Subrecoil Laser Cooling with Adiabatic Transfer

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We demonstrate subrecoil cooling of rubidium atoms by velocity-selective coherent population trapping. By adiabatic transfer of the cooled atoms into a spin polarized single momentum state we show the coherence of the trapped state. Our cooling scheme takes advantage of the rubidium hyperfine structure to integrate subrecoil and sub-Doppler cooling. Starting from an initial velocity distribution of twice the recoil temperature [$T_{\text{rec}} = (\hbar k)^2/k_B M$], we cool down to 100 nK ($\approx \frac{1}{3} T_{\text{rec}}$) within 1 ms, while almost completely suppressing the diffusive heating of velocity-selective coherent population trapping.

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Laser cooling has undergone remarkable progress in recent years. It has become a powerful tool to cool an atomic gas and to study the wave nature of atoms interacting with laser light. Cooling to a few microkelvin can be achieved within milliseconds by exposing the atomic gas to laser light. The atoms are slowed down by rapidly exchanging momentum with the laser field and dissipating energy by spontaneous emission. However, at temperatures which correspond to an atomic momentum spread of only a few photon recoils the random nature of spontaneously emitted photons hinders further cooling, unless the very cold atoms are decoupled from the laser field so that they can neither absorb nor emit further photons.

Temperatures below the single photon recoil limit were first demonstrated for helium atoms using velocity-selective coherent population trapping (VSCPT) [1,2]. In this scheme the atoms interact with the laser field and scatter photons until they are trapped in an atomic ground state which is decoupled from the laser field. This dark state is characteristically composed of different momentum components. In a one-dimensional standing wave field (wave vector k) it is a superpositon of the two momentum components $+\hbar k$ and $-\hbar k$. During the cooling process this superposition state of an atom propagating in opposite directions at once is populated by spontaneous emission.

In this Letter we experimentally show that atoms cooled by VSCPT can be coherently transferred into a single momentum state with a momentum spread smaller than $\hbar k$. This experimentally confirms that the cooling process indeed induces a coherence between the two momentum components of the dark state. In our experiment, which is also the first demonstration of VSCPT for atoms other than helium, the dark state is populated in a standing wave field composed of two counterpropagating waves. Atoms trapped in the dark state are then coherently rotated into a single momentum state by gradually decreasing the intensity of one wave. We will explain this rotation in the intuitive picture of adiabatic passage [3] which has previously been applied to describe selective population of internal molecular states using laser light and to develop atomic beam splitters [4]. The potential of velocity selection to achieve subrecoil temperatures has also been demonstrated for sodium and cesium atoms using a pulsed cooling scheme [5,6]. An alternative way to produce atomic samples with ultralow temperatures is evaporative cooling [7]; although extremely successful this technique requires high initial atomic densities and it suffers from the loss of atoms during the cooling process.

In our experiment we use a standing wave (S_{VSCPT}) resonant with the $F = 1 \leftrightarrow F' = 1$ transition of the D_1 line in ^{87}Rb for velocity-selective coherent population trapping [Fig. 1(a)] and adiabatic passage into a single momentum state. S_{VSCPT} consists of two counterpropagating waves along the x axis with different beam waists and mutually orthogonal polarizations. The Gaussian envelopes of the electric fields are given by $E_{\pm}(z) = \mathcal{E}_{\pm} \exp\{z^2/w_{\pm}^2\}$, where $2E_{\pm}$ are the real valued amplitudes of the electric field. The wave E_+ propagating in the positive x direction has the Gaussian waist w_+ and is linearly polarized along the z axis. The counterpropagating wave E_- has a waist w_- and is polarized along the y axis. Figure 1(b) shows the two ground states g_z and g_y

