2 Scientific Proposal (15 pages)

2.1 State of the art and objectives

2.1.1 State of the art

Quantum information processing (QIP). Already for a number of years the field of quantum information science [1] has been one of the most prominent areas of modern physics. In an interdisciplinary effort researchers aim at harnessing fundamental quantum mechanical effects to invent, develop and demonstrate novel concepts for information processing. Two of the most prominent applications are quantum cryptography [2] and quantum computation [1] in which, respectively, unconditionally secure data transfer and exponential speedup in solving computationally hard problems is to be realized. By now quantum cryptography has reached a rather mature state and even has been introduced as a real product into the market to establish secure communication over distances only limited by optical fiber technology [2]. Also the field of quantum information processing has demonstrated enormous progress in the last ten years. It has been put on a sound theoretical footing with a number of different approaches to quantum information processing and communication, such as the one-way, the ground-state or the standard circuit based quantum computer, developed already and a few important quantum algorithms conceived. A number of the basic concepts of quantum computation have been demonstrated experimentally in many different approaches using trapped ions, nuclear magnetic resonance, linear optics, quantum dots or superconducting circuits with first algorithms realized using photons, ions and nuclear magnetic moments. Despite the great progress, the field of quantum information science is still in its infancy. At the current state it is not known if it will be possible to realize and operate a larger scale quantum information processor that will be able to outperform a classical computer. An interesting relatively new development within the field of quantum information processing focuses on using engineered quantum systems for simulating other complex quantum systems, an idea that is believed to provide interesting results even with intermediate scale systems consisting only of a few tens to a few hundred qubits.

A major effort within quantum information science, that is gaining more and more momentum, is directed towards realizing a solid state micro-chip based quantum information processing technology. Here, the expectation is that solid state implementations of a quantum computer will be able to benefit enormously from existing integrated circuit technology to realize a larger scale quantum information processor once a viable technology is identified. However, it is a demanding task to realize quantum coherent devices in a solid state environment, where decoherence due to coupling to a large number of degrees of freedom has to be controlled effectively. In comparison, microscopic systems such as atoms or ions kept in ultra high vacuum systems and suspended using electromagnetic traps, can be isolated more efficiently from their environment, providing these systems with much longer coherence times. The goal to realize controllable quantum systems with larger number of qubits, has already triggered new efforts in atomic QIP to make use of chip-based technologies to realize more complex multi-atom systems. An increasing number of groups is currently investigating such approaches to realize larger ion trap quantum information processors. We are also actively collaborating with the group of Hartmut Häffner and Rainer Blatt at Innsbruck to realize planar micro fabricated ion trap systems. This project is currently generating first results and ion traps fabricated by our group at ETH Zurich are trapping individual ions in Innsbruck at this time.

A key aspect of quantum information processing that is getting ever more important is the realization of interfaces between massive carriers of quantum information, i.e. qubits such as atoms, spins, quantum electronic circuits etc., and massless carriers of quantum information, such as photons. Such an interface allows to convert quantum information from a stationary carrier of information to a mobile one for quantum communication over longer distances. In particular this aspect is important for interfacing different physical systems to each other using photons as a mediator for the coupling. For atoms and photons atomic cavity quantum electrodynamics (QED) [3, 4], in which the atomic degree of freedom is strongly coupled to a quantum radiation field in a high quality cavity, provides such an interface. Cavity QED is widely recognized as a key approach for realizing hybrid quantum systems, in which solid state and atomic degrees of freedom are to be coupled to each other coherently using photons. On a basic level this approach will allow to study quantum properties of atoms using solid states systems and vice versa. The combination of the strongest aspects of each physical system, such as long coherence times in atomic systems and fast operations in solid state systems, will enable new hybrid approaches for realizing a quantum information processing technologies.

Cavity Quantum Electrodynamics. The investigation of the coherent interaction of individual atoms with individual photons is traditionally a major stronghold of research within the fields of atomic physics and quantum optics where such work is known as cavity QED [4, 3]. Scientists in many other fields of physics have envisaged to couple single quantum two-level systems coherently to individual photons, see e.g. Ref. [5] and references therein. In the past few years two new and very active approaches for performing such research have rapidly developed, one using superconducting [6] the other semiconducting [7] solid state systems.

In atomic cavity QED, a wide range of fundamental experiments have been performed in the visible range with alkali atoms [4, 8] and in the microwave range with Rydberg atoms [3]. Interactions between individual atoms and individual photons have been investigated intensely in recent years. Such experiments have contributed greatly to our fundamental understanding of the interaction of matter with quantized electromagnetic fields, of the physics of open quantum systems and of coherence and decoherence. They are also a major test ground for developing and demonstrating the general concepts of quantum information processing. One of the most exciting recent developments in cavity QED with Rydberg atoms is enabled by the ability to realize extremely high quality factor mirror based microwave cavities, which allow for long photon storage times up to 100 ms or more. Probing the field state of these cavities using the dispersive quantum non-demolition interaction with a set of single atoms [9] allowed to record the progressive collapse of an electromagnetic field into a number state upon measurement and also to observe the decay of the field back into the vacuum state through subsequent discrete quantum jumps between photon number states [10]. This particular form of cavity QED will certainly hold in stock more exciting new experiments in the near future [11]. We also note that a number of approaches able to localize alkali atoms in optical cavities have been successfully developed and have allowed for new experiments such as the observation of photon blockade, the realization of single atom LASERs, for a review see [8].

Reaching the strong coupling limit has been successfully pursued in the context of semiconductor quantum dots with first results dating from the end of 2004, for a review see [7], with rapid progress [12, 13, 14]. However, the degree of control achieved over both the properties of the dots and the cavities employed is not comparable yet to what has been achieved in atomic physics or superconducting circuit settings. In 2004 we have realized strong coupling of a single photon to a single two level system in a solid for the first time [15] after having noted that a strongly coupled cavity QED system can be created in superconducting electronic circuits [5]. In our experiment we have spectroscopically observed the vacuum Rabi mode splitting of a Cooper pair box qubit coupled to a coplanar transmission line resonator [15]. Our experiment is harnessing the possibility to realize microwave frequency resonators with very small mode volume and to couple it to a superconducting two-level system with an effectively large dipole moment realizing strong coupling between a solid state quantum harmonic oscillator and a macroscopic qubit. Simultaneously the strong coupling limit was also demonstrated in an independent experiment by observing coherences on a sideband transition involving a flux qubit coupled to an almost linear oscillator realized as a superconducting quantum interference device (SQUID)[16].

