# Atomic Velocity Selection Using Stimulated Raman Transitions

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Stimulated Raman transitions between the ground-level hyperfine states of atoms have been used to manipulate slowly moving atoms in an atomic fountain. An ensemble of sodium atoms with an inferred velocity spread along one dimension of 270 $\mu$m/sec has been prepared by this technique. We also show that this velocity-selection method is effective in measuring ultracold temperatures of laser-cooled atoms in a regime where traditional ballistic methods fail.

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There has been dramatic progress in the cooling and manipulation of atoms in recent years. For example, atoms in optical molasses[1] with polarization gradients[2] have been cooled to temperatures well below the Doppler limit $k_B T = \hbar\Gamma/2$.[3] Temperatures as low as $k_B T/2 \sim \langle p^2\rangle/2M \sim (3.5\hbar k)^2/2M$, where $\hbar k$ is the momentum recoil due to the photon used in the cooling process, have been observed for sodium[3,4] ($\sim 30$ $\mu$K) and cesium ($\sim 2.5$ $\mu$K).[5] Helium atoms have been "cooled" in one dimension to 2 $\mu$K, a factor of 2 below the recoil limit $(\hbar k)^2/2M$, by velocity-selective coherent population trapping.[6]

In this paper, we describe a new type of optical velocity selection that has been shown to prepare a sample of atoms with a velocity spread 2 orders of magnitude below the velocity an atom would experience from the recoil of a single photon. This velocity spread can be characterized by an effective one-dimensional "temperature" of 24 pK. We further show that this technique will be useful in measuring the velocity spreads of atoms for $\Delta v \leq 1$ cm/sec, where time-of-flight techniques[1,2] are no longer effective because of gravitational acceleration. Other applications of this velocity-selection method will also be indicated in this paper.

The velocity-selected atoms are prepared as follows: Atoms with a ground-state hyperfine splitting $\nu_{12}$ and an optical interval $\nu_{13}$ as shown in Fig. 1 are first optically pumped into a single hyperfine level $|1\rangle$. Two counterpropagating laser beams at frequencies $\nu_{1L}$ and $\nu_{2L}$ will induce a stimulated Raman transition to the $|2\rangle$ state if atoms are in resonance with the frequency difference $\nu_{12} = \nu_{1L} - \nu_{2L}$.[7] The atoms excited into the $|2\rangle$ state will have a velocity spread given by the Doppler-shift formula $\Delta v/c = \Delta\nu/(\nu_{1L} + \nu_{2L})$, where $\Delta\nu$ is the linewidth of the transition. The velocity spread $\Delta v$ can be extremely narrow because the frequencies $\nu_{1L,2L}$ are optical frequencies and the linewidth of the $|1\rangle \rightarrow |2\rangle$ transition can be narrow. If the laser frequency $\nu_{2L} = \nu_{1L} + \nu_{\rm rf}$ is generated by an electro-optic modulator or other radio-frequency technique, the frequency jitter of the laser is canceled out. The linewidth due to the finite transit time is greatly reduced with the use of slow atoms. For example, we have demonstrated a 2-Hz-wide resonance of the sodium ground-state hyperfine splitting with atoms in an atomic fountain.[8] Even with a modest measurement time of 10 msec, the expected spread in velocity $\Delta v$ is 30 $\mu$m/sec for sodium atoms.

The basic experimental apparatus has been previously described.[8] Atoms from a thermal beam were slowed with a counterpropagating, frequency-chirped laser beam, and collected in a magneto-optic trap.[9] After approximately 0.8 sec, the magnetic field was turned off. The detuning of the trapping light, intensity 6 mW/cm$^2$, was then increased from 15 to 25 MHz below the $F = 2 \rightarrow 3$ transition in order to further cool the atoms. We had to wait at least 20 msec for stray magnetic fields to decay. These fields were due to long-lived eddy currents generated in the liquid-nitrogen–cooled copper cryoshield when the trapping field was turned off. A resonant electro-optic modulator created 1.71-GHz frequency sidebands in order to avoid optical pumping into the $F = 1$ ground-state hyperfine level. The atoms were then launched upwards in a ballistic flight by decreasing the frequency of the downward-propagating laser beams shown in Fig. 2 while increasing the frequency of the upward-propagating beams. The frequencies of the two sets of molasses beams were shifted by $\pm 2.9$ MHz with respect to the transverse beams in 250 $\mu$sec, and then left at those frequencies for an additional 750 $\mu$sec. This configuration created polarization gradients moving upwards at 250 cm/sec with respect to the laboratory frame

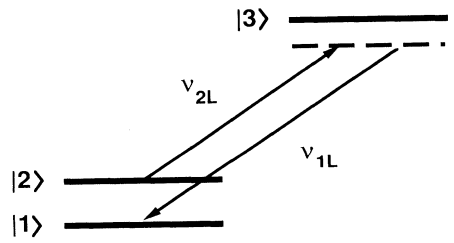


FIG. 1. A diagram of the ground hyperfine states $|1\rangle$ and $|2\rangle$ and the excited state $|3\rangle$. The frequencies $\nu_{1L}$ and $\nu_{2L}$ are used to induce a Raman transition between the two ground states.

