Eur. Phys. J. D **1**, 53–56 (1998)

THE EUROPEAN PHYSICAL JOURNAL D

Spontaneous light scattering from propagating density fluctuations in an optical lattice

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Received: 30 January 1997 / Accepted: 9 October 1997

Abstract. We report the observation of resonances in the intensity correlation spectra of a 3D rubidium optical lattice, which we attribute to light scattering from propagating atomic density fluctuations in the lattice. This process is the spontaneous analog of the stimulated scattering mechanism recently described by Courtois *et al.* [1]. We investigate the dependence of the new resonances on the lattice angle and show that they disappear for large angles, thus resolving previous discrepancies on the subject.

PACS. 32.80.Lg Mechanical effects of light on atoms, molecules, and ions – 32.80.Pj Optical cooling of atoms; trapping – 33.50.Dq Fluorescence and phosphorescence spectra

Particle transport in periodic potentials is a subject touching many fields of physics. In contrast to condensed matter systems, which are often complicated because of impurities or interparticle interactions, transport in dilute, ordered and cold atom samples is much easier to model and allows one a clean investigation of elementary processes. In optical lattices [2], laser beams (usually four or six) interact with atoms in such a way that they are trapped at the bottom of sub-micron-sized periodically spaced potential wells. This medium is particularly interesting for the study of transport for several reasons. First, since the atomic potential results from the light shift of the atomic sublevels in a standing wave, many characteristics of the potential (well depth, lattice type, amount of dissipation *etc.*) can be fixed with appropriate choices of beam geometry, polarization, intensity and detuning [3]. Second, the dynamics of atoms moving in these 3D structures may be readily characterized through spectroscopic methods [4–6]. In one previous study, polarization-selective intensity correlation spectroscopy of the scattered light has shown that atomic motion is diffusive along the symmetry axis of a four-beam lattice [6]. But a wide variety of transport properties is expected in optical lattices [7,8]. Of particular interest are newly proposed non-standard mechanisms [9] relying on atomic density fluctuations, *i.e.* density waves, propagating along a particular symmetry axis of a four-beam lattice. These processes manifest themselves in pump-probe spectra through resonances interpretated as *stimulated* Brillouin-like scattering processes and they have been experimentally observed in reference [1].

This kind of ballistic motion raises some still unanswered questions. First, does a *spontaneous* scattering process analog to the stimulated one exist? Second, why did pump-probe experiments reported in reference [10] not show any Brillouin-like resonance? Possible explanations for this discrepancy are the different atomic structures of the two elements used (xenon and cesium) and differences in the lattice geometry. In this paper, we use intensity correlation spectroscopy to answer these two questions. Our technique is sensitive to spontaneous processes and we will show that scattering of the lattice light beams from propagating density waves accounts for certain resonances on the experimental spectra. Moreover, our experimental setup permits a systematic study of the intensity correlation spectra for different lattice angles. Our conclusion is that the discrepancy between the ENS [1] and NIST [10] experiments is due to differing lattice geometries.

We consider a four-beam lin $\perp$ lin optical lattice [3] consisting of two $x-$polarized beams propagating in the $y-z$ plane and making an angle 2θ, and two $y-$polarized beams propagating in the $x-z$ plane, making the same angle (Fig. 1a). In the steady state, most of the atoms are localized at the bottom of the potential wells where they oscillate with the frequencies $\Omega_{x,y,z}$ along the x, y and $z-$axis respectively. Semi-classical numerical simulations [2] applied to atoms with a $J_g = 1/2 \rightarrow J_e = 3/2$ transition moving along the $z-$axis or in the $x-y$ plane allow one to track the motion of the small fraction of unlocalized atoms. Along the $z-$axis atomic transport proceeds essentially through a random hopping process between neighbouring optical potential wells. The dominant transport process along the x or $y-$axis is quite different.

