Laser Cooling of Rb-87 via Grey Molasses
Anna Wirth
From the Lab of Professor Alex Kuzmich

CONTENTS

1. OBJECTIVE

Professor Alex Kuzmich's lab studies atomic physics and quantum information. Many experiments used to probe these areas of science require ultracold (micro-Kelvin scale) atoms. In an experiment attempting to achieve longer ground-Rydberg coherence lifetimes, motional dephasing reduces overall atomic coherence and limits these lifetimes. Colder atoms reduce motional dephasing, therefore allowing longer lifetimes to be achieved. Additionally, lower temperatures reduce losses when transferring atoms from a magneto-optical trap to an optical lattice. Grey molasses cooling in particular has advantages over other laser cooling mechanisms due to high phase space density and low atom loss, as well as low temperature.

2. THEORY

In general, laser cooling relies on atoms with particular velocities absorbing photons from laser light with momentum $p = h/\lambda$. These atoms re-emit photons in a random direction, which is blue-shifted if the atom is moving in the direction of the emitted photon. For blue-shifted light, the wavelength λ is shortened such that $\lambda_{fluoresced} < \lambda_{absorbed}$. The momentum of the emitted photons is therefore greater:

$$\frac{h}{\lambda_{fluoresced}} > \frac{h}{\lambda_{absorbed}} \rightarrow p_{fluoresced} > p_{absorbed},$$

so the atom has lost momentum during this exchange. Over a period of many cycles, the atoms are cooled. A "cooling" laser beam accomplishes this process, and a "repumping" laser beam excites atoms that have decayed to a state from which further decay to the ground state is prohibited.

Rubidium is commonly used in laser cooling experiments due to its well-defined hyperfine splitting and because its transition frequencies are achievable using commercially available 780nm lasers. ^{87}Rb and ^{85}Rb are two stable isotopes; this study focuses on ^{87}Rb.

A. Magneto-Optical Traps

The Magneto Optical Trap (MOT) is the foundation for many laser cooling experiments. Both inhomogeneous magnetic fields and radiative selection rules create a cooling force [1]. The MOT is rather robust; that is, the beam intensities and their polarizations do not need to be perfectly balanced to achieve trapped atoms and fluorescence. Due to Zeeman shifts and the polarizations of the lasers, the atoms condense in the center of the trap where the magnetic field, usually generated by quadrupole coils and adjusted by rectangular bias coils to negate external magnetic influences, is zero [1]. A MOT can cool atoms to below 1 mK [1]; a molasses stage typically follows the loading of atoms into a MOT to achieve temperatures below 100 μK.

B. Doppler Cooling

The simplest laser cooling mechanism relies on the Doppler shift, typically with red-detuned light; i.e., the laser is detuned below an atomic transition. Therefore, the atom will only absorb this light if the light is blue-shifted via Doppler shift to be on-resonance with the transition; in other words, the atom must be moving towards the laser source. The converse is true for blue-detuned molasses; in order for the light to be absorbed, it must be red shifted, so the atom must be moving away from the laser source.

The atom will re-emit this photon in a random direction. In the case of red-detuned molasses, the photon was absorbed while the atom was moving towards the source. Photons that are emitted in the opposite direction of the atom's movement, such that the atom is moving away

from the emitted photon, will be red-shifted and therefore have less energy. Unless the re-emitted photon is emitted precisely in the direction the absorbed photon came from, the emitted photon will be blue-shifted with respect to the absorbed photon. Repeating this process over many cycles results in cooling.

However, there is a theoretical lower limit to the temperature achievable by Doppler cooling, given by $T_d = \hbar\Gamma/2k_B$ [2], where Γ is the linewidth of the D$_2$ transition. This limit is 143 μK for ^{87}Rb.

C. Polarization Gradient Cooling / Sisyphus Cooling

Polarization gradient cooling is obtained by directing three counter-propagating circularly polarized laser beams to intersect at the center of the atom cloud in a MOT. The cooling beam is red-detuned to 80 MHz below the $|5S_{1/2}, F = 2\rangle \rightarrow |5P_{3/2}, F' = 3\rangle$ transition and the repumping beam on resonance with the $|5S_{1/2}, F = 1\rangle \rightarrow |5P_{3/2}, F' = 2\rangle$ transition. In each dimension (x, y, and z), the counter-propagating beams interfere with each other and create standing waves with polarization gradient that alternates between σ^+, π, and σ^- polarizations [1]. This results in sinusoidal potentials for the ground and excited levels that are 90 degrees out of phase from each other [1].

