Diamonds Are a Physicist's Best Friend: Exploring Quantum Mechanics with NV Centers in Diamond

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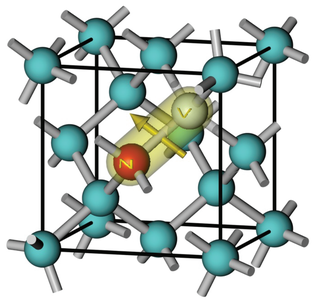
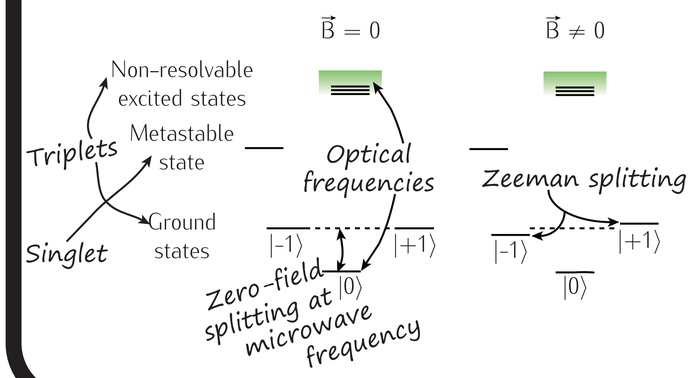
Nitrogen-Vacancy (NV) Center Structure

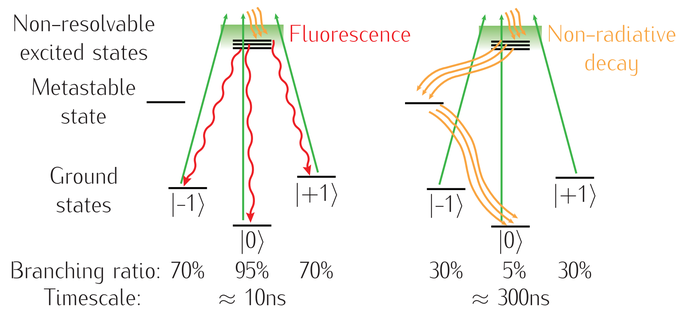
The NV center is one among 500+ naturally occurring defects in diamond. What makes it so special?

Effective electronic spin 1: A vacancy in the diamond lattice bonds with an adjacent N substitutional impurity. The energy level scheme of this effective 'trapped atom' is of note:





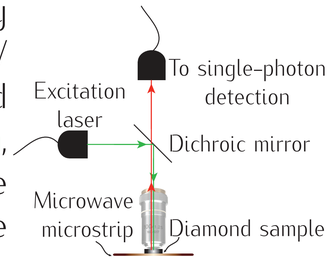
Stable: No trapping requirements;
Long coherence times: $T_1 >$ ms, $T_2 \gtrsim 0.6$ms at room temperature;
Controlled implantation: Can also be created by irradiation (vacancies, N implantation) followed by annealing (vacancies move closer to N impurity);
Color center: Absorbs light and fluoresces.



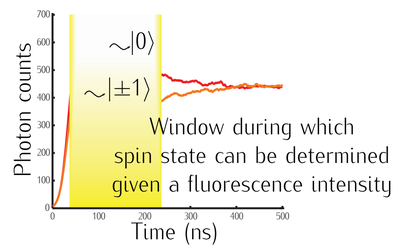
The fluorescence has a competing process: A spin in state $|0\rangle$, when excited, fluoresces back to $|0\rangle$ 95% of the time; This rate for a spin in $|\pm1\rangle$ is 70%, decaying non-radiatively to $|0\rangle$ otherwise.

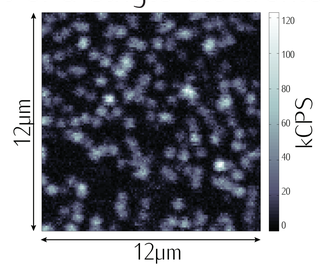
Experimental Setup

The diamond sample is probed by confocal microscopy. Single NV centers are scanned for and resolved by off-resonant excitation at 532nm, fluorescing at ≈ 637nm. Microwave radiation coherently manipulates the spin transitions at around 2.8GHz.



Single spin state observed by fluorescence: Upon continuous excitation, a NV center spin in state $|0\rangle$ will decay back to $|0\rangle$. A spin in $|\pm1\rangle$ ends up in $|0\rangle$ via the dark metastable state of lifetime ≈ 300ns, thus fluorescing less averaged over many runs. Compare: Unobservable ESR signal from the magnetic moment of a single electronic spin.

