Quantum Computation and Communication using Electron Spins in Quantum Dots and Wires

Inauguraldissertation
zur
Erlangung der Würde eines Doktors der Philosophie

vorgelegt der
Philosophisch-Naturwissenschaftlichen Fakultät
der Universität Basel

von
Guido Burkard
aus Schenkon LU

Basel, 2001

Genehmigt von der Philosophisch-Naturwissenschaftlichen Fakultät
auf Antrag von

Prof. Dr. Daniel Loss
Dr. David P. DiVincenzo

Basel, den 10. April 2001

Prof. Dr. Andreas D. Zuberbühler
Dekan

Abstract

The recent discovery of efficient quantum algorithms for factoring and database search has shown that quantum computing would allow to solve important problems which are intractable with conventional computers. In contrast to the very demanding task of building a large-scale quantum computer, there are quantum communication protocols, e.g. quantum key distribution for cryptography, which—though still difficult—require much less effort and can be implemented with current technology. Apart from the technological motivation, the study of quantum information offers (at least) two additional benefits. First, new insight into fundamental questions on quantum mechanics, e.g. concerning non-locality and entanglement, are gained from an information-theoretical approach. And second, investigating a particular physical implementation of quantum information can give rise to independent physical results. Spintronics, the use of spin as opposed to charge in (classical) electronics is a new field for which some results presented here could be relevant.

In this dissertation we investigate several theoretical aspects of the physical implementation of quantum computation and communication in which the fundamental unit of quantum information, the qubit, is represented by the spin of electrons in semiconductor quantum dots. The required coupling between the spins can be obtained by allowing for tunneling of electrons between adjacent dots, leading to a Heisenberg exchange coupling $J\,\mathbf{S}_1 \cdot \mathbf{S}_2$ between the spins, a scenario which we study for laterally coupled quantum dots in a two-dimensional electron system, and for a three-dimensional setup with vertically coupled quantum dots. Furthermore, an alternative scheme to couple the spins via the interaction with an optical cavity mode is presented.

Quantum error correction represents one of the important ingredients for the physical implementation of a quantum computer by protecting it from the effects of a noisy environment. As a first test for error-correction in a solid-state device using spins, we propose an optimized implementation of the most primitive error correction scheme (the three-bit code). In this context, we introduce parallel switching, allowing to operate a quantum computer more efficiently than the usual serial switching.

Coupling spins with the exchange interaction $J\,\mathbf{S}_1\cdot\mathbf{S}_2$ is not sufficient for quantum computation; the spins also have to be addressed individually using controllable local magnetic fields or g-factors $g_i\mathbf{B}_i\cdot\mathbf{S}_i$ in order to allow for single-qubit operations. On the one hand, we discuss several schemes for overcoming the difficulty of applying local magnetic fields (requiring large gradients), e.g. g-factor engineering, which allows for all-electric operation of the device. On the other hand, we show that at the expense of additional devices (spins) and switching operations, single-spin rotations can be dispensed with completely.

Addressing the feasibility of quantum communication with entangled electrons in mesoscopic wires, i.e. interacting many-body environments, we propose an interference experiment using a scattering set-up with an entangler and a beam splitter. The current noise for electronic singlet states turns out to be enhanced (bunching), while it is reduced for triplets (antibunching). Due to interactions, the fidelity of the entangled singlet and triplet states is reduced by z_F^4 in a conductor described by Fermi liquid theory, z_F being the quasiparticle weight factor.

Finally, we study the related but more general problem of the noise of the cotunneling current through one or several tunnel-coupled quantum dots in the Coulomb blockade regime. The various regimes of weak and strong, elastic and inelastic cotunneling are analyzed for quantum-dot systems (QDS) with few-level, nearly-degenerate, and continuous electronic spectra. In contrast to sequential tunneling, the noise in inelastic cotunneling can be super-Poissonian. In order to investigate strong cotunneling we develop a microscopic theory of cotunneling based on the density-operator formalism and using the projection operator technique. We have derived the master equation for the QDS and the current and noise in cotunneling in terms of the stationary state of the QDS. These results are then applied to QDS with a nearly degenerate and continuous spectrum.

