Dipolar interactions in dense ensembles of Nitrogen-Vacancy centers

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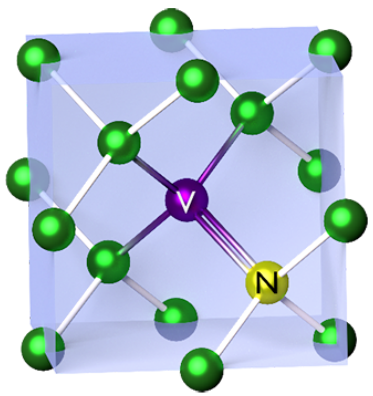
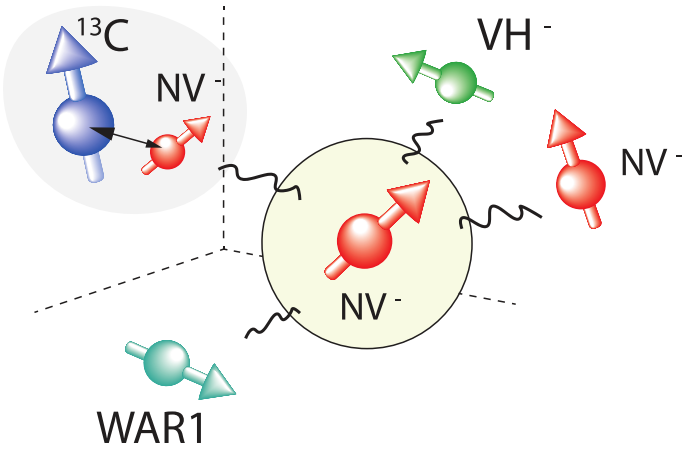
Nano-optics group

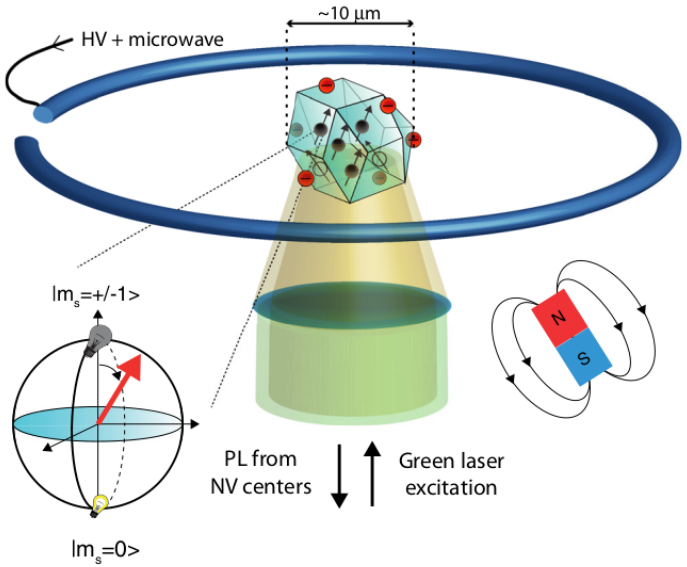


Team main activities



Dipole-dipole coupling between dense ensemble of spins

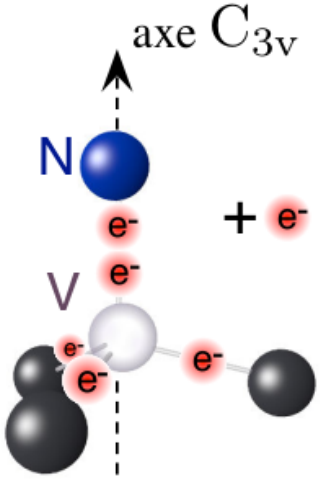
→ Modificationof the spin population dynamics

