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Cooling by Maxwell's demon: Preparation of single-velocity atoms for matter-wave interferometry

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We present an alternative method for laser cooling of atoms close to the one-dimensional recoil limit. This method is particularly suited for atoms not accessible to conventional sub-Doppler cooling methods. It is based on the repeated selection and accumulation of slow atoms from a precooled atomic cloud and on the repeated rethermalization of the remaining atoms. The prepared ensemble is used to measure atom interferences with increased visibility.

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The recent progress in the fields of atomic clocks, atom interferometry, laser spectroscopy, and Bose-Einstein condensation (BEC) was made possible only by the powerful techniques of laser cooling. From the first demonstration of Doppler-limited laser cooling [1], via the efficient polarization gradient cooling reaching unexpected low temperatures [2,3], the way led to sophisticated subrecoil cooling techniques, such as Raman cooling [4] or velocity-selective coherent population trapping (VSCPT) [5], to name only a few. Unfortunately, these efficient sub-Doppler cooling mechanisms are largely restricted to atoms with magnetic or hyperfine substructure in the ground state. On the other hand, atoms with a single ground state, such as the alkaline earths, are of special interest for atom interferometry [6], frequency standards [7], the study of cold collisions [8,9], and possibly BEC due to their small amount of sensitivity to external fields and the simplified theoretical description of their interaction. Two-stage Doppler-cooling methods that make use of the narrow intercombination lines in the alkaline earths [10] and recently applied to strontium [11,12] are not accessible in general. For many applications, e.g., atom interferometry, precision spectroscopy, and frequency standards, even a one-dimensional cooling, i.e., a reduction of the velocity width in one dimension, would already allow significant improvements in sensitivity.

In this Rapid Communication, we present an alternative scheme for such a one-dimensional cooling. In analogy to Maxwell's thought experiment [13] we select and accumulate the slowest atoms from a precooled atomic cloud. Rethermalization of the remaining hotter atoms, in addition to the action of Maxwell's ''demon,'' again provides slow atoms that can be selected and accumulated in a next cycle. Repeated application of this cycle in principle allows one to accumulate all atoms in one narrow velocity class.

We realized this scheme with the alkaline-earth calcium (see Fig. 1), which is particularly suited to atom interferometry [14] and is already used for frequency standards [15]. We start with a precooled atomic ensemble provided by a magneto-optical trap (MOT) [16]. When the trap is switched off, the atoms have a typical temperature of $T \approx 3$ mK and an rms velocity of about 1 m/s. The slowest atoms are selected by pulsed excitation from the $^1S_0$ ground state to the $^3P_1$, $m=0$ state (step 1 of Fig. 1) with a laser resonant on the intercombination transition that has a natural linewidth of less than 300 Hz [17]. The Doppler effect relates this frequency width to a minimum velocity interval of 0.2 mm/s that can be selected with this transition. The actually selected width of the velocity interval is determined by the chosen duration τ_S of the laser pulse, since the corresponding frequency width of the Fourier spectrum is inversely proportional to the pulse length τ_S. Hence, by increasing the pulse length, the velocity width is reduced at the expense of the number of excited atoms. The optimum pulse length can be adjusted according to the required number of atoms and the required velocity width. Additionally, by adjusting the frequency of the exciting laser, every desired velocity class can be selected. To avoid stimulated transitions back to the ground state in the following cycle that would prevent the efficient accumulation, the atoms are optically pumped to suitable states. We have chosen the $^3P_1$, $m=\pm 1$ states that are not accessed by the selection pulse because these Zeeman levels are shifted out of resonance in the applied homogeneous magnetic quantization field. The optical pumping is achieved by excitation with linearly polarized light ($\lambda = 430$ nm) that couples the $4s4p\,^3P_1$, $m=0$ to the $4p^2\,^3P_0$ state (step 2 of Fig. 1). On the average, 1.5 absorption processes per atom are needed to pump all atoms into the $^3P_1$, $m=\pm 1$ state. In the third step, the four MOT laser