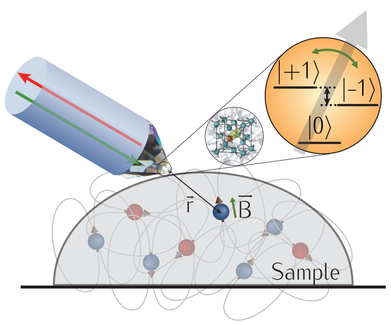




Application: Magnetometry

The NV center spin couples to other spins, both nuclear and electronic, in the environment (primarily in the diamond lattice). The presence of those spins is felt as tiny sources of magnetic field. For example, the field of a proton at a distance $|\vec{r}| = 10$nm is 3nT.

Due to the Zeeman effect, a magnetic field causes a shift in the energy spacing between the $|\pm1\rangle$ states; Monitoring such shift then probes local magnetic fields on the single spin level in a sample placed nearby a NV center 'tip'.

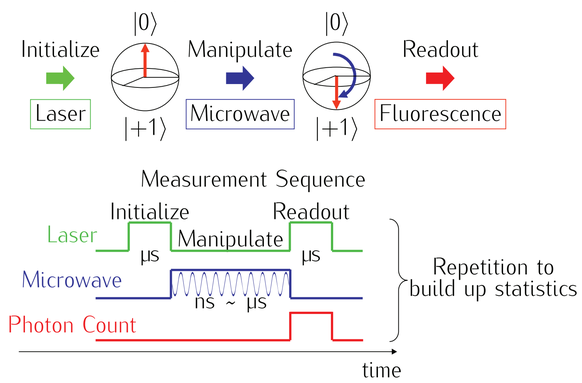


Proximity of sensor spin to sample: Strength of spin-spin couplings $\propto \frac{1}{|\vec{r}|^3}$;
Room temperature operation: Can study biological samples;
Long coherence times: Sensitivity $\propto \frac{1}{T_2^{*1/2}}$ (18 $\frac{\text{nT}}{\text{Hz}^{1/2}}$ experimentally reported).

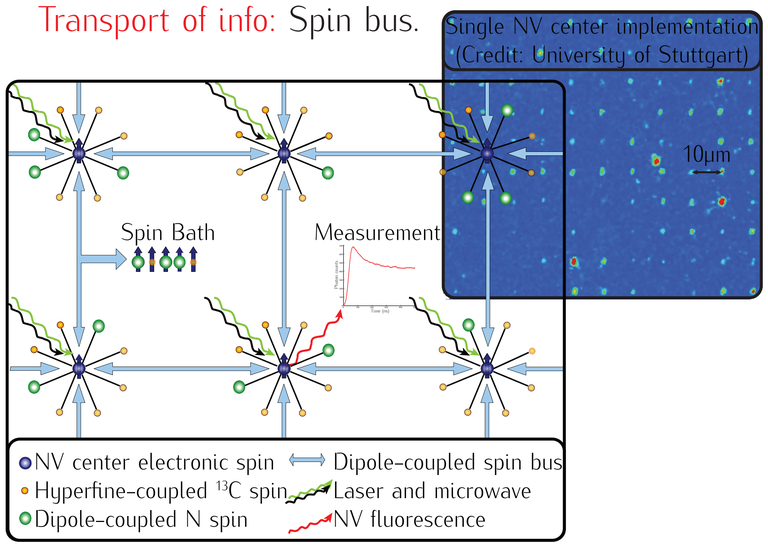
Application: Quantum Computing & Control

The fundamental unit of a quantum computer can be engineered in diamond.

Qubit: A pair of different magnetic sublevels in the electronic ground state, for example $|0\rangle$ and $|+1\rangle$;
Gates: Single qubit rotations in the NV center spin by microwave fields; Two-qubit gates (NV-NV and NV-proximal spins in the environment) using dipolar and hyperfine couplings;
Initialization: Optical pumping prepares state $|0\rangle$;
Readout: Spin-dependent fluorescence intensity;



Long coherence times: Figure of merit $\frac{T_2}{T_{gate}} \approx 10^5$ at room temperature;
Storage of info: Proximal nuclear spins;
Transport of info: Spin bus.



In order to preserve and improve its robustness, we make use of control sequences and numerical algorithms stemming from NMR.