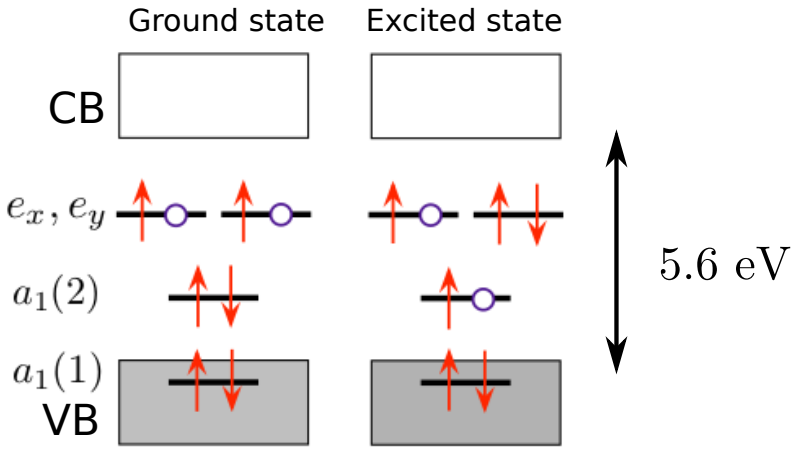


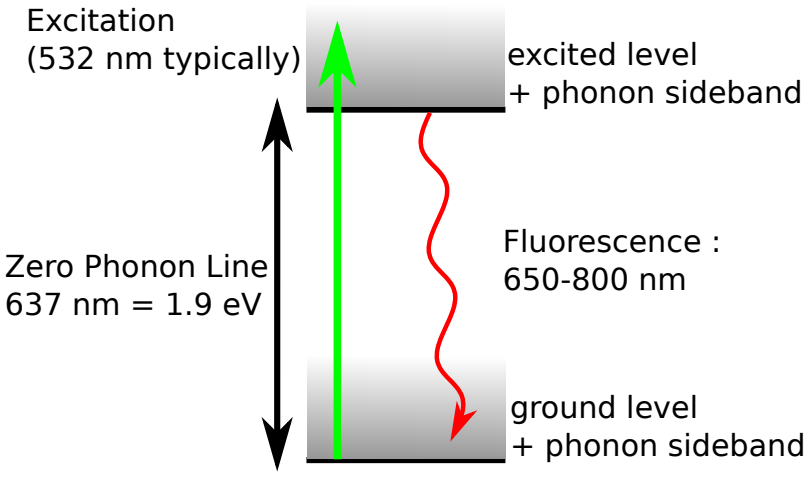
Levitation of a micro-diamond in a Paul trap

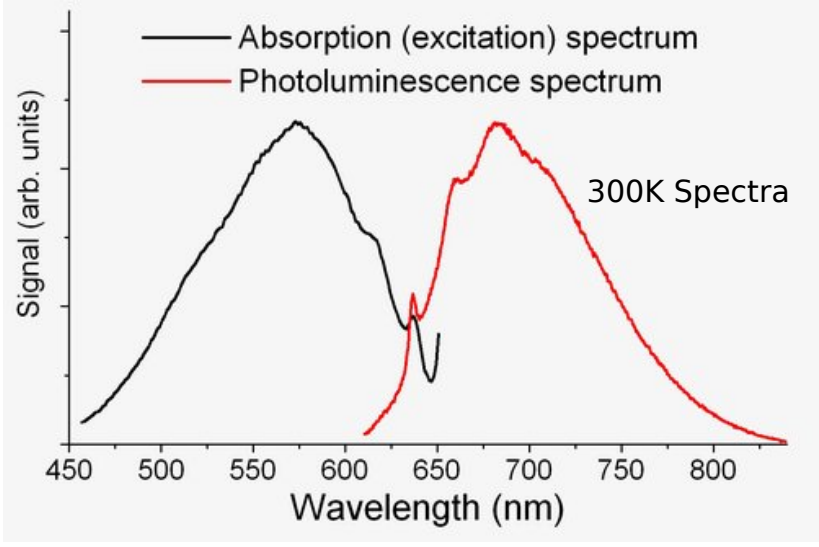
→ Coupling the spin levels to the mechanical degree of freedom of the diamond

