Mechanical and relaxation-based detection of dipolar-interactions between spins in diamond

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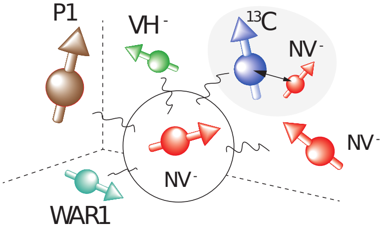
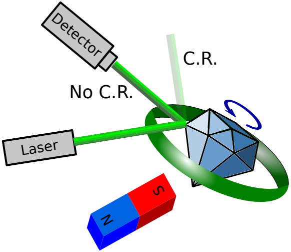
Two experiments around cross-relaxations in diamond



Cross-Relaxation between NV^-
and new spin species (VH^-, WAR1, ...)

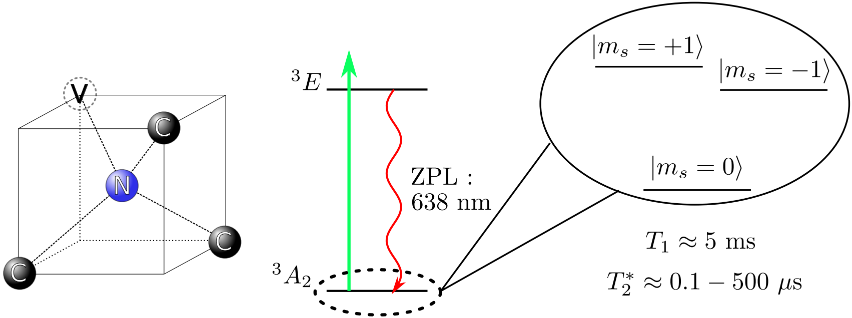


Measurement of a torque
induced by NV^-–NV^- CR
on a levitating diamond

Outline

Outline

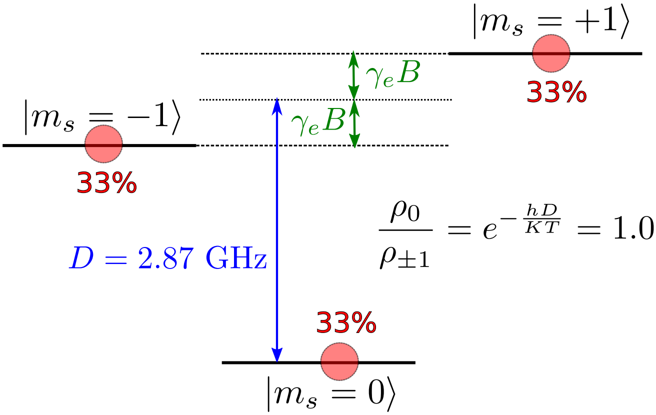
Minimalist approach to NV center



$T_1 \approx 5$ ms

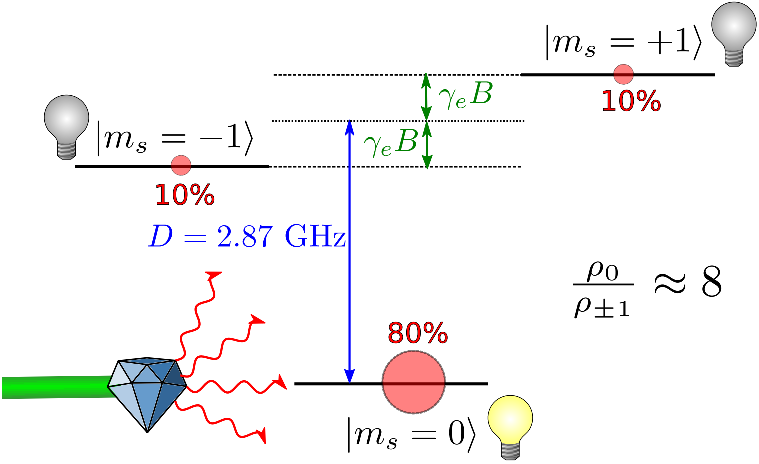