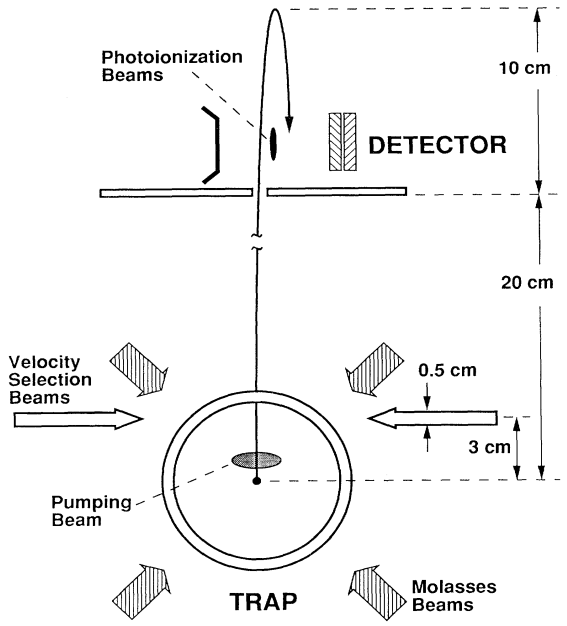


FIG. 2. A schematic diagram of the velocity-selection apparatus. The pumping beam and the photoionization beams are propagating normal to the paper. Not shown are the other set of molasses beams and the slowing beam used to load the magneto-optic trap.

of reference so that the moving optical molasses dragged the atoms upwards. Using this technique, we have previously shown that the atoms can be launched without additional heating.[10]

In order to optically pump the atoms into the $F=1$ state, the rf sideband of the molasses beams was shut off during the final 500 $\mu$sec of the launch. Once launched, the atoms were further optically pumped into the $F=1$ hyperfine level by a 1-mW/cm$^2$ "pumping" beam located 1 cm above the center of the trap as shown in Fig. 2. The frequency of the optical pumping beam was tuned midway between the $F=2$ ground-state and the $F=2$ and $F=1$ excited-state hyperfine levels. This additional pumping decreased the background counting rate by a factor of 7.5. The atoms moving at 250 cm/sec then passed through 0.5-cm-diam ($1/e^2$) Raman velocity-selection beams. The magnetic-field-insensitive transitions $m_F=0\rightarrow 0$ and $m_F\rightarrow -1+1$ were excited when one of the Raman laser beams was circularly polarized while the other beam was linearly polarized. A magnetic bias field was oriented parallel to the laser beams. The intensities of the two beams were adjusted in order to irradiate the atoms with a $\pi$ pulse.[11] A large detuning from the optical transition ensured that the probability of a spontaneous emission from the $|3P_{3/2}\rangle$ state was $\sim 10^{-4}$ during the atoms' flight through the beams. The ac Stark shifts[12] induced by the $\pi$ pulse were on the order of 1 kHz for the magnetic-field-sensitive transitions, and became clearly resolvable when the intensity was increased to a $25\pi$ pulse. There are no ac Stark shifts for the $m_F=0\rightarrow 0$ and $-1\rightarrow +1$ transitions in the limit where the detuning is large compared to the hyperfine splitting.[13]

The frequency offset of the two Raman beams is generated by an electro-optic modulator at 1.712 GHz and a double pass through a 30-MHz acousto-optic modulator. The relative beatnote frequency of the two beams was measured by combining the two beams interferometrically onto a fast photodiode, and the appropriate error signal was fed back to the acousto-optic modulator in order to lock the beat frequency to a stable rf source. This servo system reduced the effects of mirror vibrations that add relative frequency noise to the two laser beams. For transit times of 1 msec, we found that mounting the interferometer components on a standard, nonfloating, laser table was adequate. For longer measurement times, we will need to derive the beatnote error signal from a carefully suspended inertial reference frame.

The transverse velocity and velocity spread of the atoms were measured ballistically 25 cm above the trap, as shown in Fig. 2. The atoms were resonantly excited by gating on a cw laser tuned from the $F=2$ ground state to the $F=3$ excited states and 15 mJ of 355-nm light from a $Q$-switched, pulsed yttrium-aluminum-garnet laser. Sodium ions were detected by a microchannel plate above a liquid-nitrogen-cooled 0.16-cm-wide aperture that helped screen stray atoms from the detection region. By scanning the location of the $\sim$1-mm-wide ionization region, the width of the fountain of atoms was measured.