Optical properties of NV^- centers

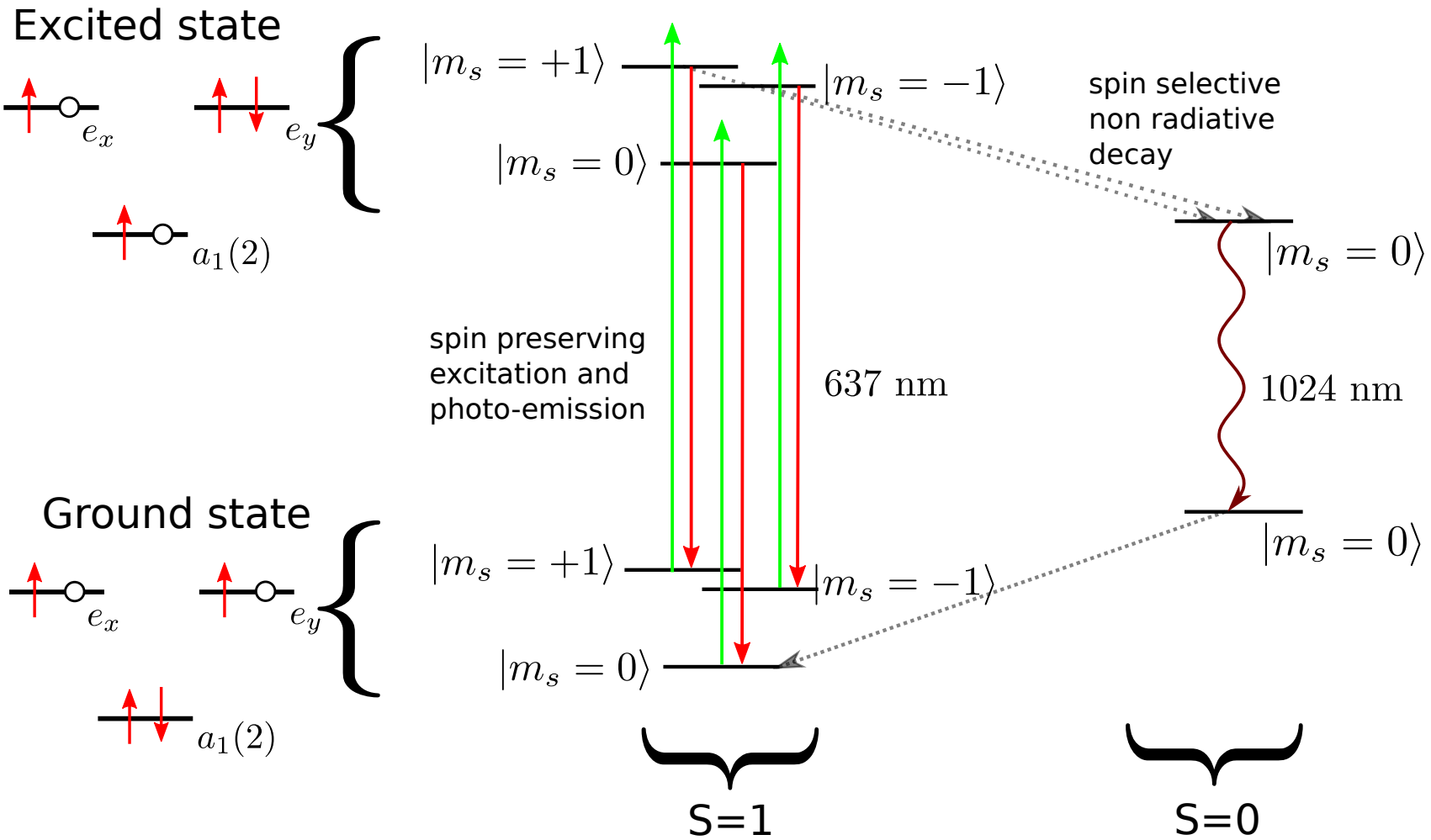








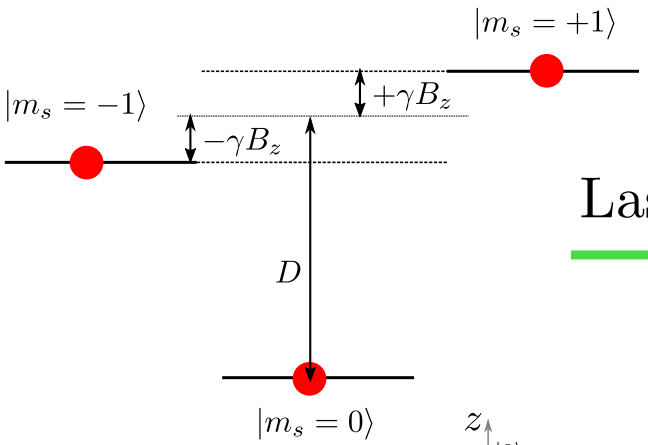
NV^- center electronic structure



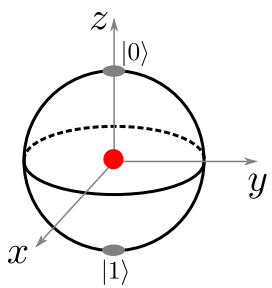
NV center spin sub-levels

$D = 2.87$ GHz
γB_z MHz $\sim$ GHz (typ.)
$k_B T = 6.28$ THz at 300 K