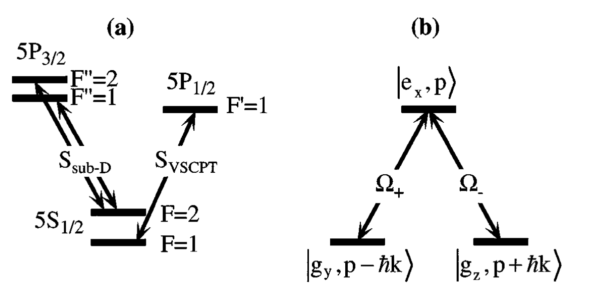

FIG. 1. (a) Atomic levels in ^{87}Rb. The velocity-selective dark state is prepared in a standing wave resonant with the $F = 1 \leftrightarrow F' = 1$ transition of the D_1 line. The sub-Doppler cooling is achieved by a second bichromatic standing wave tuned to the $F = 2 \leftrightarrow F'' = 1, 2$ transitions of the D_2 line. (b) Momentum states coupled on the $F = 1 \leftrightarrow F' = 1$ transition.

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of the $F = 1$ Zeeman manifold, and the excited state e_x of the $F' = 1$ Zeeman manifold. The state e_x (with atomic momentum p) is coupled to the state g_z (with atomic momentum $p + \hbar k$) by the y-polarized component (E_-) of the laser field and to the state g_y (with atomic momentum $p - \hbar k$) by its z-polarized component (E_+). The corresponding Rabi couplings are $\Omega_\pm(z) = 2DE_\pm(z)/\hbar$, where D is the electric dipole moment of the transitions. The velocity-selective dark state $\Psi_{\rm vsd}$ decouples from the light field for $p = 0$ and is given by [8]

$$|\Psi_{\rm vsd}\rangle = c_-|g_y, p - \hbar k\rangle + c_+|g_z, p + \hbar k\rangle, \qquad (1)$$

with $c_- = \cos\phi$, $c_+ = \sin\phi$, and $\sin\phi = \Omega_+/\sqrt{\Omega_+^2 + \Omega_-^2}$. The state $\Psi_{\rm vsd}$ is an eigenstate of the total Hamiltonian (including the kinetic energy) for $p = 0$. For $p \neq 0$, the state $\Psi_{\rm vsd}$ is kinetically coupled to the orthogonal state $|\Psi_c\rangle = c_+ \times |g_y, p - \hbar k\rangle - c_-|g_z, p + \hbar k\rangle$, which is coupled to the excited state $|e_x, p\rangle$. If one of the two polarization components of the laser field is zero, i.e., if $\phi = 0$ or $\phi = \pi/2$, the kinetic coupling vanishes. In these cases the dark state is given by either g_y or g_z, independent of p.

The experimental situation in which the waists of the two counterpropagating waves are different ($w_+ > w_-$) is shown in Fig. 2. The spatially varying Rabi couplings Ω_+ and Ω_- lead to a z-position-dependent dark state $\Psi_{\rm vsd}$ [Eq. (1)]. In the wings of the Gaussian beams, Ω_+ is smaller than Ω_- so that the amplitude c_+ is smaller than the amplitude c_-, i.e., the state $\Psi_{\rm vsd}$ is shifted towards the state $|g_y, p - \hbar k\rangle$. An atom adiabatically follows in the state $\Psi_{\rm vsd}$ if the condition $\dot{\phi}(z) \ll \sqrt{\Omega_+^2(z) + \Omega_-^2(z)}$ is fulfilled [3]. Hence we expect that those atoms which are accumulated in the dark state $\Psi_{\rm vsd}$ will follow into the state g_y and leave the standing wave $S_{\rm VSCPT}$ with the momentum $-\hbar k$. The orthogonal state Ψ_C is shifted towards the state g_z with the momentum $\hbar k$. This shows that the adiabatic transfer is sensitive to the relative phase, i.e., to the coherence of the two momentum components of the velocity-selective dark state $\Psi_{\rm vsd}$. The momentum distribution of atoms cooled into the dark state $\Psi_{\rm vsd}$ should exhibit a peak at the momentum $-\hbar k$ having a width smaller than $\hbar k$. The condition for adiabaticity rigorously holds only for $\Omega > \Gamma$ (Γ^{-1} lifetime of the excited state). This condition is not fulfilled for the parameters used in the experiment (see below). We thus numerically integrated the Schrödinger equation for an atom starting in the state $\Psi_{\rm vsd}(p = 0)$ in the center of the Gaussian beams. For the experimental parameters we expect that 83% of the population is adiabatically transferred into the state g_y with the momentum $-\hbar k$. Only 4% of the atoms undergo spontaneous emission.

