Electron spins suppress nuclear spin fluctuations: towards quantum communication

1. Applicants

Morten Bakker MSc

References
Bachelor thesis
Heat transport measurements in spin-ladder compounds
Rijksuniversiteit Groningen, The Netherlands 2008

Internship report
Shaping microwave pulses for coherent quantum dynamics experiments on flux qubits
Massachusetts Institute of Technology, Cambridge, USA 2009

Master thesis
Electromagnetically induced transparency with electron spins bound to neutral Si donors in GaAs
Rijksuniversiteit Groningen, The Netherlands 2010

Electromagnetically induced transparency with an ensemble of donor-bound electron spins in a semiconductor
submitted to *Phys. Rev. Lett.*; available at http://arxiv.org/pdf/1007.1010

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3. Abstract

In the field of solid-state quantum information processing, localized spins in semiconductors are a promising candidate and many systems have been realized with electrons localized in quantum dots, or electrons bound to donor atoms.
In all III-V semiconductors that have suitable optical transitions, such as GaAs, the nuclei have non-zero spin. The electrons feel an effective nuclear field through the hyperfine

coupling to the surrounding nuclear spins, and the spin dephasing time is limited by fluctuations in this nuclear field.

We propose here an experimental study that is based on magnetic resonance driving of electrons bound to donor atoms. First this allows for direct probing of the nuclear magnetic field. Second, since this resonant driving can selectively polarize the nuclear field, we present a control scheme that can efficiently remove all fluctuations in the nuclear field while keeping the mean polarization at zero. This will push up the electron spin coherence time up from the nanosecond towards the millisecond time scale. We then prepare the system in a state that is in a perfect condition to perform such tasks as long-distance quantum communication.

4. Duration of the Project

The duration of the project will be four years. The project will start in 2011.

5. Personnel

5.1 Senior scientists

C. H. van der Wal	daily guidance	20%

5.2 Junior scientists and technicians

Position from this proposal	execute PhD research	100%
B. H. J. Wolfs	technical support	20%

6. Cost Estimates

6.1 Personnel positions

1 PhD student (oio)	4 years	k€ 200

6.2 Running budget

Travel and subsistence for experimental PhD student	k€ 60

6.3 Equipment

Three frequency sweeping RF generators and RF couplers (Agilent) (for the NMR driving)	k€ 40
One 40 GHz microwave source (Agilent) (for the ESR driving)	k€ 40
Two single photon counters (Perkin Elmer)	k€10
Optical components	k€ 20+
Total equipment	k€ 110

6.4 Other support

For the proposed work we will collaborate (free of financial transactions) with the group of Prof A. D. Wieck and Dr. D. Reuter at the Ruhr-Universität Bochum, Germany, for growing the Si-doped GaAs wafer material.

6.5 Budget summary (in k€)

	2011	2012	2013	2014	Total
Personnel (positions): PhD student (oio)	50	50	50	50	200
Personnel (costs):					

Running budget	15	15	15	15	60
equipment	85	5	15	5	110
Total: (requested from FOM)	150	70	80	70	370

7. Infrastructure

This project will make use of the existing clean room facilities and optical experimentation setup already present in our group. No extra infrastructure will be required.

8. Research program

8.1 Introduction

Quantum information processing is based on the mapping of quantum states of matter on the quantum states of optical fields and vice versa. An important piece of hardware for such processes is the so-called Λ-system, which consists of a ground state $|g\rangle$, a meta stable state $|s\rangle$ and a common short-lived excited state $|e\rangle$, see Fig. 1 a). The lowest two states can be used to store a quantum state, and fast optical transitions to the excited state make fast coherent preparation, manipulation and coupling between quantum states possible. For this the two lowest states of the system must have a long coherence time T_2^*.

Long-distance quantum communication protocols such as the DLCZ-scheme [Duan2001], one of the most realistic proposals for quantum information technology, rely on ensembles of Λ-systems. The first step required in the DLCZ-scheme is that all N electrons in the ensemble are prepared in the ground state. A sufficiently weak optical field is then applied that drives the $|g\rangle$ - $|e\rangle$ transition and will induce population to be transferred to the $|s\rangle$ state through radiative decay. Hereby all N Λ-system are collectively excited, so every Λ-system effectively excites ~1/N photon.
This process of probabilistic photon creation is schematically shown in Fig 1 b). It lies at the heart of creating non-local entanglement between ensembles, which is prerequisite for long-distance quantum communication.

