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Neutral atoms prepared in Fock states of a one-dimensional harmonic potential

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We describe the preparation of Fock states of motion of cesium atoms trapped in potential wells of a far detuned optical lattice. Direct observation of the velocity distribution of the $|n=0\rangle$ and $|n=1\rangle$ Fock states is obtained by an absorption imaging technique. [S1050-2947(99)50701-4]

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The quantum harmonic oscillator is one of the canonical models in physics. Noninteracting boson fields, such as photons, are described, for each mode, by a harmonic Hamiltonian $H=\hbar\omega(a^{\dagger}a+1/2)$. The eigenstates of H are number states, $|n=0\rangle,|n=1\rangle,\ldots,$ called Fock states. In cavity electrodynamics, the Fock state $|n=1\rangle$ has been produced [1]. For a particle trapped in a harmonic potential, the Fock state $|n\rangle$ consists of n quanta of vibrational excitation of the center-of-mass motion. $|n\rangle$ is nothing but the vibrational state of quantum number n. A system that has been extensively studied consists of a single ion confined in a harmonic potential. Sideband cooling in the Lamb-Dicke regime has been used to prepare the ion in the ground state of a three-dimensional trapping potential [2–5]. From this pure quantum state, a number of nonclassical states of motion (Fock states $n=1,2,\ldots,$ Schrödinger cat states, etc.) have been prepared [6]. Recently sideband cooling has been extended to neutral atoms confined in optical lattices [7,8]. In each potential well of the lattice, the atoms experienced a harmonic potential and after two-dimensional sideband cooling the population of the vibrational ground state reached 98% [7].

In this paper, we present the preparation of $|n=0\rangle$ and $|n=1\rangle$ Fock states of motion of neutral atoms and a direct observation of the velocity distribution of $|n=1\rangle$. First, one-dimensional sideband cooling using Raman transitions is used to prepare 92(5)% of the atoms in the $n=0$ state. A properly chosen Raman pulse then transfers the atoms in the $n=1$ Fock state. Finally, the velocity distribution of $|n=1\rangle$ is recorded using a time-of-flight technique. In contrast to the ion experiments where the distribution over the Fock states was deduced from an analysis of Rabi oscillations, our straightforward method gives direct access to the square of the modulus of the wave function in velocity space.

We use the experimental setup described in [8]. Cesium atoms are trapped in a red detuned crossed dipole trap [Fig. 1(a)]. This trap consists of two TEM_{00} neodymium-doped yttrium aluminum garnet (Nd:YAG) laser beams with a power of 5 W, each of which crosses at its focal points with a common waist $w_0=120$ μm. The two beams are linearly polarized along the same axis, propagate in a vertical plane, and make an angle of $\alpha=\pm 53°$ with the horizontal plane. Because the detuning of the YAG laser from the D_1 and the D_2 lines (about 64 THz) is much larger than all hyperfine splittings, atoms in both hyperfine states $F=3$ and $F=4$ ''see'' the same scalar potential, proportional to the light intensity [8]. The photon scattering rate is less than 2.2 s^{-1} and can be neglected in our experiments. The lifetime of the trap is about one second, limited by collisions with the background gas.

The interference of the two YAG beams produces a modulation of the intensity along the vertical direction (z axis) with a period of $a=\lambda/(2\sin\alpha)=665$ nm. Thus the trapping potential is modulated along z with a maximum depth of 200(20) μK at the center [Fig. 1(b)]. The vertical oscillation frequency in a microwell at the center of the trap is $\nu_{\mathrm{osc}}^{0}=120$ kHz. This oscillation frequency decreases from ν_{osc}^{0} to 0 for wells far from the center. To avoid a large dispersion of the oscillation frequencies, the trap is loaded from a small cloud of atoms having an rms width of 56 μm, leading to a dispersion of the oscillation frequencies of $\sim 8\%$. This is performed by first loading from a magneto-optical trap the crossed dipole trap with orthogonal polarization of the two YAG beams. In this case, there is no intensity modulation and the atoms are confined at the bottom of the potential [8]. After 50 ms, the intensity lattice is produced by turning in 10 ms the polarization of one of the YAG beams so that it is parallel to the other. In this way, about 150 horizontal planes are populated with ~ 650 atoms in each plane. The Gaussian shape of the YAG beams provides a weak horizontal confinement with oscillation frequencies around 200 Hz. The potential wells of the optical lattice are