The cooling mechanism of polarization gradient cooling relies on the transfer of energy between these sinusoidal potentials and the emission of a blue-shifted photon. As an atom climbs a potential hill of an excited state, it converts its kinetic energy for potential energy. This potential energy is then reduced via optical pumping; the atom emits a blue-shifted photon and moves to a lower-energy state. Then the atom again climbs a potential hill, but it does so with less initial kinetic energy. Over many cycles, the atoms cluster near the colder dark state. This mechanism is also called Sisyphus cooling after the Greek myth of Sisyphus, who was doomed to roll a boulder up a hill only to have it fall back down for all eternity.

D. Grey Molasses Cooling

Like polarization gradient cooling, grey molasses cooling is obtained using three counter-propagating circularly polarized laser beams. However, the cooling beam in this case is blue-detuned to 15 MHz above the $|5S_{1/2}, F = 2\rangle \rightarrow |5P_{3/2}, F' = 2\rangle$ transition and the repumping beam is blue-detuned to approximately 15 MHz above the $|5S_{1/2}, F = 1\rangle \rightarrow |5P_{3/2}, F' = 2\rangle$ transition. See **Supplemental Figure 1.**

Grey molasses cooling relies on both bright and dark states (hence the term "grey") to undergo a mechanism similar to Sisyphus cooling, where bright states are states that are coupled to light (and therefore interact with the light field) and dark states are states that are decoupled to light (and therefore cannot interact with the light field) [3]. The dark state has an adiabatic Hamiltonian; for slow-moving atoms, the potential is able to adjust accordingly and therefore the slow-moving atoms do not observe the sinusoidal potentials of the excited states [4]. As a result, the slowest-moving (and therefore the coldest) atoms remain trapped in the dark state. For fast-moving atoms in the dark state, sinusoidal excited state potentials are observed. The fast-moving atoms couple to the first excited state at a potential minimum with high kinetic energy, climb the potential hill to attain high potential energy at the potential maximum, and then spontaneously emit a photon to return to the dark state with less energy. After many cycles, the fast-moving atoms become slow-moving atoms trapped in the dark ground state. See **Supplemental Figure 2.**

3. EXPERIMENTAL SETUP

Much of the setup described herein is modeled after [3].

A. The Laser Setup Table

The laser field requires both a cooling and a repumping laser beam; both of these are configured on the laser setup table and sent via an optical fiber to the experiment table. For simplicity and individual control of the cooling and repumping beams, separate lasers generate these beams in our setup. Other setups have generated the repumping laser beam from a sideband of the cooling beam via an electrical optical modulator [3,5]; this has the benefit that the cooling and repumping laser beams are inherently coherent, which has been shown in [3] to be important in minimizing temperature in grey molasses cooling. An electrical optical modulator may be implemented in our setup in the future.

Using a combination of half waveplates and beam splitters, a small fraction of each laser's light is picked off for tuning the laser frequencies. A fraction of the repumping light is directed into a saturation spectroscopy cell, which is used to lock the repumping laser to the $|5S_{1/2}, F = 1\rangle$ crossover of Rb-87. A fraction of both the cooling and repumping beams are aligned into a Vescent Heterodyne Module that overlaps the beams to produce an optical beat note. An optical fiber directs this optical beat note to the Beat Note Detector, where it is converted to an electrical signal and sent to an Offset Phase Lock Servo. A reference signal from an RF (radio frequency) generator is supplied to the Servo, which compares the reference signal to the beat note. The cooling laser is then locked to the desired offset (set by the reference signal) from the repumper frequency. After completing the frequency stabilizing process, both lasers are precisely locked to a known (and for the cooling beam, adjustable) frequency.

Since different repumping and cooling laser frequencies are required for the MOT loading and molasses stages, acoustic optical modulators (AOMs) are used to further tune the frequencies of the cooling and repumping beams for the molasses stage. RF (radio frequency) generators supply a reference frequency to the AOMs. The cooling and repumping beams are aligned into the AOMs, which contain a crystal which diffracts the light such that the 1st order diffraction has the frequency set by the reference frequency. These 1st order diffracted beams are then coupled into fiber optic cables leading to the experiment table.

