Atoms in the Lowest Motional Band of a Three-Dimensional Optical Lattice

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We investigate the storage of atoms in an optical lattice, using light detuned up to 2 nm to the blue of an atomic transition. Argon atoms were laser cooled in the metastable state $1s_5(J = 2)$ and optically pumped to the state $1s_3(J = 0)$. Subsequently these atoms were confined to the nodes of a three-dimensional interference pattern and stored for up to 1 s. We resolved the bands of motion in the lattice using a time-of-flight technique, and observed band-dependent losses leading to the preparation of atoms in the motional ground band. [S0031-9007(97)02360-0]

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With the development of efficient laser cooling techniques [1], it has in recent years become possible to cool atoms into the regime where the quantum nature of atomic center-of-mass (CM) motion becomes important. The recent preparation and detection of the pure motional ground state of a single ion in a Paul trap [2] accomplished one goal of this development and allowed the experimental realization of nonclassical states of motion [3] and of "Schrödinger cat" states [4].

For neutral atoms arrays of microscopic potential wells can be created in optical lattices [5], where atoms are confined in the nodes or the antinodes of an optical interference pattern. Here the confining potential is created by ac-Stark shift due to the atom-light interaction. This potential has the periodicity of the optical interference pattern and confines the atoms on a subwavelength scale. Quantized CM motion in such lattices has been observed spectroscopically [6] and also the long range order as imposed by the light field has been studied [7]. More recently, the idea of far off-resonant trapping [8] has been applied to optical lattices in order to reduce the photon scattering rate [9]. The resulting nondissipative potentials are of interest because of the long time scale over which coherent motion is preserved. The preparation of the motional ground state is a prerequisite for creating nonclassical states of motion, for studying coherent quantum motion such as tunneling [10], and for the realization of proposed atom lasers [11].

In this Letter, we report on an optical lattice which prepares the stored atoms in the lowest motional band of the periodic potential. The detuning is set far off resonant to the blue of the atomic transition, such that the atoms are trapped in the dark spots (nodes) of a light field. This reduces the scattering rate to a few Hz. The remaining photon scattering is a band-dependent loss mechanism: Higher lying bands have a larger overlap with the light field and therefore a larger photon scattering rate. As the lattice is operated on an open transition, photon scattering is a loss mechanism. Also the rate for tunneling to the edges of the lattice is highest for the higher bands. Because of these band-dependent losses [11], after about 450 ms all

remaining atoms are in the lowest band, i.e., the motional ground band. We demonstrate a novel loading scheme for our lattice, allowing it to be loaded repetitively or continuously [12]. The atoms are stored in an internal state which does not participate in the laser-cooling process and is unaffected even by a spatially overlapping magneto-optical trap. Finally, we demonstrate a novel technique that separates the populations of the various bands during a time-of-flight analysis. This demonstrates the quantization of motion in a direct way and gives access to the individual band populations.

The experiment has been performed using argon atoms. The metastable $1s_5(J = 2)$ state is used for the cooling to sub-Doppler temperatures on the transition to $2p_9(J = 3)$ [Fig. 1(a)]. The other metastable state $1s_3(J = 0)$ is stored in the lattice built by laser light detuned to the blue of the transition to $2p_4(J = 1)$. The cold atoms are transferred into the lattice by exciting them to $2p_4$. From this state they decay into $1s_3$ by spontaneous emission with 58% probability, or they cascade with 40% probability to the electronic ground state ($2p_4 \rightarrow 1s_2 \rightarrow 1s_0$) [13], which is neither trapped nor detected. The wavelength of the lattice is chosen up to 2 nm off resonant, i.e., the detuning is set up to 2.5×10^5 times the natural linewidth $2\pi \times 5.2$ MHz of the $2p_4$ level [13], leading to a reduction of the photon scattering to a few Hz.

Our optical lattice is built up by three orthogonal standing waves as illustrated in Fig. 1(b) with linear polarizations orthogonal to each other, such that the local intensity is the sum of the three standing-wave intensities. The resulting light shift potential acting on a $J = 0$ atom is proportional to the intensity pattern and independent of the local polarization. Therefore the relative time phases of the three standing light fields need not be stabilized to preserve the lattice geometry under phase fluctuations, in contrast to a six-beam 3D optical lattice for $J \neq 0$ atoms [14]. The lattice geometry is simple cubic with a lattice constant of $\lambda/2 = 397$ nm, where λ is the wavelength of the lattice light.