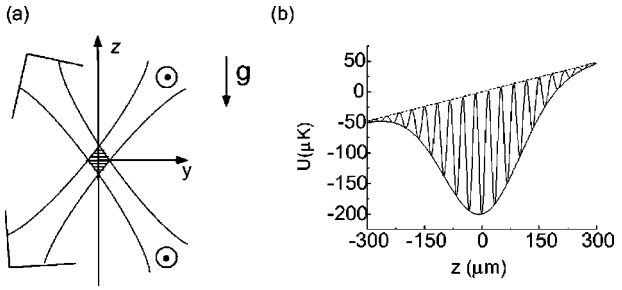

FIG. 1. (a) The dipole trap beams propagate in a vertical plane and have the same linear polarization. They create a far detuned optical lattice along z with a period of 665 nm as well as a weak confining potential in the horizontal plane. (b) Cut of the resulting trapping potential along z including the effect of gravity. The period of the modulation has been multiplied by 50. The vertical oscillation frequency in a microwell at the center of the trap is 120 kHz, whereas the horizontal oscillation frequencies are $\nu_y=180$ Hz and $\nu_x=220$ Hz.

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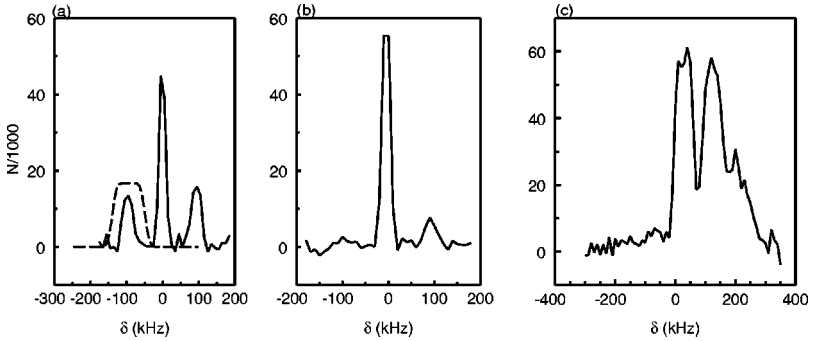

FIG. 2. Raman spectra (a) before cooling and (b),(c) after 20 cooling sequences. Plotted is the number of transferred atoms as a function of the Raman detuning δ. The Raman probing pulses for (a) and (b) are 150-μs-long Blackman pulses, in the low intensity limit for the sidebands. (a) The dotted line shows the excitation profile of the Raman cooling pulses. (b) The quasidisappearance of the red sideband and the decrease of the blue sideband indicate that most of the atoms are accumulated in the $n=0$ vibrational state. In (c), the Raman transition is performed by rapid adiabatic passage at high intensity (see text) so that the efficiency of the transfer is close to 1 for both sidebands and the central peak. From the ratio of the two sidebands we obtain $n_0=92(5)\%$.

deep enough so that, for the first 10 bound states, tunneling is negligible and the potential acts as a harmonic potential. As the initial temperature is 13 μK, about 30% of the atoms are in the fundamental vibrational state and the mean vibrational number is 3.2. The atoms are initially pumped into the $F=3$ hyperfine ground state.

The Lamb-Dicke factor of a single photon transition $\eta=k\Delta z_0$, where $k=7.4\times10^6\,\mathrm{m}^{-1}$ is the wave vector of the D_2 transition and $\Delta z_0=20$ nm is the rms width of the fundamental ground state, is small ($\eta=0.14$). In this regime resolved sideband cooling will accumulate most of the atoms in the vibrational ground state [3,5].

Sideband cooling is performed using two-photon Raman transitions between the $F=3$ and $F=4$ hyperfine states [8,5,9]. Here, we use counterpropagating Raman beams so that a Raman transfer with a change of the vibrational level is allowed: the two-photon Raman coupling between vibrational states $|n\rangle$ and $|n'\rangle$ is $\langle n|e^{2ikZ}|n'\rangle \simeq\langle n|2i\eta(a+a^{\dagger})n'\rangle$ for low n. Both beams propagate along the z axis with orthogonal linear polarizations. Their detuning from the D_2 line $\Delta=-30$ GHz is large compared to the hyperfine structure of the excited state. Their frequency difference is $\Delta_{\mathrm{HFS}}+\delta$ where δ is the Raman detuning and $\Delta_{\mathrm{HFS}}=9.2$ GHz is the frequency difference between the ground hyperfine states. With the intensity used for the cooling, the Raman spontaneous process rate is about $10^2\ \mathrm{s}^{-1}$ and the induced heating can be neglected here.

