Modified “delta kick cooling” for studies of atomic tunneling

S.H. Myrskog, J.K. Fox, H.S. Moon*, H.A. Kim*, J. B. Kim* and A.M. Steinberg

Department of Physics, University of Toronto
Toronto, ONT M5S 1A7 CANADA

* Permanent address: Dept. of Physics, Korea Nat. Univ. of Education, Chungbuk, Korea 363-791

(Submitted December 2, 1998)

We present progress towards a planned experiment on atomic tunneling of ultra-cold Rb atoms. As a first step in this experiment we present a realization of an improved form of “delta-kick cooling.” By application of a pulsed magnetic field, laser-cooled Rb atoms are further cooled by a factor of 10 (in 1-D) over the temperature out of an optical molasses. Temperatures below 700 nK are observed. The technique can be used not only to cool without fundamental limit (but conserving phase-space density), but also to focus atoms, and as a spin-dependent probe.

I. INTRODUCTION

Advances in laser cooling and atom optics have led both to the ability to directly observe new physical effects (e.g., in connection with weakly interacting Bose gases) and to develop new, potentially applicable technologies (such as atom-wave gravimetry). There has been a great deal of interest in paving the way for future developments by studying atom optical components such as mirrors, lenses, and beam-splitters [1–5]. Often, these components themselves rely on new and interesting physical effects, which is one of the explanations for the self-sustaining excitement in this field.

The long de Broglie wavelengths of ultracold atoms make them ideally suited for studies of quantum mechanics, as evidenced for example by the interference between two Bose condensates [6], or by tests of quantum chaos using cold atoms [7]. We plan to make use of the wave nature of laser-cooled Rubidium atoms to study the tunneling of atoms through optical dipole-force barriers; by focusing light into a thin sheet, one can create strong repulsive potentials for atoms, with spatial widths several times the optical wavelength. By cooling atoms to near or below the recoil temperature (where the atomic de Broglie wavelength is equal to the optical wavelength), we can enter a regime where there is significant tunneling probability. Although tunneling has been observed indirectly in several atom-optics experiments [8], this would be to our knowledge the first experiment where spatially resolvable tunneling is observed. That is, we plan to directly image the incident and transmitted atomic clouds, using the internal degrees of freedom of the atoms to address questions about the “history” of transmitted particles. This unique system should make it possible to answer long-controversial questions related to tunneling and to quantum measurement theory [9,10]. As a simple example, the question of what you see if you attempt to image atoms while they are within a forbidden region is already nontrivial [11].

In addition to the intrinsic interest of atomic tunneling, focussed dipole-force barriers may prove useful as coherent beam-splitters, velocity-selective elements, and in related roles. In this paper, we present the status of our experimental project to observe atomic tunneling, including some simulations of planned velocity-selection experiments. As a first step towards this experiment, we have used time-dependent magnetic forces to cool atoms in one dimension, in a scheme based loosely on Ammann and Christensen’s “delta-kick cooling” proposal [12]. We have achieved temperatures below 700 nK, and much lower temperatures are possible in principle. The technique is also generalizable to three dimensions. We also see some interesting effects when these magnetic kicks are applied to atoms from an optical molasses. We are still working towards a full understanding of these effects, but they appear to contain the signature of spatial spin correlations within the atom cloud. We believe that in addition to the usefulness of magnetic kicks for cooling, this Stern-Gerlach-like system will prove to be a novel probe of the atomic spin in laser-cooled atom clouds.

As alluded to above, the practical observation of atomic tunneling will require atoms with de Broglie wavelengths on the order of the width of the tunnel barrier. Our barrier is produced by using the dipole force from a 500 mW laser focused into a sheet of light which is about 10 µm wide and 2 mm tall. The atoms leaving our laser cooling and trapping system are at temperatures of 6 µK, implying a wavelength of about 0.2 µm, too short to observe any significant tunneling through an optical-scale barrier. Therefore we need to further cool our atoms to sub-recoil temperatures. Our first stage of cooling following optical molasses is to perform an improved variant of the “delta kick cooling” proposed by Ammann and Christensen [12], also similar to an independent proposal by Chu et al. [13]. Following this stage, we will have atoms with 1-D temperatures on the order of the recoil temperature of Rb and de Broglie wavelengths on the order of the optical wavelength of 780 nm. We shall perform a final step of velocity selection to select only the least energetic atoms and separate them from the remaining higher-energy atoms. By using 1-D velocity selection we
can retain about 7% of our atoms at 1/200th of the initial temperature. Given the fact that we are concerned with 1D temperatures this is more efficient than comparable evaporative cooling in 3D. Moreover, the velocity selection will suppress the thermal tails which could otherwise lead to ambiguity between tunneling and thermal activation.

