1.4 Extended Synopsis of Scientific Proposal (5 pages)

1.4.1 The Setting

The theory of quantum mechanics was developed at the beginning of the last century to explain experimental observations, such as the photo effect, the discrete emission and absorption spectra of atomic vapors, or the continuous spectrum emitted by hot bodies and many more, that puzzled scientist at the time. In the last 100 years quantum mechanics has developed into a hugely successful theory accurately describing the microscopic world around us. Initially quantum mechanics was used to describe collective phenomena in ensembles of microscopic quantum systems, such as the properties of an ensemble of a large number atoms in a vapor that emit or absorb radiation. Development of experimental techniques and technologies throughout the last decades have allowed researchers to isolate a small number of quantum systems from the ensemble which allowed them to explore the properties of individual quantum systems rather than large ensembles. These techniques allowed to shed light on peculiar aspects of quantum mechanics such as the superposition principle in a single quantum system, entanglement of multiple quantum systems, or the concept of quantum measurement. This has led scientists to address the question, if the ideas of quantum mechanics could not only be used to explain phenomena observed in nature but also made use of in novel ways, e.g. by controlling the quantum dynamics of a collection of quantum systems to perform calculations otherwise difficult or impossible to perform. This new key area of research is now commonly refered to as quantum computing.

Quantum mechanics not only accurately describes the properties of atoms, electrons, protons, neutrons, photons and other microscopic particles around us but also manifests itself on the macroscopic level such as in the formation of crystalline solids or in collective phenomena such as superconductivity. However, only in the last 10 years coherent quantum effects have been observed also in solid state systems on the level of single degrees of freedom, e.g. in superconducting circuits or quantum dots. This achievement has opened new ways for solid state physics to contribute to the fundamental understanding of quantum mechanics and the development of quantum information science.

These experimental and technological developments coincided with theoretical developments exploring the relation between fundamental concepts of information and their relation to physical systems. In particular the question was raised whether quantum systems could be used to store and process information in ways fundamentally different from any other scheme of computation. These questions led to the development of the field of quantum information science. In this field by now well known concepts for processing information and for communication making use quantum mechanics have been developed. Among the most spectacular developments are the Shor algorithm, to factor large integers exponentially faster than by classical means, the Grover algorithm, to search unstructured data bases with a quadratic speed up, and the prospects of simulating the properties of large quantum systems, such as complex molecules and solids, using quantum information processors. In quantum communication new concepts such as super dense coding, for transmitting information more efficiently, quantum teleportation, to instantaneously transport unknown information from one place to another, and quantum cryptography have attracted attention. In addition a variety of experiments have contributed to answer fundamental questions on the nature of quantum mechanics.

Many of these basic concepts have been developed theoretically in the 90's. Research in the last decade has been devoted to experimentally realize systems able to demonstrate the concepts of quantum information processing and communication in the lab. Major efforts have been made to develop and test technologies based on nuclear magnetic moments in molecules, ions and atoms in electromagnetic traps, spins and charges in semi-conductors, charges and fluxes in superconductors and also in other systems for this purpose.

By now, the basic operation principles of quantum information processors have been demonstrated in a number of systems. Here nuclear spins and ions are the most advanced in terms of the complexity where multi qubit systems have been realized and simple algorithms have been implemented. Ground breaking achievements in this area are the accurate control and read-out of quantum information from individual quantum systems, the generation and characterization of entanglement in multi-particle systems, and the realization of manipulations of complex many particle quantum systems. Here we have reached a level of development, where the understanding of the physics of individual quantum systems is very good to excellent and where one now starts to explore more complex many particle quantum systems and their interactions.

One route that is expected to be viable for initially realizing small to intermediate scale quantum information processors but eventually also larger scale systems is based on solid state electronic circuits. Here the reasoning is that once the elementary building blocks are developed, realized and tested larger systems can be constructed benefiting from the already developed techniques for integrated circuit technologies. At the current stage of development this expectation is starting to materialize.

