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Production of a Fermi gas of atoms in an optical lattice

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We prepare a degenerate Fermi gas of potassium atoms by sympathetic cooling with rubidium atoms in a one-dimensional optical lattice. In a tight lattice, we observe a change of the density of states of the system, which is a signature of quasi two-dimensional confinement. We also find that the dipolar oscillations of the Fermi gas along the tight lattice are almost completely suppressed.

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The combination of atomic Bose-Einstein condensates (BECs) and periodic potentials created by light has recently allowed the study of a variety of fundamental phenomena related to phase coherence and superfluidity [1,2], transport [3,4], and strongly correlated systems [5]. The corresponding interest in Fermi gases in optical lattices is arising [6–8], especially in view of possible application of lattices to the achievement and detection of fermionic superfluidity.

In this work, we study the production, and the basic static and transport properties of a Fermi gas of atoms in a one-dimensional (1D) optical lattice in the regime of tight confinement. We prepare a sample of degenerate fermionic potassium atoms (^{40}K) in the lattice combined with a magnetic potential by means of sympathetic cooling with bosonic rubidium (^{87}Rb). We observe that the cooling maintains its efficiency also when the atoms are confined in quasi-2D in the lattice sites. We detect the reduced dimensionality of the Fermi gas under these conditions by studying its momentum distribution. The comparison of the behavior of the Fermi gas with that of the BEC in the lattice helps to confirm the different transport properties expected for two kinds of quantum gases. In particular, we observe that the dipole oscillations of the Fermi gas are strongly reduced in the tight lattice.

The degenerate mixture is initially prepared in a magnetic potential as described in Ref. [9]. The axial and radial frequencies of the potential are $\omega_a = 2\pi\times 24(16.3)$ s^{-1} and $\omega_r = 2\pi\times 317(215)$ s^{-1}, respectively, for K (Rb). Typically, 5×10^4 fermions are sympathetically cooled to about $0.3T_F$ ($T_F = 430$ nK) in coexistence with a BEC with a similar atom number.

The lattice is created with a laser beam in a standing-wave configuration, focused to a beam waist of 500 μm and aligned along the weak axis of the magnetic potential. At a wavelength $\lambda = 754$ nm, the lattice potential is repulsive and its depth is about twice as large for K than for Rb. More precisely, the depth for the two species is almost the same in units of the recoil energy $U = sE_R$, with $E_R = \hbar^2 k^2/2m$ and $k = 2\pi/\lambda$ [10].

We have investigated the loading and cooling of the Fermi gas in the tightest lattice we could achieve, with $s = 8$. We find that the optimal loading is obtained by raising the lattice beam from zero to full power in about 500 ms during the final stage of the evaporation, in order to reach the full depth when the phase transition for bosons occurs. By continuing the evaporation of rubidium for ≈ 1 s, we observe that the mixture cools efficiently in the lattice to quantum degeneracy. The presence of the lattice shows up in the characteristic interference peaks in the momentum distribution of the BEC [11], as shown in Fig. 1. Because of the broad momentum distribution, this is not observed in fermions, which just show a faster axial expansion because of the additional confinement provided by the lattice.

Previous experiments on bosons have shown that a tight lattice can lead to a collection of BECs with a quasi-2D character, where the reduced dimensionality affects the phase transition to quantum degeneracy [12]. To understand the dimensionality of the Fermi gas, we first need to study the energy spectrum of the fermions in the combined potential. We initially use a simplified model, in which we replace the axial harmonic confinement with a boxlike potential. Within this approximation, the atoms experience a uniform lattice with N_l sites (typically, $N_l = 400$ for the Fermi gas and $N_l = 200$ for the BEC). The system can be described in terms of Bloch states of quasimomentum, whose energy spectrum

