The Collective Atomic Recoil Laser

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Abstract. An ensemble of periodically ordered atoms coherently scatters the light of an incident laser beam. The scattered and the incident light may interfere and give rise to a light intensity modulation and thus to optical dipole forces which, in turn, emphasize the atomic ordering. This positive feedback is at the origin of the collective atomic recoil laser (CARL). We demonstrate this dynamics using ultracold atoms confined by dipole forces in a unidirectionally pumped far red-detuned high-finesse optical ring cavity. Under the influence of an additional dissipative force exerted by an optical molasses the atoms, starting from an unordered distribution, spontaneously form a density grating moving at constant velocity. Additionally, steady state lasing is observed in the reverse direction if the pump laser power exceeds a certain threshold. We compare the dynamics of the atomic trajectories to the behavior of globally coupled oscillators, which exhibit phase transitions from incoherent to coherent states if the coupling strength exceeds a critical value.

Keywords: quantum optics, synchronisation, laser cooling
PACS: 42.50.vk, 05.45.Xt, 05.65.+b

INTRODUCTION

The main idea of the collective atomic recoil laser (CARL) is the following: The light of a pump laser is Bragg scattered at an atomic density grating, which itself is induced by the optical potential formed by the interference of the pump light and the scattered light. Under certain circumstances this feedback gives rise to exponential gain of the scattered light as well as of the atomic density modulation. The CARL has been predicted as the atomic analogue of the free-electron laser (FEL) about ten years ago by Bonifacio et al. [1]. Since then, several attempts have been undertaken to see this effect in experiment [2, 3]. Clear signatures of CARL have however been observed only recently [4]. The main advantages of our approach are the facts that we use cold atoms and a high-finesse ring cavity to amplify the atom-field coupling.

In the original proposals, due to the absence of an efficient dissipation mechanism, CARL amplification was treated as a transient phenomenon [1]. Our experiment went beyond this limitation and showed that by additionally applying friction forces to the atoms, steady-state CARL operation can be achieved. We call this system the "viscous CARL". In the following we will discuss how an ensemble of moving atoms may act collectively on a light field and how this action may produce laser light. We will also present an interesting interpretation of the viscous CARL in terms of self-synchronization of an ensemble of coupled oscillators in a nonequilibrium thermodynamic phase transition.

Before we present our experiment, let us start with a brief motivation of our approach. We consider an ensemble of atoms located inside an optical standing wave formed

CP770, *Atomic Physics 19,* edited by L. G. Marcassa, K. Helmerson, and V. S. Bagnato

by two counterpropagating lasers. If the frequency of the lasers is tuned far to the red of the atomic resonances, the light exerts dipole forces on the atoms attracting them towards the antinodes of the standing wave. In the photon representation the dipole force corresponds to photon rescattering between the counterpropagating modes accompanied by momentum transfer via photonic recoil. The photon scattering modifies the momentum balance of the light fields, which results in a phase shift of the standing wave. Obviously this displacement modifies the potential energy of the other atoms. As a consequence, we see that the atomic motion gets correlated. The cartoon in Fig. 1 shows one atom (the left one) initially sitting on a slope of the standing wave. While it is accelerated towards the potential valley, is pushes the standing wave slightly to the right. This imparts potential energy to the right atom, which in turn starts to move.

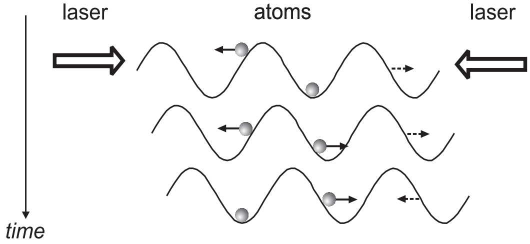

FIGURE 1. Illustration of the collective motion of two atoms (solid arrows) mediated by phase shifts of the standing wave (dashed arrows) generated by two counterpropagating laser beams.

