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Atomic diffusion in an optical quasicrystal with five-fold symmetry

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We present experimental and numerical studies of the atomic motion in an optical lattice displaying a fivefold rotational symmetry. The atomic transport has been investigated by measuring the time evolution of the size of the atomic cloud. The experimental results are compared to those of a semiclassical Monte Carlo simulation of the atomic motion in a three-dimensional optical quasicrystal. A good agreement has been obtained on the anisotropy of the diffusive expansion of the cloud. [S1050-2947(99)50312-0]

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In the last decade, rapid progress has been made in the field of cooling and trapping of neutral atoms, opening, for instance, the way to the achievement of Bose-Einstein condensation [1]. Besides this wonderful realization, a new class of objects has grown up: optical lattices [2]. They merely consist in a sample of cold atoms moving in a spatially modulated potential. This potential originates from the position-dependent light shift that affects the ground state of an atom moving in an interference pattern of several laser beams [3]. Such systems display a strong analogy with solid-state systems because the atomic motion in the optical potential is similar to the motion of the electrons in the ionic lattice. However, the typical time scales differ by several orders of magnitude, and subtle phenomena (such as the Bloch oscillations) are easier to detect in periodic optical lattices than in solid-state systems [4]. On the other hand, an optical potential, created by an interference pattern, has no defects and no phonons, and its symmetry is completely imposed by the geometric arrangement of the laser beams. The experimentalist can choose the symmetry of the lattice he creates and he is not tied to the self-arrangement of the ions in the solid lattice. This fact can be used to design optical potentials that are no longer periodic, but quasiperiodic [5]. In this situation, the solid-state analog of the optical lattice is no longer the crystal, but the quasicrystal [6].

In this paper we present some experimental and numerical results on atomic diffusion in a quasiperiodic optical lattice. The original motivation for this work is to investigate the role of the translational symmetry of the optical potential in the transport properties of bright optical lattices, in relation to the problem of electronic transport in solids. We have chosen a beam geometry such that the optical lattice is still periodic along one spatial direction while being quasiperiodic (with a fivefold rotational symmetry) in the planes orthogonal to that periodic direction [7]. This beam geometry thus leads to an optical potential analogous to the decagonal phases of some solid-state quasiperiodic alloys, for which peculiar features due to the quasiperiodic order have already been investigated [8]. Two previous experiments have studied the atomic diffusion in three-dimensional (3D) bright optical lattices, but both deal with periodic systems [9,10]. A direct measurement of the atomic diffusion (with a method similar to Ref. [9]) allowed us to observe an anisotropy in the cloud expansion. The spatial diffusion coefficient we deduce from the measurements is larger in the periodic direction than in the quasiperiodic ones.

The traditional bright optical lattices are obtained with the laser beams detuned on the red side of a $J \rightarrow J+1$ atomic transition. The atom-laser interaction results in spatially modulated light shifts for the Zeeman sublevels, and the photon scattering couples the various sublevels. For detunings Δ of a few natural linewidths Γ, the Sisyphus cooling process takes place [3], trapping the atoms at the bottom of the potential wells. The relevant quantities to describe the interaction between the atoms and the laser beams (assumed to have the same intensity, the Rabi frequency for each beam being Ω_0) are the light shifts $\Delta_0' = \Delta s_0/2$ and the photon scattering rate $\Gamma_0' = \Gamma s_0/2$, where $s_0 = \Omega_0^2/[2(\Delta^2 + \Gamma^2/4)]$ is the saturation parameter per beam.

To achieve a fivefold rotational symmetry in the xOy plane, we arrange five beams of equal intensity in this plane with 72° between them. The polarization of the beams is taken in the propagation plane to obtain an alternance of σ^+ and σ^- sites with respect to the z axis that is taken as the quantization axis. Due to the fivefold symmetry of the beam configuration the resulting 2D potential [11] has no translational symmetry, similar to the Penrose tiling [12]. The loss of the periodicity leads to potential wells with different depths [5]. The deepest potential wells then correspond to an almost purely circular polarization for the total field. To have a 3D trapping potential, we add a lin$\perp$lin standing wave along the z axis; the arrangement of the beams is shown in Fig. 1(a). The alternance of σ^+ and σ^- sites in the z direction interferes with the previous 2D potential, resulting in a potential that is then periodic along the z direction, with a λ spatial period. It consists in a periodic stacking of quasiperiodic planes with a fivefold symmetry. This rotational symmetry is clearly visible in Fig. 1(b), which represents a cut of the potential.

