SUMMARY

Some of the most intriguing phenomena in physics arise in strongly interacting many-body quantum systems. Those systems, however, e.g. solid state devices or astronomical objects, are hard to access experimentally and their theoretical understanding poses great challenges, as most theories are exact only in the regime of weak interactions. Now, ultracold gases serve as a highly controllable quantum system that allows to continuously explore all the range from weak to strong interactions by means of Feshbach resonances. Hence, ultracold gases are employed to test advanced many-body theories and to push our understanding of strongly interacting quantum matter. The present thesis is devoted to pursue this fundamental approach and discusses experiments on superfluidity in a homonuclear Fermi mixture and on the behavior of an impurity with a novel heteronuclear Fermi-Fermi mixture.

We study the rotational dynamics and coherence of a superfluid mixture of ^{6}Li atoms in two different Zeeman states. To prove superfluidity of the gas directly in the regime of strong interaction, we measure the moment of inertia of the gas. We find the moment of inertia to stay below the value of a rigid body, as a consequence of the irrotationality of the superfluid. A further property of a superfluid is the coherence among the particles, as a macroscopic fraction of the particles occupies the ground state. We probe this coherence by letting two independently created samples interfere. We observe interference for moderate repulsive interactions, where the Fermi mixture forms a Bose-Einstein condensate of weakly bound molecules. In the regime of strong interaction, however, the high scattering rate hinders the overlap of the two clouds and they collide hydrodynamically.

The heteronuclear Fermi-Fermi mixture is realized with ^{40}K and ^{6}Li atoms. First, we characterize the elastic and inelastic scattering properties at one of the interspecies Feshbach resonances. Then we demonstrate strong interactions by observing hydrodynamic expansion. The signatures are an inversion of the cloud aspect ratio and collective flow of ^{40}K and ^{6}Li atoms. In the regime of strong interactions, we investigate the behavior of few ^{40}K atoms in a Fermi sea of ^{6}Li atoms. Following Fermi liquid theory of L. Landau, impurity plus excitations are described as a quasiparticle, which is coined the "repulsive polaron" in our case. We show the existence of these repulsive many-body states in the regime of strong interaction by radio-frequency spectroscopy and measure their quasiparticle properties: interaction energy, residue, and lifetime. The remarkably long lifetime, at the specific Feshbach resonance we employ, may open up new possibilities to investigate novel quantum phases in strongly repulsively interacting Fermi gases.