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Rydberg Atoms on a Chip and in a Cell
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POPULAR SUMMARY

QUANTUM INFORMATION PROCESSING

A quantum computer is a device that uses the properties of physical systems described by quantum mechanics to carry out calculations, just like a classical computer uses the properties of systems described by classical physics. Quantum computers can potentially have significant advantages over classical computers: certain problems (such as factoring large integer numbers) can be solved much faster by a quantum computer than by any conceivable classical computer; they can also simulate other physical systems much more efficiently than conventional computers, which is of great interest in many fields of both fundamental and applied research.

The basic unit of the quantum computer is the *qubit*. Like its classical counterpart, the *bit*, information is stored in qubits. However, unlike classical bits which can either take the value 0 or the value 1, qubits can be in a so-called *superposition state* of both 0 and 1 simultaneously. Furthermore, two different qubits can be *entangled*, that is, they can possess strong non-classical correlations — neither may be described without also taking the other into account. These are the properties that make quantum information processing interesting — but they also make it very difficult: unfortunately, these effects are very sensitive to external disturbances — as soon as a qubit interacts with the environment *decoherence* sets in, modifying or destroying the quantum state of the qubit. On the other hand, *controlled* interactions with other qubits are necessary to perform calculations.

It is therefore one of the greatest challenges in building a quantum computer to on the one hand manufacture controlled interactions between qubits, while on the other hand keeping unwanted interactions with the environment to a minimum. Furthermore, one needs to do this in a way which is scalable to a large number of qubits, one needs to be able to manipulate each individual qubit coherently, and one needs to be able to accurately determine the state of the qubits at the end of a calculation.

Our vision for developing such a quantum computer is based on strongly interacting Rydberg atoms above a permanent magnetic lattice atom chip. Here qubits are defined on small clouds of ultracold rubidium atoms, trapped in a regular array of magnetic microtraps formed by the magnetic fields generated by the atom chip and external coils. The qubit state is encoded in two different hyperfine ground states of the atoms. These interact only weakly with the environment, making them very robust against decoherence. To facilitate interactions between different clouds atoms can be excited to strongly interacting high-lying Rydberg states. This is done only during *gate operations*, de-exciting the atoms again as soon as possible to limit decoherence problems. In this way the atoms are strongly interacting only when they need to be, while information storage is done in well-protected ground states. Single qubit rotations can be carried out individually via a pair of Raman lasers, or collectively via combined rf- and microwave pulses. Each qubit can easily be addressed optically due to the relatively large lattice period using relatively simple optical systems. Equally, each qubit can be imaged individually on a CCD camera for readout.

THIS WORK

In this thesis the building blocks of such a quantum computer are developed. In chapter 4 we discuss the design and implementation of the next generation atom chip for quantum information processing developed in Amsterdam. This chip features optimised lattices with both square and hexagonal geometries of 10 μm period, large trap depth and symmetric barriers. Furthermore the top layer is optimised to minimise the dipole moment of adsorbed rubidium atoms. Finally the chip assembly includes a high-NA imaging lens for sensitive absorption imaging of atoms trapped on the chip.

The limits of this imaging system are explored theoretically in chapter 5. In particular we investigate the fidelity with which a single atom in one of our microtraps can be detected using absorption imaging, and determine optimum imaging parameters. We can show that absorption imaging in a standing wave as it naturally occurs in our experiment is more sensitive than traditional single-pass absorption imaging. In our current setup, the presence of a single atom should be discernible with an accuracy of 81% in a single measurement.

In chapter 6 we carefully investigate the effect of electric fields on Rydberg states in a well-controlled environment independent of the atom chip. An accurate understanding of these effects is very important for future experiments on an atom chip due to the high sensitivity of Rydberg atoms for electric fields.

The first steps in this direction are taken in chapter 7 in which we examine the production of Rydberg atoms close to the surface of our permanent magnetic atom chip (but not yet trapped in the lattice). We find that while electric fields are present here, they only shift the Rydberg state energies, but do not lead to any additional decoherence.

While the experiments of this chapter were performed on an older chip generation, in chapter 8 we finally load atoms in the magnetic lattice microtraps of the chip described in chapter 4. We show first results on atom numbers, temperatures and trap homogeneity in this system for both square and hexagonal geometries, and provide first indications of the presence of strong three-body loss leading to number squeezing of the atom number in the traps.