The realization of the strong coupling limit in superconducting circuits has put this architecture within a short time at the forefront of research in cavity QED. The freedom to design strongly coupled systems over a wide range of parameters, such as transition frequency of the qubit and cavity, the coupling strength between the two, the photon lifetime, the qubit coherence time and number of qubits constantly coupled to the cavity at fixed positions, allows for great flexibility to explore new regimes of cavity QED in a solid state environment with figures of merit similar or better than in most other physical realizations. As a result the last three years have seen a number of exciting new results in circuit QED, the most important ones are mentioned here. In the dispersive regime we have observed the quantized AC-Stark effect [17], in which a single photon shifts the qubit transition frequency by more than a qubit line width. This also allowed us to measure the photon number statistics of coherent and thermal fields generated in the cavity. Making use of the Purcell effect at small detunings of the qubit from the cavity, a single photon source has been realized

[18]. At the same time a clever scheme to pump a qubit into the excited state and create population inversion has allowed researchers to realize a single superconducting qubit MASER [19]. In our lab, the $\sqrt{n}$ quantum nonlinearity of the circuit QED system has been demonstrated spectroscopically [20]. Fock states up to $n > 10$ have been generated and characterized by observing Rabi-oscillations of a qubit interacting with the prepared number state [21]. Indications of coherent effects with multiple photons have been observed [22] and heating and cooling ideas similar to the ideas of LASER cooling in atomic physics have been demonstrated in circuit QED [23]. This wealth of new results by a number of different groups in a short period of time clearly demonstrates the potential of our approach and gives an indication of interesting future experimental and theoretical work in the area of quantum optics with circuits that lies ahead of us. In addition, circuit QED is having a substantial impact on quantum information processing with superconducting circuits.

Quantum Information Processing with Superconductors. The quest to realize a quantum information processor based on superconducting electronic circuits had its first success story in 1999 when the first quantum coherent process - in this case Rabi oscillations - was observed [24] in a Cooper pair box qubit [25]. Due to the quickly developing interest in quantum information science and this early success, research directed towards the investigation of quantum coherent phenomena in superconducting circuits and their applications in quantum information processing intensified throughout the last ten years. Since the first operation of a Cooper pair box qubit a number of different types of superconducting qubits have been devised, realized and tested. An overview over the various realizations of qubits is given in the review articles [26, 27] and the fundamental design concepts of quantum coherent superconducting circuits are discussed in [28]. The research into the main building block of a superconducting quantum computer, the superconducting qubit, has lead to an improvement of three orders of magnitude in the coherence times of such circuits from a few nanoseconds in early experiments [24] to a few microseconds in state of the art experiments [29, 30]. Important developments were the use of symmetries of the circuit Hamiltonians and sweet spots in the bias parameters to reduce the effect of parameter fluctuations [31], the invention [32] and the realization [29] of the transmon qubit. The better understanding of the qubit life-time as limited by the Purcell-effect due to the coupling to controlled (and possibly uncontrolled) electromagnetic modes of the qubit environment [33] has also led to improved coherence times.

Further understanding of the limitations of coherence times in realistic solid state devices has to be gained to allow for continued progress towards the realization of a quantum information processor. At the level of a few microseconds the energy relaxation time T_1 of typical circuits is believed to be limited by dielectric losses [34]. Other sources of decoherence, such as charge fluctuations, flux fluctuations, critical current fluctuations, radiation loss, two level systems etc., see for example Ref. [35] and references therein, have been identified. Generically, the effort to improve coherence times will remain an important one. In principle, the number of operations that are possible within a coherence time, an important figure of merit for a quantum computer, can also be improved by realizing faster operations. Currently, quantum operations in electronic circuits are limited from below to a few nanoseconds, if reasonable cost of the control instrumentation is a limiting factor. Therefore, in the long run materials and fabrication techniques that would be able to overcome the current limitations in coherence times have to be developed.

The important aspect of realizing a high fidelity readout for superconducting qubits has been addressed with quite some success in the past few years. One successful approach is using dispersive measurement techniques [5, 36, 37], which have demonstrated close to unit visibility [38] and are expected to be able to reach a fidelity above 90% for optimized system parameters. Another successful readout approach is based on the bifurcation amplifier [39], using switching of a bistable rf-driven nonlinear oscillator coupled to the qubit. With these or similar approaches almost ideal quantum non-demolition projective measurements have been demonstrated [40, 41]. A readout optimized for phase qubits [42] makes use of high fidelity switching current measurements with which it was possible to demonstrate full single qubit state tomography in superconducting qubits [43].

A main effort in current research is directed towards realizing controllable coupling between individual qubits, preferably in a truly scalable architecture. In the early stages, a number of experiments have demonstrated direct two-qubit coupling spectroscopically [44, 45, 46] followed by time-resolved measurements of direct coupling oscillations in both charge qubits [47] and current biased junctions [48]. In recent experiments it was possible to fully characterize the nature of the entanglement and correlations in tomographic measurements of the qubit states generated by direct coupling of two phase qubits [49]. First steps of realizing gate operations between a pair of qubits have been taken in early experiments with charge qubits [50] and more recently the principle of operation of a CNOT gate was demonstrated [51]. These inter-qubit coupling schemes implemented were based on nearest-neighbor couplings with a fixed strength. Realization of controllable couplings using a number of different coupling schemes is intensely investigated currently [52, 53]. To realize more complex quantum algorithms it is essential to allow for non-local couplings between distant qubits as demonstrated recently by coupling a pair of qubits through a quantum bus [54, 55] realized in the circuit QED architecture [15]. This approach is likely to enable the creation of realistic multi-qubit circuits. It provides both the possibility of coupling multiple qubits to a single resonator used as a coupling bus as well as multiplexing of a number of resonators to the same input/output interface. In all two qubit interaction schemes the fidelity of the desired operations is so far limited notably by decoherence. Therefore, identifying optimized interactions to realize fast logical operations will be a successful path to realize better gate operations. The recent progress in improving coherence times, optimizing readout fidelity, implementing qubit tomography, and realizing inter-qubit coupling will likely enable the demonstration of first quantum algorithms using superconducting circuit technology in the near future.