In the original proposal of “delta-kick cooling” Ammann and Christensen suggested a form of cooling in which an atomic wavepacket prepared in a minimum-uncertainty state within an optical lattice is first allowed to freely expand for a short period to allow position to become correlated with momentum. Application of a position-dependent force from a standing wave can then be used to reduce the mean momentum of the atoms. Near the bottom of the potential well the atoms essentially experience a harmonic potential. As the atoms expand beyond this harmonic region the proposed cooling process breaks down. Instead of a sinusoidal potential, we consider a true harmonic potential, easily generated with magnetic field coils. This variant is not only easier to understand and to implement; it is also immune to the original proposal’s cooling limit.

Consider an ensemble of laser-cooled atoms initially confined within a small region of size $r_i$ with mean thermal velocity $v_o$. At time $t = 0$ the trap is turned off and atoms are allowed to freely expand away from the trap center. After a time $t_f$, long compared to $r_i/v_o$, the atoms are located at positions essentially given by $x_a = v_o t_f$, where $v_o$ is the velocity of a particular atom. Application of a harmonic potential $U = \frac{1}{2} m \omega^2 x^2$ for a short time will apply an impulse to the atoms proportional to position $\Delta p = -m \omega^2 x t_k$ where $t_k$ is the duration of the kick. If this impulse is chosen to be equal to $-m x_a / t_f \approx -m v_o$, all atoms will essentially be brought to rest. The condition for such an optimal kick is $t f t_k = 1/\omega^2$.

In reality several factors place limits on the achievable temperature. At time $t = 0$ the atoms are not all located at the center of the trap, but instead have some distribution of initial positions. As the ratio between the final size to initial size increases, the correlation between position and momentum improves, allowing greater degrees of cooling. At any finite time, the correlations will be imperfect, preventing the cooling from being optimal. Practical considerations may limit the time for which the atoms can be allowed to expand.

After free expansion, the typical atom is at a position on the order of $r_f = \sqrt{r_i^2 + (v_o t_f)^2}$, and has a velocity on the order of $v_o$. Each individual velocity class has a spread in position given by the initial size $r_i$ of the cloud. A transferred impulse proportional to distance, and designed to cancel out the mean velocity of $v_o$ at a typical distance of $r_f$, will therefore transfer a random velocity on the order of $v_o r_0 / r_f$ to each velocity group of atoms. Indeed, a more careful phase-space treatment shows clearly that the rms velocity of the kicked atoms decreases by a factor of $r_0 / r_0$, leading to a temperature reduction of $(r_0 / r_f)^2$.

In other words, this technique is the moral equivalent of adiabatic expansion. At a practical level, however, it has the advantage that there is no adiabatic criterion to meet. To cool a cloud by a factor of $N$ would require a time of $\sqrt{N} t_0$ where $t_0$ is a secular period in the harmonic oscillator. A similar adiabatic expansion would need to be accomplished slowly relative to the instantaneous secular period $(N t_0)$ by the end of the expansion.

The cooling process can be readily understood in a phase-space picture. Figure 1 shows the evolution of an atomic cloud in phase space from the initial state at the start of expansion, to after free expansion and finally, the distribution after application of a kick. We start with a phase-space distribution characterized by the widths of the distribution in momentum and position. Free expansion stretches the distribution in position, but has no effect on momentum. The effect of a harmonic kick is to rotate the distribution in phase space. If the duration of the kick is chosen correctly, this rotates the distribution back onto the position axis, thereby lowering the temperature. Note that this does not require a true “delta-kick” in the sense of a very short duration. By Liouville’s theorem, the area in phase space is conserved both during free expansion and during the kick, yielding $v_f = v_0 x_0 / x_f$. The longer the cloud is allowed to undergo free expansion before the kick, the narrower the final distribution is in momentum, resulting in lower temperatures.

![FIG. 1. Phase space diagrams. a) is a distribution of the localized cloud. b) shows the cloud after a period of free expansion prior to a kick. c) A harmonic kick rotates the distribution onto the x-axis, lowering the temperature of the cloud.](image-url)

In addition to cooling via harmonic potentials, it is also possible to cool atoms using a pulsed quadrupole potential. Although this technique cannot match the ideal harmonic kicks, it is substantially easier to generate strong field gradients than higher-derivative terms. In 1D, a quadrupole field exerts a fixed impulse toward the center of the potential. If the atoms have been allowed to expand significantly, most are moving away from the center, and a kick chosen to be equal to the mean thermal velocity concentrates the atoms near $v=0$ (in a highly non-thermal, nearly flat-topped distribution). In 1D, the mean kinetic energy may be reduced by up to a factor of 6 in this way. Simulations for a true 3D quadrupole
potential show even greater cooling (predominantly along the symmetry axis), due to the “rounding” of the potential energy surface when transverse excursions are taken into account. The cooling is predominantly along the quadrupole axis, but some cooling does occur in the other directions as well.

