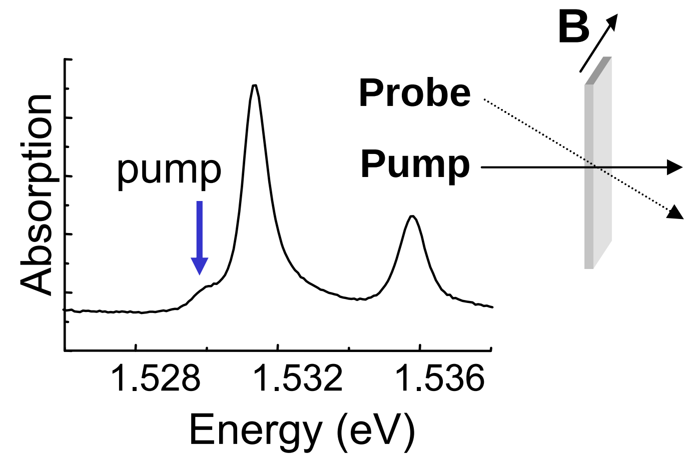


Λ-type Three-Level System via Trions

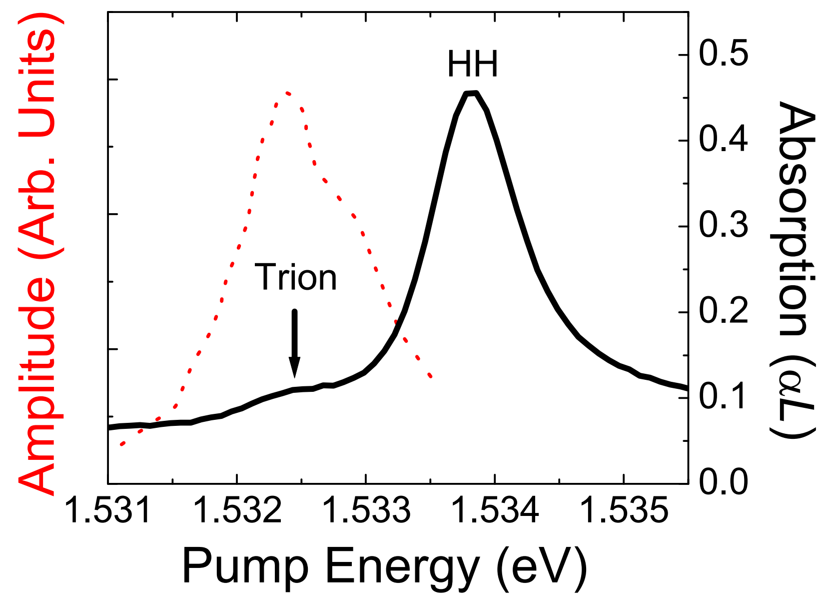


Coherent Zeeman Resonance in the Λ-System



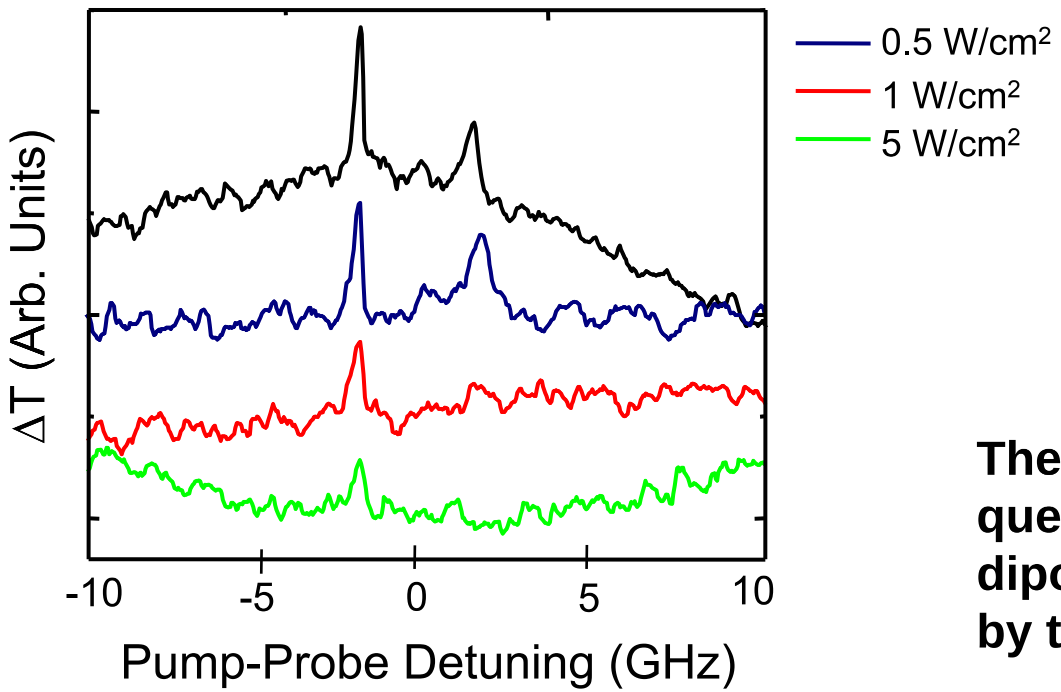


- **The width of the coherent Zeeman resonance corresponds to a spin decoherence time of 1 ns.**



