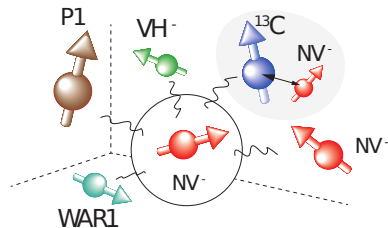


# Mechanical and relaxation-based detection of dipolar-interactions between spins in diamond

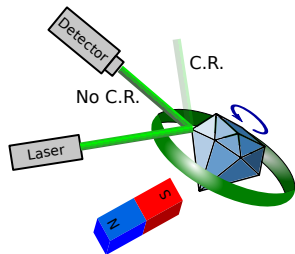
Clément Pellet-Mary  
Laboratoire de physique de l'ENS  
*ENS, Paris*

November 23, 2020

# Two experiments around cross-relaxations in diamond



Cross-Relaxation between NV<sup>-</sup> and new spin species (VH<sup>-</sup>, WAR1, ...)



Measurement of a torque induced by NV<sup>-</sup> – NV<sup>-</sup> CR on a levitating diamond

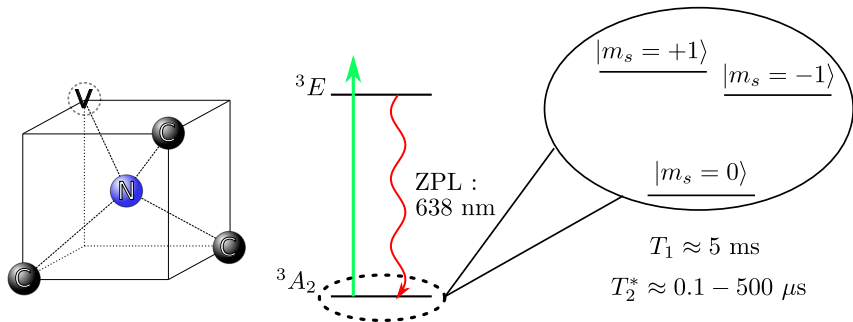
# Outline

- 1 Nitrogen Vacancy center presentation
- 2 Cross-relaxations with new spin species
- 3 Cross-relaxation between NV centers
- 4 Torque induced by cross-relaxation on a levitating diamond

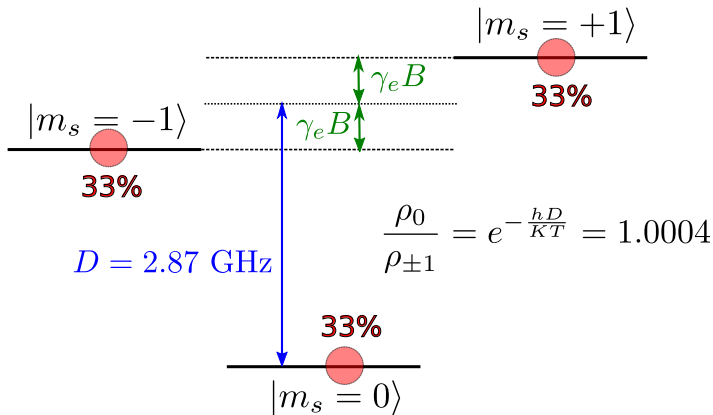
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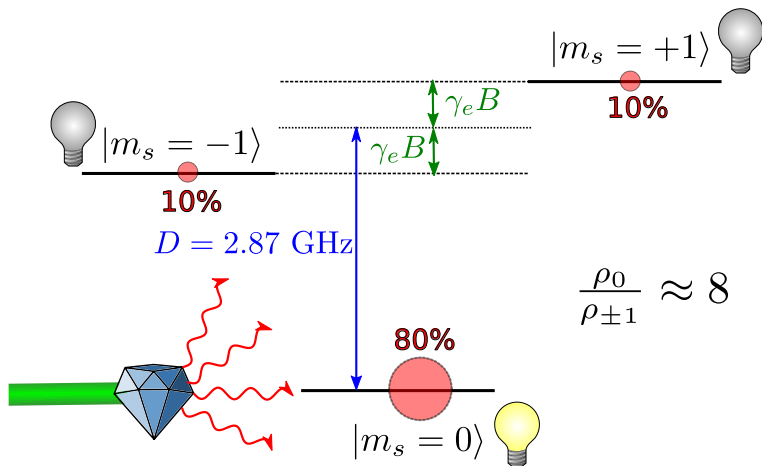
# Minimalist approach to NV center