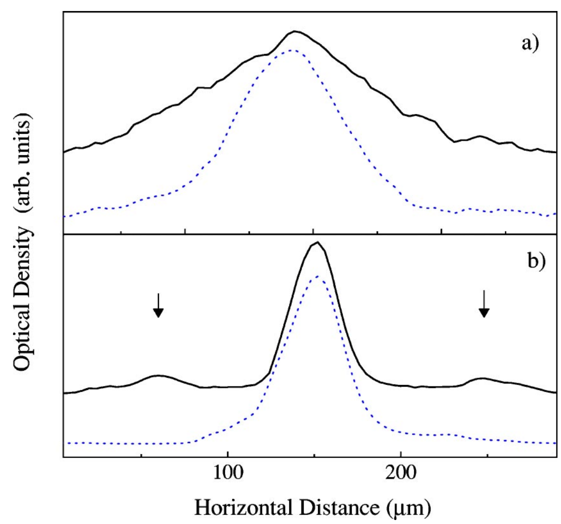

FIG. 1. Axial profiles of the Fermi gas (a) and of the BEC (b) after ballistic expansion from a 1D lattice combined with the magnetic trap (continuous lines). The interference peaks in the BEC profile (arrows) do not show up in the Fermi gas. The expansion from the pure magnetic trap is shown for comparison (dotted lines, the curves are offset for clarity). The expansion time is 8 ms and 17 ms for the Fermi gas and the BEC, respectively.

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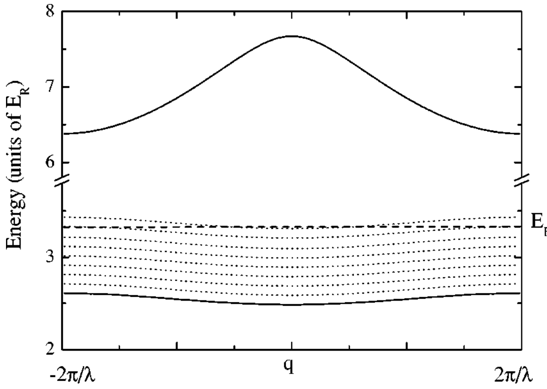

FIG. 2. Calculated energy spectrum of the first two bands of the 1D lattice for $s=8$. Many bands, whose spacing has been exaggerated for clarity, are actually present (dotted lines). The dashed line represents the Fermi energy of the system.

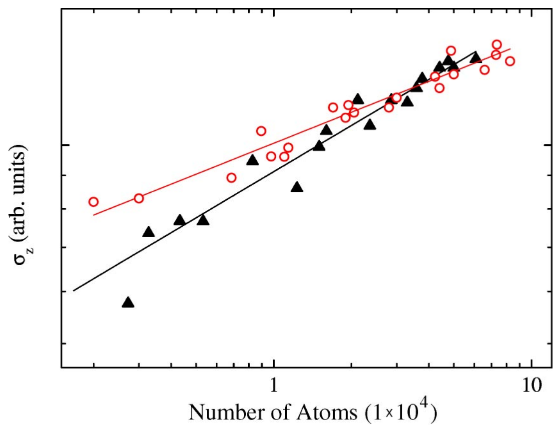

FIG. 3. Width of the Fermi gas after ballistic expansion for the magnetic potentials (circles) and for the combined magnetic and optical potential (triangles). The different power law in the lattice is due to the reduced dimensionality of the Fermi gas.

$E(q)$ is shown in Fig. 2 for the first two bands for a lattice with $s=8$. The width of the first band $\delta E=0.12E_R$, is much smaller than the gap $\Delta E=3.8E_R$. The ground-state energy is half the oscillator quantum in each lattice site $E_0=\hbar\omega_l/2\approx 2.49E_R$, and corresponds to rather large oscillating frequencies $\omega_l=2\pi\times 43\,000$ s^{-1} and $\omega_l=2\pi\times 20\,000$ s^{-1} for K and Rb, respectively. Due to the presence of the radial degrees of freedom, the system has actually bundles of bands with identical dispersion, spaced by the radial energy quantum $\hbar\omega_r\approx 0.038E_R$ (dotted lines in Fig. 2). We note that the degeneracy of the nth band is $n+1$, since two radial dimensions are involved.

