# Limiting lifetimes for localized spins in GaAs

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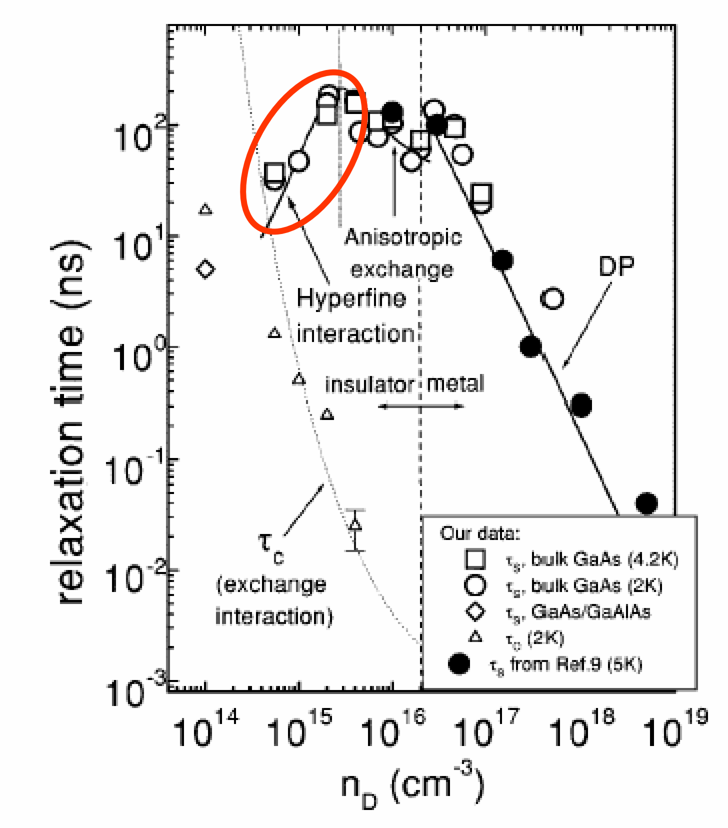
& Josh Caldwell

# Outline

1. Background
    1. Long lifetimes for spins in non-magnetic semiconductors
    2. Work with donor ensembles
2. Magnetic resonance detected through Faraday Rotation
    1. Method
    2. Nuclear effects
    3. Probe light effects
    4. Higher concentration sample
    5. g-factor and Lifetime
3. Summary and Future Work

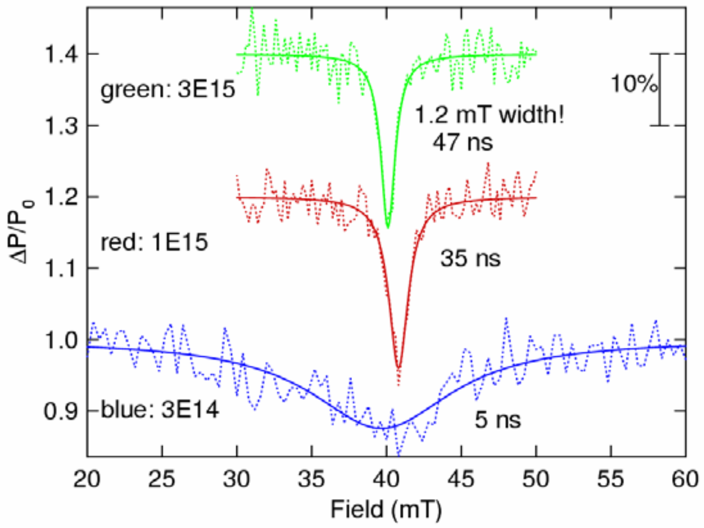
# Background

- Long lifetimes in non-magnetic semiconductors
  - Kikkawa and Awschalom, PRL and Science
- Move to localized spins—qubits and quantum information
  - In III-V's—GaAs donors provide a good ensemble
  - Metal-insulator transition is at 2 X $10^{16}$ $cm^{-3}$
  - Isolated donors for $N_D$ < 4 X 10 $^{14}$ $cm^{-3}$ for B = 0 T

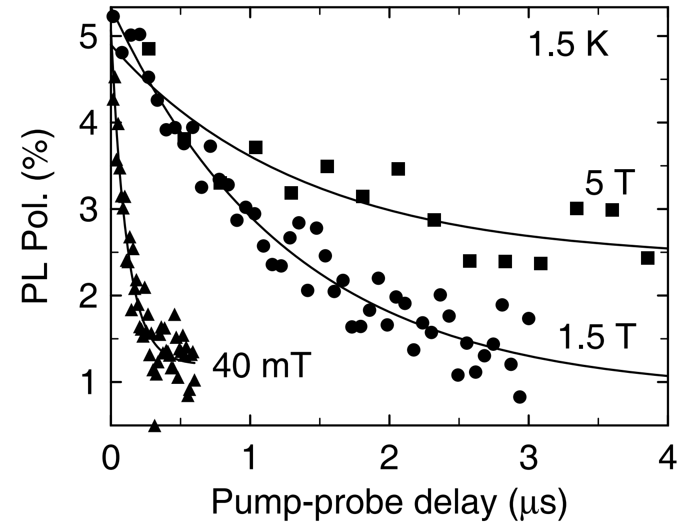


Dzhioev *et al.*, Phys. Rev. B **66**, 245204 (2002)

