Rydberg atoms on a chip and in a cell
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INTRODUCTION

1.1 QUANTUM INFORMATION PROCESSING

In classical computers, structures in logic chips and memory have become exponentially smaller over the last 40 years, enabling an exponential increase in computing power, power efficiency and storage capacity. As this trend continues, quantum processes are expected to play an ever more important role. While this is usually seen as a threat to the development of (classical) computers, already in the early 1980s it was proposed to make use of quantum mechanical effects for information science and computing purposes [1]. Since that time the field of quantum information processing has rapidly expanded, and one can now distinguish between two distinct strands:

**Quantum Simulation** which uses one well-controllable quantum mechanical system to simulate the behaviour of another system in which it is much harder to directly control or determine (microscopic) quantum states. This is particularly useful as the resources necessary to simulate quantum mechanical systems on classical computers grow exponentially with the size of the system to be simulated.

**Quantum Computation** in which quantum mechanical systems are used to solve certain problems much more efficiently than possible on classical computers. A number of algorithms have been developed for such a quantum computer, the most famous being a method of factoring large integer numbers [2] and for searching an unsorted database [3].

While a tremendous amount of effort has gone into realising physical implementations of a universal quantum computer, success has been limited. David DiVincenzo identified a number of requirements for physical implementations of a universal quantum computer [4], which for our purposes can be summarised as:

**Scalable Qubits**, i.e. the ability to define and address a sufficiently large number of qubits,

**Initialisation** of these qubits, i.e. the ability to put all qubits into a well-defined initial state,

**One-Qubit Operations**, i.e. the ability to perform high-fidelity rotations on each individual qubit, and
TWO-QUBIT OPERATIONS, i.e. the ability to manufacture and control strong interactions between individual qubits,

COHERENCE, i.e. gate operations based on the above capabilities need to be much faster than the decoherence time of the qubit states.

READOUT finally is the ability to accurately determine the quantum state of each qubit after performing a calculation.

While initialisation and one-qubit operations tend to be relatively simple to implement, the other requirements are harder to fulfil. In particular, performing high-fidelity two-qubit operations in a scalable system, has proven to be very challenging. We propose to solve this problem by combining neutral atoms trapped near the surface of a permanent magnetic atom chip with Rydberg interactions between individual trap sites. Using such an atom chip we are able to define a lattice of hundreds of microtraps, each of which can act as a single qubit. By exciting atoms in these traps to Rydberg states we can implement efficient, controllable two-qubit interactions between neighbouring lattice sites; furthermore, the logical qubit can be encoded in the ground state of the atom, using Rydberg excitations only for gate operations, which should drastically improve the coherence times of the system. The relatively large lattice periods in our system should allow optical addressing and readout of single qubits.

1.2 ATOM CHIPS

Ultracold atoms on atom chips are key to new atom-based technologies such as interferometers and precision sensors and provide access to fundamental aspects of many-body physics, atom-surface interactions, quantum metrology and quantum information science. So far experiments have dealt with atoms prepared in the electronic ground state, due to their intrinsic stability. Despite their weak interactions, ground-state atoms on atom chips have been used to sensitively probe the intrinsic thermal noise near surfaces, map magnetic and electric field distributions, and investigate the Casimir-Polder potential in the micrometer range.

While most atom chips employ current-carrying wires in order to create the magnetic potential necessary for trapping neutral atoms, we use a layer of permanent-magnetic FePt magnetised perpendicular to the plane of the chip. Using lithographic techniques we remove parts of the magnetic material to form a pattern which can – in conjunction with an external homogeneous magnetic field – be used to create a lattice of microtraps for neutral atoms. The lattice period in our system is currently 10 µm, a value which would lead to prohibitively high current densities using current-carrying wires rather than permanent magnets. This lattice period allows us to populate hundreds of traps, i.e. to form hundreds of potential qubits while retaining the ability to optically resolve individual trap sites.