$T_2^* \approx 0.1 - 500\ \mu$s

Triplet spin levels at rest



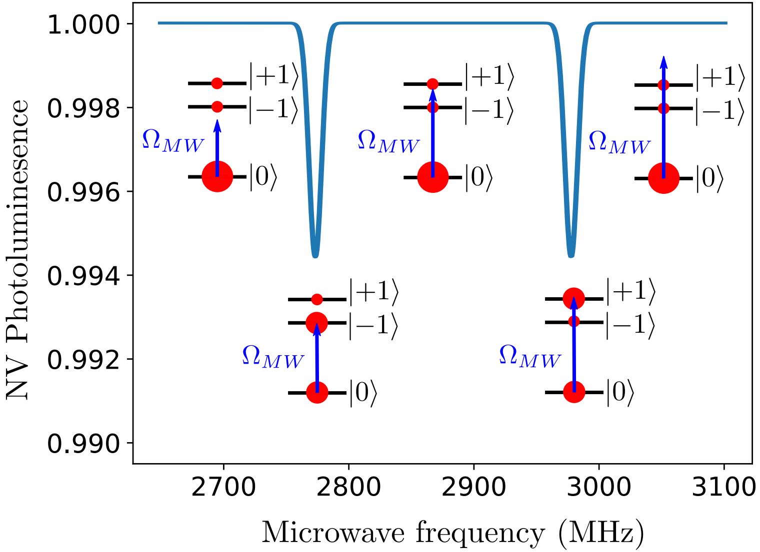
$$\frac{\rho_0}{\rho_{\pm 1}} = e^{-\frac{hD}{KT}} = 1.0004$$

Triplet spin levels with optical pumping

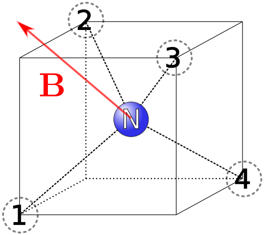


$$\frac{\rho_0}{\rho_{\pm 1}} \approx 8$$

Magnetometry with NV centers : ODMR with a single spin



Spin Hamiltonian and orientation of the centers



$|m_s = 0, \pm 1\rangle$: Eigenstates of $S_{\mathbf{z}}$

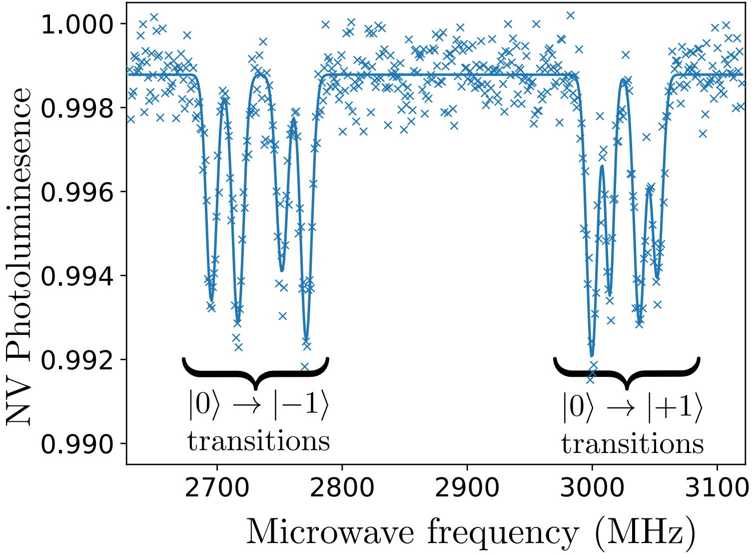
$$\hat{\mathcal{H}}_s = \underbrace{D\hat{S}_z^2}_{} + \gamma_e \hat{\mathbf{S}} \cdot \mathbf{B}$$