Thermal equilibrium



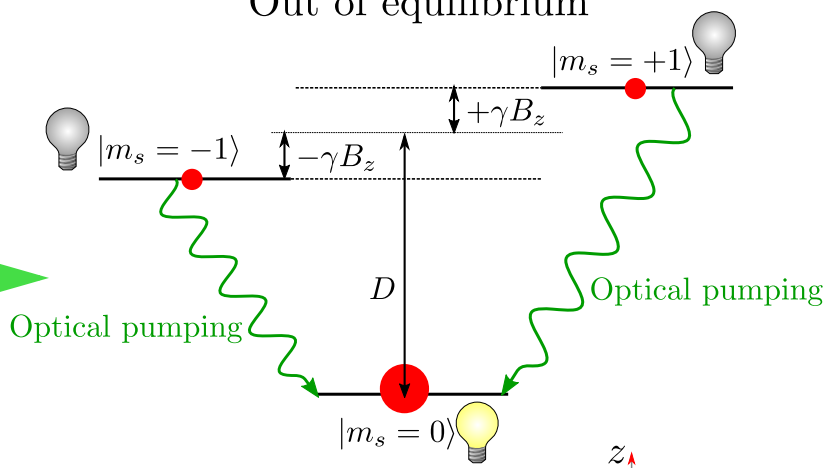
$$\hat{\rho} = \begin{pmatrix} 0.33 & 0 & 0 \\ 0 & 0.33 & 0 \\ 0 & 0 & 0.33 \end{pmatrix}$$



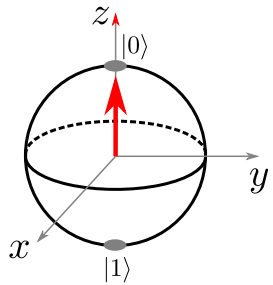
Laser ON

Spin properties (300K) :
$T_1 \sim$ ms (phonon limited)
$T_2^* \sim \mu$s (magnetic noise)

