Spatially truncated optical pumping cooling

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Abstract
We present both the theoretical description and experimental implementation of a novel cooling technique for ultracold atoms trapped in a confining potential. We call the technique 'spatially truncated optical pumping cooling.' By using the fact that the internal states of atoms can be manipulated by laser light focused on only part of a confined ultracold gas, high energy atoms can be preferentially selected and then slowed to achieve cooling without requiring the loss of any atoms. This technique uses cooling photons more efficiently on a per photon basis than Doppler or polarization gradient cooling, while having approximately the same degree of difficulty with regard to experimental implementation.

1. Introduction
Laser cooling has enabled a large number of experiments at ultracold temperatures [1–5]. The most common forms of laser cooling, Doppler and polarization gradient cooling, are useful as a first stage in laser cooling in a wide variety of systems. These have temperature limits such that additional cooling is needed in order to perform experiments in Bose–Einstein condensation [6, 7], Fermi degenerate gases [8, 9], precision atomic clocks [10, 11], ultracold molecule physics [12, 13], and other areas [14, 15]. Both evaporative cooling [16, 17] and laser cooling methods [18–20] beyond Doppler and polarization gradient cooling have been used to extend the temperature range for such experiments. Each method has advantages and disadvantages, and so the exploration of new techniques broadens the range of possible experimental parameters for advantageous laser cooling, allowing either improvements in experiments or enabling experiments to be performed that otherwise could not be.

This article describes a laser cooling technique we call 'spatially truncated optical pumping (STOP) cooling.' STOP cooling is designed to cool a gas of ultracold atoms that have been initially cooled and then confined in a conservative potential. In STOP cooling, the atoms need to have multiple ground states (e.g. different hyperfine states) so that some atoms can selectively be made to interact with a particular laser frequency while the remainder do not. Atoms in the latter category are referred to as being in 'bright states' while those in the former are in 'dark states'. The main idea behind the cooling scheme is to use the fact that the atoms in a conservative potential oscillate spatially in that potential. The atoms thus continuously trade energy back and forth between potential energy and kinetic energy. By selecting atoms with high potential energy, waiting for that energy to be converted to kinetic energy, and then removing that kinetic energy via light scattering, STOP cooling reduces the temperature of the gas.

Our cooling technique has several advantages. First, STOP cooling is straightforward to implement in most ultracold atom experiments that use a magneto-optical trap (MOT) [2–4] as the first stage of laser cooling. Through the use of acousto-optic modulators (AOMs), all of the required STOP laser beams can be derived from the existing MOT beams. More broadly, STOP cooling makes efficient use of photons for cooling in that, as will be described in detail below, they are all directed opposite to average atom motion and only high-energy atoms scatter the light. Since cooling limitations are very often ultimately linked to the rate of photon scattering [21–23] efficient use of cooling photons is potentially quite advantageous. Experiments that can only initially achieve a limited number of trapped atoms would benefit from the fact that STOP cooling does not require the loss of the...
trapped atoms in order to cool. This technique has relatively few requirements for the internal structure of the atoms to be cooled, and so should be widely applicable. Again, the main requirements are the presence of dark and bright states and a confining potential. The availability of a cycling transition is useful, but not critical. This means that STOP cooling can be extended to cooling some types of ultracold molecules, although in that case an additional laser or lasers may be necessary, as we discuss later in this article.

As a first step in describing STOP cooling, we present an overview of the cooling technique. Our implementation of STOP cooling consists of a sequence of four steps, which are illustrated in figure 1. The starting point for STOP cooling begins with atoms in thermal equilibrium and trapped in a confining potential. It is assumed that all of the atoms are optically pumped into one or more dark states. The first step is to spatially overlap a laser beam with the edge of the trapped gas where the potential energy of the trapped atoms is the highest. The atoms that are in the region of overlap are optically pumped into an internal bright state. The optically pumped atoms are then given time to move on average to the center of the confining potential, where much of their initial potential energy is converted into kinetic energy. At this time, a scattering beam is directed...
opposite to the optically pumped atoms’ center-of-mass motion. By transferring linear momentum from the scattering beam photons to the atoms that have been optically pumped, those atoms’ center-of-mass velocity is reduced to zero. Once they have been slowed, the final step is to optically pump the atoms back into dark states. This results in a reduction of the average energy. Upon rethermalization, the temperature of the gas is reduced. STOP cooling is similar in some ways to one-way wall [24–27] and Sisyphus cooling techniques that rely on trapping potentials [28–31], but is very different from those in how the cooling mechanism works and because there is no need for the confining potential to depend on the internal state.