The data presented in this paper all concern one-dimensional cooling. However, the harmonic kicks are easily generalizable to 3D by application of successive kicks along the three Cartesian axes. With quadrupole kicks, perfect spherical symmetry cannot be achieved, but may be approximated using a similar approach.

II. EXPERIMENT

Our MOT coils are located horizontally around the cuvette and define the z-axis of the trap. The coils are made of 200 turns of wire with a radius of 4 cm and separated by 8 cm. This is twice the separation required for a Helmholtz configuration, leading to a nonvanishing \( d^2 B/dz^2 \). With the currents in opposing directions as used in a MOT or a quadrupole kick, the coils can produce gradients up to 180 G/cm given our present maximum current of 18 A. These same coils are also used for generation of a harmonic potential. By reversing the direction of current in one of the coils we can achieve harmonic fields with a second derivative of about 60 G/cm², corresponding to a trap frequency of about 60 Hz. The coils can be switched on and off in 200 µs, residual fields falling to 1% in 1 ms.

We start by cooling and trapping \(^{85}\text{Rb}\) atoms within our MOT using a field gradient of 20 G/cm, and 40 mW of total power in trapping beams with 2 cm diameter. The trapping beam is detuned 10 MHz to the red of the D2 \((F = 3 \Rightarrow F = 4)\) transition at 780 nm. We cool and trap about \(10^8\) atoms in our MOT with a diameter of 0.5 mm. We further cool the atoms to 6 µK in 1 millisecond of \(\sigma^+\sigma^-\) optical molasses detuned 34 MHz to the red of the \(F = 3 \Rightarrow F = 4\) transition.

We then turn off all light and magnetic fields to allow the atoms to undergo free expansion. After a time of 9 to 15 ms we apply a short (3 ms) pulse of the quadrupole field. The resulting force is directed towards the origin, mostly along the symmetry axis of the coils, and applies an impulse to the atoms opposing their direction of motion.

The temperature of the resulting cloud is determined by time-of-flight imaging. A series of images is taken as a function of time after the kick, and the temperature is extracted from the expansion curve.

The existence of multiple spin levels in atoms released from an optical molasses implies that different atoms experience different magnetic potentials, making distributions difficult to interpret. For this reason we select the atoms in a doubly polarized state \(F = 3, m_F = 3\) by capturing the atoms within a weak magnetic trap which is unable to hold atoms with \(m_F < 3\) against gravity. We release the doubly polarized atoms from the magnetic trap after 200 ms and allow the \(m_F = 3\) atoms to expand freely before application of the quadrupole magnetic field.

Figure 2 shows fluorescence images of the atoms under free expansion and after application of a delta kick. The atoms released from the magnetic trap have a temperature of 7.5 µK with an rms velocity of 2.7 cm/s. The atoms are first allowed to undergo free expansion for a time of 11 ms and then have a kick applied for 3 ms, imparting a change in velocity of 3 cm/s. After application of the kick, the temperature of the cloud along the coil axis has decreased by a factor of about 6, from 7.5 µK down to 1.2 µK. Expansion curves for a cloud for several kick strengths are observed in Figure 3. For a kick of 2.4 cm/s, near the original rms velocity of the atoms, we observe optimal cooling. Over 20 ms, essentially no expansion of the atom cloud is seen, and fits indicate a temperature below 700 nK. For stronger kicks, the atoms are impelled back to the center of the cloud, where they come to a focus. As the strength of the kick increases the atoms come to a smaller focus (consequently heating the atom cloud), until the strongest kick strength results in a cloud hotter than the cloud from the original magnetic trap.

![FIG. 2. A sample of the fluorescence images obtained. The upper set of images corresponds to atoms undergoing free expansion. The lower set of images corresponds to the atoms having undergone free expansion for 11 ms followed by a quadrupole kick for 3 ms, followed by further free expansion for temperature measurement. The temperature of the atoms along the coil axis (horizontal) after a kick has been reduced from 7.5 µK to 1.2 µK by application of the kick.](image-url)
FIG. 3. The ballistic expansion of atom clouds is shown for free expansion and after kicks of various kick strengths. At high kick strengths the cloud can be brought to a focus, with a tighter focus achieved as the strength of the kick is increased. For a nearly ideal kick, no expansion can be observed over 20 ms; the temperature is lower than 700 nK.

