Coherent delocalization of atomic wavepackets in driven lattice potentials

V. V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni§, M. L. Chiofalo†, G. M. Tino

Dipartimento di Fisica and LENS - Università di Firenze, CNR-INFM, INFN - Sezione di Firenze, via Sansone 1, 50019 Sesto Fiorentino, Italy
§ Department of Chemistry and Physics of Materials - University of Brescia, and LENS, Italy
† CNISM and INFN, Classe di Scienze, Scuola Normale Superiore, Pisa, Italy

Atomic wavepackets loaded into a phase-modulated vertical optical-lattice potential exhibit a coherent delocalization dynamics arising from intraband transitions among Wannier-Stark levels. Wannier-Stark intraband transitions are here observed by monitoring the in situ wavepacket extent. By varying the modulation frequency, we find resonances at integer multiples of the Bloch frequency. The resonances show a Fourier-limited width for interrogation times up to 2 seconds. This can also be used to determine the gravity acceleration with ppm resolution.

PACS numbers: 42.50.Vk, 03.75.Lm, 03.75.-b, 04.80.-y

Controlling quantum transport through an external driving field is a basic issue in quantum-mechanics [1], yet with relevance to fundamental physics tests and precision measurements [2] as well as to applications, such as the design of novel miniaturized electronic [3] and spintronic [4] devices. Quantum transport control has however gained a renewed interest with the advent of optical lattices for ultracold atoms. These are in fact increasingly employed to realize laboratory models for solid state crystals. The accurate tunability of atomic parameters such as the temperature, the strength of interaction and the dimensionality, bring ultracold atoms samples within the extreme quantum regime sought for precise quantum transport control [5], gravity measurements [6, 7, 8], and metrology [9].

Atoms transport control in optical lattices depends in general on the form of the external driving field [10] and, in particular, on its strength and frequency whose values may be chosen so as to span from transport enhancement [11] to suppression [12]. Within this context Bloch oscillations [13], Landau-Zener tunnelling [14], and resonant tunnelling enhancement in tilted optical lattices [15] are certainly worth being mentioned. Likewise important manifestations comprise transport in the well-known kicked-atom model where quantum transport could actually be engineered both by semiclassical [16] and by purely quantum [17, 18] effects.

In this Letter we experimentally demonstrate for the first time Wannier-Stark intraband transitions in lattice potentials, a phenomenon which has been studied theoretically [19, 20] but has never been observed before. Our lattice potential has the form:

\[ U(z,t) = mgz + \frac{U_0}{2} \cos \left[ 2k_L(z - z_0 \cos(2\pi \nu_M t)) \right] \]  

(1)

where \( mgz \) is the gravity potential, \( U_0 \) is the lattice depth, \( k_L \) is the optical lattice wavevector while \( z_0 \) and \( \nu_M \) are respectively the phase-modulation amplitude and frequency.

Intraband transitions between Wannier-Stark levels give rise to coherent delocalization effects which we observe through a coherent ballistic expansion of an initially well localized atomic wavepacket. Wannier-Stark intraband tunneling, unlike the more familiar Landau-Zener tunnelling occurring between different bands [14, 15], is not affected by typical decoherence mechanisms occurring in the Landau-Zener interband case, such as line broadening due to the transverse profile of the lattice potential. Furthermore we work with an atomic species remarkably robust against decoherence processes [21, 22], which enables us to observe transitions up to five neighboring Wannier-Stark levels, corresponding to a coherently driven tunneling across five neighboring sites. Owing to such a quantum robustness the resonance spectra exhibit Fourier-limited widths over excitation times of the order of seconds. Such a high-resolution enables us, in turn, to measure the local acceleration of gravity with ppm relative precision.
We start by trapping and cooling about $2 \times 10^7 \text{ } ^{88}\text{Sr}$ atoms at 3 mK in a magneto-optical trap (MOT) operating on the $^1S_0-^1P_1$ resonance line at 461 nm \[8, 22\]. The temperature is further reduced by a second cooling stage in a red MOT operating on the $^1S_0-^3P_1$ narrow transition at 689 nm. Finally we obtain $\sim 5 \times 10^5$ atoms at 1 \( \mu \)K. This preparation phase takes about 2.5 s. Then, the red MOT is switched off and a one-dimensional optical lattice is switched on adiabatically in 150 \( \mu \)s. The lattice potential is originated by a single-mode frequency-doubled Nd:YVO\(_3\) laser ($\lambda_L = 532$ nm) delivering up to 170 mW on the atoms with a beam waist of 100 \( \mu \)m. The beam is vertically aligned and retro-reflected by a mirror producing a standing wave with a period $\lambda_L/2 = 266$ nm. The corresponding photon recoil energy is $E_R = h^2/2m\lambda_L^2 = k_B \times 381$ nK, and the maximum lattice depth is $20 E_R$. In order to modulate the phase of the lattice potential, the retro-reflecting mirror is mounted on a piezo-electric transducer (PZT) which is driven at frequency $\nu_M$ by a synthesized frequency generator.

The voltage applied to the PZT allows to modulate the position of the lattice potential by up to 6 sites peak-to-peak. The electronic-to-optical transfer function was verified to be linear on the applied voltage and substantially independent from the considered frequency. For a lattice potential depth corresponding to $20 E_R$, the trap frequencies are 71.5 kHz and 86 Hz in the longitudinal and and radial direction, respectively. Before being transferred to the optical lattice, the atomic cloud in the red MOT has a disk shape with a vertical size of 12 \( \mu \)m rms. In the transfer, the vertical extent is preserved and we populate about 50 lattice sites with $10^5$ atoms. After letting the atoms evolve in the optical lattice, we measure in situ the spatial distribution of the sample by absorption imaging of a resonant laser beam detected on a CCD camera. The spatial resolution of the imaging system is 7 \( \mu \)m.

