

Dipolar interactions in dense ensembles of Nitrogen-Vacancy centers

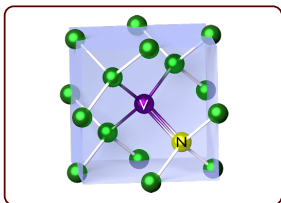
Clément Pellet-Mary, Maxime Perdriat, Gabriel Hétet

Nano-optics group

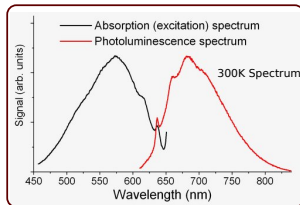
Mettre logos ici

What are NV centers and why are they everywhere?

Crystalline structure

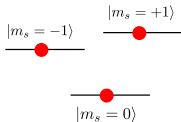


Optical properties



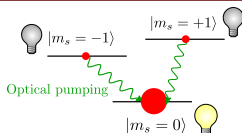
Spin properties

$S = 1$ in the electronic ground state



Unpolarized at 300 K :
 $\rho_{00} \approx 1/3 \approx \rho_{+1+1} \approx \rho_{-1-1}$

Interplay between spin and light



- Optical pumping in the $|m_s = 0\rangle$ state
- $|m_s = 0\rangle$ state brighter than $|m_s = \pm 1\rangle$

What are NV centers and why are they everywhere ?

- Good optical properties : quantum yield ≈ 1 , stable in time and temperature
- Good spin properties : $T_1 \approx \text{ms}$ and $T_2^* \sim \mu\text{s}$ at 300 K.
- Optical polarization (up to 90%) and readout (fidelity up to 0.3) of the spin at room temperature

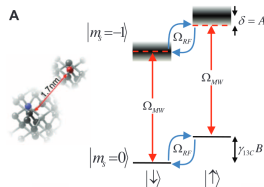
→ One of the most versatile spin qubit at room temperature

What are NV centers being used for ?

- Quantum memories :

Room-Temperature Quantum Bit Memory Exceeding One Second

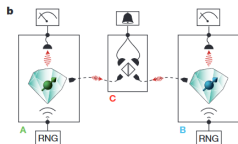
P. C. Maurer,^{1*} G. Kucsko,^{2*} C. Latta,¹ L. Jiang,² N. Y. Yao,¹ S. D. Bennett,¹ F. Pastawski,³ D. Hunger,³ N. Chisholm,⁴ M. Markham,⁵ D. J. Twitchen,⁵ J. I. Cirac,³ M. D. Lukin^{1†}



- Intrication :

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen^{1,2}, H. Bernien^{1,2}, A. E. Dr  au^{1,2}, A. Reiserer^{1,2}, N. Kalb^{1,2}, M. S. Blok^{1,2}, J. Ruitenberg^{1,2}, R. F. L. Vermeulen^{1,2}, R. N. Schouten^{1,2}, C. Abell  n³, W. Amaya³, V. Pruneri^{3,4}, M. W. Mitchell^{3,4}, M. Markham⁵, D. J. Twitchen⁵, D. Elkouss¹, S. Wehner¹, T. H. Taminiau^{1,2} & R. Hanson^{1,2}

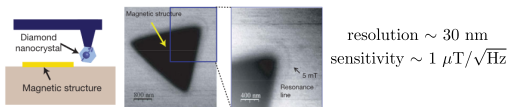


Magnetometry with NV centers : big or small

- AFM nano-scale magnetometry :

Nanoscale imaging magnetometry with diamond spins under ambient conditions

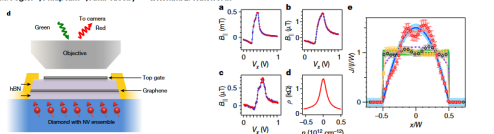
Gopalakrishnan Balasubramanian¹, I. Y. Chan^{2†}, Roman Kolesov¹, Mohannad Al-Hmoud¹, Julia Tisler¹, Chang Shin³, Changdong Kim³, Aleksander Wojcik³, Philip R. Hemmer³, Anke Krueger⁴, Tobias Hanke⁵, Alfred Leitenstorfer⁵, Rudolf Bratschkov⁵, Fedor Jelezko¹ & Jörg Wrachtrup¹



- Diamond magnetic microscopy :

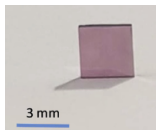
Imaging viscous flow of the Dirac fluid in graphene

Mark J. H. Ku^{1,2,3,4,5}, Tony X. Zhou^{1,4,5}, Qing Li¹, Young J. Shin^{1,5}, Jing K. Shi¹, Claire Burch⁶, Laurel E. Anderson¹, Andrew T. Pierce¹, Yonglong Xie^{1,7}, Assaf Hamo¹, Uri Vogt^{1,8}, Huiliang Zhang^{1,5}, Francesco Casola^{1,5}, Takashi Taniguchi⁹, Kenji Watanabe⁹, Michael M. Fogler¹⁰, Philip Kim^{1,4}, Amir Yacoby^{1,4,12} & Ronald L. Walsworth^{1,2,3,11,12,13,14}