Opt. Lett. **32**, 569 (2007).

Effects of Electron Injection

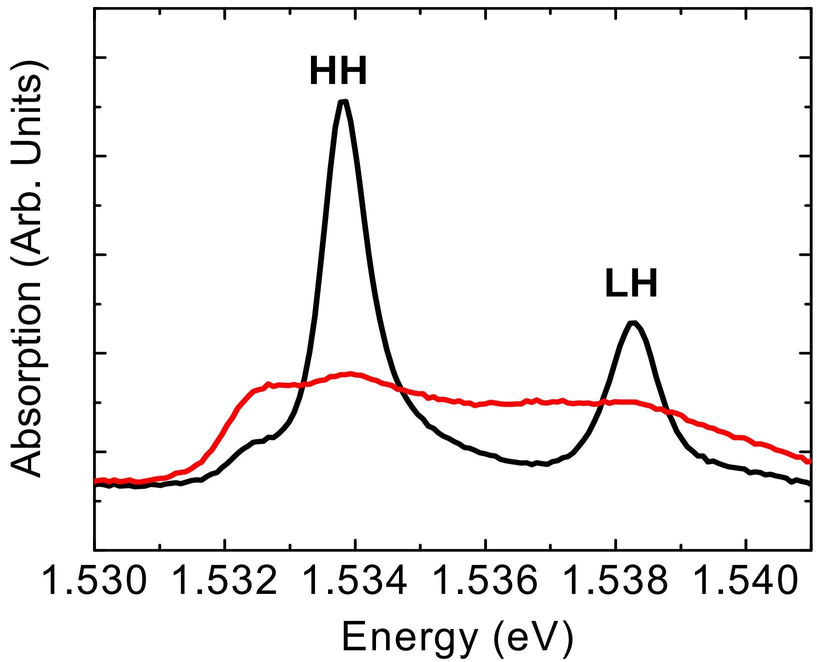


$$P^{NL} \propto \frac{1}{\gamma^2}$$

The coherent response is quenched by the increased dipole decoherence induced by the carrier injection.

