Atomic Transport in an Optical Lattice: An Investigation through Polarization-Selective Intensity Correlations

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We present an experimental investigation of the local dynamics and spatial diffusion of atoms in a rubidium optical lattice using polarization-selective intensity correlation spectroscopy in both the time and frequency domains. Autocorrelations of the circularly polarized components of the fluorescence light are shown to give access to the atomic dynamics in a single optical potential well. By contrast, cross correlations between opposite circular components of the scattered light provide information about atomic transport in the lattice through escape and recapture between neighbor potential wells. [S0031-9007(96)01042-3]

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The transport properties of microscopic particles immersed in a surrounding medium are extremely diverse. Depending on the detailed characteristics of their coupling with the environment, their motion can take the form of free propagation, ballistic movement, oscillations, viscous damping, Brownian motion, Lévy flights, etc. Past advances in probability theory and statistical physics allow one to connect the associated particle transport properties to macroscopic quantities accessible to experiments. Such quantities can be investigated through a variety of techniques, among which intensity correlation spectroscopy [1–3] plays an important role for several reasons. It is a noninvasive *in situ* technique that is sensitive to time correlations in the position of individual scattering particles and, consequently, to their microscopic motion. Unlike traditional imaging methods consisting of monitoring the extension of an initially well localized ensemble of particles [4], it can be employed reliably in systems of large size or exhibiting a very slow or complex dynamics, and is much less sensitive to the preparation of the initial particle sample. In the situations where the motion of particles is correlated with a change in their optical properties and/or in the local polarization of light, polarization-selective intensity correlation spectroscopy can, moreover, give access to otherwise unavailable information through the polarization of the scattered light.

These characteristics are of particular value for the investigation of the transport properties of atoms in optical lattices [5], which remain one of the most poorly studied features of this medium although some unusual characteristics have been predicted and observed [6]. Optical lattices are periodic structures of micron-sized potential wells induced by the light shift of the atomic sublevels in a standing wave exhibiting a gradient of polarization. In the most studied situation [5], the light polarization is alternately σ^+ and σ^- at the bottom of adjacent potential wells where atoms accumulate as a result of Sisyphus cooling [7]. According to the standard representation of this cooling mechanism, atomic transport in optical lattices proceeds through escape and recapture of atoms from and by neighbor optical potential sites, which are generally associated with opposite circular polarizations. As a consequence, it is appealing to try and trace atomic jumps between potential wells through intensity correlations between cross-circular polarizations of the light scattered by the atoms. In this Letter, we present the results of such an experimental investigation in rubidium using polarization-selective intensity correlation spectroscopy in the time and frequency domains. We consider, on the one hand, autocorrelation spectra of the σ^+ or σ^- light intensity, which essentially provide information about atoms localized in a well-defined potential well. In particular, we have access to the escape rate of atoms from a potential well and to the details of the vibrational motion of atoms at the bottom of the wells. In the time domain, the damped oscillatory motion can be directly visualized, and different dynamics can be clearly attributed to localized and delocalized atoms. On the other hand, we also consider cross-correlation spectra between the σ^+ and σ^- light components, which are shown to display a narrow feature giving access to the transport rate between σ^+ and σ^- wells, hence providing information about spatial diffusion in the lattice.

We consider a four-beam lin $\perp$ lin optical lattice [5] consisting of two x-polarized beams propagating in the y-z plane, making an angle 2θ, and two y-polarized beams propagating in the x-z plane, making the same angle (Fig. 1). Such lattices have been recently investigated using various experimental methods such as pump-probe spectroscopy [8], heterodyne fluorescence measurements [9], or spontaneous Bragg scattering [10]. These techniques have already revealed a number of features: oscillating motion of the atoms in the optical potential wells, Lamb-Dicke narrowing of the vibrational lines due to strong spatial confinement of the atoms at the bottom of the wells [11], occurrence of very long evolution times in the atomic external dynamics, etc.