We aim to achieve 180 mW of cooling laser power and approximately 15 mW of repumping laser power at the experiment table. A tapered amplifier is placed after the cooling laser's output to meet this requirement. The amplifier provides up to 2.1 W of optical power, but a significant fraction of the beam's optical power is lost during the tuning of the beam. An isolator after the amplifier is approximately 80% efficient, the AOM is approximately 75% efficient, and the fiber coupling is approximately 55% efficient, with lenses and mirrors contributing small additional power losses. Additionally, part of the beam is picked off for the Heterodyne Module and another part is directed into a photodiode for diagnostics. Despite these losses, we are easily able to achieve 180 mW at the experiment table.

B. The Experiment Table

Three orthogonal laser beams ensure that the sample is cooled in three dimensions, and cooling of both forwards- and backwards-moving atoms is achieved by counter-propagating beams. To achieve the counter-propagating circularly polarized configuration, a cooling beam of

approximately 180 mW of optical power and a repumping beam of approximately 15 mW of optical power are combined on a beam splitter and then expanded via a set of two telescopes. A series of two half wave plates and beam splitters splits the incoming mixed cooling/repumping beam into three beams of approximately 60 mW of optical power each. Two of these beams are directed parallel to the table and orthogonal to each other (*x* and *y* dimensions), and the third beam is directed vertically through the center of the table (*z* dimension); thus three orthogonal beams are achieved. A quarter wave plate applied to each beam before it meets the sample circularly polarizes the light. Finally, mirrors placed after the sample in each beam's path reflect the beam back onto the sample, resulting in counter-propagating light. These beams intersect at the center of a glass cell containing Rubidium atoms in ultra high vacuum.

A set of two circularly wound, insulated copper coils comprise the quadrupole fields, and a set of three (for *x*, *y*, and *z* dimensions) rectangularly wound, insulated copper coils comprise the bias fields. A current was set for the quadrupole fields to adjust the compression of the MOT at the center of the field. Then, a Gauss meter was used to measure the magnetic field at the center of the MOT and the bias fields were adjusted as necessary to achieve zero magnetic field at the center.

We used an infrared surveillance camera to observe fluorescence for rough alignment. An Andor Solis CCD camera on an incrementally adjustable mount was used for recording fluorescence. To correct for background light, a background image was taken while blocking the repumper laser beam; this prevents the atoms from fluorescing but allows most of the laser light to cross the camera's field of view, resulting in a good approximation of the background light while the atoms are fluorescing.

C. The Experimental Procedure

Cicero Word Generator Software [6] was used to control our experiment with sub-millisecond time resolution.

The first stage of the experimental procedure is loading the MOT. The cooling and repumping beams are on, tuned to their loading frequencies, and the quadrupole fields are on for 100 ms. For the molasses stage directly following, the quadrupole fields are turned off and the frequencies of the laser beams are changed to the detunings used for molasses. The optical power of the laser beams is also decreased by approximately 50%. Following [3], the optimal duration of the molasses stage is 3 ms.

The time of flight stage follows. The laser beams and the quadrupole fields are turned off, allowing the atoms to freely expand for a set period of time. For measuring temperature, the time of flight is varied from 0 to 20 ms. Finally, an image is taken using fluorescence imaging. Both the cooling and repumping lasers emit a short, bright laser pulse; this causes the atoms to fluoresce. The camera shutter opens for 30 ms to record the image.

As a control to test the efficacy of the molasses stage, data was also recorded for procedures run without the molasses stage; for these control measurements, the 3 ms molasses stage was replaced with 3 ms time of flight.

D. Extracting Temperature

During time of flight, the atoms expand according to the formula

$$\sigma_i(t_{TOF}) = \sqrt{(\sigma_i^0)^2 + \frac{k_B T_i}{m}(t_{TOF})^2} \quad [3],$$

where $\sigma_i(t_{TOF})$ is the i-dimension half width at half-maximum at time of flight t_{TOF}, σ_i^0 is the i-dimension half width at half-maximum at time of flight 0 (i.e., immediately after the molasses stage), k_B is Boltzmann's constant, m is the mass of the molecule (86.909187 amu for Rb-87), and T_i is the temperature in the i-dimension at time of flight 0.

To extract the temperature, $\sigma_i(t_{TOF})$ is measured for time of flight from 0 to 20 ms, a curve is fitted to those data points, and the temperature is extracted as a parameter from that curve. To measure σ_i for each time of flight, the experimental procedure is run with the time of flight duration first set to 0 ms. To reduce noise in the data, typically three images at this time of flight are taken and their pixel values added together to create an average image. This process is repeated for 1, 2, … , 20 ms time of flight to achieve 20 images, each of which is the accumulation of three images of the same time of flight.