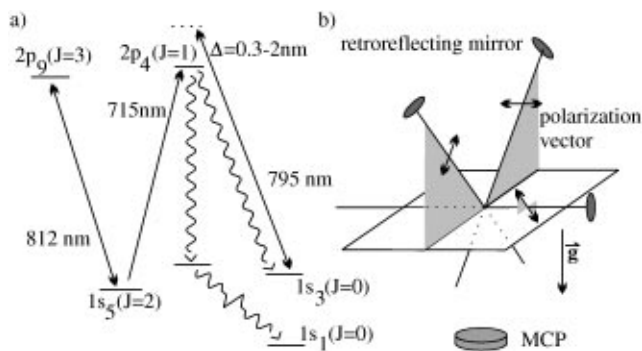The quantum-mechanical motion of an atom in our lattice potential separates in Cartesian coordinates

FIG. 1. (a) Relevant transitions and energy levels in argon. Slowing and cooling is done on the closed transition $1s_5$ ($J = 2$) to $2p_9$ ($J = 3$) at 812 nm. Laser light at 715 nm is used to transfer the atoms to the state $1s_3$. The lattice is built up by three standing waves detuned up to 2 nm to the blue of the transition $1s_3$ to $2p_4$ at 795 nm. (b) Setup and field configuration of the optical lattice. Three standing waves are built by retroreflecting two beams at 45° to the horizontal and one in the horizontal plane. They intersect at the location of the optical molasses. For TOF analysis a multichannel plate detector is placed 10 cm below.
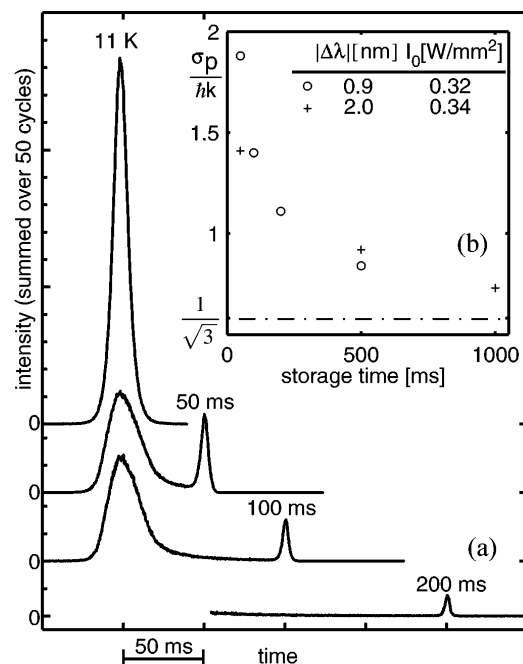

FIG. 2. (a) TOF spectra registered with the MCP detector after variable storage time (50, 100, 200 ms) in the optical lattice. The atoms stored in the lattice with the wavelength set off resonant by $|\Delta\lambda| = 0.9$ nm and $I_0 = 0.32$ W/mm² can clearly be distinguished as a narrow peak separated by the storage time from the signal of the untrapped atoms. Atoms leaking out of the lattice are registered as a decreasing tail between the two peaks. For comparison the spectra are scaled to the initial sample of $1s_3$ atoms at 11 μK. Both the number of atoms and their rms momentum decreases with storage time. (b) The inset shows the evolution of the rms momentum σ_p as a function of the storage time in the lattice for different parameter sets.

yielding, for each coordinate, the Schrödinger equation for a spinless particle in a sinusoidal potential. The time-independent Schrödinger equation thus reduces to Mathieus differential equation [15] which is analyzed along the lines of band theory in analogy to solid state physics [16].

Because of the blue detuning the potential minima coincide with the nodes of the standing waves and the atoms are trapped at the dark spots of the lattice. This minimizes the overlap with the light field and reduces the photon scattering rate. The ground band has the lowest overlap with the light field, while atoms in excited bands have a larger overlap. Within the harmonic potential approximation around a node the scattering rate γ_{sc} for atoms in the bound band with the indices (l, m, n) can be expressed in the form

$$\gamma_{sc} \propto \sqrt{\frac{I_0}{\Delta^3}} \left(l + m + n + \tfrac{3}{2}\right)$$

as a function of the intensity I_0 and the detuning Δ. With the typical experimental parameters of Fig. 2(a) γ_{sc} of the ground band with indices $(0,0,0)$ is 6 s^{-1}. As the branching ratio from the $2p_4$ to the ground state $1s_1$ is 40%, an atom is lost after two scattering events on average. We take advantage of these losses by photon scattering to implement a band selective loss mechanism. With a blue detuning this mechanism favors the survival of the atoms in the ground band.