- **Coherent Zeeman resonance amplitudes are suppressed with increased electron injection.**
- **The linewidth does not appreciably broaden .**

Effects of Carrier-Carrier Interactions

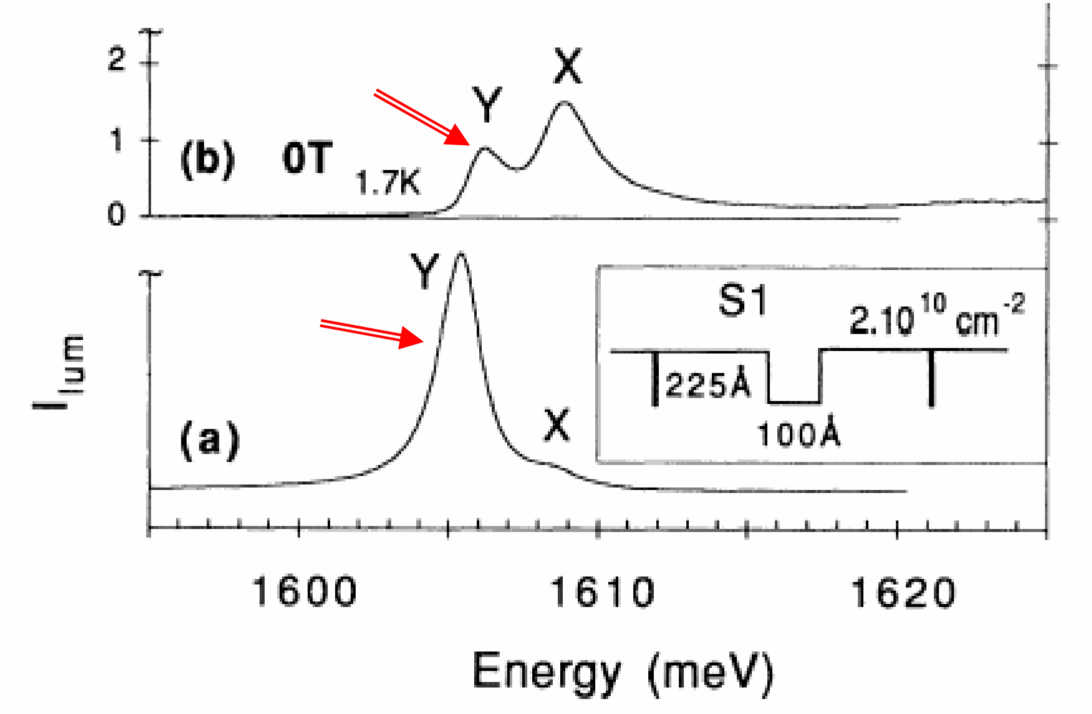


Red curve: absorption spectrum obtained at an injection level of 0.25 mW/cm^2

- Trion resonance present without injection due to residual doping.
- Trion absorption peak enhanced by the injection of electrons.
- Absorption resonance broadens dramatically due to efficient carrier-carrier carrier scattering.

What is next?