In the rest of this article, we describe STOP cooling theoretically and present an experimental implementation of the technique. Section 2 presents the theory used to model STOP cooling, along with predictions for expected energy reduction from applying STOP cooling to an ultracold gas. Section 3 describes our initial experimental implementation used to perform measurements of STOP cooling. Section 4 discusses the results from our STOP cooling experiments. Section 5 discusses comparisons between model predictions and experimental results. Lastly, section 6 summarizes our conclusions.

2. Theory of STOP cooling

In order to predict STOP cooling performance in a general way, we perform a series of calculations assuming idealized conditions. In these calculations, the atoms are assumed to be confined in a one-dimensional simple harmonic oscillator potential. The atoms are also assumed to be in thermal equilibrium. A characteristic oscillation frequency, \( \omega \), is chosen for the atoms. Their time dependent positions and velocities are then determined using the basic equations of motion for a simple harmonic oscillator.

Assuming the atoms are in thermal equilibrium leads to a spatial density distribution proportional to \( \exp(-U/(k_B T)) \), where \( U \) is the harmonic trapping potential, \( k_B \) is Boltzmann’s constant, and \( T \) is the temperature of the gas. The experiment is performed with \(^{87}\text{Rb}\), so its mass, \( m \), and parameters appropriate to its \( 5S_{1/2} \) to \( 5P_{3/2} \) cycling transition are used for these calculations. To model the spatial selection in the first step of the technique, a cooling cycle calculation starts by identifying all of the atoms with a spatial position greater than an axial cut-off distance, denoted by \( z_0 \) in figure 1, as atoms that will be subjected to the STOP laser beams. To model the optical pumping process in the first step of STOP cooling, each of these atoms is assumed to randomly scatter photons from the first STOP cooling beam such that each photon scatter has a 50% probability of transferring the atom into the bright state. It is also assumed that enough photons are scattered by these atoms so that all are in the bright state, and the number of photons scattered by a given atom is labeled as \( n_i \). Physically, the cut-off distance corresponds to the ideal edge of the laser overlap region in the experiment where atoms with the highest potential energy were optically pumped into a bright state.

With a well-defined fraction of atoms in a bright state, the next step of the calculation is to allow those high-energy atoms’ center-of-mass to move to the center of the harmonic potential. The ideal time that allows the atoms’ center-of-mass to reach a maximum velocity is used (\( \frac{\pi}{2} \) period of the atoms’ oscillation in the potential). After this time, the bright state atoms’ center-of-mass is slowed by simulating the application of a scattering beam. This is done by simulating scattering photons directed opposite to the atoms’ center-of-mass motion. We assume that each bright state atom randomly scatters \( n_2 \) photons according to a Poisson distribution, \( P_{n_2}(n_2) \), where \( n \) is the mean number of photon scatters. Once the atoms’ center-of-mass has been slowed, the last step is to close the STOP cooling cycle by optically pumping the atoms back into their original dark state. It is assumed that each atom randomly scatters photons from this final beam with each scatter resulting in a 50% probability of the atom being optically pumped to the dark state. The number of photons scattered by an atom in this step is labeled \( n_3 \). Since this final optical pumping beam propagates in the same direction as the scattering beam, it also provides slowing power for the atoms’ center-of-mass motion. An absorbed photon from the scattering beam or the final optical pumping beam is assumed to impart \( \hbar k \) of momentum (where \( \hbar \) is the reduced Planck constant and \( k = 2\pi/\lambda \) where \( \lambda \) is the wavelength) directed along the z-axis.

Putting the above considerations together leads to the following set of equations to model the change in energy from a single STOP cooling cycle. Equation (1) is the normalized one-dimensional Maxwell–Boltzmann thermal phase space density describing the position and velocity distribution of the atoms at time \( t = 0 \) (where \( z_0 \) is the initial position and \( v_0 \) is the initial velocity). Equation (2) is the average energy of the bright state atoms as a function of \( n \) photons scattered, where \( n = n_2 + n_3 \). Equation (3) is the average single-cycle energy reduction as a function of \( n \). Note that the integrations in equations (2) and (3) are over the initial condition variables and the limits of integration extend over all relevant positions and velocities for the bright state atoms.