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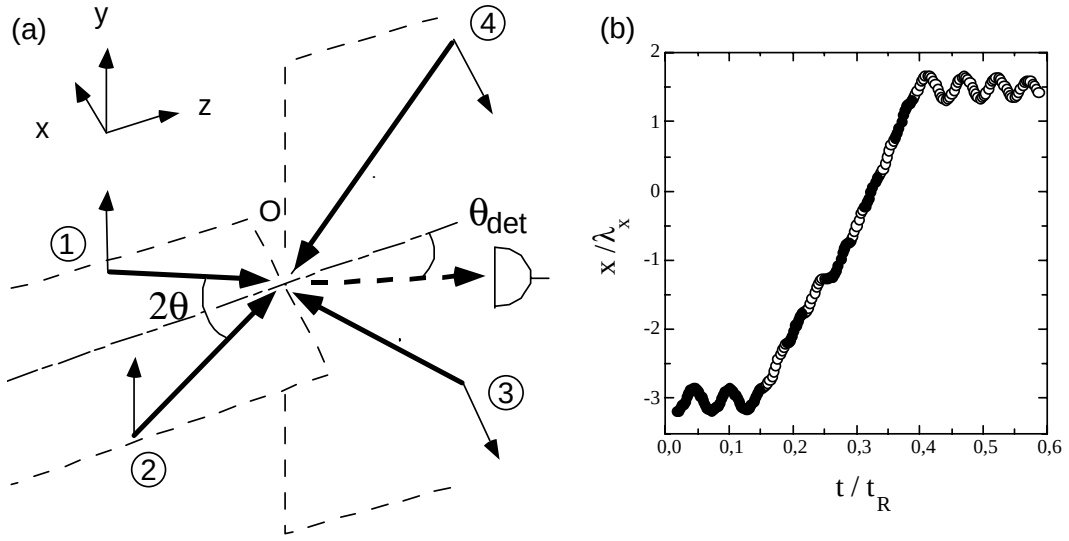

Fig. 1. a) Field configuration of the lattice and detection setup. The detector is located in the $x-z$ plane and the detection angle $\theta_{\rm det}$ varies between 0 and 10°. The lattice angle θ varies between 20 and 40°. b) Computed trajectory of an atom with a $J_{\rm g}=1/2 \rightarrow J_{\rm e}=3/2$ transition: the atom is in the $m_z=-1/2$ ($m_z=1/2$) state when the dot is black (empty). Time is in units of $t_{\rm R}=2\pi/E_{\rm R}$ where $E_{\rm R}=\hbar^2k^2/2m$ is the recoil energy of the atom ($k=2\pi/\lambda$, m is the atomic mass) and the position unit is $\lambda_x=\lambda/\sin\theta$. The potential well depth is 1000 $E_{\rm R}$ and the frequency detuning is -5Γ.

In fact, as can be seen in figure 1b, atoms perform a long-range motion with a quasi-constant average velocity and alternate periodically their internal state [1]. This process is due to a synchronization between optical pumping cycles at the top of a potential well and half oscillations at frequency Ω_x. This behaviour is only observed for the x or y component of atomic motion because the variation of the optical pumping rate is quartic along the x and $y-$axis, so that a spin flip is much more likely to occur at the top of the potential wells than near the bottom, in contrast with the spin flips of atoms moving along the $z-$axis where the optical pumping rate varies quadratically. From a macroscopic point of view, all comparable trajectories of unlocalized atoms lead to density fluctuations having a propagating behaviour either along the x or the $y-$axis. One should note that these fluctuations occur naturally in the optical lattice, in the absence of any additional resonant probe beam. The scattering of the lattice beams by these fluctuations results into specific *spontaneous* scattering processes analogous to spontaneous Brillouin scattering [11]. However, in contrast with acoustic waves in condensed matter, the kind of density wave we are studying here does not involve any interaction between atoms.

We performed a first series of intensity correlation experiments in order to demonstrate the spontaneous analog of stimulated scattering from a density wave. Our experimental setup was described previously [6]. The lattice beams have a typical intensity 5 mW/cm^2 and are tuned to the red side of the $F_{\rm g}=3 \rightarrow F_{\rm e}=4$ component of the D_2 resonance of rubidium (^{85}Rb isotope) around the wavelength $\lambda=780$ nm, the frequency detuning being $\delta=-5\Gamma$ (Γ: natural linewidth of the excited state) for all the reported experimental spectra. The atomic density is 2×10^9 cm^{-3}, which allows one to neglect interactions between atoms. We collect one of the two linearly polarized components (x or y) of the scattered light in a direction making a small angle $\theta_{\rm det}$ with the $z-$axis (see Fig. 1a) in the $x-z$ plane and intensity correlations are recorded using a FFT-spectrum analyzer [12].

