

Chapter 8

Conclusions

My thesis explores the method of quenched narrow-line laser cooling, which we show can produce sub-Doppler cooling in ^{40}Ca atomic samples. The impetus for this research lay in improving the optical frequency standard based on the $^1S_0 \rightarrow ^3P_1$ intercombination line in neutral ^{40}Ca being developed at NIST. The cooling techniques developed for trapping and cooling of neutral atoms had greatly increased both the stability and accuracy of microwave-based frequency standards. Optical frequency standards have the potential to improve upon the original microwave standards, but the atomic systems that provide ideal optical transitions, the alkaline-earth atoms and other atoms with singlet to triplet forbidden transitions, typically only have Doppler-limited cooling available on their strong $^1S_0 \rightarrow ^1P_1$ lines. The implementation of narrow-line cooling allowed Sr and Yb atoms to reach the same microkelvin temperatures as their alkali counterparts, bursting through this Doppler barrier limiting alkaline-earth atom's usefulness. Our successful investigation and implementation of quenched narrow-line laser cooling (QNLC) extends the utility of the alkalines to include Ca and Mg. Even without QNLC our demonstrations of the ^{40}Ca optical frequency standard show more than an order of magnitude improvement in short-term stability over microwave-based standards. With quenched-cooled atom we stand poised to reach the accuracy of the best Cs-fountain clocks. Even greater potential for improvements in this accuracy and stability will be gained by the standard through the transfer of the ultracold atoms into

a lattice trap.

Monte Carlo simulations of 1-D QNLC taught us much about the quenched narrow-line cooling process and the best methods for experimental implementation. Using this knowledge, we demonstrated QNLC of ^{40}Ca atoms first in one and then in three dimensions. The techniques were quite different, as in the 1-D case we used a sequential, pulsed scheme, and in the 3-D case we used a simultaneous quenching and cooling method. We were able to cool calcium atoms to $9\ \mu\text{K}$ in three dimensions, which allowed us to use these atoms to significantly improve the stability and accuracy of the ^{40}Ca -based optical frequency standard. Further demonstrations of third-stage, 1-D cooling showed the potential for the creation of an increasingly coherent atomic sample, which will be useful for spectroscopy and other atomic physics experiments.

“Extreme frequency metrology”[101], that is, metrology performed with the high level of stability and accuracy already achieved and still potentially achievable with optical frequency standards, has many more applications than simply for absolute frequency measurement. Navigation and communication technology can be expected to find ways to utilize the improved accuracy and stability of optical frequency standards, just as the GPS navigational system came into being with advances in microwave-based standards. I have already discussed uses for optical frequency standards in secure communications based on their increased short-term stability over microwave standards. Another use for these very accurate optical frequency measurements is to test for possible changes in fundamental constants (such as α) over time. Our absolute frequency measurements gave stringent restraints on the change in the measured frequency ratios of Ca and Hg^+ to Cs over time[91] Direct connection of these ratios to α will require further theoretical analysis. The high levels of stability and accuracy that have been demonstrated could also be used to test the isotropy of space, if there is a preferred reference frame, and for Lorentz and CPT (charge-parity-time) symmetry violations.[102, 103, 104, 105, 106]

New directions in optical frequency metrology include confinement of alkaline-

earth atoms in optical lattices. Not only does this potentially improve the conditions for their use as a frequency standard, but can be used as a springboard to other atomic physics realms. Many physicists are looking towards alkaline-earth atoms as the next group for the exploration Bose-Einstein condensation (BEC). Many of the alkaline-earth elements have multiple even and odd isotopes with relatively large natural abundances that researchers are excited to use for making mixtures of BEC and degenerate fermi gasses. There are many different ways in which these atoms can be cooled to approach the temperatures and densities needed for BEC, including using dipole and lattice traps. Due to the large densities of dipole-trapped atoms, these traps greatly reduce the time needed to create a BEC, and atoms confined in an optical lattice can be evaporatively cooled to high phase space densities. Another option for the alkaline-earth elements is magnetic trapping in the 3P_2 state, which looks quite promising.[26, 29] Compression of the trapped atoms with magnetic fields to increase the density, and evaporative cooling on this transition could facilitate the densities needed to produce a BEC.

With the development of narrow-line cooling and now our demonstration of quenched narrow-line laser cooling, alkaline-earth atomic temperatures can be reduced to the microkelvin range and below. These unique atomic systems stand poised for deeper exploration. Recent advances in odd isotope trapping [2, 101] show just a few of the many unexplored facets of alkaline-earth atom physics still to be explored. Just as the cooling and trapping of alkali atoms to the microkelvin range led to astounding new research in BEC, fermi degenerate gasses, high resolution spectroscopy, and high accuracy and stability microwave frequency standards, ultracold alkaline-earth atoms have great potential in optical frequency metrology, high resolution spectroscopy and for presently unknown and unimagined applications in atomic physics.