Chapter 1

Introduction

Laser cooling of atoms has led to many spectacular advances in atomic physics, including precision atom interferometry, atomic-clock technology, and has made possible the creation of Bose-Einstein condensates and degenerate Fermi gases, which have spawned countless experiments furthering our understanding of atomic physics and the quantum world. These remarkable results have been primarily confined to systems using alkali neutral atoms and ions, and metastable noble gas atoms, due mainly to initial experimental ease of atomic manipulation and cooling, and the resultant extremely low (microkelvin) temperatures to which they could readily be cooled. There is, however, great interest in extending these experiments to a larger pool of atom choices. The alkaline-earth atoms are of particular interest and hold great promise for use in a variety of atomic physics experiments. The even isotopes of the alkaline-earth atoms have no nuclear spin, simplifying their atomic structure. Also, the narrow singlet-to-triplet intercombination lines common to all alkaline-earth atoms present themselves as possible choices for novel optical frequency standards based on neutral atoms, as well as other spectroscopic and atomic experiments utilizing narrow transitions. Due to the abundance of even and odd isotopes available among these atoms, physicists are also looking towards the alkaline-earth atoms for the next-generation Bose-Einstein condensate and degenerate fermi gas experiments.

Successful pursuit of these various applications will require laser-cooled alkaline-earth atoms at approximately the same temperatures that have made cold alkali atoms so useful to atomic physicists. However, progress in the laser cooling of alkaline-earth atoms has been hampered by two main factors: technical challenges and comparatively warm (mK) trapped-atom temperatures. Over the past decade, the technical challenges including low vapor pressure and awkward laser wavelengths, have been, for the most part, successfully addressed by several groups, culminating in numerous demonstrations of laser-cooled alkaline-earth atoms, beginning with Kurosu and Shumizu[1]. The temperature of the trapped atoms, however, presents a larger problem. In contrast to the alkali atoms, using the most straightforward methods of laser cooling and trapping on alkaline-earth atoms has led to temperatures of a few millikelvin, rather than a few microkelvin, (except in some extremely recent experiments with odd isotopes of Sr[2]). This is not the result of technical problems of cooling, but is rather due to a fundamental limit set by the energy-level structure of the atoms themselves. Thus, new strategies for the cooling of alkaline-earth atoms must be developed.

This thesis focuses on our development of a novel method of second-stage cooling for alkaline-earth atoms and our experimental demonstrations of this new cooling method, which have reduced the temperature of neutral ^{40}Ca from the millikelvin to the sub-microkelvin range. This technique, termed "quenched narrow-line laser cooling" (QNLC), exploits the energy-level structure of alkaline-earth atoms, and can be readily extended to other atomic systems with narrow transitions. In addition to experiments with QNLC in one and three dimensions, this thesis also describes an important application of the cooling, namely to improve the performance of optical atomic clocks, which hold great promise as frequency standards of the future. Our frequency metrology experiments based on neutral Ca atoms at microkelvin temperatures will be explored, with focus on the limitation of these measurements due to the temperature of the atoms. With the use of ultracold Ca atoms derived from QNLC, we have shown that systematic errors and frequency shifts in the atomic standard can be dramatically reduced, and would improve the performance of the Ca optical frequency standard at NIST by more than an order of magnitude, making it competitive with the best atomic Cs-based fountain clocks in accuracy and far better than existing standards in frequency stability.

The layout of my thesis is as follows. The next chapter gives an overview of alkaline-earth atom cooling and an introduction to second-stage QNLC. In Chapter 3 QNLC itself is discussed in more detail, including 1-D Monte Carlo simulation results of QNLC specifically designed to explore experimental cooling options for ^{40}Ca. A description of the Ca experimental apparatus follows in the next chapter, outlining the necessary components for both second-stage quenched cooling and for frequency metrology. Chapter 5 details our 1- and 3-D quenched cooling experiments and results, and compares those results to theory and simulation. Measurements of the fractional frequency instability and absolute frequency of the Ca "clock" transition using millikelvin temperature atoms are documented and discussed in Chapter 6, including systematic uncertainty analysis. Spectroscopy with ultracold atoms is demonstrated in the penultimate chapter, and spectroscopic and experimental techniques are explored for the improvement of the calcium optical frequency standard. The final chapter summarizes my work with ^{40}Ca and describes other uses for ultracold Ca atoms and the high level of stability and accuracy possible with optical frequency standards.