In order to have theoretical support for our experimental investigations, we have adapted a semiclassical Monte Carlo numerical simulation to the three-dimensional quasiperiodic lattices. In the dissipative regime where the experiments are

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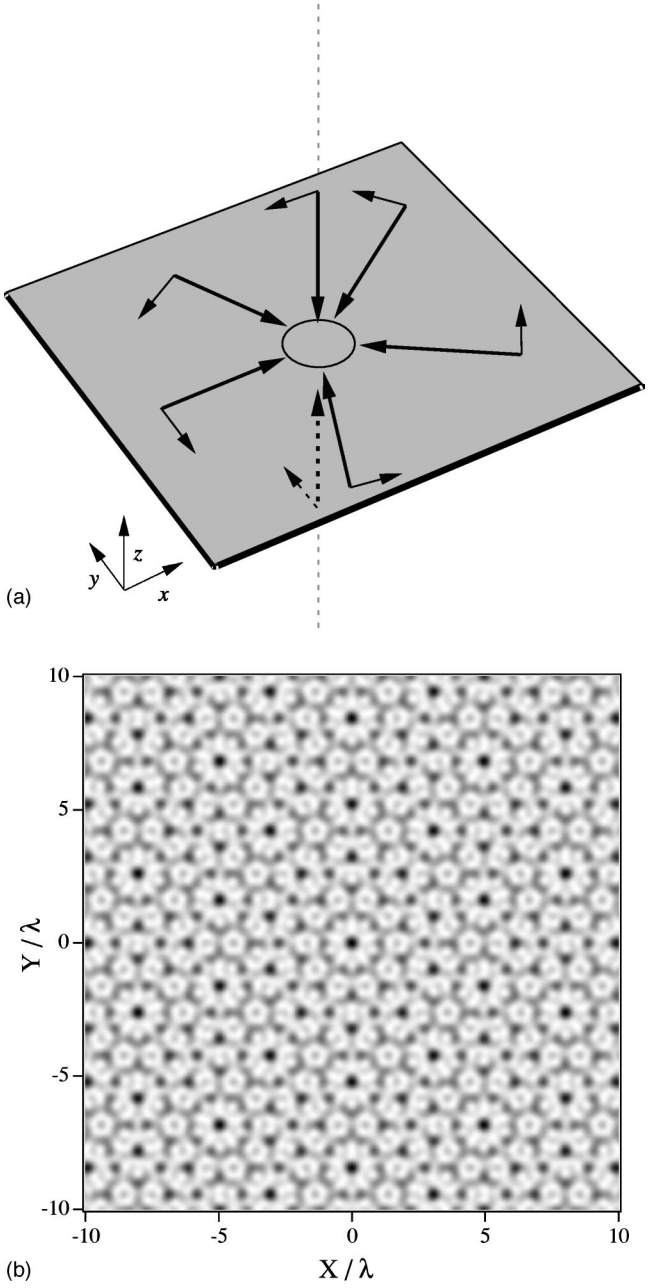

FIG. 1. (a) Beam configuration used to create the decagonal potential. (b) 2D cut in the $z=0$ plane of the optical potential for the previous beam configuration on a $1/2 \rightarrow 3/2$ transition ($m_F = 1/2$ Zeeman sublevel). The darker regions correspond to the potential wells.

done, the system is fairly described by a semiclassical model, because the spontaneous emission kills the coherent quantum effects. Semiclassical Monte Carlo simulations are widely used to make predictions in laser cooling, but as they are computer-time consuming, they are mainly used in 1D or 2D models [13,14]. However, to describe correctly the atomic diffusion in optical lattices, it is important to take into account all possible paths in 3D space. To avoid useless growth in complexity, we study an atom with the mass of cesium but with a $1/2 \rightarrow 3/2$ transition instead of the actual $4 \rightarrow 5$ transition. We do not introduce any adjustable parameter to compensate for the huge differences in matrix elements. We have developed an *ad hoc* formulation of the optical pumping rate,