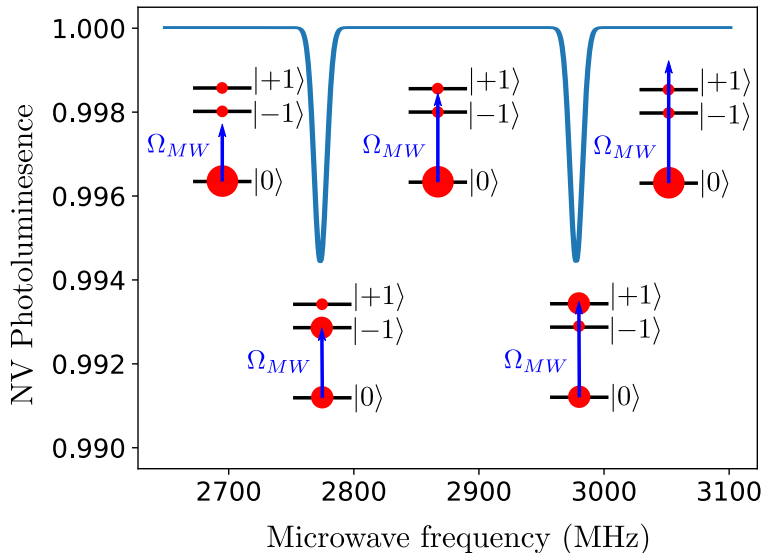
# Triplet spin levels at rest



# Triplet spin levels with optical pumping

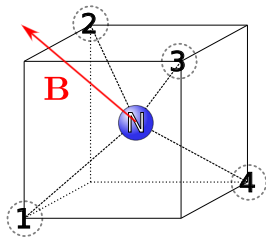


# Magnetometry with NV centers : ODMR with a single spin





# Spin Hamiltonian and orientation of the centers



$|m_s = 0, \pm 1\rangle$  : Eigenstates of  $S_z$

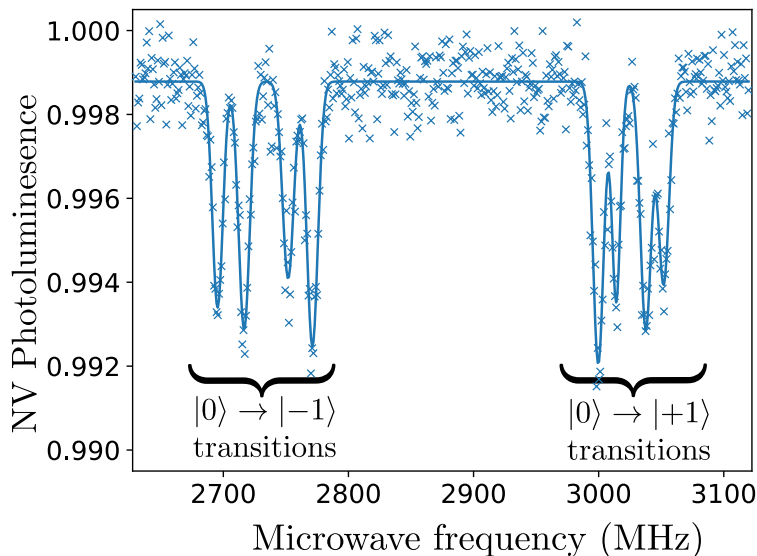
$$\hat{\mathcal{H}}_s = \underbrace{D\hat{S}_z^2} + \gamma_e \hat{\mathbf{S}} \cdot \mathbf{B}$$