Zusammenfassung

Die Entdeckung von effizienten Quantenalgorithmen für die Faktorisierung und für das Suchen in Datenbanken vor wenigen Jahren hat gezeigt, dass Quantum Computing die Lösung von Problemen erlauben würde, die mit konventionellen Computern praktisch unlösbar sind. Die Herstellung eines Quantencomputers genügender Grösse, um diese Vorteile nutzen zu können, ist technisch sehr anspruchsvoll. Im Gegensatz dazu existieren Anwendungen in der Quantenkommunikation, z.B. Quantum Key Distribution, die mit kleinerem technischem Aufwand realisiert werden können. Neben den Anwendungen gibt es (mindestens) zwei weitere Anreize für das Studium der Quanteninformatik. Erstens können damit neue Einsichten in fundamentale Fragen zur Quantenmechanik, z.B. bezüglich Nicht-Lokalität und Verschränkung (entanglement), gewonnen werden. Zweitens kann die Untersuchung einer Implementierung der Quanteninformatik Anlass zu unabhängigen physikalischen Resultaten geben. Die Verwendung des Spins anstelle der Ladungsfreiheitsgrade in der (klassischen) Elektronik (spintronics) ist ein neues Forschungsgebiet, für welches einige der hier präsentierten Resultate relevant sein könnten.

In dieser Dissertation untersuchen wir theoretische Aspekte der Implementierung von Quantum Computing und Communication, bei der die kleinste Informationseinheit, das Qubit, durch den Elektronenspin in einem Quantendot dargestellt wird. Die nötige Kopplung zwischen den Spins wird erreicht durch das Tunneln von Elektronen zwischen zwei benachbarten Dots, das zu einer Heisenberg Austauschwechselwirkung $J\,\mathbf{S}_1\cdot\mathbf{S}_2$ zwischen den Spins führt. Wir studieren diesen Mechanismus für lateral gekoppelte Dots in einem zweidimensionalen Elektronensystem, sowie für vertikal gekoppelte Dots in drei Dimensionen. Ausserdem diskutieren wir die indirekte Kopplung von Spins über die Wech-

selwirkung mit einer optischen Kavität.

Weil es die Quanten-Fehlerkorrektur erlaubt, einen Quantencomputer von störenden äusseren Einwirkungen zu schützen, ist sie eine wichtige Komponente bei dessen physikalischer Implementierung. Wir schlagen als ersten Test für die Fehlerkorrektur in einem Festkörpersystem mit Spins eine optimierte Realisierung des einfachsten Codes für die Fehlerkorrektur mit drei Code-Qubits vor. In diesem Kontext führen wir das parallele Schalten ein, das es erlaubt, einen Quantencomputer effizienter zu betreiben als das gewöhnliche serielle Schalten.

Die Austauschkopplung von Spins untereinander reicht nicht aus für einen Quantencomputer; die Spins müssen auch einzeln mit lokalen Magnetfeldern oder g-Faktoren $g_i\mathbf{B}_i \cdot \mathbf{S}_i$ adressierbar sein. Wir zeigen einerseits, wie dies ohne (schwer realisierbare) lokale Magnetfelder möglich ist, z.B. mit einem ortsabhängigen g-Faktor, welcher die Operation nur mit elektrischen Gates erlaubt. Andererseits zeigen wir, dass es durch den Aufwand eines Vielfachen an Spins und Schaltoperationen möglich ist, auf die Adressierung einzelner Spins vollständig zu verzichten.

Sind verschränkte Elektronen in mesoskopischen Drähten, also in wechselwirkenden Mehrteilchensystemen, geeignet für Quantenkommunikation? Zur teilweisen Beantwortung dieser Frage schlagen wir ein Streuexperiment mit einem Verschränker (entangler) und einem Strahlteiler vor. Wir finden, dass das Stromrauschen für Elektronen im Singulettzustand erhöht ist (bunching), während es im Triplett unterdrückt ist (antibunching). Durch die Wechselwirkung in einer Fermiflüssigkeit wird die Güte (fidelity) der verschränkten Singulett- und Tripplettzustände um einen Faktor z_F^4 reduziert (z_F ist das Quasiteilchengewicht).

