

Chapter 2

Cooling alkaline-earth atoms

2.1 Doppler cooling

When looking to cool alkaline-earth atoms, experimentalists naturally turned to the techniques that have been used with such success for alkali atoms. The simplest of these, Doppler cooling, based on initial proposals by Wineland and Dehmel, and Hänsch and Schaulow[3, 4], can be applied to and works quite efficiently with alkaline-earth atoms. The name Doppler cooling comes from the fact that the radiation pressure force in this cooling method can be made to be velocity dependent by taking advantage of the Doppler shift. By carefully detuning the laser light to about a natural linewidth below the resonance frequency of an atomic transition, atoms with velocity opposing the \vec{k} of the red-detuned laser beam are brought into resonance. If a resonant atom absorbs a photon, conservation of momentum of the photon + atom system dictates that it will gain that photon momentum as it becomes excited, reducing its velocity. When the atom spontaneously emits a photon during the decay process, a momentum kick of one photon recoil in a random direction will change the velocity of the atom, but this additional velocity gain averages out in all dimensions leading to overall cooling. In its simplest form, the mechanics of Doppler cooling can be used in the creation of an “optical molasses”[5], where atoms are slowed using one or many red-detuned laser beams, and are slowed as if travelling through a viscous medium.

One can utilize the power of the velocity reduction of Doppler cooling to help trap

atoms, as well. In a weak inhomogeneous magnetic field the internal energy levels of the atoms are split into their Zeeman components. By using circularly polarized light to cool the atoms in the presence of this magnetic field, these atoms can also feel a spatial force pushing them towards the zero of the field. Using a quadrupole magnetic field and retroreflected, circularly polarized laser beams in a 3-D geometry enables cooling and trapping in all three dimensions.[6] This type of magneto-optical trap, or MOT, was first demonstrated with the trapping and cooling of alkali atoms, but the method can be easily extended to atomic states that have broader cooling linewidths by increasing the magnetic field gradient.

The basic differences between alkali and alkaline-earth MOTs come in how the MOT is loaded with atoms and in the strength of the magnetic field needed for trapping. The most common type of alkali MOT is a vapor cell MOT, where atoms are loaded into the MOT from atomic vapor in the vacuum system housing the trap. Alkaline-earth atoms need to be heated to higher temperatures to achieve the same vapor pressure as alkali atoms. While a specially designed alkaline-earth vapor cell MOT has been implemented [7], other alternative methods first developed for alkali atoms, such as Zeeman slowers [8] and additional far-detuned laser beams used to slow an atoms coming out of an oven [9] have been successful in loading large numbers of alkaline-earth atoms into a MOT. The second difference is that alkaline-earth atoms need a larger magnetic field gradient for trapping, as the needed field scales roughly with the linewidth of the cooling transition. Alkaline-earth atom cooling transitions, with linewidths 3 to 10 times greater than alkali atoms, cycle photons that much faster, making the cooling process quicker, but require magnetic field gradients 3 to 10 times times greater to induce the same trapping force. With these needs taken into consideration, alkaline-earth atoms of Ca, Sr, and Mg [1, 10] have been cooled and trapped in MOTs using their respective broad and nearly closed $^1S_0 \rightarrow ^1P_1$ transitions, with atom cloud temperatures approaching the Doppler limit. While Yb is not an alkaline-earth element, its two-

electron structure gives it many similarities to the alkaline-earths, and I will often group them together. Yb has also been Doppler cooled and trapped in broad-line MOTs, achieving similar millikelvin temperatures.[11]

The theory of Doppler cooling was well understood at the time of the first cooling experiments. Using a semi-classical theoretical model as described in detail in Reference [12], Doppler cooling has a limit for the lowest achievable temperature of the atoms at