Each of these images is flattened into x and y dimensions; the pixel values in each row and in each column are summed to create Gaussian curves as shown in Figure 3D-1. The half width at half maximum of each of these curves is $\sigma_i(t_{TOF})$, which are plotted and fit to the equation above, as shown in Figure 3D-2.
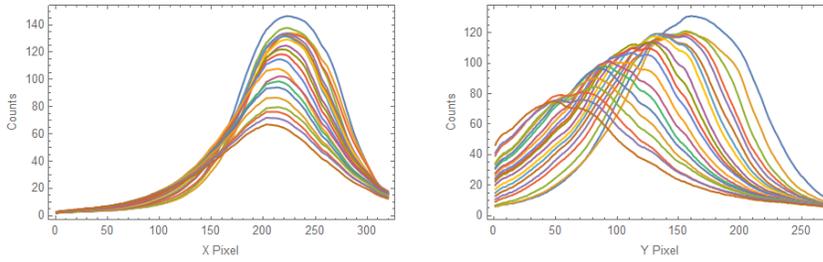

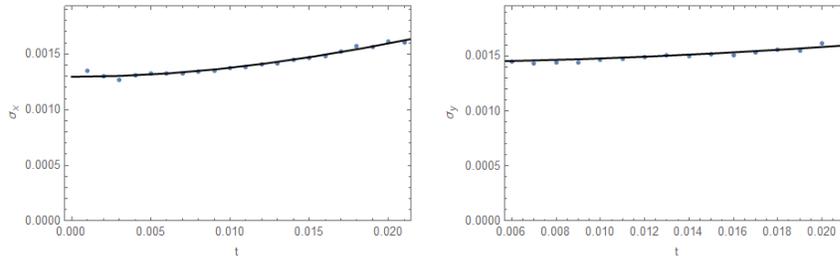**Figure 3D-1.** Each line represents a different time of flight.

Figure 3D-2. This particular example exhibits temperatures of 22.26 μK in the x-direction and 10.89 μK in the y-direction.

E. Determining Atom Losses

The molasses cooling stage typically reduces the number of atoms in the MOT; generally, it is desirable to minimize this loss. The number of atoms contained in the MOT, N, is assumed to be directly proportional to the fluorescence; therefore, N is directly proportional to the number of counts recorded by the camera. The region of interest for measuring the number of counts was the entire camera screen; while this includes significantly many counts from the background, we felt it was the best way to control for the changing shape of the atomic cloud and its diffuse boundaries. The fraction of atoms retained is given by

$$Atom\ retention = \frac{N_{Molasses}}{N_{Control}} \propto \frac{Total\ Counts_{Molasses}}{Total\ Counts_{Control}},$$ where $Total\ Counts_{Molasses}$ refers to the number of counts recorded directly after the 3 ms molasses stage and $Total\ Counts_{Control}$ refers to the number of counts recorded directly after a 3 ms time of flight stage in place of the molasses stage.

4. DATA AND RESULTS

It should be noted that due to factors including, but not limited to, fiber coupler alignment, cooler and repumper beam alignment, temperature fluctuations, and amplifier degradation, and our continual efforts to reduce negative factors, results from day to day were variable. The size of the MOT, which is affected by loading time, magnetic field strength, and laser beam intensity and alignment, also affected results; larger atom clouds are generally more difficult to cool. Differences in T_x and T_y are due to slight imbalances in the relative strengths of the three intersecting laser beams and the vertical movement of the atom cloud as it falls under the influence of gravity.

[3] reports optimal repumper/cooler intensity ratio of 0.07 for a combination of low temperature, high phase space density, and minimal atom loss. Our primary objective was low temperature, and we found a higher power repumper beam to be beneficial for producing low temperatures. We generally worked with repumper/cooler intensity ratio of 0.10 to 0.15.

For polarization gradient cooling, we achieved a temperature of T_x = 21.5 μK and T_y = 22.9 μK[1]. Without the polarization gradient molasses stage, the temperatures were of T_x = 121.1 μK and T_y = 69.0 μK. Therefore, polarization gradient cooling in free space was highly effective.

