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Quantum Optical Control of Donor-bound Electron Spins in GaAs

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Chapter 2

Towards quantum optics and entanglement with electron spin ensembles in semiconductors

We review a technique that enables the controlled realization of quantum entanglement between collective excitations in electron spin ensembles in two spatially separated pieces of semiconductor material. The discussion assumes electron spin ensembles bound to neutral donors in GaAs, that are located inside optical waveguides. This material system has optical transitions that obey well-defined selection rules, which allows for selectively addressing the two electron spin states. Long-lived superpositions of these electron spin states can then be controlled with a pair of optical fields that form a resonant Raman system. Entangled states of collective spin excitations are prepared by applying quantum-optical measurement techniques to optical signal pulses that result from Raman transitions in the electron ensembles.

2.1 Introduction

Entanglement is the phenomenon that the quantum states of two (or more) degrees of freedom are inseparable, and is arguably the most distinct aspect of quantum theory [1]. It results in non-classical correlations between observable physical properties of the two subsystems. For *nonlocal entanglement* this concerns two degrees of freedom that are spatially separated over a large distance. The occurrence of such correlations has been thoroughly tested in several experiments, and the results leave little doubt that quantum theory provides the valid predictions. Experimental realizations were, until now, carried out with pairs of elementary particles or photons [2, 3], or with spins in very simple quantum systems as for example trapped ions [4] or alkali atoms [5, 6]. It is nevertheless interesting to continue research on the controlled realization of nonlocal entanglement with other material systems, in particular with degrees of freedom in solid state.

In part this interest is fundamental. Whether entangled states loose their coherence in a different manner than superposition states of individual degrees of freedom is still not fully understood [7, 8]. Recent developments here include an all-optical experiment that showed that entanglement can be lost much more rapidly than the loss of coherence in the two subsystems [9]. Another interesting result from work with entangled photon pairs showed that the relation between the amount of entanglement and the degree of mixedness of a two-particle state can only be represented by a plane of possibilities. Specific points in this plane depend on the nature of the environment that is decohering the initial maximally-entangled pure state [10, 11]. Furthermore, it is still not firmly established that quantum theory does not break down when applied to collective or macroscopic degrees of freedom [12, 13]. This justifies a study of how entangled states can be realized in solid state, and how these states loose their coherence: solid state can provide model systems with complex (collective) degrees of freedom, or systems with elementary degrees of freedom in a complex environment.

Research on the controlled realization of entanglement in solid state systems is also driven by the prospect that it may provide tools for quantum information technologies. Relevant to the discussion here is a proposal for long-distance quantum communication [14], that was until now mainly explored with ensembles of alkali atoms [5, 6], or alkali-atom-like impurities in solids [15–17]. However, widespread implementation favors a technique that can be implemented in micron-scale devices that fit inside optical fibers, which are compatible with high-speed opto-electronic operation[18]. Here, the electronic and optical properties of III-V semiconductors outperform the atomic or impurity-based systems. The coherence times of degrees of freedom in these materials, however, tend to be too short for any realization of quantum information technology in the near future, but are long enough for initial experimental studies on entangled states.

We discuss here a technique that enables the controlled realization of nonlocal entanglement between collective spin excitations in ensembles of electrons bound to the neutral donors, which are located in two spatially separated pieces of GaAs semiconductor material. In Section 2.2 we review an approach where quantum-optical measurement techniques are used for preparing entangled states of spin degrees of freedom in ensembles of three-level quantum systems. Details on the GaAs material system that is suited for isolating and operating such three-level quantum systems are presented in Chapter 3.

2.2 Preparing and detecting entangled states via quantum optical measurement

We propose here to use the so-called DLCZ scheme [14] for preparing nonlocal entanglement with solid state devices. The main idea behind this approach is that spontaneous emission of a quantum optical pulse results in quantum correlations (entanglement) between the state of the optical pulse and the state of the system that emits. To illustrate this, consider a two-level system that is initially in its excited state $|\,s\rangle$. It is emitting a single photon while relaxing to its ground state $|\,g\rangle$. If we would be able to have control over this process such that it relaxes to a superposition of the states $|\,s\rangle$ and $|\,g\rangle$, the system would emit an optical pulse that is a superposition of the states with 0 and 1 photon, $|0_{pulse}\rangle$ and $|1_{pulse}\rangle$. The quantum state of the system and the optical pulse are then in fact entangled, and the only pure states that can describe the state of the combined system are of the form $|\Psi_{com}\rangle = c_0\,|\,s\rangle|0_{pulse}\rangle + c_1\,|\,g\rangle|1_{pulse}\rangle$.