Information on the vertical motion of the atoms is provided by ''Raman spectra'' that depict the number of atoms transferred from $F=3$ to $F=4$ by a Raman probe pulse as a function of δ. The number of transferred atoms is measured, after the probe pulse, by the fluorescence induced by a laser resonant with the transition $6S_{1/2},F=4\rightarrow6P_{3/2},F'=5$. The Raman probe pulse is, for Figs. 2(a) and 2(b), a Blackman pulse [10] with an overall duration of 150 μs. The Raman spectrum [Fig. 2(a)] consists of three peaks. A central peak (carrier) at zero Raman detuning corresponds to a transfer to $F=4$ without change of vibrational level: $\Delta n=0$. Two sidebands at a Raman detuning $\delta=\pm\nu_{\mathrm{osc}}\simeq\pm100$ kHz correspond to a transfer with a change of the vibrational level $\Delta n=\pm1$. The width of the sidebands is larger than that of the central peak because of the slight inhomogeneity of the oscillation frequency across the trapped atom cloud [see Fig. 1(b)]. In addition to Raman spectra, we perform two-dimensional absorption images on a charge-coupled-device camera with a horizontal probe beam. The probe is σ_+ polarized, tuned to the $F=4\rightarrow F'=5$ transition and turned on for 60 μs. First, an image taken just after the switching off of the YAG gives a measurement of the trap size. Second, images taken after a long free expansion of the atoms reflect the velocity distributions along z and x (time-of-flight method).

Our Raman cooling process consists of a sequence of Raman pulses tuned to the red sideband followed by a 20-μs repumping pulse (resonant with the $D_2F=4\rightarrow F'=4$ transition), which returns the atoms to the $F=3$ state. The Raman cooling pulse is a 500-μs-long Blackman pulse chirped from $\delta=-50$ kHz to $\delta=-140$ kHz covering the red sideband of Fig. 2(a). When repeating this sequence 20 times (in 10 ms), the rms width of the velocity distribution along z, measured by time of flight, decreases from 31(3) mm/s to 11(1) mm/s [Fig. 3(a)]. Within our experimental error, this value is equal to the rms width v_0 of the velocity distribution $|\langle v|n=0\rangle|^2$ of the Gaussian vibrational ground state: $v_0=\sqrt{h\nu_{\mathrm{osc}}/(2m)}=12$ mm/s [Fig. 3 (c) smooth line]. During cooling, the horizontal temperature rises from 13 to 20 μK. On the Raman spectrum after cooling [Fig. 2(b)], the red sideband disappears as expected if all the atoms are in the ground state. The height of the blue sideband also decreases as expected if the atoms are pumped into lower n states, since the Rabi frequency of the $n\rightarrow n+1$ transition decreases as n decreases. From Fig. 2(b), it is in principle possible to infer the population of $|n=0\rangle$ [3,4], but the weakness of the red sideband makes this measurement imprecise.

To circumvent this limitation, we use a Raman probe pulse that has a transfer efficiency close to 1 for both sidebands and the central peak. This pulse is realized by slowly chirping its frequency ($d\delta/dt\simeq-60$ kHz/ms) in order to perform a rapid adiabatic passage between $F=3$ and $F=4$ as the detuning crosses a resonance [11]. The adiabatic condition is fulfilled with a Rabi frequency of $\sim2\pi\times13$ kHz for the transition $F=3,n=0\rightarrow F=4,n=1$. The pulse duration is 1 ms and the amplitude of the frequency chirp is 60 kHz so that it covers completely each of the sidebands but still resolves them [Fig. 2(c)]. The Raman spectrum of Fig. 2(c) depicts the number of atoms transferred to $F=4$ as a func-