Another band-dependent loss mechanism relies on tunneling of atoms out of the finite spatial extension of the optical lattice. This loss rate is strongly band dependent which also causes the population of excited bands to die out faster than the one of the ground band. A numerical simulation of the experimental situation, based on the group velocity of Bloch states, shows that the loss rates

caused by tunneling are comparable to the loss rates by photon scattering. However, our experiment is not able to isolate unambiguously the tunneling mechanism from other losses.

We find that after some storage time only the population of the ground band survives. When the lattice potential is then switched off adiabatically [17], the ground band evolves into free particle states with momenta between $-\hbar k$ and $\hbar k$ in each coordinate, where $k = 2\pi/\lambda$. Assuming a homogeneous distribution over the Bloch states of the ground band, adiabatic potential turnoff results in a rms momentum of the free particle state $\sigma_p = \hbar k/\sqrt{3}$ per dimension.

In the experiment we first prepare a sample of $\approx 10^5$ cold argon atoms in the state $1s_5$. For this purpose argon atoms are excited to the metastable state in a discharge source on a beam machine. Then the atoms are decelerated by a Zeeman slower and cooled in a magneto-optical trap in a differentially pumped ultrahigh vacuum chamber with a background pressure of 5×10^{-7} Pa while the atomic beam is on. The atoms were further cooled by a σ^+–σ^- optical molasses to temperatures of 11 μK corresponding to a rms momentum of 3.8 recoils

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per dimension. Slowing and cooling is done with an all diode laser setup at 812 nm.

In a subsequent step the atoms were transferred to the state $1s_3$. For this purpose the cooling molasses was switched off and the laser light resonant with the transition $1s_5$-$2p_4$ at 715 nm was applied. The laser light is generated by a liquid nitrogen cooled external grating diode laser stabilized with optical double resonance spectroscopy [18] to the $1s_5$ to $2p_4$ transition. A single photon scattering event takes the atom to the state $1s_3$. The ratio of the number of atoms optically pumped to the state $1s_3$ to the number of initially present $1s_5$ atoms was measured to be 60%. The experimentally achieved intensity of ≈ 5 mW/cm^2 transfers all atoms out of $1s_5$ in less than 2 ms.

The laser light for the optical lattice was generated by a single-mode Ti:Sapphire laser. After passage through an optical monomode fiber the beam was split into three beams of equal power (within 5%) that were retroreflected to create the standing waves. The intensities of the forward and backward going beams were adjusted to be equal. The $1/e^2$ radius w at the location of the lattice was 0.55 mm, comparable with the size of the atomic cloud. The peak intensity in a single beam was $I_0 = 0.4$ W/mm^2. The alignment of the lattice beams with respect to the atomic cloud was done by tuning them on resonance of the $1s_3$ to $2p_4$ transition and by maximizing individually their optical pumping rate to the ground state. Assuming an ideal overlap the number of lattice sites can be estimated to be $w^3/(\lambda/2)^3 \approx 10^9$. With the parameters of Fig. 2(a) the potential height between nearest neighbor lattice sites is 54 photon recoil energies and of the same order of magnitude as the kinetic energy of the atomic cloud. No more than four bands are bound per dimension ($l, m, n \leq 3$) and in the harmonic approximation at the nodes the angular frequency of vibration is $2\pi \times 115$ kHz.

The lattice was loaded in two different ways: (1) The atoms were pumped to the $1s_3$ state in free space and the lattice was subsequently ramped up adiabatically, (2) the atoms were pumped into an initially present lattice [11]. Both loading processes led to indistinguishable results: 10^4 atoms were captured in the optical lattice, which corresponds to a filling factor of $\approx 10^{-5}$.

