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High-brightness atom source for atomic fountains

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We launch Cs atoms using a moving three-dimensional (3D) optical lattice. Atoms are initially spin polarized and cooled to the ground state of the optical potential using 3D Raman sideband cooling and then accelerated in the lattice to velocities of up to 3 m/s. Subsequent adiabatic lowering of the potential releases the atoms from the lattice. Three-dimensional kinetic temperatures as low as 200 nK were achieved. The observed temperature of the launch is independent of the acceleration and final velocity of the atoms. In an alternative approach, we first accelerate the atoms to velocities of up to 5 m/s using moving molasses and then cool them with the lattice in the comoving frame of the atoms to temperatures as low as 150 nK.

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Atomic fountains are the starting point for many precision experiments in atomic physics, such as atom interferometers or atomic clocks. The standard technique to create an atomic fountain [1] is to capture atoms in a magneto-optical trap (MOT) [2] and then launch them using moving molasses [3]. This technique faces several limitations: The lowest temperature that has been achieved with moving molasses is 1.5 μK [4–6], and often additional velocity selection is necessary to further reduce the momentum spread of the atom cloud. At the same time, the launched atoms are not spin polarized, leading to a substantial loss in the number of atoms available for experiments if a spin polarized sample is needed. This limits the time averaged brightness of the atom source, defined as the atom number per unit time, per unit source area, and per three-dimensional (3D) velocity spread, to a few times 10^{20} atoms/($m^5\,s^{-2}$).

3D Raman sideband cooling in optical lattices has recently been demonstrated to be a useful technique to overcome the temperature and density limitations of optical molasses. Temperatures as low as 290 nK have been achieved in a stationary lattice, yielding a source brightness of 4×10^{22} atoms/($m^5\,s^{-2}$). By comparison, a Bose-Einstein condensate of 5×10^6 atoms dropped every 45 s has the same source brightness. Compared to using a BEC source of cold atoms, a fountain of sideband cooled atoms is easier to implement. Furthermore, the symmetry of the fountain launch can be exploited in an appropriate experimental setup to cancel out systematic effects that otherwise influence the outcome of precision measurements.

In this Rapid Communication, acting on our previous proposal [7], we report the use of 3D degenerate Raman sideband cooling with adiabatic release in an optical lattice to cool and accelerate Cs atoms [7–9]. An atomic fountain with a temperature of 200 nK in all three dimensions was created. The maximum launch height of our fountain is 50 cm if the atoms are accelerated in the optical lattice and the observed temperature of the launch is independent of the launch height for values accessible with our experiment. For accelerations above 450 m/s^2, we observe a loss of atoms due to tunneling out of the potential wells. In an alternative approach, we launch the atoms at a 3D temperature as low as 150 nK to an even greater height of up to 1 m by first accelerating them using moving molasses and then Raman sideband cooling them in a comoving frame with the lattice. This temperature is 10 times lower than the lowest temperature of 1.5 μK measured in atomic fountains using moving molasses. In contrast to moving molasses, the atoms are simultaneously spin polarized in our experiment. With our fountain, we achieve a source brightness of 2×10^{22} atoms/($m^5\,s^{-2}$).

Our degenerate Raman sideband cooling scheme is similar to the one described in Ref. [7]. Atoms are optically pumped into the lowest energy magnetic sublevel $F=3$, $m_F=3$ and trapped in the lattice potential created by four intersecting laser beams far detuned below the $6S_{1/2}$, $F=3\rightarrow6P_{3/2}$, $F'=4$ transition. A small magnetic field of typically 60 mG introduces a Zeeman shift between neighboring magnetic sublevels that equals the vibration energy of the potential wells. A cooling cycle starts with atoms initially trapped in a high-lying vibrational level ν. Energy selective Raman transitions, induced by the same light that provides the optical potential, transfer the atom from the $m_F=3$ to the neighboring $m_F=2$ magnetic sublevel and further on to $m_F=1$, thereby reducing the vibrational quantum number by two units. Optical pumping back to $m_F=3$ tends to preserve the vibrational quantum number for a trap in the Lamb-Dicke regime where the vibration frequency exceeds the recoil energy, effectively cooling the atoms by two vibrational quanta per cooling cycle. This cooling continues until most of the atoms are cooled to the vibrational ground state of the $m_F=3$ sublevel, which is a dark state to both the Raman transitions and the optical pumping.