1.4.2 Hybrid Quantum Systems

Currently a new focus of research on quantum systems for information technology is quickly developing, namely *hybrid quantum systems*. Realizing hybrid systems researchers aim at combining the very best properties of different physical quantum systems to simultaneously explore new regimes of quantum mechanics and to advance the development of quantum information processing technology. Until now, most of the research in quantum information science has focused on investigating particular implementations, e.g. either microscopic quantum systems such as atoms or ions or solid state systems. These different directions of research were sharing conceptual ideas, but were not really joining forces to reach a common goal or gain new insights by making use of the techniques and technologies available in the other field. On the fundamental level, interactions between distinct quantum systems of different nature are just starting to be investigated. A particular focus on trying to evaluate possibilities to realize larger scale quantum systems is developing, in which one is able to maintain full control over the quantum dynamics of all of its constituents.

One major goal is to combine the long coherence times available in microscopic quantum systems with the strong interactions and integration possibilities available in solid state systems. Atoms and ions for example can be effectively isolated from their environment using electromagnetic traps in ultra high vacuum systems allowing for coherence times of up to minutes. On the other hand, the interactions of these systems with control fields are usually weak limiting the effective time scales over which the quantum systems can be manipulated. In a solid state environment the situation is opposite. There the interaction of the quantum system with its environment is strong. This allows for strong interactions with control fields and thus fast manipulation of the quantum state of a system. However, simultaneously these systems tend to have much shorter coherence time due to their stronger interaction with uncontrolled degrees of freedom in the solid.

Thus combining the two, long coherence times of atomic systems with the fast control available in solid state systems, may point towards an interesting route to realize larger scale quantum systems. However, there are three major sets of challenges to be met before such a goal can be reached.

A) The first major challenge is to identify two suitable physical systems between which a quantum coherent interface can be realized. This interface is crucial as it will enable the transfer of information from one system to the other. A particularly important aspect to address concerns the potentially different energy scales of different quantum systems. Some solid state quantum systems have characteristic energy scales in the microwave frequency range where as those of atomic systems are frequently in the optical range.

B) Both solid state approaches to quantum information and atomic approaches to quantum information processing have a high degree of complexity by themselves. Current state of the art experiments performed on theses systems in the context of quantum information are likely among the most complex performed in their respective fields. Thus combining the experimental techniques in a single experimental setup for a joint benefit will be a major effort.

C) To successfully realize a hybrid atomic/solid state quantum system the individual systems and their interactions have to be carefully characterized on a fundamental level. A thorough set of intermediate level experiments have to be performed to successively merge the two technologies into a single one and to perform new break-through experiments with hybrid quantum systems.

The benefits of such an approach will become apparent on a number of different levels. We will experimentally explore and develop novel interfaces between different physical systems and also develop interfaces between the different fields of physics. We will develop new experimental techniques and new tools that go beyond the state of the art in both fields. Gaining full quantum coherent control over hybrid systems will allow us to explore new approaches to quantum information processing and potentially enable us to build more resourceful systems to process quantum information.

1.4.3 The Project

The main goal of this project is to develop an interface between solid state quantum systems and atomic degrees of freedom. In particular we will consider 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 this hybrid quantum information processing approach beyond the current state of the art.

Circuit QED. Since 2002 we have been developing a novel and very successful approach to perform quantum information processing and quantum optics experiments using superconducting electronic circuits. This approach is based on coupling superconducting qubits with large effective dipole moments to on-chip superconducting microwave frequency resonators with large vacuum fields. In this architecture known as circuit quantum electrodynamics (QED) an individual photon stored in the resonator can be coherently coupled to an individual superconducting qubit such that the coherent exchange rate of a single quantum of energy between the resonator and the qubit is much larger than the rate at which the quantum is lost from the qubit or the cavity. In this solid state system, the strong coupling limit of cavity QED was realized for the first time outside the domain of atomic physics. Our achievement now allows researchers in a number of labs world-wide to perform state of the art quantum optics experiments in superconducting electronic circuits. Major achievements include the observation of the vacuum Rabi mode splitting, the time resolved observation of vacuum Rabi oscillations, the demonstration of the quantum-nonlinearity of the Jaynes-Cummings ladder, the realization of a single photon source, the operation of an injection locked single-qubit MASER, the observation of the quantum a.c.-Stark shift, the observation of the Lamb shift, the generation and detection of Fock states, the measurement of the Wigner function of a radiation field, evidencing the great potential of this novel approach to perform quantum optics experiments in electronic circuits.