Our experiment proceeds as follows: Rubidium atoms are cooled and trapped in a low pressure cell by a magneto-optical trap. After a 200 ms loading and cooling

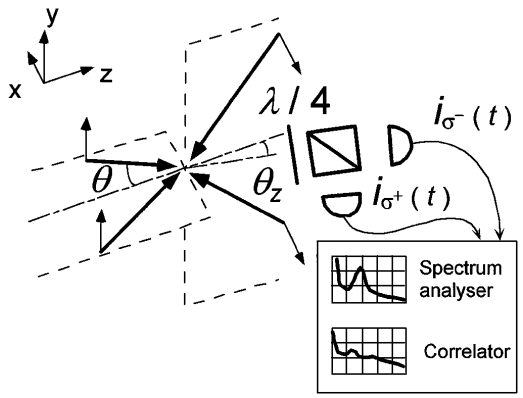

FIG. 1. Field configuration of the lattice and detection setup. Two detectors, sensitive to oppositely circularly polarized scattered light along a single direction θ_z, are located in the x-z plane.

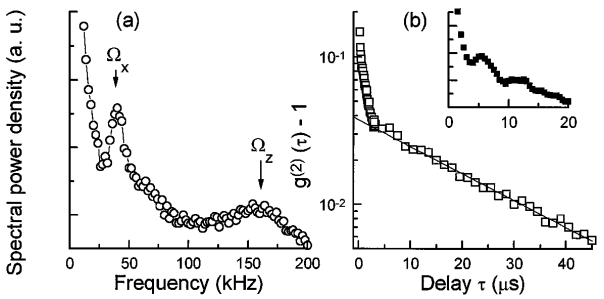

FIG. 2. σ^- intensity autocorrelations in the frequency (a) and the time (b) domains for two different geometries: $\theta = 20°$, $\theta_z = 10°$ (a) and $\theta = 30°$, $\theta_z = 0°$ (b). The inset of (b) shows data taken under the same conditions with a different sampling interval. The autocorrelation spectrum displays two sideband resonances at the vibrational frequencies Ω_x and Ω_z. The time correlation function shows not only the oscillations (inset) but also two exponential time constants.

phase, both the inhomogeneous magnetic field and the trapping beams are switched off in less than 1 ms. The lattice beams (typical intensity $1-5\ \mathrm{mW/cm^2}$) are then switched on for 5 ms, allowing the atoms to reach their steady state, corresponding to a rms momentum of 10–14 times the one-photon recoil momentum and a density of $2 \times 10^9\ \mathrm{cm^{-3}}$ (the filling factor of the lattice is of the order of 10^{-4}). All laser beams are derived from a frequency-stabilized diode laser (jitter <1 MHz) and have a detuning Δ of 5Γ to 10Γ (Γ the natural linewidth of the excited state) to the red side of the $F_g = 3 \rightarrow F_e = 4$ component of the D_2 resonance of rubidium. After equilibration, intensity correlations are recorded for 100 ms, during which atom losses remain negligible. The two circularly polarized components of the light scattered in a single spatial mode are separated and directed towards separate detectors. The detectors are avalanche photodiodes and the typical counting rates are 10^5 to 10^6 counts $\mathrm{s^{-1}}$. We checked that, at these count rates, our measurements are shot noise limited [2]. Intensity correlations in the frequency or time domain are recorded using a spectrum analyzer [2] or a digital correlator which measures the normalized intensity correlation function $g^{(2)}(\tau)$ [1]. The measurement cycle is repeated and averaged 10^2 to 10^5 times.

We show in Fig. 2(a) an example of an autocorrelation spectrum of the σ^- light intensity recorded in the x-z plane at a $\theta_z = 10°$ angle with respect to the symmetry axis Oz of a tetrahedron with $\theta = 20°$ (see Fig. 1). Figure 2(a) displays a narrow feature at zero frequency, a broad pedestal, and two sideband resonances labeled Ω_x and Ω_z. These sidebands are centered around the expected positions for the Ω_x and Ω_z vibrational frequencies of the atoms along the x and z axes, respectively, and are associated with spontaneous Raman scattering of the lattice beams by atoms oscillating at the bottom of the optical potential wells. As it is now well known [11], the widths of these resonances are dramatically reduced compared to the typical light scattering rate because of the subwavelength atomic localization (Lamb-Dicke effect).