The geometry of our lattice and an overview of the experimental setup are shown in Fig. 1. The optical potential is formed by the interference of four linearly polarized laser beams, two counterpropagating along the x axis, and two running waves along y and z. The choice of only four beams ensures that the lattice geometry is unchanged by fluctuations in the relative phases of the beams apart from an overall translation of the lattice [10]. The polarizations of the beams are all in the y-z plane, maximizing the Raman coupling for a magnetic field in that plane. The polarizations of the counterpropagating beams subtend angles of typically

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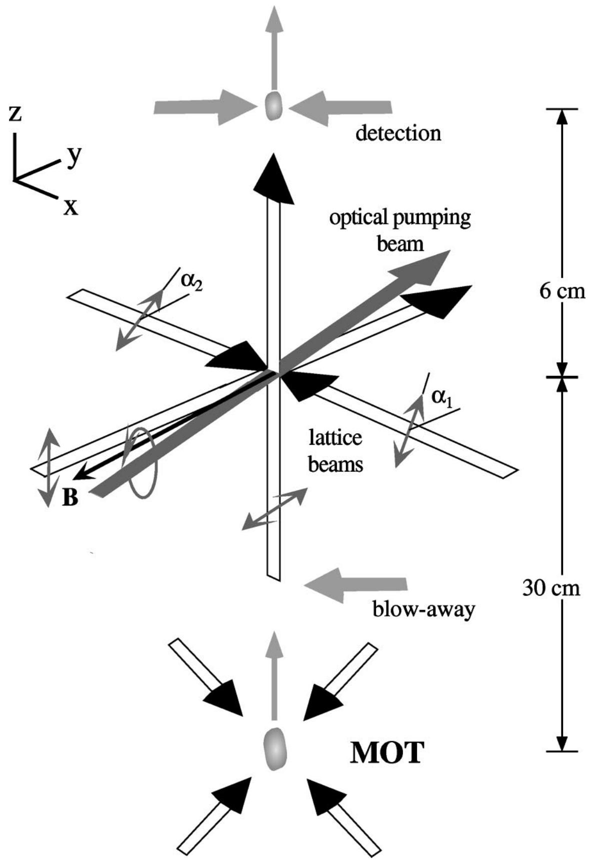

FIG. 1. Our optical lattice configuration. Typical peak intensities for the four linearly polarized lattice beams are 155 mW/cm^2 for the counterpropagating beams, 140 mW/cm^2 for the horizontal running wave and 210 mW/cm^2 for the vertical beam. Typically, $\alpha_1=30°$, $\alpha_2=15°$ with respect to the y axis. The lattice is loaded from a MOT 30 cm below the lattice. The blow-away beam can be used to cut the atom cloud in the vertical dimension to load only the lower part of the cylindrical lattice volume.

30° and 15° with respect to the y axis. This angle as well as the intensity ratios between the beams are optimized for given launch parameters of the atomic fountain to obtain low temperatures in all three dimensions. The large Raman coupling is comparable to the trap vibration frequency.