Trions in II-VI Semiconductors

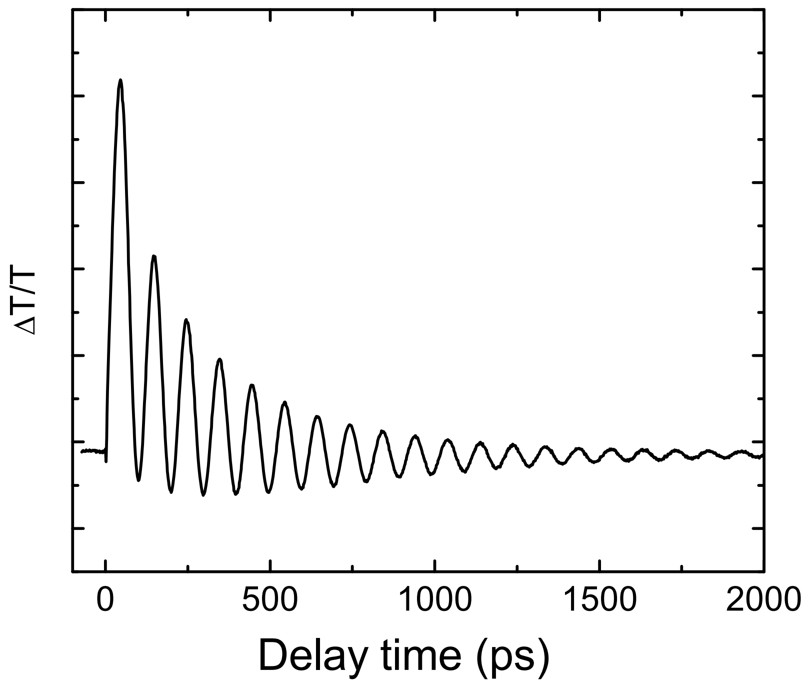


- CdTe/CdZnTe quantum well
- Modulation doping: $2 \times 10^{10}/cm^2$

Kheng *et al*., PRL 71, 1752 (1993).

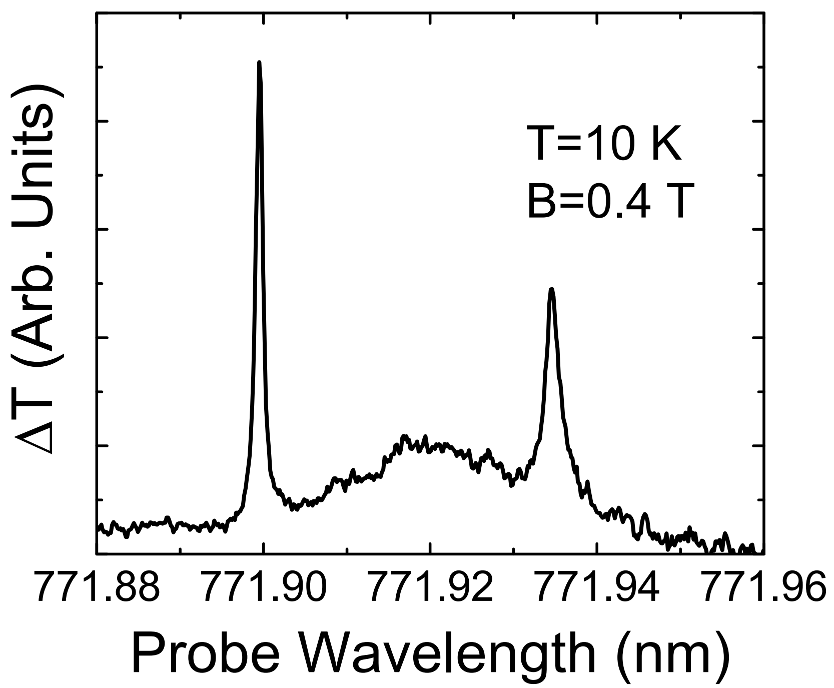
- II-VI semiconductors feature greater binding energy.
- Pronounced and robust trion resonance in both absorption and emission spectra (the Y-resonance).

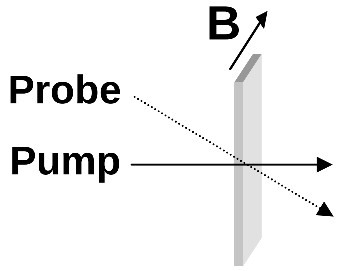
Spin Precession from Trions in CdTe QW



- **Spin decoherence time ~ 1 ns**
- **Modulation doping: $2x10^{10}/cm^2$**

EIT from Trions in CdTe Quantum wells





- **The pump is at the trion resonance (λ ~ 771.92 nm).**
- **Pronounced coherent Zeeman resonance arising from destructive interference induced by the electron spin coherence.**

Future Work

- **Optimize the EIT process using trions and electron spin coherences.**
- **Coherent spin flipping via adiabatic passage.**
- **Incorporate EIT via trions in a waveguide geometry.**
- **Spin-phonon correlations.**
- **Generation of entangled photons.**

Summary

- Main Theme: EIT can be realized in semiconductors.
  - Demonstrated EIT with exciton spin coherence and biexciton coherence.
  - EIT can also be realized with robust electron spin coherence, opening possibilities for applications.
  - Manybody interactions between optical excitations modifies fundamentally coherent optical processes in semiconductors.

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