Quantum devices using ultracold atoms show extraordinary features. Atom interferometry is used for precision inertial sensors \cite{1, 2}, to measure fundamental constants \cite{3, 4, 5}, and testing relativity \cite{6}. The small size enables precision measurements of forces at micrometer scale. This is a challenge in physics for studies of surfaces, Casimir effects, and searches for deviations from Newtonian gravity predicted by theories beyond the standard model. We report on the observation of Bloch oscillations on the unprecedented time scale of several seconds. The experiment is carried out with ultra-cold bosonic strontium-88 loaded into a vertical optical standing wave. The negligible atom-atom elastic cross section and the absence of spin makes \(^{88}\text{Sr}\) an almost ideal Bose gas insensitive to typical mechanisms of decoherence due to thermalization and to external stray fields. The small size enables precision measurements of forces at micrometer scale. This is a challenge in physics for studies of surfaces, Casimir effects, and searches for deviations from Newtonian gravity predicted by theories beyond the standard model.

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Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale

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Quantum devices using ultracold atoms show extraordinary features. Atom interferometry is used for precision inertial sensors \cite{1, 2}, to measure fundamental constants \cite{3, 4, 5}, and testing relativity \cite{6}. The small size enables precision measurements of forces at micrometer scale. This is a challenge in physics for studies of surfaces, Casimir effects \cite{7}, and searches for deviations from Newtonian gravity predicted by theories beyond the standard model \cite{8, 9}. Here we show that using laser-cooled strontium atoms in optical lattices, persistent Bloch oscillations are observed for \(t \simeq 10\) s, and gravity is determined with ppm precision on micrometer scale. The insensitivity to stray fields and collisions makes Sr in optical lattices, a candidate also for future clocks \cite{10}, a unique sensor for small-scale forces with better performances and reduced complexity compared to proposed schemes using degenerate Bose \cite{11} or Fermi \cite{12} gases. This improves the feasibility of new experiments on gravity in unexplored regions.

The confinement of ultracold atoms in optical lattices, regular structures created by interfering laser beams where the atoms are trapped by the dipole force, provides clean model systems to study condensed-matter physics problems \cite{13}. In particular, Bloch oscillations were predicted for electrons in a periodic crystal potential in presence of a static electric field \cite{14} but could not be observed in natural crystals because of the scattering of electrons by the lattice defects. They were directly observed using atoms in an optical lattice \cite{15}.

In our experiment, laser-cooled \(^{88}\text{Sr}\) atoms are trapped in a 1-dimensional vertical optical lattice. The combination of the periodic optical potential and the linear gravitational potential gives rise to Bloch oscillations at frequency \(\nu_B\) given by

\[
\nu_B = \frac{mg\lambda_L}{2h}
\]

where \(m\) is the atomic mass, \(g\) is the acceleration of gravity, \(\lambda_L\) is the wavelength of the light producing the lattice, and \(h\) is Planck's constant. Since both \(\lambda_L\) and \(m\) are well known, the overall force along the lattice axis can be determined by measuring the Bloch frequency \(\nu_B\). In order to do a force measurement with given interrogation time, the atomic wavefunction has to undergo a coherent evolution on the same time timescale. The most common effects limiting the coherence time for ultracold atoms are perturbations due to electromagnetic fields and atom-atom interactions. \(^{88}\text{Sr}\) is in this respect a good choice because in the ground state it has zero orbital, spin and nuclear angular momentum that makes it insensitive to stray electric and magnetic fields that otherwise need to be shielded. In addition, \(^{88}\text{Sr}\) has remarkably small atom-atom interactions \cite{16}: this prevented so far the achievement of Bose-Einstein condensation for this atom \cite{16, 17} but becomes an important feature in experiments where collisions lead to a loss of coherence limiting the measurement time and the potential sensitivity.

The experimental setup used in this work is schematically shown in Fig. 1. The method used to produce ultracold Sr atoms was already described in \cite{18}. The experiment starts with trapping and cooling \(\sim 5 \times 10^7\) \(^{88}\text{Sr}\) atoms at 3 nK in a magneto-optical trap (MOT) operating on the \(^{1}\text{S}_0 - ^{1}\text{P}_1\) blue resonance line at 461 nm. The temperature is then further reduced by a second cooling stage in a red MOT operating on the \(^{1}\text{S}_0 - ^{3}\text{P}_1\) narrow transition at 689 nm and finally we obtain \(\sim 5 \times 10^5\) atoms at 400 nK. After this preparation phase, that takes about 500 ms, the red MOT is switched off and a one-dimensional optical lattice is switched on adiabatically in 50 µs. The lattice potential is originated by a single-mode frequency-doubled Nd:YVO4 laser (\(\lambda_L = 532\) nm) delivering up to 350 mW on the atoms with a beam waist of 200 µm. 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. As expected from band theory \cite{16}, the amplitude of the oscillation in momentum space decreases as the lattice depth...
is increased. This suggests that in order to measure the Bloch frequency with maximum contrast the intensity of the lattice laser should be reduced. On the other hand, reducing the intensity results in a loss in the number of trapped atoms because of the smaller radial confinement. For this reason, we used a lattice depth of $10 \, E_R$. For a lattice potential depth corresponding to $10 \, E_R$, the trap frequencies are $50 \, kHz$ and $30 \, Hz$ in the longitudinal and radial direction, respectively. Before being transferred in the optical lattice, the atom cloud in the red MOT has a disk shape with a vertical size of $12 \, \mu m$ rms. In the transfer, the vertical extension is preserved and we populate about $100$ lattice sites with $2 \times 10^5$ atoms with an average spatial density of $\sim 10^{11} \, cm^{-3}$. After letting the atoms evolve in the optical lattice, the lattice is switched off adiabatically and we measure the momentum distribution of the sample by a time-of-flight measurement, after a free fall of $12 \, ms$, using a resonant probe laser beam and absorption imaging on a CCD camera.