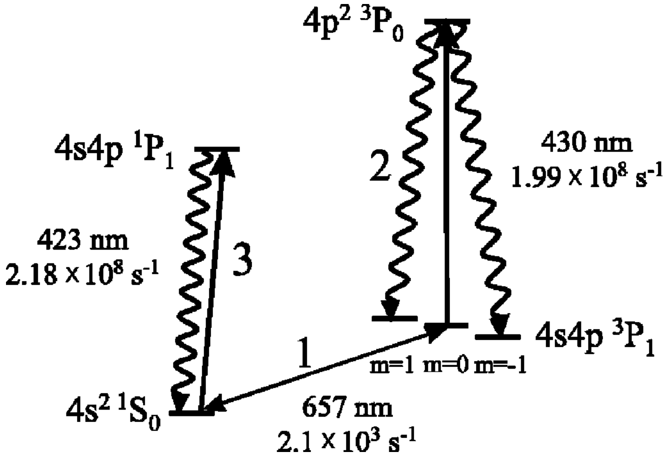

FIG. 1. Partial energy diagram with wavelengths and transition rates relevant to the Maxwell's-demon cooling of ^{40}Ca. The numbers denote the steps of the cooling scheme (see text).

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beams ($\lambda = 423$ nm, $^1S_0$-$^1P_1$ transition) perpendicular to the homogeneous magnetic field are switched on again to rethermalize the velocity distribution of the ground-state atoms in a two-dimensional optical molasses. By repeating these three steps several times the number of slow atoms in the $^3P_1$, $m = \pm 1$ states is increased.

The laser beams for the MOT and the molasses are generated by a frequency-doubled diode-laser system. A frequency-stabilized dye laser is used for the excitation of the Ca intercombination transition ($\lambda = 657$ nm) [18] and another dye laser system for generating the 430-nm radiation. The MOT is loaded from a thermal beam for 15 ms to 30 ms leading to about 10^7 atoms confined to a volume of about 1 mm^3. Then the magnetic fields and laser beams of the MOT are switched off and the magnetic quantization field is switched on. After a delay of 0.5 ms necessary for the magnetic field to become sufficiently constant, the described Maxwell's-demon cooling is started by applying the velocity-selecting 657-nm pulse. It is followed by the pulse of the colinear 430-nm pumping beam with duration between 1 and 5 μs. The cycle is ended by switching on the molasses beams for rethermalization for 5–10 μs. After repeating the cooling cycle N times and waiting for about two lifetimes (1 ms) of the excited atoms for their spontaneous decay into the ground state, we measured the velocity distribution of the ensemble. A 657-nm pulse with a duration τ_D of up to 30 μs was used to scan the intercombination line and the fluorescence was detected. Due to the small natural linewidth the measured linewidth results mainly from the Doppler effect and therefore monitors the velocity distribution of the atomic cloud.

In the measured spectrum (Fig. 2) the Maxwell's-demon cooled atoms show up as a narrow needle on a broad pedestal caused by the precooled atoms. The width of the needle of 150 kHz corresponds to a width of the velocity distribution of 10 cm/s. This width results from the randomly distributed recoils of the spontaneous-emission processes involved in the cooling scheme and from the Fourier width of the selecting pulse. As an estimate, we take the root mean square of the three independent contributions to the linewidth, i.e., 100 kHz due to the excitation pulse with $\tau_S = 10$ μs, and 1.5×35 kHz and 23 kHz due to the recoil shifts resulting from the spontaneous emissions at 430 nm and 657 nm, respectively. We end up with an estimated width of about 130 kHz for the resulting needle, neglecting the spatial dipole characteristics of the involved transitions. This is in reasonable agreement with the measured value. However, the use of significantly longer pulses with up to $\tau_S = 30$ μs only leads to a small reduction of the resulting linewidth [full width at half maximum (FWHM) ≈ 100 kHz] accompanied by a decrease of the number of accumulated atoms. We measured a shift of 52(2) kHz of the needle, when the pumping pulse was used as compared to the position of the small peak already observed without this pulse. This is in fair agreement with the estimated value of 1.5×35 kHz due to the photon recoil of the pumping pulse. For small numbers of cooling cycles ($N < 5$) the height of the needle increases linearly with N and reaches a maximum for N between 10 and 20, depending on the times involved in the Maxwell's-demon cooling. We attribute this behavior to the fact that the useful time of the cooling scheme is limited by the velocities of the atoms perpendicular to the direction of the selecting beam. Consequently, for higher N, corresponding to longer cooling times, more of the accumulated atoms leave the interaction region than can be added by another cooling cycle. In order to get a pure ensemble of the prepared low-velocity atoms, the residual ground-state atoms can be removed immediately after the cooling scheme with a blue-detuned 423-nm beam pushing them out of the interaction region (inset of Fig. 2).