\[ f(z_0, v_0) = \frac{m \omega}{2\pi k_B T} \exp \left( -\frac{m}{2k_B T} \left( v_0^2 + \omega^2 z_0^2 \right) \right), \] (1)
The second double integral term in equation (2) accounts for the recoil energy from a spontaneously-emitted photon that occurs after each absorption from the scattering beam or final optical pumping beam. Additionally, the energy imparted from absorbing and scattering \( n_1 \) photons from the first optical pumping beam is included as the first summation in equation (3). The upper limits for the summations are chosen to be large enough to ensure convergence of the sums to our desired precision. Using parameters based on our experiment, we calculate the cooling-cycle-induced change in energy \( \Delta E \). The mean number of photons scattered in the Poisson distribution is optimized to produce maximum cooling. The net result of this calculation is a prediction of the amount of energy removed in one STOP cooling cycle.

Figure 2 shows the results of this calculation for a range of initial temperatures. For each curve, the axial cut-off distance is continuously adjusted so that the selected bright state atom fraction remains constant. This calculation is repeated for several different optically pumped fractions. Being more selective by optically pumping a smaller fraction tends to increase the amount of energy removed per selected atom, but tends to decrease the total energy removed from the gas since fewer atoms are selected. The 25% fraction of optically pumped atoms has the highest predicted energy reduction rate, although the 15% and 10% fractions are only slightly lower. As the temperature decreases the energy reduction becomes less efficient as the heat imparted by absorption and random recoils during scattering becomes more important.

The rate at which energy is removed depends on the time that a STOP cooling cycle takes. For typical confining potentials this will often be on the order of several ms. For a sense of scale, the per atom energy removal rate for the whole gas for a 25% selected fraction and 50 \( \mu \text{K} \) initial gas temperature with a 20 ms STOP cooling cycle time is \( 5.8 \times 10^{-27} \text{W} = k_B \cdot 420 \mu \text{K} \cdot \text{s}^{-1} \). While this provides a scale for the energy removal rate, it is not directly a temperature reduction rate as energy is removed in one-dimension and STOP cooling distorts the velocity distribution away from equilibrium. Depending on different alignments of lasers, STOP cooling can in principle be applied in three-dimensions or there can be mixing of motion between the dimensions through energy mixing in the confining potential. In the absence of those mechanisms, energy mixing between dimensions will occur naturally via collisions between atoms. To characterize collision-induced...
cross-dimensional energy reduction rates and the effect of collisions on STOP cooling, we performed an additional set of calculations.

These additional calculations consisted of a three-dimensional calculation of STOP cooling where we included the possibility of collisions for any atom during the bright state atoms’ center-of-mass motion. To avoid the computational difficulties of a direct \(N^2\)-type binary collision simulation, we calculated an average collision probability for each atom in each timestep based on local density and temperature parameters and then generated a random number to see if a collision occurred. If a collision occurred for an atom, its velocity was changed by simulating an isotropic collision of that atom with a randomly-generated representative ‘target’ atom given the temperature-determined velocity distribution. While computationally more efficient than a more complete \(N^2\)-type calculation, this treatment ignores the possibility of non-isotropic scattering and precise details of the atoms’ density and velocity distribution during STOP cooling. However, we expect these considerations to be small and this calculation sufficient for characterizing the general impact of collisional effects on STOP cooling.

To evaluate the effect of collisions, we identified the following timescale to quantify the energy reduction rate of STOP cooling: the time period, \(\Delta t\), required to reach 20% overall energy reduction in the gas using continuous STOP cooling cycles. This time period was determined for both a 10% selected fraction and a 25% selected fraction over a range of collision rates spanning two orders of magnitude. We calculated the total energy reduction rate over time \(\Delta t\) and the energy reduction rate in only the non-STOP-cooled radial directions as well. Since energy in the radial directions is removed only through the actions of collisions, examining radial energy reduction is useful for evaluating the influence of collisions. The results of these calculations are shown in figure 3.

Figure 3 indicates that STOP cooling results in energy reduction over a range of gas densities. Because collisions disrupt the bright state atoms’ center-of-mass motion during the second step of STOP cooling (see figure 1(b)), the amount of total average energy reduction is highest when no collisions are present. For the radial directions, (under the assumptions used for the calculation) energy reduction can only occur through collisions. This leads to the radial energy reduction rate increasing as the collision rate increases and then turning over as collisions reduce the STOP cooling energy reduction rate. The calculation included some heating in the radial direction from random photon scatters, and so a minimum collision rate is necessary to achieve net energy reduction in the radial direction.

