Dissipation-Induced Symmetry Breaking in a Driven Optical Lattice

R. Gommers, S. Bergamini, and F. Renzoni

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

(Received 19 April 2005; published 12 August 2005)

We analyze the atomic dynamics in an ac driven periodic optical potential which is symmetric in both time and space. We experimentally demonstrate that in the presence of dissipation the symmetry is broken, and a current of atoms through the optical lattice is generated as a result.

DOI: 10.1103/PhysRevLett.95.073003 PACS numbers: 32.80.Pj, 05.40.−a, 05.45.−a

Brownian motors [1–7] are devices which rectify the random motion of Brownian particles, generating in this way a current. Quite recently a large amount of work has been devoted to the study of Brownian motors [8–17], as they seem to have important applications in very different areas. On one hand, Brownian motors may be the key for the understanding of the working principle of molecular motors, tiny biological engines which transform the energy produced in chemical reactions into unidirectional motion along periodic structures which are macroscopically flat [8]. On the other hand, the mechanism of rectification of fluctuations identified in the study of Brownian motors may lead to new electron pumps, and indeed the study of solid state devices which implement Brownian motors is at present a very active area of research [18–21].

The realization of a Brownian motor is a quite subtle task and requires one to overcome the limitations imposed by the second principle of thermodynamics and to break the symmetries which inhibit directed motion. Indeed, as the second principle of thermodynamics does not allow the appearance of a current in a system at thermal equilibrium, Brownian motors are realized by driving Brownian particles out of equilibrium, as identified in the early proposals for flashing [1] and rocking [2,3] ratchets. In order then to obtain directed motion in the system out of equilibrium, relevant symmetries have to be broken.

Theoretical work [3,14] clearly identified the symmetries which in the Hamiltonian limit, i.e., in the absence of dissipation, inhibit directed motion. However, in the presence of dissipation the scenario may change [14–16], and it was theoretically shown that the symmetry properties of the system are modified by the presence of dissipation and a current can be generated even when the symmetries of the Hamiltonian would prevent current generation in the Hamiltonian limit [14,15].

In this work we demonstrate experimentally the phenomenon of dissipation-induced symmetry breaking using cold atoms in an ac driven periodic optical potential [22] which is symmetric in both time and space. We show that in the presence of dissipation the symmetry is broken, and a current of atoms through the optical lattice is generated as a result.

Before describing our experimental observations, it is essential to introduce the relevant symmetries which control the current generation in the Hamiltonian limit [3,14,15]. We consider a particle in a spatially symmetric periodic potential, periodically rocked by a zero-mean force $F(t)$ of period $T = 2\pi/\omega$. In this case, there are two relevant symmetries which need to be examined to determine whether current generation is possible. Following the notations of Ref. [15], we say that $F(t)$ possesses $\hat{F}_s$ symmetry if $F(t)$ is symmetric, after some appropriate shift: $F(t + \tau) = F(-t + \tau)$. Moreover, if $F(t)$ satisfies $F(t) = -F(t + T/2)$, we say that F possesses F_{sh} symmetry. The symmetry $\hat{F}_{sh}$ of the driving implies that the system is invariant under the shift-transformation $\hat{S}_a:(x, p, t) \to (-x, -p, t + T/2)$, while the symmetry $\hat{F}_s$ leads to invariance under the time-reversal transformation $\hat{S}_b:(x, p, t) \to (x, -p, -t)$. The invariance of the system under any of these two transformations forbids the appearance of a directed current [14,15]. To elaborate further, we consider the specific form for $F(t)$:

$$F(t) = F_0[A\cos\omega t + B\cos(2\omega t + \phi)]. \quad (1)$$

The presence of both harmonics ($F_0, A, B \neq 0$) breaks the shift symmetry F_{sh}, independently of the value of the relative phase ϕ. On the other hand, whether the F_s symmetry is broken depends on the value of the phase ϕ: for $\phi = n\pi$, with n integer, the symmetry F_s is preserved, while for $\phi \neq n\pi$ it is broken. Therefore for $\phi = n\pi$ current generation is forbidden in the Hamiltonian limit, while for $\phi \neq n\pi$ it is allowed. Perturbative calculations [14] show that the average current of particles is, in leading order, proportional to $\sin\phi$, in agreement with the symmetry considerations discussed above. The limit in which the effect of dissipation on the symmetries is negligible was already experimentally examined in Ref. [23] where the dependence $I \sim \sin\phi$ was demonstrated.