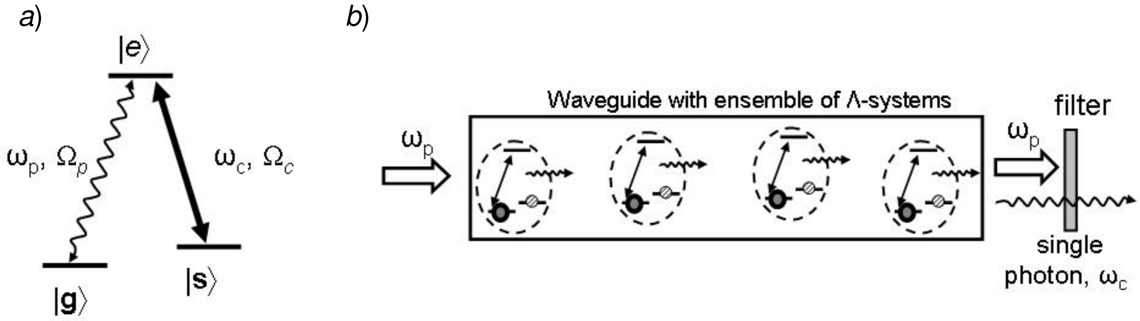

Fig. 1: a) A Λ-system, consisting of a ground state $|g\rangle$, the meta stable state $|s\rangle$ and the short-lived excited state $|e\rangle$. A probe (p) and coupling (c) optical field are applied that have frequencies ω_p and ω_c and intensities that give transition Rabi frequencies Ω_p and Ω_c.
b) An ensemble of Λ-systems in an elongated waveguide is used to create single-photons on demand. This is a prerequisite for creating non-local entanglement which lies at the heart of quantum communication. An applied optical drives the $|g\rangle$-$|e\rangle$ transitions of the N Λ-systems and every Λ-systems excites ~1/N photon per collectively emitted photon.

We realize an ensemble of Λ-systems by making use of Gallium Arsenide doped with a low concentration of Silicon (n-GaAs). The two lowest states are formed by the Zeeman split electron spin states of the electron bound to a neutral donor (D^0) and the excited state is formed by the ground state of an exciton bound to a neutral donor (D^0X).

The Bohr radius of the D^0 is about 1/15 the average distance between donor sites, so the different donor sites are well separated and show very little inhomogeneity. Such an ensemble of identical Λ-systems has good coupling between light and the system, removing the need for (technologically challenging) optical cavities.

Since the radius of the D^0 system is much larger than the lattice constant, the electron is delocalized over about $N_{\mathrm{nuc}}\sim10^5$ lattice sites. The hyperfine coupling of the electrons to the lattice atoms acts as an effective nuclear magnetic field (called the Overhauser field) which can take up values $B_{\mathrm{nuc}}=5.3$ T when all nuclei are polarized. At a temperature of 100 mK and experimentally accessible magnetic fields of $B\leq18$ T, the nuclei are all randomly polarized however such that the average effective nuclear field $B_{\mathrm{nuc}} = 0$ T. The deviation of the nuclear field scales by $\sqrt{N_{\mathrm{nuc}}}$ and is about $\Delta B_{\mathrm{nuc}} \approx 20$ mT. These fluctuations are the main limitation of the spin dephasing time $T_2^* \approx 2$ ns. If this limitation is removed T_2^* moves closer towards the theoretical limitation set by the spin-flip time $T_2^* \leq 2T_1$ of the electron spin states, which can be as high as a few ms.

However other processes, where pairs of nuclear spins flip-flop through hyperfine-mediated or dipole-dipole interactions, will still cause fluctuations in the nuclear field and limit T_2^* to a value around ~100 µs [vink2008].

8.2 Objective of the proposed research

I propose here an experimental technique that is based on the magnetic resonant driving between the two lowest spin states of localized electrons bound to donors in GaAs (n-GaAs). It has recently been demonstrated that the electron spin resonance (ESR) technique is able to efficiently polarize nuclei; thereby creating a nuclear magnetic field that acts on the donor bound electrons [kennedy2006].

Making use of this technique it is possible to probe the nuclear field. I then propose a scheme, based on the ESR technique, that can selectively drive nuclear fields $|B_{\mathrm{nuc}}| >0$ T towards $B_{\mathrm{nuc}} =0$ T. This removes the decohering effect of nuclear fields and will push up the electron spin coherence time up from the nanosecond towards the millisecond time scale.