$\mathbf{z}$ direction defined by the crystal lattice for $D > \gamma_e B$

$\mathcal{E}^i_{\pm 1} \approx D \pm \gamma_e \mathbf{B} \cdot \mathbf{e_i}$

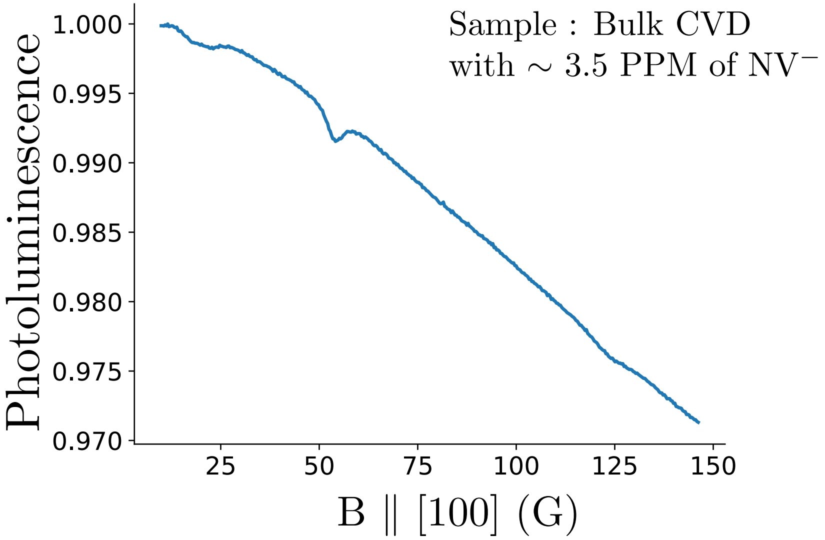
$\rightarrow$ 4 possible pairs of $\mathcal{E}^i_{\pm 1}$ (4 classes of NV)

ODMR with an ensemble of NV centers

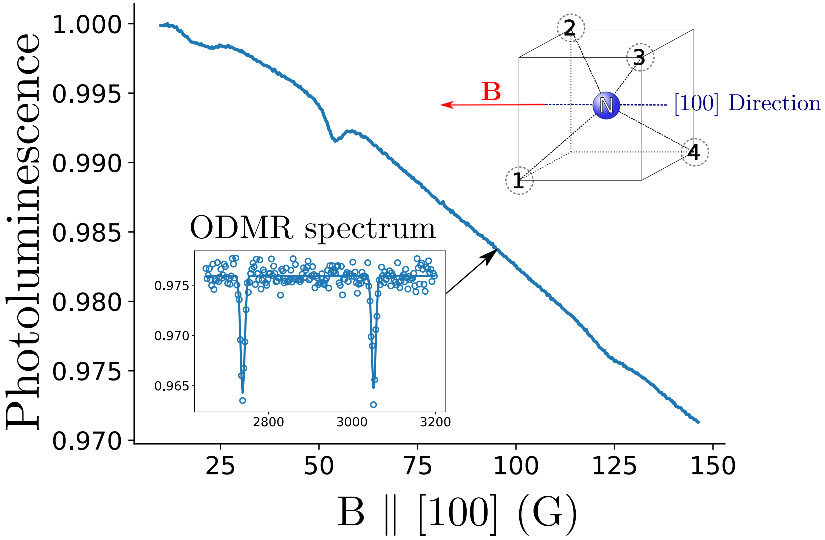


Outline

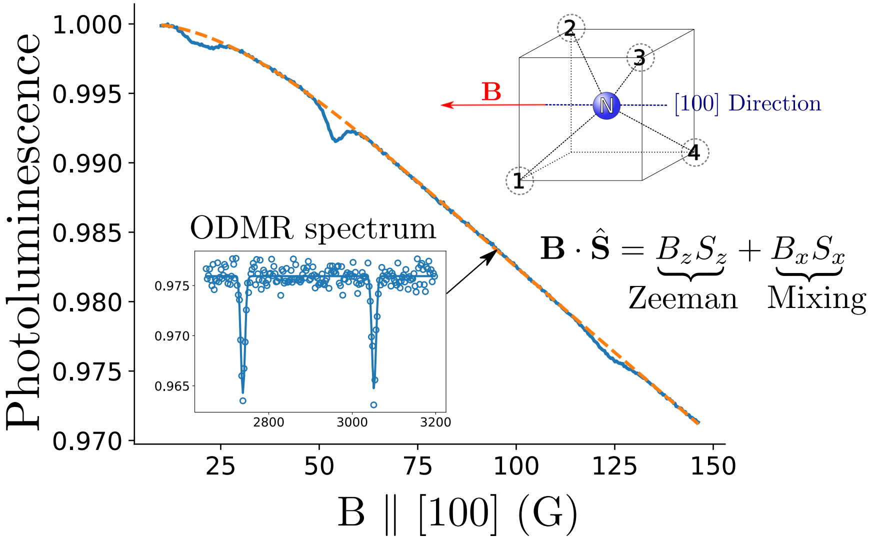
Photoluminescence change with magnetic field amplitude