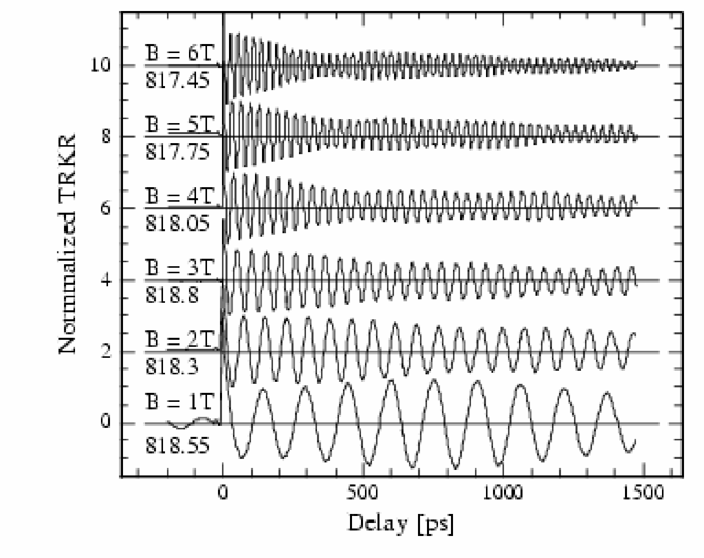
# Spin lifetimes for donors in GaAs



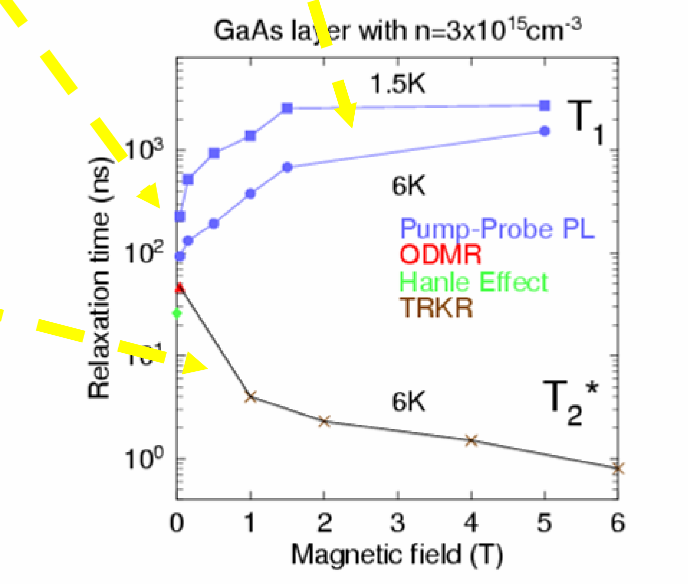
J.S. Colton *et al.*, SSC **132**, 613 (2004)



J.S. Colton *et al.*, PRB 69, 121307 (2004)



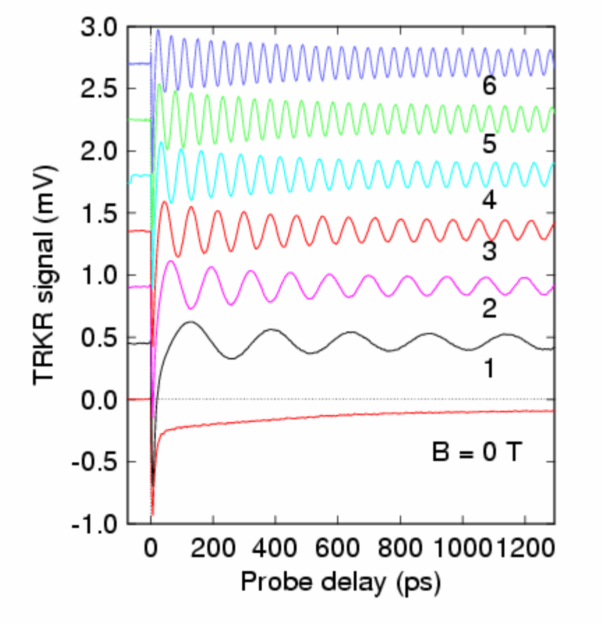
Michael Scheibner *et al.*, to be pub.



JSC: $T_1$ = 24 μs for 1E15 at 7T

# Previous work leads to

Wide Quantum Well—
Simplified energy levels
through HH/LH splitting



T.A. Kennedy *et al*., PRB **73**, 045307 (2006)

Goal of Measuring $T_2$—Use pulsed magnetic resonance

**Two challenges**

- Low spin concentration
- Well defined nuclear spin state--unpolarized

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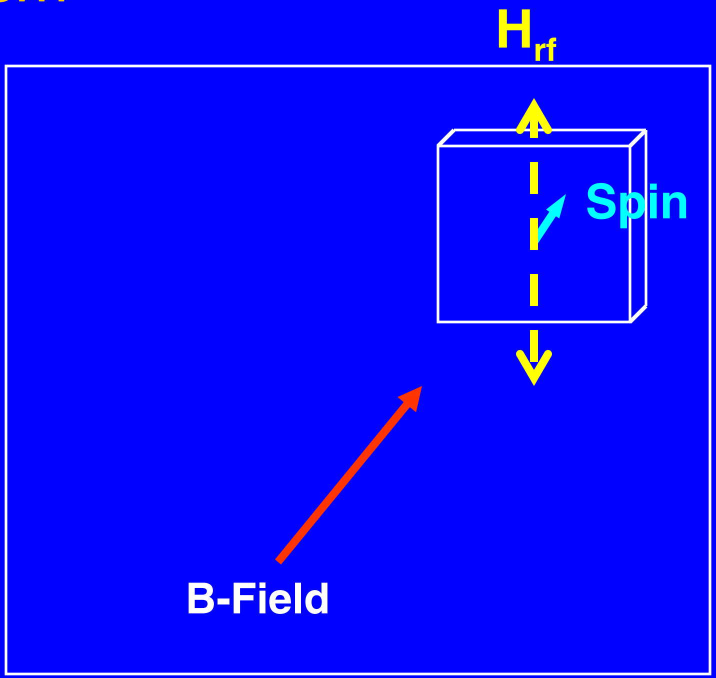
1. Background
    1. Long lifetimes for spins in non-magnetic semiconductors
    2. Work with donor ensembles
2. **Magnetic resonance detected through Faraday Rotation**
    1. **Method**
    2. Nuclear effects
    3. Probe light effects
    4. Higher concentration sample
    5. g-factor and Lifetime
3. Summary and Future Work

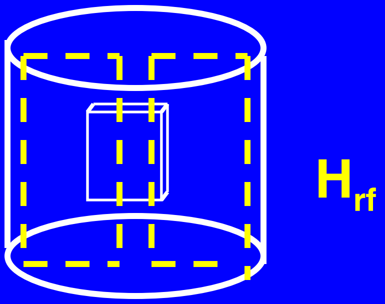
# Background to This Approach

- Faraday Rotation and EPR
  - R. Romestain (1980): donors in CdS
- GaAs donors
  - Seck, Potemski and Wyder (1997): EPR—DNP enhanced
  - Karasyuk et al. (1994): Donor-bound excitons
  - Kai-Mei Fu (Stanford), Spin-flip Raman Scattering
- Nuclear Effects: ESR pinning in 2DEG’s
  - Olshanetsky et al., Physica B **373**, 182 (2006)
  - Hillman and Jiang, PRB **64**, 201308 (2001)
  - Dobers et al., PRL **61**, 1650 (1988)
- ESE in GaAs
  - Petta et al. Science **309**, 2180 (2005)—$T_2$ of 1 to 10 $\mu$s
  - Loss (Basel), Sham (UCSD), Whaley (UCB), Das Sarma (Maryland),ETH (Zurich), SUNY (Buffalo) and others