Hybrid Systems. Our development of Circuit QED has spawned a wide range of activities investigating possibilities to couple atomic degrees of freedom to microwave photons. The long coherence times of atoms combined with the strong quantum fields realized in circuit QED may enable new and promising approaches to quantum information processing and also provide new routes to explore atom/solid interactions. These bright prospects have recently led a number of groups to start experimental efforts into that direction and more are getting ready to explore this new area of research.

A key ingredient for successful realization of hybrid coherent quantum systems is the strong coupling of atoms to photons in a solid state environment. This is expected to be realizable with polar molecules or Rydberg atoms, for example, which have dipole moments exceeding the ones of ground state atoms by orders of magnitude. These prospects have led to proposals to couple individual polar molecules or ensembles of polar molecules to microwave photons stored in transmission line resonators [56, 57, 58] or even to superconducting qubits [59, 60] and use these systems for quantum information processing. Until recently, it seemed very challenging to even create the cold polar molecules needed for such experiments. But now first break-through experiments have succeeded [61] increasing the likelihood of successful use of polar molecules in quantum information science.

Rydberg atoms instead are already used in atomic beam experiments for quantum optics and quantum information processing [3]. They possess large electric dipole moments of 10^4 atomic units (ea_0) that scale as n^2 with the principle quantum number, see Fig. 3B. This key feature enables the realization of strong coupling to microwave photons and has led to the first observation of strong coupling cavity QED, which has been pioneered also with Rydberg atoms [3]. The properties of circular Rydberg atoms have been well investigated in the context of cavity QED and quantum optics and also for applications in quantum information processing. Rydberg atom dipole moments are of similar magnitude as the ones realized in superconducting qubits. The transition frequency between neighboring Rydberg states is determined by the principle quantum number n and is in the microwave frequency range (< 50GHz) for $n > 50$, see Fig. 3A. At the same time Rydberg atoms have long excited state life times in the range of hundreds of microseconds to milliseconds. These properties make Rydberg atoms extremely attractive atomic candidate for coupling to the circuit QED architecture. It has also already been suggested to mediate atom/atom interactions through mesoscopic wires [62] making use of the large dipole moment of Rydberg atoms. Trapping individual Rydberg atoms on a chip remains a challenge but plans do exist [63, 64]. First steps towards achieving this goal are currently made, localizing ensembles of Rubidium atoms in superconducting traps [65, 66]. Also ensembles of Rydberg atoms generated in supersonic atomic beams have recently been decelerated and trapped [67]. A number of proposals to use Rydberg states in ensembles for quantum information processing exist [68, 69] and first experiments are in progress [70].

We also point out that the number of activities in which solid state systems are used as some component of atomic physics experiments is strongly increasing currently. In ion trap quantum computing and basic research on ion physics, chip based traps are already in use and become constantly more widely used [71]. There, integrated solid state chips at low temperatures are expected to increase integration and scalability of these systems and also reduce sources of decoherence, e.g. by avoiding Johnson noise [72]. Our group is already involved in a collaborative project with the University of Innsbruck to realize on-chip coupling of ions in different traps through an individual wire for which the chips have been fabricated in our lab. In addition, theoretical proposals to couple ions to superconducting qubits do [73]. On-chip traps are intensely investigated in the context of neutral atoms and BECs as well [74]. In this area, the coupling of cold atomic ensembles to on-chip microwave resonators is considered for basic quantum optics but also for quantum information processing experiments [75]. The coupling of cold gases to mechanical degrees of freedom is of interest [76]. Even in solid state hybrid approaches coupling between semiconductor qubits mediated by microwave photons in superconducting on-chip resonators is envisaged [77] and coupling of collective spin excitation through non-linear cavities has been proposed [78].

Clearly, mediating coupling between distinct quantum systems of different nature through exchange of microwave photons contained in a quasi 1D on-chip resonator is receiving substantial attention in the scientific community. We plan to experimentally explore coupling between Rydberg atoms, on-chip resonators and superconducting qubits. This is one of the most promising hybrid quantum systems. At the same time we feel confident exploring this system, because of our strong position in the field of circuit QED, the excellent research environment in the area of atomic physics and quantum optics at ETH and the already active and to be itensified collaborations with Frederic Merkt and Tilman Esslinger on the subject.

2.1.2 Objectives

The main goal of this project will be to develop a novel hybrid approach to quantum information science aiming at the exploration of the coherent interaction between atomic degrees of freedom and solid state degrees of freedom. The key ingredient here will be the development and exploration of an interface between solid state qubits and atoms. In particular we intend to study superconducting quantum electronic circuits and Rydberg atoms. We will explore the basic properties of both systems and their interactions and will evaluate the potential for developing a novel hybrid quantum information processing approach.

Circuit QED is a new and very successful approach to perform quantum information processing and quantum optics experiments using superconducting electronic circuits. Major current challenges are to improve coherence times, to realize high fidelity single shot qubit read-out and to demonstrate the execution of a simple quantum algorithm in a superconducting circuit architecture. In this project we will go beyond the current state-of-the art of the circuit QED approach to quantum optics and quantum information processing along two tracks. Along the first track we will explore circuit QED based detection schemes with single photon sensitivity. These will be based on non-linear parametric amplifiers or on cavity QED approaches to resonantly detect individual photons. Such an achievement will allow us to perform experiments in which photon correlation measurements can be used to characterize properties of quantum and classical sources of microwave radiation. It will also improve the single shot fidelity of dispersive qubit state detection schemes enabling qubit correlation measurements and real-time feedback that will be required to realize quantum teleportation protocols in superconducting circuits. These developments will be directly beneficial to the planned dispersive Rydberg atom detection scheme discussed below.