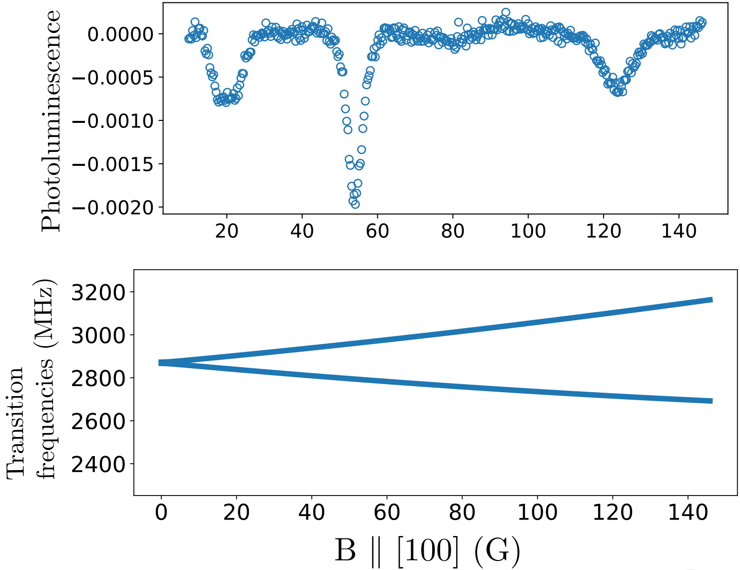
PL change with magnetic field : [100] direction



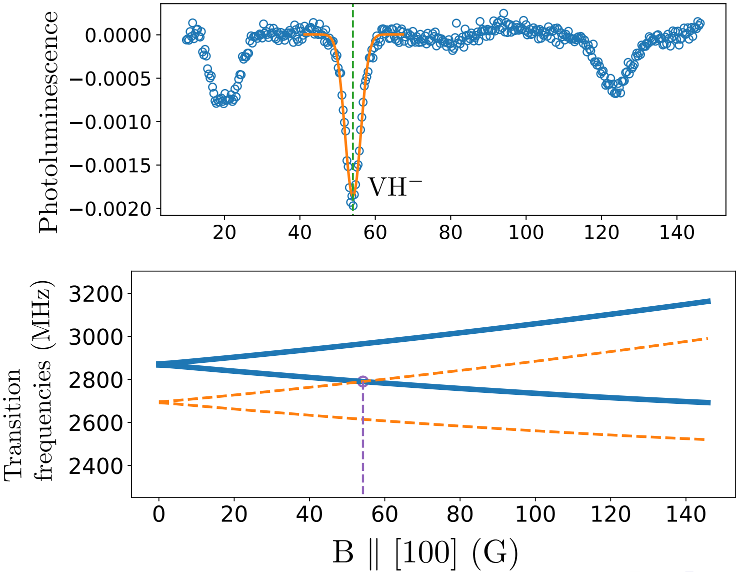
PL change with magnetic field : transverse field



