Universiteit van Amsterdam

An Atomic Marble Run to Unity Phase-Space Density
C.C. Chen

Summary

This thesis describes an experimental setup for expanding the Sr “laser cooling to Bose-Einstein condensate (BEC)” experiment into a steady-state system. The apparatus was designed to explore the possibility of realizing a long-awaited holy grail for ultracold atoms, a steady-state BEC to feed a steady-state atom laser. At the beginning of my thesis, the experiment was started from scratch with an empty table. Four and a half years later we have achieved a steady-state ultracold Sr sample with a unity phase-space density (PSD), of the same order of magnitude as a quantum degenerate gas. Our first attempt to make a steady-state Bose-Einstein condensate was unsuccessful, but from this we have come up with an alternative deceleration scheme in order to load efficiently the reservoir, which so far was the experiment’s main bottleneck. We will soon implement this solution in a second attempt to reach steady-state BEC. In the following I summarize the results of my thesis work.

In our work on a steady-state high-PSD magneto-optical trap (MOT), we have demonstrated a proof of principle “atomic marble run” experiment, a cooling architecture in which laser cooling modules employing two different wavelengths are implemented successively. The modules consist of an atomic beam source, a transversal cooling, beam deceleration and trapping. The first module starts with the Sr oven beam source and ends in a 2D broad-line MOT. This MOT feeds the second module, which ends in a narrow-line “capture” MOT. This last MOT is the source of the third and final module, which ends in a steady-state reservoir of atoms. Atoms are continuously decelerated and cooled from a few hundred Kelvin to about 1 μK. The two cooling transitions (broad-line, blue cooling at 461-nm wavelength and narrow-line, red cooling at 689 nm), which in conventional Sr quantum gas experiments are used in time-sequential cooling steps, are in our machine implemented sequentially in space. In the steady-state “capture” red MOT, we show slowing of an atomic beam with a starting velocity of 6 m/s and followed by trapping in a MOT using the 689-nm intercombination transition with a natural linewidth of 7.4 kHz. In the high-PSD MOT configuration, we demonstrate a steady-state red MOT with a PSD of 10^{-3}, two orders of magnitude better than reported in previous

steady-state MOTs. The experiment illustrates the concept of an “atomic marble run” and shows that it is compatible with future experiments on the creation of a continuously existing quantum degenerate gas and dead-time free atom interferometers or clocks.

In our work on steady-state ultracold Sr near quantum degeneracy, the experiments were carried out by extending the steady-state high-PSD MOT work and adding another cooling module. We realized an ultracold beam with a 10^{-5} PSD, an ideal source for future steady-state superradiant laser applications. We also took a first attempt at expanding the “laser cooling to BEC” experiment into a steady-state experiment. We showed a method that can continuously fill atoms into the reservoir trap of the "laser cooling to BEC" scheme. We achieved a steady-state ultracold Sr sample with a unity phase-space density, only a factor of 2.6 away from steady-state quantum degeneracy. This experiment ultimately was limited by the reservoir temperature.

To circumvent this temperature bottleneck, we developed a new and more efficient method to decelerate the atomic beam in our last cooling step before loading atoms into the reservoir trap. Inspired by a theoretical paper of Peter Zoller from 1994 and a cooling proposal originally formulated for cooling anti-hydrogen, we demonstrated a new deceleration scheme using a Sisyphus cooling mechanism in an optical lattice instead of a radiation pressure force commonly used in laser cooling. The optical lattice induces a periodic ac Stark shift on atoms’ excited state, creating a spatially varying potential landscape. Thanks to selective excitation to the lattice potential minimums, an atom loses energy via repeatedly “climbing uphill” through multiple cycles of excitation and spontaneous emission. We characterized the performance of this deceleration method and developed a semi-classical model describing its various working regimes, which depends on the relative magnitude of atoms kinetic energy with respect to the lattice height. Such a method not only provides a new deceleration scheme for our future attempts to reach steady-state BEC, but it can also bring laser cooling to a broad range of atomic and molecular species.