The controlled coupling of photons to qubits in a superconducting architecture has also enabled progress in superconducting quantum information processing, such as the demonstration of high visibility dispersive qubit read-out, the protection of the qubit from its electromagnetic environment making use of the Purcell effect, the realization of resonant and non-resonant qubit/qubit coupling using the resonator as a quantum bus, the demonstration of quantum geometric phases in superconducting qubits and many more. Accurate control and read-out of individual qubits is realized and first two-qubit circuit QED experiments have been performed. However, high fidelity two qubit manipulations, two-qubit read-out, implementation of quantum algorithms and scalability of the architecture is still to be demonstrated.

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 in a twofold approach. Along one path of research we will explore photon correlation measurements and their use to characterize properties of non-classical radiation fields, such as those generated by sources of single photons or squeezed light. To achieve this goal we will develop circuit QED based detection schemes with single photon sensitivity, which will be based on non-linear parametric amplifiers, on cavity QED approaches to resonantly detect individual photons or on entirely novel approaches. This development will also improve the single shot read-out fidelity of dispersive qubit state detection schemes that may enable multi qubit correlation measurements and fast read-out for implementation in quantum feed-back schemes. The same development will also contribute to the efficient detection of Rydberg atoms as discussed below. Along the major line of research to be funded through this proposal we will explore possibilities to realize an interface between superconducting quantum bits 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 atomic interface to the circuit QED architecture.

