

Appendix D

Reaching the Doppler limit: Broadline cooling of ^{40}Ca atoms

Since the first-stage cooling produces the effective starting point for the second-stage cooling, it is useful to discuss the blue Doppler cooling in a little more detail. In ^{40}Ca we use the broad, 34 MHz, $^1S_0 \rightarrow ^1P_1$ transition at 423 nm to initially Doppler cool the atoms. Even though the theory of two-level Doppler cooling seems quite straightforward, we find that using standard Doppler-cooling methods, we can only cool our trapped atoms to about 2 mK. This is in fact not at the Doppler limit, as the theoretical limit is 813 μK . Other alkaline-earth atom trappers have seen similarly warm MOT temperatures. Extensive work was done by Vogel *et al.* at JILA [45] to bring Sr trapped atom temperatures down to the true Doppler limit. The most obvious experimental reason for the warmer temperatures is that the Doppler limit itself is misleading in an experimental sense, since it refers to the limit when the cooling laser intensity is reduced to zero.

The following equation gives the expected 1-D rms velocity of a broad-line Doppler-cooled atom cloud, taking into consideration the power and detuning of the trapping beams.

$$v_{rms} = v_D \sqrt{\frac{1 + \beta + \delta^2}{2|\delta|}}$$

In this equation, $v_D = \sqrt{\hbar\Gamma/2M}$ is the Doppler limit for the velocity of the atoms. The v_{rms} will deviate from this lower limit unless the normalized detuning $\delta = 2\Delta/(\Gamma/2\pi)$ is equal to 1, implying that the detuning Δ of the trapping beams is at half a natural

linewidth Γ of the transition. Also, to reach the Doppler limit, β must go to zero. This is a low intensity limit, as β is the ratio of the sum of the intensity of all six cooling and trapping beams to the saturation intensity, which is defined as the amount of intensity needed to excite half the atoms ($I_{sat} = 2\pi^2 c \hbar \Gamma / 3\lambda^3 = 57.7 \text{ mW/cm}^3$ for our 423 nm transition.) Under standard operation in our system, where the ratio of $I/I_{sat} = 0.26$ and the blue light is detuned about one linewidth from resonance, we would expect v_{rms} to be about 47 cm/s, and it is instead nearly a factor of 2 higher, about 70 cm/s. Similar results were seen in the Ca experiments at PTB [66] and with Sr atoms [33, 7]. Many possible heating sources such as stimulated emission and molecule formation were discussed and discarded in the thesis of Kurt Vogel.[45] In recent discussions with Alan Gallagher at JILA, a new possibility has surfaced. This heating mechanism could be related to the dispersive force of the standing wave created by the trapping beams, although this still needs to be verified experimentally. (Note: Recent experiments specifically designed to probe the Doppler limit in ^{88}Sr have been performed in the Ye group at JILA. Reference [108] gives the details of this work.)

Since the second stage cooling schemes under consideration in our lab had limited capture ranges, it was clear that reaching closer to the Doppler limit with first-stage cooling could improve second-stage transfer efficiency. Thus, we followed the lead of the JILA group in attempting to reduce our MOT temperatures by reducing the intensity of the trapping beams. Termed “transient Doppler cooling” by the JILA group, large numbers of atoms are first trapped in a “high power” MOT and then the trapping light intensity is ramped down to reduce the temperature of the trapped atoms.

As you can see from Figure 4.1, we were able to greatly reduce our atom cloud rms velocity, but were not able to maintain large atom numbers in the process. Very interesting to note is that we were able to cool the atoms to sub-Doppler temperatures with this transient Doppler cooling. We believe that this was possible due to the fact that, in the cooling time shown, the atomic cloud had not reached an equilibrium state

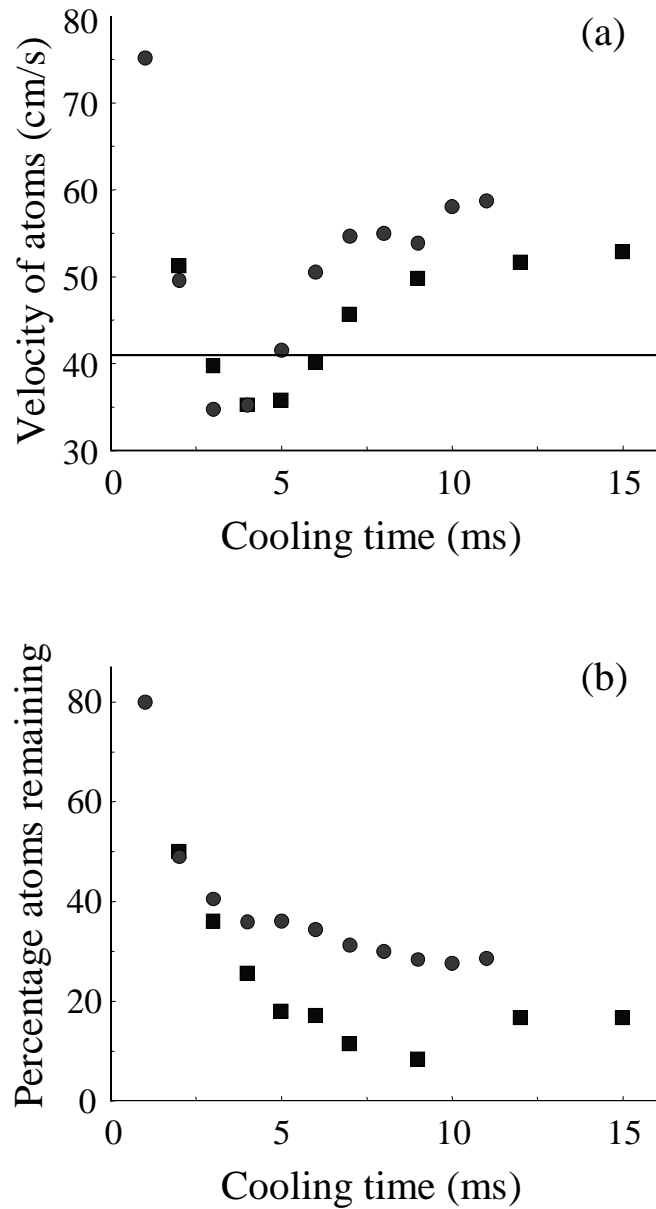


Figure D.1: Atoms are trapped and cooled with a high power blue MOT for 12 ms. Plotted are the resultant velocity (a) and percentage (b) of atoms remaining after some ms of reduced blue intensity cooling. Square data points refer to data taken for a blue intensity ramping down time constant of $600 \mu\text{s}$ and circles are data taken with a ramp decay of $100 \mu\text{s}$. The solid line in (a) shows the theoretical Doppler limit for the rms velocity of the atom cloud.

in three dimensions, and that, although the atoms reached sub-Doppler temperatures in the dimension we were measuring, the other dimensions may well be heating. Similar oscillations into the sub-Doppler regime were seen by the JILA group, who were able to attribute this to a sloshing of the atom cloud's center of mass in the trap. By varying the speed at which we ramped down the blue laser intensity from "high" power to the minimum power ($\beta = 1/16$), we reached approximately the same lowest frequency in about 3 ms, but with the slower time constant (600 μs vs. 100 μs), many more atoms were lost. If we were to increase the speed of the blue light turn off any more, the atoms number would again be reduced due to atoms sloshing out of the trap.

After these trials, it was decided that the extra time needed to reduce the temperature and the significant loss of atoms would not outweigh the possible benefits of increased transfer efficiency to a second-stage MOT. Thus, we did not use this method to reduce the MOT temperatures in practice for pre-second-stage cooling.