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

$$\mathcal{E}_{\pm 1}^i \approx D \pm \gamma_e \mathbf{B} \cdot \mathbf{e}_i$$

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

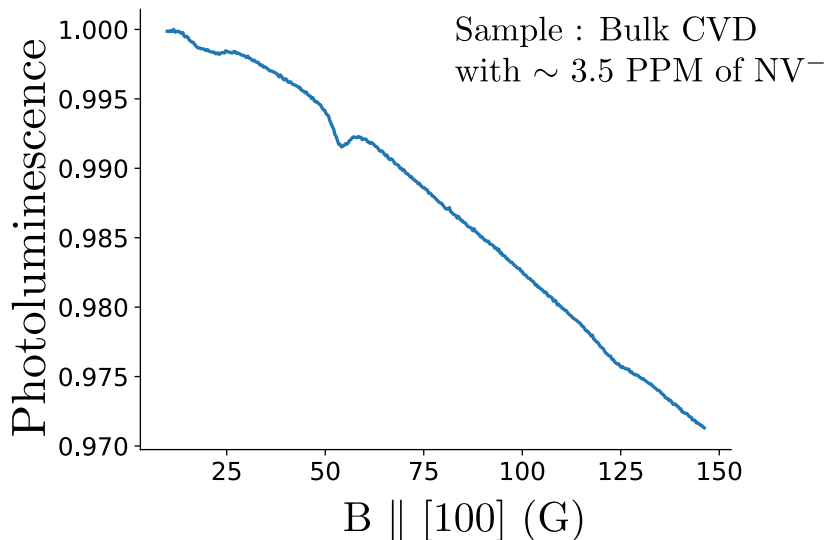
# ODMR with an ensemble of NV centers



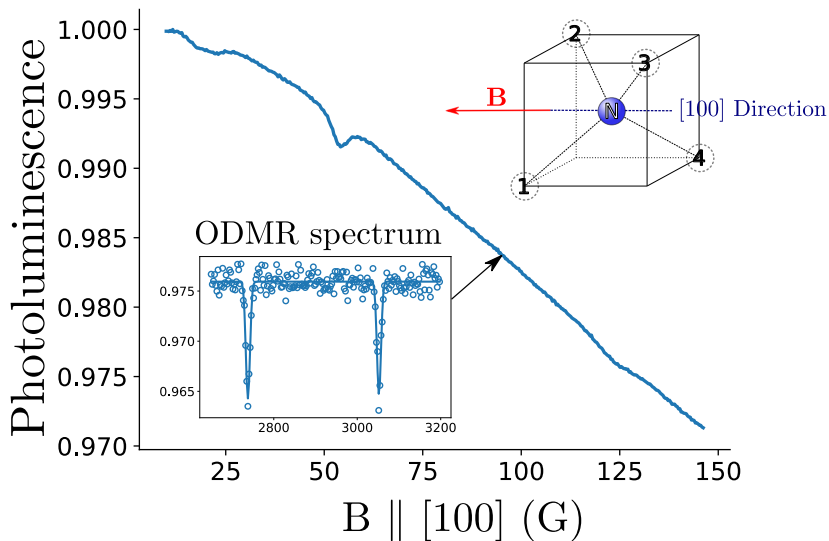
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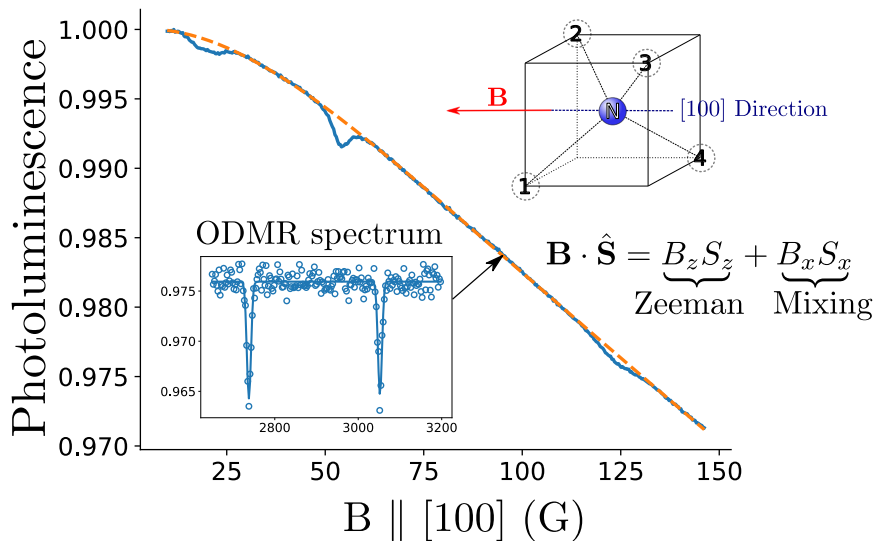
# Photoluminescence change with magnetic field amplitude



