Abstract

We explore the crossover from a molecular Bose-Einstein condensate (BEC) to a Bardeen-Cooper-Schrieffer (BCS) superfluid of "Cooper paired" fermions with an ultracold gas of fermionic ^{6}Li atoms. The crucial parameter in the crossover is the coupling strength between the paired atoms. At sufficiently low temperatures a BEC of tightly bound molecules is formed in the strong coupling limit, while in the weak coupling limit a BCS state of delocalized pairs is created.

A magnetically tunable scattering resonance at a magnetic field of about 834 G serves as the experimental key to explore various coupling regimes. Through this Feshbach resonance we control the interactions in the gas and vary the coupling strength over a broad range. The starting point for our experiments is a molecular BEC of tightly bound pairs that we produce by evaporative cooling of an optically trapped ^{6}Li spin mixture. Exploiting the Feshbach tuning, we explore the BEC-BCS crossover by studying elementary macroscopic and microscopic properties of the gas.

The analysis of density profiles of the trapped cloud in the BEC-BCS crossover shows that it is smooth and reversible. Moreover, from the measured cloud size on resonance we are able to determine the value of an universal parameter, which characterizes the interaction energy of the unitary limited quantum gas.

To investigate the collective dynamics of the gas in the BEC-BCS crossover we excite energetically low-lying collective modes in the axial and radial directions of our cigar shaped trap. The collective oscillations of the modes in the axial direction show the expected behavior of a gas in the BEC-BCS crossover with a particularly small damping rate in the vicinity of the Feshbach resonance. The modes in the strongly confined radial direction, however, show an abrupt change in the collective oscillation frequency at a magnetic field value that corresponds to a Fermi gas in the strongly interacting regime. A plausible explanation for the observed breakdown of the hydrodynamic behavior is the coupling of the collective oscillation to the pairs in the strongly interacting Fermi gas, which leads to pair breaking.

Employing radio-frequency spectroscopy, we study the pairing energy in the BEC-BCS crossover. We demonstrate the dependence of the pairing energy on the coupling strength, temperature, and Fermi energy. The observation of an early onset of the pairing in the evaporative cooling process strongly suggests that for full evaporation the strongly interacting Fermi gas is in the superfluid phase.

Our experiments open up intriguing prospects for further experiments on the fascinating properties of strongly correlated many-body regimes that are of great relevance for several fields of physics; like quantum fluids, neutron stars, and most prominently high T_c superconductors.