Such control over spontaneous emission can be realized with a three-level Raman system (Fig. 2.1a). The states $|\,g\rangle$ and $|\,s\rangle$ are here typically the states of a spin, which both have an optical transition to a state $|\,e\rangle$. When this system is initially in the state $|\,g\rangle$, there will be only spontaneous emission of a Raman photon from the transition $|e\rangle-|\,s\rangle$ while a control field is driving the $|\,g\rangle-|e\rangle$ transition. Figure 2.1b illustrates how an extension of this scheme can be used to entangle the states of two three-level systems that are at different locations. Say Alice and Bob both have an identical version of such a three-level system prepared in the state $|\,g\rangle$. They both use a classical field to drive the $|\,g\rangle-|e\rangle$ transition, in order to get very weak spontaneous emission from the $|e\rangle-|\,s\rangle$ transition, such that each system emits an optical pulse that is a superposition of the photon-number states $|0_{pulse}\rangle$ and $|1_{pulse}\rangle$ (note that each of these pulses is then entangled with the system that emitted it). The timing and propagation of these two pulses should be controlled such that they arrive at the same time at a measurement station, that consists of a 50/50 beam splitter with a photon counter at each of its two output channels. If the number of photons in the pulses are now measured after combining the two pulses on the beam splitter, there is some probability that one of the two detectors counts 1 photon and the other 0 photons. In that case, the total number of spin flips in the two three-level systems is 1, but it is impossible to tell which of the two emitted the photon. As a result, the systems of Alice and Bob have been projected onto an entangled state of the form $|\Psi_{AB}\rangle = \frac{1}{\sqrt{2}}\left(| s_A\rangle \, | g_B\rangle + \mathrm{e}^{i\varphi} \, | g_A\rangle \, | s_B\rangle\right)$ (where the phase φ can be derived from experimental conditions [14, 19].

Figure 2.1b depicts in fact emission from ensembles of three level systems. For weak (slightly detuned) driving of the $| g\rangle - |e\rangle$ transition, the expectation value for the total number of $|e\rangle - | s\rangle$ photons emitted by an ensemble of identical three-level systems can still be less than 1 photon. Notably, the spin excitation is then not stored on an individual three-level system. Instead, it is stored as a spin-wave mode (collective spin excitation) in this medium, with each three-level system having its spin flipped only by a very small amount. Thus, one can also use this approach for preparing entanglement between spin-wave modes in two different ensembles.

These ensembles should have a long elongated shape that is co-linear with the driving field. An important advantage of using such ensembles is that spontaneous emission becomes highly directional [14], with emission predominantly co-propagating with the driving field. In principle the system will emit very weak in all directions, but an initial spontaneous emission event (extremely weak, far below the single-photon level) is strongly amplified (gain) when it co-propagates with the driving field [20]. For very weak driving, the total energy in all of the spontaneous emission can still be at the single-photon level, and the gain then ensures that emission into the desired direction is exponentially stronger than into other directions. Thus, the collection efficiency for the total number of emitted photons by such ensembles can be near unity. This removes the need for using high-finesse optical cavities as in cavity-QED experiments, which is technically very demanding [21, 22].

One should also be able to confirm that entangled states have been prepared by reading out the states of each ensemble of a pair that has been entangled. Correlations between the spin excitations in the two ensembles (Fig. 2.1b) can be studied with an optical readout scheme that uses the inverse of the initial Raman transition. For each system separately, the number of flipped spins in its ensemble can be measured using a control field that is now driving the $| s\rangle - |e\rangle$ transition. This converts the spin state that is stored in an ensemble into the state of an highly-