$$T_D \simeq \frac{\hbar\Gamma_{cool}}{2k_B} \quad (2.1)$$

where T_D is the Doppler limit temperature, k_B is the Boltzmann's constant, and Γ_{cool} is the natural linewidth of the transition. It was then quite a surprise to the atomic physics community when alkali atoms were cooled to far below this theoretical limit using a simple optical molasses.[13] Theoretical investigations of this result focused on the fact that in Doppler-cooling theory, only a simple, two-level atomic model had been used. Sub-Doppler cooling was made possible through an additional frictional force on the atoms that occurs when the Zeeman and hyperfine level structures of the atoms being cooled interact with the spatially varying polarization gradient of the cooling light in a non-adiabatic manner.[14, 15] Because hyperfine level structure was inherently present in the alkali atoms being used for all initial cooling experiments, sub-Doppler cooling by these mechanisms was bound to occur, creating cold, trapped atoms with temperatures corresponding to a few photon recoils, ranging from 1-20 μK for the various alkali atoms. In fact the sub-Doppler cooling limit results from the photon energy imparted to the atom during spontaneous decay rather than being set by the transition linewidth.

Subsequent cooling methods, including velocity selective coherent population trapping (VSCPT) [16] and coherent optical Raman coupling [17, 18], took advantage of these microkelvin atomic temperatures to help further cool the atoms by exploiting the ground-state sub-structure in other ways. Due to the quantum-mechanical nature of the internal states of atoms, it is possible not only to excite an atom into another

energy eigenstate (as is done in Doppler cooling), but to excite the atom into a superposition state of multiple (usually two) levels. With this method the superposition state is decoupled from the laser fields and is no longer resonant with the optical pumping lasers, leaving the atoms “trapped” in an unexcitable dark state. A special case of this is VSCPT, in which the dark state created by the Raman beams is velocity dependent. This allows atoms that are in or can be transferred into arbitrarily narrow velocity classes to be trapped, leading to ensembles of atoms with the characteristic of having extremely well defined momenta that are necessarily incredibly delocalized. (A more in-depth theoretical analysis of VSCPT can be found in References [19] and [20].) This cooling method is in fact able to achieve temperatures well below what would be the recoil limit for sub-Doppler cooling mechanisms.[16]

Raman cooling can be used not only to select certain velocity classes of atoms [21], but to actually cool atoms [22, 23]. Like VSCPT, Raman cooling allows the loading of a velocity dependent dark state, but in a more active way. Using a sequence of stimulated Raman pulses, atoms can be excited with resonant light, the recoil energy of the absorbed photon slowing down or speeding up the velocity of the atoms until they are in a velocity class that can no longer be excited by the available light. These dark states can be quite narrow. Raman cooling is powerful in the way that one can tailor the Raman pulse shape so as to enhance and improve cooling, achieving trapped atom temperatures well into the subrecoil regime.[22] (As we will see in Chapter 3, Raman cooling has several features in common with the quenched narrow-line laser cooling (QNLC) that we use in our second-stage cooling of calcium. Of course we cannot use Raman cooling with ^{40}Ca atoms, as its ground state has no hyperfine levels to support a Raman two-photon transition; we instead utilize the narrow $^1S_0 \rightarrow ^3P_1$ transition for velocity selective cooling.)

The most abundant isotopes of the alkaline-earth atoms have zero nuclear spin, which leaves their singlet ground-state (1S_0) with no magnetic sub-structure, and, there-

fore, they cannot benefit from the additional sub-Doppler cooling mechanisms in the same way as their alkali counterparts. Thus, laser-cooling utilizing the ground state of the alkaline-earth atoms is truly Doppler limited, which for the broad $^1S_0 \rightarrow ^1P_1$ cooling transition yields temperatures of ~ 1 mK, corresponding to a velocity of nearly 1 m/s. Further reduction of the atomic temperature thus requires a fundamentally different approach to laser cooling.

2.2 Methods for sub-Doppler cooling of alkaline-earth atoms

In searching for cooling methods that could bring the temperature of alkaline-earth atoms down to the microkelvin regime, there were some distinctly different directions one could pursue.