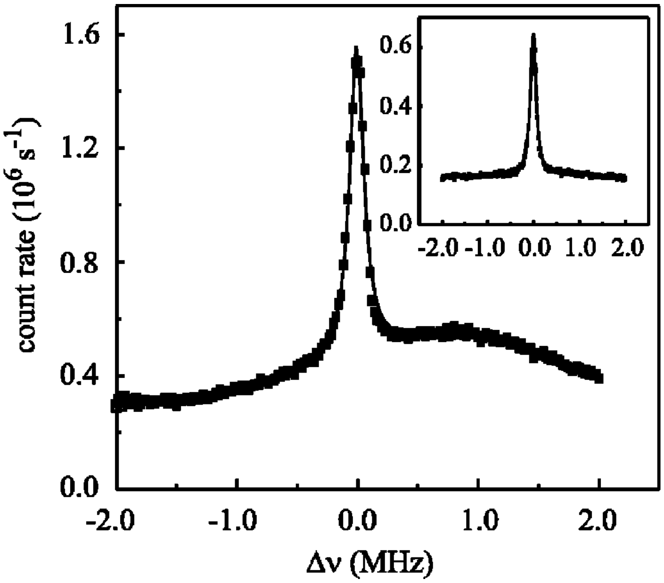

FIG. 2. Observed fluorescence from the intercombination transition vs detuning of the 657-nm probe beam after 20 cooling cycles with $\tau = 10$ μs. The needle resulting from the cooled atoms has a FWHM of 150 kHz. Due to the acceleration in the rethermalizing molasses the center of the pedestal is shifted. The inset shows the Doppler profile of the cooled atoms when the residual ground-state atoms have been removed by a pushing beam.

To optimize the different steps of the cooling scheme we have devised a method where we probe the population difference between the ground state and the $^3P_1$, $m = 0$ state. The selecting pulse with fixed frequency leads to a population of the excited state and a hole in the velocity distribution of the ground state (Bennet hole). Owing to the photon recoil these two features are separated in velocity space, and can be probed by the change of the fluorescence resulting from a counterpropagating probe pulse that is scanned in frequency. Hence, the excitation spectrum shows two dips, corresponding to the hole in the ground-state velocity distribution and the population of the excited state [19], if this distribution is probed with sufficiently high resolution [Fig. 3(a)]. By monitoring the depths of the two dips after the different steps of the cycle, we obtain information about the population of the relevant states to optimize the efficiency of each step. With the 430-nm laser on, the excited atoms are pumped to the other magnetic substates, which leads to a reduction of the low-frequency dip [Fig. 3(b)]. When additionally the ground-state atoms are rethermalized by the 423-nm molasses the hole burnt in the ground-state velocity distribution is filled.