Techniques or trap configurations that mix radial and axial energy will result in faster radial energy reduction rates than the rates shown in figure 3. Even in the absence of such considerations, STOP cooling is still effective for three-dimensional cooling even when applied along one-dimension over a range of collision rates. STOP cooling’s reliance on the motion of the atoms reduces its intrinsic cooling rate to be less than some other extensions to laser cooling (e.g. Raman cooling [20, 32]). Ultimate achievable temperatures, however, are a
ultracold atoms is on the order of milliseconds and the technique works with the scattering beam on or near center-of-mass motion is slowed with a small number of photon scatters. Since the typical timescale of trapped laser cooling techniques this case, the bright state is the.

Because the direction of the scattering beam is directly opposed to the atoms’ center-of-mass motion, the atoms’ center-of-mass motion is slowed with a small number of photon scatters. Since the typical timescale of trapped laser cooling techniques this case, the bright state is the.

Alternatively, substantially larger detunings and correspondingly larger intensities could be used instead if that were advantageous. In addition to practical advantages, this low level of photon scattering rate can be used to mitigate reabsorption-based heating effects [2, 3, 21, 33] that limit light-based cooling. Moreover, the most effective radial cooling range in figure 3 corresponds to the range where collisions typically start to disrupt other laser cooling techniques (e.g. [20, 32]).

While we have focused on atoms so far in this article, STOP cooling can be extended to cooling of molecules. Those molecules which can be cooled and trapped in a MOT are prime candidates [34–37]. Recent progress in laser cooling optically trapped diatomic calcium monofluoride [38, 39] motivates the following described adaptation of STOP cooling, and so the following discussion will be presented in the context of that particular system.

Figure 4 shows the relevant energy levels [40] that could be used to implement STOP cooling in optically trapped CaF. Initializing the molecules by placing them into a dark state is accomplished by optically pumping into the \( \nu = 1 \) electronic ground state via the \( \nu = 0 \rightarrow A(\nu' = 1) \) transition. The first step of STOP cooling is the application of the beam that optically pumps the molecules into a bright state (see figure 1(a)). In this case, the bright state is the \( \nu = 0 \) electronic ground state. After waiting for the bright state molecules’ center-of-mass to move to the center of the optical trap (see figure 1(b)), a scattering beam slows the center-of-mass velocity by scattering photons on the \( \nu = 0 \rightarrow A(\nu' = 0) \) transition. The final step is to optically pump the molecules back into the \( \nu = 1 \) dark state (see figure 1(c)). Many of these beams are duplicates of those used in the MOT cooling stage. Hyperfine structure would require either AOMs or a few stages of each STOP cooling step. It is likely the trapped molecule densities will continue to improve as techniques develop, making the advantages of STOP cooling increasingly relevant to such systems.

An alternative implementation of STOP cooling optically trapped CaF could rely on the hyperfine structure in \( \Sigma^+ \rightarrow \Sigma^+ \) \( \nu = 0, N = 1 \) [37, 40, 41] to serve as dark and bright states. The 606 nm laser (see figure 4) with AOMs is then used to both optically pump and cool the molecules so the need for a 585 nm laser is eliminated. The 628.5 nm laser remains in the scheme to pump molecules back to the \( \nu = 0 \) electronic ground state in the event of vibrational branching that will occur over the course of many STOP cooling cycles. By using only the hyperfine levels, existing experiments that laser cool optically trapped CaF can immediately adapt STOP cooling into their system without requiring an additional laser. The disadvantage with this implementation is that the comparatively close (~100 MHz) resonant frequencies between the different hyperfine states will limit the range of detunings that can be used as compared to the scheme shown in figure 4. However, as long as conditions allow for all of the STOP beams to be nearly on-resonance, this alternate approach should be effective for STOP cooling in this system.
3. Experiment

