Ultra-Cold Atomic Strontium: Sub-Photon Recoil Cooling, Momentum-Space Crystals, and High Precision Optical Metrology

Narrow line magneto-optical traps (MOTs) are rapidly advancing the frontier for high precision metrology, exotic states of matter, and tests of fundamental symmetries. These unique and versatile systems have, for example, enabled all-optical pathways to quantum degeneracy, nuclear-spin based sub-Doppler cooling, recoil-free spectroscopy of both dipole allowed and doubly-forbidden optical transitions, and neutral atom optical clocks with record-setting fractional uncertainties of $< 10^{-15}$. In the future, narrow line MOTs will likely play key roles in next generation tests of the time invariance of fundamental constants and studies of the qualitatively new, anisotropic physics expected to operate in ultra-cold samples of heteronuclear molecules. Narrow line cooling, via the relative size of the transition natural width and the single-photon recoil frequency shift ω_R , also displays a novel set of thermal-mechanical cooling dynamics. In this seminar, I will review my recent work with narrow line Strontium (Sr) MOTs and the application of these systems to high-precision optical metrology. By controlling the relative size of ω_R and the effective cooling transition linewidth, I first show that it is possible to smoothly bridge the gap between semiclassical and quantum mechanical cooling. In the latter case, temperatures of roughly half the photon recoil limit are achieved despite the incoherent excitation provided by the trapping beams. Unique semiclassical cooling processes, some of which explicitly depend on the relative size of gravity and the radiative force, will also be described. The talk will next focus on gravitationally assisted cooling with blue-detuned light and the formation of 3D momentum-space crystals containing up to 26 well-defined packets arranged according to a face-centered-cubic lattice. Finally, I will conclude with a description of absolute frequency measurements of the ⁸⁸Sr ${}^{1}S_{0}$ - ${}^{3}P_{1}$ clock transition (frequency f_{c}) performed with a phase-coherent optical comb and referenced to the NIST F1 primary Cs time standard; the leading contributors to systematic shifts, in this case due largely to density-dependent processes, will also be detailed. The final value, $f_c = [434\ 829\ 121\ 312\ 334\ \pm 20(\text{stat})\ \pm 33(\text{sys})]$ Hz, reduces the previous uncertainty for this line by > 200× and is the most accurate value for the ⁸⁸Sr $^{1}S_{0}$ - $^{3}P_{1}$ clock frequency obtained to date.