NV-Centers in Diamond as a Qubit Platform

An Overview

Alex Heilman

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Two-level Quantum System:

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What criteria for physical systems do we need to satisfy?

Criteria for Qubit Platforms

DiVincenzo's Criteria: The first five are for quantum computers.

- Scalable and discernible
- Fiduciary initial state
- Long decoherence time
- Universal gate set
- Measureable

These next two are for quantum communication

- Memory $\rightarrow$ Computation
- Faithful transmission

Criteria for Qubit Platforms cont.

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- Coherence Time

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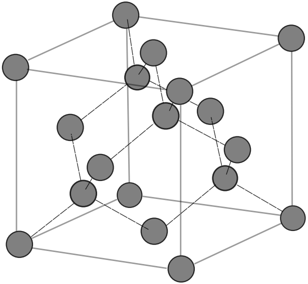
Really, the concepts discussed below should apply to most similar systems, it's just that this system is well-studied and has convenient energy levels/properties

Why Diamond?

Diamond is an ideal candidate due to low density of phonon modes (relatively high Debye temperature)



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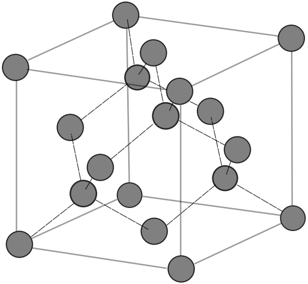

This leaves spins of defects and electrons less influenced by phonon modes, increasing their coherence times

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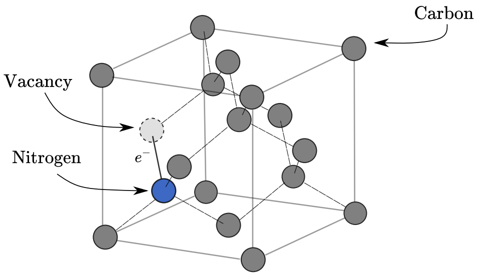
NV-Center refers to a type of defect in diamond lattices with several charge states (-, $+$, neutral). The most commonly discussed charge state is the (-) NV-Center. If unspecified, this is most likely the defect under consideration.

What's an (-) NV-Center

An (-) NV-Center is a neighboring nitrogen-vacancy defect in diamond with an extra electron



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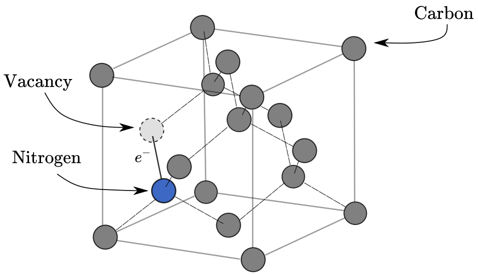

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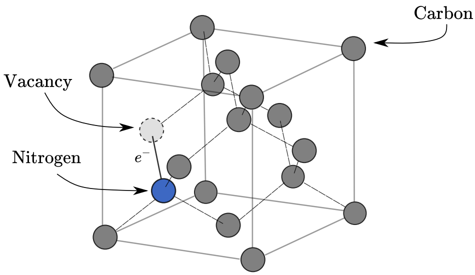

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These energy states may be used as a Qubit platform.

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Let's see the Hamiltonian...

NV-Center Hamiltonian

The electron will be taken to be localized to the defect. We'll take this localized two electron state to be the unperturbed solution and apply some interaction effects, with the corresponding interaction Hamiltonian below (again, assuming no external electric field/Stark effects):

$$H = \underbrace{\vec{\hat{S}}\mathbf{D}\vec{\hat{S}}}_{\text{ZFS}} + \underbrace{\vec{\hat{I}}_N\mathbf{Q}\vec{\hat{I}}_N}_{\text{Quadrapole}} + \underbrace{\vec{\hat{S}}\left(\mathbf{A}_N\vec{\hat{I}}_N + \sum_i \mathbf{A}_{C_i}\vec{\hat{I}}_{C_i}\right)}_{\text{Hyperfine}}$$

$$+ \underbrace{\left(\vec{\hat{S}}\mathbf{g}_s + \vec{\hat{I}}_N\mathbf{g}_N + \sum_i \vec{\hat{I}}_{C_i}\mathbf{g}_{C_i}\right)\vec{B}}_{\text{Zeeman}} \quad [3]$$

Simplifications

Assuming we apply a magnetic field only along the symmetry axis, which we define to be the z direction

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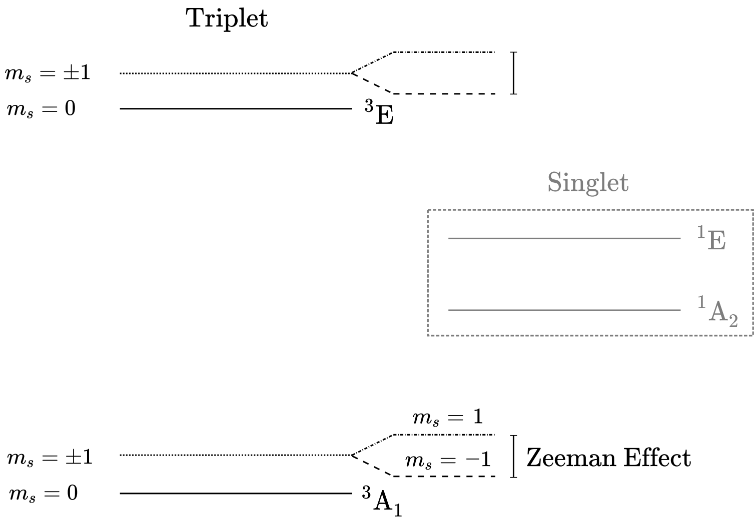
Assuming we apply a magnetic field only along the symmetry axis, which we define to be the z direction, and neglecting the surrounding carbon's effects (both Zeeman and hyperfine, though these allow us to use the nv-center as register for these surrounding sites [1]):

$$H_{NV} \approx DS_z^2 + \omega_e S_z + QI_z^2 + \omega_n I_z + AS_z I_z \quad [2]$$

where $\omega_i = \gamma_i B$, the Larmor frequency.
$D = 2\pi \times (2.87GHz)$, the dipole coupling constant
$Q = 2\pi \times (-4.95GHz)$, the nuclear quadrapole coupling constant
$A = 2\pi \times (-2.16GHz)$, the hyperfine coupling constant

