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Cold atoms in a high-Q ring cavity

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We report the confinement of large clouds of ultracold ^{85}Rb atoms in a standing-wave dipole trap formed by the two counterpropagating modes of a high-Q ring cavity. Studying the properties of this trap, we demonstrate loading of higher-order transverse cavity modes and excite recoil-induced resonances.

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The tremendous progress of ultracold atomic physics in the past decades is mainly due to the invention of powerful techniques for trapping and cooling atoms. Besides magnetic traps, optical forces are used to store atoms in tightly focused red-detuned laser beams, in the antinodes of a standing wave formed by two counterpropagating laser beams or even in three-dimensional optical lattices. Spontaneous scattering processes are avoided by tuning the lasers far from resonance. High light intensities are then needed to keep the atom-field coupling strong. Large intensity enhancements are achieved with optical cavities [1]. The coupled system made up of the cavity mode and the atoms exhibits fascinating novel features [2–4]. For example, cooling procedures have been proposed [5–8], where the kinetic energy of the atoms is dissipated via the decay of the cavity field to which the atoms are coherently coupled, rather than via spontaneous decay of atomic excitation energy. This bears the advantage that the cooling is only limited by the technical parameter of the cavity decay rate. As the cooling procedure is quite insensitive to the details of the atomic level structure, it should work even for molecules.

In this paper, we study atomic trapping in a high-Q ring cavity with both propagation directions pumped. This kind of cavity is particular in the following sense. The optical dipole force exerted by a standing wave on atoms can be understood in terms of a momentum transfer by coherent redistribution (via Rayleigh scattering) of photons between the counterpropagating laser beams. In multimode configurations, e.g., a ring cavity, the photon redistribution can occur between *different* modes [9]. This implies that the atoms have a noticeable back action on the optical fields and that the atomic dynamics can be monitored as an intensity [10,11] or a phase imbalance between the modes. In a ring cavity, the scattering of a photon between the counterpropagating modes slightly shifts the phase of the standing wave. This shift, being strongly enhanced by a long cavity lifetime, is sensed by all atoms trapped in the standing wave. Consequently, the simultaneous interaction of the atoms with the two field modes couples the motion of all atoms [12,13], so that in contrast to conventional standing-wave dipole traps, the atoms do not move independently of each other.

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In a recent paper [14], we have shown that a far-detuned optical lattice can be formed inside a high-Q ring cavity and that heating due to intensity fluctuations can be kept at very low levels despite of the need to maintain a sharp resonance condition by a high-bandwidth servo control. Here, we present a setup where we show that the atomic motion can be probed nondestructively and *in situ* by recoil-induced resonances [15]. There is an important reason to look for methods to study the atomic motion which do not rely on sudden changes of the intracavity intensity. This is because the long lifetime of a high-Q cavity inhibits the nonadiabatic switch off of deep cavity dipole traps and thus impedes a straightforward interpretation of time-of-flight (TOF) images to determine the temperature.

We fill our ring-cavity dipole trap with ^{85}Rb atoms from a standard magneto-optical trap (MOT) that is loaded from a vapor generated by a rubidium dispenser. Typically, we load 10^8 atoms into the MOT at temperatures around 140 μK with a vapor pressure of 3×10^{-9} mbar.

The geometry of the ring cavity is shown in Fig. 1. The transmissions T_i of the mirrors depend on the (linear) polarization of the light modes. For s polarization $T_0=27\times10^{-6}$, $T_1=T_2=2\times10^{-6}$, while for p polarization $T_0=2200\times10^{-6}$, $T_1=T_2=9\times10^{-6}$. The experiments pre-

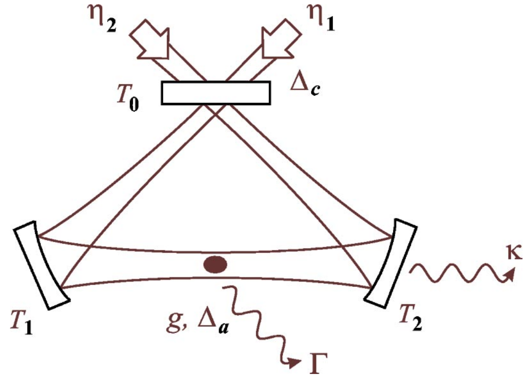

FIG. 1. Geometry of the ring cavity. The atomic cloud is located in the free space waist of the cavity mode. The system is characterized by the pumping parameter η_i, the atom-field coupling g, the laser detuning with respect to the cavity Δ_c and to the atomic resonance Δ_a, and the decay rate of the atom Γ and of the cavity field κ.