Our experimental measurements of STOP cooling were conducted with ultracold $^{87}$Rb atoms. In our experimental realization of STOP cooling there is a laser beam for each beam depicted in figure 1. These beams are straightforwardly derived by inserting an AOM into beam paths associated with the usual MOT cooling and repump lasers as appropriate. The first laser beam is responsible for optically pumping atoms from the lower hyperfine ground state ($^5S_{1/2} F = 1$; dark state) into the upper hyperfine ground state ($^5S_{1/2} F = 2$; bright state). We will refer to this beam as the ‘up-pump’ beam and atoms in the upper hyperfine ground state will be referred to as ‘up-pumped’ atoms. The next step in the cooling cycle is the application of the scattering beam that opposes the up-pumped atoms’ center-of-mass motion at the center of the confining potential. This beam will be referred to as the ‘stop’ beam. The light of the stop beam is tuned to the $^5S_{1/2} F = 2$ to $^5P_{3/2} F = 3$ cycling transition. Finally, the last step in the cooling cycle is to optically pump atoms back into the lower hyperfine ground state ($^5S_{1/2} F = 1$). The laser beam responsible for this will be referred to as the ‘down-pump’ beam. A schematic depicting the experimental implementation of STOP cooling is shown in figure 5.

We started our experiments by loading ultracold $^{87}$Rb atoms from a MOT into a far-off resonance trap (FORT) [42]. The MOT was prepared using standard techniques [43] and the FORT was created using an AOM-controlled 60 W (10.64 $\mu$m wavelength) CO$_2$ laser beam focused to a spot size of approximately 120 $\mu$m. The focus of the CO$_2$ laser beam was overlapped with the MOT atoms and loading from the MOT into the FORT was performed following the techniques of [44, 45]. Once loaded into the FORT, the atoms were given several seconds to reach thermal equilibrium. This resulted in a trapped gas of ultracold $^{87}$Rb atoms with a peak spatial density of $5 \times 10^{13}$ cm$^{-3}$ and a temperature of 45 $\mu$K. The atom temperature is measured to a precision better than a percent while the accuracy of the measurement is estimated to be at the 20% level. The confined atoms had axial and radial oscillation frequencies of 14 Hz and 550 Hz, respectively, measured with an accuracy at the 10% level. These parameters lead to a collision rate of approximately 0.16 Collisions/STOP cycle.

After reaching thermal equilibrium in the confining potential, the trapped atoms were optically pumped into the lower hyperfine ground state ($^5S_{1/2} F = 1$). STOP cooling cycles were then applied to the gas. The up-pump laser beam was overlapped with the edge of the FORT for 500 $\mu$s to ‘up-pump’ the selected atoms. A sharp edge corresponding to the axial cutoff position for the overlap region was realized by partially blocking the up-pump beam with a razor blade external to the vacuum chamber. The edge of the razor blade was imaged onto the atoms using a lens. After being up-pumped, those atoms’ center-of-mass was then allowed to move to the center of the trapping potential, where it reached a maximum velocity. At that time, a 1 ms duration stop beam pulse was applied to slow the center-of-mass velocity of the up-pumped atoms. Immediately following the stop beam
was a 1 ms down-pump beam used to optically pump the up-pumped atoms back to the lower hyperfine ground state (5S1/2 F = 1), thus completing a single cycle of STOP cooling. Each intermediate step of the STOP cooling cycle was individually optimized. The up-pump beam was tuned 25 MHz below the 5S1/2 F = 1 to 5P3/2 F = 2 transition and the intensity of the beam was set to optically pump all of the overlapped atoms into the upper hyperfine ground state (5S1/2 F = 2). The experiments were performed using a 10% selected fraction. With a well-defined fraction of up-pumped atoms, we then measured the amount of time it took the atoms’ center-of-mass to reach the middle of the optical trap to determine the time to apply the stop laser pulse. The stop beam was tuned to be approximately on-resonance with the 5S1/2 F = 2 to 5P3/2 F = 3 cycling transition and its intensity was adjusted to reduce the up-pumped atoms’ center-of-mass velocity to near zero at the optical trap center. Finally, the down-pump beam was tuned 5 MHz below the 5S1/2 F = 2 to 5P3/2 F = 2 transition and the intensity of the beam was set to optically pump all of the up-pumped atoms back into the lower hyperfine ground state (5S1/2 F = 1). The selected fraction of up-pumped atoms, the time for the atoms’ center-of-mass to reach the middle of the optical trap, and the optimal intensity of each beam were determined through absorption imaging.