Consider now the case of weak, nonzero dissipation. The presence of dissipation breaks the invariance under time-reversal transformation $\hat{S}_b$ even if the driving is $\hat{F}_s$ symmetric. Therefore for a biharmonic force of the form of Eq. (1) both time-reversal and shift symmetries are violated in the presence of dissipation. A current can be generated as a result. An interesting issue is how the dependence of the current on the phase ϕ is modified by the presence of dissipation. Calculations done by solving the kinetic Boltzmann equation for an ensemble of interacting particles [15] showed that in the presence of weak dissipation the average current of particles I still shows an approximate sinusoidal dependence on the phase ϕ, but a phase lag ϕ_0 appears as a result of dissipation:

$$I \sim \sin(\phi - \phi_0). \tag{2}$$

The phase lag ϕ_0 vanishes in the Hamiltonian limit and is an increasing function of the relaxation rate [15]. This dependence is consistent with the previous observation that weak dissipation breaks the time-reversal symmetry of the system and leads to the generation of current also for $\phi = n\pi$. In other words, the shift ϕ_0 is a signature of the phenomenon of dissipation-induced symmetry breaking, and in our experiment ϕ_0 will precisely be the quantity examined to detect the phenomenon.

In our experiment, we demonstrate the phenomenon of dissipation-induced symmetry breaking by using cold atoms in an ac driven near-resonant optical lattice [22]. This is the same system used previously to demonstrate the rectification of fluctuations [24] and to investigate the phenomenon of resonant activation [25]. These investigations clearly showed that near-resonant optical lattices represent an ideal model system to investigate phenomena of statistical physics. In fact, in near-resonant optical lattices the laser fields create both a periodic potential for the atoms and introduce dissipation. More precisely, the interference of the laser fields creates one periodic potential for each ground state of the atoms. The laser fields also introduce stochastic transitions (optical pumping processes) between different ground states. This leads to damping, an effect named Sisyphus cooling, and a fluctuating force. As a result of the fluctuations, the atoms undergo a random walk through the periodic potential, and indeed normal diffusion was observed for atoms in dissipative optical lattices [26].

The experimental setup is the same as the one used in our previous work [24,25]. Cesium atoms are cooled and trapped in a 3D optical lattice created by four laser beams arranged in the so-called umbrellalike configuration. One beam (beam 1) propagates in the z direction; the three other beams (beams 2–4) propagate in the opposite direction, arranged along the edges of a triangular pyramid having the z direction as axis. For further detail on the lattice beams arrangement, as lattice beams' angles and polarizations, we refer to Ref. [24]. A zero-mean oscillating force of the form (1) can be applied by phase modulating one of the lattice beams. More precisely [24], a phase modulation of beam 1 of the form

$$\alpha(t) = \alpha_0[A\cos\omega t + \tfrac{B}{4}\cos(2\omega t - \phi)] \tag{3}$$

will result, in the accelerated frame in which the optical lattice is stationary, in an homogeneous force in the z direction of the form of Eq. (1) with $F_0 = m\omega^2\alpha_0/2k$, where m is the atomic mass and k the laser field wave vector.