In order to allow the atoms to travel a certain distance upwards while the potential is accelerated, we choose elliptical beam profiles for the horizontal lattice beams, typically with e^{-2} beam waists of 2 mm in the x and y dimension and 25 mm in the z dimension for the highest launches. In the vertical dimension the horizontal beams are cut off at the 75% intensity level. The beam along z has a circular profile with an e^{-2} waist of 2 mm. The lattice beams are derived from the same laser that provides the trapping light for our MOT. The detuning is 9.2 GHz to the red of the $6S_{1/2}$, $F=3\rightarrow 6P_{3/2}$, $F'=4$ transition at $\lambda=852$ nm. At this detuning, the lattice beams also provide hyperfine repumping light to quickly recycle atoms that are off-resonantly pumped to the upper hyperfine manifold. The optical pumping beam that is used to pump atoms into the $F=3$, $m_F=3$ state propagates along y and is typically detuned $+7$ MHz from the $F=3\rightarrow F'=2$ transition. It is derived from the same laser that provides the repumping light for the MOT and has an intensity of 0.3 mW/cm^2. In order to obtain both σ^+ and π polarization along the magnetic field **B**, we orient **B** in the x-y plane at a small angle of $\sim 5°$ with respect to y and adjust the polarization of the pumping beam to eliminate the σ^- component.

Two different procedures can be implemented to accelerate and cool the atoms: in the first scheme, the lattice is used to first cool and then accelerate the atoms. In the second procedure, the atoms are accelerated instead using moving molasses and then cooled in a comoving frame with the lattice.

Cooling and accelerating the atoms in the lattice. We begin with about 10^9 atoms collected in a MOT from a room-temperature vapor. Our MOT is located ~ 30 cm below the lattice and produces an atomic cloud of 1.5 mm rms radius. Using moving optical molasses, we launch the atoms with a temperature of 2.5 μK so that the turning point of the cloud coincides with the position of the lattice. A $F=4\rightarrow F'=5$ blow-away beam can be used to cut the atom cloud in the vertical dimension to load only the lower part of the cylindrical lattice volume. By switching on the lattice and optical pumping beams along with the magnetic field, we pump the atoms into the $F=3$, $m_F=3$ state and trap 10^8 atoms in the lattice. The small fraction of atoms captured from the MOT cloud in our lattice is due to the difference in size between the lattice and the atom cloud after expanding for about 250 ms. In a more natural approach (which we could not follow due to experimental constraints), one would start with a small MOT contained completely in the lowest part of the lattice volume. It has been shown in [7] that in such a situation the capturing efficiency of the lattice is 95%.

After 6 ms of initial cooling in a stationary lattice, we start a linear ramp of the frequency of the vertical lattice beam to accelerate the optical potential upwards at rates corresponding to accelerations up to 1000 m/s^2. Final velocities of up to 3.0 m/s are reached after several milliseconds of acceleration. After the frequency ramp the lattice is kept moving with a constant velocity and the optical pumping beam is extinguished. For adiabatic cooling, the lattice intensity is decreased according to $P(t)=P(0)[1+t/t_0]^{-2}$ for 500 μs [11], where t_0 is typically chosen to be 100 μs, before the light is switched off completely. For accelerations below 450 m/s^2, we launch 95% of the atoms initially trapped in the lattice and cooled down to the ground state of the potential in a cloud of typically $1\times1\times1.8$ mm rms radius.

The 3D velocity distribution of the launched atom cloud is determined using a time-of-flight technique with a detection beam 6 cm above the lattice. The atoms pass this detection region right after the launch and again a few hundred milliseconds later after they reached the turning point of their trajectory. The temporal and spatial widths of the atom cloud are measured at both times and the temperature is determined from the observed spreading. This method allows us to correct the measured width of the atom cloud for the initial size of the lattice. For different launch heights and accelerations, a temperature of 200 nK after adiabatic release is consis-