Once the single-cycle optimizations had been determined, the application of multiple cycles was performed. We began by measuring the cooling from 3 successive cycles and then from 5 successive cycles. From there, we added 3 additional STOP cooling cycles to each cooling experiment (i.e. 8 cycles, 11 cycles, etc) until reaching 20 successive cooling cycles. At that point, we broke up the application of STOP cooling into ‘blocks’, which consisted of 20 cooling cycles applied successively. Blocks were then separated by a rethermalization time estimated from collision rate calculations. This gave time for the gas to re-establish thermal equilibrium, allowing for further temperature reduction through the application of additional STOP cooling blocks. Our final STOP cooling experimental procedure consisted of 3 blocks of 20 successive cycles, with each block followed by a 500 ms rethermalization time. The total duration for 3 blocks of 20 successive cycles plus rethermalization periods was between 2.64 s to 2.76 s, with the variation owing to slight differences in the time between the up-pump and the stop pulses that we deliberately introduced to search for optimal multi-cycle cooling parameters.

After the STOP cooling cycles and rethermalization were completed, data collection was performed using standard time-of-flight and absorption imaging techniques. The absorption imaging allowed the determination of the number of atoms in the trap and the temperature of the gas. This is the main diagnostic that we use in order to evaluate how much cooling has occurred.

Three absorption measurements were taken to characterize the amount of STOP cooling. The first measurement was taken at the beginning of the STOP cooling sequence to measure the initial temperature of the gas. The second measurement was taken after the STOP cooling cycles had been applied to measure the final temperature of the gas. The third measurement was taken at an equivalent time required to complete the STOP cooling cycles, but without applying any STOP cooling to the gas. The difference between the first and third types of measurements indicated there was a small amount of evaporative cooling over the time scale measured.

As one way to analyze our data, our two-dimensional absorption images of the gas were integrated along the shorter (radial) extent of the gas to produce one-dimensional spatial density distributions. To do this, the pixels in a processed image file were divided into bins along the axial direction of the gas. The pixel values were summed in each bin to produce a one-dimensional spatial density profile of the confined atoms. Figure 6 shows such a set of binned data depicting the spatial density profiles of each of the three types of measurements described in the previous paragraph. STOP cooling produces a clear reduction of high energy atoms at the edges of the spatial density distribution and a corresponding increase in peak spatial density at the center of the distribution.

4. Results

Figure 7 shows the results for the temperature reduction as a function of an increasing number of applied STOP cooling cycles. From these data we derived a single-cycle cooling efficiency of 0.0091(5) fractional temperature reduction. For our STOP cooling experiment consisting of 3 blocks of 20 successive cycles conducted under the optimal conditions that we examined, we measured a 0.282(4) fractional temperature reduction for the cooled atoms compared to the initial gas temperature. Over the same time period, the mild evaporation described in section 3 resulted in only a 0.031(4) fractional temperature reduction. Thus, STOP cooling produced a significant and well-resolved temperature reduction in the gas.

The number of atoms in each measurement were also calculated, and we observed a 0.71(1) fraction of atoms remaining in the gas that had STOP cooling applied versus a 0.75(2) fraction of atoms remaining in the gas with no STOP cooling applied. The majority of the atom loss in both cases is due to the background-gas-determined 10 second lifetime of atoms in the optical trap. The difference with and without STOP cooling translates to 7(4) × 10⁻⁴ fractional atom loss per cooling cycle. Therefore, substantial cooling with small atom loss was
observed with STOP cooling. We attribute the small loss from applying STOP cooling cycles to be a result of light-assisted collisional loss effects [46–48].

In terms of a cooling rate, the 3 blocks of 20 successive cycles resulted in a temperature reduction rate of 4.7 $\mu$K s$^{-1}$, as determined by the radial temperature. Converting this rate to a total energy reduction rate results in $k_B \cdot 14.1$ $\mu$K s$^{-1}$ and converting to a total radial energy reduction rate results in $k_B \cdot 9.4$ $\mu$K s$^{-1}$. These rates demonstrate the efficacy of the cooling technique and we expect these rates to increase with improvements to the experimental apparatus. While clear evidence of successful cooling was obtained, the measurement of 0.0091 (5) fractional temperature reduction from a single cycle of STOP cooling is approximately 5 times smaller in magnitude than the temperature reduction predicted from the harmonic oscillator potential model in this implementation of STOP cooling. Details of why this is the case along with improvements to the experiment will be discussed in the next section.