Much more surprising is the relative width of these resonances [12]. Indeed, the usual estimate of the Raman widths based on the lifetime of the *individual* vibrational levels yields a decreasing function of the vibrational frequency [11], in complete contradiction with the experiment. In fact, such an estimate does not take into account the inhomogeneous broadening of the Raman lines due to the potential anharmonicity. Furthermore, as was recently pointed out by Grynberg and Triché [13], in the limit of small anharmonicity of the optical potential an efficient coherence transfer mechanism [14] may take place and constitute an additional lengthening mechanism for the vibrational coherence lifetime. We attribute the observation of Fig. 2(a) to the fact that, in the limit of small tetrahedron angles, the anharmonicity, i.e., the dependence of the separation of adjacent bound levels on vibrational quantum number, is stronger in the z direction than in the x, y directions. So both the coherence transfer and the reduction of the inhomogeneous broadening contribute to a relative narrowing of the Ω_x line. The study of the relative contributions of both effects is under way and will be published elsewhere.

We complemented the investigation of the oscillatory behavior of the atoms by observing the intensity autocorrelation in the time domain. The inset of Fig. 2(b) displays damped temporal oscillations directly reflecting the relaxation of the vibrational atomic motion under the combined influence of the potential anharmonicity, heating and optical pumping transitions toward adjacent wells.

A broad pedestal is also clearly visible in Fig. 2(a), although its shape is difficult to characterize precisely. It appears much more transparent in the time domain signal of Fig. 2(b), which demonstrates the occurrence of two well-defined time constants in the system dynamics. The short time constant, of the order of 2 μs, is consistent with the typical light scattering rate by free atoms.

We therefore attribute the pedestal in Fig. 2(a) to light scattering by the small fraction of delocalized atoms flying over the optical potential wells. Because autocorrelations are mainly destroyed by optical pumping transitions of the atoms toward neighbor potential sites, we interpret the long time constant of Fig. 2(b) (approximately 25 μs) as resulting from initially well-localized atoms escaping from their potential wells through heating and optical pumping. In other words, the width of this resonance is approximately the escape rate of localized atoms from their potential wells [15]. All these interpretations are supported by numerical calculations of the light autocorrelations based on the semiclassical Monte Carlo simulation technique for a $F_g = 1/2 \rightarrow F_e = 3/2$ atomic transition [16,17]. In particular, we checked that deleting the contribution of delocalized atoms results in the disappearance of the short time constant and that the large time constant is approximately equal to the decay time of the atomic internal state autocorrelation function [18].

The time constants we deduced from the autocorrelation signals relate almost exclusively to the dynamics of an atom in one well. This information is also accessible through pump-probe or heterodyne fluorescence spectroscopy. By contrast, σ^+-σ^- cross correlations (the σ^+ intensity times the σ^- intensity at a later time) essentially involve atoms initially localized in a σ^+ optical potential well and which are later transferred through optical pumping toward a σ^- potential site. If the atom does not change site, it contributes very little to the cross-correlation signal. Because the potential wells are spatially separated, cross-correlation signals provide new information about atomic transport in the lattice. We show in Fig. 3(a) an example of such a spectrum recorded in a $\theta = 30°$ tetrahedron lattice with a detector aligned along the z axis. One first notes [inset of Fig. 3(a)] that the cross-correlation spectrum displays no vibrational line (this was checked carefully by zooming on the expected frequency domain for the Raman resonances). This observation, together with numerical simulations exhibiting no significant differences between cross-correlation spectra involving all atoms or restricted to atoms experiencing spin flips, strongly supports the assumption that cross correlations are insensitive to atoms remaining localized in a given potential well.