We propose to perform these experiments with n-GaAs embedded in elongated waveguides that forms an ensemble of identical Λ-systems. After bringing the fluctuations in the nuclear field down to zero, the system is prepared in a state where all electrons occupy the ground state. This is an excellent starting point to perform long-distance quantum communication experiments [vanderwal2009].

8.3 State of the art and scientific importance of proposal

Nuclear fluctuations are at the moment the key obstacle in the field of solid-state quantum information processing that makes use of semiconductor materials. All III-V semiconductor materials, such as GaAs, that have suitable optical properties have nuclei with non-zero spin. Due to the small Zeeman splitting of nuclear spins it would require temperatures below 0.1 mK to achieve full nuclear polarization in magnetic fields $B\leq18$ T, something which is experimentally very challenging. The most promising approach is therefore to achieve nuclear polarization through the transfer of angular momentum from

electron spins to lattice nuclei, a process that is called dynamic nuclear polarization (DNP).
Recent experiments using quantum dots indicate that DNP effects, through optical driving of electron spins, tend to drive the nuclear field to a state that enhances transitions to the excited state [xu2009, latta2009]. Hereby it was shown that nuclear fluctuations are reduced and the spin coherence time increases [xu2009]. Theoretical investigation however seems to indicate that such DNP processes rely on anisotropic hyperfine interaction, which happens when hole spins are confined and mixing of heavy and light holes occurs. This does not happen in bulk GaAs and no such effects have been observed with donor-bound electrons in bulk GaAs material.

Strong DNP in n-GaAs material has however been demonstrated by driving the electron spin resonance (ESR) [kennedy2006], although no attempts have been made to use ESR to decrease the nuclear field fluctuations. Such a demonstration would be applicable not only to n-GaAs, but also to related research using GaAs quantum dots and systems in other semiconductor materials.

The proposed work overlaps with developing long-distance quantum communication in which eavesdropping is fundamentally impossible [duan2001]. Using an ensemble of identical donor sites in GaAs embedded in waveguides gives an advantage above related work using quantum dots, since these require the, technically very demanding, use of optical cavities [hennes2007], while ensembles of identical quantum dots have too much inhomogeneities [greilich2007].

8.4 Summary of recent results

Our results were recently obtained with a sample of Gallium Arsenide lightly doped with Silicon (n-GaAs), using an experimental setup to perform transmission spectroscopy at liquid Helium temperatures [sladkov2010]. Using pump assisted spectroscopy we were able to identify the Λ-system that is based on the optical transitions between the Zeeman split electron spin states of a donor bound electron (D^0) and the ground state of an exciton bound to a neutral donor (D^0X), see Fig 2. a,b).
Electromagnetically induced transparency (EIT) is the phenomenon that an otherwise opaque medium can become transparent under the application of an optical field. When two optical fields are applied which are equally detuned from the excited state, destructive quantum interference prevents population being transferred to the excited state, thereby increasing the transmission. EIT occurs in Λ-systems that posses a long coherence time and is a prerequisite for the implementation of the system in applications of quantum information processing.
By applying a control field, which is detuned from the *A* transition resonance by Δ_c, we see an EIT-peak occur when scanning a weaker probe laser along the *A** transition, see Fig. 2 c,d). We found that the spin dephasing time $T_2^* \approx 2$ ns is equal to the limitation set by the hyperfine coupling to a fluctuating nuclear field.