Along the second and main line of research to be funded by through this ERC grant proposal we will explore the realization of an interface between superconducting and atomic carriers of quantum information using microwave photons. Rydberg atoms, simultaneously possessing large dipole moments and long excited state lifetimes are natural candidates to realize such an interface to the circuit QED architecture. In the beginning of the project, we will study the interaction of Rydberg atoms with microwave fields contained in superconducting transmission line resonators. A first set of experiments will be perfomed on Rydberg atoms excited to different quantum numbers n to control both their transition frequency and their dipole moment, see Fig. 3. Ensembles of these atoms will be prepared by Laser excitation from a cold atomic beam. For maximum flexibility we will initially consider hydrogen Rydberg atoms, the preparation of which

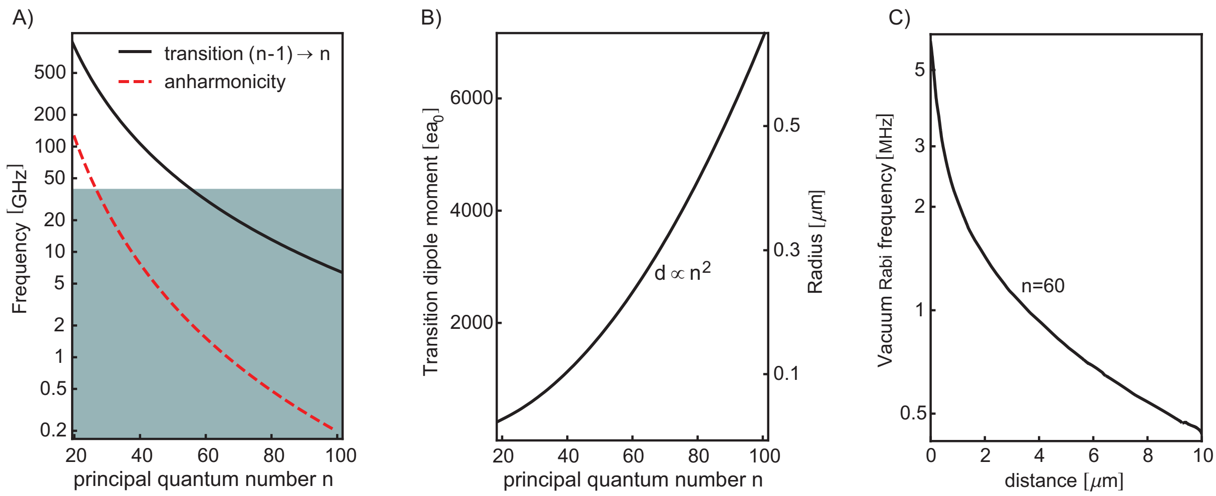

Figure 3: A) Dependence of the transition frequency and the the absolute anharmonicity between neighboring levels of circular Rydberg atoms on the principal quantum number n. B) Transition dipole moment and radius of circular Rydberg atom *vs.* n. C) Vacuum Rabi frequency of Rydberg atom coupled to transmission line field in dependence on atom/surface distance for different n in the geometry depicted in Fig. 2.

is well established at ETH. In first experiments the atomic beam will propagate in a controllable distance from a coplanar microwave strip line resonator. When tuned into resonance with the microwave radiation the Rydberg atoms will undergo excitation from n to $n+1$. The interaction with the microwave field will then be characterized using field ionization detection of the Rydberg atoms. This experiment will reveal first signs of interaction between on-chip microwave photons and Rydberg atoms. We will explore the dependence of the interaction strength on the separation between the atomic beam and the surface and explore the effect of the surface on the Rydberg atoms. We will also explore the possibility to detect Rydberg atoms in the vicinity of a microwave resonator using the dispersive shift induced in the resonator frequency. This experiment could lead to a quantum non-demolition detection scheme for Rydberg atoms that could prove useful in a number of quantum information processing schemes. The described experiments will first be performed at temperatures between 10 and 2 Kelvin and ultimately at dilution refrigerator temperatures in the range of 250 to 20 mK.

A second major goal will be to slow down and trap ensembles of Rydberg atoms in a controllable distance from microwave on-chip circuitry. The trapping of Rydberg atoms from a beam has been demonstrated in three dimensional electrostatic trap geometries, which we will employ initially. We will develop and test planar trap configurations to ultimately realize an all chip based trap that benefits from the flexibility and parallel production of integrated circuits. In these experiments we will explore the dynamics and coherence properties trapped Rydberg atoms. At this stage of the proposal we will carefully evaluate the optimal principle quantum number to be used for on-chip Rydberg atom experiments. After this decision we will reconsider the choice of atomic species to potentially reduced the complexity of the LASER excitation scheme and make it more suitable for future experiments. In a next step of the experiment we will explore approaches to reduce the Ryderg atom number trapped on the chip to the few or single atom level and evaluate coherence properties and our ability to manipulate individual atoms.

Finally, we will explore the possibility to strongly couple a single Rydberg atom to a single microwave photon stored in a on-chip resonator. The expected vacuum Rabi frequency in dependence on the atom/chip distance is depicted in Fig. 2C. This will potentially realize the strong coupling limit of cavity QED in this hybrid atomic/solid-state system. At this point we will be able to experimentally approach the task to transfer quantum information stored in a single superconducting qubit to an atomic qubit making use of the strong coupling of both systems to the same single mode of the radiation field. The operation of the experiment in the temperature regime below 100 mK will become essential to achieve optimum superconducting qubit coherence.

This experiment will be among the first ones to experimentally explore atom/solid-state interfaces and hybrid quantum systems. When realized such hybrid systems will advance the development of quantum information processors by combining long coherence times of atoms with strong interactions and fast operations in solid state quantum systems. On the way towards realizing such a system we will investigate in detail the interaction of Rydberg atoms with solid state environments in general and superconducting circuits in particular, exploring the effects of different materials at different temperatures and conditions on atomic coherence. At the same time we will develop new tools for atomic physics, such as a dispersive quantum non-demolition detector Rydberg atoms and other atomic degrees of freedom with sufficiently large dipole moments. Simultaneously, we will use atoms as coherent probes for materials properties of solids under various ambient conditions. On a technological level we will have developed a platform to perform atomic physics experiments in a sub-Kelvin temperature environment. Such systems will be beneficial for other directions of quantum information science, such as ion trap quantum information processing with integrated on chip traps at low temperatures.

2.2 Methodology

2.2.1 Objective: Generation and detection of non-classical states of light in circuit QED

We plan to explore novel schemes to generate and to detect microwave radiation in the circuit QED architecture. In addition, we will explore possible operating conditions under which superconducting qubits can be interfaced to Rydberg atoms.