Before describing the experimental results, it is necessary to analyze theoretically our system to determine whether the description of the dissipation-induced symmetry breaking in terms of a phase lag ϕ_0 derived for an ensemble of particles in the presence of collisions [15] applies also to the present case of noninteracting atoms, with the dissipation associated with the scattering of photons. For the sake of simplicity, and to make the analysis more transparent, we consider the simplest atom-light configuration in which Sisyphus cooling takes place: a $J_g = 1/2 \to J_e = 3/2$ atomic transition, and a 1D light configuration consisting of two linearly polarized laser fields, counterpropagating and with orthogonal polarizations—the so-called lin $\perp$ lin configuration [22]. This atom-light configuration results in two optical potentials $U_\pm$ for the atoms, one for each ground state $|\pm\rangle$, in phase opposition: $U_\pm = U_0[-2 \pm \cos 2kz]/2$, where z is the atomic position along the axis Oz of light propagation and U_0 is the depth of the optical potential. The damping arises from stochastic transitions between the two optical potentials $U_\pm$. These stochastic transitions correspond to the absorption and subsequent spontaneous emission of photons. Quantitatively, the departure rates $\gamma_{\pm\to\mp}(z)$ from the $|\pm\rangle$ states can be written in terms of the photon scattering rate Γ' as $\gamma_{\pm\to\mp} = \Gamma'(1 \pm \cos 2kz)/9$ [22]. The level of dissipation can therefore be quantitatively characterized by the photon scattering rate Γ', which can be

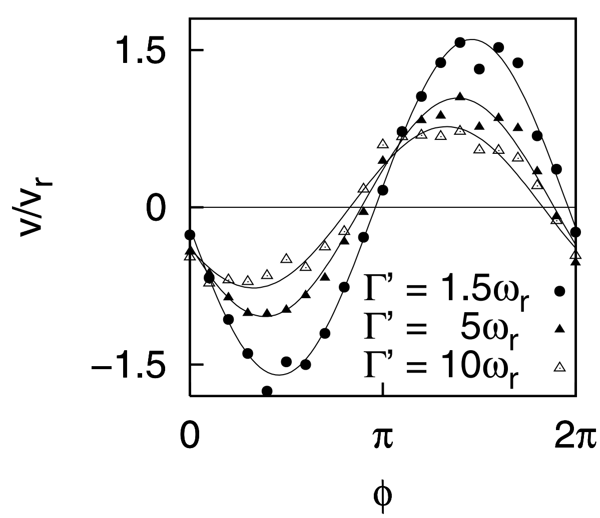

FIG. 1. Results of semiclassical Monte Carlo simulations for a sample of $n = 10^4$ atoms in an ac driven 1D lin $\perp$ lin optical lattice. The average atomic velocity, in units of the atomic recoil velocity $v_r = \hbar k/m$, is shown as a function of the phase difference ϕ between the two harmonics of the driving force; see Eq. (1). Different data sets correspond to different scattering rates Γ', expressed in units of the recoil angular frequency ω_r. The lines are the best fits of the data with the function $v/v_r = A\sin(\phi - \phi_0)$. The calculations were done for a lattice with depth $U_0 = 100E_r$. The parameters of the driving are $A = 1.5$, $B = 6$, $\alpha_0 = 0.2\pi$, and $\omega = 0.75\omega_v$, where ω_v is the vibrational frequency of the atoms at the bottom of the wells.

controlled experimentally by varying the lattice fields parameters.

We studied the atomic dynamics in the presence of biharmonic driving by semiclassical Monte Carlo simulations [22]. For a given optical potential depth U_0, we calculated the average atomic velocity v as a function of the phase difference ϕ between driving fields, for different values of the scattering rate. The results of our calculation are shown in Fig. 1. The atomic current shows a dependence of the type of Eq. (2), with the phase lag ϕ_0 vanishing in the Hamiltonian limit ($\Gamma' \to 0$) and increasing for increasing scattering rate. Values for ϕ_0 as a function of the scattering rate, determined by fitting data as those of Fig. 1 with $A\sin(\phi - \phi_0)$, are reported in Fig. 2 for two different values of the driving force amplitude. It can be seen that although the magnitude and sign of the phase lag ϕ_0 are different for the two different driving strengths considered, the general behavior described above is observed in both cases. For completeness, we mention here that also the sign and magnitude of the amplitude A varies depending on the driving strength. We notice that the dependence of the sign of ϕ_0 and A on the driving strength is consistent with previous observations of current reversals as a function of the driving amplitude at a given relative phase ϕ between the two driving fields [24].