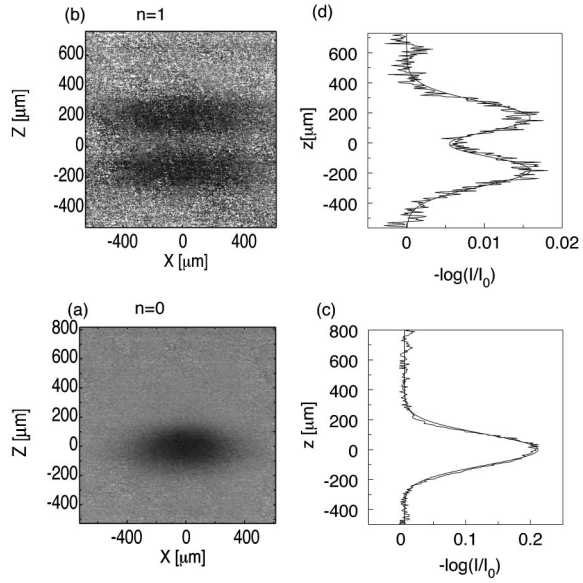

FIG. 3. Absorption images of Fock states (a) $|n=0\rangle$ and (b) $|n=1\rangle$ taken after a time of flight of (a) 6 ms and (b) 10 ms. Measured distributions along z are compared to the calculated ones in (c) and (d). The calculation assumes that all the atoms are in the corresponding Fock state and takes into account the initial size of the cloud along z measured independently (rms width of 56 μm).

tion of the initial detuning of this pulse. On this spectrum, the blue sideband has the same height as the central peak and the transfer efficiency is consistent with 1 within our 5% experimental error. On the other hand, the red sideband remains barely visible. As the blue (red) sideband corresponds to a transfer $n\rightarrow n+1$ ($n\rightarrow n-1$), all atoms contribute to the blue sideband, whereas only atoms that are in the excited vibrational levels (i.e., $n>0$) contribute to the red one. The ratio between the height of the red sideband and that of the blue sideband is equal to $1-n_0$, where n_0 is the fraction of atoms in the fundamental vibrational state. From Fig. 2(c) we obtain $n_0=92(5)\%$. Thus, we have prepared a sample of about 150 horizontal planes in which almost all atoms occupy the lowest quantum state of the vertical motion.

Once the atoms are cooled to the fundamental quantum state, it is straightforward to prepare any other Fock state of motion by a sequence of transfers performed on the sidebands or carrier. For instance, we prepare $|n=1\rangle$ as follows. Using a single Raman pulse tuned to the blue sideband, we transfer the atoms in the vibrational state $|n=1\rangle$ of $F=4$. Again, to achieve a transfer efficiency of ~ 1 we use a 1-ms Raman pulse frequency chirped over 60 kHz and centered at 90 kHz.

The velocity distribution of the vibrational state $n=1$ is

$$P(v)=|\langle v|n=1\rangle|^2=\frac{1}{\sqrt{2\pi}\,v_0^3}v^2\,e^{-v^2/2v_0^2}. \qquad (1)$$

It displays two peaks at $\pm\sqrt{2}v_0$ and $P(v=0)=0$. The image taken after 10 ms of time of flight [Fig. 3(b)] indeed exhibits this double peak structure.

To make a quantitative comparison between observed and expected spatial distributions along z after a time of flight of duration t, we must take into account the finite initial size of the cloud. The expected spatial distribution $F_t(z)$ is

$$F_t(z)=\frac{1}{t}\int_{-\infty}^{\infty}F_0(z_0)\,P\left(\frac{z-z_0}{t}\right)dz_0, \qquad (2)$$

where $F_0(z_0)$ is the initial spatial distribution which is Gaussian with an rms width of 56 μm, and $P((z-z_0)/t)=P(v)$ is given by Eq. 1. As shown in Fig. 3, the calculated distribution agrees well with the measured distribution, with no other adjustable parameter than the amplitude. Any higher Fock state could be prepared by applying a succession of Raman pulses that transfer the atoms into the other hyperfine state with an increase of the vibrational number of 1. For example, to produce the Fock state $|n=2\rangle$, a first Raman pulse on the blue sideband transfers the atoms in $F=4$ in $|n=1\rangle$ and then a Raman pulse on the red sideband brings them back to $F=3$ in $|n=2\rangle$.

Two directions could be explored for a future work. First, the manipulation of quantum states can be pushed further: a time-dependent coherent superposition of vibrational states could be produced and detected in the same manner as here. The quantum control of the single particle and the entanglement of several particles are essential ingredients for the realization of a quantum computer [12]. Second, it would be interesting to study the behavior of the trapped gas strongly confined in one dimension. For instance, after sideband cooling, the cloud is out of thermal equilibrium, the horizontal kinetic energy being larger than the vertical one. We have observed that the cloud thermalizes by collisions with a time constant of $\sim$100 ms. Since the width of the vibrational ground state along z is 20 nm and the collisional cross section for Cs atoms in free space at $T=20\,\mu$K is on the order of $(50\,\text{nm})^2$ [13] how should the collisions be described? Finally, it would be interesting to search for a two-dimensional Bose-Einstein condensation in a harmonic trap [14] by cooling the horizontal motion of our trapped gas.

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