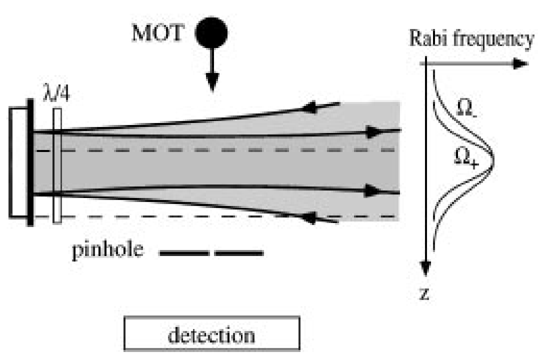

FIG. 2. Geometry of the experiment. The Rabi couplings Ω_- and Ω_+ of the two counterpropagating waves forming the standing wave $S_{\rm VSCPT}$ are illustrated on the right. The standing wave $S_{{\rm sub}-D}$ is indicated by the dashed lines.

To efficiently accumulate the atoms in the state $\Psi_{\rm vsd}$ a second overlapping bichromatic standing wave ($S_{{\rm sub}-D}$) is employed. Each frequency component of $S_{{\rm sub}-D}$ is composed of two counterpropagating waves with mutually orthogonal linear polarizations. The first frequency is tuned to a value 2.5Γ higher than the $F = 2 \leftrightarrow F'' = 2$ resonance of the D_2 line. The second frequency is resonant with the $F = 2 \leftrightarrow F'' = 1$ transition of the same line. The coupling of the $m_F = 2$ ($m_F = -2$) magnetic sublevel of the $F = 2$ ground state to the exited states $F'' = 1$ and $F'' = 2$ vanishes when both frequency components have pure σ^+ (σ^-) polarization. The atoms in the standing wave $S_{{\rm sub}-D}$ are thus optically pumped into weakly coupling states which are localized where the polarization of the standing wave is almost circular [9]. As the other magnetic sublevels of the atomic ground states are shifted towards higher energies, we expect the atoms to be cooled during these optical pumping cycles [10]. Our configuration resembles that of a dark or gray optical lattice with a single frequency light field and an additional static magnetic field [11].

The dynamics of the atoms in the light fields can be understood in the following way. The cooling in the standing wave $S_{{\rm sub}-D}$ provides confinement of the atoms at low velocities. The atoms are also continuously optically pumped into the $F = 1$ ground state and can be trapped in the dark state $\Psi_{\rm vsd}(p \approx 0)$ which is adiabatically transferred into the momentum state $p \approx -\hbar k$, when the atoms leave the light field. As the experiment is performed in one dimension, the atoms are heated by the spontaneously emitted photons in the directions perpendicular to the standing wave axis.

In our experiment we load 3×10^8 rubidium atoms from the background gas of a rubidium cell into a magneto-optical trap (MOT) [12] and prepare a high-density monoenergetic rubidium beam ($\Delta v/v < 1/20, n \approx 10^{10}$ atoms/cm^3) using the moving optical molasses technique [13]. The atoms are accelerated vertically downwards to a velocity of 1.7 m/s. Then the laser beams of the moving molasses are shut off and the atoms follow their ballistic trajectory towards the interaction region which is 17 cm below the MOT. The interaction region is differentially pumped to

2×10^{-9} mbar and is shielded against magnetic fields to better than 0.5 mG using three layers of Mu metal. In the interaction region the atoms interact with the standing waves for 0.6 ms.