Figure 3 shows the spatial distribution of atoms velocity selected 140 msec after the launch (atoms going up), and the distribution of the atoms 370 msec after the launch (atoms returning down). For the data taken 140 msec after launch, the magnetic field was reduced to $\sim$3 mG, measured by making the beams copropagate and tuning the light to the field-sensitive transitions. (The excitation of the field-sensitive transitions when the beams are in the velocity-selective mode only adds a small amount of velocity spread to the atoms which translates into an additional width of $\sim$150 $\mu$m contributing to the 1.6-mm width in Fig. 3.) For the data taken 370 msec after launch, a bias field of 80 mG applied parallel to the direction of the light beams was used to separate the magnetic-field-insensitive $m_F=0\rightarrow 0$ and $-1\rightarrow +1$ transitions from the field-sensitive $m_F=\pm 1\rightarrow \pm 1$ and $0\rightarrow +2$ transitions. There was no significant spread in the atomic beam after 0.23 sec, giving an upper limit of $\Delta v \leq 0.1$ cm/sec for the transverse velocity of the atoms. The transit-time-limited linewidth of the Raman transition was measured to be 900 Hz by aligning the two copropagating laser beams. With this frequency width, the velocity spread of the selected atoms is inferred to be 270 $\mu$m/sec, corresponding to an effective temperature of 24 pK and a minimum wave-

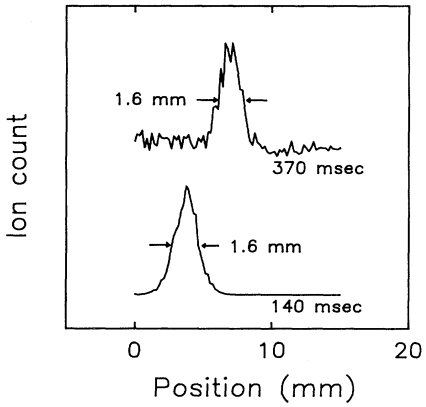


FIG. 3. A measurement transverse spread of the atoms after passing through the 1.6-mm-wide aperture. Not shown are the background counts, measured by recording the ionization signal with Raman beams turned off. The peak background level, due to incomplete optical pumping, was $\sim\frac{1}{4}$ of the peak signal. The peak counting rate after 370 msec was 30 counts/sec, 50 times less than the data rate at 140 msec. The 370-msec data represent 11 min of integration time. If the frequency difference between the two laser beams is exactly equal to the hyperfine splitting, atoms with a velocity equal to $2\hbar k/M$ will be selected. The frequency difference between the two laser beams was 1771.540 MHz, 86 kHz from the measured hyperfine splitting of 1771.626 MHz, whereas the recoil of two photons corresponds to a shift of 204 kHz. The mean transverse velocity of the atoms was $\sim$1.4 cm/sec. These numbers can be reconciled if the Raman beams deviated from the horizontal plane by 8 mrad.

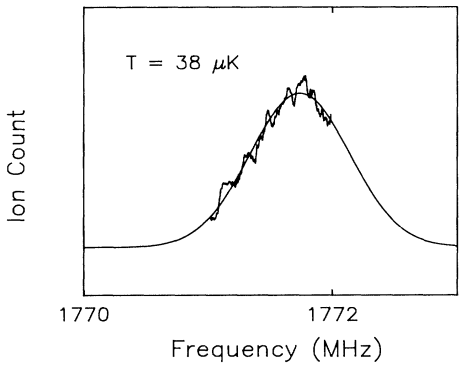


FIG. 4. A measurement of the transverse velocity distribution of the atoms in the atomic fountain. The temperature is slightly higher than what is usually achievable with polarization gradient molasses cooling because of the small amount of heating due to optical pumping.

packet width of 51 $\mu$m.

As the temperature of laser-cooled atoms continues to decrease, it will be necessary to find a more sensitive method of determining the velocity spread of the atoms. Because the acceleration due to gravity is 980 cm/sec, velocity spreads of less than 1 cm/sec will be difficult to measure with ballistic techniques. Heterodyne techniques may be possible, but so far it has proven difficult to disentangle the velocity measurement from effects of the probing light that might cause effects such as Dicke line narrowing.[14] Narrow transitions in the uv have also been used to measure the Doppler width of laser-cooled atoms, but a highly frequency-stabilized laser is required.[15] The Raman transition provides a simple means of making Doppler-width measurements for state-prepared atoms without an ultrastable laser.

