

Atom Interferometry with Trapped Fermi Gases

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We realize an interferometer with an atomic Fermi gas trapped in an optical lattice under the influence of gravity. The single-particle interference between the eigenstates of the lattice results in macroscopic Bloch oscillations of the sample. The absence of interactions between fermions allows a time-resolved study of many periods of the oscillations, leading to a sensitive determination of the acceleration of gravity. The experiment proves the superiority of noninteracting fermions with respect to bosons for precision interferometry and offers a way for the measurement of forces with microscopic spatial resolution.

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In recent years ultracold atomic gases have been successfully employed to perform high-precision measurements with interferometric methods [1–3]. The sensitivity of an interferometer usually increases with the brightness of the source. The advent of Bose-Einstein condensates (BEC) was expected to produce in atom interferometry the same dramatic progress faced by photon interferometry after the invention of the laser. A BEC is the brightest atom source with all the particles in the same quantum state, hence leading to an increase of the contrast of the interference signal [3–7]. However, differently from photons, atoms interact and this can dramatically affect an interferometric measurement, giving rise to a shift or decay of the signal. To avoid this problem high-precision interferometry in combination with BECs has been performed so far only with samples in free fall where interactions are weaker, but the observation times are limited [3]. On the other hand, collisions are suppressed in an ultracold sample composed of identical fermions. However, the same Pauli principle that forbids collisions also limits the phase-space density of fermions to unity. The question is now whether this constitutes an obstacle to precise interferometry.

In the present work we observe the interference of fermionic atoms trapped in the sites of a one-dimensional vertical optical lattice. The gravitational energy difference between the eigenstates of the system results in a periodic oscillation of the macroscopic interference pattern, also known as Bloch oscillations [8]. The absence of interactions between atoms allows the oscillations to proceed with high contrast for many periods. We repeat the same experiment with a BEC: in this case the interference shows a lower effective contrast and decays rapidly because of interactions. We show how interferometry with trapped fermions gives the possibility of a sensitive measurement of forces with spatial resolution at the micrometer scale.

We employ fermionic ^{40}K atoms, which are brought to quantum degeneracy by sympathetic cooling with bosonic ^{87}Rb atoms [9]. Both species are held in a harmonic

magnetic potential and have a horizontal cigar shape. The bosons are completely removed from the trap at the end of the evaporation, leaving a pure Fermi gas of about 3×10^4 atoms spin polarized in the $F = 9/2$, $m_F = 9/2$ state. The typical temperature is $T = 0.3T_F$, where $T_F = 330$ nK is the Fermi temperature. We then switch on adiabatically a lattice created by a retroreflected laser beam aligned along the vertical direction. The wavelength of the lattice laser is far detuned to the red of the optical atomic transitions ($\lambda = 873$ nm) to avoid photon scattering. The depth of the potential can be adjusted in the range $U = 1-4E_R$, where $E_R = h^2/2m\lambda^2 = k_B \times 310$ nK is the recoil energy. Since $k_B T_F \approx E_R$, at the low temperatures of the experiment the atoms are loaded mostly in the first Bloch band of the lattice. The Gaussian profile of the lattice beams provides also a confinement of the atoms in the horizontal directions. Using different intensities for the two beams we obtain a radial depth of such optical trap of about $10E_R$, with a typical trapping frequency of $2\pi \times 30$ s $^{-1}$.

To observe the interference we suddenly switch off the magnetic trap and let the atoms evolve in the combined lattice and gravitational potential. In our range of lattice depths only the atoms in the first band are trapped against gravity, while the small fraction in excited bands falls down freely. The energy spectrum of such a combined potential is the well-known Wannier-Stark ladder of states [10], which is equally spaced by $\Delta E = mg\lambda/2$. For the typical lattice depth $U = 2E_R$ each of the Wannier-Stark states extends over about ten lattice sites. The vertical distribution of the atomic cloud has a Gaussian envelope with a full width at $1/e^2$ of 55 μm , and therefore extends over about 125 sites [11]. Radially, the atoms occupy the harmonic oscillator states of the trap, with a full width of 200 μm . Each of the atoms in the cloud is therefore prepared in a coherent superposition of several Wannier-Stark states. Because of their energy difference, neighboring states evolve in time with a phase difference $\Delta\phi = \Delta Et/\hbar$, and their interference pattern is periodic in time, with a period $T_B = h/\Delta E$.