The two standing waves S_{VSCPT} and $S_{\mathrm{sub}-D}$ are derived from grating stabilized laser diodes [14]. The laser beams are spatially filtered to achieve Gaussian modes. The standing waves are formed by retroreflection off a mirror which is 13 cm away from the interaction region. The frequency of the standing wave S_{VSCPT} is tuned 0.5Γ above the $F = 1 \leftrightarrow F' = 1$ transition. In the interaction region, the waist along the z axis of the incoming beam is $w_- = 390\ \mu$m, and $w_+ = 290\ \mu$m of the reflected beam. The retroreflecting mirror has a reflectivity of 75%, which gives a resonant Rabi coupling in the center of the Gaussian profiles of $\Omega_+(z = 0) = \Omega_-(z = 0) = 0.16\Gamma$. The standing wave $S_{\mathrm{sub}-D}$ has a beam waist of $w = 480\ \mu$m in the interaction region. The resonant rms Rabi coupling for each traveling wave in the Gaussian center is 0.8Γ on the $F = 2$ to $F'' = 2$ transition and 0.17Γ on the $F = 2$ to $F'' = 1$ transition. We have positioned the center axis of the standing wave $S_{\mathrm{sub}-D}$ 300 μm below the center axis of the standing wave S_{VSCPT} so that those atoms that have not been trapped in the state Ψ_{vsd} are optically pumped into the $F = 1$ ground state when leaving the interation region. This allows detection of each atom with the same efficiency.

To determine the transverse momentum distribution of the atoms, a pinhole ($\phi = 75\ \mu$m) is placed 3 mm underneath the standing wave and the spatial atomic distribution is measured 10 cm further below (Fig. 2). There we image the fluorescence of the atoms in a standing light wave using an intensified charge coupled device (CCD) camera [15]. The standing wave light field is resonant with the $F = 2 \leftrightarrow F'' = 3$ closed cycle transition of the D_2 line. An additional laser beam resonant with the $F = 1 \leftrightarrow F' = 1$ transition of the D_1 line optically pumps the atoms which arrive in the $F = 1$ ground state into the closed cycle. This elliptically shaped beam is concentric to the standing wave and forms a sheet of light that defines the plane of detection. We detect approximately one photon per atom with the CCD camera. The time of flight of the atoms between the pinhole and the imaging region is 35.4 ms for our experimental parameters. The momentum resolution of our detection scheme is $0.6\hbar k$ and is limited by the resolution of our optical imaging system.

Without any interaction, the measured atomic momentum distribution in the $x - y$ plane is determined by those atoms from the magneto-optical trap whose ballistic trajectories pass through the pinhole. Since the accelerated atomic cloud expands on its way downwards to the pinhole, only atoms with very small transverse velocities are selected by the pinhole, allowing us to study the cooling process at ultralow temperatures. We measure the initial momentum distribution by blocking the standing wave S_{VSCPT} so that the atoms are optically pumped into the $F = 1$ ground state by the standing wave $S_{\mathrm{sub}-D}$.

Figure 3 shows the cooled and the initial two-dimensional atomic momentum distributions. Both distributions are obtained by adding up 200 single shots and subtracting the stray light background. We measured this background by switching off the MOT and then summing over 1000 pictures and dividing the result by 5. In the cooled distribution 67% of the atoms diffuse out of the detection region due to their high momentum along the uncooled y direction. In the upper section of Fig. 3 we plotted the corresponding one-dimensional momentum distributions calculated by integrating the two-dimensional distributions along the y direction.

In the cooled distribution the atoms accumulate at the momentum $-\hbar k$, as we have anticipated. A few atoms diffuse to states with negative momenta of down to $-10\hbar k$. We attribute this diffusion to atoms that are not trapped in the velocity-selective dark state and