We show in figure 2a an example of a spectrum of the $y-$polarized light scattered exactly along the $z-$axis ($\theta_{\rm det}=0°$). Two resonances labeled Ω_z and $\Omega_{\rm S}$ are observed. The Ω_z one is centered around the expected position for the vibrational frequency along the $z-$axis and is associated with spontaneous Raman scattering of the lattice beams by localized atoms oscillating at the bottom of the optical potential wells [6]. Although the $\Omega_{\rm S}$ resonance is located at the position of the vibrational frequency of the atoms moving along the x or $y-$axis, we attribute it to spontaneous scattering from density waves propagating along the $x-$axis instead of vibrational Raman scattering. This interpretation is supported by the following arguments. First, in the geometry of the experiment where light is detected exactly along the $z-$axis, the symmetry prevents any vibrational Raman resonance at the frequency Ω_x. In other words, oscillations perpendicular to the observation direction produce no modulation of the scattered light at the oscillation frequency. Note, however, that even harmonic resonances are excited, as can be seen in the spectrum of localized atoms in figure 2b. By contrast, in the case of off-axis detection (see Fig. 2c), the symmetry is broken and one observes a Raman resonance which is much narrower than the on-axis resonance. Our second argument relies on semi-classical numerical simulations of the intensity correlation spectra, in the case of a $J_{\rm g}=1/2 \rightarrow J_{\rm e}=3/2$ atomic transition and for an atom propagating in the $x-y$ plane [9]. Apart from the Ω_z resonance which cannot be reproduced in this kind of simulation, there is a good qualitative agreement between

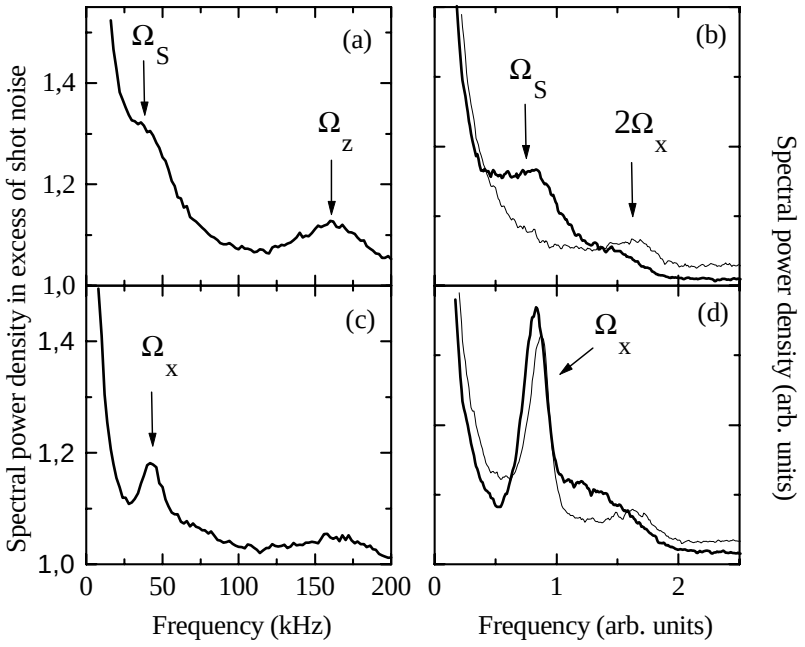

Fig. 2. Experimental (a)-(c) and theoretical (b)-(d) intensity correlation spectra of $y-$polarized light scattered around the $z-$direction. The lattice angle is set to $\theta = 20°$ and the detection angle is $\theta_{\rm det} = 0°$ (a)-(b) or $\theta_{\rm det} = 10°$ (c)-(d). The theoretical curves are simulated in a 2D geometry, for atoms moving in the $x-y$ plane. The thin lines represent the contribution to the spectrum due to localized atoms whose total energy is less than two thirds of the potential well-depth while the thick ones are the spectra calculated with all atoms. The resonance at $2\Omega_x$ is the second harmonic of the vibrational resonance at Ω_x. Note that the normalizations of the thin and thick theoretical curves are not the same.

the theoretical spectra in figure 2b and 2d (thick lines) and the experimental ones in figure 2a and 2c. The simulation is especially interesting since it allows one to delete the contribution of unlocalized atoms (*i.e.* atoms performing the same kind of trajectory as the one represented in Fig. 1b) to the spectra. The resulting spectra (thin lines in Fig. 2b and 2d) clearly show that the off-axis vibrational Raman resonance arises from well localized atoms whereas the on-axis $\Omega_{\rm S}$ resonance is associated with unlocalized atoms. A third bit of evidence confirming the nature of the resonance at $\Omega_{\rm S}$ is its sensitivity to the detection polarization. It is observed exclusively in the $y-$polarized component of the scattered light whereas the Raman resonance is present for both x and y components. This is related to the fact that the contribution to the $\Omega_{\rm S}$ resonance from $y-$polarized beams 1 and 2 (see Fig. 1a) through *forward* scattering is much less Doppler-broadened by the $z-$component of the atomic motion than the contribution from $x-$polarized beams 3 and 4, which is associated to *backward* scattering. Since scattering from density waves keeps the polarization of the incoming beams preserved, the $\Omega_{\rm S}$ component of the scattered light is thus $y-$polarized [13].