Schliesslich studieren wir das allgemeine Problem des Rauschens im Cotunnelstrom durch ein System von Quantendots (QDS) im Coulomb-Blockade Regime. Schwaches und starkes, elastisches und inelastisches Cotunneling werden für QDS mit diskretem, fast entartetem, und kontinuierlichem Spektrum analysiert. Im Gegensatz zum sequentiellen Tunneln kann das Rauschen beim inelastischen Cotunneln dasjenige eines Poisson-Prozesses übersteigen. Zur Untersuchung des starken Cotunneln entwickeln wir eine mikroskopische Theorie, die auf dem Dichteoperatorformalismus und der Projektortechnik aufbaut. Wir leiten die Mastergleichung für das QDS her, drücken Strom und Rauschen durch den stationären Zustand aus, und wenden die Resultate auf ein QDS mit fast entartetem und kontinuierlichem Spektrum an.

Acknowledgments

It is a great pleasure to thank my thesis advisor Prof. Daniel Loss for his support and good advice during my time as a graduate student. I have enjoyed working on interesting and timely problems in an exciting field under his invaluable scientific guidance, and I'm grateful for the innumerable hours he spent explaining physics to me!

I have also enjoyed the collaboration with Dr. David DiVincenzo and I thank him for his support, for many discussions, and for answering questions on both solid-state physics and quantum information theory.

Our research group in Basel has always been a very good environment for doing physics, and I'd like to thank in particular my (former and present) office mates Dr. Jordan Kyriakidis, Dr. Eugene Sukhorukov, Hans-Andreas Engel, and Dr. Alexander Khaetskii for their help and for many discussions on physics which were both instructive and fun, but also on many other topics (which were also instructive and fun!). I'd also like to acknowledge my colleagues Prof. Christoph Bruder, Veronica Cerletti, Dr. Alain Chiolero, Dr. Mahn-Soo Choi, Hanno Gassmann, Vitaly Golovach, Michael Leuenberger, Florian Marquardt, Florian Meier, Dr. Bruce Normand, and Patrik Recher. It was also a great pleasure to work with our (former) diploma students Georg Seelig and Oliver Gywat.

Besides the constant flow of ideas and many contributions of my supervisor Prof. Daniel Loss, I would like to acknowledge the contributions to this thesis due to my collaborators Prof. David Awschalom, Dave Bacon, Dr. David DiVincenzo, Prof. Ataç Imamoḡlu, Julia Kempe, Georg Seelig, Prof. Mark Sherwin, Alexander Small, Dr. John Smolin, Dr. Eugene Sukhorukov, and Prof. Birgitta Whaley.

Finally, I would like to thank Barbara Krismer for her love and for her support during my time as a graduate student.

Contents

Chapter 1

Introduction

1.1 The physics of information

Storing and processing information can only be done with the use of suitable physical systems, e.g. magnetic discs or tapes, electronic circuits, pencil on paper, the human brain, etc. Landauer's principle, saying that erasing one bit of information dissipates the energy $k_B T \ln 2$, is an example of the fundamental importance of physical considerations when dealing with information. Whereas for today's computers this tiny amount of energy is irrelevant, Landauer's principle may obtain some practical value in the future when the ongoing downsizing of electronic devices reaches the atomic scale. As shown by Bennett, any computation can in principle be done reversibly by carefully avoiding the erasure of information, thus producing an arbitrarily small amount of heat [1].

The recent discovery of Shor's quantum algorithm for efficiently factoring large numbers [2, 3] clearly demonstrates that the choice of the underlying physical representation—in this case between classical and quantum—can determine not only the energy, but also the time consumption of a computation. For the factoring problem, the difference between the classical and the quantum representations is essential; it appears that the problem is intractable for a classical computer[1] while—as Shor proved—it would be efficiently solvable with a quantum computer.

[1] The fact that no classical algorithm for factoring large integers is known is the basis of the widely used RSA scheme for public key cryptography.

$t(n) \propto$	classical	quantum
factoring	$\exp\left[c\, n^{1/3}(\ln n)^{2/3}\right]$ (number field sieve)	$n^2(\ln n)(\ln\ln n)$ (Shor)
database search	n (linear search)	$\sqrt{n}$ (Grover)

Table 1.1: Comparison between the scaling of the time consumption $t(n)$ for the best known classical and quantum algorithms as a function of the size of the input n. For the factoring problem, $n = \log_2 N$ where N is the number to be factorized, and c is a numerical constant of order 1. For database search, n is proportional to the number of entries of the database.

By efficiency we mean that the required computational resources (time t, or memory) scale polynomially with the size n of the problem (input data). The classical and quantum complexities of factoring and database search are compared in Table 1.1. Shor's factoring algorithm and the algorithm for searching unsorted databases found by Grover [4] provide the main motivation for studying possible physical representations of quantum information, such as electron spins in quantum dots [5] and wires, with which we shall be concerned in this dissertation.