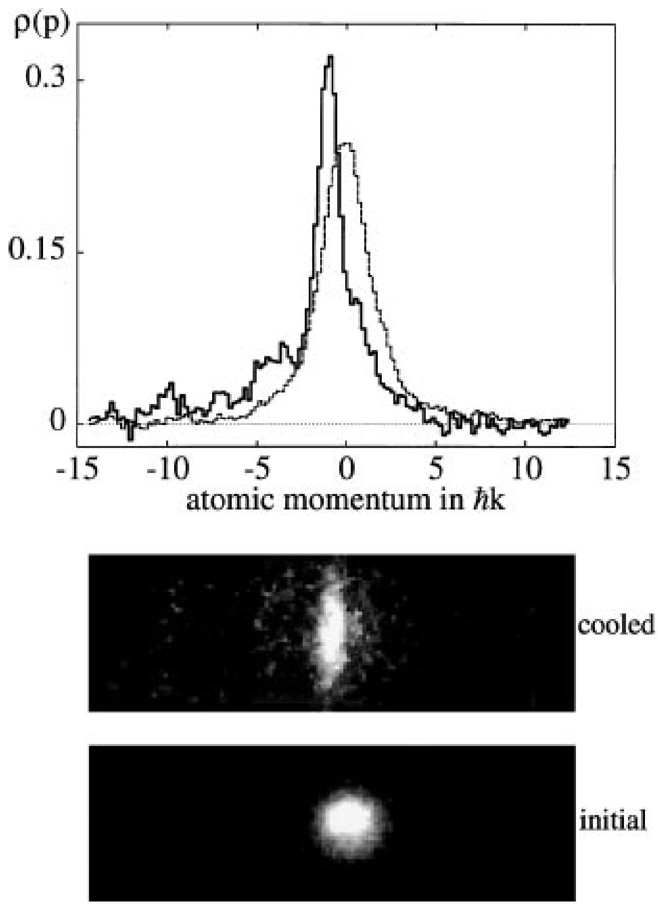

FIG. 3. Images of the cooled and the initial atomic velocity distributions. The cooled distribution forms a stripe since the atoms accumulate at momentum $-\hbar k$ along the cooling axis and diffuse in the perpendicular direction. The corresponding one-dimensional momentum distributions $\rho(p)$ in units of $(\hbar k)^{-1}$ are shown above. The dashed line shows the initial distribution.

experience unbalanced light pressure when leaving the laser beams. There is no diffusion of atoms to positive momentum. To obtain a value for the temperature we have fitted a Gaussian curve to the cooled momentum distribution, taking into account all data points in a $2\hbar k$ wide momentum interval centered at $-\hbar k$. The fitted Gaussian curve corresponds to a temperature of 110 nK and an rms velocity spread of $0.6\hbar k/M$. The actual temperature is believed to be lower, since the limited momentum resolution of the detector has not been taken into account. For comparison we also fitted a Gaussian curve to the initial velocity distribution. It has an rms velocity spread of $1.4\hbar k/M$ corresponding to 700 nK. The increase in one-dimensional momentum space density is 30% for the cooled atoms. Furthermore the atoms cooled into the dark state are spin polarized since they leave the light field in the state g_y. Experimental demonstration of cooling to much lower temperatures will be possible by improving the momentum resolution of our detector and increasing the interaction time. Off resonant excitation of the dark state Ψ_{vsd} to the $F' = 2$ excited state of the D_1-line has a rate of below 50 Hz and can therefore be neglected. The optical potentials induced by the off resonant coupling of the $F = 1$ ground state to the $F' = 2$ excited state have a modulation depth of below $1/20$ of the recoil energy, so that at least another order of magnitude lower temperatures should be achievable in our experiment.

Our experiment clearly shows the coherence properties of the dark state in VSCPT cooling and that these can be used to obtain spin polarized atoms at subrecoil temperatures. This is of particular interest, since spin polarization at ultralow temperatures cannot be achieved by normal optical pumping which immediately heats the sample above the recoil temperature. The extension of our cooling scheme to two and three dimensions should be possible by adding additional laser beams along the y and z axes [2,16,17]. The adiabatic transfer into a single spin polarized momentum state is then achieved by adiabatically switching off all beams except one. Since we reach subrecoil temperatures within a very short period of time (<1 ms), two- and three-dimensional subrecoil cooling should be considerably faster than the previously demonstrated Raman-cooling technique [5]. In three dimensions our method will produce an ultracold spin polarized sample that is ideal for efficiently loading a magnetic trap.

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