FIG. 4. A comparison of simulation and experimental data for the ratio of final temperature to initial temperature as a function of the expansion ratio of the atomic cloud. For short expansion times the kick is unable to provide much cooling to the atomic cloud, whereas at longer times (i.e. larger size ratio), cooling improves. Experimental data shows cooling by a factor of 10, somewhat better than originally predicted by the simulations, which neglect the effect of gravity.

At short times such that the radius of the cloud has not increased by very much, the positions and momenta of the atoms are not very correlated and the kick does little to cool the atoms. In Figure 4 we show results (solid circles) and simulations (smooth curve) on the cooling ratio versus the ratio of final size to initial size.

FIG. 5. Final temperature over initial temperature as a function of the kicking strength. The theoretical curve has a minimum at a point where the change in velocity imparted by a kick is equal to the rms velocity of the atomic cloud. The experimental data points from two different data sets (triangles and circles) yield qualitative agreement, but a great deal of scatter due to sensitivity to other initial conditions. The minimum temperature appears to occur for somewhat larger kick strengths than predicted by the simple simulations; this can be understood by taking gravity into account.

The temperatures obtained experimentally were lower than the initial temperature by as much as a factor of 10, even at times when the simulations predicted only a factor of 5. Additionally, Figure 5 suggests that optimal cooling occurs for a somewhat stronger kick strength than originally expected theoretically. Both these effects can be qualitatively understood by considering the effect of gravity. When the atoms are allowed to freely expand for a long time, they also begin to fall under the influence of gravity. If the cloud falls in the conical potential by a distance larger than the spatial extent of the cloud, then the horizontal potential seen by the atoms looks like a conic section, i.e. a parabola. Thus transverse cooling is accomplished by a harmonic kick, much more efficient than the quadrupole, yet much stronger than the true harmonic potential achievable by reversing the current in one of our coils.
Simulation of Quadrupole kick with cloud falling under gravity

FIG. 6. The addition of gravity into our simulations demonstrates that more cooling is possible than the quadrupole kick simulations suggest. The data from Fig. 5 are compared with a simulation neglecting gravity (dashed curve) and one including gravity (solid curve). Clearly, the inclusion of gravity improves the cooling, as seen experimentally. The data are not perfectly modelled by this simulation due to the strong dependence on details of the initial size and temperature which may differ from point to point.

When we include gravity into our simulations, both the extra cooling and increased potential strength requirements are observed. Figure 6 shows the achievable temperature with the inclusion of gravity. As the atoms move down from the center of the potential, the strength of the horizontal force decreases. To optimize cooling requires the use of a stronger potential than expected for a 1D quadrupole. Simulations run with various parameters have shown cooling by as much as a factor of 30.

Kicks have also been performed upon atoms coming out of an optical molasses. Since there are 7 different spin states in the F=3 ground state of Rb, we expect the different states to undergo different amounts of cooling or heating. We therefore expect to see a multimodal distribution, in which from the initial cloud radius, each spin component expands at a different rate. Figure 7 shows the results of a kick on an optical molasses. The upper set of expansion images shown free expansion and the lower set displays the atom cloud after a kick. After the kick, the cloud separates as expected into a bi-modal distribution consisting of a very cold central stripe and a broader, hotter background. The unusual feature comes in when we realize that the central stripe is significantly smaller than the size of the atom cloud at the time of kick as seen clearly in Figure 8. We believe this may indicate a pre-existing correlation between position in the optical molasses and spin state. We are continuing to study these effects, for which the Stern-Gerlach-like analysis possible using pulsed field gradients appears to be a very promising new probe.

FIG. 7. Free expansion and kicked atoms from a molasses. Following application of a kick a narrow stripe appears in the center of the cloud. The temperature of the stripe is measured to be about 700 nK. The width of the stripe is smaller than the size of the cloud at the time of a kick, possibly implying a pre-existing correlation between spins and position.

FIG. 8. Radius vs time for a number of kick strengths. The anomalously small stripe size is clearly seen after a kick. The lowest temperature observed is about 700 nK.