1.3 RYDBERG ATOMS

Rydberg atoms possess a number of properties making them interesting both from the perspective of fundamental research, but also as a tool for quantum information processing.
In particular, atoms excited to high-lying Rydberg states have extremely large transition dipole moments (scaling with $n^2$) resulting in long-range interactions and have large electric polarisabilities ($\propto n^7$) which can greatly enhance both atom-atom and atom-surface interactions. Because atoms can be coherently brought from ground to Rydberg states and vice versa they promise not only strong interactions, but *controllable* strong interactions. This means that atoms can be briefly excited to a Rydberg state to perform e.g. a quantum gate operation, but the quantum state can be encoded in the ground states of the atom, making it much more robust to external perturbations.

Recent experiments with Rydberg atoms have largely been motivated by the excitation blockade mechanism [25, 26]. The research in ultracold Rydberg atoms has resulted in two landmark experiments demonstrating dipole-blockade for two individual atoms [27, 28] as well as c-NOT quantum gates between two atoms mediated by Rydberg interactions [29, 30], but has also inspired further experiments on mesoscopic ensembles in the blockade regime [31]. Cold ensembles of Rydberg atoms have been used for electrometry [32–35]. Rydberg dipole blockade has been observed in cold ensembles of atoms using Electromagnetically Induced Transparency (EIT) [36–38] and it has been proposed to directly observe spatially resolved dipole blockade through EIT [39, 40]. Interactions can be further enhanced and controlled in the presence of modest electric fields via Förster resonances [41] over distances of tens of micrometers [42–44], making them very suitable for generating interactions in our atom chip setup.

1.4 THIS THESIS

In this thesis we explore the potential of combining ultracold atoms trapped on a permanent-magnetic lattice atom chip with the excitation to strongly interacting Rydberg states. The results presented here are merely the first steps towards strongly interacting Rydberg atoms on an atom chip.

We first discuss some of the theoretical background of Rydberg excitation in both room-temperature and ultracold atomic vapours in chapter 2. We primarily concentrate on the properties of individual Rydberg atoms as well as optical methods of Rydberg state detection. As dipole-interacting Rydberg atoms do not play an important role in the experimental results presented here, these are not discussed in detail. Furthermore, the theoretical background necessary for the understanding of all of the common tools of ultracold atomic physics, such as magneto-optical trapping and cooling, magnetic trapping and forced radio-frequency evaporation is not discussed here in any more detail. For this the reader is referred to a number of excellent theses, review articles and books [45–48] and references therein.

We describe the experimental apparatus used for our experiments in some detail in chapter 3. This includes the laser- and vacuum systems, electronic components and computer control. In chapter 4 the permanent magnetic lattice atom chip developed as part of this thesis is described in detail. Here some background is given on optimising the magnetic pattern for different trapping geometries, including the basic theory necessary for understanding magnetic trapping in z-wire traps as well as our microtrap arrays. The magnetic patterns chosen in our setup are discussed, as well as further technical aspects of the infrastructure surrounding the atom chip.
Absorption imaging is used for the detection of atoms in our setup. This has a number of interesting properties if employed in a reflecting double-pass geometry as is the case here. The merits of such an approach to absorption imaging are discussed in chapter 5, where detailed simulations of the absorption signal of individual atoms in different geometries are presented. These allow us to determine the optimum imaging parameters for our setup, as well as to estimate the fidelity of single-atom detection.

Chapter 6 finally presents the first experimental results on Rydberg atoms. However, we first investigate the rich level structure of Rydberg atoms in electric fields in an independent setup involving a room-temperature rubidium vapour in a glass cell. This greatly simplifies the experimental setup, allowing us to investigate the effects of both static as well as time-dependent electric fields on Rydberg states in a rapid manner. It is particularly surprising to find that even in a room-temperature vapour Rydberg spectroscopy can be performed with excellent frequency resolution, allowing the investigation of Rydberg state hyperfine splittings in addition to (and combination with) Stark spectroscopy in electric fields.

Chapter 7 combines Rydberg excitation with ultracold atoms trapped near the surface of our atom chip. This allows us to investigate the effects of the chip surface on Rydberg state energy levels in a spatially resolved manner. The results can be used to determine electric fields near the chip surface with very high accuracy.

Finally in chapter 8 we show the first results of loading neutral atoms in the magnetic lattices presented in chapter 4. Here we present both hexagonal as well as square trap geometries with a lattice period of 10 µm. This should prove to be an excellent starting point for demonstrating strong dipole-interactions on our chip in the future.