Fig. 1 illustrates the loss of visibility of the two-component momentum distribution at the Bragg reflection. The persistent visibility of the bimodal distribution on more than $10^4$ atoms directly reflects the single atom coherent evolution on seconds timescale, while the reduction in the signal-to-noise ratio is due to the $5 \, s$ $e^{-1}$ lifetime of the sample limited essentially by residual background vapor pressure in the MOT chamber. It is worth noting that the $5 \, s$ lifetime is not inconsistent with the observed $12 \, s$ coherence time: the atoms that collide with the room temperature background vapor are ejected from the $\mu K$ deep lattice potential and do not contribute to the measured signal.

The micrometric spatial extension of the atomic cloud in the vertical direction, and the possibility to load it into the optical potential at micrometric distance from a surface, makes the scheme we demonstrated particularly suitable for the investigation of forces at small spatial scales. The possibility of investigating the gravitational force at small distances by atomic sensors was proposed in [21], discussed in detail in [22], and preliminarily demonstrated in [23]. Deviations from the Newtonian law are usually described assuming a Yukawa-type potential.
FIG. 2: Time-of-flight images of the atoms recorded for different times of evolution in the optical lattice potential after switching-off the MOT. In the upper part of each frame, the atoms confined in the optical lattice perform Bloch oscillations for the combined effect of the periodic and gravitational potential. The average force arising from the photon recoils transferred to the atoms compensates gravity. In the lower part, untrapped atoms fall down freely under the effect of gravity.

FIG. 3: Bloch oscillation of $^{88}$Sr atoms in the vertical 1-dimensional optical lattice under the effect of gravity. Two quantities are extracted from the analysis of the data: The average vertical momentum of the lower peak (a) and the width of the atomic momentum distribution (b). From the fit of the data in b, a Bloch frequency $\nu_B = 574.568(3)$ Hz is obtained with a damping time $\tau \sim 12$ s for the oscillations.

$$V(r) = -G \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

where $G$ is Newton’s gravitational constant, $m_1$ and $m_2$ are the masses, $r$ is the distance between them. The parameter $\alpha$ gives the relative strength of departures from Newtonian gravity and $\lambda$ is its spatial range. Experiments searching for possible deviations have set bounds for the parameters $\alpha$ and $\lambda$. Recent results using micro-cantilever detectors lead to extrapolated limits $\alpha \sim 10^4$ for $\lambda \sim 10 \, \mu m$ and for distances $\sim 1 \, \mu m$ it was not possible to perform direct experiments so far.

The small size and high sensitivity of the atomic probe allows a direct, model-independent measurement at distances of a few $\mu m$ from the source mass with no need for modeling and extrapolation as in the case of macroscopic probes. This allows to directly access unexplored regions in the $\alpha - \lambda$ plane. Also, in this case quantum objects are used to investigate gravitational interaction.

Our results indicate that our Sr atoms when brought close to a thin layer can be used as probe for the gravitational field generated by the massive layer. If we consider, in fact, a material of density $\rho$ and thickness $d$, the added acceleration of gravity in proximity of the source mass is $a = 2\pi G \rho d$ so that when $d \sim 10 \, \mu m$ and $\rho \sim 10 \, g/cm^3$ as for tungsten crystals the resulting acceleration is $a \sim 4 \times 10^{-11} \, ms^{-2}$. Measuring $\nu_B$ at a distance $\sim 4 \, \mu m$ away from the surface would allow to improve the constraint on $\alpha$ by two orders of magnitude at the corresponding range $\lambda \sim 4 \, \mu m$. Spurious non-gravitational effects (Van der Waals, Casimir forces), also present in other experiments, can be reduced by using an electrically conductive screen and performing differential measurements with different source masses placed behind it. Moreover, by repeating the same measure with the 4 stable isotopes (3 bosons, 1 fermion, with atomic mass ranging from 84 to 88), hence modulating the gravity
potential through the probe mass instead of the source mass, we can further discern among gravitational and QED forces.

In conclusion, we observed persistent Bloch oscillations of weak-interacting bosonic Sr atoms in a vertical optical lattice for a time longer than 7 s, with more than 8000 photon momenta coherently transferred to the atoms. In addition to the intrinsic interest of the observed effect, these results can be important for different experiments as, for example, in the measurement of fundamental constants. The small size and high sensitivity of the new atomic sensor are important for the investigation of small spatial-scale forces as in atom-surface interactions, surface-induced decoherence, Casimir-Polder interaction, and for the search of recently predicted deviations from the Newtonian gravitational law at the micrometer scale. Crucially enough, when compared with other proposals using Bose-Einstein condensates and degenerate Fermi gases as probe, our scheme is not affected by collisional and mean-field degrading effects. This enables us to reach much longer observation times and higher sensitivities. In addition, our atoms are insensitive to stray electric and magnetic fields and an all-optical procedure is used for the cooling and the confinement. The preparation of the ultracold atom sample takes less than 0.5 s, which is negligible with respect to measurement duration, and much faster the typical tens of seconds needed for a cycle of evaporative and sympathetic cooling when using degenerated gases.

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