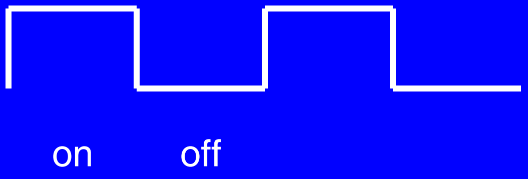
# ODMR mechanism

- Polarization
  - Thermal: B=6 T and T=1.5 K—$g\beta H \sim kT$
  - Off-cycle of microwaves long with respect to $T_1$
  - Thermalized electron spins: $\langle S_T \rangle$
- Resonance with microwaves reduces the polarization
  - $h\nu = g\beta B$
  - Frequency $\nu$ = 35 GHz
  - Decreases the $\langle S \rangle$ from $\langle S_T \rangle$
- Detection…

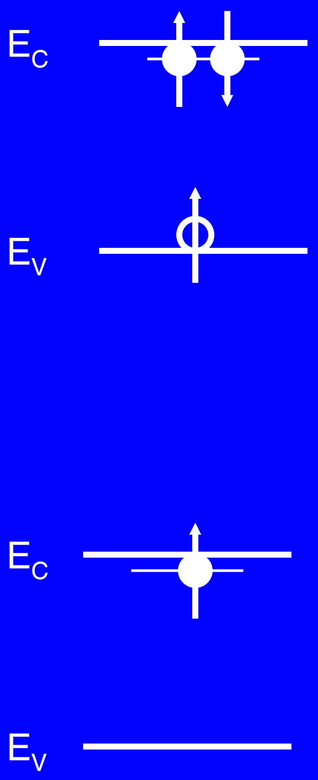




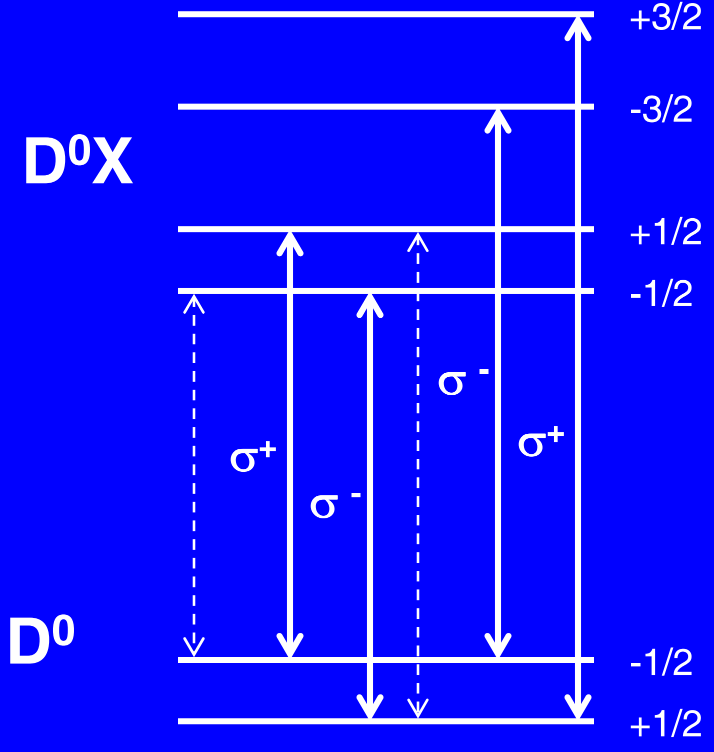
35 GHz cavity



# Detection by Kerr Rotation

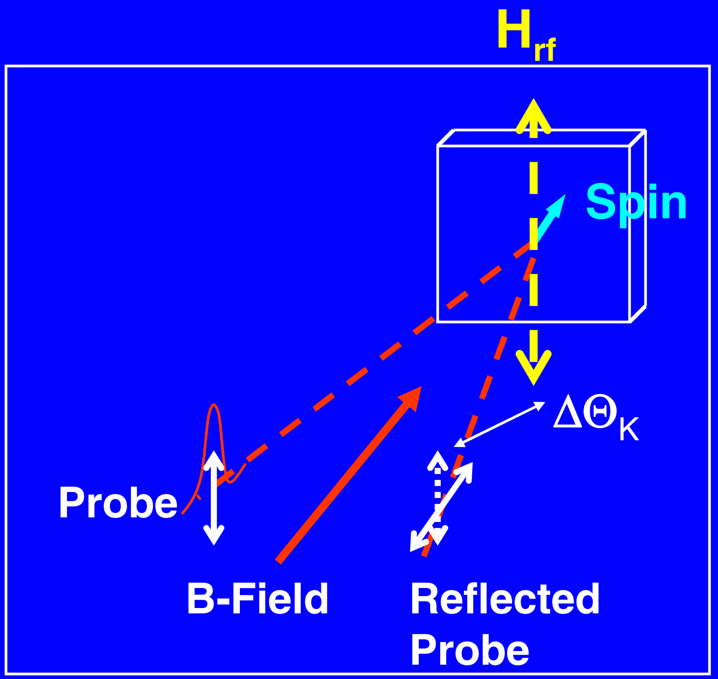


Single-Particle States



Simplified Optical Transitions

cf. Karasyuk et al., PRB **49**,16381 (1994)

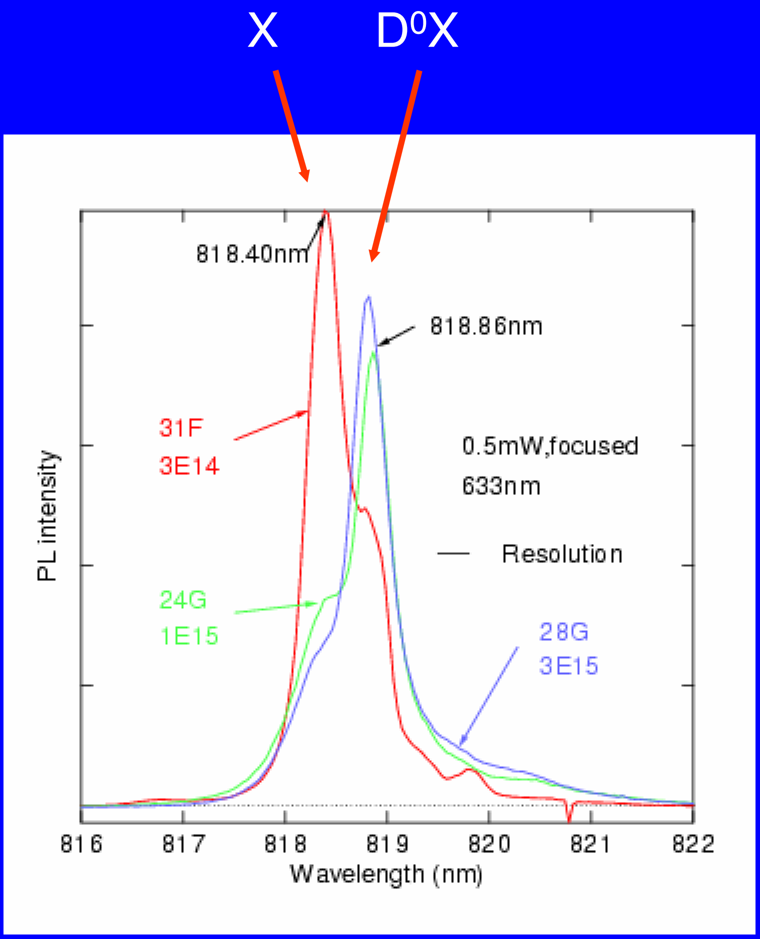


$\Delta\Theta = -\pi(d/\lambda)(n_+ - n_-)$

(in transmission)