1.2 Quantum computation

A quantum computer coherently processes quantum states. Its memory is therefore a quantum system, which is usually thought of as a collection of quantum two-level systems, named quantum bits, or qubits. In contrast to a classical bit (a classical two-state system) which can take the two values 0 and 1, a qubit can exist in any linear superposition[2] of the basis states $|0\rangle$ and $|1\rangle$,

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{1.1}$$

where α and β are complex numbers which satisfy the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. A spin 1/2 system (say, the spin of an electron) is a very natural example for a qubit; we can identify the spin up and down states with respect to an arbitrary quantization axis with the

[2] In general, a qubit can also be in a mixed state, described by a density matrix ρ.

logical basis, i.e. $|\uparrow\rangle \equiv |0\rangle$ and $|\downarrow\rangle \equiv |1\rangle$. When several, say n, qubits are combined, then the resulting quantum register (memory) has the possibility to be in an arbitrary superposition

$$\sum_{x=0}^{2^n-1} \alpha_x |x\rangle, \tag{1.2}$$

where $|x\rangle$ is the product basis vector defined by the binary representation of x, e.g. $|6\rangle = |110\rangle = |1\rangle|1\rangle|0\rangle$. Roughly, a quantum computation works as follows.

- Initially, some product state $|x\rangle$ is prepared (e.g. $x = 0$, by maximally polarizing all spins).

- Then, the actual quantum algorithm is performed. Any time evolution of the (closed) quantum system consisting of n qubits—including the quantum algorithm which is to be performed—can be described by a unitary $2^n \times 2^n$ matrix. It has been demonstrated [6] that any unitary operation on n qubits can be represented as a series of elementary local operations acting on one or two (adjacent) qubits only. During this period, the quantum register will usually be in non-trivial quantum superpositions, and has therefore to stay phase coherent.

- At the end of the computation, the final state of the quantum register is measured by measuring each qubit one-by-one, i.e. each qubit is projected in the basis $|0\rangle$, $|1\rangle$. Thus, the outcome of the quantum computation consists of n *classical* bits.

For a thorough introduction into quantum information theory and quantum computation, we refer the reader to Preskill's lecture notes [7].

The reason why there are no large-scale quantum computers at work yet is that it is hard to find a suitable physical implementation of qubits, because the requirements [8, 9] for such an implementation are extremely demanding. Quantum phase coherence needs to be maintained over a long time compared to the length of an elementary step in the computation, in order to allow for quantum error correction [10, 11, 12, 13, 14, 15, 16, 17]. As a further requirement, it has to be possible to couple pairs of qubits in a controlled manner in order to carry out elementary quantum logic. Moreover, operations on single qubits need to be implemented, and at the end of a computation, the qubits have to be read out by performing a quantum measurement. Finally, the design of the quantum computer should be scalable[3] to a large number of qubits.

1.3 Coherence

Phase coherence is one of the vital ingredients for quantum computation. Decoherence (loss of coherence) happens because every quantum system, including the memory of a quantum computer, is coupled to external degrees of freedom. In order to describe the decoherence of a single qubit, it it convenient to first rewrite its initially pure state Eq. (1.1) in terms of the density matrix

$$\rho = |\psi\rangle\langle\psi| = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}. \tag{1.3}$$

In the case of a single qubit (i.e. a spin 1/2) one commonly describes decoherence by two times[4]: T_1 describes how fast the spin is depolarized, while T_2 is the characteristic time after which the phase information is lost. For the systems we are interested in, $T_2 < T_1$, therefore the decoherence time T_2 is the more restrictive and thus more important quantity for quantum information storage and processing. We can describe the process of decoherence for a single qubit roughly as follows. After a time of order T_2, the off-diagonal matrix elements of Eq. (1.3) will have decayed, leaving us with a incoherent mixture $\rho = |\alpha|^2|0\rangle\langle 0| + |\beta|^2|1\rangle\langle 1|$. Then, after time T_1 the diagonal elements go to thermal equilibrium $\rho = \frac{1}{Z}e^{-\beta H}$, where $\beta = 1/k_BT$ and H is the Hamiltonian of the qubit. If there is no splitting, $H \ll k_BT$, then this state is completely mixed, $\rho = \frac{1}{2}1$, where 1 denotes the unity matrix.