The odd-numbered alkaline-earth isotopes do have ground-state sublevel structure due to a non-zero nuclear spin, and can reach sub-Doppler temperatures through the same polarization gradient processes as the alkali atoms. Kurosu and Shimizu were the first to trap some of the odd isotopes of Ca and Sr.[1] For some atoms, such as Ca, the natural abundance of these isotopes is small (~ 0.1 % for ^{43}Ca and significantly less for the other isotopes), but for some of the other alkaline-earths, the natural abundance can be significantly greater (e.g. ~ 7 % for ^{87}Sr). Katori was the first to discuss the use of odd Sr isotopes as the basis for an optical frequency standard.[24] Very recently the Jun Ye group at JILA has trapped and cooled the ^{87}Sr isotope to sub-Doppler (300 μK) temperatures using the broad $^1S_0 \rightarrow ^1P_1$ cooling transition and standard $\sigma^+ - \sigma^-$ MOT light, showing that single-stage cooling with a large trapped atom number is possible with the odd-numbered alkaline-earth isotopes.[2] A very simple dual-isotope MOT has been demonstrated to trap various combinations of bosonic and fermionic Yb isotopes in the same trap.[25] These are very promising results as there may be some advantages in using odd-numbered isotopes for optical frequency standards, even beyond their easily obtained microkelvin temperatures, as I will discuss in Chapter 7.

Although the ground-state of the even-numbered isotopes has no sub-structure, polarization-gradient cooling methods could be applicable to these alkaline-earth elements by first exciting the atoms to a metastable state with Zeeman substructure before cooling. Unfortunately this would add to the experimental difficulty of the cooling method, as atoms would first have to be pumped into an excited state that would hold them long enough to cool on a further excited state. To facilitate the transfer of atoms into one of these excited states, we can utilize the fact that in alkaline-earth atoms the 1P_1 energy level has other decay routes besides the direct decay to the 1S_0 state. Atoms excited to the 1P_1 state slowly leak into the 3P_2 energy level via a singlet D level (see Fig. 2.1 for the representative energy level scheme for calcium). Because of the long lifetime and magnetic sublevels of the 3P_2 state, there has been much speculation about using this level to magnetically trap these atoms [26], and experimental insight is given for Mg, Ca, Sr and Yb atoms in a recent paper by Loftus *et al.*[27]. With a trap depth on the order of ~ 1 K, atoms in the 3P_2 state do not need any extra cooling beyond initial Doppler cooling on the $^1S_0 \rightarrow ^1P_1$ transition in order to be magnetically trapped. In fact, one would expect atoms in the weak-field seeking states to be already trapped in our MOT's quadrupole field. Sr and Ca atoms have both been magnetically trapped in this state.[28, 29] Indeed, Grünert and Hemmerich have also shown that additional sub-Doppler cooling of atoms in this state is possible. His group utilized the leak to the 3P_2 state during cooling on the broad line, which allowed atoms to collect in this state. They then superimposed a second MOT over the first, cooling on the $^3P_2 \rightarrow ^3D_3$ line at $\sim 1.9 \mu\text{m}$, whose $J = 2 \rightarrow J = 3$ level structure enabled polarization gradient cooling processes. With this experimental design, they have been able to trap 3×10^8 atoms in this 3P_2 level, with MOT temperatures of $< 20 \mu\text{K}$. This is a promising method, as the Doppler-limited temperature and recoil-limited temperature are $1.3 \mu\text{K}$ and 122 nK , respectively, but $1.9 \mu\text{m}$ is a difficult laser color to work with, and an additional repump laser at 430 nm is also needed in order to return the atoms to the ground state.