Kerr rotation is sensitive to $D^0$ spin through SO-coupling of hole in $D^0X$

# Experimental Details



- Samples
  - 1 μm GaAs surrounded by doped and undoped AlGaAs for flatbanding
  - Concentrations of 3E14, 1E15 and 3E15
  - (Metal-insulator transition at 2 X $10^{16}$ $cm^{-3}$ )
- Equipment
  - Oxford 7 T magneto-cryostat
  - Spectra Physics ps Ti:Sa laser (Δν~1meV (0.5nm))
  - Agilent 250kHz to 40GHz signal generator

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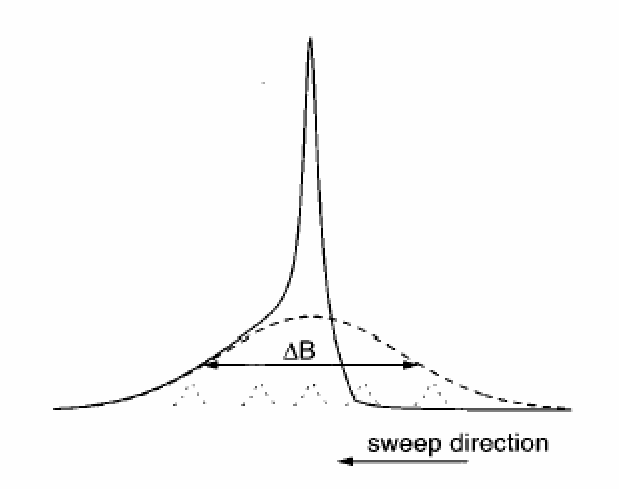
# Nuclear Spin Effects

1. Without nuclei, the Bloch equations describe the saturation of the ESR amplitude (A) with microwave power (P):

$$A = (\alpha P) / (1 + \beta P)$$

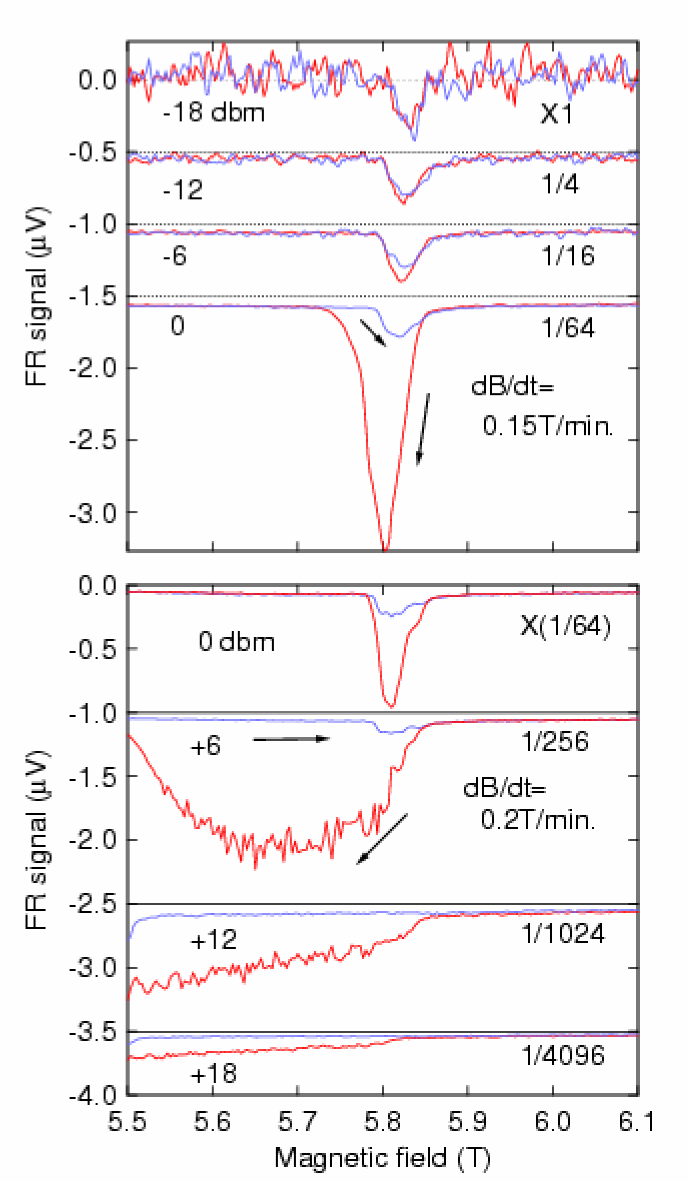
2. With nuclei, Dynamic Nuclear Polarization arises from the Overhauser effect: Saturated e-spins try to relax through the nuclear spins using the $(I^+ S^- + I^- S^+)$ part of the hyperfine interaction
3. Sign of the nuclear field: $B_N$ adds to the external field ($B_{ext}$)
   a. $< I > \; = \; [\, I\,(I + 1)/ S\,(S+1)\,] * [\, < S > - < S_T > \,] \; < 0$
   b. $B_N = A < I > / g_e\, \beta \; ; \; g_e < 0; \; B_N > 0$
   c. $h\nu = g\beta\,(B_{ext} + B_N)$
4. Enhancement and pinning of the ESR can occur:
   a. Compare $dB_N/dt$ with $dB_{ext}/dt$
   b. DNP $\propto$ P
   c. Nuclear relaxation time ~ 1 minute
   d. Strong effects occur for downward field sweeps



Seck et al., 1997

Olshanetsky et al., Physica B 373, 182 (2006)