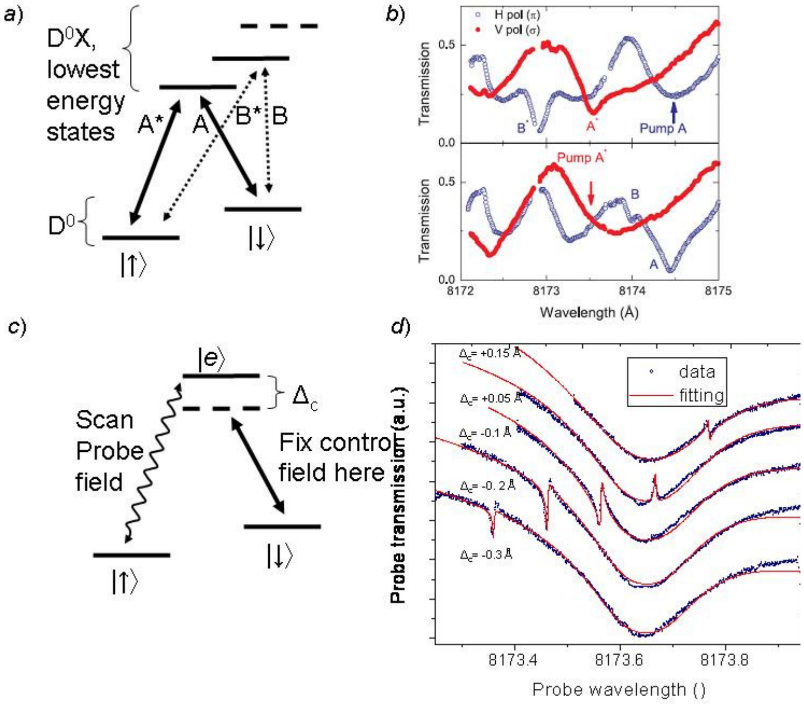

Fig. 2: a) Energy level diagram of the lowest states of the D^0 and D^0X system.
b) Pump-assisted spectroscopy: setting a fixed laser at the *A* (*A**) transition increases absorption in the second laser when it scans past *A** (*A*), a confirmation that we have the system in a).
c/d) When now a control field is applied at the A transition detuned by Δ_c, an EIT peak occurs when a second laser is scanned past the *A** transition. From the height of the EIT peak we found $T_2^* \approx 2$ ns.

We also managed to induce DNP by driving the electrons into a non-equilibrium spin population. In thermal equilibrium the population is evenly spread between the two spin states, but by fixing the pump laser on the *A** transition for ~30 minutes the population is transferred to the spin down |↓⟩ state. Afterwards the system was kept in the dark and fast EIT ‘snapshots’ were taken. A blue-shifted and sharpened EIT peak was observed, which corresponded to an increase in the magnetic field B_{nuc}=20 mT straight after pumping and an increased T_2^*=3 ns. The system then relaxed back to the equilibrium situation on a ~30 min timescale
The observed nuclear polarization is due to a phonon-assisted relaxation process of non-equilibrium electron spins while the system is pumped. Our DNP is however much less than the amount of DNP B_{nuc} = 500 mT that was reported by [kennedy2006]. During ESR driving of the system a photon-assisted process occurs that also causes DNP. This photon-assisted process is however much more efficient than the phonon-assisted process, as our results also indicates.

8.5 Proposed project

I will now discuss a proposed scheme which is based on electron spin resonance (ESR) driving of the n-GaAs system. This has been shown to be a more efficient way to drive dynamical nuclear polarization (DNP) than optical driving to the excited state alone.

First the principle behind DNP through ESR driving is discussed. Based on this technique I propose to apply a NMR assisted scheme that keeps the nuclear polarization at zero, but pumps away any nuclear fluctuations.

8.5.1 ESR driving

The Zeeman splitting E_Z between the spin up $|\uparrow\rangle$ ground state and the spin down $|\downarrow\rangle$ state is given by:

$$E_Z = g\mu_B B\,,$$

where g is the g-factor, μ_B is the Bohr magneton and B is the sum of the external (B_{ext}) and nuclear (B_{nuc}) magnetic field. When an oscillating magnetic field with frequency v is applied to the system such that E_Z=hv, where h is the Planck constant, the electron is resonantly driven between the two spin states. This is called electron spin resonance (ESR). Kennedy *et al*. [kennedy2006] showed that by driving ESR the nuclear field can be directly probed and at sufficiently high microwave powers, the nuclei can be polarized such that the nuclear field increases. This is shown in Fig. 3.