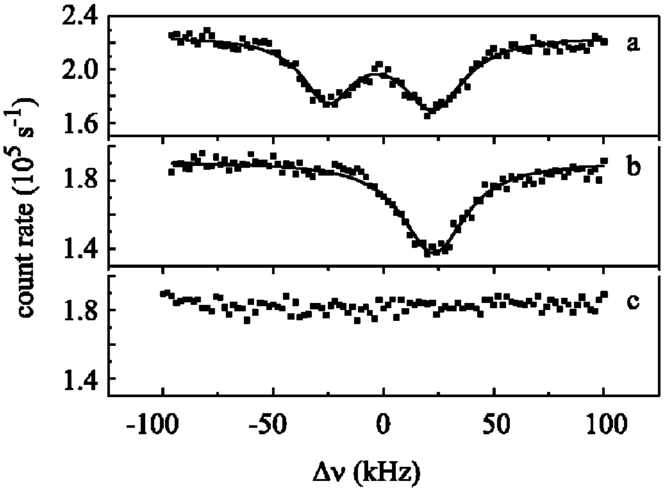

FIG. 3. Fluorescence measured with a probe pulse ($\tau_D = 30$ μs) after the different steps of the Maxwell's-demon cooling scheme: immediately after the selection pulse (a), after the 430 nm pumping pulse (b), and finally after the rethermalization pulse (c).

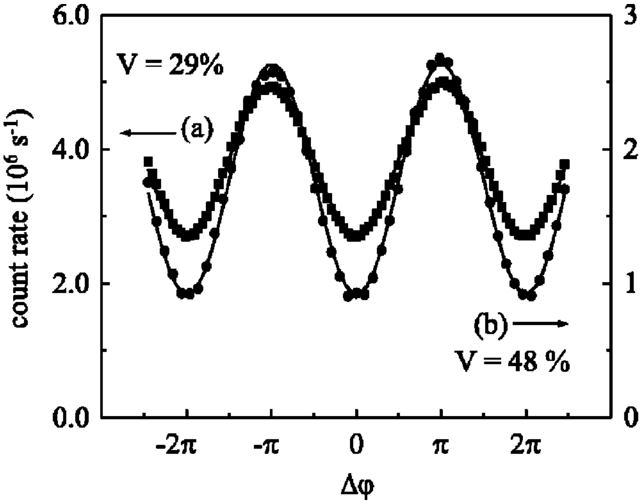

FIG. 4. Interference pattern for a Bordé-type atom interferometer comprised of three pulses of a laser beam for a Doppler-cooled atomic ensemble [(a), squares] and for a Maxwell's-demon cooled ensemble [(b), circles]. The visibility is increased due to the reduced velocity width.

Consequently, the second dip also disappears [Fig. 3(c)]. The reduction of the fluorescence signal baseline results from the reduced detection of fluorescence photons from the $m = \pm 1$ states due to their angular emission characteristic that differs from that of the $m = 0$ state for which the detection was optimized.

To assign an efficiency to the Maxwell's-demon cooling one could compare the number of atoms in the needle with the number of the remaining atoms. By dividing the area of the needle by the area of the pedestal, we derive an efficiency of 25%. This estimate does not take into account that the number of available atoms is significantly higher immediately after switching off the MOT. Compared to this number we derive an efficiency of slightly more than 5%. If we use the Maxwell's-demon cooling for atom interferometry (see below) the situation is much more favorable. From Fig. 4 we see that, despite the dramatically reduced number of atoms, we can obtain virtually the same signal-to-noise ratio, but now in a well-defined velocity interval.