These results for the phase lag ϕ_0 are in agreement with general symmetry considerations [14] and also extend the validity of the theoretical results obtained for an ensemble of interacting particles [15] to the present system of noninteracting atoms, with the dissipation associated with the scattering of photons.

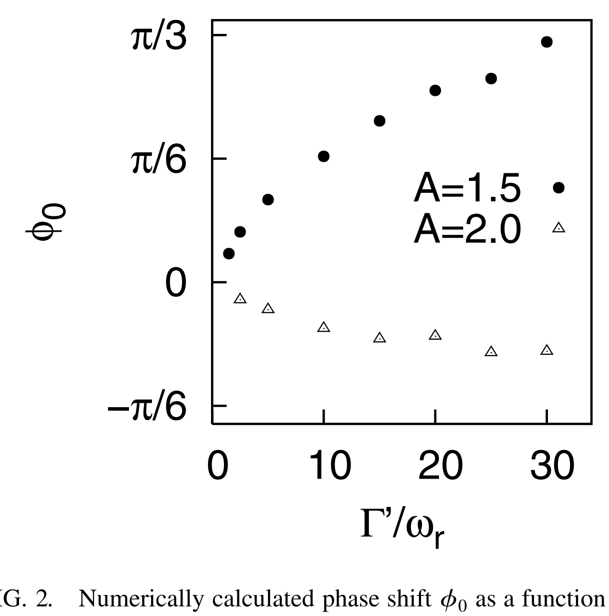

FIG. 2. Numerically calculated phase shift ϕ_0 as a function of the scattering rate Γ'. The phase shift is determined by fitting data as those in Fig. 1 with the function $v/v_r = A\sin(\phi - \phi_0)$. Different data sets correspond to different driving strength, i.e., to different values of A, with the ratio of the strengths of the two harmonics kept fixed: $B = 4A$. All the other parameters are the same as for Fig. 1.

The experimental procedure closely followed the approach of our numerical simulations. Precooled cesium atoms are loaded in a near-resonant optical lattice. The phase modulation $\alpha(t)$ is then slowly turned on. By direct imaging the atomic cloud with a charge-coupled device camera, we then derived the average atomic velocity. By repeating the experiment for different values of the phase difference ϕ, we determined the average atomic velocity as a function of the phase ϕ.

Different sets of measurements were taken for different values of the scattering rate Γ' at a constant depth of the optical potential. This was done by simultaneously varying the intensity I_L and detuning Δ of the lattice beams, so to keep the potential depth $U_0 \propto I_L/\Delta$ constant while varying the scattering rate $\Gamma' \propto I_L/\Delta^2$. We notice that as I_L and Δ can be varied only within a finite range, we cannot completely suppress dissipation, i.e., obtain $\Gamma' = 0$. However, as we will see, for the driving strength considered in the experiment, the smallest accessible scattering rate results in a phase shift which is zero within the experimental error; i.e., this choice of parameters well approximates the dissipationless case. By then increasing Γ' it is possible to investigate the effects of dissipation.

The results of our measurements, reported in Fig. 3, demonstrate clearly the phenomenon of dissipation-induced symmetry breaking. In agreement with our numerical calculations and with previous theoretical work