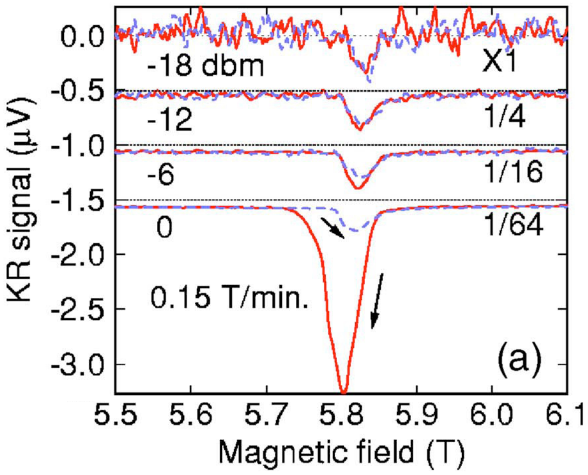

Fig. 3: Experimental results taken from [kennedy2006]. A sample of n-GaAs was used at T=1.5 K such that the population is mainly in the spin up $|\uparrow\rangle$ ground state. A microwave field was applied such that it is in resonance with the Zeeman splitting at B ~ 5.82 T (but not at higher or lower magnetic fields), thereby driving electrons to a mixed state. When the magnetic field is changed (the arrows in the figure) the increase in the population in the spin down $|\downarrow\rangle$ state is observed by a negative increase in the Kerr-rotation (KR) signal. At sufficiently high microwave powers, the nuclear polarization was observed to be such that it compensates the decreasing external field, thereby maintaining the magnetic resonance condition. No such pinning effect was seen when the magnetic field was increased, indicating the nuclear field is only increased by the ESR induced DNP effect.

8.5.2 Dynamical nuclear polarization through the ESR process

Dynamical nuclear polarization is the process that angular momentum is transferred from electron spins to nuclear spins through the hyperfine interaction. This process must conserve both angular momentum and energy. Since the energy change of the flipping of an electron is much larger than the flipping of a nuclear spin, this process requires the assistance of either a photon or a phonon. The phonon-assisted electron-nuclear flip-flop is generally weak at low temperatures due to the small amount of phonons present and the weak coupling between electrons and phonons [danon2008, khaetskii2001].

Therefore the photon-assisted process is the dominant process at T=100 mK and is the most efficient way to achieve DNP.

When ESR drives the electron spin population $\langle S \rangle$ out of thermal equilibrium $\langle S \rangle_T$, the photon-assisted electron-nuclear flip-flop process induces the average nuclear spin $\langle I \rangle$ to be:

$$\langle I \rangle = I(I+1)/S(S+1)\left(\langle S \rangle - \langle S \rangle_T\right), \tag{1}$$

where I=3/2 is the spin of the nuclei and S=1/2 is the electron spin. The effective nuclear field B_N is given by:

$$B_N = C\langle I \rangle / g\mu_B\,, \tag{2}$$

where C is the hyperfine constant. When T=100 mK and the external magnetic field is set to B_{ext}=5.5 T, the electrons fully relax to the spin up state, so $\langle S \rangle_T$ =+1/2. ESR driving causes electrons to also populate the spin down state, so the average populate changes towards $\langle S \rangle$=0. Due to the negative sign of g this causes the nuclear field B_N to become positive. The pinning of the nuclear field to the external field and thus the amount of nuclear polarization depends on the power of the ESR source and the rate with which the external magnetic field is changed. At high microwave power and a magnetic field which is slowly decreased, a nuclear polarization exceeding 0.5 T, or about 10% of the maximum nuclear polarization, was found.

8.5.3 Experimental realization

A schematic drawing of the proposed device is shown in Fig. 4. Light is coupled into an optical waveguide which is etched out of the n-GaAs wafer. Light leaving the waveguide can be coupled into a fiber and analyzed by photodetectors. The waveguide acts as an elongated medium containing an ensemble of Λ- systems and is therefore a suitable device for the DLCZ-scheme. Microwaves for the NMR and ESR driving of the system are applied to the waveguide by a coplanar microwave strip that can operate up to v =40 GHz. This strip is located in the vicinity of the waveguide in order to apply fields with a high intensity. The device can be fabricated using our existing clean room facilities and can be mounted into the existing optical setup.

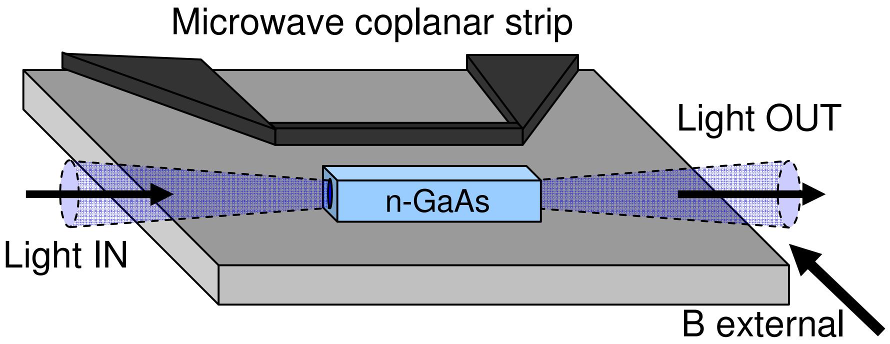

Fig 4: Schematic drawing of the experimental setup. Light is coupled into the waveguide etched out of n-GaAs. A coplanar strip in its vicinity is used for the NMR and ESR driving of the system.