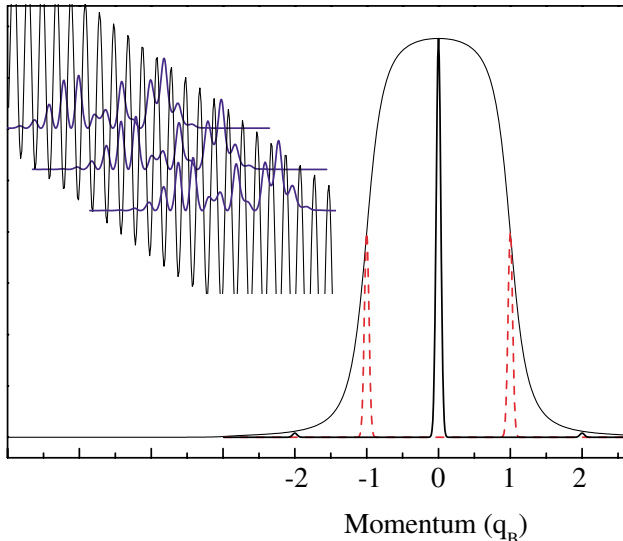


FIG. 1 (color online). Momentum distribution of a coherent superposition of Wannier-Stark states. Although the single state fills completely the first Brillouin zone (thin line), the interference of several states gives narrow momentum peaks. Shown are the cases of a phase difference between successive states of $\Delta\phi = 0$ (continuous line) and $\Delta\phi = \pi$ (dashed line). The inset shows the square of Wannier-Stark wave functions calculated for ^{40}K atoms in a lattice with $U = 2E_R$ subjected to gravity (for clarity, the states shown are separated by four lattice sites).

In particular, the interference of Wannier-Stark states results in equally spaced peaks in momentum space that move with constant velocity $\dot{q} = mg$. The peaks spacing is the inverse of the spatial period of the lattice and can be written as $2q_B$, where $q_B = h/\lambda$ is the Bragg momentum. Therefore only one or two peaks appear at the same time in the first Brillouin zone of the lattice $[-q_B, +q_B]$, as shown in Fig. 1.

To study the momentum distribution in the trap, we release the cloud from the lattice, thus stopping the evolution of the interference pattern at a given time. We then probe the cloud by absorption imaging after a 8-ms ballistic expansion, which maps the initial momentum distribution into a position distribution. Actually, the lattice depth is lowered to zero in about $50 \mu\text{s}$, a time scale longer than the oscillation period of the atoms in each lattice well. The adiabatic release allows us to study the evolution of the momentum in the first Brillouin zone.

Figure 2 shows the time evolution in q space detected in the experiment. We can clearly see the vertical motion of the peak of the distribution, initially centered in $q = 0$ at $t = 2$ ms. It gradually disappears as it reaches the lower edge of the Brillouin zone at $t = 2.8$ ms, while a second peak builds up at the upper edge and then scans the whole Brillouin zone as the first one. The periodicity of this interference pattern amounts to about 2.3 ms, in agreement with the expected $T_B = 2h/mg\lambda$.

A quantitative description of the observations becomes particularly easy in a semiclassical approach. Here the atomic cloud is described as a single wave packet that moves uniformly in q space under the influence of gravity and is gradually reflected each time it reaches the lower band edge. These phenomena are the well-known Bloch oscillations [8,12], which have been studied for a variety of systems including cold atoms in accelerated horizontal lattices [13,14], or BECs tunneling out of a shallow lattice under gravity [5]. Note that at the zone edge there is a finite probability of Zener tunneling to the continuum [15]. However, we suppress the tunneling by using a sufficiently tight lattice, different from the study performed in [5]. This allows us to keep the atoms oscillating in the lattice for very long times.

If we follow the vertical position of the peak of the distribution in Fig. 2, we get the periodic motion shown in Fig. 3, which has the peculiar sawtooth shape expected for Bloch oscillations [16]. We can follow the oscillations for more than 250 ms, that correspond to about 110 Bloch periods, and only at later times the contrast is degraded by a broadening of the momentum distribution. This is to our knowledge the longest lived Bloch oscillator observed so far in all kinds of physical systems. The reduction of contrast is illustrated in Fig. 4(a). For our parameters ($E_F \approx E_R$) the initial half-width of the wave packet is $\delta q \approx 0.75q_B$, which fulfills the requirement of a momentum distribution narrower than the first Brillouin zone of the lattice to observe the interference. During Bloch oscillations the distribution broadens steadily and eventually fills completely the first Brillouin zone.