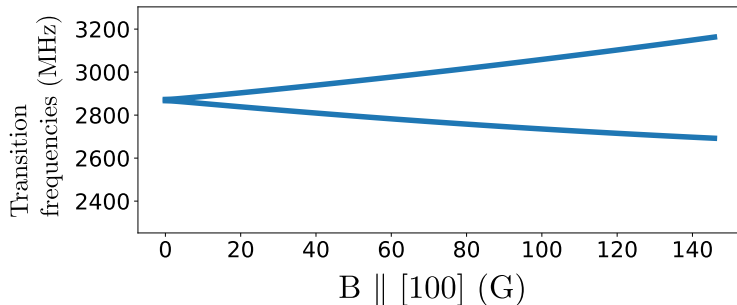
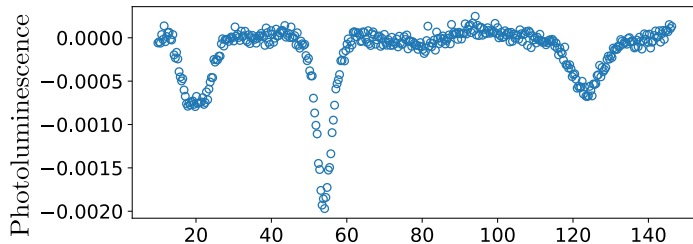
# PL change with magnetic field : $[100]$ direction



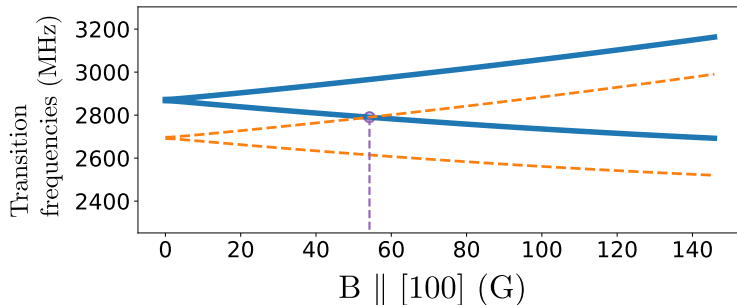
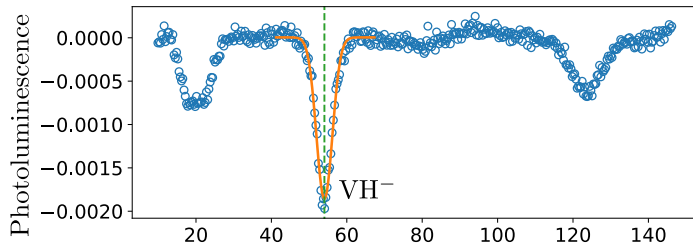
# PL change with magnetic field : transverse field