# Dependence on Microwave Power

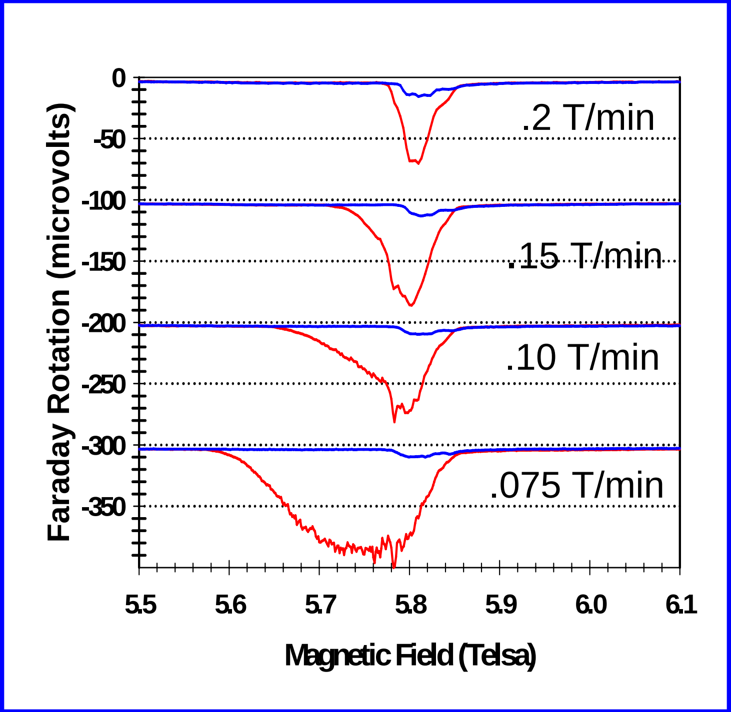


$dB_N/dt \propto$ Saturuation $\propto P$

- Unsaturated limit
  - Down & up are the same
  - Amplitude $\propto$ power
- DNP enhanced: $dB_N/dt \approx |-dB_{ext}/dt|$
  - Strong for down sweeps
  - Broadened & shifted
  - Up sweeps unaffected
- ESR pinning: $dB_N/dt > |-dB_{ext}/dt|$
  - Resonance not achieved
  - $B_N$ becomes > 0.3 T

817.8 nm (near res.), 9/20 &9/19 data, 31F, T = 1.5 K, 35 GHz

# Dependence on Rate of Change of External Magnetic Field



- Dyanamics is again controlled by the relative size of $dB_N/dt$ and $-dB_{ext}/dt$
- Rate of DNP induced $B_N$ is constant since microwave power ( P ) is constant.
- Decreasing the sweep rate of magnetic field ($-dB_{ext}/dt$) changes the response from DNP enhanced to ESR pinning.

- 0 dbm, 9/17/05, 817.8 nm

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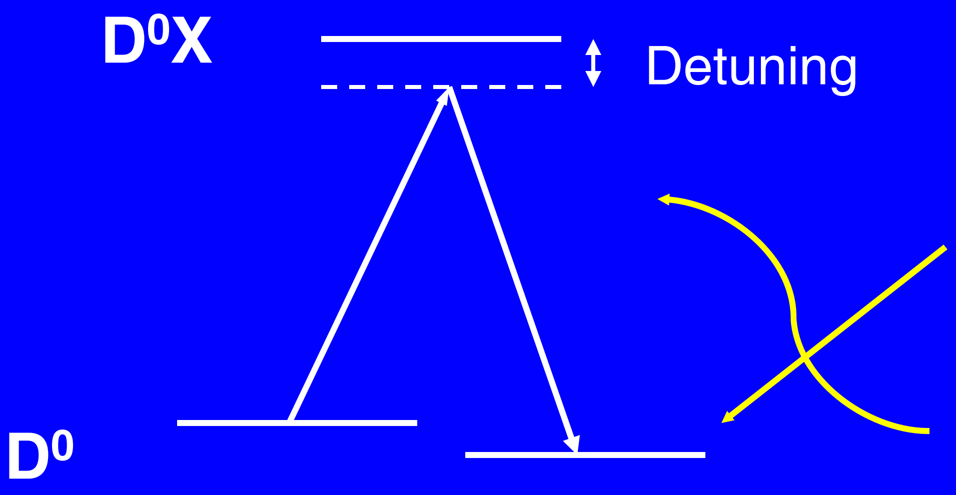
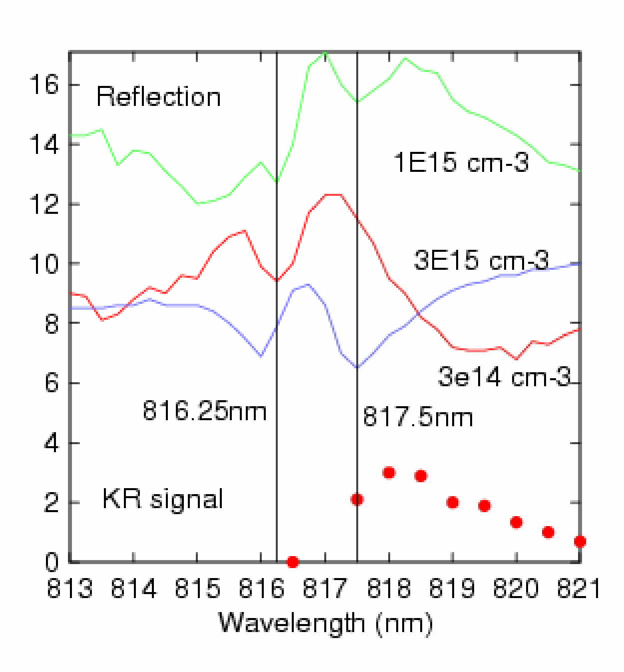
# Effects of the Probe Light

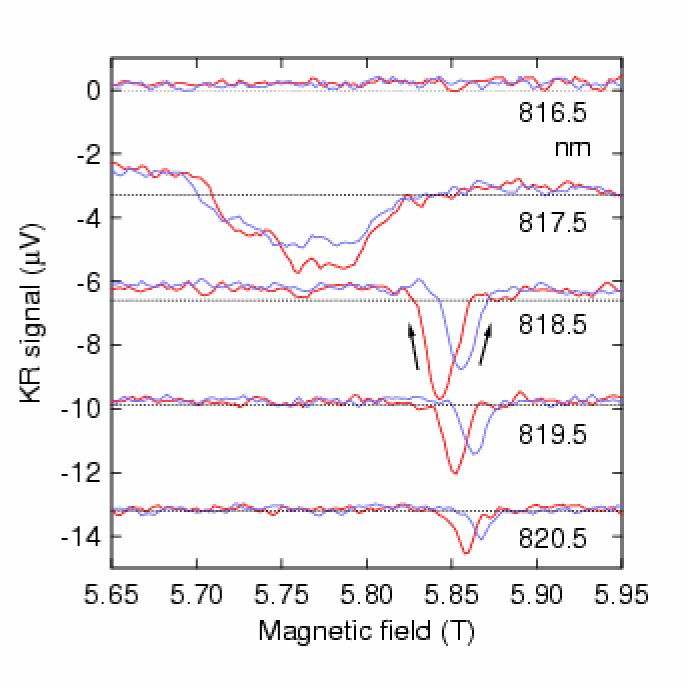


**The experiment is a double resonance**

- Microwave resonance in the ground state—tuned by changing the magnetic field
- Optical resonance to the excited state—tuned by changing the laser wavelength