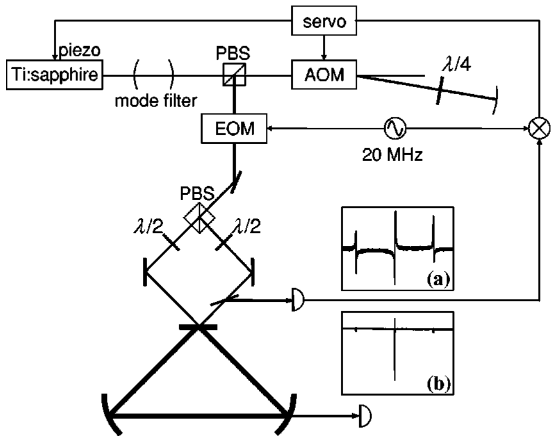

FIG. 2. Experimental setup for pumping both directions of the ring cavity, while locking the laser to a resonator eigenfrequency via the Pound-Drever-Hall technique. The AOM and the piezo rule out the laser frequency fluctuations. Also shown are the demodulated reflection signal (a) and the transmission signal (b) of the cavity.

sented here are carried out with p-polarized light and a measured finesse of $F=2500$, which corresponds to an intracavity intensity decay rate of $2\pi\times1.4$ MHz. However, by simply rotating the polarization of the light injected into the cavity, we can switch to s polarization, where we measure using the ring-down method a much higher finesse of $F=170\,000$ corresponding to $2\pi\times21$ kHz. The round-trip length of the ring cavity is $L=85$ mm, the beam waists in horizontal and in vertical direction at the location of the MOT are $w_v=129$ μm and $w_h=124$ μm, respectively. This yields a cavity mode volume of $V_{mode}=(\pi/2)Lw_vw_h=2$ mm^3. The intracavity power P, largely enhanced by the factor F/π to values around 10 W, gives rise to an optical potential with a depth of $k_B\times1.4$ mK at the wavelength 799 nm. The radial and axial secular frequencies in the harmonic region close to the center of the trap are $\omega_{rad}/2\pi=1$ kHz and $\omega_{ax}/2\pi=700$ kHz.

The ring cavity is driven by a titanium-sapphire laser delivering up to 2 W output power into three optical modes separated by 1.2 GHz [16]. The central mode is filtered by an external confocal Fabry-Perot etalon. The titanium-sapphire laser is locked to one of the eigenfrequencies of the ring cavity using the Pound-Drever-Hall locking technique [17,18] (see Fig. 2). A feedback servo drives a piezoelectric transducer mounted in the titanium-sapphire laser cavity, whose frequency response is limited to 10 kHz. Faster fluctuations of the laser frequency are balanced by means of an external double-passed acousto-optic modulator (AOM). The servo bandwidth of 1 MHz is limited by a 100 ns time delay in the response of the AOM. The laser frequency is stable enough to yield intensity fluctuations observed in the cavity transmission signal below 2 % even in the high finesse case.

The dipole trap is permanently operated, because keeping the titanium-sapphire laser locked requires a certain amount of light inside the cavity. The standing-wave dipole trap is loaded from a spatially overlapping MOT for a period of 15 s. Before switching off the MOT, we apply a 40-ms-

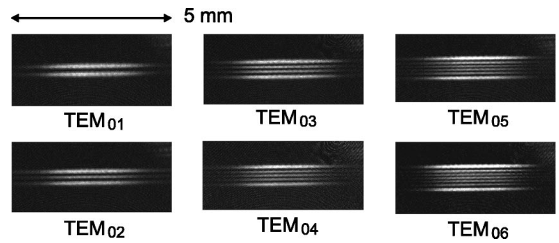

FIG. 3. Absorption pictures of atoms stored in higher-order transverse cavity modes.

temporal-dark MOT stage [19] by increasing the detuning of the MOT laser beams to -90 MHz and reducing the intensity of the repumping beams. For the conditions given above, we typically capture 3×10^7 atoms distributed over 10 000 antinodes of the standing wave. The temperature of the atomic ensemble is measured using the TOF method. We suddenly switch off the dipole trap and image the shadow that the cloud imprints on a weak probe beam after a period of ballistic expansion. Note that, since we operate in a regime of low cavity finesse, the switch-off time is fast compared to the trap's secular frequencies. During the expansion, the initial momentum distribution of the cloud evolves into a density distribution, whose radial width yields the temperature of the cloud. Depending on the potential well depth, we obtain temperatures between 70 and 280 μK, corresponding to roughly 1/5 of the well depth. The peak density is typically 3×10^{12} cm^{-3}. The lifetime of the dipole trap measured at 799 nm is 0.5 s. A thorough investigation of trap loss processes in a similar system is presented in Ref. [14].