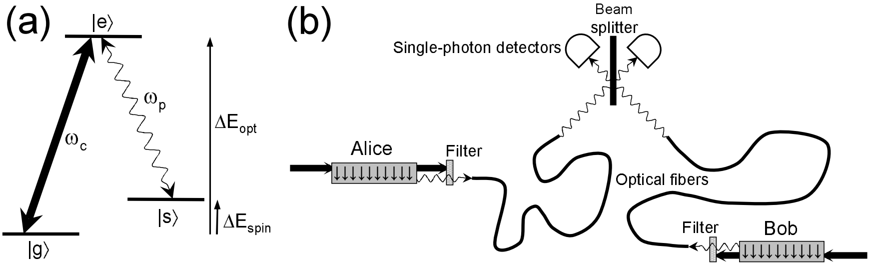

Figure 2.1: **a)** A three-level system with $\Delta E_{spin} << \Delta E_{opt}$. The transition between two low-energy spin states $|\, g\rangle$ and $|\, s\rangle$ under spontaneous emission of a signal photon from the transition $|e\rangle - |\, s\rangle$ (with energy $\hbar\omega_s$) can be controlled with an optical field (tuned to photon energy $\hbar\omega_c$) driving the transition $|\, g\rangle - |e\rangle$. The two legs can be selectively addressed using the optical frequency difference or their dependence on the polarization of the fields. **b)** Scheme for entangling the states of collective spin excitation modes in two different spin ensembles, see the text for details.

directional optical pulse (again a superposition of photon-number states $|0_{pulse}\rangle$ and $|1_{pulse}\rangle$) that results from a subsequent $|e\rangle - |\, g\rangle$ transition. This process fully returns the spin excitation into the $|\, g\rangle$ state. The detection should now directly count the number of photons in the emission from the ensemble that is measured (not using a configuration with a beam splitter). Each of the two ensembles should be measured separately in this manner. If the two ensembles were prepared in a state of the form $|\Psi_{AB}\rangle = \frac{1}{\sqrt{2}}\left(|\, s_A\rangle\, |\, g_B\rangle + e^{i\varphi}\, |\, g_A\rangle\, |\, s_B\rangle\right)$, the number of detected photons from the ensemble of Alice can be 0 or 1, each with probability $\frac{1}{2}$. However, for either measurement outcome, subsequent measurement of the number of photons emitted by Bob's ensemble must yield that it is perfectly anti-correlated with the result of Alice.

Such measurements can already provide evidence for the quantum nature of these correlations (in particular, the variance of these photon-count correlations should show strong sub-Poissonian statistics [20]). However, it does not yet allow for a formal test of Bell inequalities (testing for non-classical correlations), since this requires the ability to rotate the basis in which the state of each of the two-level systems is measured (with respect to the basis defined by $|0_{pulse}\rangle$ and $|1_{pulse}\rangle$). This cannot be performed directly with a readout technique based on photon-number measurements. To overcome this, the observation of entanglement between two ensembles of alkali atoms [5] used an approach where a local phase shift was applied to one of the two systems, either to the optical signal pulse from readout [5] or to the stored spin excitation. However, the readout then requires once more to combine the signal pulses from readout of the two ensembles on a beam splitter, and to study the interference fringe that results from the local phase shift. A scheme that only relies on local readout of each ensemble can be realized when the states of both Alice and Bob are not stored in a single ensemble but in a pair of ensembles [14]. The photon-number readout can then be implemented with a certain setting for a phase difference between the states of these two ensembles. However, both of these approaches require that the path length between the ensembles and detector stations are stabilized with interferometric precision. An alternative more robust approach could be realized with alkali atom ensembles [6] and used the fact that in these systems the states $|g\rangle$ and $|s\rangle$ consist of multiple (degenerate) Zeeman sublevels. How a spin excitation is distributed over these Zeeman sublevels is then mapped onto two orthogonal polarizations of a signal field, and polarization selective readout then enables to rotate the basis in which signal fields are measured. Other solutions that are technically even less demanding are currently investigated [23–26].

Applying this quantum-optical measurement scheme for preparing entangled states in spatially separated electronic devices is an interesting alternative to related research that uses electronic control and measurement techniques. Activities here use for example electron spins in quantum Hall states [27] or quantum dots [28], or superconducting qubits [29]. A first advantage of this quantum optical approach is that it naturally allows for having the two devices separated by a large distance, whereas for electronic control coherent interactions are typically limited to short distances. More importantly, it allows one to use photon-number detection. This is a unique quantum measurement tool in the sense that projective measurement can be used for preparing states with very high fidelity. Tools for electronic readout have typically much higher noise levels, which results in a much weaker correlation between a measurement outcome and the state of the quantum system immediately after measurement.

