Abstract

The investigation of dilute gases of ultracold atoms is currently a fast growing field, both in experimental and theoretical physics. Major research directions include the simulation of condensed matter systems, the investigation of superfluidity and the realization of controlled quantum chemistry. In this thesis we present our contributions in form of several experiments covering four different topics, sharing the usage of optical lattice potentials and the tunability of interatomic interactions.

In a three-dimensional optical lattice, we investigate the properties of ultracold atoms for various interatomic interaction strengths. Such a system can be described by the Bose-Hubbard model, which originates from solid state physics. For large repulsive values of the interaction strength, we create a strongly interacting system and show the breakdown of the basic assumptions of the Bose Hubbard model by precisely measuring the excitation spectrum. When preparing a Mott insulating state and subsequently changing to attractive interactions, we observe a surprising stability and find indications that the system stabilizes itself via inhibited three-body loss, grounded on the quantum zeno effect.

We examine the dynamics of matter waves along a lattice potential by analyzing Bloch oscillations, which occur when a force is applied along the lattice direction. The effect of interactions and of external force gradients is investigated in detail, and we can demonstrate the analog between this system and the Talbot effect known from classical optics. When modulating the applied force, we observe large oscillations in position space, so called super Bloch oscillations, which can be used to induce transport along the lattice direction without dissipation.

In a set of experiments, we achieved the production of ultracold rovibronic groundstate molecules, a prerequisite for many fundamental studies in quantum chemistry. We associate ultracold atoms to weakly bound dimers employing a Feshbach resonance, and use an optical lattice to shield the molecules against inelastic collisions. Subsequently we transfer them into the rovibronic ground state using the STIRAP technique, removing a binding energy corresponding to a temperature of $\sim 5200\,\mathrm{K}$ without additional heading. This allows full control over all internal and external degrees of freedom.

Elongated tubes created by an optical lattice potential realize an effective one-dimensional geometry, which we use to study the physical models describing such systems. For strong repulsive interactions we enter deeply into the regime of the Tonks-Girardeau gas, a gas of impenetrable pointlike particles. Employing a confinement induced resonance, we can switch the interactions to strong attractive values and thereby prepare a novel, highly excited quantum phase, the Super-Tonks-Girardeau gas. By adding a weak lattice along the tubes, we observe the so-called pinning quantum phase transition from a Luttinger liquid to a Mott insulator.