With a slight misalignment of the incoupled laser beam, the ring cavity can be locked to higher-order transverse modes, into which the atoms can settle. Figure 3 shows absorption pictures of atomic clouds confined in different higher-order transverse modes. Such modes exhibit an enhanced surface-to-volume ratio, which may prove advantageous for forced evaporation.

We perform spectroscopy of recoil-induced resonances (RIR) [15,20,21], i.e., we probe two-photon Raman transitions between two velocity states of the same atom. Two Raman beams $\mathbf{k}_1$ and $\mathbf{k}_2$ enclosing a small angle $\theta=13.1°$ are radiated onto the atomic cloud such that the difference vector $\mathbf{q}=\mathbf{k}_1-\mathbf{k}_2$ is oriented nearly parallel to the dipole trap symmetry axis $\hat{z}$. The two beams, whose frequencies are ω_1 and ω_2, give rise to a standing wave with periodicity $2\pi/q$ slowly moving in $\hat{z}$ direction with velocity $v_z=\Delta\omega/q$, where $q=(k_1+k_2)\sin(\theta/2)$ and $\Delta\omega=\omega_1-\omega_2$. The light wave leads to a periodic dipole potential for the atoms, which in our experiment has a well depth of 60 μK in units of k_B. Only atoms satisfying the energy and momentum conservation requirement can undergo Raman transitions, i.e., only atoms moving synchronously to the standing wave can scatter light from one beam into the other. This scattering is monitored as an intensity variation in one of the beams. The net rate for scattering from beam 2 into beam 1 may be written as $W(v_z=\Delta\omega/q)=(\hbar\pi/2)\Omega_R^2N\partial\Pi/\partial v_z$, where $\Pi(v_z)$ denotes the Maxwell-Boltzmann momentum distribution, N the number of atoms, and $\Omega_R=\Omega_1\Omega_2/2\Delta$ with the

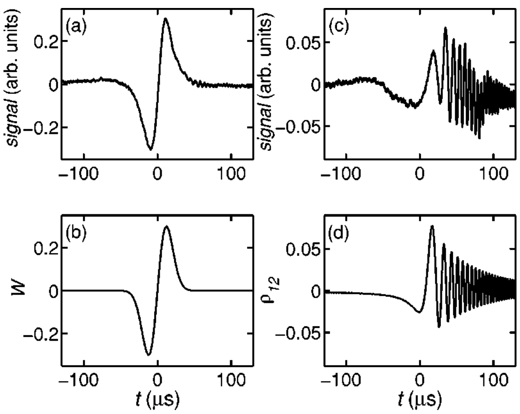

FIG. 4. Trace (a): Spectrum of RIR resonances recorded on *free* atoms. The intensity of Raman beam with ω_2 is measured, while the frequency of beam with ω_1 is scanned. Both beams were detuned by -110 MHz from resonance and their peak intensities were 50 mW/cm^2. The scan rate was 2.1 kHz/μs. Trace (b): Calculated transition rate for the same parameters assuming a 100-μK cold cloud. Trace (c): Same conditions but recorded on *trapped* atoms. The trap had a well-depth of $U_0 = h\times 30$ MHz$= k_B \times 1.4$ mK corresponding to secular frequencies $\omega_z = 2\pi\times 700$ kHz and $\omega_r = 2\pi \times 1$ kHz. Trace (d) shows a simulation (see text) of the susceptibility of a two-level atom subject to a laser quickly swept over its resonance. The chosen decay rate was $\Gamma = 2\pi\times 5$ kHz and the Rabi frequency $\Omega = 0.1\ \Gamma$.

resonant Rabi frequencies Ω_i for each Raman beam. By varying $\Delta\omega$, the derivative of the Maxwell-Boltzmann momentum distribution is scanned from which the temperature can be derived [21]. Trace (a) of Fig. 4 shows such RIR-scans recorded on a cloud 200 μs after being released from the dipole trap. Trace (b) has been calculated assuming a 100 μK cold cloud.