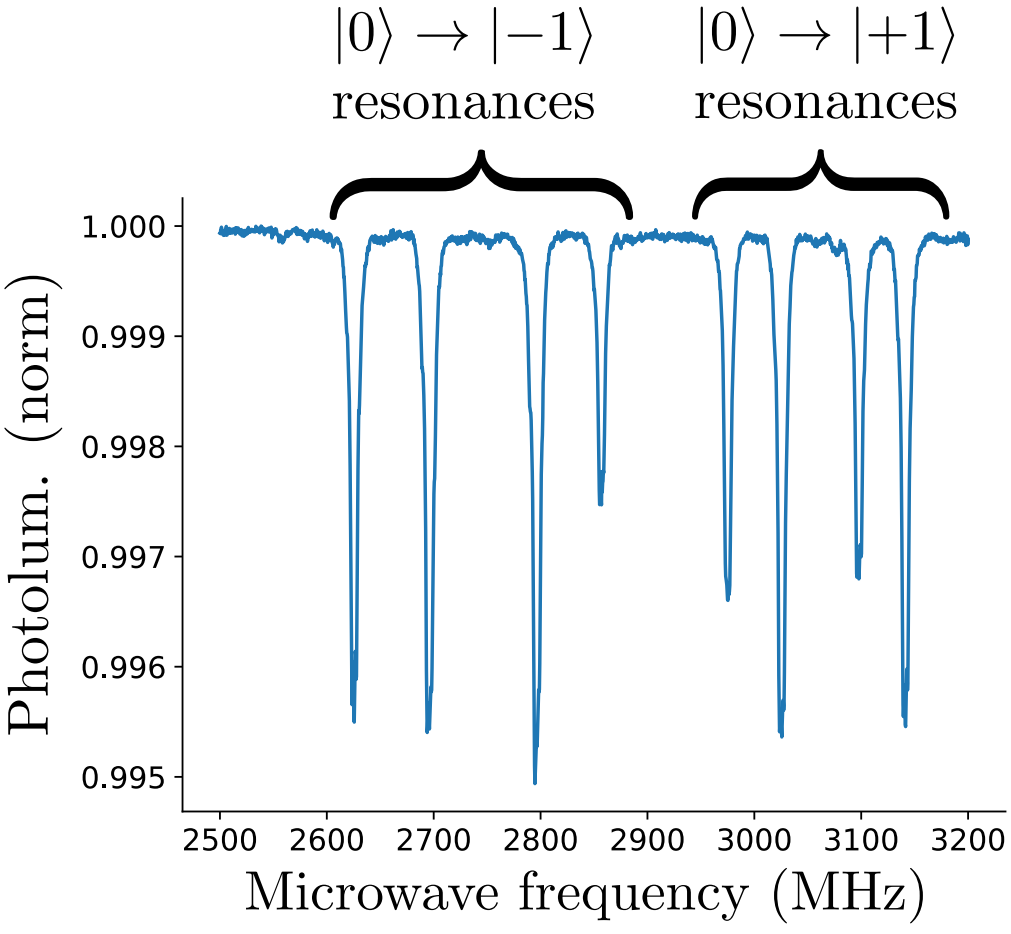
Out of equilibrium

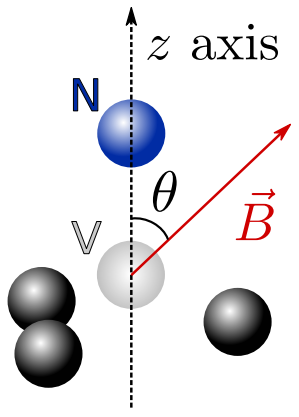


$$\hat{\rho} = \begin{pmatrix} 0.05 & 0 & 0 \\ 0 & 0.9 & 0 \\ 0 & 0 & 0.05 \end{pmatrix}$$



Optically Detected Magnetic Resonance (ODMR)





