Dipolar interactions in dense ensembles of Nitrogen-Vacancy centers

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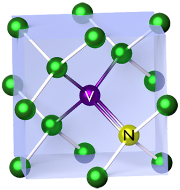
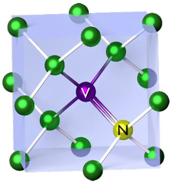
Nano-optics group

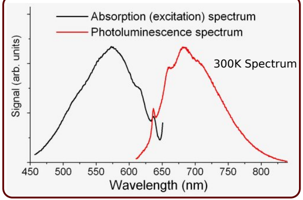


What are NV centers ?

Crystalline structure

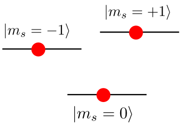


Optical properties

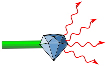


Spin properties

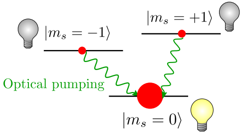
$S = 1$ in the electronic ground state



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

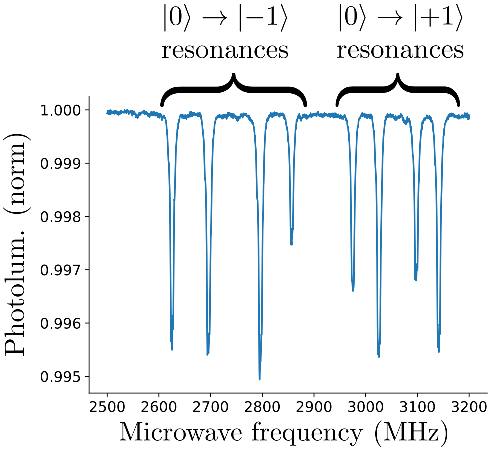


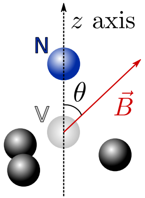
Interplay between spin and light



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

Common example : 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 $\vec{B}$

$\to$ 4 classes of resonances

What are NV centers and why are they everywhere ?

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

$\rightarrow$ One of the most versatile spin qubit at room temperature

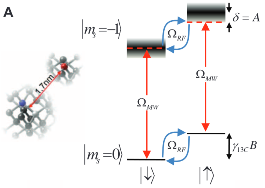
What are NV centers being used for ?

- Quantum memories :

Room-Temperature Quantum Bit Memory Exceeding One Second

P. C. Maurer,[1*] G. Kucsko,[1*] 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]†

A

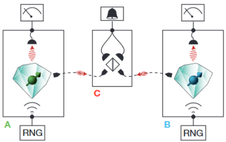


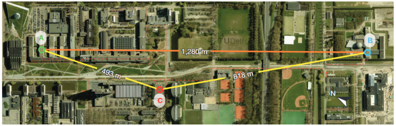
- Intrication :

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

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[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. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

b



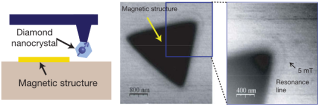


Magnetomtry with NV centers : big or small

- AFM nano-scale magnetomtry :

Nanoscale imaging magnetometry with diamond spins under ambient conditions

Gopalakrishnan Balasubramanian[1], I. Y. Chan[2]†, Roman Kolesov[1], Mohannad Al-Hmoud[1], Julia Tisler[1], Chang Shin[3], Changdong Kim[3], Aleksander Wojcik[3], Philip R. Hemmer[3], Anke Krueger[4], Tobias Hanke[5], Alfred Leitenstorfer[5], Rudolf Bratschitsch[5], Fedor Jelezko[1] & Jörg Wrachtrup[1]



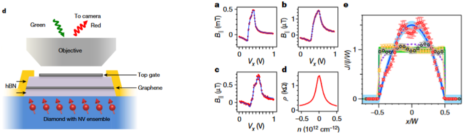
resolution $\sim$ 30 nm
sensitivity $\sim 1\ \mu\mathrm{T}/\sqrt{\mathrm{Hz}}$

- Diamond magnetic microscopy :

Imaging viscous flow of the Dirac fluid in graphene

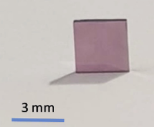
Mark J. H. Ku[1,2,3,14,15], Tony X. Zhou[1,4,15], Qing Li[1], Young J. Shin[1,5], Jing K. Shi[1], Claire Burch[6], Laurel E. Anderson[1], Andrew T. Pierce[1], Yonglong Xie[1,7], Assaf Hamo[1], Uri Vool[1,8], Huiliang Zhang[1,3], Francesco Casola[1,3], Takashi Taniguchi[9], Kenji Watanabe[9], Michael M. Fogler[10], Philip Kim[1,4], Amir Yacoby[1,4]✉ & Ronald L. Walsworth[1,2,3,11,12,13]✉

resolution $\sim \mu$m
sensitivity $\sim \mathrm{pT}/\sqrt{\mathrm{Hz}}$



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

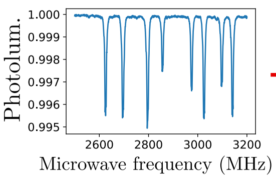


- $\sim$ ppm density of NV centers
- Up to 40% of defects are NV centers

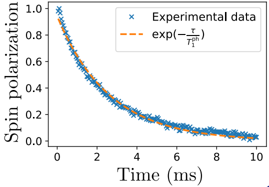
- When the defects density reaches a critical point, many body effects start to appear due to dipole-dipole interaction and charge tunneling (3 ppm of NV = 30 kHz dipole coupling between NV neighbors)