# Subtracting the transverse field envelope

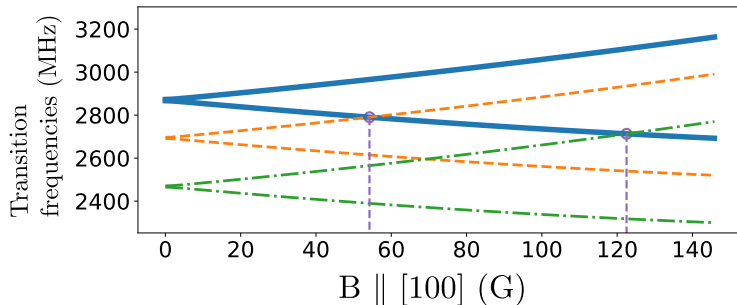
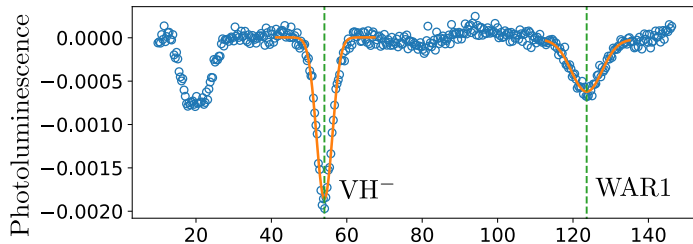


# Cross-relaxation between $NV^-$ and $VH^-$





# 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<sup>-1</sup> and WAR1<sup>2</sup> have been observed by EPR spectroscopy in CVD diamonds by Mark Newton's team at the University of Warwick.

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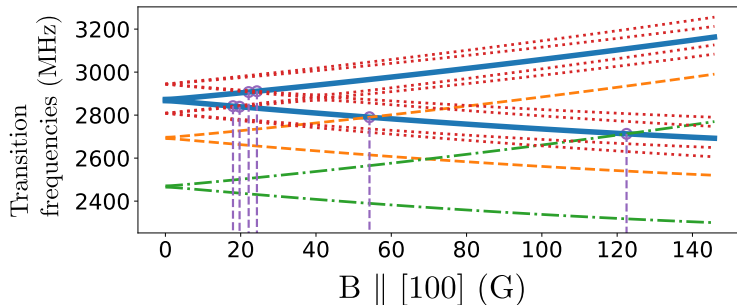
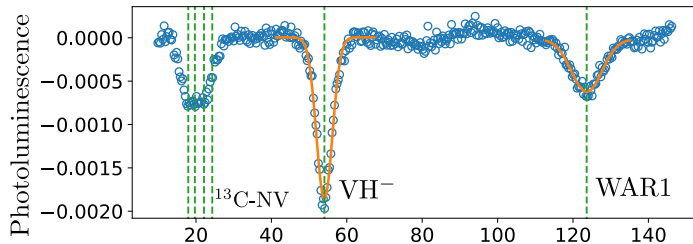
<sup>1</sup>Claire Glover et al. "Hydrogen Incorporation in Diamond: The Vacancy-Hydrogen Complex". In: *Phys. Rev. Lett.* 92.13 (Mar. 2004), p. 135502.

<sup>2</sup>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 $\text{NV}^-$ and $^{13}\text{C}-\text{NV}^-$

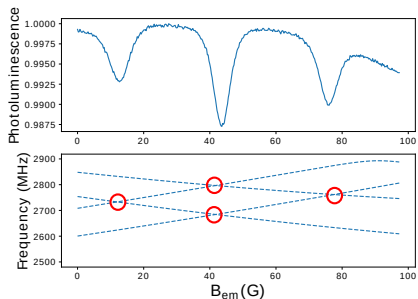


# Outline

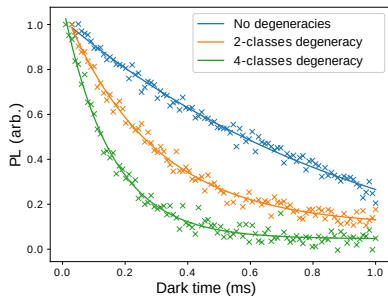
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# Experimental proofs of NV-NV CR