[3] Scalability means that there is a method (e.g. photolithography) which allows to increase the number of fundamental units of a device (e.g. the number of transistors on a chip) once it is known how a single unit can be fabricated.

[4] This description is incomplete. Under the assumption that the environment is memoryless (Markovian approximation), it takes 12 independent numbers to completely describe decoherence.

1.4 Existing proposals and implementations

There is a growing number of proposals for implementing quantum computation in various physical systems (for a more comprehensive review, see e.g. Ref. [18]). A few of them have already been demonstrated in small-scale (but nevertheless very interesting) experiments:

- The theoretical proposal for using the internal degrees of freedom of cold trapped ions as qubits and coupling them via their motional degrees of freedom (phonons) [19] was quickly followed by its implementation [20] at the level of a single quantum gate.

- Quantum gate operation with atoms in optical cavities [21] — using photons instead of phonons — was also shown in experiment [22].

- Quantum gate operation and small-scale quantum algorithms involving up to seven qubits have been performed using liquid-state nuclear magnetic resonance (NMR) [23, 24, 25, 26], where the qubits are encoded in specific nuclear spins of a molecule. In NMR, gate operations and measurements are performed on a macroscopic ensemble of this molecule, typically at room temperature. The operation at high temperature using so-called pseudo pure states implies that the state at every step of the computation can be described classically, a fact which has led to debates whether the NMR experiments are real quantum computation at all [27, 28].

Besides the solid-state proposals which we discuss separately in the following section, we mention that there are further proposals for quantum computing, including neutral atoms in optical lattices [29] and electrons floating on liquid helium [30].

1.5 Why solid-state quantum computation?

The scalability (see footnote 3) of conventional electronic solid-state devices suggests that solid-state realizations of quantum computation have the potential for being scalable to large numbers of qubits which contrasts with the known limitations of existing small-scale implementations. In this dissertation, we will concentrate on a theoretical proposal to use coupled semiconductor quantum dots in which the spin of the excess electron on each dot represents a qubit [5]. Apart from electron spins in quantum dots, a number of other solid-state systems have been proposed for quantum computation: nuclear spins of donor atoms in silicon [31], ESR transistors in SiGe heterostructures [32], electrons trapped by surface acoustic waves [33], charge degrees of freedom in quantum dots [34, 35, 36, 37, 38]; charge states [39, 40] or flux states [41] in coupled Josephson junctions, and d-wave Josephson junctions [42].

1.6 The spintronics proposal for quantum computation

We will now focus on using the spin of electrons in quantum dots for quantum computation, as suggested by Loss and DiVincenzo [5]. The spin of electrons in a semiconductor has several properties which make it a good candidate for a qubit:

- *Long decoherence time.* Recently, the decoherence time T_2^* of an ensemble of spins in a semiconductor (GaAs) was measured using time-resolved Faraday rotation [43, 44, 45]. It turns out that at zero field and $T = 5\,K$, the transverse spin lifetime (decoherence time) T_2^* can exceed 100 ns. This lifetime is much longer than typical decoherence times associated with the charge (or orbital) degrees of freedom of electrons in the same material, which are usually of the order of picoseconds up to few nanoseconds at very low (mK) temperatures [46]. Time-resolved Faraday rotation was also used to probe the spin decoherence times in semiconductor (CdSe) quantum dots [47]. The relatively small T_2^* (a few ns at zero field) which have been seen in these experiments presumably originate from a large inhomogeneous broadening due to a strong variation of g-factors. Theoretical estimates predict much longer single-spin decoherence times T_2 [48].

- *Natural two-state system.* A spin 1/2 is the equivalent of a qubit, i.e. it has the same (two-dimensional) Hilbert space. In contrast to this, the orbital degree of freedom of a confined electron or Cooper pair allows for more than two states. If the latter are to be used as a qubit, then the Hilbert space has to be truncated, and it has to be made sure that transitions into "forbidden" states ("leakage" effects) can be suppressed.

- *Scalability.* As mentioned in the previous section, solid-state physics and in particular semiconductor physics offer the advantage that there exists a well-developed technology for fabricating large arrays of small structures, such as quantum dots and wires.

- *Mobility.* Being attached to electrons in a semiconductor, the spin-qubit can be moved around by applying an external field, and is therefore of interest for applications in quantum communication (the transport of quantum information), see also Sec. 1.7.