An atomic wavepacket moving in an optical lattice potential is characterized by an energy and a quasi-momentum belonging to a specific band. Owing to the potential translational symmetry, the wave-packet propagates typically unbound through the lattice. Under the effect of a constant force $f_0$, however, the band splits into a series of Wannier-Stark resonances separated by integer multiples of the Bloch frequency $\nu_B = \lambda_L f_0/2h$. In our case $f_0$ is the gravity frequency which breaks the translational symmetry suppressing atomic tunneling between lattice sites, hence localizing the wavepacket, and $\nu_B \approx 575$ Hz. We observe indeed this localization in the absence of modulation ($z_0 = 0$) or for modulation frequencies $\nu_M$ far from Wannier-Stark resonances. Conversely, wavepacket delocalization, assessed through an increase of the atomic distribution width, sets in instead for modulation frequencies $\nu_M = \nu_B$, as shown in the inset of Fig. 2 or multiple integers of $\nu_B$ suggesting that tunneling occurs not only between nearest neighboring sites ($n=1$) but also between sites that are $n$ lattice periods apart ($n=2, 3, 4$). The atomic cloud spreads along the lattice axis and its width is plotted in Fig. 2 for increasingly larger modulation times. At resonance and after a transient due to the initial extent, the width grows linearly in time undergoing a ballistic expansion as due to coherent site-to-site tunneling. Broadening proceeds at different velocities which we report in Tab. 1. These are determined, for each $n$, by fitting the width with the function $\sigma_n(t) = \sqrt{\sigma_0^2 + v_n^2 t^2}$, which is the convolution of two gaussians: one accounting for the initial atomic distribution, the second accounting for the wavepacket expansion. The delocalization slows-down with increasing $n$ due to a sharp reduction of the tunneling rate with increasing separation between the initial and final Wannier-Stark states. If $v_n \approx (n\lambda_L/2)\gamma_n$, is the wavepacket broadening velocity associated with the $n$–th harmonic modulation, the relevant tunneling rate $\gamma_n$ across $n$ sites, as reported in Tab. 1 is seen to decrease exponentially roughly as $3^{-n}$.
the resonance linewidth is purely Fourier limited. Spurious incoherent processes may limit the coherence time of the system on a timescale longer than 15 s, suggesting that the delocalization dynamics is largely determined by coherent tunnelling. In fact, given the initial size of the sample (12 μm vertical extent equivalent to 50 lattice sites) and the resolution of the imaging system, the driving induces a broadening of the atomic distribution over a large number of lattice sites. If this were to be due to incoherent tunnelling of the atoms between the lattice sites, such as in a random walk process, we would expect a minimum resonance width equal to the Fourier limit multiplied by the total number of jumps. A broadening over more than 50 lattice sites, as we observe, would yeald a resonance linewidth orders of magnitude larger than the one we observe in the experiment. In case of a random walk in the lattice sites, at long times we would further expect a spatial broadening increasing as the square root of the time, again this is not consistent with our observations.

These Fourier-limited resonances turn out to be a powerful tool to measure accelerations with high accuracy. Similarly to the first harmonic, higher harmonics also exhibit a Fourier limited resonance linewidth for an interaction time longer than 2 s. In Fig. 4 we compare the resonance shape at νB with those at 2νB and 4νB for a 2 s excitation time. The different resonances are quite similar in shape and within the error bars we find that they remain Fourier limited regardless of the order of the harmonic. Previous applications of Bloch frequency measurements to determine the gravity acceleration had a resolution limited by the quality factor νB/δν of the line (where δν was the Fourier limit set either by the coherence time [6], or the lifetime of the sample [8]), and by the signal-to-noise ratio which depended also on how much the temperature of the atoms is lower than the re-
coil energy. It is worth noting that in our case the initial temperature is about twice the recoil.

Our results can be exploited to improve acceleration measurements resolution owing to the absence of a specific requirement on the sample temperature with respect to the photon recoil energy and to the possibility of measuring higher harmonics of $\nu_B$ at a constant resonance linewidth (see Fig. 4). Working with atoms at a temperature nearly at or above the recoil temperature reduces substantially the technical constraints on sample preparation, making more atoms available in the test sample, and making possible the employ of additional atomic or molecular species which can not be cooled to sub-recoil temperatures. In addition, working at higher harmonics with a constant resonance linewidth allows to improve the line quality factor by the index of the considered harmonic. This improves the final resolution on the acceleration measurement correspondingly. Modulating over $2 \pi$ the line quality factor by the index of the considered harmonic temperatures. In addition, working at higher harmonics to the photon recoil energy and to the possibility of measuring higher harmonics of $\nu_B$. It is worth noting that in our case the initial 200 nm wavepacket width to more than $10 \mu m$. Under our experimental conditions the wavepacket expansion increases linearly with the lattice modulation amplitude, though possible nonlinearities in the response may arise and will be the object of future investigations. Coherent intraband resonant tunneling turns out to be quite practical for increasing the sensitivity of force measurements with sub-millimeter spatial resolution as in the case of Casimir forces and in Newtonian gravity at small distances. It may also be useful for atomtronic devices such as parallel quantum atomic couplers.

We thank G. C. La Rocca for fruitful discussions, F. S. Pavone for the lending of part of the equipment, and R. Ballerini, M. De Pas, M. Giuntini, A. Hajeb, A. Montori for technical assistance. This work was supported by LENS, INFN, EU (under contract RII3-CT-2003 506350 and the FINAQS project), ASI and Ente CRF.

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