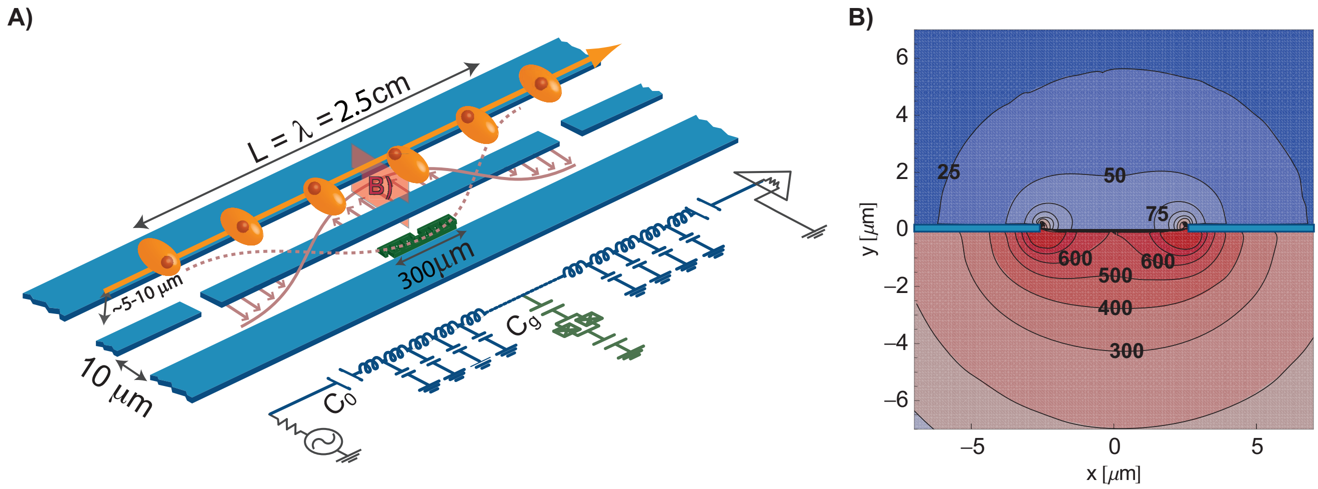

Figure 2: A) Schematic of a circuit quantum electrodynamics resonator (light blue) with an integrated superconducting qubit (green) and Rydberg atoms from a beam passing across the chip. B) Electric field profile of resonator at position indicated in A. Actual vacuum field will scale with operation frequency and geometrical parameters of resonator.

Rydberg Atoms. Rydberg atoms possess large electric dipole moments of several 10^3 atomic units (ea_0) at $n \sim 50$ that scale as n^2 with the principal quantum number. This is the key feature which enables the realization of strong coupling to microwave photons. It has led to the observation of strong coupling cavity quantum electrodynamics which has also been pioneered with Rydberg atoms. The properties of circular Rydberg atoms have been extremely 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 $n > 50$. At the same time Rydberg atoms have long excited state life times in the range of milliseconds. These properties make Rydberg atoms an extremely attractive atomic candidate for coupling to the circuit QED architecture.

Therefore, 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. 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 is well established in the group of Frederic Merkt at ETH. In first experiments the atomic beam will propagate in a controllable distance from a coplanar microwave strip line resonator, see Fig. 2. When tuned into resonance with 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 the 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. Initial experiments will be performed at room temperature. While doing so we will prepare low temperature setups that will work at 70-2 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 of trapped Rydberg atoms. We will carefully evaluate the optimal principal quantum number to be used for final Rydberg atom experiments. Adapting the choice of the atomic species to be used for will allow reduced complexity of the LASER excitation needed to generate Rydberg. 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.

Hybrid Circuit QED. In the final stage of the project we will explore the possibility to strongly couple a single Rydberg atom to a single microwave photon stored in an on-chip cavity. 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 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. We will explore resonant, dispersive and side-band mediated interactions for this purpose. At this point the operation of the experiment in the temperature regime below 100 mK will become essential to achieve optimum superconducting qubit coherence properties.

1.4.4 Impact and Feasibility

This experiment will be among the first ones to experimentally explore atom/solid-state interfaces to realize hybrid quantum systems. When realized such hybrid systems will further 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 circuits on a fundamental level, exploring the effects of materials, temperature and ambient conditions on atomic coherence. At the same time we will develop new tools for atomic physics, such as a dispersive quantum non-demolition detector for Rydberg atoms which could also be used for other atoms or ensembles of atoms with sufficiently large dipole moment. 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.

ETH Zurich will provide one of the worlds best environments to perform the planned research. ETH hosts a number world-class research groups in the field of quantum information science in the areas of atomic physics, physics of super- and semiconducting quantum electronic circuits and in cavity quantum electrodynamics. It provides a stimulating research environment and attracts excellent and motivated students and PostDocs. ETH also provides world class micro- and nano-fabrication infrastructure within its clean-room facilities, and a number of centers in the areas materials research, micro- and nano-sciences, optics and quantum information that facilitate collection of relevant expertise to realize scientifically and technologically demanding projects.

Most importantly, ETH is home to our research group that has developed a high level programm on quantum optics and quantum information processing in the circuit quantum electrodynamics architecture during the last two and a half years. This ERC grant will be an important contribution to establishing our group in the European quantum information science research community. It will also allow us to establish a new direction of research at the intersections of solid state and atomic physics in our group. In the realization of the proposed project we will benefit from expertise and experience of the Molecular Physics and Spectroscopy Group of Frederic Merkt, that is part of the Laboratory of Physical Chemistry in the Department of Chemistry and Applied Biosciences at ETH Zurich. The interaction with the Merkt group and with the group of Tilman Esslinger will facilitate the start our research effort in the direction of Rydberg atom / solid state hybrid quantum systems.