It is interesting to compare the behavior of fermions and bosons to study the role of interactions. In our apparatus we can simply repeat the experiment with a BEC of rubidium atoms. We use a sample of typically 5×10^4 atoms, at temperatures $T < 0.6T_c$, which is transferred into the lattice with the same procedure described above for the Fermi gas. The lattice depth is in the range $2-4E_R$

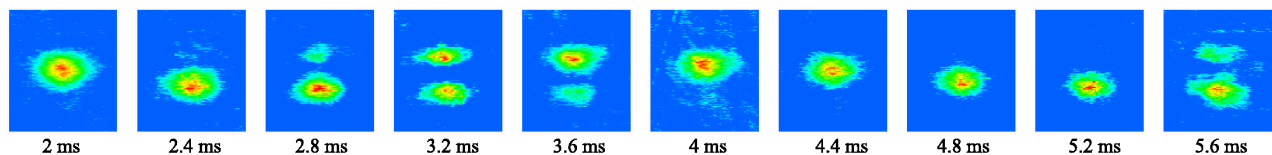


FIG. 2 (color online). Evolution of the interference pattern of the Fermi gas for increasing holding times in the vertical lattice. The spatial distribution of the cloud detected after 8 ms of free expansion reflects the momentum distribution in the trap at the time of release.

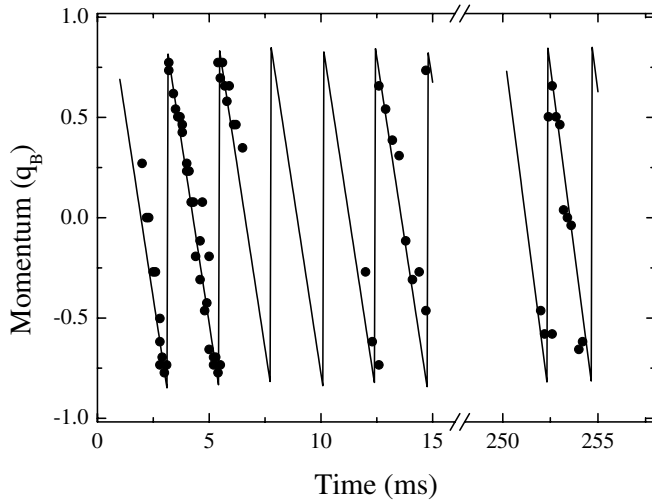


FIG. 3. Bloch oscillation of the Fermi gas driven by gravity: the peak of the momentum distribution of the sample scans periodically the first Brillouin zone of the lattice. More than 100 oscillations can be followed with large contrast.

(for rubidium $E_R = k_B \times 150$ nK). The phenomenology that we observe is analogous to that found for fermions: the momentum distribution performs Bloch oscillations with a period which is now $T_B \approx 1.2$ ms because of the different mass. Two striking differences however appear, as shown in Fig. 4(b). First of all, at very short times the momentum width of the BEC is comparable to q_B and therefore even larger than that of the Fermi gas. This result, that may seem in contrast with the expectation of a much narrower momentum distribution for the BEC, is actually the consequence of the unavoidable conversion of interaction energy into kinetic energy at the release from the lattice. Also the evolution in the lattice is affected by interactions, which tend to destroy the interference between the Wannier-Stark states occupied by the condensate. We detect this effect as a very rapid broadening of the momentum distribution, which tends to wash out the contrast of the Bloch oscillations. This phenomenon has already been the object of experimental and theoretical investigations [17–19]. As shown in Fig. 4, in a lattice with depth $U = 2E_R$, after typically 4 ms the momentum distribution fills completely the Brillouin zone. We have checked that the decay time for the contrast gets shorter with an increasing lattice depth and radial confinement, as expected because of the larger density of the sample. We have measured the longest decay time of about 10 ms, with a lattice depth of $1.5E_R$ and an almost absent radial confinement. In these conditions the lifetime of the sample due to Zener tunneling was however comparable to the decay time of the contrast. We have also repeated the experiment with a cold but uncondensed cloud of bosons at $T \approx 250$ nK, which again showed a steady broadening of the distribution due to interparticle collision. In this case the contrast degraded on a longer time scale of about 10 ms, which is still much shorter than the one observed for fermions. This comparison proves the