Generation and detection of light. We will explore the generation of single microwave photons in Circuit QED using side-band transitions [79]. This particular approach will allow the controlled generation of photons in the resonator using qubits detuned from the cavity. Detection of single microwave photons is a challenge. Current techniques usually require averaging over a large number of repetitions of the photon generation [18]. Here we will investigate the use of superconducting parametric amplifiers [80] to detect microwave radiation with high signal to noise ratios and explore if the quantum limit of amplification can be reached in the context of circuit QED. We will also investigate possibilities to perform photon correlation measurements in Circuit QED. We will use chip based microwave frequency beam splitters and interferometers combined with uncorrelated amplification chains to achieve this goal. Previously similar techniques [81] have been used in a different context. We believe that this on-chip interferometry techniques will allow for a new range of linear optics experiments to be approached in Circuit QED. The use of parametric amplifiers will also allow us to improve the single shot fidelity of our dispersive qubit read-out. Parametric amplifiers will be useful to investigate the properties of squeezed light in the circuit QED architecture. Squeezed microwave radiation can be generated using non-linear resonators [82, 83]. The techniques to be developed in the context of this objective will also be useful for the dispersive QND detection of Rydberg atoms discussed in a later section.

Hybrid circuit QED. We will explore circuit QED architectures that allow integration of superconducting qubits with on chip trapping of Rydberg atoms. We will operate superconducting qubits while applying the fields that will be required to trap Rydberg atoms on chip. Using the results of such experiments we will develop schemes that will allow us to integrate Rydberg atoms and superconducting qubits in the same environment.

2.2.2 Objective: Investigation of the interaction of Rydberg atom ensembles with microwave photons.

Construction of measurement setup. We will construct a measurement setup in which we will generate Hydrogen Rydberg atoms over a large range of principle quantum numbers n and investigate their interaction with microwave radiation guided by microwave transmission lines.

Hydrogen Rydberg atoms will be generated [67] in a high vacuum system from a pulsed supersonic beam of Hydrogen atoms. The hydrogen atoms are generated by photolysis of NH_3 seeded in Ar using a pulsed excimer LASER at 193 nm. In a two stage process Hydrogen is first excited from the 1s state to the 2^2p state using light at 121 nm generated in a four wave mixing process in Krypton. This involves a 2 photon transition pumped by a frequency tripled tunable dye LASER, mixed with a tunable IR dye LASER. Using a third dye LASER the Hydrogen atom can directly be excited into a given Rydberg state with a principle quantum number in the range $n = 20...200$. This will allow us to generate Hydrogen Rydberg atoms over a large range of transition frequencies and dipole moments as shown in Fig. 3. Such a beam will contain about 10^6 Rydberg atoms per pulse which propagate at a velocity of 500...700 m/s. The atoms will be detected state-sensitively with a high quantum efficiency multi-channel plate using field ionization. The setup will be constructed such that an on-chip coplanar microwave transmission line can be approached to the beam of the Rydberg atoms while accurately controlling the separation between the beam center and the surface of the chip using a piezo-electrical and mechanical positioning system.

Rydberg atom spectroscopy using microwave transmission lines. We will perform spectroscopy of Rydberg atoms traversing the field generated by a microwave transmission line. The experiment will be performed with ensembles or Rydberg atoms and strong microwave fields in the transmission lines to facilitate first characterization of the interaction between the atom and the field.

We will initially fabricate continuous coplanar waveguide transmission line circuits to efficiently generate on-chip microwave radiation over a wide range of frequencies. We plan to limit ourselves to 40 GHz as a maximum operation frequency, which will put a constraint on the minimum n suitable for the Rydberg atoms. This limitation on the frequency range is imposed by constraints on the quality of the on-chip microwave circuits. It will also facilitate the use of superconducting qubits in a more suitable frequency range in later hybrid circuit QED experiments. By varying the geometry and materials of the coplanar waveguide transmission line we will be able to control the distribution of the microwave field in front of the chip surface, see Fig. 2. This will allow us to investigate the atom field interaction over a wide range of suitable atom surface distances. We will carefully analyze the transition matrix elements of the Rydberg atom in the presence of the combined dc-electric field determining the quantization axis and the microwave field generated by the coplanar waveguide in dependence on the position of the atom. The resonant interaction with the microwave field of the coplanar wave guide will induce transitions between neighboring Rydberg states in the atom. These transition will initially be detected using state selective field ionization [84].

Experiments will start out with large atom/chip separations and will subsequently reduce the separation. From this data we will extract the atom/field interaction strengths. We will also evaluate possible sources of decoherence induced in the Rydberg atoms by the surface.

Reduced temperature experiments. To investigate the interactions of Rydberg atoms with surfaces at low temperatures and to reduce the effect of Johnson noise, we will perform experiments with coplanar wave guides cooled to temperatures down to 4...2 K. These experiments will be realized by integrating a pulse tube cooler based cryogenic system into the measurement setup. This low temperature capability will be considered in the initial design of the experimental setup.

Cooling the chip and its environment to low temperature will allow us to investigate the effect of the temperature dependent Johnson noise emitted by the conductors on the Rydberg atom life times and dephasing times. At the same this approach will enable us to make first use of superconducting on-chip structures. This will drastically reduce dissipation in the coplanar wave guide electrodes. At the same time we will explore the effect of superconducting electrodes on Rydberg atoms. In finite magnetic fields the superconductors will expel the magnetic field due to their ideal diamagnetism, i.e. the Meissner effect, changing the local fields in the vicinity of the trap. In two-dimensional films the presence of vortices and their effect on the coherence of Rydberg atoms will be investigated. This experiment at low temperatures will also help us to evaluate the practical issues of eventually operating the Rydberg atom experiment at dilution refrigerator temperatures.

2.2.3 Objective: Dispersive quantum non-demolition detection of Rydberg atoms.

In circuit QED experiments we detect the quantum state of a superconducting qubit via its non-resonant (dispersive) interaction with the radiation field of an on-chip transmission line resonator. Under appropriate conditions this detection is quantum non-demolition [5, 85]. Here we will perform an experiment aimed at detecting Rydberg atoms in the vicinity of a high quality microwave resonator using the same effect. The presence of the Rydberg atoms in a given Rydberg state will induce a dispersive shift in the resonator frequency that sensitively depends on the state dependent dipole moment of the atom. The large dipole moment d of the Rydberg atoms should allow the observation of these shifts.

The sensitivity of the measurement will depend on measurement parameters, i.e. the effective atom/resonator coupling g, depending on the separation between the atom and the resonator and the dipole moment vector d of the atom, the quality factor Q of the resonator, and the atom/resonator detuning Δ. In initial experiments the resonance frequency of the coplanar waveguide resonator in the presence of Rydberg atoms will be compared to the one in the absence of atoms. As we will be able to prepare large numbers of Rydberg atoms traversing the chip we are certain that this scheme will result in a detectable signal. We will then explore, the possibility to resolve different Rydberg states with different dipole moments. We will also investigate the singal to noise ratio, with which such experiments can be performed. We will evaluate, if detection of the Rydberg state on a single atom level is feasible. The described experiments will first be performed at temperatures of $2 - 4$ Kelvin and ultimately at dilution refrigerator temperatures in the range of 250 to 20 mK.