We observed temperatures of T_x = 6.52 μK and T_y = 6.09 μK with coherent grey molasses cooling[2]. We investigated Raman detuning, the relative difference in detuning between the cooling and repumping lasers, and achieved results similar to those reported in [3]; see Figure 4-1. The Raman detuning is defined by $\delta_R \equiv \Delta_{RC} - E_{HFS}/\hbar$, where Δ_{RC} = (repumper detuning) = (cooler detuning); $\frac{E_{HFS}}{\hbar}$ = 6834.68 MHz, the energy splitting between the F=1 and F=2 hyperfine states of the atomic ground state $5^2S_{1/2}$ of ^{87}Rb [1]. The constant $\Gamma = 2\pi \times 6.065$ MHz is the linewidth of the D_2 transition.
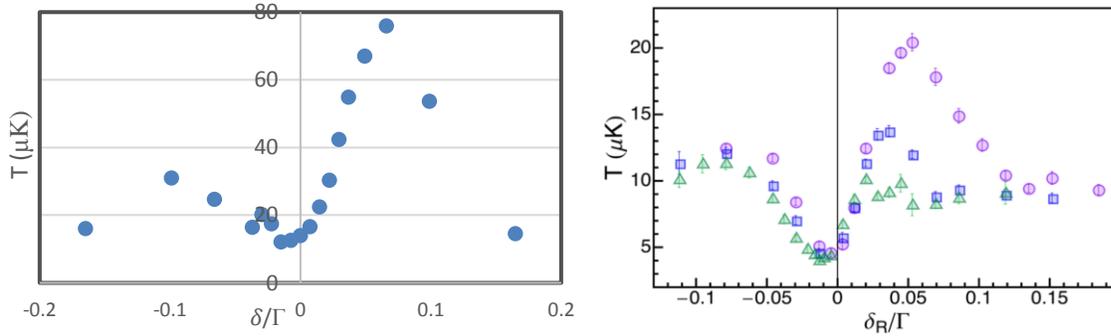

Figure 4-1. Temperature as a function of Raman detuning. Results shown on the left are laboratory results, compared to the plot on the right from [3]. The plot on the right displays several datasets: Δ22 = 5 Γ (pink circles), Δ22 = 8 Γ (blue squares) and Δ22 = 12 Γ (green triangles), where Δ22 is the detuning of the cooler beam from the $\left|5S_{1/2}, F = 2\right\rangle \to \left|5P_{3/2}, F' = 2\right\rangle$ transition (see Supplementary Figure 1). Laboratory results used Δ22 = 5 Γ.

5. ACKNOWLEDGEMENTS

---

[1] Data taken on 07/09/2018.
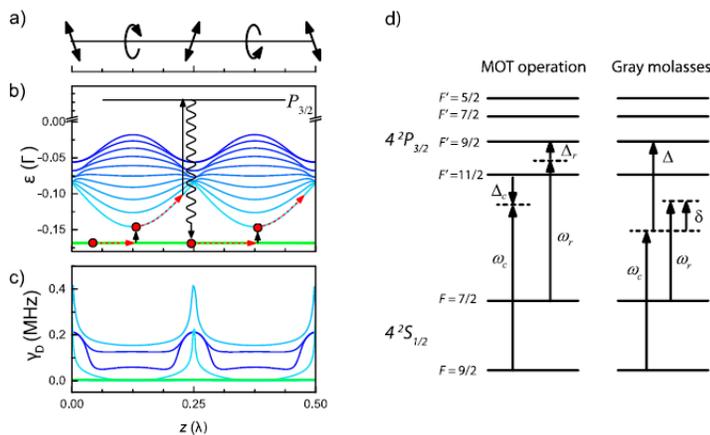[2] Data taken on 07/22/2019.

6. REFERENCES

[1] Metcalf, Harold J. and Peter van der Straten (1999). Springer-Verlag New York, Inc. *Laser Cooling and Trapping*.

[2] Lett, Paul D.; Watts, Richard N.; Westbrook, Christoph I.; Phillips, William D.; Gould, Phillip L.; Metcalf, Harold J. (1988). Observation of Atoms Laser Cooled below the Doppler Limit. Physical Review Letters. 61 (2): 169–172.

[3] Rosi, Sara, A. Burchianti, S. Conclave, D.S. Naik, G. Roati, C. Fort, and F. Minardi (2017). Λ-enhanced grey molasses on the D_2 transition of Rubidium-87 atoms. Nature Scientific Reports, 8: 1301.