In our experiment, the ballistic measurement of the vertical velocity component yields an effective temperature of $35\pm7$ $\mu$K, where the estimated uncertainty is due to the vertical extent of the detection region. The horizontal velocity distribution was obtained by measuring the number of atoms that make the Raman transition a function of the frequency offset between the two laser beams. Figure 4 shows the results of the measurement where the frequency was tuned in 4-kHz (0.1-cm/sec) steps and each data point was a moving average of a 40-kHz window of data. The total data integration time was 250 sec. The unsmoothed data were fitted to a thermal distribution with a temperature of $38\pm2$ $\mu$K. Assuming that the horizontal and vertical velocity spreads in optical molasses are the same, there is good agreement between the ballistic and Raman measurements.

Our present signal-to-background ratio allows us to select a slice out of the velocity distribution that is $3\times10^{-4}$ of the initial population, corresponding to a 7-order-of-magnitude decrease in the effective transverse temperature. However, if only a narrow velocity slice is selected, most of the atoms in the fountain would not be used. In order to increase the number of atoms used in the measurement, the velocity selection can be done using the Ramsey technique of two separated $\pi/2$ pulses. The first $\pi/2$ pulse would put a large number of atoms into a superposition state of both hyperfine levels, causing the atom's internal state to precess at the hyperfine frequency. The second $\pi/2$ pulse will interact with the atoms differently, depending on their velocity along the direction of the laser beams. If the laser frequencies of the two beams are in phase with the precessing atoms, the atoms will be excited into the other hyperfine level. An atom will also be excited if the accumulated phase difference between the atom's internal state and the Doppler-shifted laser oscillators is $\pm2\pi$, $\pm4\pi$, etc. Hence a periodic ("picket-fence") distribution of velocities will be selected, with the periodicity equal to the inverse of the time between the $\pi/2$ pulses. If one applies an external perturbation that is independent of the atomic velocity, the entire picket-fence distribution can be used in the experiment. Examples of such experiments include the deflection of atoms by an electric field in a charge neutrality measurement of an improved measurement of the acceleration due to gravity.[10,16]

Raman velocity selection is superior to velocity selection with slits. Given the finite size of the source of atoms, narrow slits would drastically reduce the counting rate. Also, narrow slits will necessarily create a momentum spread by the uncertainty principle. In comparison to cooling by coherent population trapping,[6] Raman velocity selection does not increase the number of atoms within a narrow velocity spread, but there are many applications for which this velocity-selection technique is preferable. Experiments that can use a picket-fence velocity distribution will still have a high counting rate. The velocity width of the Raman-selected state decreases as $1/t$, where $t$ is the time of the velocity selection, whereas the velocity width of the nearly "noncoupled" (trapped) quantum state decreases as $1/\sqrt{t}$.[17] Also, population trapping requires that magnetic-field-sensitive states be used.

Although Raman velocity selection is not a *cooling* technique, it should be possible to construct a Maxwell demon by cycling velocity selection with optical molasses in order to obtain cooling below the recoil limit.[16] For example, consider an ensemble of atoms cooled in optical molasses. After optically pumping them into a particular hyperfine state, atoms within a small velocity spread can be put into the other hyperfine state with the Raman transition. The velocity-selected atoms would then be removed by some appropriate stimulated processes, leaving a Gaussian velocity distribution except for the narrow hole left by the velocity-selected atoms. The velocity hole is filled with the reapplication of the optical molasses and the process is cycled until an appreciable fraction of the atoms have been velocity selected.

Another possible exploitation of the mechanical effects of the stimulated Raman transition is in atom interferometry. Because the Raman transition adds two photon momenta to the transverse velocity of an atom (6 cm/sec in the case of sodium), it can be used to create a spatially separated wave packet. Consider the spatial wave function of the atom in state $|1\rangle$ described by a wave packet centered about $p-\hbar k$. A $\pi/2$ pulse may be used to put the atom into a coherent superposition of the two states $|1,p-\hbar k\rangle$ and $|2,p+\hbar k\rangle$ with momentum components centered about $p-\hbar k$ and $p+\hbar k$, respectively. After a time $\Delta t$, the wave packets will have separated by an amount $2(\hbar k/M)\Delta t$. A $\pi$ pulse induces transitions $|1,p-\hbar k\rangle \rightarrow |2,p+\hbar k\rangle$ and $|2,p+\hbar k\rangle \rightarrow |1,p-\hbar k\rangle$. After another interval $\Delta t$, the two wave packets merge again, and a final $\pi/2$ pulse with the appropriate phase shift can put the atom into either of the hyperfine levels. This geometry is the atomic analog to a Mach-Zender interferometer and is related to a proposal for an atomic interferometer by Bordé.[18]

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