# Dependence on Wavelength of the Probe Light



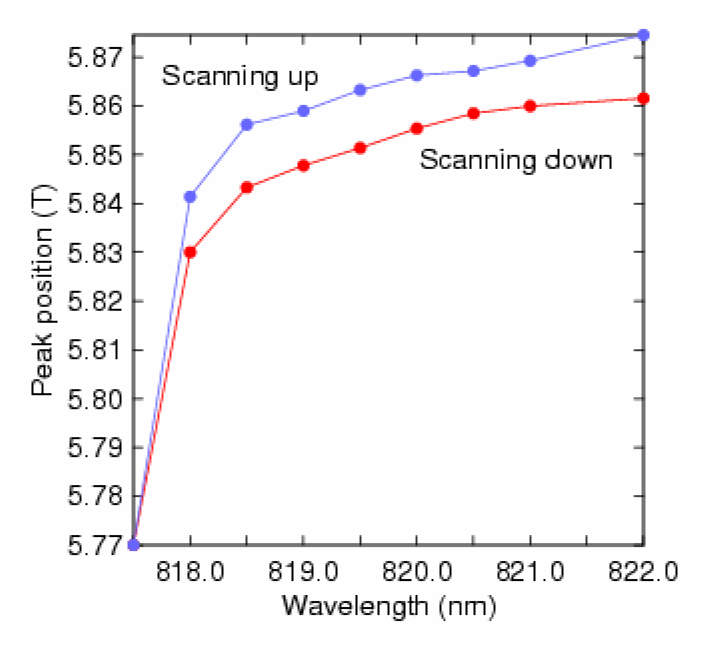


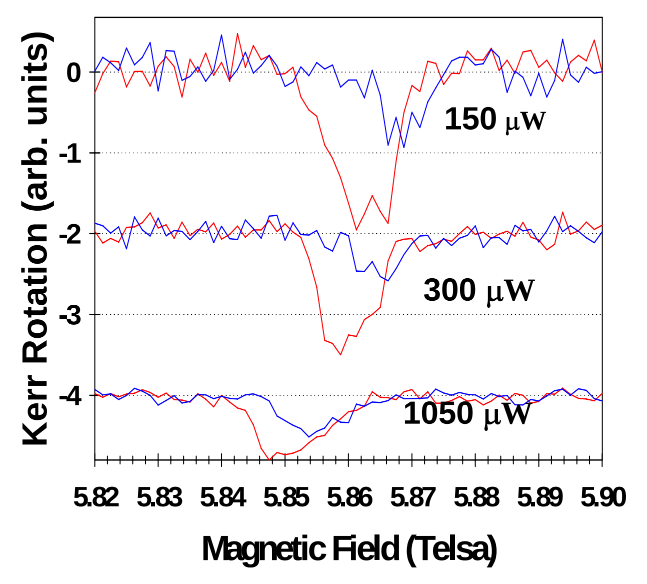
- Optical Resonances for B = 6T
  - $D^0X$ at 817.5 nm
  - X at 816.25 nm

-6dbm, 34.694, 300 uW probe, 9/20/05 data

- On resonance
  - Large shift
  - Extra line
- Detuned to lower E (longer $\lambda$)
  - Sharp single line
  - Decreasing amplitude
  - Slow shift

# Peak Position versus probe wavelength and power





## Position versus wavelength

- Approaches a limit off-resonance

9/20/05 data—31F, light unfocussed

## Position versus power

- Shifts to lower fields with increasing power
- DNP by slight depolarization of <S> by the linearly polarized light

9/21/05 data, 820.5nm,-6dbm

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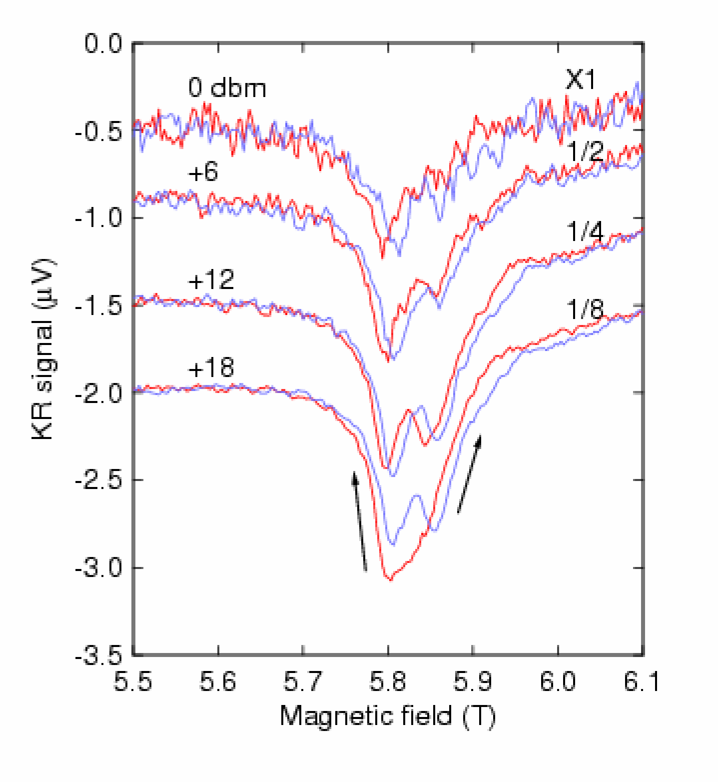
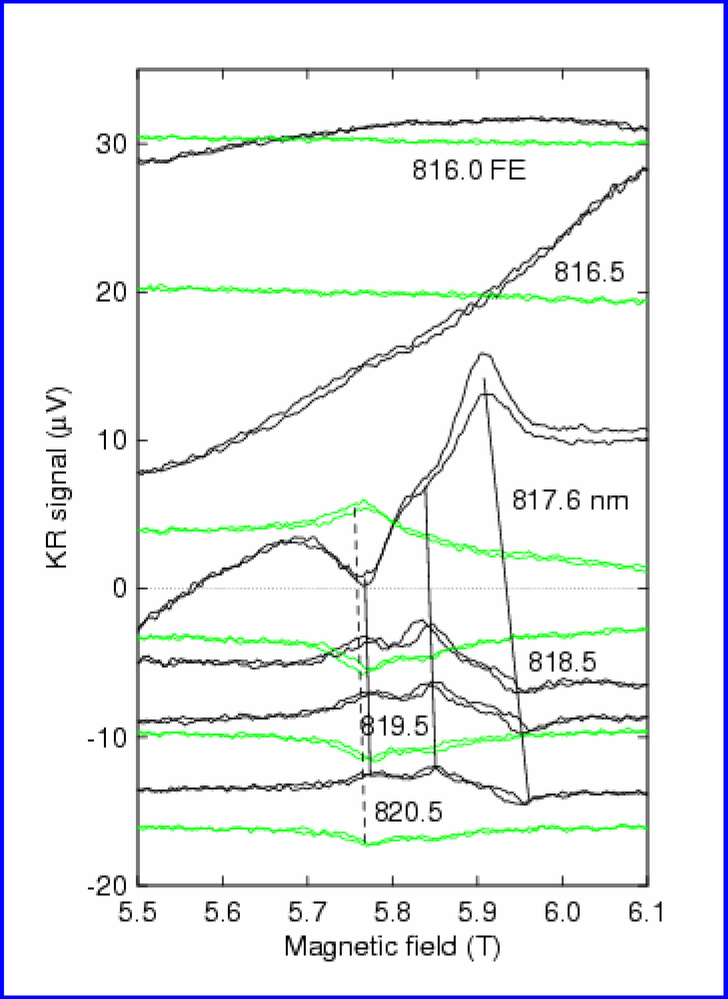
# Dependence on Microwave Power for 3E15