Sample : 15  $\mu\text{m}$  HPHT diamond with  $\sim 5$  PPM of NV (Adamas)

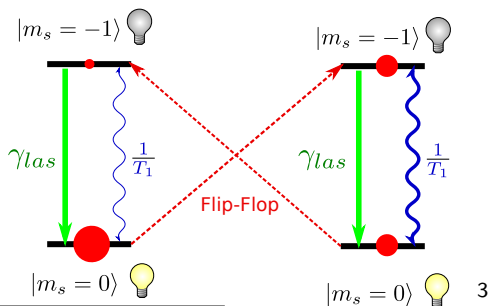
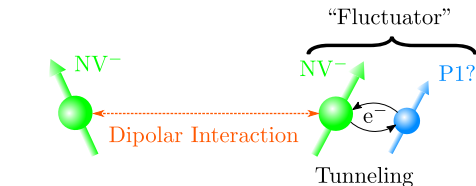


Photolum. Scan



$T_1$  for a single class

# Microscopic explanation of the NV-NV CR



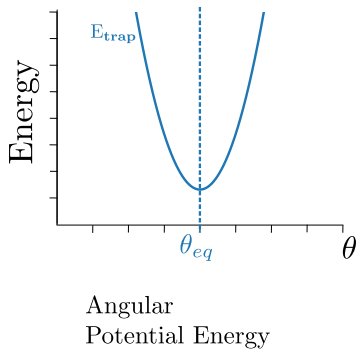
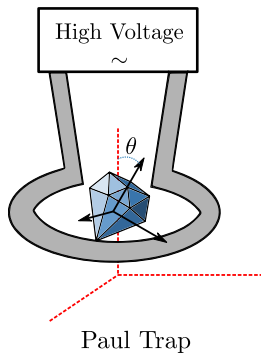
<sup>3</sup>Joonhee Choi et al. "Depolarization Dynamics in a Strongly Interacting Solid-State Spin Ensemble". In: *Phys. Rev. Lett.* (Mar 2017).

# Outline

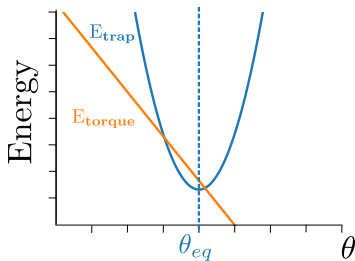
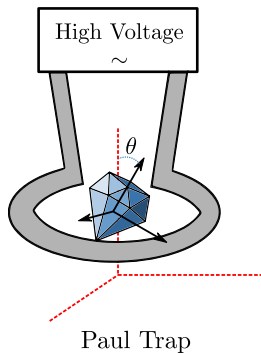
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# Torque measurement with a levitating diamond

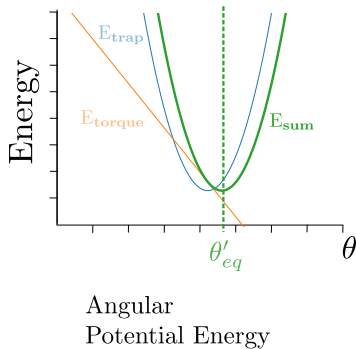
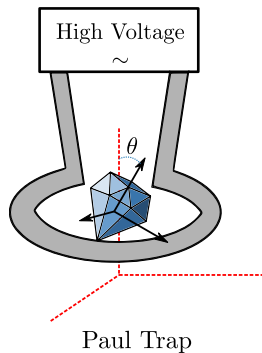