Energy Levels



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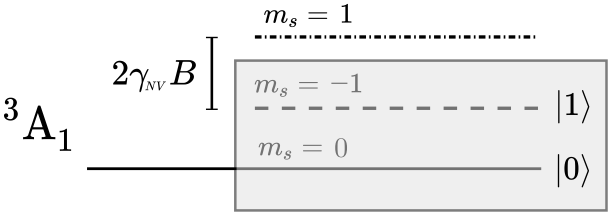

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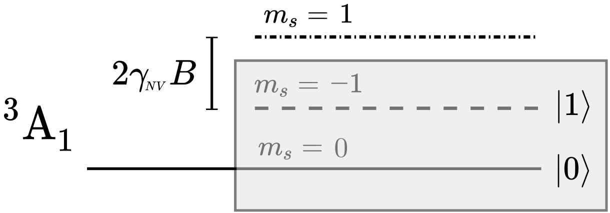
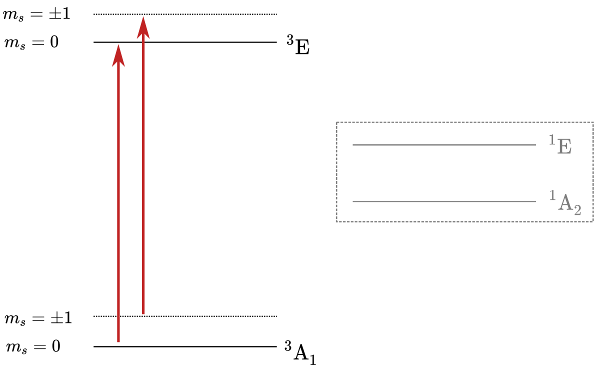


The transitions between these states are in the microwave regime.

Initialization

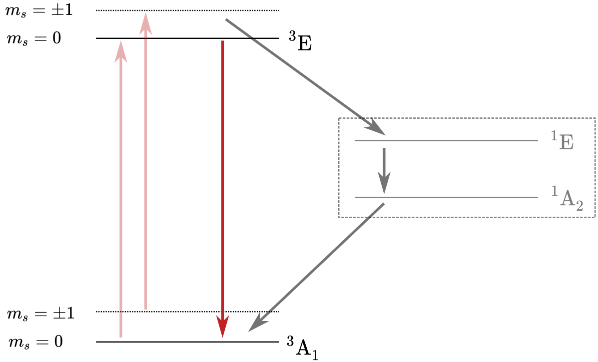
Initialization to the zero state can be achieved by an asymmetric relaxation from the first excited triplet state (^3E) to the triplet ground state (^3A).



Applying a resonant pulse (532 nm) excites all triplet ground states to their corresponding excited states ($\Delta m_s = 0$).

Initialization cont.

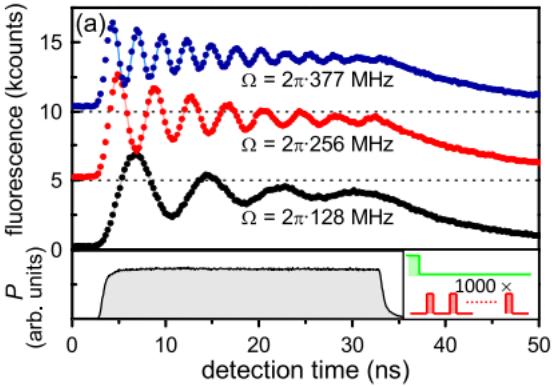
Excited $m_s = 0$ states have been shown to decay back into $m_s = 0$ ground states, but $m_s = \pm 1$ excited states favor a non-radiative (vibrational) decay mode via the singlet states, back into the $m_s = 0$ ground state.



This may be exploited to intialize the spin state into our $|0\rangle$ state.

Local Control

Perpendicular (polarization relative symmetry axis) microwave pulses can induce Rabi flopping of state between $|0\rangle$ and $|1\rangle$



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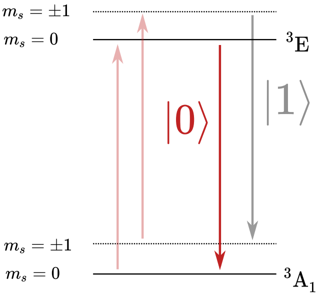
Optically Detected Magnetic Resonance

Much like the initialization technique, optically detected magnetic resonance (ODMR) takes advantage of the asymmetric relaxation modes of the excited state.



Hence, if the defect flouresces when hit with a resonant pulse, it was measured to be in the $|0\rangle$ state, but if it's 'dark' after a resonant pulse, it can be considered to have been in the $|1\rangle$ state.

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Conclusion & Outlook

Promising candidate due to practical methods of initialization, measurement, and qubit manipulation.

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Some have also considered defect levels as qutrits [2]

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