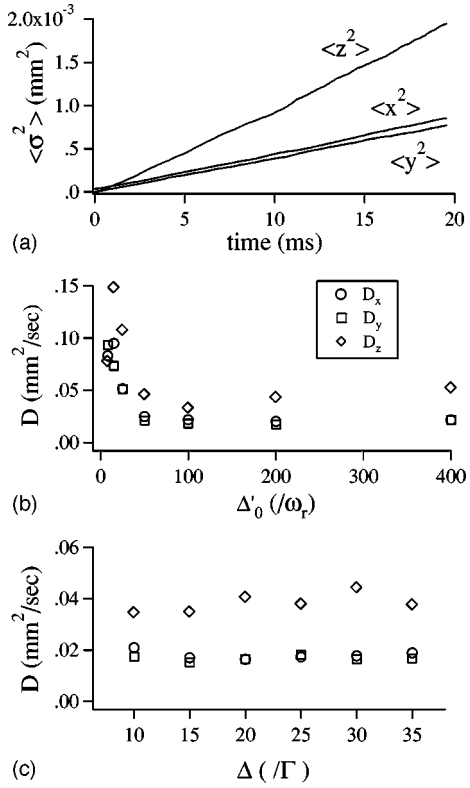

FIG. 2. (a) Time evolution of the variance of the atomic distributions along the three spatial directions evaluated for 5000 trajectories. The detuning is -30Γ and the light shift per beam Δ' is $100\omega_R$, where $\omega_R = \hbar k^2/2M$ is the recoil frequency. The slope of this variance directly gives the diffusion coefficient. These diffusion coefficients have been reported in (b) for a fixed detuning (-10Γ) and different potential depths, and in (c) for fixed potential depth ($100\omega_R$) and different detunings [the same symbols have been used for Figs. 2(b) and 2(c)].

reactive and dissipative forces, and momentum diffusion tensor to allow an efficient computing code that runs on any laser beam configuration [15].

The program computes several trajectories corresponding to different initial conditions and also different pseudorandom variable sequences. For this ensemble of 10^3 to 10^4 trajectories, we calculate the mean values and variances of the position and of the velocity. The evolution with time of these quantities gives some interesting information. As the radiation pressure is compensated, the average velocity is zero and the mean position of the cloud does not change. The rms velocities in each direction rapidly reach a stationary value that is isotropic. On the other hand, the variance (mean square) of the coordinates evolves linearly with time as shown in Fig. 2(a). This linear behavior is characteristic of a diffusive motion (we define, as usual, the diffusion coefficient by $\langle x^2 \rangle = 2D_x t$). Despite the isotropy of the temperature (the rms velocity), we clearly see in Fig. 2(a) that the diffusion coefficient in the z direction (the periodic direction) differs from those in the xOy plane [17]. In Fig. 2(b), we have reported the spatial diffusion coefficients as a function of the potential depth. For small intensities, we obtain a divergence of the diffusion coefficients that is also related to the ''*décrochage*'' observed in the temperature dependence of Sisyphus cooled samples [16]. Some discrepancies be-

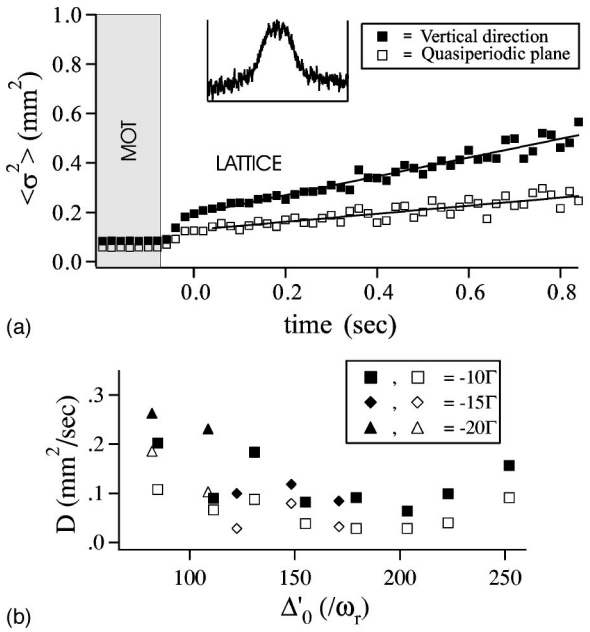

FIG. 3. (a) Time evolution of the square of the size of the atomic cloud as measured in an experiment. The detuning is -10Γ and the intensity per beam is $I_0=7.6$ mW/cm^2. The size of the cloud in the x and z directions is evaluated by a Gaussian fit of the fluorescence. In the inset, we show a typical horizontal slice of an image. (b) Diffusion coefficients, as measured from the curves of (a) versus the light shift per beam at different detunings. The filled symbols indicate the vertical direction; the open ones the quasiperiodic plane.

tween the simulation data and the linear behavior, possibly due to anomalous diffusion, are also observed in the very shallow potential-well limit; however, the complete study of this limit is far beyond the scope of this Rapid Communication. On the other hand, for deep potential wells, the diffusion coefficients hardly depend on the detuning [Fig. 2(c)]. The diffusion coefficient for the periodic direction is about twice that for the x and y directions that are in the quasiperiodic plane.