Modification of the spin T_1 due to resonant dipole coupling

No classes degeneracy
$\rightarrow$ effective resonant population $= 1/4$

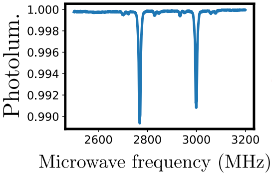


- Longer lifetime
- Exponential profile

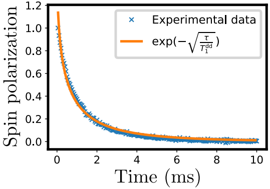


Changing $\vec{B}$

All four classes degenerate
$\rightarrow$ effective resonant population $= 1$



- Shorter lifetime
- Stretch-exponential profile



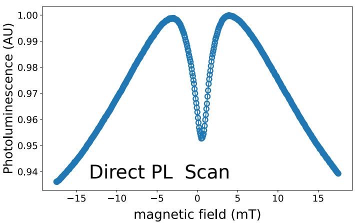
Conclusion

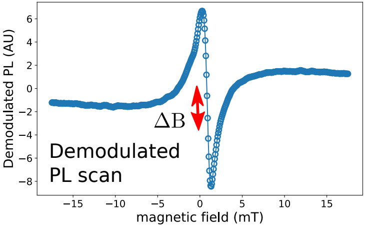
Acknowledgments : Christine et les autres

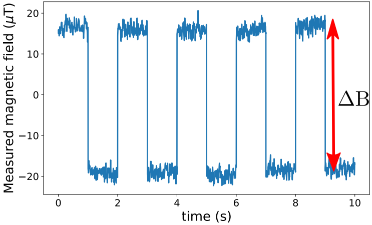
Take home messages :

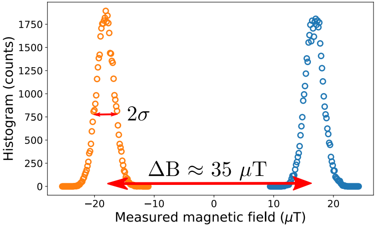
- NV centers are defects in diamond with an optically controllable and readable spin at room temperature
- Many body effects start to manifest with the new NV-rich samples being made

Bonus : Magnetometry in zero magnetic field



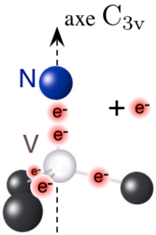


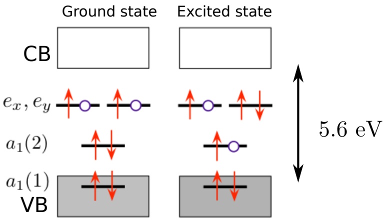


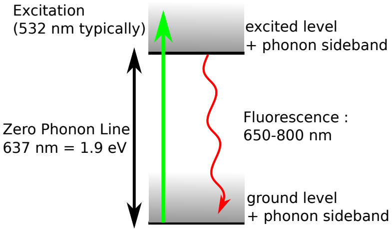


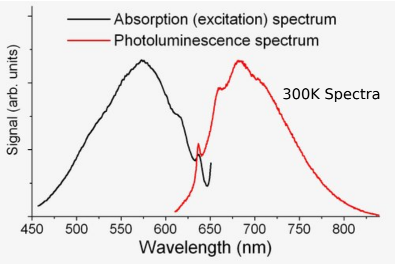
$$\boxed{\begin{aligned}\text{Sensitivity} &= \sigma\sqrt{\tau_{\text{meas}}} \\ &\approx 100\ \text{nT}/\sqrt{\text{Hz}}\end{aligned}}$$

Optical properties of NV$^-$ centers

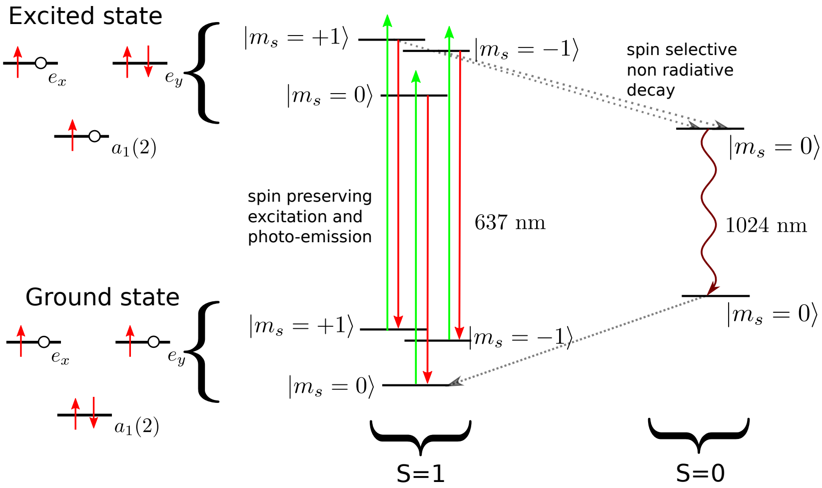








NV$^-$ center electronic structure

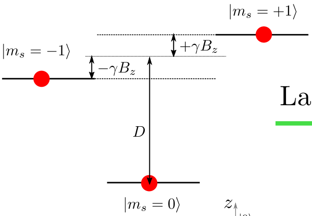


NV center spin sub-levels

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

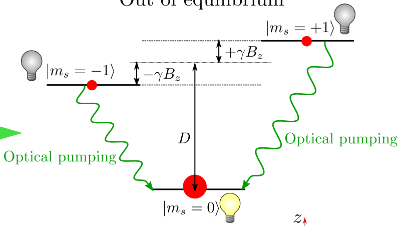
Spin properties (300K) :
$T_1 \sim$ ms (phonon limited)
$T_2^* \sim \mu$s (magnetic noise)

Thermal equilibrium

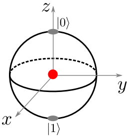


Laser ON

Out of equilibrium



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



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