8.5.4 Probing of the nuclear field

For the future experiments the system should be cooled down to 100 mK and an external magnetic field B_{ext} = 5.5 T is applied, such that the electron spin population fully relaxes to the spin up ground state of D^0. When now a microwave field is applied, with a frequency v~ 40 GHz, it is resonant with the Zeeman splitting (E_Z) of the electron spin states and population is pumped between the spin up and the spin down state. This increases the absorption of a field applied to the A transition, see Fig. 5. When the ESR driving is weak and the probe field is sufficiently strong, only a small amount of population will relax back to the ground state by the photon-assisted electron nuclear spin flip-flop process and induce a small amount of DNP. The DNP will induce an increase in E_Z, therefore by scanning the microwave source from high to low frequency at a sufficiently high rate electrons that induce DNP are ideally only excited once and so only a small amount of DNP is induced.

When the electrons are excited by the probe field they relax from the excited state back to the ground state through radiative decay, a process that does not drive any DNP. By scanning the frequency of the microwave source and measuring the change in transmission, the Zeeman splitting and the nuclear field can be directly probed.

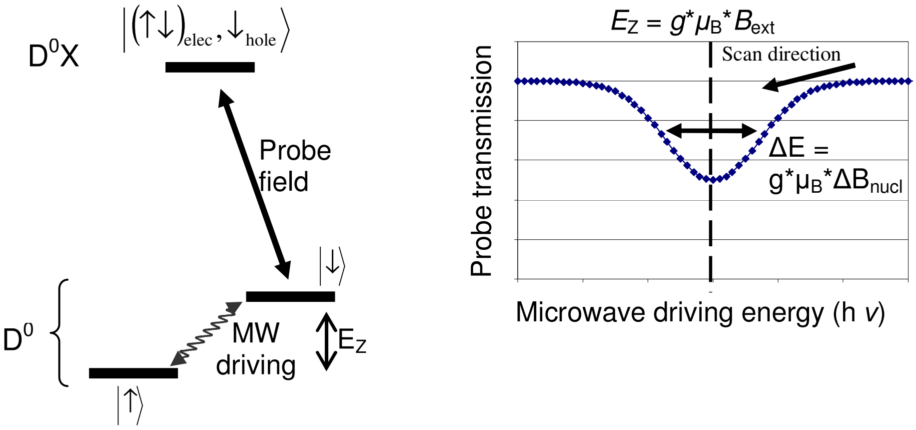

Fig 5: At low temperatures (T=100 mK), the population relaxes to the spin up ground state of D^0. When a microwave (MW) field is applied in resonance with the electron spin splitting E_Z, electrons are transferred to the spin down state. This decreases the transmission of the probe field.

8.5.5 Pumping away nuclear fluctuations

I now propose a scheme that can be used to selectively pump away fluctuations in the nuclear field, but keeps the nuclear polarization close to zero, see Fig. 6.

One starts with red-detuning the microwave source to the spin resonance (so $hv<E_Z$). Electrons at donor sites with $B_{nucl}<0$ T are now selectively addressed and through the DNP process B_{nuc} increases and is driven towards B_{nucl} = 0. The nuclear spins are then flipped over an angle of 180° by applying three NMR π-pulses, since there are three species of nuclear atoms present (^{75}As, ^{69}Ga, ^{71}Ga). Now the ESR driving is turned back on and the process is repeated. The microwave frequency is then slowly increased towards the resonance condition, but is not set to exact resonance. The fluctuation in the nuclear field ΔB_{nucl} is now strongly reduced and the microwave source is then turned off.