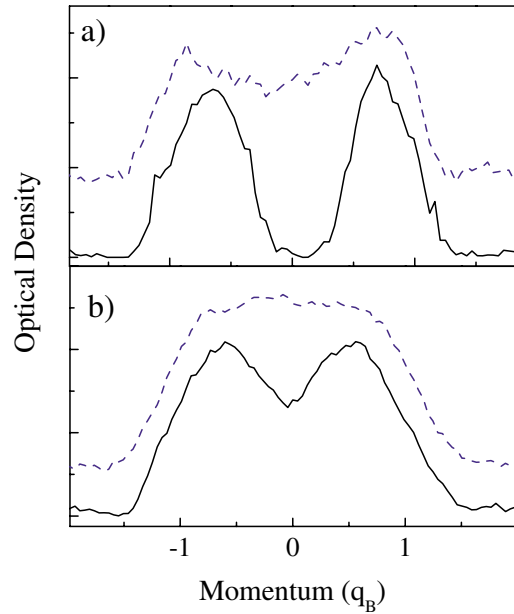


FIG. 4 (color online). (a) Momentum distribution of fermions at two different holding times in the lattice: 1 ms (continuous line) and 252 ms (dashed line). (b) Momentum distribution of bosons at 0.6 ms (continuous line) and 3.8 ms (dashed line). The much faster broadening for bosons is due to the presence of interactions.

superiority of noninteracting fermions with respect to bosons to perform interferometry with trapped samples.

We now discuss the possible application of this interferometric scheme to the measurement of forces. From the period of the Bloch oscillations we can indeed measure the force acting on the atoms along the lattice as $F = 2\hbar/T_B\lambda$. As an example, by means of a nonlinear squares fitting to a sawtooth function, we extract from the experimental data in Fig. 3 a period $T_B = 2.32789(22)$ ms. Assuming that the only uniform force acting on the atomic sample is gravity, we determine a local gravitational acceleration as $g = 9.7372(9)$ m/s². At this level of sensitivity the relative uncertainty on g is just the same as on T_B , since both \hbar and m are known with a high accuracy and also λ can be accurately determined [20]. An interferometer based on trapped atoms opens the possibility of probing forces with a high spatial resolution. We note that the vertical size of the sample in the present experiment is substantially determined by the initial size in the magnetic trap, which in principle can be reduced by increasing the vertical confinement. The minimum possible size is instead set by the extension of a single Wannier-Stark state, which also corresponds to the amplitude of the Bloch oscillations in real space. At $U = 2E_R$ this amounts to about $4 \mu\text{m}$ and decreases further for increasing depths as $2\delta/F$, where 2δ is the width in energy of the first Bloch band of the lattice.

Clearly, the use of a tight optical lattice to trap the sample might affect the accuracy of a measurement of forces. In particular, any axial gradient in the intensity of

the lattice beams will result in an additional force on the sample. In the experiment we have checked the absence of a dipole force at the level of our present sensitivity, by repeating the experiment with a 50% larger intensity of the lattice beams. This did not produce a noticeable change of the Bloch period. Since the fermions have a magnetic moment, the interferometer is sensitive also to magnetic forces. We actually keep a small homogeneous magnetic field (about 1 G) to avoid spin flips, which would produce distinguishable particles. Inhomogeneities in the magnetic field could produce residual forces. However one can control this effect by repeating the measurement with two atomic states with different magnetic moment. Another possibility is to use two different atomic species. For instance we have compared the values of g measured in the same conditions with potassium and rubidium, checking the absence of magnetic forces at the level of 10^{-3} [21].

The sensitivity of the present apparatus is limited to 10^{-4} mainly by the 250-ms time interval available for the measurement. This is much shorter than the characteristic time for p -wave collisions [22] that we estimate for our sample, which exceeds 100 s. The main sources of the broadening shown in Fig. 4(a) are presumably intensity and phase noise in the lattice beams. Also ergodic mixing of the radial and axial motions, a finite axial curvature of the lattice intensity, and a residual scattering of the lattice photons could contribute to the observed broadening. A reduction of all these effects, by using active stabilization of the lattice, a proper beam geometry, and a larger detuning, should allow one to extend the observation time to several seconds, with a corresponding increase of the sensitivity. The sensitivity can be increased also by using a larger atom number and/or a longer wavelength for the lattice. Both operations tend to broaden the momentum distribution with respect to q_B : on one hand in a Fermi gas the momentum spread increases with the atom number N according to $\delta q \propto N^{1/6}$, and on the other hand the Brillouin zone shrinks for increasing wavelengths as $q_B \propto 1/\lambda$. One could however compensate for both these effects by using a looser radial confinement of the atoms, which would reduce the momentum spread without affecting the axial size of the cloud.

In conclusion, we have studied the interference arising from identical fermions trapped in a vertical optical lattice. The absence of interactions allows one to follow the time evolution of the interference for more than 100 periods, whereas in a sample of bosons this is very rapidly washed out by the interactions. Interferometry with trapped fermions is promising for a sensitive determination of forces with high spatial resolution. Possible applications are the study of forces close to surfaces and at the submillimeter scale, recently motivated by the possibility of new physics related to gravity [23].

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