The only salient feature in the spectrum [Fig. 3(a)] is a narrow peak at zero frequency. As it is transparent in Fig. 3(b), this feature is associated with a single well-defined time constant of the order of 50 μs [19]. In order to interpret this result, we restrict ourselves for simplicity to the atomic motion along the z axis [20]. One can readily show that the long time behavior of the cross-correlation signal is then simply proportional to $g^{(2)}_{+-}(\tau) - 1 \propto |\langle e^{i\delta k[z(t+\tau)-z(t)]}\rangle_{+-}|^2$, where the average $\langle\,\rangle_{+-}$ runs over atoms experiencing a $|g, +F_g\rangle \rightarrow |g, -F_g\rangle$ spin flip between times t and $t + \tau$, and where $\delta k = k(1 - \cos\theta)$ denotes the difference between the z components of the wave vectors of the field scattered in the direction of the detector and of the lattice beams. It thus appears that the cross-correlation signal decreases as a result of atomic transport in the lattice on a spatial scale of the order of $2\pi/\delta k$ [21]. In order to connect the width of the central resonance to a physically more meaningful quantity, we consider a simple random walk model of the atomic position characterized by a spatial diffusion coefficient D_z which yields $g^{(2)}_{+-}(\tau) - 1 \propto e^{-2\delta k^2 D_z \tau}$. Note that the exponential form of the decay indicates a diffusion process. Ballistic motion of a thermal ensemble, for example, would yield a Gaussian decay. We checked in our numerical simulations that D_z, deduced from intensity correlation spectra, was an underestimate of its actual value by a factor of less than 2. We have plotted in Fig. 4 the spatial diffusion coefficient deduced from this model, and the width of the central resonance of Fig. 3(a), as a function of the optical potential depth normalized to the one-photon recoil energy. We note

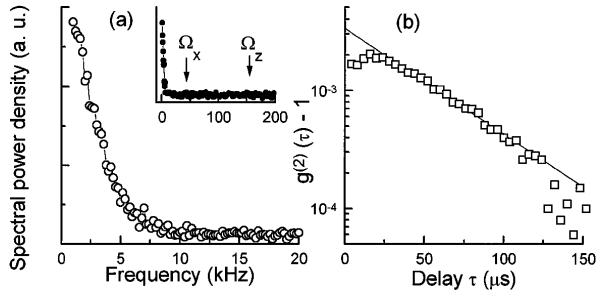

FIG. 3. σ^+-σ^- intensity cross correlations in the frequency (a) and the time (b) domains. The cross-correlation function (b) displays a pure exponential decay at long times. Note in the inset the absence of sideband resonance on the spectrum around Ω_x and Ω_z.

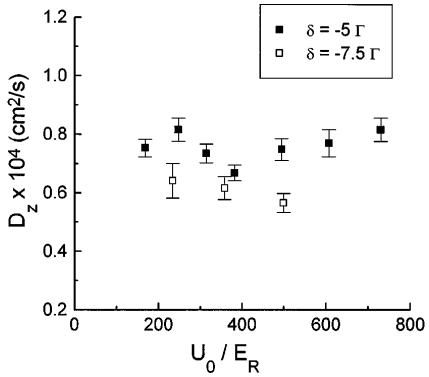

FIG. 4. Diffusion coefficient of the atoms D_z as deduced from the width of the central resonance of the cross-correlation spectrum (see text). We have represented D_z for different values of characteristic parameters of the lattice: the optical potential depth U_0 normalized to the recoil energy E_R and the detuning δ in units of the natural linewidth Γ.

that our typical value for D_z is an order of magnitude smaller than the one measured in optical molasses [4]. Also, the rough independence of D_z on U_0 for our values of the laser parameters is consistent with recent theoretical calculations of such coefficients [6].

Intensity correlation spectroscopy should yield interesting new information in other areas of cold atom physics. Direct applications in optical lattices include the search for anomalous diffusion and escape lines [6], or for density dependent effects [22]. We have obtained preliminary results indicating a significant modification in the spectra for occupation factors of the lattice as small as 10^{-3}. Intensity correlations should also be a sensitive probe of multiple scattering effects [1]. Correlation measurements along Bragg directions should also prove interesting. In this situation, the correlation function is expected to reflect the dynamics of individual atoms so that new quantum antibunching phenomena involving optical pumping or the external atomic dynamics may occur [23]. Finally, intensity correlations may prove interesting for the investigation of quantum statistical effects or the investigation of the recently discovered atomic Bose-Einstein condensates [24].

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