2.3 Conclusions

The reasonably long coherence times for electron spin ensembles in n-doped GaAs materials allows for studies of how such ensembles can act as a medium for quantum optics. In turn, this allows for preparing entanglement between states of spin wave modes in two different ensembles. For initial studies, a low-doped n-GaAs system provides one of the most promising model systems. The electron ensembles are then addressed by placing the n-GaAs epi-layers inside optical waveguides, with in-plane propagation of optical control and signal fields. Realizing such systems is compatible with standard epitaxial growth techniques for GaAs/$Al_xGa_{1-x}As$ heterostructures. In the following chapters we analyze that an optimal system is formed in n-GaAs with Si doping at 10^{14} cm^{-3}, since this gives access to studies in a medium with optical density $OD = 1$. In this system one can address electron spin degrees of freedom inside ensembles of three-level quantum systems with optical transitions that correspond to the excitation of donor-bound excitons D^0X, from the Zeeman-split spin states of donor-bound electrons D^0. Selective control over these two transitions is possible with polarization selection rules that naturally occur in this system. In addition, these transitions have very narrow lines and this allows for using spectral selectivity as well.

Progress towards the realization of entanglement with such a system first requires spectroscopy to confirm the optical selection rules. A crucial next step is then to demonstrate electromagnetically induced transparency (EIT) [30], as this provides evidence that a medium is suited for the quantum optical techniques that we discussed here. If these steps are successful, this clean material system is a very promising candidate for studies of entanglement with ensembles of electron spins in solid state. In particular, the observed long spin coherence times for electron spin ensembles imply that the Zeeman splittings are very homogeneous in these ensembles. This allows to generate Raman scattered fields from two different ensembles that are centered at identical optical frequencies, while their spectral width is tuned by the EIT bandwidth [30]. Consequently, the two signal pulses then have very good spectral overlap, and preparing entanglement by interfering these two pulses on a beam splitter should indeed be possible.

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References

[1] M. A. Nielsen and I. L. Chuang, *Quantum computation and quantum information* (Cambridge University Press, Cambridge UK, 2000).

[2] A. Aspect, J. Dalibard, and G. Roger, *Experimental test of Bell's inequalities using time-varying analyzers*, Physical Review Letters **49**, 1804 (1982).

[3] W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, *Violation of Bell Inequalities by Photons More Than 10 km Apart*, Physical Review Letters **81**, 3563 (1998), ISSN 0031-9007.

[4] M. Rowe, D. Kielpinski, V. Meyer, C. Sackett, W. Itano, C. Monroe, and D. Wineland, *Experimental violation of a Bell's inequality with efficient detection*, Nature **409**, 791 (2001).

[5] C. W. Chou, H. de Riedmatten, D. Felinto, S. V. Polyakov, S. J. van Enk, and H. J. Kimble, *Measurement-induced entanglement for excitation stored in remote atomic ensembles.*, Nature **438**, 828 (2005), ISSN 1476-4687.

[6] D. N. Matsukevich, T. Chanelière, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, and A. Kuzmich, *Entanglement of Remote Atomic Qubits*, Physical Review Letters **96**, 030405 (2006), ISSN 0031-9007.

[7] T. Yu and J. H. Eberly, *Finite-Time Disentanglement Via Spontaneous Emission*, Physical Review Letters **93**, 140404 (2004), ISSN 0031-9007.

[8] P. Dodd and J. Halliwell, *Disentanglement and decoherence by open system dynamics*, Physical Review A **69**, 052105 (2004), ISSN 1050-2947.

[9] M. P. Almeida, F. de Melo, M. Hor-Meyll, A. Salles, S. P. Walborn, P. H. S. Ribeiro, and L. Davidovich, *Environment-induced sudden death of entanglement.*, Science (New York, N.Y.) **316**, 579 (2007), ISSN 1095-9203.

[10] G. Puentes, A. Aiello, D. Voigt, and J. Woerdman, *Entangled mixed-state generation by twin-photon scattering*, Physical Review A **75**, 032319 (2007), ISSN 1050-2947.

[11] A. Aiello, G. Puentes, D. Voigt, and J. Woerdman, *Maximally entangled mixed-state generation via local operations*, Physical Review A **75**, 062118 (2007), ISSN 1050-2947.

[12] A. Leggett and A. Garg, *Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks?*, Physical Review Letters **54**, 857 (1985).

[13] A. J. Leggett and A. Shimony, *Quantum measurement: Beyond paradox* (University of Minnesota Press, Minneapolis, 1998).