# Torque potential energy

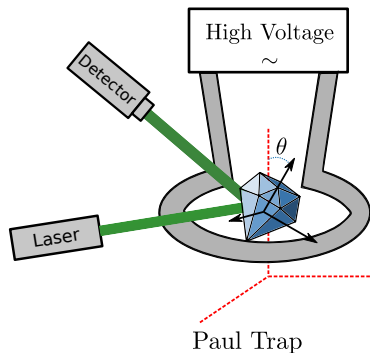


Angular  
Potential Energy

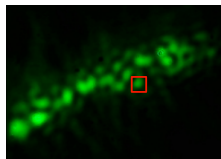
# Displacement of equilibrium



# Back-scattered laser detection

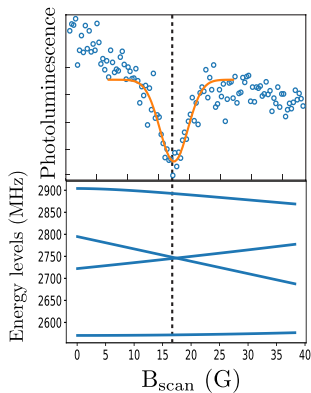


Speckle pattern

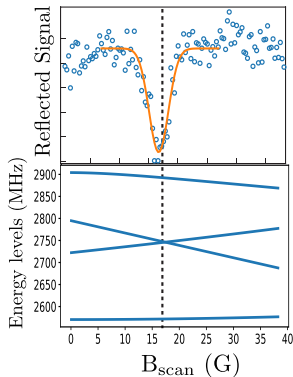


Resolution  $\sim 100\mu\text{rad}/\sqrt{\text{Hz}}$

# Torque caused by cross-relaxations

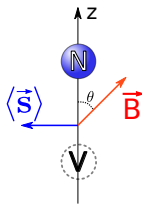


PL detection

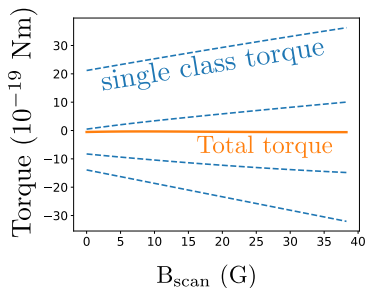


Torque Detection

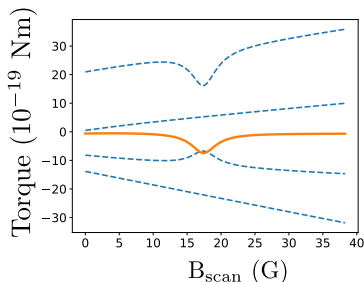
# Origin of the magnetic torque



$$\vec{\Gamma} = \vec{\mu} \times \vec{B} = \gamma_e \langle \hat{\vec{S}} \rangle \times \vec{B}$$

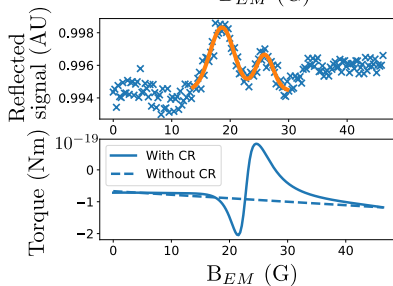
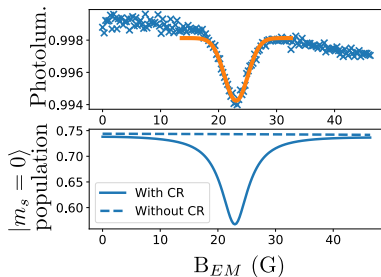
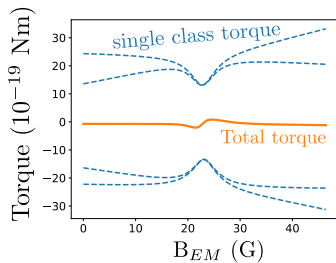
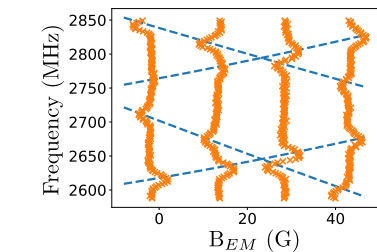


Without Cross-Relaxations



With Cross-Relaxations

# Torque caused by CR : other configuration



# Conclusion

- Detection of new spin defects in diamond through Cross-Relaxations
  - Potential for hyperpolarization 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