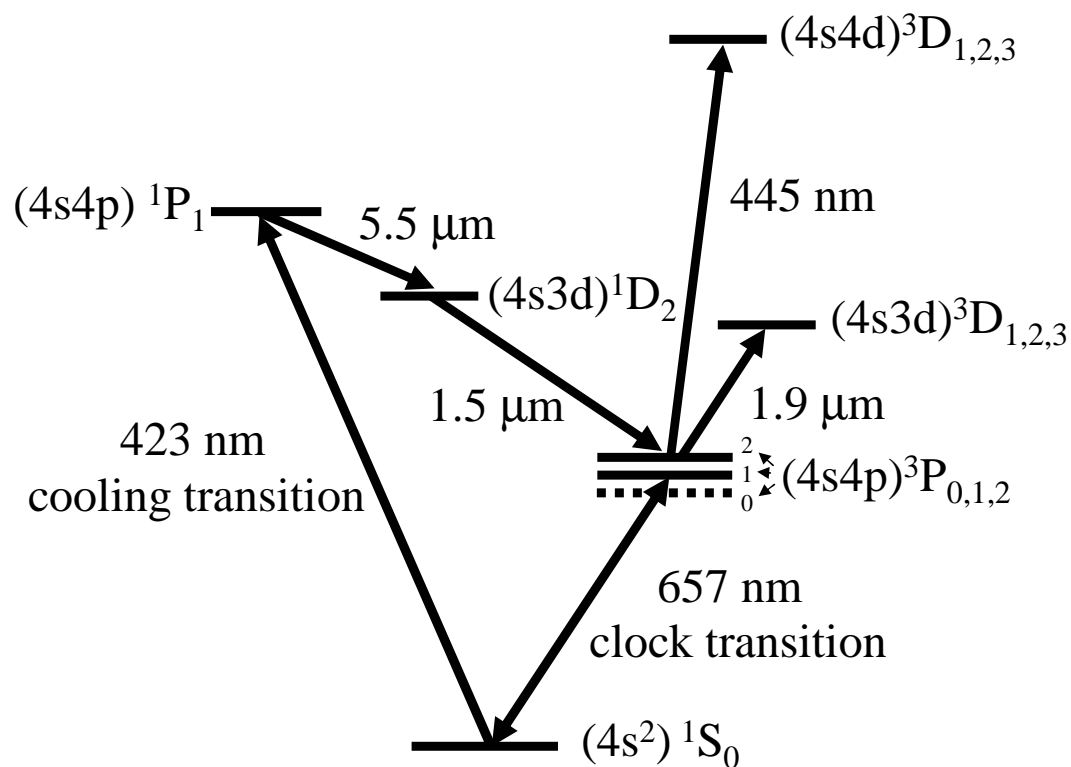


Figure 2.1: Atoms excited into the $1P_1$ state leak into the $3P_2$ state via a $1D_2$ state. Once there, the atoms can be magnetically trapped in the $3P_2$ state and further cooled using higher level triplet-D states.

Although unexplored to date, another possible transition in Ca for cooling the 3P_2 state is the 445 nm line. Cooling on this line would lead to a recoil-limited temperature of $\sim 2.4 \mu\text{K}$.

Still, if we could cool atoms to lower temperatures directly from excitation of the ground state, we could greatly simplify the cooling process. To this end, one can use the $^1S_0 \rightarrow ^3P_1$ transition at 657 nm to cool the atoms. Due to the relatively long lifetime ($\sim 400 \mu\text{s}$) of this transition it can act as a velocity selector, picking out narrow subsets of atoms from the initial velocity distribution. If one excites a narrow (cold) subsection of the atoms from the ground state into the 3P_1 state, one can then use the broad transition at 423 nm to rethermalize the atoms remaining in the ground state, reducing the overall temperature of the system. By repeating this process one can accomplish substantial cooling in 1-D as was demonstrated by Binneweis *et al.*[30]. Unfortunately, this method cannot be extended into multiple dimensions due to heating of the other dimensions during the rethermalization of the atom cloud. For many applications, including atomic frequency standards, atoms must be cold in all three dimensions to be useful.

2.2.1 Narrow-line cooling

Alternatively, one can take advantage of the high velocity selectivity of the clock transition in a more general way. I discussed before that the relatively warm temperatures of the laser-cooled alkaline-earth atoms come from Doppler limitations of cooling on a broad transition. In fact, Doppler cooling can also be implemented using a narrow transition, which at least on the surface is an extremely promising proposition, as the Doppler limit goes as the natural linewidth of the transition. For the Ca intercombination line, with a natural linewidth, $\Gamma/2\pi = 400 \text{ Hz}$, this would correspond to a Doppler limit of $\sim 10 \text{ nK}$! However, for cooling on extremely narrow lines, the photon recoil frequency becomes larger than the natural linewidth of the cooling transition, invalidating the semi-classical model of Doppler cooling assumption of $\nu_{recoil} \ll \Gamma_{cool}$.

Doppler-cooling theory can be extended to include narrow transitions, as long as a full quantum-mechanical treatment is used, as explored in detail in References [31] and [32], where the intercombination line of the alkaline-earth atoms is discussed as a likely candidate for narrow-line cooling. In the special case of these narrow lines, it is encouraging to note that the true Doppler-cooling limit can be shown to be about half of the recoil temperature, which is more than a factor of 1000 below that of typical broad-line Doppler limits, easily allowing the atoms to reach temperatures of just a few microkelvin. This method is technically straightforward to implement because experiments using these atoms often already contain lasers at the intercombination-line frequency. But, as we will see, the implementation of narrow-line cooling techniques varies with different species of alkaline-earth atoms.