This experiment has the potential to realize quantum non-demolition detection of Rydberg atoms that could prove useful in a number of quantum information processing settings. It might also find a prominent application in as a chip-based QND atom detector in other atomic physics settings.

2.2.4 Objective: Trapping of Rydberg atoms in the vicinity of electronic circuits.

In this part of the project we will to slow down and trap ensembles of Rydberg atoms in a controllable distance from microwave on-chip circuitry. To realize this goal will be useful both for performing spectroscopy of the atoms and for measuring their state on-chip. It will also be a crucial ingredient to later realize an atom qubit interface in the same architecture.

3D traps. The slowing down and trapping of Rydberg atoms from a beam has recently been demonstrated in three dimensional (3D) electrostatic trap geometries [67]. We will initially explore the use of this 3D electrode geometry to trap Rydberg atoms in a controllable distance from the surface of the chip containing the coplanar waveguide or resonator. We will carefully analyze how to integrate the chip with the current trap geometry and consider the possibility to realize one or two of the trap electrodes on-chip. The details of trap potentials will be analyzed using finite element based electromagnetic calculations.

Chip-based planar traps. We will develop and test planar trap configurations [64] to ultimately realize an all chip based trap that benefits from the flexibility and parallel production of integrated circuits to optimize trapping parameters and trap integration. We will also design on-chip trapping circuits that incorporate microwave transmission lines and resonators to build a fully integrated system. Eventually, a goal to achieve is to perform spectroscopy and detection of an ensemble of Rydberg atoms on a single integrated microwave frequency circuit. Here, the project we will strongly benefit from our prior work an expertise on realizing planar ion traps with Hartmut Häffner at Innsbruck University.

Coherence of trapped Rydberg atoms. We will explore the dynamics and coherence properties of Rydberg atoms trapped in planar and 3D traps. This will be done either with the novel approaches for on-chip spectroscopy and detection developed during this project or with the more conventional approach using field ionization. The state of the Rydberg atoms will be controlled with pulsed microwaves.

2.2.5 Objective: Realization of hybrid circuit QED systems

In the final stage of the project we will explore the possibility to strongly couple a single Rydberg atom and a single superconducting qubit to the same microwave frequency transmission line resonator. In this step we will potentially be able to realize the strong coupling limit of cavity QED in a hybrid atomic/solid-state system. This capability will enable the coherent transfer of quantum information between atomic and solid state quantum systems.

Optimization of system parameters. Here we will make use of the detailed analysis of all prior experiments to evaluate the optimal principle quantum number n and optimal system parameters to be used for coherent on-chip Rydberg atom experiments. This critical analysis will allow us to reconsider the choice of atomic species. The use of hydrogen Rydberg atoms has the benefit of flexibility and simplicity of the atomic excitation spectrum at the expense of complexity of the LASER excitation scheme involving UV and VUV frequencies that are challenging to generate and to handle in the experiment. Using different alkali atoms such as Rubidium may substantially reduce the complexity of the LASER system and will allow to build more straightforward and more stable systems for a specific atomic species and its transitions. This will potentially reduce complexity, which will be more suitable for final experiments.

On-chip single atom cavity QED. We will explore the possibility to reach the strong coupling limit with multiple Rydberg atoms where the coupling strength scales with the square root of the number N of atoms interacting simultaneously with the same mode of the radiation field. We will consider the atom/atom interaction in such ensembles in dependence on the trap potential. Then we will explore techniques to reduce the atom number down to the single atom level and evaluate the coupling strength. In this limit we will also evaluate coherence properties and our ability to manipulate individual Rydberg atoms on chip.

Hybrid circuit QED. At this point we will be able to experimentally approach the transfer of quantum information stored in a single superconducting qubit to an atomic qubit making use of the strong coupling of both systems to the same single mode of the radiation field of the on-chip transmission line resonator. The operation of the experiment in the temperature regime below 100 mK will become essential to achieve optimum superconducting qubit coherence properties. To perform this experiment we will have constructed a mK temperature set-up to perform Rydberg atom experiments. When this infrastructure is available we can explore different ways to realize effective atom/qubit coupling. Possible approaches are, resonant coupling of both systems to the same cavity mode. Here the coupling is mediated by the exchange of a real photon. Alternatively we will explore dispersive coupling schemes, where qubits and atoms exchange virtual photons through a detuned cavity mode. Yet another approach could be the use of side-band transitions. In this situation atom and qubit could maintain different frequencies, both of which are detuned from the resonator mode. Joint blue (and/or red) sideband transitions could be employed to entangle the atom or the superconducting qubit with a photon in the cavity. This entanglement could then be mapped to the other partner generating an atom/superconducting qubit, i.e. hybrid, entangled state. Similar approaches could then be used to store quantum information in Rydberg atom memories with storage-times exceeding the life time of superconducting qubits.

If this task can be realized one could also imagine to realize processes that would allow to convert the information stored in a Rydberg state of an atom to a visible photon using a coherent process. This might be useful for realizing an interface from the solid state microwave frequency domain into the optical frequency domain, that would then enable conversion of quantum information between different frequency domains.

2.2.6 Time Line and Intermediate Goals

We present an approximate time line for the expected progress of the project. The main tasks to be addressed or problems to be solved in each half of each project year ('09 to '14) are listed. Major goals or milestones to be reached are printed in bold. The time line also indicates which of the graduate students (GS1,2,3) and the

References

[1] Nielsen, M. A. & Chuang, I. L. *Quantum Computation and Quantum Information*. Cambridge Univertity Press (2000).

[2] Gisin, N. *et al.* Quantum cryptography. *Rev. Mod. Phys.* **74**, 145 (2002).

[3] Haroche, S. & Raimond, J.-M. *Exploring the Quantum: Atoms, Cavities, and Photons*. OUP Oxford (2006).

[4] Kimble, H. J. The quantum internet. *Nature* **453**, 1023 (2008).

[5] Blais, A. *et al.* Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation. *Physical Review A* **69**, 062320 (2004).