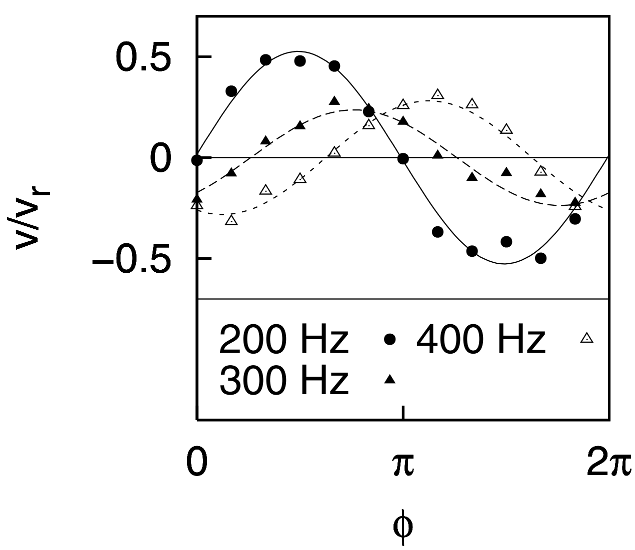

FIG. 3. Experimental results for the average atomic velocity, in units of the recoil velocity, as a function of the phase ϕ. The lines are the best fit of the data with the function $v/v_r = A\sin(\phi - \phi_0)$. The optical potential is the same for all measurements and corresponds to a vibrational frequency $\omega_v = 2\pi\,170$ kHz. Different data sets correspond to different lattice detuning Δ, i.e., to different scattering rates as the optical potential is kept constant. The data are labeled by the quantity $\Gamma_s = [\omega_v/(2\pi)]^2/\Delta$, which is proportional to the scattering rate. The parameters of the driving are $\omega = 2\pi\,100$ kHz, $A = 1$, $B = 4$, and $\alpha_0 = 27.2$ rad. The errors on v/v_r are of the order of 0.05.

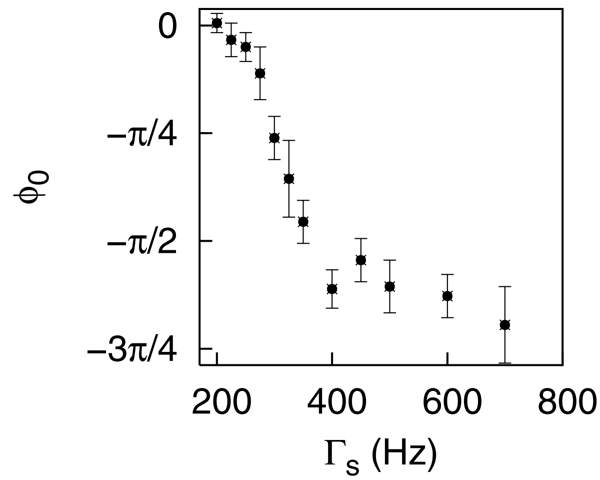

FIG. 4. Experimental results for the phase shift ϕ_0 as a function of $\Gamma_s = [\omega_v/(2\pi)]^2/\Delta$, which is proportional to the scattering rate. All the other parameters are kept constant and are the same as for Fig. 3.

[14,15], the measured current of atoms is well approximated by $A \sin(\phi - \phi_0)$. Therefore, by fitting data as those reported in Fig. 3 with the function $v/v_r = A \sin(\phi - \phi_0)$, we were able to determine the phase shift ϕ_0 as a function of Γ', as reported in Fig. 4. The measured phase shift ϕ_0 is zero, within the experimental error, for the smallest scattering rate examined in the experiment. In this case, no current is generated for $\phi = n\pi$, with n integer, as for this value of the phase the system is invariant under time-reversal transformation. The magnitude of the phase shift ϕ_0 increases at increasing scattering rate, and differs significantly from zero. The nonzero phase shift corresponds to current generation for $\phi = n\pi$, i.e., when the system Hamiltonian is invariant under the time-reversal transformation. This clearly demonstrates the breaking of the system symmetry by dissipation.

In conclusion, we demonstrated experimentally the phenomenon of dissipation-induced symmetry breaking with cold atoms in an optical lattice. We analyzed the atomic dynamics in an ac driven periodic optical potential which is symmetric in both time and space. These symmetries forbid the generation of a current. We showed that in the presence of dissipation the symmetry is broken, and a current of atoms through the optical lattice is generated as a result. Our results also show the generality of the phenomenon, in particular, extending the results [15] previously obtained for an ensemble of interacting particles in the specific framework of the kinetic Boltzmann equation to a system in which the dissipation mechanism is of a completely different nature. The present work is of relevance for the research on control of transport by time-dependent fields in a variety of system, ranging from optical tweezer setups [27] to quantum dots and wires [28].

We thank EPSRC, U.K., and the Royal Society for financial support.

