

Abstract

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Introduction

1.1

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1.2

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Electronic spins in Diamond

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2.1 Spin Control

The Nitrogen Vacancy centre in diamond is a well investigated system [3] and a promising candidate for quantum computation [1]. In order to implement three qubit measurement based QEC we need three qubits plus ancillae that we can initialise, measure and conditionally perform operations on. These extra qubits are found in Carbon-13 atoms, which are normally a source of decoherence. These atoms can be addressed using a resonant decoupling sequence [7].

It has been shown that the nuclear- and electron- spin-state of the NV- centre can be initialized, coherently controlled and read-out using microwaves and laser pulses [6]. These are essential tools in controlling the NV- centre. In this chapter I will explain how control over the electron-spin-state can be used to address weakly coupled Carbon-13 atoms.

2.1.1 Spin Control

The electronic ground state Hamiltonian can be written as [5]:

$$H_{GS} = \Delta S_z^2 + \gamma_e \mathbf{B} \cdot \mathbf{S} \quad (2.1)$$

With zero field splitting $\Delta \approx 2.88\text{GHz}$ and gyromagnetic ratio $\gamma_e = 2.802 \text{ MHz/G}$. In this expression the interactions with the Nitrogen nucleus and the Carbon spin bath are not included. By applying a magnetic field B_z along the N-V axis the degeneracy of the $m_s = \pm 1$ states is lifted by the Zeeman effect. A two level system that serves as a qubit can be defined with $m_s = 0 := |0\rangle$ and $m_s = -1 := |1\rangle$.

On the Bloch-sphere the state vector rotates around the quantisation axis with a frequency depending on the energy splitting of the two states given by the Larmor frequency $\omega_L = \Delta - \gamma_e B_z$.¹ By applying an external field a term is effectively added to the Hamiltonian, changing the quantisation axis and thereby its evolution. By applying microwaves with the right frequency this can be used to selectively drive the transition from the $|0\rangle$ state to the $|1\rangle$ state [4].

In a similar fashion the state of a Carbon-13 atom can be controlled by switching an additional term in the Hamiltonian on and off. The Hamiltonian of the nuclear spin depends on the electron state [9]:

$$H_0 = \gamma_C B_z I_z \quad (2.2)$$

$$H_1 = \gamma_C B_z I_z + H_{HF} = \gamma_C B_z I_z + A_{\parallel} I_z + A_{\perp} I_x \quad (2.3)$$

¹When ω_L is used as a vector it is pointing in the \hat{z} direction.

The the hyperfine term is not present when the electron is in the $m_s = 0$ state. The hyperfine term consists of a contact term and a dipole term. For carbons with weak couplings ($A < 200\text{kHz}$) the contact term is expected to be negligible and the dipole term is given by [2]:

$$H_{dip} = \frac{\mu_0 \gamma_e \gamma_C \hbar^2}{4\pi r^3} [\mathbf{S} \cdot \mathbf{I} - 3(\mathbf{S} \cdot \hat{n}_{hf})(\mathbf{I} \cdot \hat{n}_{hf})] \quad (2.4)$$

From this equation the parallel and orthogonal components of the Hyperfine interaction, with respect to the N-V axis along the z direction, can be derived to be:

$$A_{\parallel} = -\frac{\mu_0 \gamma_e \gamma_C \hbar^2}{4\pi r^3} \left(3 \cdot \frac{z^2}{r^2} - 1 \right) \quad (2.5)$$

$$A_{\perp} = -\frac{\mu_0 \gamma_e \gamma_C \hbar^2}{4\pi r^3} \left(3 \cdot \frac{\sqrt{x^2 + y^2} \cdot z}{r^2} \right) \quad (2.6)$$

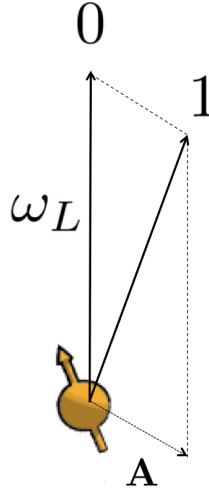


Figure 2.1 – Flipping the electron spin from the $m_s = 0$ to the $m_s = -1$ state changes the quantization axis of ^{13}C nuclear spins. For $m_s = 0$ spins precess about ω_L . For $m_s = -1$ spins precess about a distinct axis $\tilde{\omega} = \omega_L + \mathbf{A}$ [8]

2.2 Structure of a typical experiment

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Weakly Coupled Carbon Spins

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3.1 Controlling a Carbon trough dynamical decoupling

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3.2 Characterizing the Nuclear spin environment

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3.3 Carbon Initialization & Readout

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Deterministic Parity Measurements

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4.1 Entanglement

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4.2 Verification of Entanglement

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Outlook: towards Quantum Error Correction

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Entanglement witness

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Acknowledgements

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Bibliography

- [1] L. Childress and R. Hanson. Diamond nv centers for quantum computing and quantum networks. *MRS Bulletin*, 38(02):134–138, 2 2013.
- [2] G. de Lange. *Quantum Control and Coherence of Interacting Spins in Diamond*. PhD thesis, Delft University of Technology, 2012.
- [3] M.W. Doherty, N.B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L.C.L. Hollenberg. The nitrogen-vacancy colour centre in diamond. page 101, 2 2013.
- [4] F. Jelezko, T. Gaebel, I. Popa, a. Gruber, and J. Wrachtrup. Observation of coherent oscillations in a single electron spin. *Physical Review Letters*, 92(7):076401, 2 2004.
- [5] W. Pfaff. *Quantum Measurement and Entanglement of Spin Quantum Bits in Diamond*. PhD thesis, Delft University of Technology, 2013.
- [6] L. Robledo, L. Childress, H. Bernien, B. Hensen, P.F.A. Alkemade, and R. Hanson. High-fidelity projective read-out of a solid-state spin quantum register. *Nature*, 477(7366):574–8, 9 2011.
- [7] T. H. Taminiau, J. J. T. Wagenaar, T. van der Sar, F. Jelezko, V. V. Dobrovitski, and R. Hanson. Detection and control of individual nuclear spins using a weakly coupled electron spin. *Physical Review Letters*, 109(13):137602, 9 2012.
- [8] T. H. Taminiau, J.J.T. J. T. Wagenaar, T. van der Sar, F. Jelezko, V.V. V. Dobrovitski, and R. Hanson. Detection and control of individual nuclear spins using a weakly coupled electron spin. *Physical Review Letters*, 109(13):137602, 9 2012.
- [9] T. H. TH Taminiau, J. Cramer, T. van der Sar, V. V. Dobrovitski, and R. Hanson. Universal control and error correction in multi-qubit spin registers in diamond. *Nature Nanotechnology*, 2(February):2–7, 9 2014.