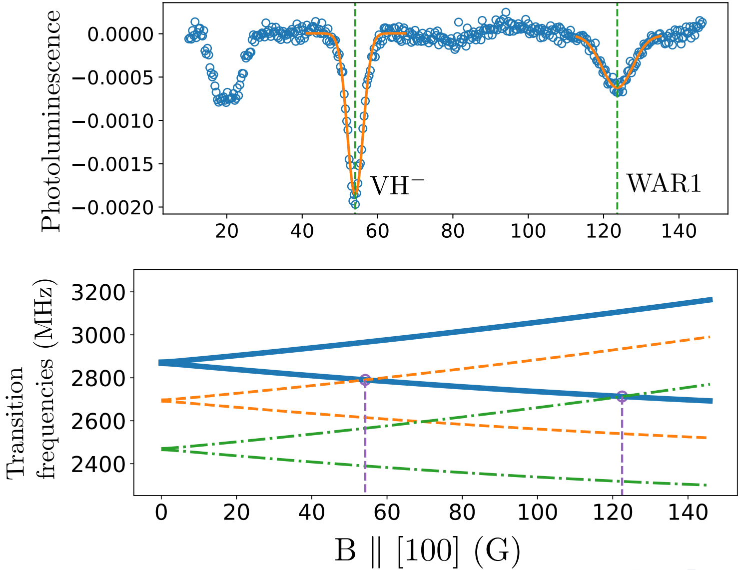
Subtracting the transverse field envelope



Cross-relaxation between NV$^-$ and VH$^-$



Cross-relaxation between NV$^-$ and WAR1



EPR spectroscopy

Electron Paramagnetic Resonance : A spectroscopy technique using absorption of a microwave at a given frequency (typically 9.5 GHz) as a function of magnetic field to detect paramagnetic defects.

VH^{-}[1] and WAR1[2] have been observed by EPR spectrocopy in CVD diamonds by Mark Newton's team at the University of Warwick.

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[1] Claire Glover et al. "Hydrogen Incorporation in Diamond: The Vacancy-Hydrogen Complex". In: *Phys. Rev. Lett.* 92.13 (Mar. 2004), p. 135502.

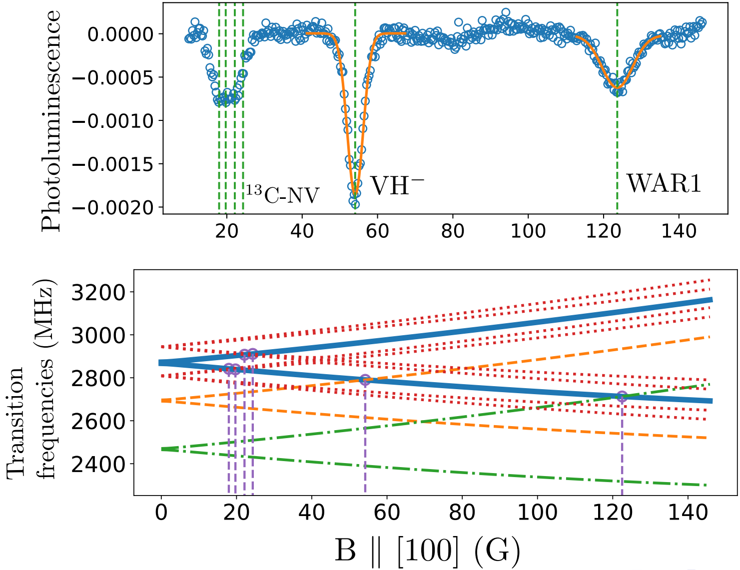
[2] Robin Cruddace. "Magnetic resonance and optical studies of point defects in single crystal CVD diamond". PhD thesis. University of Warwick, 2007.

Comparison between CR and EPR

- CR experiments are much simpler to setup (low B, no microwave)
- NV centers produce a calibration for $B \rightarrow$ Better precision on the ZFS measurement
- Potential for polarization transfer

- Requires a high NV concentration and quickly becomes unreadable on non-[100] directions.

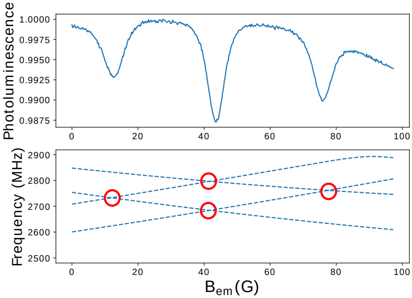
Cross-relaxation between NV^- and $^{13}C\text{—}NV^-$