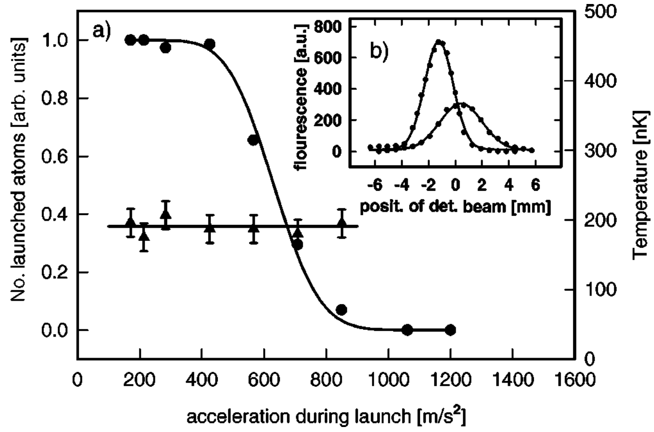

FIG. 2. (a) Number of launched atoms for different accelerations and otherwise identical lattice parameters (circles). The fit of the expected loss due to Landau-Zener tunneling as a function of acceleration corresponds to $a_c = 3920\ \text{m/s}^2$. The temperature of the launch remains constant (triangles), consistent with the assumption that only atoms in the ground state are launched. (b) Scan across atom cloud passing the detection region while moving upwards and falling down again. The Gaussian fits give a temperature of 190 nK.

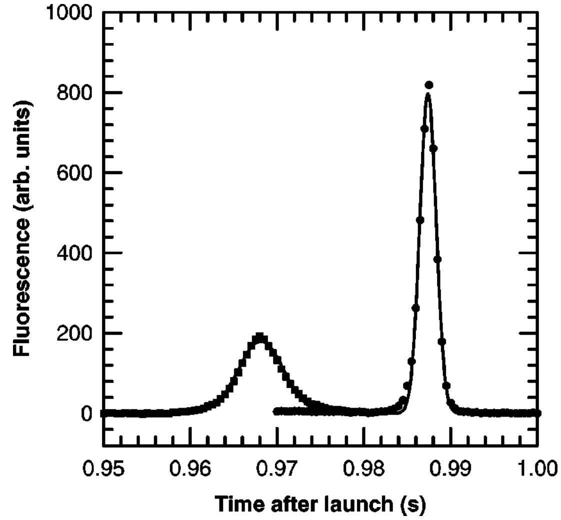

FIG. 3. A comparison of the fluorescence due to atoms from a moving molasses launch with (squares) and without (circles) additional cooling in the lattice. The atoms spend about 1 s in flight. Atoms from moving molasses alone have an rms velocity spread of about 10 mm/s, while those additionally cooled in the lattice have a spread of 3 mm/s. Since the atoms in the moving molasses launch are not spin polarized, another factor of 7 in signal enhancement is possible for precision experiments, e.g., atomic clocks and atom interferometers, that use $m_F = 0$ atoms, if one coherently transfers the atoms cooled in the lattice from $m_F = 3$ to $m_F = 0$.

tently reached in all three dimensions. We estimate an uncertainty of $\pm 10\%$ on the temperature measurements, mainly due to influences of the size of the detection beam. The temperature was also measured independently using velocity-sensitive Raman transitions [12,13], yielding the same result. To study the influence of adiabatic release on the final temperature, we shut off the lattice in less than 500 ns at the end of the frequency ramp. The temperature of the launch without adiabatic release was 600 nK.

It is critical that the frequency ramp during the launch is phase continuous. A sizeable phase discontinuity leads to a sudden jump in the position of the potential wells that cannot be followed by the trapped atoms. The ejection of all the atoms due to a single random phase jump of 180° was observed.

While the observed temperature of the launch is independent of the acceleration and final velocity of the atoms for values accessible with our experiment, the number of launched atoms drops for accelerations above $450\ \text{m/s}^2$ (Fig. 2). This drop is due to Landau-Zener (LZ) tunneling [14–17] of atoms out of the ground state of the potential wells under the influence of the acceleration. The LZ tunneling rate across the energy gap above the ground state of the potential can be estimated as [17]

$$\Gamma = \frac{ma}{2\hbar k_L} \exp(-a_c/a), \tag{1}$$

where $a_c = 2\pi(E_{gap}/2)^2/2\hbar^2 k_L$ is a critical acceleration and E_{gap} is the energy gap above the ground state. Atoms tunneling out of the ground state enter into higher energy states in adjacent lattice sites, which have higher tunneling rates associated with them, until they are lost from the potential and no longer accelerated. The lost atoms from the lattice have been detected with an additional detection beam below the lattice.