In order to resolve the ENS-NIST discrepancy, we investigated the dependence of the spectra on the lattice angle θ. This is an important parameter for the potential's topography (the distance between two potential wells is $\lambda/(2\sin\theta)$ along the $x-$axis and $\lambda/(4\cos\theta)$ along the $z-$axis) but its influence on transport properties has not yet been investigated. Intensity correlation spectra for different lattice and detection angles are shown in figure 3. Whereas the vibrational Raman resonances are observed off-axis for any lattice angle, the $\Omega_{\rm S}$ resonance is broadened to the point where it is not visible anymore when the lattice angle goes from $\theta = 20$ to $40°$. This somewhat surprising phenomenon is an important feature of the difference between the Raman resonances and the resonances induced by density waves in optical lattices. It is connected with the nature of the involved atomic dynamics (local *vs.* non local). As for the polarization effect we described earlier, our interpretation of the disappearance of the $\Omega_{\rm S}$ resonance at large lattice angles is related to the Doppler broadening by the $z-$component of the atomic motion. As mentioned earlier, the spectral features due to density waves essentially originate from the forward scattering of beams 1 and 2. For this reason, the field scattered by an atom performing a trajectory as in figure 1b is proportional to the phase factor $e^{ik(1-\cos\theta)\Delta z(t)}$, where $k = 2\pi/\lambda$ and $\Delta z\,(t)$ is the atomic displacement along the $z-$axis during time t. Whereas, for small lattice angles, the $z-$displacement during a large step along the $x-$axis is too small to make the complex exponential vary substantially, it is not the case for large values of θ. In this situation, the $z-$component of the motion makes the exponential vary randomly during a large step and is therefore responsible for a wash-out of the spectral features related to the $x-$motion, *i.e.* the resonance at $\Omega_{\rm S}$. This phenomenon accounts for the discrepancy between the NIST and ENS results: in the ENS experiment, the lattice angle was $\theta = 30°$, an angle at which we also observe the resonance, whereas the NIST angle ($\theta = 45°$) is even larger than the one at which our resonance was not visible anymore.

Having demonstrated the presence of propagating density fluctuations, it is natural to wonder how they affect the nature of the transport. Preliminary numerical simulations in the $x-y$ plane show that it is still diffusive, but that the spatial diffusion coefficient is much bigger than the one computed along the $z-$axis. This is because the type of motion we have described here results in random walks with much larger mean step sizes. It is in this sense that we believe that the density waves dominate

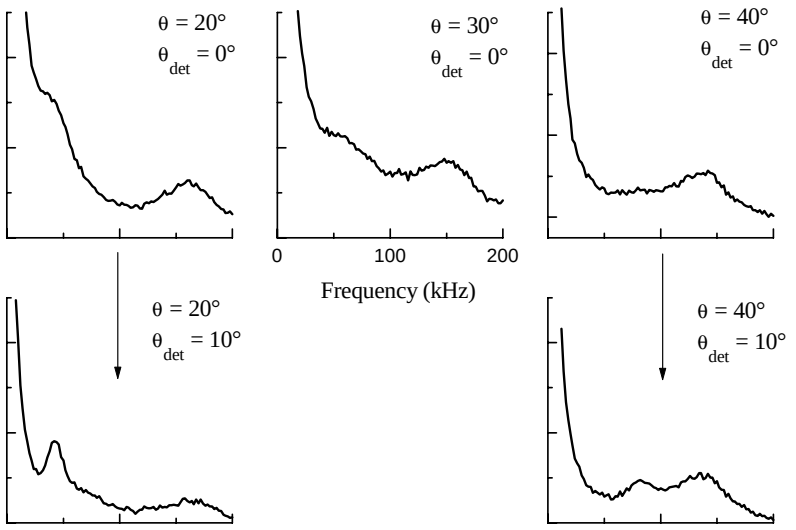

Fig. 3. Intensity correlation spectra of the $y-$polarized light for various angles of the lattice θ and of the detector $\theta_{\rm det}$. The $\Omega_{\rm S}$ resonance is clearly visible on axis for small θ angles while it is so broadened for $\theta = 40^\circ$ that it is not visible anymore. By contrast, a Ω_x Raman vibrational resonance is present for an off-axis detection whatever θ.

the transport in the $x - y$ plane. Thus, direct diffusion measurements such as reported in reference [14] could give interesting information. In particular, although the resonances are washed out at large lattice angles, density waves may still be present, yielding anisotropic diffusion coefficients even at large (*e.g.* $\theta = 45^\circ$) lattice angle. Various other transport phenomena are expected, especially at the border between classical and quantum transport [8,15].

We are grateful to A. Ezzine De Blas and G. Birkl for help in the acquisition of the data.

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