The scan rate must be judiciously chosen [22]. If the scan rate is too slow, the atoms are notably redistributed between the velocity classes while scanning. The above expression shows that the scattering process preferentially occurs towards higher velocities, so that although the momentum transfer is quite small, the cloud is slightly heated under the influence of the Raman beams. If, on the other hand, the scan rate is too fast the signal can be strongly distorted and a ringing-type oscillation is observed [23]. For an untrapped cloud of atoms first indication of ringing can be observed for scan rates above 2.1 kHz/μs. For trapped atoms, however, ringing is already very pronounced at this rate [Fig. 4(c)]. Ringing is a general feature of resonant phenomena and can be observed for a simple mechanical oscillator as well as in an optical resonator or for standard two-level quantum systems. The critical scan rate for ringing is roughly given by the square of the linewidth. For slower scan rates, the system can follow adiabatically, i.e., the sweep time across the resonance is longer than the inverse linewidth.

In our experiment, we observe that the critical scan rate is dramatically reduced if the atoms are trapped in the standing-wave dipole trap. A qualitative explanation of this effect is possible by using the following simple picture. For an untrapped cloud of atoms the potential generated by the Raman beams has its principal effect on the atoms near zero detuning. Then, the speed of the potential wave is sufficiently slow for the atoms to react and form a standing wave like density pattern that mirrors the shape of the potential wave. For positive detunings the potential wave starts moving with an increasing speed relative to the static atomic distribution and the atoms within the density modulation are subjected to an oscillating dipole force. This force is accompanied by a periodic photon redistribution between the Raman beams which is observed in the experiment. The ringing fades away as the atomic density modulation slowly decays due to thermal drifts of the atoms. For trapped atoms this picture does not seem to apply since the atoms are strongly confined within the antinodes of the resonator dipole trap such that a density pattern cannot form. However, if we neglect the weak confinement in radial direction and thus regard a thermal distribution of atoms that can still propagate freely along the valleys of the resonator dipole trap, this is only true if $\mathbf{q}$ is strictly parallel to the symmetry axis of the dipole trap. With only a slight misalignment of $\mathbf{q}$ by an angle ϕ the atoms can follow the force of the Raman potential by traveling along those valleys. In order to form a density modulation similar to the untrapped case the atoms now have to propagate a distance that is longer by a factor $f = 1/\sin\phi$. Similarly, the lifetime of the modulation pattern is enhanced by the same factor since the atoms have to drift over a longer distance with the same thermal velocity. The critical scan rate for ringing is therefore reduced by the factor f^2. The same situation can be explained from a different perspective. Since the phase speed of the Raman potential along the valleys is enhanced by f the atoms that interact with the Raman potential have to move with a velocity given by $f\Delta\omega/q$. The resulting reduction of the linewidth by $1/f$ can easily be understood by the fact that for an axially confined atom undergoing a two-photon Raman transition only the radial momentum component with $q_r = q/f$ has to satisfy the momentum conservation requirement. From the data, we can estimate the coherence lifetime to be 100 μs. By comparison of the corresponding linewidth with the linewidth resulting from the critical scan rate in the case of free atoms, we estimate our misalignment angle to be $\phi = 3°$.

A full quantitative description is beyond the scope of this paper, however it is interesting to note that the data can be well described by the dynamics of a degenerate two-level quantum system. The curve in Fig. 4(d) shows the coherence Imρ_{12} calculated by numerical integration of two-level Bloch equations (ρ is the density matrix). The resonance occurs at $\Delta\omega = 0$. At the beginning of the scan, where $\Delta\omega$ is far from resonance, the population of the excited level ρ_{22} is just too small and the system does not react to the light field. As soon as $\Delta\omega$ passes through the resonance, the coherence ρ_{12} is excited and can now be driven by the laser even when $\Delta\omega$ is tuned far away. The two levels can be identified with two velocity states that are coupled by the Raman beams. In the experiment, the thermal distribution causes an inhomogeneous broadening that is accounted for in the simple two-level model by introducing an effective decay rate Γ.

To conclude, we introduced our ring-cavity standing-wave dipole trap and characterized it by lifetime and by temperature measurements. We have shown that by driving recoil-induced resonances, we can excite and probe the motion of atoms trapped in the ring-cavity field. In the near future, we plan to look for the expected feedback of the atomic motion on the standing light wave and for interatomic coupling induced by the standing wave. It is also tempting to explore the predicted new types of cavity cooling in view of their aptitude of cooling below the threshold of quantum degeneracy. The Bose-Einstein condensates are very appealing objects in the context of ring-cavity studies. For example, Meystre and co-workers [25] have discussed the use of ring cavities for recycling super-radiant light pulses produced by Rayleigh-scattering off condensates [26] and predict for such systems the possibility of mutual coherent quantum control between optical and matter-wave modes.

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