[6] Schoelkopf, R. & Girvin, S. Wiring up quantum systems. *Nature* **451**, 664 (2008).

[7] Khitrova, G. *et al.* Vacuum Rabi splitting in semiconductors. *Nature Physics* **2**, 81 (2006).

[8] Ye, J., Kimble, H. J., & Katori, H. Quantum state engineering and precision metrology using state-insensitive light traps. *Science* **320**, 1734 (2008).

[9] Gleyzes, S. *et al.* Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* **446**, 297 (2007).

[10] Guerlin, C. *et al.* Progressive field-state collapse and quantum non-demolition photon counting. *Nature* **448**, 889 (2007).

[11] Deleglise, S. *et al.* Reconstruction of non-classical cavity field states with snapshots of their decoherence. *Nature* **455**, 510 (2008).

[12] Hennessy, K. *et al.* Quantum nature of a strongly coupled single quantum dot-cavity system. *Nature* **445**, 896 (2007).

[13] Englund, D. *et al.* Controlling cavity reflectivity with a single quantum dot. *Nature* **450**, 857 (2007).

[14] Srinivasan, K. & Painter, O. Linear and nonlinear optical spectroscopy of a strongly coupled microdisk-quantum dot system. *Nature* **450**, 862 (2007).

[15] Wallraff, A. *et al.* Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics. *Nature* **431**, 162 (2004).

[16] Chiorescu, I. *et al.* Coherent dynamics of a flux qubit coupled to a harmonic oscillator. *Nature* **431**, 159 (2004).

[17] Schuster, D. I. *et al.* Resolving photon number states in a superconducting circuit. *Nature* **445**, 515 (2007).

[18] Houck, A. *et al.* Generating single microwave photons in a circuit. *Nature* **449**, 328 (2007).

[19] Astafiev, O. *et al.* Single artificial-atom lasing. *Nature* **449**, 588 (2007).

[20] Fink, J. M. *et al.* Climbing the Jaynes-Cummings ladder and observing its nonlinearity in a cavity QED system. *Nature* **454**, 315 (2008).

[21] Hofheinz, M. *et al.* Generation of Fock states in a superconducting quantum circuit. *Nature* **454**, 310 (2008).

[22] Deppe, F. *et al.* Two-photon probe of the Jaynes-Cummings model and controlled symmetry breaking in circuit qed. *Nat Phys* **4**, 686 (2008).

[23] Grajcar, M. *et al.* Sisyphus cooling and amplification by a superconducting qubit. *Nat Phys* **4**, 612 (2008).

[24] Nakamura, Y., Pashkin, Y. A., & Tsai, J. S. Coherent control of macroscopic quantum states in a single-cooper-pair box. *Nature* **398**, 786 (1999).

[25] Bouchiat, V. *et al.* Quantum coherence with a single Cooper pair. *Physica Scripta* **T76**, 165 (1998).

[26] Wendin, G. & Shumeiko, V. Superconducting quantum circuits, qubits and computing. In Rieth, M. & Schommers, W. (eds.), *Handbook of Theoretical and Computational Nanotechnology*, volume 3. American Scientific Publishers (2006).

[27] Clarke, J. & Wilhelm, F. K. Superconducting quantum bits. *Nature* **453**, 1031 (2008).

[28] Devoret, M. H. & Martinis, J. M. Implementing qubits with superconducting integrated circuits. *Quantum Information Processing* **3**, 163 (2004).

[29] Schreier, J. *et al.* Suppressing charge noise decoherence in superconducting charge qubits. *Physical Review B* **77**, 180502(R) (2008).

[30] Leek, P. J. *et al.* Observation of Berry's phase in a solid-state qubit. *Science* **318**, 1889 (2007).

[31] Vion, D. *et al.* Manipulating the quantum state of an electrical circuit. *Science* **296**, 886 (2002).

[32] Koch, R. H. *et al.* Experimental demonstration of an oscillator stabilized Josephson flux qubit. *Phys. Rev. Lett.* **96**, 127001 (2006).

[33] Houck, A. A. *et al.* Controlling the spontaneous emission of a superconducting transmon qubit. *Phys. Rev. Lett.* **101**, 080502 (2008).

[34] O'Connell, A. D. *et al.* Microwave dielectric loss at single photon energies and millikelvin temperatures. *Appl. Phys. Lett.* **92**, 112903 (2008).

[35] Ithier, G. *et al.* Decoherence in a superconducting quantum bit circuit. *Physical Review B* **72**, 134519 (2005).

[36] Schuster, D. I. *et al.* AC Stark shift and dephasing of a superconducting qubit strongly coupled to a cavity field. *Physical Review Letters* **94**, 123602 (2005).

[37] Lupascu, A., Harmans, C. J. P. M., & Mooij, J. E. Quantum state detection of a superconducting flux qubit using a dc-SQUID in the inductive mode. *Phys. Rev. B* **71**, 184506 (2005).

[38] Wallraff, A. *et al.* Approaching unit visibility for control of a superconducting qubit with dispersive readout. *Physical Review Letters* **95**, 060501 (2005).

[39] Siddiqi, I. *et al.* Rf-driven josephson bifurcation amplifier for quantum measurement. *Phys. Rev. Lett.* **93**, 207002 (2004).

[40] Lupascu, A. *et al.* Quantum non-demolition measurement of a superconducting two-level system. *Nat Phys* **3**, 119 (2007).

[41] Boulant, N. *et al.* Quantum nondemolition readout using a josephson bifurcation amplifier. *Phys. Rev. B* **76**, 014525 (2007).

[42] Martinis, J. M. *et al.* Rabi oscillations in a large Josephson-junction qubit. *Physical Review Letters* **89**, 117901 (2002).

[43] Steffen, M. *et al.* State tomography of capacitively shunted phase qubits with high fidelity. *Physical Review Letters* **97**, 050502 (2006).

[44] Berkley, A. J. *et al.* Entangled macroscopic quantum states in two superconducting qubits. *Science* **300**, 1548 (2003).

[45] Majer, J. B. *et al.* Spectroscopy on two coupled superconducting flux qubits. *Phys. Rev. Lett.* **94**, 090501 (2005).

[46] Izmalkov, A. *et al.* Evidence for entangled states of two coupled flux qubits. *Phys. Rev. Lett.* **93**, 037003 (2004).

[47] Pashkin, Y. A. *et al.* Quantum oscillations in two coupled charge qubits. *Nature* **421**, 823 (2003).