As will be explained in more detail in Chapter 2, two spins in tunnel-coupled quantum dots experience an exchange coupling which can be described by an isotropic Heisenberg Hamiltonian

$$H_{\mathrm{s}}(t) = J(t)\,\mathbf{S}_1 \cdot \mathbf{S}_2. \tag{1.4}$$

This interaction is sufficient for generating a two-qubit gate (e.g. the XOR gate) [5] which, when complemented with single-spin rotations, can be used to assemble any quantum algorithm [6]. A similar coupling (described by the XY model) which is also suited for quantum computing can be obtained when the quantum dots are not coupled directly but via an optical cavity mode [49], see Chapter 5.

1.7 Quantum communication

The recently demonstrated injection of spin-polarized electrons into semiconductor material [50, 51] is an important progress towards replacing the spatial (charge) degrees of freedom of the electron by its spin as the carrier of information in electronics [52, 53, 54]. Moreover, the long spin decoherence times found in GaAs by Kikkawa *et al.* [43] (see above) makes them suitable carriers for transporting quantum information. Such quantum communication protocols usually require much smaller resources (number of qubits and gate operations) than quantum computation and their implementation is therefore technically less demanding.

The fundamental resource for many applications in quantum communication are pairs of entangled particles [55]. Two qubits (spins) are called entangled if their state cannot be expressed as a tensor product of single qubit (spin) states. Well-known examples of maximally entangled states of two qubits are the spin singlet and triplet (with $m_z = 0$) of two spin-1/2 particles,

$$\frac{1}{\sqrt{2}}\Big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\Big). \tag{1.5}$$

In quantum optics, violations of Bell inequalities and quantum teleportation with photons have been investigated [56, 57, 58], while so far, no corresponding experiments for electrons in a solid-state environment are reported. This reflects the fact that it is harder to produce and to measure entanglement of electrons in solid-state.

One possibility for producing entangled states from product states is using the quantum gates which are the building blocks of quantum computers [5, 59]. Another possibility for the production of spin-entangled electron pairs in mesoscopic systems is to use the properties of the superconducting condensate and the simultaneous tunneling of a Cooper pair into a pair of quantum dots as it is proposed in Ref. [54].

The persistence of this entanglement during electron transport in quantum wires under the influence of interactions [60] is addressed in Chapter 8, where we also discuss an interference experiment, in which EPR pairs can be unambiguously tested for entanglement by measuring the shot noise. Recently, another detection scheme for the entangled ground states in coupled quantum dots (Chapter 2) was proposed in Ref. [61], which involves the Aharonov-Bohm phase in the cotunneling current in the Coulomb blockade regime.

1.8 Outline

This thesis is organized as follows. In Chapter 2 (see Ref. [59]) we analyze the spin dynamics of two laterally coupled quantum dots in a two-dimensional electron system, containing a single electron each, compute the spin exchange coupling J [cf. Eq. (1.4)] as a function of external parameters, and discuss the application of this setup as a quantum gate. For vertically coupled quantum dots this analysis is extended to three dimensions in Chapter 3 (see Ref. [62]). The influence of the direction of the applied electric and magnetic fields in this case is discussed. Chapter 4 (see Ref. [9]) is a short study on g-factor engineering in semiconductor heterostructures and its possible application for all-electric switching for quantum computing. Chapter 5 (Ref. [49]) introduces an alternative method for coupling electron spins in quantum dots via an optical cavity.

Chapters 6 and 7 contain general considerations on quantum computation using the Heisenberg (or XY) interaction and are therefore relevant in connection with Chapters 2, 3, and 5. In Chapter 6 (Ref. [63]) we find the most optimal implementation of a very basic error-correction code and introduce parallel switching. In Chapter 7 (see Ref. [64]) it is shown that the exchange interaction alone—without the additional use of single-spin rotations—can be used for quantum computation at the expense of additional resources (qubits, quantum gate operations).

In Chapter 8 we consider the potential use of spins in quantum wires for quantum communication, the persistence during the transport of pairwise entangled states through a Fermi liquid and its detection via a measurement of the shot noise. In Chapter 9 (see Ref. [65]) a more comprehensive theory of the shot noise in the cotunneling regime which can be used (among other applications) as a tool for studying the transport of quantum information (as e.g. in Ref. [61]).

The Appendices A–J contain additional material related to the Chapters 2, 3, 6, and 9.