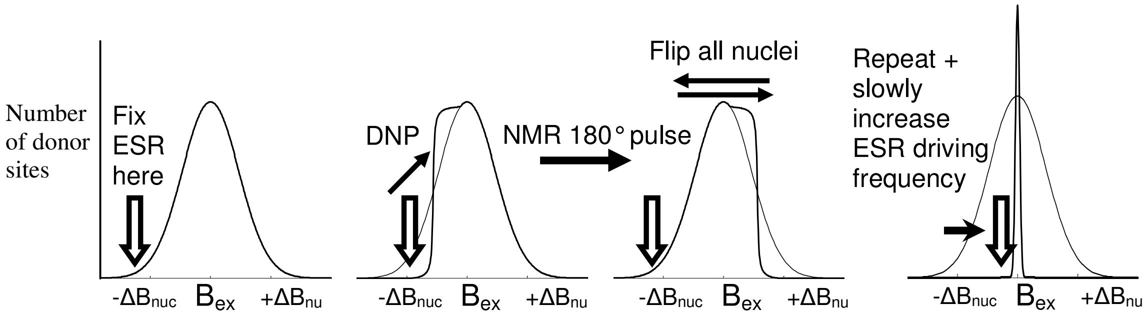

Fig 6: Scheme to reduce nuclear polarization. Selective ESR driving of electrons that are surrounded by a nuclear field $B_{\mathrm{nucl}}<0$ T cause DNP to drive B_{nucl} towards $B_{\mathrm{nucl}}=0$T. NMR pulses flip the nuclear field, and by slowly increasing the microwave frequency the nuclear fluctuations ΔB_{nucl} are removed.

Once the microwave source has been turned off, electrons which are possibly still in the spin down state will relax to the ground state. With the microwave source on this process was photon-assisted and induces nuclear polarization. Now it is turned off however, the electrons relax through an one-phonon spin-orbit relaxation process that does not involve any nuclear polarization [fu2006].

The system has now been prepared in a state where all electrons are thermally relaxed in the ground state and the nuclear fluctuations are reduced to zero. It is now ready to perform experiments related to quantum communication, such as probabilistic photon creation, see Fig. 1 b). Since these experiments require approximately only one electron at a time to be transferred from one state to another and the total amount of donor sites in the waveguide is ~10^5 or more, the DNP that these processes will (possibly) induce is negligible.

However, although it is known that a polarized nuclear field relaxes back to zero on an hour timescale [fu2007], the timescale that nuclear fluctuations start increasing again is shorter. Simulations indicate that the time it takes for the nuclear fluctuations to increase from zero to the value it has in thermal equilibrium is <0.1 the relaxation time of the polarized nuclear field. Once a nuclear state is prepared it should therefore stay stable on a second–minute timescale, something which previous work with quantum dots also demonstrates where the nuclear state was seen to persist for >10 s [reilly2008]. After a certain timescale the ESR based DNP process will have to be repeated to reduce the nuclear field again.

Other processes will however keep the nuclear fluctuations constant, but limit the coherence time [vink2008]. Nuclear-nuclear flip-flop processes occur that keep the polarization of all the nuclei constant, but can still change the polarization of the nuclei that couple to the electron. The predicted coherence time due to flip-flop processes by hyperfine coupling of the nuclear spins to the electron is estimated to be ~100 μs, but some theories predict that this process can also be reversed [Shenvi2005]. Dipole-dipole interaction between neighboring nuclei also flip-flops two nuclear spins, this process is estimated to limit the coherence time to more than ~100 μs.

For first steps towards long-distance quantum communication [duan2001] however, these coherence times are sufficient.

8.6 Planning, experimental realization and follow-up experiments

Year 1	Preparation of device, calibration of ESR and NMR driving equipment, develop technique to probe the nuclear field.
Year2	Fully mastering the nuclear polarization process by ESR driving of the system, perform key experiments on decreasing nuclear fluctuations.
Year 3	Optimize the ESR+NMR driving scheme. Investigate influence of optical driving and external field on increase of the nuclear fluctuations. Investigate how performing EIT experiments affects the nuclear polarization.
Year 4	Perform first single-photon on demand experiments. Further investigate decohering mechanisms.

9 Application perspective in industry, other disciplines or society

This proposal is clearly aimed at fundamental and exploratory research. The low temperatures and high magnetic fields that are required make applications on a short-term not feasible. Also the ~ns coherence times that can be achieved with this system at the moment are too short for any commercial applications. However, this work explores how the coherence time of electron spins can be increased. As was discussed in section 8.1, this research is directly relevant for research on solid-state implementation of the DLCZ scheme for secure quantum communication. Also the techniques that are realized will be applicable on other systems and materials that are aimed at quantum information processing.

9. References

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