[48] McDermott, R. *et al.* Simultaneous state measurement of coupled Josephson phase qubits. *Science* **307**, 1299 (2005).

[49] Steffen, M. *et al.* Measurement of the entanglement of two superconducting qubits via state tomography. *Science* **313**, 1423 (2006).

[50] Yamamoto, T. *et al.* Demonstration of conditional gate operation using superconducting charge qubits. *Nature* **425**, 941 (2003).

[51] Plantenberg, J. H. *et al.* Demonstration of controlled-NOT quantum gates on a pair of superconducting quantum bits. *Nature* **447**, 836 (2007).

[52] Hime, T. *et al.* Solid-state qubits with current-controlled coupling. *Science* **314**, 1427 (2006).

[53] Niskanen, A. O. *et al.* Quantum coherent tunable coupling of superconducting qubits. *Science* **316**, 723 (2007).

[54] Majer, J. *et al.* Coupling superconducting qubits via a cavity bus. *Nature* **449**, 443 (2007).

[55] Sillanpää, M. A., Park, J. I., & Simmonds, R. W. Coherent quantum state storage and transfer between two phase qubits via a resonant cavity. *Nature* **449**, 438 (2007).

[56] Andre, A. *et al.* A coherent all-electrical interface between polar molecules and mesoscopic superconducting resonators. *Nat Phys* **2**, 636 (2006).

[57] Rabl, P. *et al.* Hybrid quantum processors: Molecular ensembles as quantum memory for solid state circuits. *Physical Review Letters* **97**, 033003 (2006).

[58] Rabl, P. & Zoller, P. Molecular dipolar crystals as high-fidelity quantum memory for hybrid quantum computing. *Physical Review A* **76**, 042308 (2007).

[59] Tordrup, K. & Molmer, K. Quantum computing with a single molecular ensemble and a cooper-pair box. *Physical Review A* **77**, 020301 (2008).

[60] Tordrup, K., Negretti, A., & Molmer, K. Holographic quantum computing. *Physical Review Letters* **101**, 040501 (2008).

[61] Ni, K.-K. *et al.* A high phase-space-density gas of polar molecules. *Science* **322**, 231 (2008).

[62] Sørensen, A. S. *et al.* Capacitive coupling of atomic systems to mesoscopic conductors. *Phys. Rev. Lett.* **92**, 063601 (2004).

[63] Hyafil, P. *et al.* Coherence-preserving trap architecture for long-term control of giant Ryberg atoms. *Phys. Rev. Lett.* **93**, 103001 (2004).

[64] Mozley, J. *et al.* Trapping and coherent manipulation of a rydberg atom on a microfabricated device: a proposal. *The European Physical Journal D* **35**, 43 (2005).

[65] Nirrengarten, T. *et al.* Realization of a superconducting atom chip. *Physical Review Letters* **97**, 200405 (2006).

[66] Roux, C. *et al.* Bose-Einstein condensation on a superconducting atom chip. *Europhysics Letters* **81**, 56004 (6pp) (2008).

[67] Hogan, S. D. & Merkt, F. Demonstration of three-dimensional electrostatic trapping of state-selected rydberg atoms. *Physical Review Letters* **100**, 043001 (2008).

[68] Brion, E., Molmer, K., & Saffman, M. Quantum computing with collective ensembles of multilevel systems. *Physical Review Letters* **99**, 260501 (2007).

[69] Petrosyan, D. & Fleischhauer, M. Quantum information processing with single photons and atomic ensembles in microwave coplanar waveguide resonators. *Physical Review Letters* **100**, 170501 (2008).

[70] Johnson, T. A. *et al.* Rabi oscillations between ground and Rydberg states with dipole-dipole atomic interactions. *Physical Review Letters* **100**, 113003 (2008).

[71] Blatt, R. & Wineland, D. Entangled states of trapped atomic ions. *Nature* **453**, 1008 (2008).

[72] Labaziewicz, J. *et al.* Suppression of heating rates in cryogenic surface-electrode ion traps. *Physical Review Letters* **1** (2008).

[73] Tian, L. *et al.* Interfacing quantum-optical and solid-state qubits. *Phys. Rev. Lett.* **92**, 247902 (2004).

[74] Fortagh, J. & Zimmermann, C. Magnetic microtraps for ultracold atoms. *Reviews of Modern Physics* **79**, 235 (2007).

[75] Verdu, J. *et al.* Strong magnetic coupling of an ultracold gas to a superconducting waveguide cavity. arXiv:08092552 [cond-mat.mes-hall].

[76] Treutlein, P. *et al.* Microwave potentials and optimal control for robust quantum gates on an atom chip. *Physical Review A* **74**, 022312 (2006).

[77] Trif, M., Golovach, V. N., & Loss, D. Spin dynamics in inas nanowire quantum dots coupled to a transmission line. *Physical Review B* **77**, 045434 (2008).

[78] Imamoglu, A. Cavity-QED based on collective magnetic dipole coupling: spin ensembles as hybrid two-level systems. arXiv:0809.2909v1[quant-ph] (2008).

[79] Wallraff, A. *et al.* Sideband transitions and two-tone spectroscopy of a superconducting qubit strongly coupled to an on-chip cavity. *Physical Review Letters* **99**, 050501 (2007).

[80] Castellanos-Beltran, M. A. *et al.* Amplification and squeezing of quantum noise with a tunable josephson metamaterial. arXiv:0806.0659v1 [cond-mat.mes-hall] (2008).

[81] Gabelli, J. *et al.* Hanbury Brown–Twiss correlations to probe the population statistics of GHz photons emitted by conductors. *Physical Review Letters* **93**, 056801 (2004).

[82] Palacios-Laloy, A. *et al.* Tunable resonators for quantum circuits. *Journal of Low Temperature Physics* **151**, 1034 (2008).

[83] Sandberg, M. *et al.* Tuning the field in a microwave resonator faster than the photon lifetime. *Appl. Phys. Lett.* **92**, 203501 (2008).

[84] Vliegen, E. *et al.* Stark deceleration and trapping of hydrogen rydberg atoms. *Physical Review A* **76**, 023405 (2007).

[85] Boissonneault, M., Gambetta, J. M., & Blais, A. Nonlinear dispersive regime of cavity qed: The dressed dephasing model. *Physical Review A* **77**, 305 (2008).