Of course, the phase shift of the standing wave is a very weak effect. To detect it, the standing wave should be decoupled as much as possible from the driving light fields, which tend to impose their phase by continuously pumping photons into the interaction region. Furthermore, the atoms should move synchronously, in order to avoid that their influence on the phase mutually cancels out. A method to satisfy the above conditions is to use a high-finesse ring cavity. Ring cavities are particular in the sense that the phase of a standing wave in the ring cavity is not fixed by boundary conditions at the mirror surfaces, but can be moved around. Furthermore the counterpropagating modes have independent photon budgets, which means that photons can be pumped from one mode to the other by some scattering mechanism, and the scattering process conserves the total momentum, which is not the case for linear cavities. The high finesse ensures that the intracavity fields efficiently decouple from the driving laser beams and guarantees in the same time a strong atom-field coupling. The use of a high-finesse ring cavity permitted us the first observation of backaction of the atomic motion on the phase of a standing light wave.

EXPERIMENT

Fig. 2 shows the optical layout of our experiment [5]. A titanium-sapphire laser is phase-matched to a high-finesse ring cavity. Only one direction is pumped and we generate a running wave inside the ring cavity. The laser is tightly phase-locked to a cavity eigenfrequency via a Pound-Drever-Hall type servo control. Our ring-cavity is 8.5 cm long, has a beam waist of 130 μm at the position of the atoms and a finesse of 80000.

The power circulating inside the cavity is about 10 W, obtained with only a few milliWatts injected pump power. The pump laser is tuned very far, between 0.5 and 10 THz, below the rubidium D_1 line. The red-detuned light gives rise to a conservative potential, which attracts the atoms towards the intensity maxima near the beam waist. We collect rubidium atoms with a standard MOT and transfer them into the ring cavity field. We typically load several million atoms into the dipole trap at temperatures of a few 100 μK.

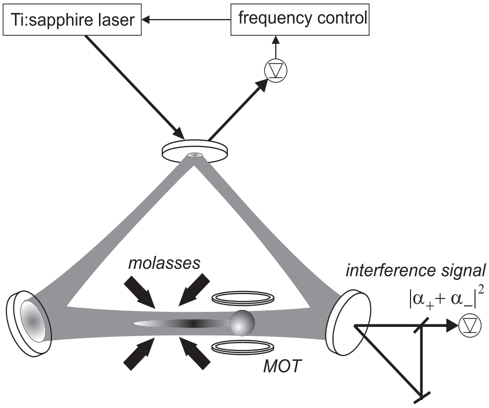

FIGURE 2. Optical layout of the experiment. Atoms are loaded from a magneto-optical trap into the dipole potential formed by a ring cavity. Then they are subject to an optical molasses. Phase shifts of the standing wave are monitored via the frequency beat of the counterpropagating cavity modes.

After a while, when the atoms have found their thermal equilibrium and form a homogeneous cloud (on the scale of an optical wavelength) follows a crucial step: We again switch on the MOT laser beams, but without the quadrupole magnetic field. In this way we obtain an optical molasses, in which the atoms move like in a viscous fluid. The optical molasses thus behaves like a velocity-dependent friction force.

We observe various signals: Photons that are scattered from the pumped mode into the reverse mode interfere with the latter one and give rise to a standing wave fraction which modulates the light intensity along the cavity axis. The evolution of this standing wave is monitored via the interference signal obtained by phase-matching the two counterpropagating ring cavity modes on a photodetector. Any phase-shift of one beam with respect to the other translates into interference fringes on the beat signal (see Fig. 2). Fig. 3 shows the time evolution of the beat signal. Initially (for times $t < 0$ s) no oscillations are distinguishable. There is only a small amount of noise. As soon as the molasses is irradiated at $t = 0$ s, strong oscillations appear, whose frequency is fixed. They persist for more than 100 ms. When the optical molasses is turned off again, we observe an acceleration of the beat signal oscillation accompanied by a fast decay of its amplitude. A Fourier analysis of the beat signal performed over subsequent time intervals is shown in Fig. 3(b).

Absorption imaging of the atomic cloud allows us to probe the atomic density distribution. The absorption pictures (not shown) reveal a net displacement of the atomic center-of-mass already after a few ms in the direction of the pump light [4]. Spectroscopy of recoil-induced resonances (RIR) [6, 7] provides us with information about the atomic

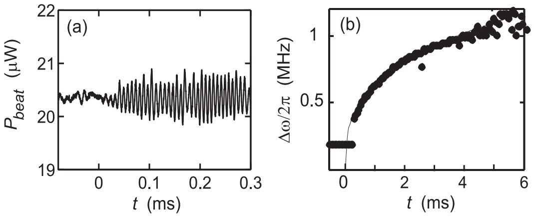

FIGURE 3. **(a)** Observed beat signal. The optical molasses is switched on at time $t = 0$. **(b)** Evolution of the beat frequency when the molasses is suddenly turned off.

velocity distribution.