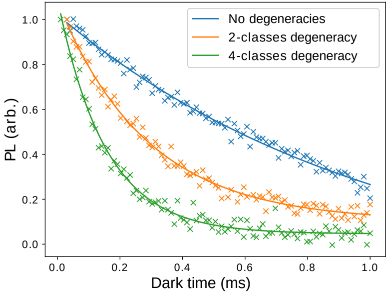
Outline

Experimental proofs of NV-NV CR

Sample : 15 μm HPHT diamond with $\sim$ 5 PPM of NV (Adamas)

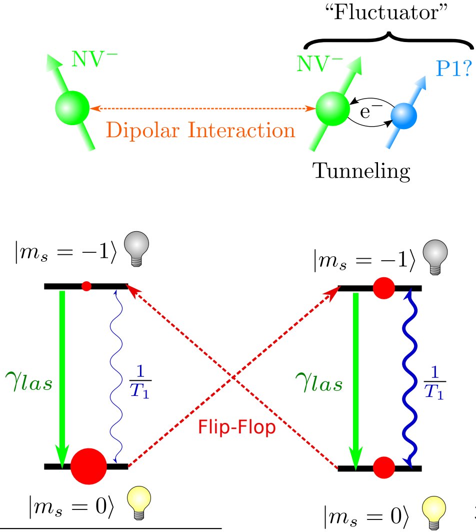


Photolum. Scan



T_1 for a single class

Microscopic explanation of the NV-NV CR

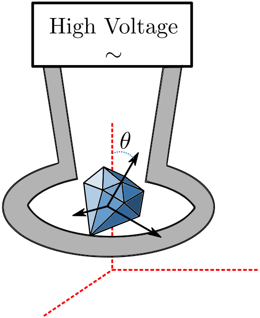


[3]

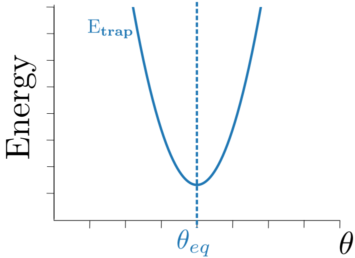
[3] Joonhee Choi et al. "Depolarization Dynamics in a Strongly Interacting Solid-State Spin Ensemble". In: *Phys. Rev. Lett.* (Mar. 2017).