[4] G. D. Bruce et al (2017). Sub-Doppler laser cooling of ^{40}K with Raman gray molasses on the D_2 line. J. Phys. B: At. Mol. Opt. Phys. 50. Excerpt from Figure 1.

[5] Salomon, G., L. Fouché, P. Wang, A. Aspect, P. Bouyer, and T. Bourdel (2013). Gray-molasses cooling of ^{39}K to a high phase-space density. EPL, 104 (2013) 63002

[6] MIT Center for Ultracold Atoms (2008). Cicero Word Generator. Copyright 2008, Aviv Keshet.

7. SUPPLEMENTAL FIGURES

Supplemental Figure 1. Laser detunings for red molasses (polarization gradient cooling) and grey molasses. With Rb-87 energy level D line diagram from Steck, Daniel A (2001). Rubidium 87 D Line Data. *Los Alamos National Laboratory*.
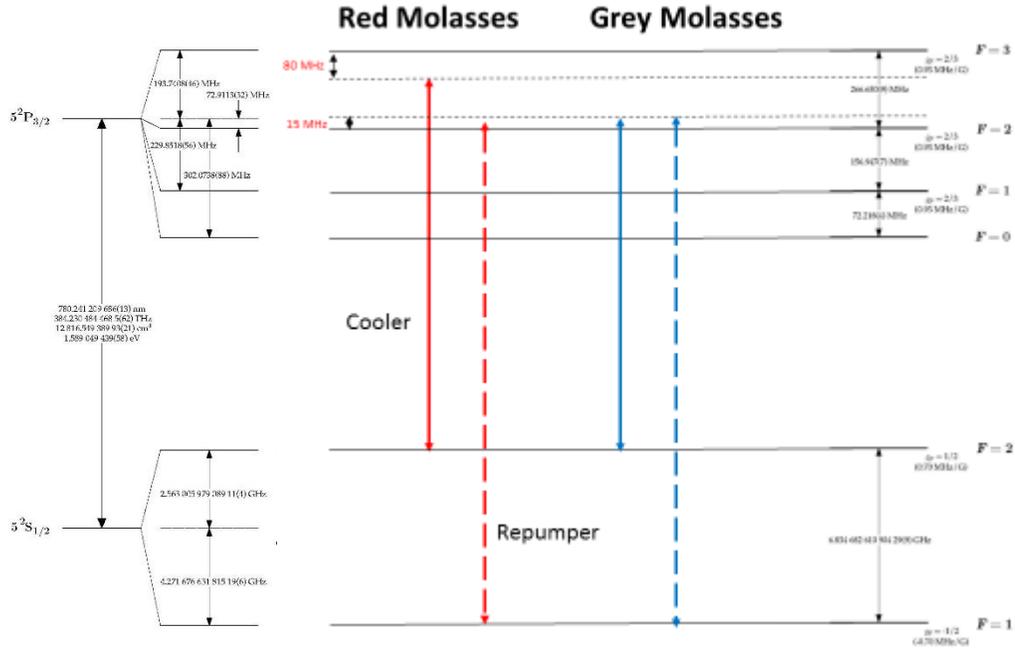
Supplemental Figure 2. Gray Molasses Cooling Mechanism. Taken from [4]: G. D. Bruce et al (2017). Sub-Doppler laser cooling of ^{40}K with Raman gray molasses on the D_2 line. J. Phys. B: At. Mol. Opt. Phys. 50. Figure 1 and associated caption.

Cooling mechanism in 1D lin⊥lin red-detuned gray molasses (δ = -0.17 Γ). (a) Variation of polarization with position z over the period of the standing wave. (b) Energies, ε, of the dressed states which group in families of bright (blue) and dark states (green). An atom (red circle) in a dark state moving along +z most efficiently couples to a bright state at $z = \lambda/8$. The atom undergoes Sisyphus-like cooling by traveling to an increased potential energy before an absorption followed by a spontaneous emission event returns it to a dark state at $z = \lambda/4$. (c) Optical pumping rate γ_D, showing the dark states and the bright states corresponding to m_F = -9/2, -7/2, 3/2, and 1/2 at positions of σ+ polarization (others omitted for clarity). The most likely pumping to dark states occurs at $z = \lambda/4$. (d) Atomic level scheme of then ^{40}K D_2 line together with the relevant laser fields and detunings for MOT operation (left) and gray molasses cooling (right). Cooling light and repumping light are at frequencies w_c and w_r, respectively.