We use an experimental RIR setup previously described in Ref. [5]. Two laser beams propagating within the ring cavity plane and enclosing a small angle $\theta = 8^\circ$ are aligned nearly perpendicularly to the dipole beam. The laser beams are tuned to Raman resonance 200 MHz blue of the $F = 3 \rightarrow F' = 4$ transition of the D_2 line. The RIR spectra are recorded by ramping the frequency of one of the beams with respect to the other one. The Raman detuning of the ramp ranges from -200 to 200 kHz. The scan rate is 2 kHz/μs. The power transmission of the Raman beam which is not scanned is recorded on a photodetector. The RIR spectra are taken at various delay times after switching off the optical molasses. A typical RIR spectrum is shown in Fig. 4(a).

For a cloud in thermal equilibrium we expect that the net rate for scattering photons between the beams is proportional to the number of atoms and to the derivative of a Gaussian velocity distribution. However, the type of signal that we observe in our experiment is different [see Fig. 4(a)]. Apparently it consists of a superposition of two dispersive lineshapes. With the assumption that the two line profiles result from two atomic clouds well-separated by a different center-of-mass velocity we fit the data by a superposition of two distinct Gaussians having different atom numbers, different temperatures and different center-of-mass velocities. From a fit to the RIR signal shown in Fig. 4(a), we determine the relative Doppler-shift $\Delta(kv)$ resulting from the different center-of-mass velocities. For increasing delay times before the RIR scan we observe larger relative Doppler-shifts. Fig. 4(b) shows the correlation between the relative Doppler-shift and the instantaneous beat frequency according to Fig. 3(b). Apparently, $\Delta\omega = 2\Delta(kv)$ holds within the experimental accuracy.

INTERPRETATION AS CARL

To understand the observations, we consider a homogeneous atomic cloud [see Fig. 5(a)]. Pump light which is irradiated on this cloud is not coherently backscattered, because the backscattered photons have random phases and interfere destructively. The situation is different, if there is a tiny density fluctuation creating an inhomogeneity on a length scale smaller than an optical wavelength [see Fig. 5(b)]; then a certain amount of light can be backscattered. The backscattering atoms are accelerated due to photonic recoil, and the backscattered light is red-detuned due to the Doppler effect. Together with the pump light, the backscattered probe gives rise to a weak modulation of the light

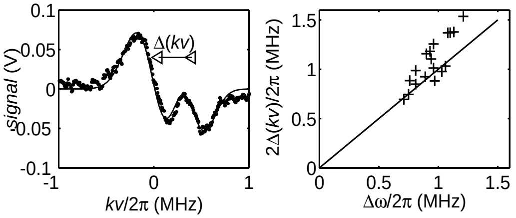

FIGURE 4. **(a)** RIR momentum spectra of a CARL accelerated atomic cloud. Note that the velocity axis is rescaled in terms of the Doppler shift occurring at the cavity field wavelength. The fitted curve assumes a superposition of two displaced Gaussian derivatives. **(b)** Splitting $\Delta(kv)$ of the two Gaussians shown in (a) for various CARL acceleration times plotted as a function of the beat frequency $\Delta\omega$ measured simultaneously with the RIR spectrum.

intensity, i.e. a standing wave fraction, which propagates in the same direction as the atoms, because of the different frequencies of pump and probe. If no other forces are applied, the accelerated atoms redistribute and merge with the rest of the homogeneous cloud: The inhomogeneity and the probe light decay. However, if now (at time $t = 0$) an optical molasses is activated [see Fig. 5(c)], the atomic acceleration is slowed down. They now have time enough to probe the dipole potential of the standing wave, and be pulled towards the potential valleys arranging themselves into a periodic pattern, which dramatically increases the backscattering efficiency. This in turn amplifies the tendency of the atoms to self-organize, thus leading to a feedback exponential gain mechanism. The red-detuned probe moves to the right and drags along the atoms, which in turn drag the standing wave. The propagation velocity corresponds to an equilibrium between the acceleration force exerted by the coherent backscattering and the velocity-dependent friction force exerted by the molasses. It suffices now to record the displacement of the standing wave via the frequency beat of the counter-propagating modes on a photodetector [see Fig. 5(c)].