Outline

Torque measurement with a levitating diamond

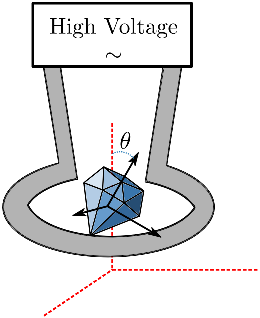


Paul Trap

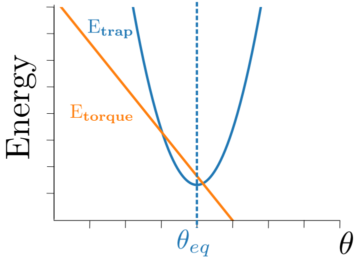


Angular
Potential Energy

Torque potential energy

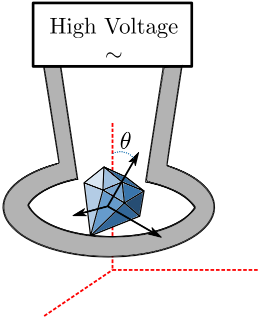


Paul Trap

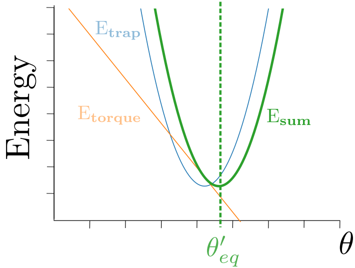


Angular
Potential Energy

Displacement of equilibrium

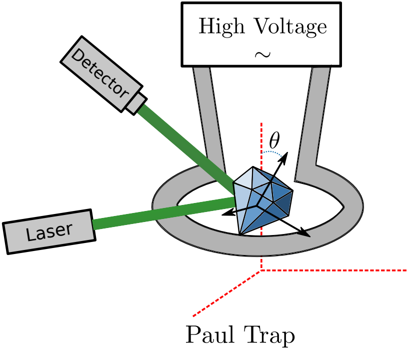


Paul Trap

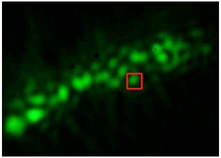


Angular
Potential Energy

Back-scattered laser detection

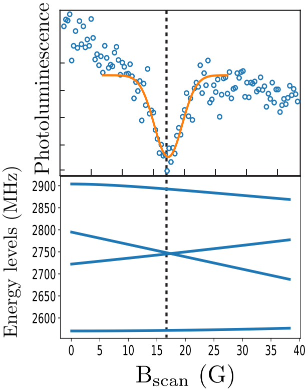


Speckle pattern

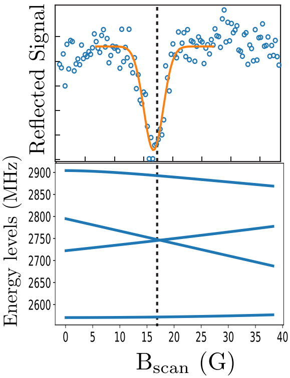


Resolution $\sim 100\mu\text{rad}/\sqrt{\text{Hz}}$

Torque caused by cross-relaxations



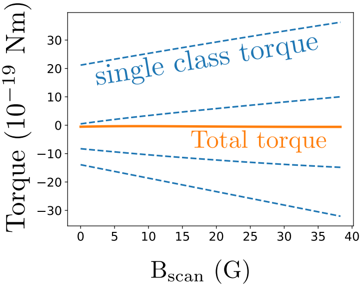
PL detection



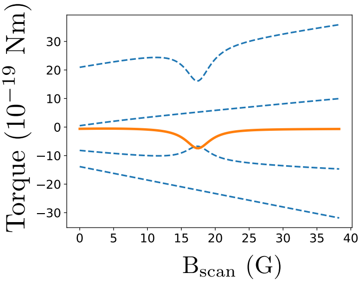
Torque Detection

Origin of the magnetic torque

- Solve the master equation to get ρ (With or without modified T_1
- Derive $\vec{S} = \mathrm{Tr}(\rho \hat{\vec{S}})$ for all four classes
- Derive $\Gamma_t = \sum_i \gamma_e \vec{S}_i \times \vec{B}$

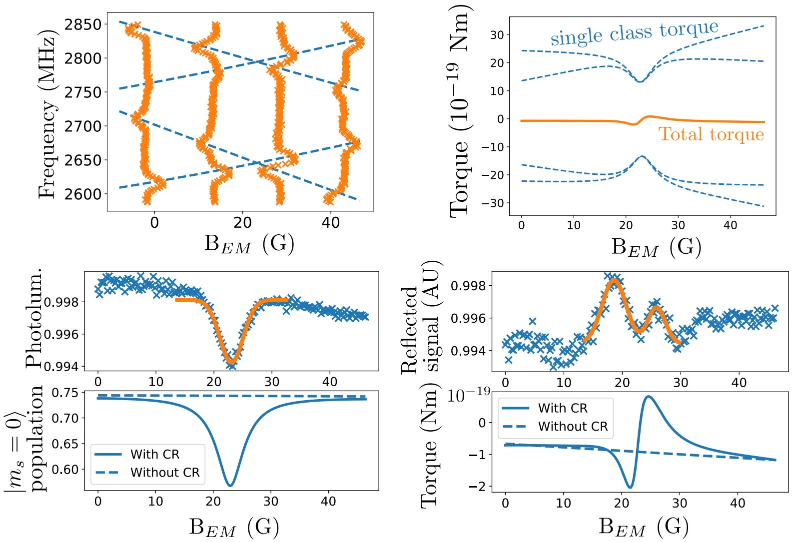


Without Cross-Relaxations



With Cross-Relaxations

Torque caused by CR : other configuration



Conclusion

- Detection of new spin defects in diamond through Cross-Relaxations
  - Potential for hyperpolariaztion of new dark electronic spins
- Observations of NV$-$NV Cross-Relaxations
- Mechanical detection of NV$-$NV Cross relaxations :
  - Potential for mechanical detection of new spin species
  - Potential for Resonant Einstein-De-Haas effect