Strontium is perhaps a particularly good candidate for narrow-line cooling and trapping. It has both a broad cooling transition in the blue at 460 nm that is ideal for first-stage cooling, and a narrow transition in the red at 689 nm, which is 7.6 kHz wide, for use in narrow-line cooling. Much work has been done in the past few years in the groups of Hall and Katori, demonstrating how second-stage narrow-line cooling can reduce Sr atom temperatures to the recoil limit.[7, 33] More recently, neutral Yb, which has energy-level structure quite similar to the alkaline-earth atoms, was loaded into a narrow-line MOT without any first-stage broad-line cooling. Instead of an initial MOT stage, the atoms from an atomic beam were slowed with the use of a Zeeman slower furnished with light from the broad transition, and then loaded directly into the narrow-line MOT ($T = \sim 20 \mu\text{K}$).[34]

These groups found that they could not simply mimic the broad-line methods of Doppler cooling to achieve efficient cooling and trapping in 3-D. In fact, it is not possible to cool an entire millikelvin distribution of atoms by just shining light from the narrow transition on them, as is done for broad-line cooling. A disadvantage of narrow-line cooling, which is equally problematic for all alkaline-earth elements, is that these

narrow lines cannot access all velocity classes of atoms at just a single laser detuning, since the Doppler coverage of the light is so much narrower than the Doppler width of the atomic velocity distribution.

There are many ways to overcome this difficulty and cool and trap large numbers of atoms using a narrow transition. The design of the Sr and Yb narrow-line MOTs were both based on the theoretical work of Wallis and Ertmer [35], who discuss in the cited reference a way to expand the velocity subsection that could be cooled. If the actual laser being used for narrow-line cooling is broadened spectrally either with noise or in a more controlled way, such as with modulation sidebands, then a broader distribution is created in the frequency (velocity) domain. This cw, broadened light can be engineered to cool a significantly larger number of atoms than can single-frequency narrow-line cooling. The Wallis and Ertmer paper also discusses the use of second-stage cooling for alkaline-earth atoms, where the atoms are initially cooled using the broad line before beginning the narrow-line cooling.

The Katori group was the first to trap Sr on the intercombination transition in three dimensions. They utilized the approach of first-stage cooling on the broad $^1S_0 \rightarrow ^1P_1$ line to amass a large number of atoms. The magnetic field gradient was then reduced from ~ 80 G/cm to 5 G/cm, and these atoms were transferred into a red MOT. In order to capture a larger percentage of the atoms from the initially broad velocity distribution, the laser light for the red trap was frequency modulated, producing a comb of frequencies covering the Doppler shift of the initial distribution. At the end of the cooling processes, single-frequency light was used to further narrow the final velocity distribution. Their narrow-line trap yielded atom temperatures of < 400 nK, with phase space densities (density of atomic sample divided by the atoms' de Broglie wavelength) of 10^{-2} .

Although this second-stage narrow-line cooling scheme was shown to work well in Sr and Yb, Ca atoms are at a disadvantage for exactly the same reason that Ca was

chosen over these atoms for the development of our optical frequency standard: the 400 Hz natural linewidth of the narrow transition. The broader intercombination lines of Sr and Yb can cycle many more photons for narrow-line cooling during a set amount of time than can the corresponding transition in Ca. Also in Ca, the force created by these few photons is barely enough to hold the atoms up against gravity, as $a = v_{rec}\Gamma/2 = 19 \text{ m/s}^2$ for the 657 nm transition, where a is the acceleration, v_{rec} is the recoil velocity for the 657 nm transition, and Γ is the linewidth of the transition. Another issue due to the long decay time comes to light when the blue trapping beams are turned off, as is necessary in order for second-stage cooling to induce no heating. The millikelvin-temperature atoms have enough initial velocity to move out of the area of the trapping region where the cooling beams are located before the red cooling light can sufficiently reduce their velocity. These same problems hold for Mg atoms. Both Ca and Mg show great promise for use in atomic interferometry and as optical frequency standards, but in order to be able to use their narrow transitions for second-stage cooling to more useful microkelvin temperatures, we have to find a way to speed up the cooling process.