When the molasses is turned off, the mutual acceleration of the atoms and the standing wave induced by the positive feedback is not counterbalanced by any friction force, i.e. the standing wave and the atoms start to run, until the backscattered light is so far detuned from the cavity resonance that the feedback breaks down: The standing wave contrast diminuishes and the acceleration gradually slows down, as can be seen in Fig. 3(b). However, the bimodal RIR spectra reveal that not all atoms participate in this self-accelerated dynamics. The atoms separate into an accelerated and a stationary fraction. Fig. 4(b) shows that the accelerated atoms move in phase with the standing wave.

The observations may be summarized in the following way: Mediated by collective atomic recoil, laser light is generated in the direction reverse to the pump laser. At the same time, the atoms self-organize into a periodic lattice, while breaking translational symmetry in a thermodynamic phase transition. The coupled dynamics can be visualized as atoms surfing down a light wave which they have themselves created. This behavior is characteristic for collective atomic recoil lasing.

The role of the molasses is twofold: On one hand, it dissipates the kinetic energy of the atoms, and this dissipation permits to reach a steady-state. On the other hand, atomic

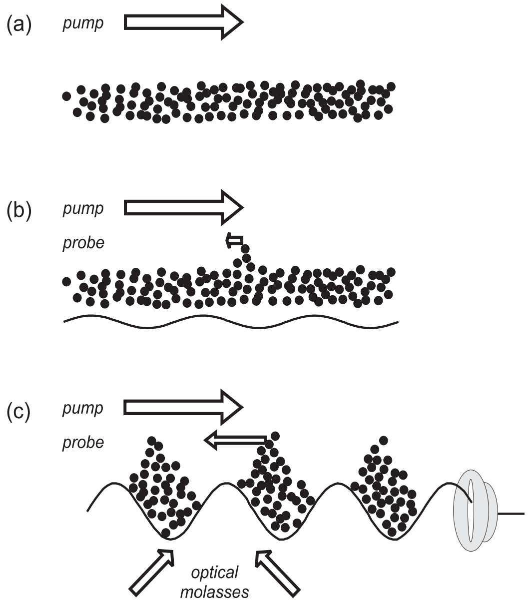

FIGURE 5. Illustration of the self-amplified backscattering process, see text.

momentum-diffusion processes, which are intrinsically connected to optical molasses, limit the equilibrium temperature. The interplay of dissipation and diffusion rules the phase transition, and gives rise to a threshold behavior of the CARL radiation.

We indeed observe this threshold in the experiment [8]: By ramping the pump laser power we found that a minimum power is needed to trigger the CARL and obtain probe laser emission. This is shown in Fig. 6(a) which plots the measured probe laser power vs. the applied pump laser power. The solid line reproduces a numerical calculation based on a Fokker-Planck treatment of our system [9]. This Fokker-Planck theory also permits us to calculate the so-called bunching parameter [shown in Fig. 6(b)], i.e. a kind of Debye-Waller factor which measures the quality of the periodic arrangement of the atoms. The bunching parameter disappears below the threshold pump power and approaches unity above threshold. In other words the bunching parameter plays the role of an order parameter for the thermodynamic phase transition.

INTERPRETATION AS COOPERATIVE SYNCHRONIZATION

The CARL bunching may be understood as a synchronization of the atomic trajectories. Synchronization is, in fact a very general phenomenon. It occurs in physical systems, for example in laser arrays or coupled Josephson junctions, as well as in biological systems like cardiac pacemaker cells or chorusing crickets. It is even observed in social systems, like the synchronization of clapping leading to rythmic applause [10].

The epitome of all synchronizing systems is an ensemble of weakly and universally

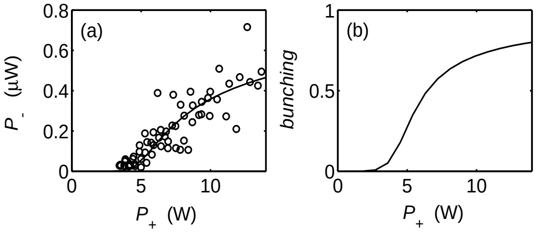

FIGURE 6. Probe power **(a)** and bunching parameter **(b)** as a function pump power. The fitted curves are based on a Fokker-Planck theory.

coupled oscillators. We may carry in mind Huygens' pendulum clocks sketched in Fig. 7(a). The oscillator model, which is also known as the Kuramoto model [11], predicts the occurrence of spontaneous synchronization, when a critical number of oscillators is put together or if the coupling strength exceeds a critical value [12]. Under certain approximations, the Kuramoto model is also applicable to describe the CARL-bunching of the atomic trajectories [8]. However in the case of CARL and unlike for the Kuramoto model the collective oscillation frequency is self-determined.