$\hat{\mathcal{H}}_{\text{Zeeman}} \approx \gamma_e B \cos\theta \, \hat{S}_z$

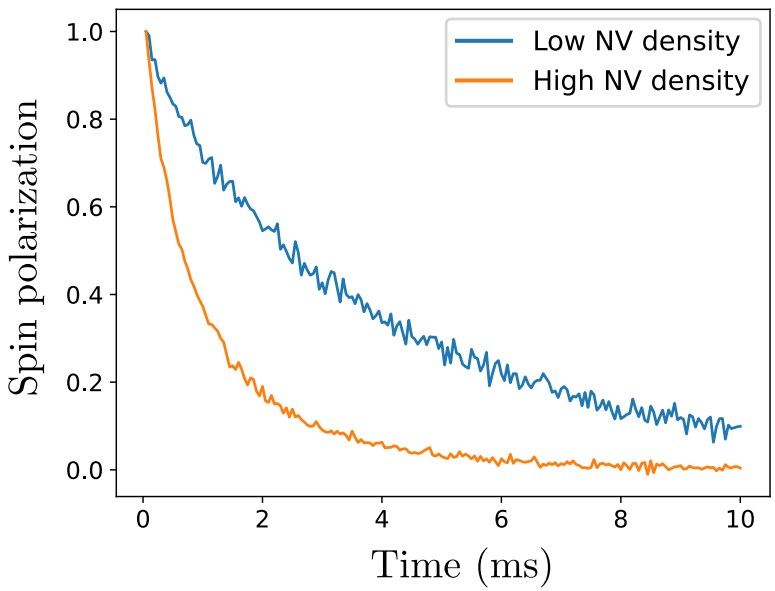
$\gamma_e = 2.8$ MHz/G

4 possible projections of $\vec{B}$

$\rightarrow$ 4 classes of resonances

Modification of the spin T_1 with dense ensemble

Spin polarization = difference in population between $|0\rangle$ and $|\pm 1\rangle$



When reaching a critical ($\sim$ 1 ppm) NV density :

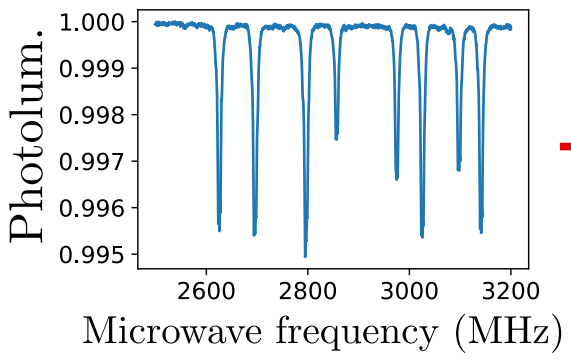
- Lifetimes get shorter
- Polarization profile get non-exponential

Dipole-dipole coupling $J \approx 30$ kHz for [NV]=3 ppm
$\rightarrow$ Depolarization slower than the flip-flop rate

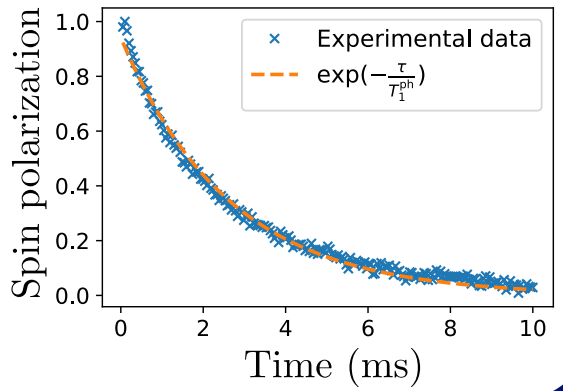
Modification of the spin T_1 due to resonant dipole coupling

Changing $\vec{B}$

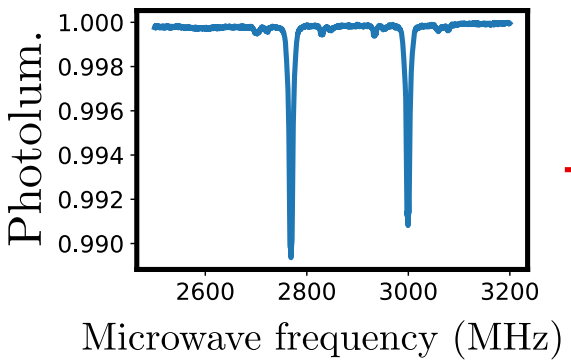
No classes degeneracy
→ effective resonant population = 1/4