The experiment is performed with cesium atoms in a low-pressure cell. We first cool and trap the atoms with a magneto-optical trap. Then we switch off the magnetic field and the trapping laser beams and switch on the seven beams to create the decagonal quasilattice. A time-of-flight diagnostic allows the determination of the vertical temperature. The measured values and their dependence on the laser detuning and intensity exhibit the usual behavior of Sisyphus cooling. To measure the spatial diffusion coefficient, we observe the expansion of the atomic cloud, as in Ref. [9]. For this purpose, we have developed a special acquisition system that loads directly into the computer 54 consecutive images with a 12-bit dynamics. The camera is located in the horizontal plane, in order to see one quasiperiodic direction and the periodic one. We extract the dimension of the cloud along the two orthogonal directions with a Gaussian fit. In Fig. 3(a) we report the square of the size of the cloud in the x and z directions versus time, with the expected linear behavior. The anisotropy of the diffusion is clearly visible in this figure, as the z dimension increases with twice the slope of the x dimension.

The experiment has been repeated for several sets of parameters. The laser intensity (per beam) was varied in the 2–40-mW/cm^2 range, while the detuning varied from -5Γ to -30Γ ($\Gamma/2\pi=5.2$ MHz). The measured diffusion coefficients are reported in Fig. 3(b). They are in qualitative agreement with the result of the numerical simulations. The absolute values also fall in the same range, 5 – 40 10^{-8} m^2/s (110 – 880 $\hbar$/M), within a factor of 2. Such an agreement was not really expected because of the absence of an adjustable parameter and because of the differences in the Clebsh-Gordan coefficients between simulation and experiment. Except for the anisotropy, the diffusion coefficients are of the same order of magnitude as the coefficients measured in six-beam periodic optical molasses [9]. On the other hand, they contrast with the values estimated for periodic optical lattices [10]. However, the method used in that case differs greatly from the macroscopic method we use. In fact, the authors of Ref. [10] measure the decay time of an intensity cross correlation $g^{(2)}_{+-}(\tau)$, and deduce a diffusion coefficient from it. This cross correlation signal is only sensitive to the atoms experiencing a spin flip, so the atoms moving around while remaining in the same sublevel are not taken into account [18].

The atomic transport anisotropy that we have measured in the quasiperiodic optical lattices exhibits the same trend as the anisotropy in electron transport properties observed in decagonal phases of quasicrystals. However, one can wonder about the precise role of the quasiperiodicity in our bright optical lattice. We must stress that we work in a dissipative regime and that the atomic wave function collapses very often because of the spontaneous emission of photons. Thus, the role of the quasiperiodicity is not to localize the wave functions, as in solid-state quasicrystals. However, its influence on atomic diffusion is more subtle than a mere anisotropy of different wells and hills. A simple hand-waving argument helps to understand the role of the quasiperiodicity in the dissipative regime. It is well known that in the absence of periodicity the atoms preferentially fill the deepest wells [5,7]. Just assume that the most frequent event when an atom escapes a potential well is that it falls in the neighboring one ($\lambda/2$ random walk). If an atom moves in the periodic direction, it will fall in a well equivalent to the previous one; the next step can then be forwards or backwards with even probabilities. On the other hand, if the motion is in the quasiperiodic plane, the atom leaving a deep well can find only shallower ones within λ: the probability for the next step to be in the backward direction is then slightly higher since it puts the atom back in the deepest neighboring well. On the experimental side, we have performed some preliminary measurements in a periodic optical lattice directly obtained from the seven-beam quasilattice just by blocking two beams among the five that propagate in the quasiperiodic plane. In this particular case, the atomic diffusion becomes perfectly isotropic, while the measured values of D are comparable with the mean values obtained in the quasiperiodic configuration. A more detailed comparison between periodic and quasiperiodic systems is in progress.

In conclusion, we have reported experimental and numerical results on a quasiperiodic optical lattice with a fivefold rotational symmetry. We have measured the spatial diffusion of the atoms trapped in this decagonal potential and we have

shown that the atomic diffusion is not isotropic. The diffusion is slower in the quasiperiodic plane than in the periodic direction. These results are in agreement with the numerical simulations that we have developed. The natural extension of this work is to switch to a nondissipative regime where the atomic wave function can spread over several potential wells. In this quantum regime, one can expect to mimic more realistically the behavior of the electrons in the potential of the ions in a quasicrystal.

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[17] These results are in strong contrast with those obtained from the numerical simulation of a periodic lattice created by four beams aligned along a regular tetrahedron. In that case, the temperature is anisotropic (by 20%) and the diffusion is isotropic [7].

[18] The authors of Ref. [10] have also measured a second and much shorter characteristic time (2 μs instead of 50 μs) in the autocorrelation. This time is associated with a small fraction of delocalized atoms that should also contribute to the diffusion.