[14] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, *Long-distance quantum communication with atomic ensembles and linear optics.*, Nature **414**, 413 (2001), ISSN 0028-0836.

[15] J. J. Longdell, E. Fraval, M. J. Sellars, and N. B. Manson, *Stopped Light with Storage Times Greater than One Second Using Electromagnetically Induced Transparency in a Solid*, Physical Review Letters **95**, 063601 (2005), ISSN 0031-9007.

[16] L. Rippe, M. Nilsson, S. Kröll, R. Klieber, and D. Suter, *Experimental demonstration of efficient and selective population transfer and qubit distillation in a rare-earth-metal-ion-doped crystal*, Physical Review A **71**, 062328 (2005), ISSN 1050-2947.

[17] M. V. G. Dutt, L. Childress, L. Jiang, E. Togan, J. Maze, F. Jelezko, A. S. Zibrov, P. R. Hemmer, and M. D. Lukin, *Quantum register based on individual electronic and nuclear spin qubits in diamond.*, Science (New York, N.Y.) **316**, 1312 (2007), ISSN 1095-9203.

[18] M. D. Lukin and A. Imamoglu, *Controlling photons using electromagnetically induced transparency.*, Nature **413**, 273 (2001), ISSN 0028-0836.

[19] C. Cabrillo, J. Cirac, P. García-Fernández, and P. Zoller, *Creation of entangled states of distant atoms by interference*, Physical Review A **59**, 1025 (1999), ISSN 1050-2947.

[20] C. H. van der Wal, M. D. Eisaman, A. André, R. L. Walsworth, D. F. Phillips, A. S. Zibrov, and M. D. Lukin, *Atomic memory for correlated photon states.*, Science (New York, N.Y.) **301**, 196 (2003), ISSN 1095-9203.

[21] J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich, and H. J. Kimble, *Deterministic generation of single photons from one atom trapped in a cavity.*, Science (New York, N.Y.) **303**, 1992 (2004), ISSN 1095-9203.

[22] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatüre, S. Gulde, S. Fält, E. L. Hu, and A. Imamoglu, *Quantum nature of a strongly coupled single quantum dot-cavity system.*, Nature **445**, 896 (2007), ISSN 1476-4687.

[23] S.-Y. Lan, S. Jenkins, T. Chanelière, D. Matsukevich, C. Campbell, R. Zhao, T. Kennedy, and a. Kuzmich, *Dual-Species Matter Qubit Entangled with Light*, Physical Review Letters **98**, 123602 (2007), ISSN 0031-9007.

[24] B. Zhao, Z.-B. Chen, Y.-A. Chen, J. Schmiedmayer, and J.-W. Pan, *Robust Creation of Entanglement between Remote Memory Qubits*, Physical Review Letters **98**, 240502 (2007), ISSN 0031-9007.

[25] L. Jiang, J. Taylor, and M. Lukin, *Fast and robust approach to long-distance quantum communication with atomic ensembles*, Physical Review A **76**, 012301 (2007), ISSN 1050-2947.

[26] S. Chen, Y.-A. Chen, B. Zhao, Z.-S. Yuan, J. Schmiedmayer, and J.-W. Pan, *Demonstration of a Stable Atom-Photon Entanglement Source for Quantum Repeaters*, Physical Review Letters **99**, 180505 (2007), ISSN 0031-9007.

[27] C. Beenakker, C. Emary, M. Kindermann, and J. van Velsen, *Proposal for Production and Detection of Entangled Electron-Hole Pairs in a Degenerate Electron Gas*, Physical Review Letters **91**, 147901 (2003), ISSN 0031-9007.

[28] J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird, A. Yacoby, M. D. Lukin, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *Coherent manipulation of coupled electron spins in semiconductor quantum dots.*, Science (New York, N.Y.) **309**, 2180 (2005), ISSN 1095-9203.

[29] J. H. Plantenberg, P. C. de Groot, C. J. P. M. Harmans, and J. E. Mooij, *Demonstration of controlled-NOT quantum gates on a pair of superconducting quantum bits.*, Nature **447**, 836 (2007), ISSN 1476-4687.

[30] M. Fleischhauer, A. Imamoglu, and J. Marangos, *Electromagnetically induced transparency: Optics in coherent media*, Reviews of Modern Physics **77**, 633 (2005), ISSN 0034-6861.