Towards Quantum Information processing on *Atom Chips*

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Scientific and technological progress in the last decades has proven that miniaturization and integration are important steps towards the robust application of fundamental physics, be it electronics and semiconductor physics in integrated circuits or optics in micro-optical devices and sensors. We postulate the same to be true for atomic physics and quantum optics. We envision the atom chip [1] as a monolithic integrated matter wave device combining the best of two worlds: the extensive techniques of coherent quantum manipulation established in quantum optics and atomic physics and the capabilities of micro-fabrication, micro-electronics and micro-optics to implement these processes in a very robust way. A successful implementation will allow us to establish a new experimental toolbox to study fundamental questions in mesoscopic quantum physics of small highly entangled systems which holds good promise for quantum information technology [2,3,4]. In the framework of this talk we will give an overview of the various methods to implement QIP on an atom chip and of the current status of the experiments.

On the atom chip cold neutral atoms can be stored, guided and manipulated in miniaturized traps above a substrate using either microscopic patterns of permanent magnetization, micro-fabricated wire structures carrying current or charge, or specially designed light fields and dipole traps. Bose-Einstein condensates (BEC) can be loaded into such atom chip micro-traps, and then serve as a coherent source of atoms. An open question is the role of the interactions between the warm surface and the atoms, and the resulting decoherence. Within our EU collaboration ACQP we have been engaged in developing theoretical models for the relevant loss, heating, and decoherence rates. At distances of the order of 10 μm from the hot chip surface, decorence rates of ~1s are expected [5].

Besides this general outline of QIP on atom chips we will report on recent results on the way towards this goal in our experiments.

With thermal ^{7}Li atoms we loaded a spiral-shaped magnetic two-wire guide which, in contrast to the regular single-wire guide, allows guiding of atoms along any direction on the surface. The potential minimum is formed by two counter-propagating currents together with a homogeneous bias field in the direction perpendicular to the chip surface. The symmetry of this configuration allows guiding in arbitrary directions on the chip. This will be necessary to access arbitrary individual sites in a micro-trap array forming a qubit register.

In a second experiment, we are investigating the novel capabilities introduced by adding electrostatic fields which provide an additional degree of freedom in designing the potentials. The key issue for QIPC is here that such traps are qubit state dependent, and can be used for state dependent manipulation. This is based on the fact that in a combined magnetic-electrostatic potential $U = g_F \mu_B m_F B - \frac{1}{2}\alpha E^2$ the magnetic part depends on the magnetic quantum number m_F while the electrostatic part does not. This can be exploited in a magnetic double well potential: The height of the barrier between the two wells will be different for different m_F-states so that it can be state-selectively removed by introducing an attractive electrostatic field. Atoms in the magnetically strongly confined state will then remain in two separated traps while atoms in the weakly confined state will be able to collide.

So far we have employed in our experiments electrostatic fields to modulate the potential of a magnetic guide so that new three-dimensional trap geometries are formed. We have experimentally demonstrated an electric, potentially state selective motor, where individual such traps can be moved along a guide by ramping the voltages on different electrodes along the path of the guiding wire. This constitutes a useful method for a controlled transport of atomic clouds and eventually individual qubits. We are currently studying state dependent conditional operation with clouds of thermal atoms as a first step towards implementing the 2-qubit gate based on controlled collisions as proposed by [3]. The progress towards this goal will be discussed.

In a different set of experiments we are aiming at testing the feasibility of an implementation of a qubit using the external (e.g. motional states in the trapping potential) degrees of freedom of the atom [4]. A newly set up apparatus was designed to facilitate the production of a Bose-Einstein condensate of ^{87}Rb atoms which forms the starting point for the experiments. Our progress towards probing the coherent evolution of motional states using various interferometers in the atom chip environment will be presented.

An important step will be to individually select, address, manipulate and detect single atoms and small mesoscopoic ensembles on the chip. To achieve this we work towards the integration with other quantum optics, micro optics and photonics techniques involving micro-lenses, wave guides, micro-cavities, and photonic band gap materials. As an example we will discuss a scheme to detect single atoms using moderate Q micro-cavities. Such a cavity could be created for example by two wave guides on a chip or using a DBR fiber cavity or a ring cavity, with a small gap for the cold atoms. Having atoms localized to better than 100 nm (<< wavelength of light) in steep traps should allow a small gap, a small waist and precise positioning of the atoms for maximum coupling. Recently we could show that signal to noise ratios of $>5\sigma$ can be obtained for detection of a single atom in 10 μs using existing technology [6]. We will discuss the progress towards an experimental realization of such a detector.

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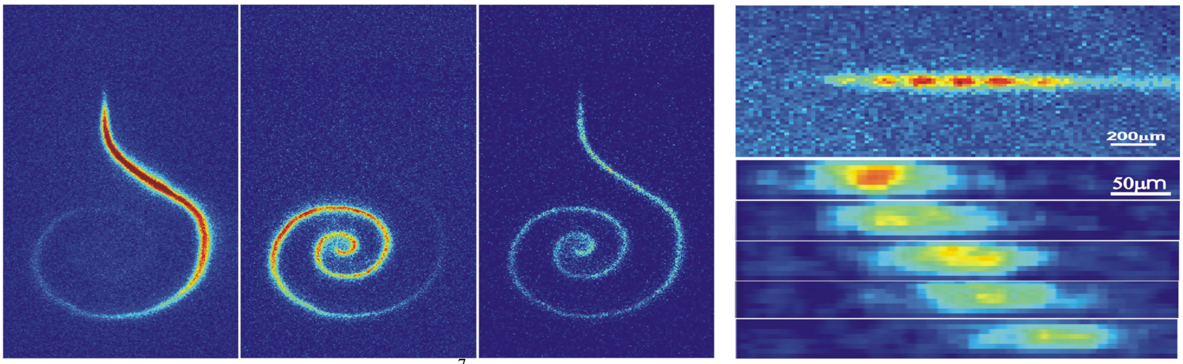

Left: Sequence of fluorescence images of ^{7}Li atoms expanding into a 2cm long spiral-shaped magnetic two-wire guide (15, 70, and 235ms after release into the guide). Atoms reaching the end of the guide after several turns are reflected.

Top right: ^{7}Li atoms in a string of six combined electrostatic-magnetic traps. A magnetic side guide (I=1.6A, B_{bias}=44G) is modulated by applying 300V to electrodes along the guide. **Bottom right**: An electrostatic ‘motor’: By ramping the voltages on the electrodes, a moving trap can be used to transport atoms along the guide. In this example, the atoms were moved over a distance of 140µm within 30ms.