Figure 2 shows a fit of the tunneling loss from the lattice according to Eq. (1) to the data, with the critical acceleration as a parameter. The fit gives a critical acceleration of $a_c = 3920\ \text{m/s}^2$, corresponding to a vibration frequency of $\omega = 2\pi \times 30$ kHz in a harmonic lattice potential. This vibration frequency is higher than the average vibration frequency of our lattice, $\omega = 2\pi \times 21$ kHz, as measured independently using parametric excitation [9]. We believe that the higher accelerations achievable with our lattice are due to the fast Raman cooling that is still operating during the launch, giving a probability for tunneled atoms to be cooled back to the ground state. Accordingly, if the optical pumping beam is turned off during the launch, the observed loss at a given acceleration is larger. To minimize the loss from the lattice, the magnetic field during the launch was optimized individually for the different values of the acceleration. Higher accelerations require smaller magnetic fields, consistent with a slightly lower vibrational spacing in the accelerated potential.

For accelerations close to but below the onset of LZ tunneling from the ground state, the launch height of our atomic fountain was ultimately limited by the size of our lattice beams. If the distance traveled by the atoms during acceleration and adiabatic release becomes too large, some atoms drop out of the lattice volume without proper adiabatic release and without being fully accelerated to the final velocity. The dropped out atoms were seen as a tail of the atom cloud in the time-of-flight signal. By reducing the length of the lattice in the vertical dimension, we studied the loss in the number of atoms as a function of the distance the atoms travel during the launch. Our highest launch to a height of

~ 50 cm corresponds to a traveled distance of ~ 14 mm for the atom cloud during acceleration and adiabatic release.

Using the lattice to cool in a comoving frame. In order to overcome the limitations in launch height, we implemented a second experimental procedure. After collecting atoms in the MOT, we use moving molasses to accelerate the atoms to a velocity of 5 m/s. When the atoms enter the lattice region, we switch on the lattice and optical pumping light, detuning the frequency of the vertical lattice beam to compensate the Doppler effect for the moving atoms. This creates an optical lattice in the comoving frame of the atoms. We cool the atoms for 2.6 ms followed by 500 μs of adiabatic release to switch off the light before the atoms travel out of the lattice region. In order to separate the time-of-flight signal of the MOT and the lattice, we slightly accelerate the lattice by 34 m/s^2 during the whole process.

With this technique, we achieve launch heights up to the top of our vacuum chamber, ~ 1 m above the lattice. After careful optimization of all lattice parameters, we consistently achieve three-dimensional temperatures of 150 nK (Fig. 3). By retrapping the atoms that fall down to the position of the MOT from the previous launch, we are able to load about 7×10^8 atoms in the MOT in 150 ms. We estimate that 2.5×10^8 atoms are cooled in the lattice in a cloud of 3 mm^2 rms source area. This corresponds to a source brightness of 2×10^{22} atoms/(m^5 s^{-2}).

In conclusion, we have shown that 3D Raman sideband cooling in an optical lattice can be used to reduce the temperature of atomic fountains below the single-photon recoil temperature defined by $\frac{1}{2}mv_{\rm rec}^2=\frac{1}{2}kT_{\rm rec}$ and an order of magnitude below the values achievable with moving molasses. This technique can be used to greatly enhance the performance of precision experiments that are limited by the brightness of the atom source. In an optimized setup with a small MOT located in the lower part of the cylindrical lattice volume, it should be possible to increase the number of atoms in the lattice, further increasing the brightness of the launch to values on the order of 10^{23}, surpassing those achievable with Bose-Einstein condensates. Even lower temperatures could be achieved in a lattice with larger lattice spacing, trading off density for a lower velocity spread after adiabatic release.

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