Figure 6. One-dimensional spatial density profiles of confined atoms. O.D. is the optical depth. The blue curve is a measurement taken after STOP cooling cycles have been applied to the gas. The green curve is a measurement of atoms that have been held for an equivalent amount of time required to complete the STOP cooling cycles but without applying any cooling cycles. The red curve is a measurement taken at the beginning of a STOP cooling experiment before any cycles have been applied to the gas.

Figure 7. Fractional temperature reduction resulting from the application of successive STOP cooling cycles. $T_0$ is the temperature of the gas when no STOP cooling cycles have been applied. $T_0$ is measured at an equivalent amount of time required to complete the corresponding number of STOP cooling cycles and rethermalization for a given data point (blue diamonds). $\Delta T$ is the difference between $T_0$ and the temperature of the gas after STOP cooling cycles have been applied. The green curve is a second-order polynomial fit to the data.
5. Comparison of measured cooling to model predictions

The difference between predicted and measured temperature reduction is due to the fact that our experimental system deviated from the assumptions of the ideal calculation. First, the actual confining potential was not harmonic. Second, the axial cut-off distance for the optically pumped atoms at the edge of the potential was not perfectly sharp. Finally, the confining potential in the experiment was non-separable in the radial and axial directions. For the most part, these deviations are not inevitable and so understanding them is useful in achieving closer-to-ideal performance in future implementations.

Before describing the impact of these known imperfections on the cooling rate, we consider the possibility of additional heating beyond the minimum amount of recoil heating from the beams used to optically pump the high energy atoms in the first and last step of a STOP cooling cycle. To search for any unusually large heating from such a mechanism, a fraction of atoms at the edge of the trap was optically pumped to the $5S_{1/2} F = 2$ state, allowed to move to the center of the trap, and then was optically pumped back to the $5S_{1/2} F = 1$ state. This was performed using 10 or more successive cycles, all of which were in the absence of the intermediate stop beam. The same experiments were repeated but without performing any optical pumping (i.e. the atoms were held for an equivalent amount of time without applying any light). Comparing the temperatures with and without the atoms being optically pumped indicated a decrease in temperature of approximately 70 nK per cycle. Rather than heating, this test produced a small amount of cooling, likely owing to the fact that the down-pump beam has stop beam-like characteristics. In any case, there was no evidence of any excess heating.

To gain further insight as to where cooling efficiency losses may have occurred, we developed a more extensive model of STOP cooling than the idealized collisionless calculation described in section 2. We replaced the harmonic oscillator potential with a more realistic optical trapping potential and performed a three-dimensional calculation. We also included a non-ideal axial cut-off region instead of an infinitely sharp cut-off.

In this more extensive model we simulated atom motion and all of the applied STOP beam pulses numerically. We used random number generation to initialize atom positions and velocities given a thermal equilibrium distribution, and modeled photon scattering through determining the random number of photons scattered given the average photon scattering rate. For the optical potential, we used the approximate potential

$$U = U_0 \frac{1}{1 + (z/z_R)^2} \exp \left(-\frac{2r^2}{w_0^2(1 + (z/z_R)^2)}\right).$$

where $z$ and $r$ are the axial and radial position coordinates, respectively, $U_0$ is the trap depth, $z_R = \pi w_0^2 / (\lambda M^2)$ is the Rayleigh length, $w_0$ is the spot size of a Gaussian laser beam, $\lambda$ is the optical trap wavelength, and $M^2$ is to correspond to the beam quality factor. For $M^2 = 1$ this would be exact, but our beam did not have an $M^2$ value of one and the potential in equation (4) allows an approximation of the effect that will have without being an exact match to an optical potential. Through this simulation, we could model the energy reduction in a single cycle of STOP cooling for more realistic experimental parameters.

We concentrated our initial studies assuming a 10% up-pumped fraction and we varied the $M^2$ value to alter the anharmonicity of the potential. The deviation from $M^2 = 1.0$ estimated through the effective axial oscillation frequency and the confined atoms’ spatial extent was determined to be $M^2 = 1.65$. The increased axial anharmonicity in the model potential resulted in further reduction of cooling efficiency compared to the harmonic confining potential predictions. We also conducted calculations where we accounted for the influence of the non-ideal edge of the axial cut-off. Given the measured experimental axial cut-off width, a sigmoid function was used to model the non-ideal cut-off for the initial spatial density distribution of the 10% up-pumped fraction and additional lowering of the cooling efficiency was observed. With these considerations, the experimentally observed reduction in single cycle cooling efficiency can be reproduced by model parameters consistent with the non-TEM$_{100}$ optical trap beam and imperfect axial cut-off.

