

Minimising the Decoherence of Rare Earth Ion Solid State Spin Qubits

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Statement of authorship

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

Elliot Fraval
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“In the beginning the Universe was created. This made a lot of people very angry and has been widely regarded as a bad move.”

– Douglas Adams

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Abstract

This work has demonstrated that hyperfine decoherence times sufficiently long for QIP and quantum optics applications are achievable in rare earth ion centres. Prior to this work there were several QIP proposals using rare earth hyperfine states for long term coherent storage of optical interactions [1, 2, 3]. The very long T_1 ($\sim$ weeks [4]) observed for rare-earth hyperfine transitions appears promising but hyperfine T_2 s were only a few ms, comparable to rare-earth optical transitions and therefore the usefulness of such proposals was doubtful.

This work demonstrated an increase in hyperfine T_2 by a factor of $\sim 7 \times 10^4$ compared to the previously reported hyperfine T_2 for $Pr^{3+}:Y_2SiO_5$ through the application of static and dynamic magnetic field techniques. This increase in T_2 makes previous QIP proposals useful and provides the first solid state optically active Λ system with very long hyperfine T_2 for quantum optics applications.

The first technique employed the conventional wisdom of applying a small static magnetic field to minimise the superhyperfine interaction [5, 6, 7], as studied in chapter 4. This resulted in hyperfine transition T_2 an order of magnitude larger than the T_2 of optical transitions, ranging from 5 to 10 ms. The increase in T_2 was not sufficient and consequently other approaches were required.

Development of the *critical point* technique during this work was crucial to achieving further gains in T_2 . The *critical point* technique is the application of a static magnetic field such that the Zeeman shift of the hyperfine transition of interest has no first order component, thereby nulling decohering magnetic interactions to first order. This technique also represents a global minimum for back action of the Y spin bath due to a change in the Pr spin state, allowing the assumption that the Pr ion is surrounded by a thermal bath. The *critical point* technique resulted in a dramatic increase of the hyperfine transition T_2 from ~ 10 ms to 860 ms.

Satisfied that the optimal static magnetic field configuration for increasing T_2 had been achieved, dynamic magnetic field techniques, driving ei-

ther the system of interest or spin bath were investigated. These techniques are broadly classed as Dynamic Decoherence Control (DDC) in the QIP community. The first DDC technique investigated was driving the Pr ion using a CPMG or *Bang Bang* decoupling pulse sequence. This significantly extended T_2 from 0.86 s to 70 s. This decoupling strategy has been extensively discussed for correcting phase errors in quantum computers [8, 9, 10, 11, 12, 13, 14, 15], with this work being the first application to solid state systems.

Magic Angle Line Narrowing was used to investigate driving the spin bath to increase T_2 . This experiment resulted in T_2 increasing from 0.84 s to 1.12 s. Both dynamic techniques introduce a periodic condition on when QIP operation can be performed without the qubits participating in the operation accumulating phase errors relative to the qubits not involved in the operation.

Without using the *critical point* technique Dynamic Decoherence Control techniques such as the *Bang Bang* decoupling sequence and MALN are not useful due to the sensitivity of the Pr ion to magnetic field fluctuations. *Critical point* and DDC techniques are mutually beneficial since the *critical point* is most effective at removing high frequency perturbations while DDC techniques remove the low frequency perturbations. A further benefit of using the *critical point* technique is it allows changing the coupling to the spin bath without changing the spin bath dynamics. This was useful for discerning whether the limits are inherent to the DDC technique or are due to experimental limitations.

Solid state systems exhibiting long T_2 are typically very specialised systems, such as ^{29}Si dopants in an isotopically pure ^{28}Si and therefore spin free host lattice [16]. These systems rely on the purity of their environment to achieve long T_2 . Despite possessing a long T_2 , the spin system remain inherently sensitive to magnetic field fluctuations. In contrast, this work has demonstrated that decoherence times, sufficiently long to rival any solid state system [16], are achievable when the spin of interest is surrounded by a concentrated spin bath. Using the *critical point* technique results in a hyperfine state that is inherently insensitive to small magnetic field perturbations and therefore more robust for QIP applications.

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