Through the use of these kicks we have achieved temperatures as low as 700 nK both on atoms released from a magnetic trap and on a subset of the atoms released from an optical molasses. Cooling ratios as large as a factor of 10 have been observed. The effect of gravity may be used to enhance cooling, but also limits this technique for certain applications. Since the atoms begin to fall due to gravity, they are no longer located at the origin of the potential, and cannot be recaptured without heating.
The gain in cooling may still be useful for experiments in which the atoms are allowed to fall for some distance, such as atomic mirrors, lensing and atom deposition systems. Along these lines Maréchal et al. [14] have studied a system where inhomogeneous magnetic potentials separate the spin components of a cloud and provide cooling as the cloud falls a distance of about a meter. The addition of a 1D optical lattice or anti-gravity field will allow us to reach greater ratios in the size of the atoms without having the atoms fall from the center of the trap, to obtain cooling greater than a factor of 10.

III. TUNNELING AND VELOCITY SELECTION

Having achieved recoil-velocity atoms we are moving on to study properties of atoms while they are tunneling. We shall use a line-focused beam of intense light detuned far to the blue of the D2 line to create a dipole-force potential for the atoms. Using a 500 mW laser at 770 nm focused into a sheet 10 µm wide and 2 mm tall, we will be able to make repulsive potentials with maxima as large as 50 µK, without significant scattering rates. The potential will be modulated using an acousto-optic deflector allowing us to rapidly shift the focus of the beam. Since we may shift the focus of the beam more quickly than the atomic center-of-mass motion can follow, the atoms see a time-averaged potential. This will allow us to make nearly arbitrary potential profiles.

Following the application of a delta-kick to obtain sub-recoil 1-D velocities, our atoms will have a thermal de Broglie wavelength of about 1 micron, still too small to observe significant tunneling through a 10 µm dipole-force barrier. We will therefore follow the delta kick with a velocity-selection phase. We will use the same beam which is to form the tunnel barrier but dither the focus of the laser quickly. The atoms shall see a time-averaged potential many times larger than the de Broglie wavelength of the atoms, thereby appearing as an essentially classical barrier. By sliding this “classical” barrier through our atomic cloud, it will be possible to adiabatically sweep the lowest energy atoms away from the center of the magnetic trap, leaving the hot atoms behind. The coldest atoms will thus be in a spatially separated local minimum from which tunneling may be observed when the width of the barrier is decreased. Figure 9 shows the results of quantum-mechanical simulations for atoms at an initial temperature of 1.3 µK, trapped in a 5 G/cm field (300 µ K/cm). We superpose a 20 µm Gaussian beam with a peak height of 600 nK onto the V-shaped potential. This creates a potential minimum of 16 nK which is swept through the magnetic trap at a rate of 0.5 mm/s. The minimum supports a quasi-bound state with energy 5 nK, and we see 7% of the atoms transferred into this minimum. Classically, we would expect the number of atoms to be transferred equivalent to √T_f/T_i. In Figure 10 we observe steps in the probability of transfer as a function of the barrier height, indicating the number of quasi-bound states supported.

![Velocity Selection vs Barrier Height Simulation](image_url)

**FIG. 9.** This quantum-mechanical simulation demonstrates what we expect to achieve with our dipole-force velocity-selection. Starting with an atom cloud near 1 µK and sweeping an appropriately tuned 20 µm laser beam through the atoms adiabatically, we will create a very small auxiliary potential well capable of separating the coldest sub-sample of atoms from the cloud.

![1-D Simulation of Velocity Selection](image_url)

**FIG. 10.** The probability of transfer exhibits steps as a function of well depth, indicating the number of quasi-bound states supported. A well with a single bound state is seen to capture about 7% of the atoms, in a state with an energy of only 5 nK, corresponding to a de Broglie wavelength of about 6 µm. Such a state will be an ideal source for our atom-tunneling experiments.

After velocity-selection we will narrow the beam to 10 µm to allow the cold atoms to tunnel. The velocity-selected sub-sample of atoms will have a de Broglie wavelength of 6 µm, leading to a significant tunneling probability through a 10-micron barrier. We expect rates of order 5% per secular period, causing the auxiliary trap to decay via tunneling on a timescale of the order of 600 ms.
Progressing towards this tunneling experiment we have achieved temperatures of 700 nK for atoms released both from magnetic traps and optical molasses by application of a quadrupole delta-kick. Given longer expansion times, this temperature should drop even further. Once these cooling and velocity selection techniques are perfected, we shall have a unique system in which to study tunneling. By using optical probes such as absorption, optical pumping and stimulated Raman transitions, we will be able to go beyond studies of simple wavepacket tunneling to investigate the interactions of tunneling atoms while in the forbidden region. Studies of measurement of the tunneling time are planned as well as investigations into quantum-mechanical nonlocality [15].

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