After a storage time of up to 1 s the argon atoms were released by switching off the light. In the first experiment the switching was done with a mechanical shutter placed before the passage through the fiber. The atoms dropped onto a two stage microchannel plate detector with an active surface diameter of 2.5 cm, situated 10 cm below the trap. The arrival time distribution on the detector is registered as a time-of-flight (TOF) signal with a multichannel scaler. If the storage time exceeds approximately 20 ms, the TOF signal of the trapped atoms can be separated from the signal of the untrapped atoms. Note that in contrast to the case of red detuning, with blue detuning atoms cannot be trapped accidentally by a Gaussian beam. They can be stored only at the minima of the intensity pattern created

by interference. As a function of the storage time in the lattice we observed not only a reduction of the number of stored atoms but also a reduction of the width of the TOF signal, i.e., the rms momentum σ_p as shown in the inset of Fig. 2. This latter process has to be attributed to the band-dependent loss mechanisms as described above. Ultimately σ_p approaches $\hbar k/\sqrt{3}$, the value expected when only the ground band is homogeneously populated. The measured value remains slightly higher; this may be caused by the remaining population in excited bands or a violation of the adiabaticity in the switch-off process resulting in interband transitions. To fulfill the adiabaticity criterion the mechanical shutter was set up with the 90%–10% closing time of 70 μs, i.e., slow compared to the oscillation period of 9 μs in the potential well.

The band-selective loss was observed directly by resolving the bands in the TOF signal. To this end, $|\Delta\lambda|$ was set to 2 nm and I_0 to 0.18 W/mm^2 resulting in only two bound bands per dimension. The light intensity was kept constant during the storage time and then ramped down linearly in 40 ms with an electro-optic modulator. Atoms are released when their energy in a given direction exceeds the potential barrier height in that direction. First the population of excited bands is released, later also the ground band is set free. Figure 3 shows that we could determine their population for different storage times as
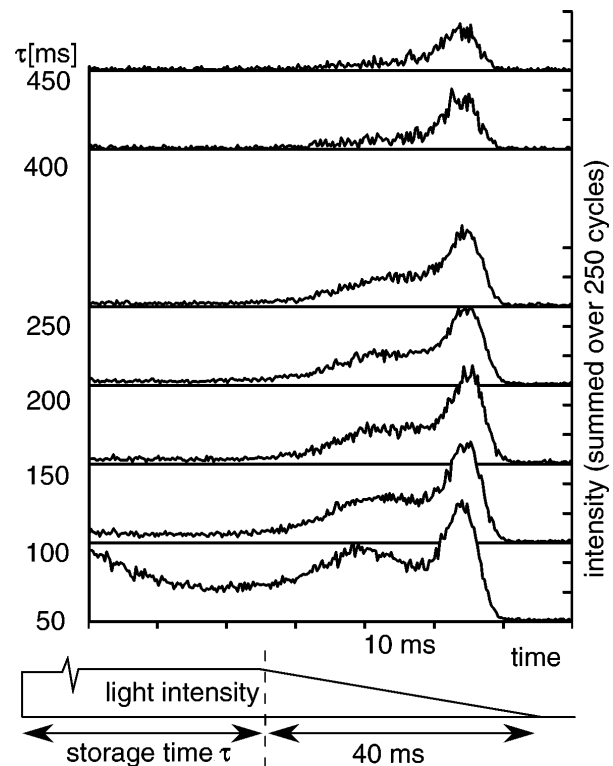

FIG. 3. TOF spectra taken for variable storage time in the lattice. After the storage time the light intensity is ramped down in 40 ms and the bound bands are set free one by one. The parameters of the lattice were chosen such that two bands are bound per dimension. After 450 ms about 50 atoms are prepared in the motional ground band.

two peaks separated by 15 ms and resolve the band dependency of the loss mechanism. From the peak height the time constant for the decay of the higher lying bands was determined to be 0.13 s, while the time constant of the ground band was 0.31 s. The ratio of these measured rates is in good agreement with the calculated value of 2.1 if only photon scattering is considered [19]. After about 450 ms the band-dependent losses led to the preparation of about 50 atoms in the ground band of motion.

The atoms in the state $1s_3(J = 0)$ are insensitive to the magnetic and light fields used for preparing the sample of cold $1s_5$ atoms. This opens up the way to increase the density of atoms in the lattice by multiple loading [12]. To demonstrate this we repeated the loading cycle while the optical lattice was running. The total number of atoms of this two-step loading process was exactly the sum of the individual steps showing that $1s_3$-$1s_5$ collisions do not play a significant role at our densities.

In summary, we investigated band-dependent loss mechanisms and were able to prepare atoms in the ground band of motion in the potential wells of a 3D optical lattice. From there on nonclassical states of motion can be generated as with a single ion in a Paul trap [3,4]. Predicted quantum-mechanical effects whose observation was obscured by scattering in solid states can now be investigated [20]. Additionally the technique of increasing the filling with multiple loads opens up the way for the realization of a laserlike source for atoms [11].

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