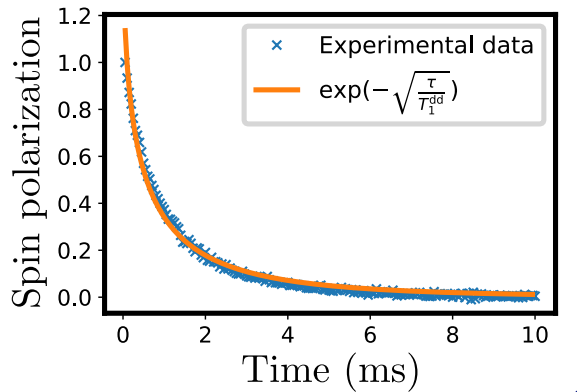
- Longer lifetime
- Exponential profile



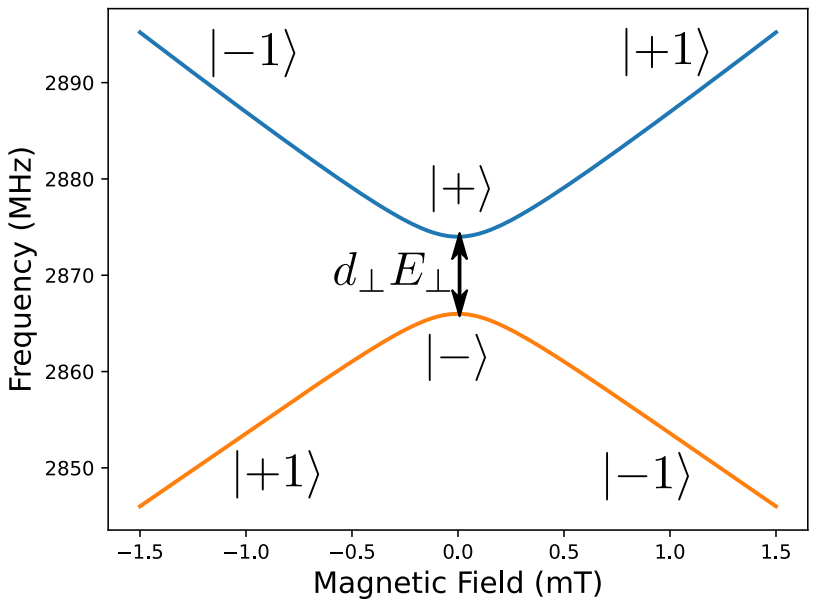
All four classes degenerate
→ effective resonant population = 1



- Shorter lifetime
- Stretch-exponential profile



Dipole-dipole coupling in zero magnetic field



$|+\rangle = \frac{|+1\rangle+|-1\rangle}{\sqrt{2}} \quad |-\rangle = \frac{|+1\rangle-|-1\rangle}{\sqrt{2}}$

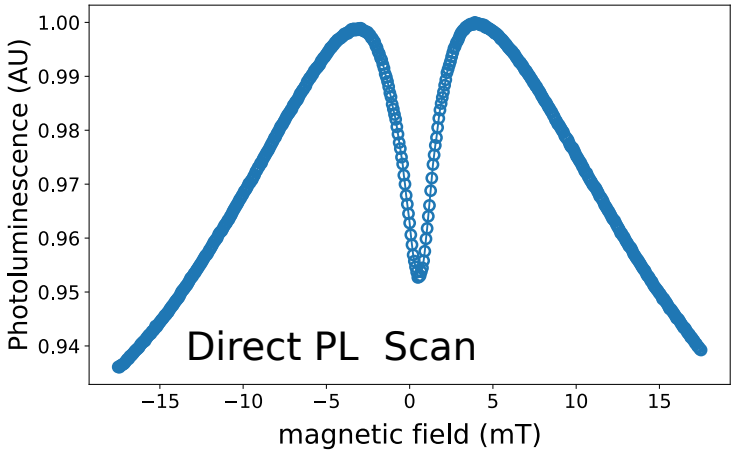
- Level anti-crossing in zero magentic field
  → New single-spin Hamiltonian eigenstates
  → Modification of the dipole-dipole interaction