The reported results were obtained with an existing apparatus used in a frequency standard. Further improvement of the cooling scheme is possible since at present the efficiency of the Maxwell's-demon cooling is mainly limited by the experimental setup. E.g., due to eddy currents and frozen magnetic fields in the vacuum apparatus it takes about 0.5 ms until the magnetic quantization field is sufficiently constant. This limitation can be overcome in an apparatus with optimized design, where the cooling scheme can start immediately after the release of the precooled cloud of atoms from the MOT. The use of four independent laser beams for the rethermalizing molasses would allow one to avoid acceleration of the ground-state atoms in imperfect molasses. Currently, this effect limits the efficiency of the cooling scheme because after a few cycles all atoms are accelerated and no more atoms with $v = 0$ can be excited. As mentioned above, the minimal velocity width of the cooled ensemble is limited by the recoils from the spontaneous emitted photons. The spontaneous emission within the optical pumping step is essential for the cooling scheme and cannot be easily circumvented. The broadening due to the spontaneous decay into the ground state after the cooling scheme, however, can be avoided by the use of a stimulated emission process. The velocity width would be reduced close to the recoil velocity due to the photon emitted during the optical pumping, $v_{recoil,\,430\,nm} = 2.3$ cm/s. Furthermore, without delay for spontaneous emission to the ground state, fewer atoms could leave the interaction region due to their transverse velocity before the measurement starts. Additionally, the background on the fluorescence signal caused by atoms that have not decayed yet to the ground state before taking data will be largely eliminated. These atoms mainly lead to the background in the inset of Fig. 2.

The presented one-dimensional cooling scheme has an enormous potential for Ramsey-Bordé-type atom interferometers [20] in the time domain with resonant optical light fields acting as beam splitters. There, the laser necessary to produce the beam-splitting pulses can also be used for the selection of slow atoms in the Maxwell's-demon cooling scheme. We applied this scheme in combination with the simplest of these interferometers comprising ideally a sequence of $\pi/2-, \pi-, \pi/2$ pulses of a laser beam for splitting, deflecting, and recombining the atomic waves [14,21]. The π pulse is defined by the Rabi angle $\theta = \pi$ and at resonance $\theta \propto \sqrt{I}\tau\Gamma^2$ holds. For a given laser intensity I, frequently limited by the available laser systems, and a narrow atomic linewidth Γ, the pulse length τ required for a π pulse corresponds to a Fourier width smaller than the Doppler width of the precooled ensemble. Consequently π pulses can only be realized for a small part of the atomic ensemble resulting in a reduced visibility $V = (R_{max} - R_{min})/(R_{max} + R_{min})$ of the interference signal, where R_{max} and R_{min} are the maximum and minimum count rates, respectively. In our experiment with a three-pulse interferometer a phase difference $\Delta\varphi$ between the partial waves is introduced by varying the phase of the third laser pulse with respect to that of the first two pulses. The visibility of the resulting interference pattern that is detected by the fluorescent decay of excited atoms (Fig. 4) is considerably increased by the use of a Maxwell's-demon cooled ensemble [Fig. 4(b)]. The maximum detected visibility of $V\approx 0.5$ does not reach the theoretical limit of $V=1$, even though the Fourier width of the beam-splitting pulses ($\approx 1/\tau = 1$ MHz) is bigger than the Doppler width (FWHM<150 kHz) of the prepared ensemble. Again, this is no principle limitation but it is due to the available setup. Within the time of about 2 ms currently needed for the preparation of the ensemble, the cloud expands to a size of about 2 mm in the direction perpendicular to the exciting laser beams. Accounting for the Gaussian intensity profile (beam diameter of 3.5 mm) atoms at different locations experience different Rabi angles. Hence, a π or $\pi/2$ pulse cannot be achieved for all atoms simultaneously resulting in a reduced visibility.

In conclusion, we have prepared a Ca atomic ensemble with a narrow velocity distribution in one dimension. Our scheme utilizes a very narrow atomic transition but does not suffer from the associated small forces. In contrast to VSCPT or Raman cooling, where atoms with the wrong velocity are cycled until they finally reach the desired velocity, we directly select the desired velocity class. This approach has some drawbacks due to the heating of the selected ensemble by spontaneous emission. But the Maxwell's-demon cooling is advantageous in many existing applications that do not allow one to implement these other methods. In addition to the existing laser system for spectroscopy there is only a simple laser with low requirements for frequency stabilization needed. The scheme is particularly suited for preparing atomic ensembles for atom interferometry where it leads to an increased visibility.

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