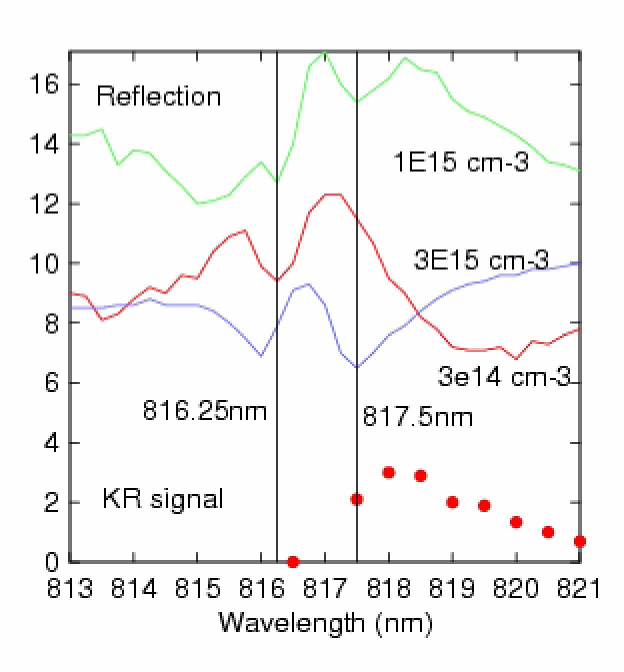
- Different scaling
- Two lines
- Strong signals in quadrature
- DNP enhanced for high-field line at highest power
- Localized and de-localized electrons

28G, 818.6nm, 8/9/05, no offset added

# Dependence on wavelength of probe



24 G, 3E15, 8/11/05,
+6dbm,0.15 T/min



- Black: in phase; Green: in quadrature
- In Phase
  - 2 or 3 resonances
  - phase changes
- In Quadrature
  - one resonance
  - reveals dynamics ~ 3 kHz

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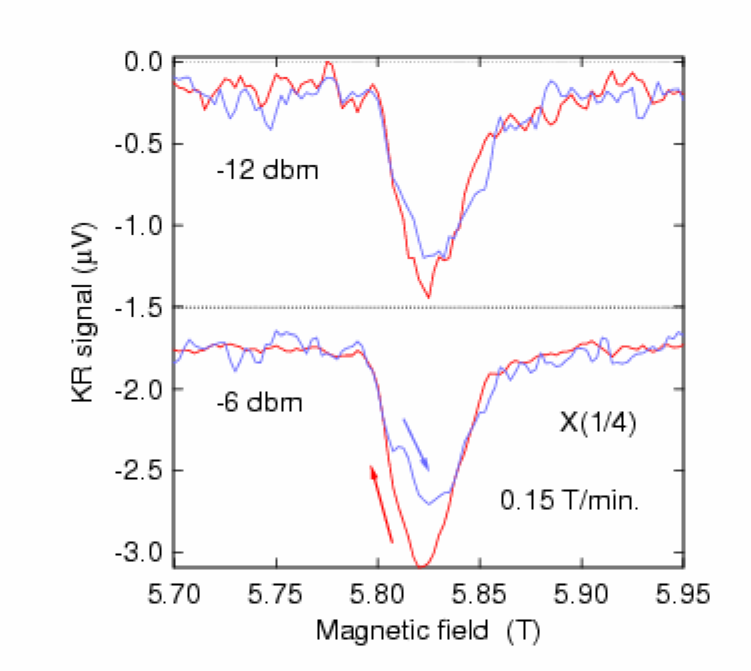
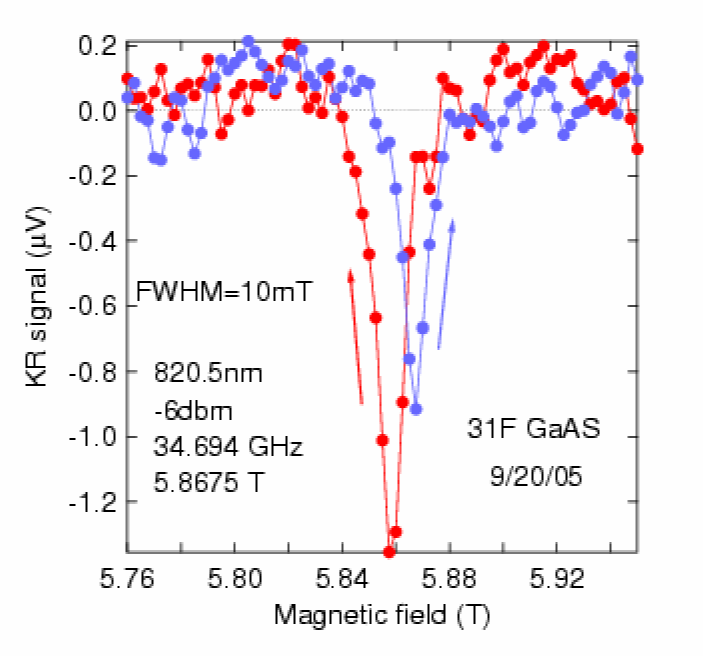
# g-factor and linewidth