[1] A. Ajdari and J. Prost, C.R. Acad. Sci. Paris **315**, 1635 (1992).
[2] M. O. Magnasco, Phys. Rev. Lett. **71**, 1477 (1993); R. Bartussek, P. Hänggi, and J. P. Kissner, Europhys. Lett. **28**, 459 (1994).
[3] A. Ajdari, D. Mukamel, L. Peliti, and J. Prost, J. Phys. I (France) **4**, 1551 (1994).
[4] M. M. Millonas and M. I. Dykman, Phys. Lett. A **185**, 65 (1994).
[5] M. C. Mahato and A. M. Jayannavar, Phys. Lett. A **209**, 21 (1995).
[6] D. R. Chialvo and M. M. Millonnas, Phys. Lett. A **209**, 26 (1995).
[7] For a review on Brownian motors, see R. D. Astumian, Science **276**, 917 (1997); R. D. Astumian and P. Hänggi, Phys. Today **55**, No. 11, 33 (2002); P. Reimann, Phys. Rep. **361**, 57 (2002); P. Reimann and P. Hänggi, Appl. Phys. A **75**, 169 (2002); see also P. V. E. McClintock, Nature (London) **401**, 23 (1999).
[8] F. Jülicher, A. Ajdari, and J. Prost, Rev. Mod. Phys. **69**, 1269 (1997).
[9] F. Marchesoni, Phys. Rev. Lett. **77**, 2364 (1996).
[10] M. I. Dykman, H. Rabitz, V. N. Smelyanskiy, and B. E. Vugmeister, Phys. Rev. Lett. **79**, 1178 (1997).
[11] I. Goychuk and P. Hänggi, Europhys. Lett. **43**, 503 (1998).
[12] Ya. M. Blanter and M. Büttiker, Phys. Rev. Lett. **81**, 4040 (1998).
[13] D. G. Luchinsky, M. J. Greenall, and P. V. E. McClintock, Phys. Lett. A **273**, 316 (2000).
[14] S. Flach, O. Yevtushenko, and Y. Zolotaryuk, Phys. Rev. Lett. **84**, 2358 (2000).
[15] O. Yevtushenko, S. Flach, Y. Zolotaryuk, and A. A. Ovchinnikov, Europhys. Lett. **54**, 141 (2001).
[16] P. Reimann, Phys. Rev. Lett. **86**, 4992 (2001).
[17] C. Van der Broeck, R. Kawai, and P. Meurs, Phys. Rev. Lett. **93**, 090601 (2004).
[18] H. Linke, W. Sheng, A. Löfgren, H. Xu, P. Omling, and P. E. Lindelof, Europhys. Lett. **44**, 341 (1998).
[19] H. Linke, T. E. Humphrey, A. Löfgren, A. O. Sushkov, R. Newbury, R. P. Taylor, and P. Omling, Science **286**, 2314 (1999).
[20] S. Weiss, D. Koelle, J. Müller, R. Gross, and K. Barthek, Europhys. Lett. **51**, 499 (2000).
[21] J. E. Villegas, S. Save'ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. García, and J. L. Vincent, Science **302**, 1188 (2003).
[22] For a recent review of optical lattices, see G. Grynberg and C. Mennerat-Robilliard, Phys. Rep. **355**, 335 (2001).
[23] M. Schiavoni, L. Sanchez-Palencia, F. Renzoni, and G. Grynberg, Phys. Rev. Lett. **90**, 094101 (2003).
[24] P. H. Jones, M. Goonasekera, and F. Renzoni, Phys. Rev. Lett. **93**, 073904 (2004).
[25] R. Gommers, P. Douglas, S. Bergamini, M. Goonasekera, P. H. Jones, and F. Renzoni, Phys. Rev. Lett. **94**, 143001 (2005).
[26] F.-R. Carminati, M. Schiavoni, L. Sanchez-Palencia, F. Renzoni, and G. Grynberg, Eur. Phys. J. D **17**, 249 (2001).
[27] S.-H. Lee, K. Ladavac, M. Polin, and D. G. Grier, Phys. Rev. Lett. **94**, 110601 (2005).
[28] S. Kohler, J. Lehmann, and P. Hänggi, Phys. Rep. **406**, 379 (2005).