2.2.2 Quenched narrow-line laser cooling

One way to circumvent the long lifetime of the narrow cooling transition while still utilizing its special cooling properties is to optically quench the slow spontaneous decay from the 3P_1 state. Quenching describes the act of using a second intermediate state in order to facilitate the return of the atoms to the ground state from their position in the excited state *without* having to wait the duration of the natural lifetime of the narrow (long-lived) transition. The concept of quenched cooling as a way to enhance narrow-line cooling rates first appeared in the context of sideband cooling of trapped ions [36]. In an effort to use laser cooling to reduce the energy of a single ion to the ion trap's zero-point motional energy ground state of motion, the Wineland group at NIST, Boulder, first cooled a single $^{198}\text{Hg}^+$ ion using standard Doppler cooling on its

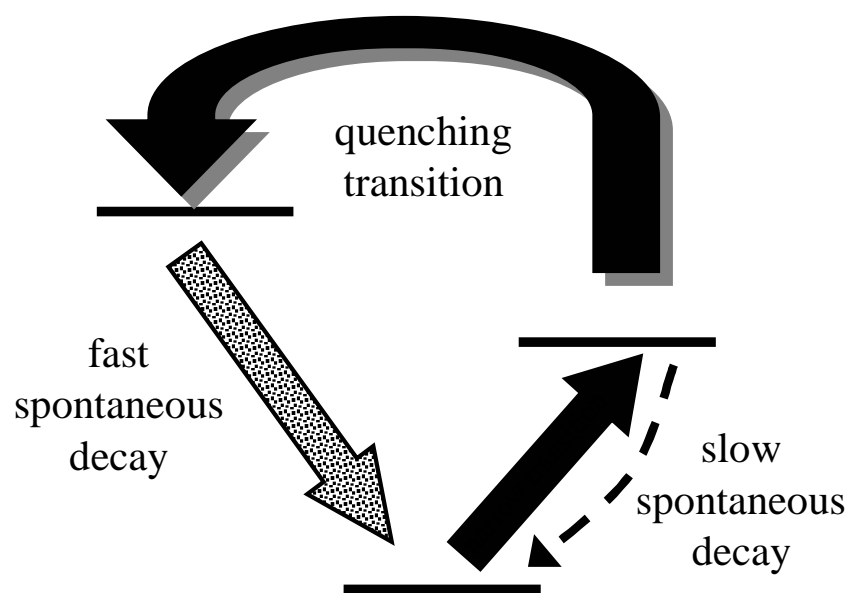


Figure 2.2: Basic energy levels involved in quenching a narrow transition. Atoms are excited on the narrow transition and then transferred to another state with a shorter lifetime, from which the atoms will quickly decay back into the ground state.

broad transition. They then applied light on the narrow transition to induce side-band cooling. To circumvent an extremely slow scattering rate of 6 photons/s on this narrow transition (and needing about 6 photon-atom interactions for the ion to be sufficiently cooled), they coupled the excited state to a much faster decaying state, where the atom would have a high probability of quickly returning to the ground state. Once back in the ground state, the ion could once again be excited by a narrow-line photon. In this way the ion's sideband cooling could progress at a much faster rate. When applied to neutral atoms, quenching can be used to increase the cycling rate of absorbed photons in exactly the same manner. The technique of quenching would make it possible to use the intercombination line to second-stage narrow-line cool our Ca atoms.

With quenching in place to speed up the cooling process, many of the same transition broadening tricks I discussed before with Sr and Yb can be applied when trying to cool Ca atoms. However, another way to effectively broaden the narrow transition without modulation is to use pulses of light with a discrete temporal length, rather than a continuous light source. Using a pulsed method of cooling, the breadth of the velocity distribution covered in a single cooling pulse can be varied by changing the width and power of the cooling pulses.

In the next chapter I will describe in more detail our theoretical exploration of 1-D cooling using this method of pulsed, single-frequency quenched narrow-line laser cooling, and also how broadened narrow-line cooling could be effective for cooling and trapping ^{40}Ca in 3-D.