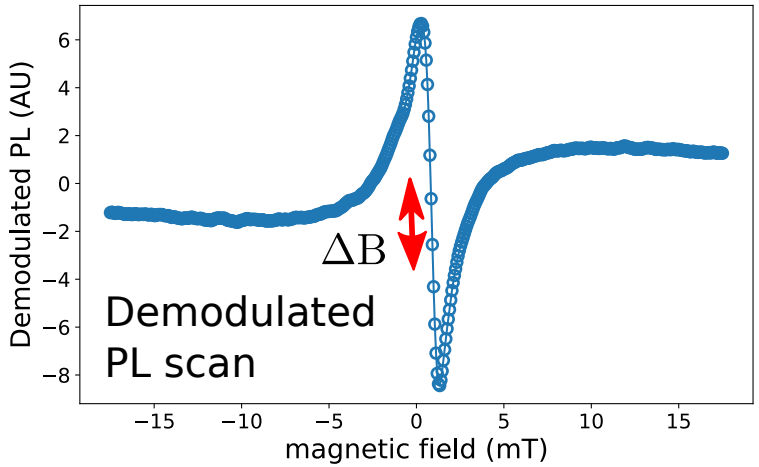
- Near-resonance of double-flip terms $|0,+\rangle\langle -,0|$

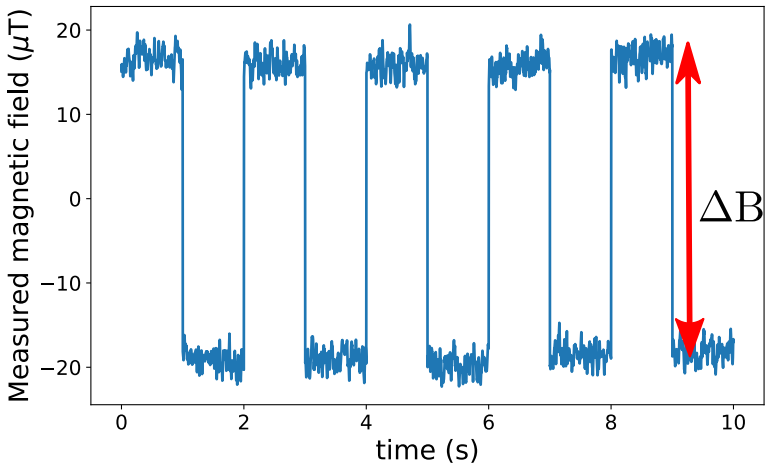
Conclusion

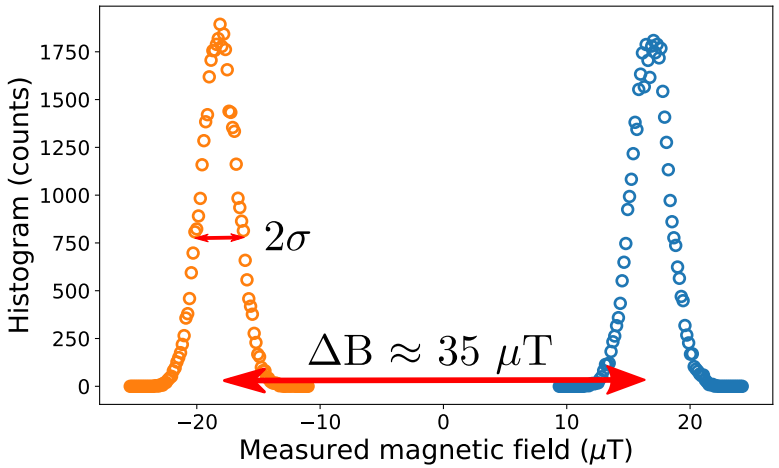
- The NV^- center is an optically active defect in diamond which allows an optical control and readout of its spin state.
- The depolarization of the spins is modified in dense ensemble due to dipole-dipole coupling.
- This effect is even stronger in zero-magnetic field.

Bonus : Magnetometry in zero magnetic field









$$\text{Sensitivity} = \sigma\sqrt{\tau_{\text{meas}}} \approx 100\ \text{nT}/\sqrt{\text{Hz}}$$