The atomic self-synchronization corresponds to a thermodynamic phase transition, whose control parameter is time. It is however important to note that the CARL system is always far from thermal equilibrium. To maintain order, energy must constantly be injected via the pump laser. The produced entropy is dissipated through the reservoir of the optical molasses. The CARL thus represents an open system: The coupling to a finite-temperature reservoir introduces diffusion, which is a source of disorder and rules the phase transition by competing with the dynamical coupling. It now becomes clear why CARL, like any other laser (this also holds for BECs), must display a built-in irreversibility: No system can deliver energy while maintaining long-range order without dumping entropy to some reservoir.

The transition towards a state with a higher order (periodic atomic arrangement) and lower symmetry has certain analogies with the dissipative structures postulated by Prigogine [13] or with Haken's synergetic systems [14] [see Fig. 7(b)].

CONCLUSION

We summarize by emphasizing that our experiment brought the CARL into a new regime. This is mainly due to the very high finesse of our ring cavity, which allows us to realize strong atom-field coupling forces very far from resonance, i.e. in a regime where the atomic excitation plays no role. The large power enhancement of our high-finesse cavity allows us to obtain deep optical potentials, to confine the atoms inside the cavity mode-volume and thus to have quasi unlimited interaction times. The atoms are as cold as 100 μK and the densities are so low, that we expect only few collisions per atom per second. Therefore collisions play no role in the dynamics.

We have observed coherent dynamics of the motion of atoms with two counterpropagating modes of a ring cavity and demonstrated that the position of the atoms acts back

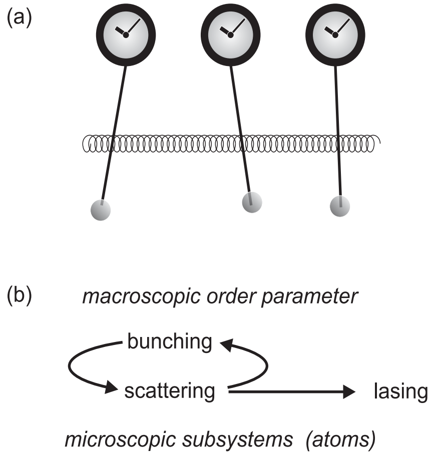

FIGURE 7. **(a)** Array of pendulum clocks weakly coupled by springs. The Kuramoto model assumes uniform coupling of every oscillator to all others. **(b)** Scheme used by Haken [14] to visualize the slaving of subsystems by an order parameter. The scheme shows the positive feedback responsible for the CARL process.

on the position of the cavity standing wave in a collective way. We observed emission of coherent radiation in the direction reverse to the pumped cavity mode, without any seed field applied. CARL is typically a transient effect due to the absence of damping for the atomic motion microscopic environments. We have however demonstrated that by applying optical molasses, we can generate external friction and obtain a stable and even settable CARL emission frequency. The fact that CARL exhibits a threshold is a strong indication for the occurrence of a phase transition. In this respect our system is analogous to a network of coupled oscillators.

For the future it would be interesting to harness other reservoirs able to dissipate the excess energy produced in the CARL process. Optical molasses are difficult to control and to model in theory, and the minimum attainable temperature is limited by resonant scattering processes. Vuletic and others have shown that the finite cavity lifetime can by itself give rise to cooling mechanisms [15, 16, 17]. These mechanisms can, in principle, lead to extremely low temperatures. A major difference with our viscous CARL seems however to be, that the electromagnetic vacuum to which the cavity couples acts like a zero-temperature reservoir, in which case we would do not expect reservoir-induced momentum-diffusion to limit this cooling process and thus no threshold behavior.

ACKNOWLEDGMENTS

We acknowledge financial support from the Landesstiftung Baden-Württemberg.

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