While cooling was experimentally observed, more realistic modeling suggests that our single-cycle temperature reduction could be increased by at least a factor of 2 for the same initial conditions while still using a realistic optical trap. To realize this increase in cooling, several improvements for the next iteration of experiments are expected to be advantageous. A sharper edge for the optically pumped region of the gas can be achieved by using a higher-quality lens to image the razor edge. Since our modeling indicates the amount of cooling depends on the shape of the confining potential, the trapping potential specific to our experiment can be improved by switching to a fiber laser, resulting in a higher quality TEM mode.

Additionally, other gains in the temperature reduction can be made in the multi-cycle cooling experiments. As the gas cools, the axial extent becomes smaller. This in turn reduces the region of overlap between the confining potential and the beam used for optically pumping atoms in the first step of STOP cooling. Rather than a static overlap position, the relevant lens can be mounted to a motorized translation stage and used to deflect the optical pumping beam during multi-cycle cooling to better maintain an optimal optically pumped
fraction as the cooling proceeds. In fact, such an improvement is required in order to obtain a meaningful
determination of the lowest temperatures that could be achieved with this cooling technique.

For this initial implementation of STOP cooling, the long cooling time combined with the finite background
lifetime resulted in losses that hindered the phase space density increase of the gas. The phase space density
increased by a factor of 2.3 over the course of the 3 block experiment. Enhancing the cooling rate through
addressing the imperfections described above and extending the cooling further to lower temperatures will
improve this factor substantially. After addressing the known imperfections of the system, the limitations to
further performance increases due to other factors may become significant, however.

For instance, light-assisted collisional losses will become more significant at higher atom densities [49], and
would be substantial at a density an order of magnitude higher than that of the current experiments. Due to the
flexibility of the scheme, the wide parameter space (i.e. detuning, intensity) available for exploration, and the
difference in the dependence of light-assisted collision rates and light scattering rates on experimental
parameters, we expect an acceptable region of operation could very likely be found. Searching for such an
acceptable region is far easier when the light-assisted collision losses are more easily detectable.

Light-based cooling schemes also suffer when the gas being cooled becomes sufficiently optically thick
[21–23]. Due to two-photon scattering physics in reabsorption, adjusting the detuning of the light used for
cooling cannot remove this issue. We saw no evidence of reabsorption-related effects for our conditions, but
again an increase in performance and therefore optical depth could possibly cause this common limitation to
cooling to become significant. The efficient use of photons, very low required photon scattering rates, and the
fact that the cooling does not have to occur between particular magnetic sublevel combinations means that
STOP cooling is much less sensitive to this physics than other cooling techniques, however. Additional routes
to mitigate this optical-density-related limit include reducing the selected fraction of bright state atoms or
applying a magnetic field to produce slight Zeeman shifts. These mitigation techniques may introduce
different problems (e.g. smaller fractions would result in a slower cooling rate) so any implementation would
need to be evaluated.

6. Outlook and conclusions

We have presented a description of a new cooling technique for ultracold gases. The technique is based on
using STOP to create a group of atoms that move in a known direction at a known time such that they can be
slowed with light. The cooling technique only requires that a gas be trapped and that a dark state exists for the
technique to be applicable. We have performed experimental measurements that demonstrated the cooling
method. We observed a 0.0091(5) fractional single-cycle temperature reduction and a 0.282(4) fractional
temperature reduction from 60 cycles. These measurements were less than the predicted ideal cooling but the
observed reduction is explicable through the non-harmonic oscillator nature of the confining potential
and other non-ideal factors. Our numerical modeling of the cooling technique indicates that with
reasonable improvements to the experimental system increased cooling performance should be
realizable.

We note there are several advantages to using the STOP cooling technique. Since photons are used efficiently
in the cooling process, a minimal amount of power is required for the laser beams. This is beneficial for
experiments cooling on transitions where laser light is difficult to produce. Light-assisted collision losses and
reabsorption effects [21, 33, 50] that often limit laser cooling techniques were small for the amount of cooling
obtained in STOP cooling. This is advantageous for experiments that begin with small initial numbers.
Furthermore, the STOP cooling that we implemented is not the only way that this cooling scheme could be
applied. Rather than resonant scattering, stimulated Raman transitions could be used to slow the selected atoms
and would be expected to have even higher efficiency.

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