Context of my PhD work : new physics with dense ensemble of NV centers

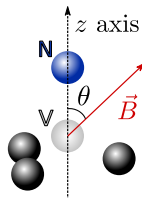
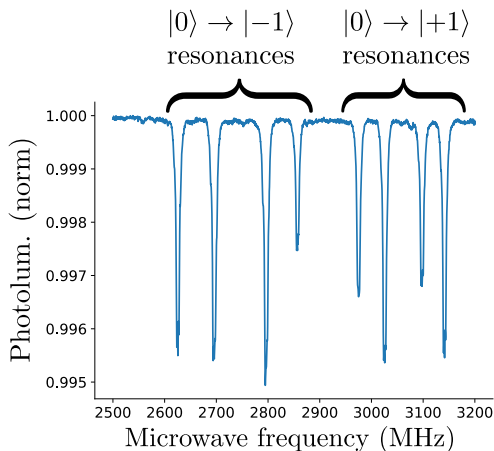
- To increase the ensemble sensitivity we need to increase the density of NV centers
- Chemists and material scientists have made huge progress to grow NV-rich diamond with little other impurities



- \sim ppm density of NV centers
- Up to 40% of defects are NV centers

- When the defects density reaches a critical point, many body effects start to appear due to dipole-dipole interaction and charge transfer (3 ppm of NV = 30 kHz dipole coupling between NV neighbors)

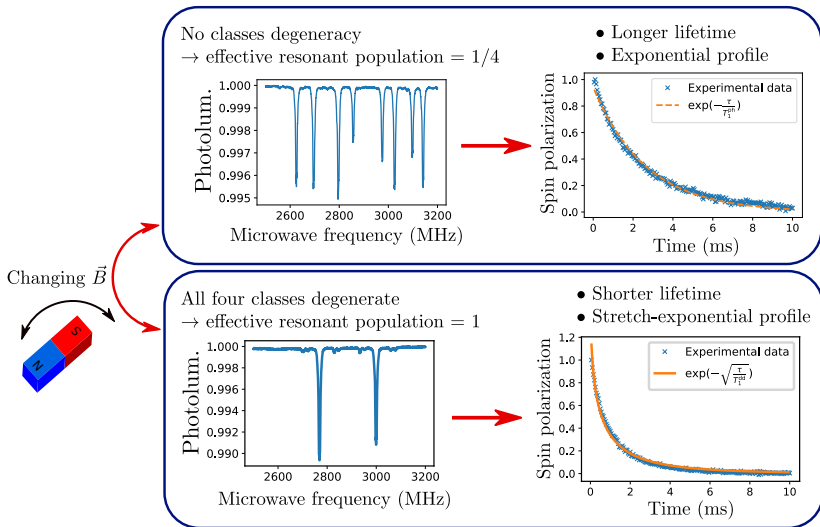
Basic example : Optically Detected Magnetic Resonance (ODMR)



$$\hat{H}_{\text{Zeeman}} \approx \gamma_e B \cos \theta \hat{S}_z$$
$$\gamma_e = 2.8 \text{ MHz/G}$$

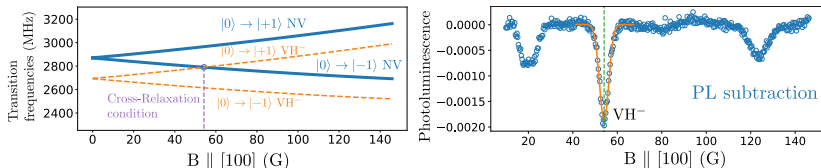
4 possible projections of \vec{B}
→ 4 classes of resonances

Modification of the spin T_1 due to resonant dipole coupling

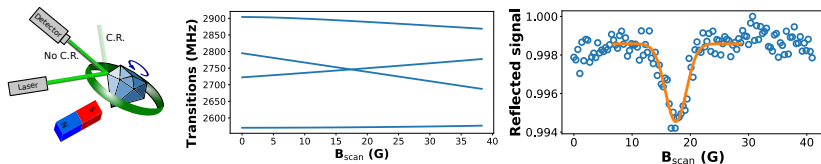


Other results with dense ensemble of spins

- Optical detection of dark spins :



- Mechanical detection of resonant dipolar coupling :



Conclusion

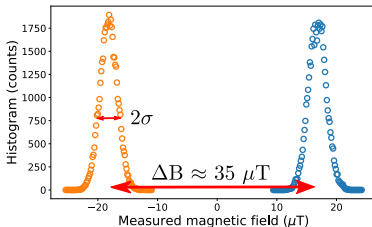
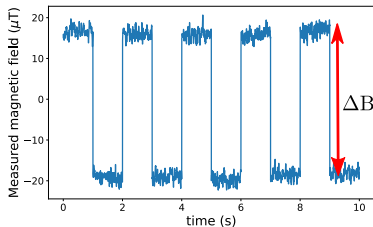
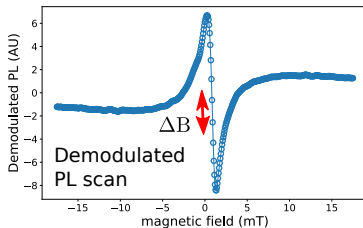
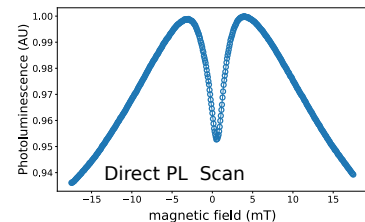
Acknowledgments

The team : Gabriel, Maxime, André, the former members : Paul, Louis Tom, the nano-optics group and the technical staff : Christine, Pascal, Arnaud...