**Near resonance—817.8 nm**

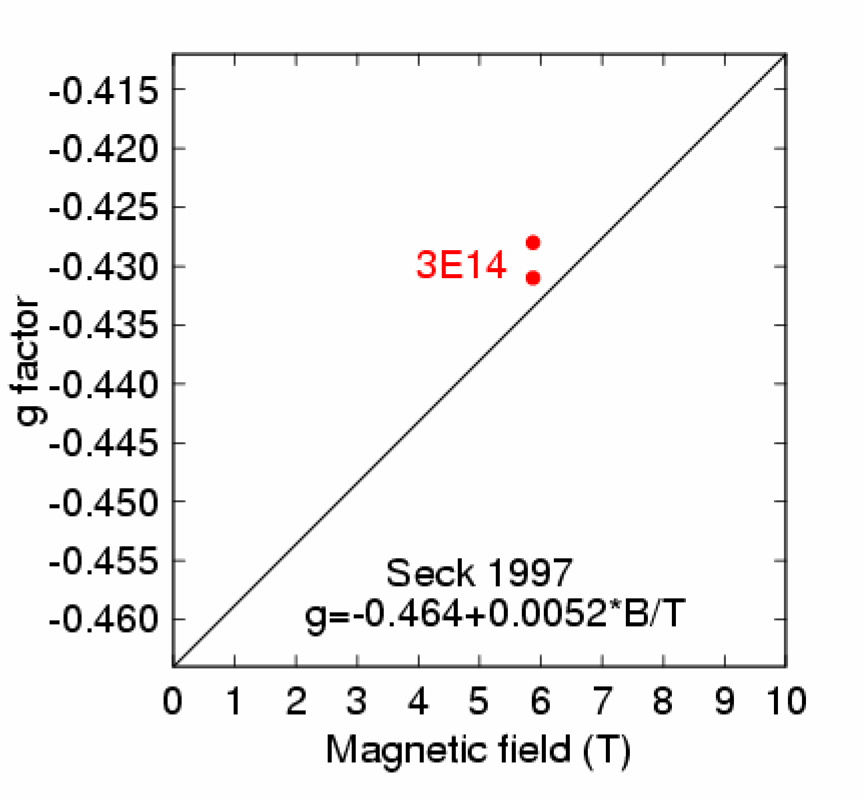
- g = 0.431; FWHM = 49 mT
- Real transitions
  - $D^0X$: holes
  - X: electrons and holes

**Off resonance—820.5 nm**

- g = 0.428; FWHM = 10 mT
- Dispersive part of the index

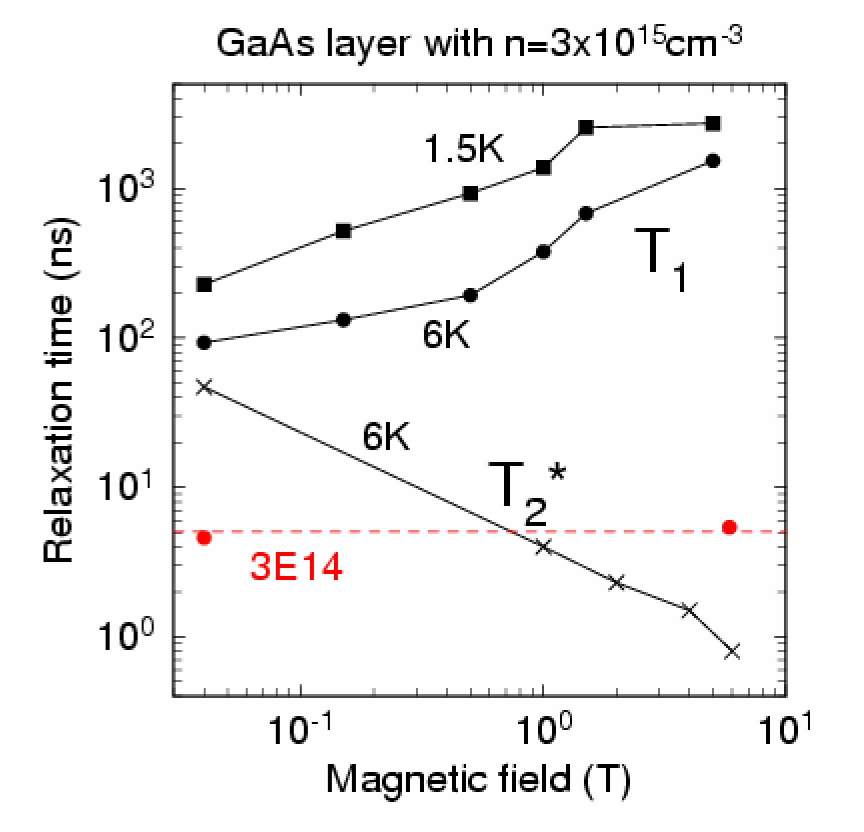
Sweep rate 0.15 T/min

# Comparison of g-factors with other work



- Negative sign added
- 31F shown for near resonance & off-resonance

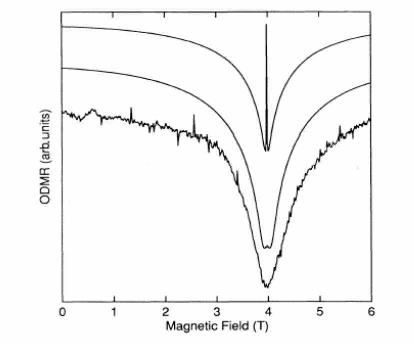
# $T_2^*$ for donors in GaAs



- ~5 ns for low and high magnetic fields
- Limited by fluctuation in nuclear spin
- Good starting point for measuring $T_2$

# Lifetimes for donors at high magnetic fields

| | Sample | $\Delta$B<br>FWHM (mT) | $T_2^*$ |
|---|---|---|---|
| This work | $N_D$-$N_A$ = $3X10^{14}$ cm$^{-3}$ | 10 | 5.4 ns |
| Kai-Mei Fu et al. (06) | $N_D$-$N_A$ = $5X10^{13}$ cm$^{-3}$ | -- | 2.3 ns |
| Seck et al. (1997) | $N_D$-$N_A$ = $6.6X10^{14}$ cm$^{-3}$ | 50 | 1.1 ns |
| Kikkawa & Awschalom (1998) | Semi-insulating | -- | 100 ps |
| Trombetta & Kennedy (1993) | Semi-insulating | 900 | 60 ps |



g-broadening is small, possibly negligible

*March 2006*

# Summary and Future Work

- **Kerr rotation provides adequate sensitivity to work with isolated donors**
- **Nuclear effects**
  - Resonance without DNP enhancement –unpolarized nuclei
  - DNP enhancement—good for finding ESR
  - ESR-pinning—possibly good for polarizing nuclei
- **Linewidth** near or at the hyperfine limit—little or no g-broadening

- **Measuring $T_2$ with electron-spin-echo in ensembles**