Take home messages

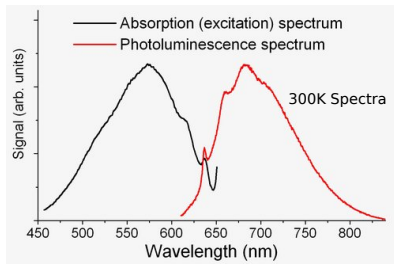
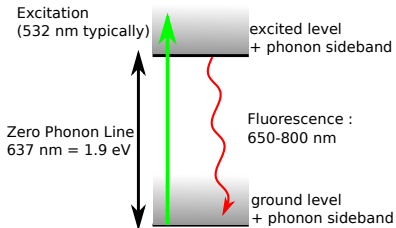
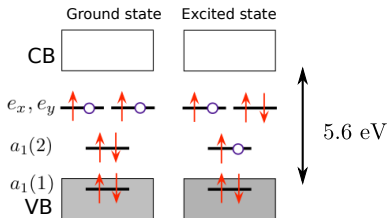
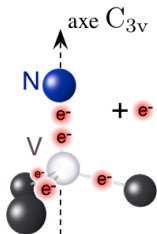
- NV centers are defects in diamond with an optically controllable and readable spin at room temperature
- Many body effects start to manifest with the new NV-rich samples being made

Bonus : Magnetometry in zero magnetic field

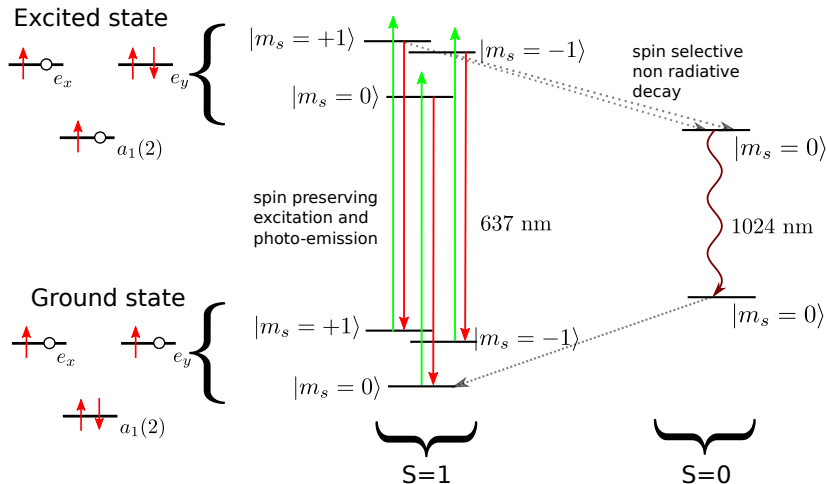


$$\text{Sensitivity} = \sigma \sqrt{\tau_{\text{meas}}} \\ \approx 100 \text{ nT}/\sqrt{\text{Hz}}$$

Optical properties of NV⁻ centers



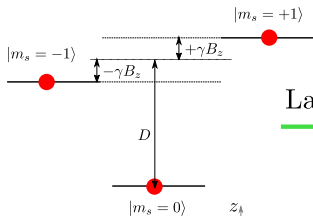
NV⁻ center electronic structure



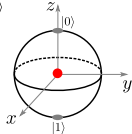
NV center spin sub-levels

$$\begin{aligned}
 D &= 2.87 \text{ GHz} \\
 \gamma B_z \text{ MHz} &\sim \text{GHz (typ.)} \\
 k_B T &= 6.28 \text{ THz at 300 K}
 \end{aligned}$$

Thermal equilibrium

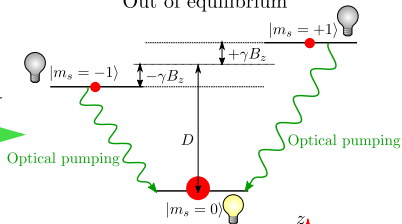


$$\hat{\rho} = \begin{pmatrix} 0.33 & 0 & 0 \\ 0 & 0.33 & 0 \\ 0 & 0 & 0.33 \end{pmatrix}$$



$$\begin{aligned}
 \text{Spin properties (300K) :} \\
 T_1 &\sim \text{ms (phonon limited)} \\
 T_2^* &\sim \mu\text{s (magnetic noise)}
 \end{aligned}$$

Out of equilibrium



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