While the condensate occupies macroscopically the state at $q=0$ in the fundamental band, identical fermions can have only single occupancy of the N_l momentum states in each band. At the low temperatures of our system ($k_BT<\Delta E$), we can restrict our attention to the bundle of radial bands relative to the fundamental band of the lattice. If we also neglect the band structure, i.e., the motion along the lattice, since $\delta E\ll E_F$, the system has clearly a quasi-2D character, with the axial motion within each lattice site frozen to the zero-point motion. To confirm this expectation, we have looked for a change of the momentum distribution of the Fermi gas, since this is one of the properties that can be more easily measured in the experiment. In an harmonic potential of dimensionality d, with density of states $g(E)\propto E^{d-1}$, the Fermi momentum at $T=0$ is linked to the number of atoms by the relation $k_F\propto N^{1/2d}$. In each quasi-2D lattice site, we should therefore expect a dependence $k_F\propto N^{1/4}$ of the radial Fermi momentum in each lattice site, which is notably different from the $k_F\propto N^{1/6}$ expected in 3D.

In the experiment, we have measured the radial momentum distribution of the Fermi gas in the lattice as a function of the total number of atoms. This can be easily varied by adjusting the initial loading of potassium in the magnetic trap. At an expansion time $\tau=8$ ms$\gg\omega_r^{-1}$, the radial profile reflects the initial momentum distribution. The experimental observation is summarized in Fig. 3, where we compare the radius of the Fermi gas released from the combined potential with that released from the pure magnetic potential. Each radius is measured with a Gaussian fit to the central section (about 20μm) of the cloud. The best fit of the two sets of data with $\sigma_z(N)=aN^{1/n}$ curves gives $n=4.3\pm0.3$ and $n=6.1\pm0.6$, respectively, confirming our expectation of reduced dimensionality in the lattice [13].

The appropriateness of using this low-temperature model of the system is confirmed by a one-dimensional Thomas-Fermi fit to the radial profile of the clouds to determine the 2D temperature. For the measurements of Fig. 3, we find $T^{2D}/T_F^{2D}\approx 0.4$, where $k_BT_F^{2D}=\hbar\omega_r(2N/N_l)^{1/2}$. We observe that the reduced temperature does not change appreciably with N, consistent with what we usually observe in the 3D trap. Note that the minimum temperature is however higher than the one we usually reach in 3D [9].

We have repeated the same measurement with nondegenerate fermions in the lattice at $T\approx 700$ nK$>T_F$, where we have observed no variation of the radius with N. This is consistent with the expectation of a number-independent momentum distribution for a classical gas, even in reduced dimensionality.

We can now take into account the contribution of the band structure to the density of states. In the approximation of a boxlike axial magnetic trapping, i.e., assuming that the fermions are evenly distributed along the lattice, we have calculated the dependence of the radial Fermi momentum on the atom number at $T=0$. For high enough N, we can neglect the discreteness of the radial energy levels, and we obtain a behavior $k_F\approx N^{1/n}$, with $n=4.2$. This is very close to the result for 2D, as expected because of the smallness of the axial energy $\delta E\ll E_F$. Note that the atoms are loaded in the lattice at $T\approx 0.5T_F$, where also the 3D radius of the cloud begins to be dependent on N. In the limiting case of loading at $T\ll T_F$, the 3D Fermi radius scales as $N^{1/6}$, and by computing the number of atoms per site we would obtain an exponent $n=4.8$ for the radial momentum.

An interesting question is how the sympathetic cooling varies along the lattice. To check our ability to address small axial sections of the Fermi gas, we have to consider the axial expansion from the combined trap. The axial profile of the expanding cloud is, in general, a convolution of the profile of each lattice site and the distribution along the sites. At expansion times $\tau \gg \omega_l^{-1}$, i.e., when the individual site has merged, the axial width of the cloud has the form $\sigma(\tau) \approx R_F/2\sqrt{1+2(\sigma_l/R_F)^2\omega_l^2\tau^2}$, where $R_F \propto N^{1/6}$ is the axial Fermi radius in the 3D trap and σ_l is the width of each site, $\sigma_l = \sqrt{\hbar/m\omega_l} \approx 76$ nm. At the time $\tau \approx 8$ ms that we normally use in the experiment, the width of each cloud initially confined in an individual site is comparable to the overall width. Although the axial selectivity would obviously be better at shorter times, here we estimate that the lateral lattice sites give still only a small contribution to the radial profile at the center of the cloud. For example, in the case of a constant reduced temperature T/T_F along the lattice, the central section of the expanded cloud would be just 10% narrower than the individual central site. In the experiment, we typically measure a constant radius along the lattice, which instead indicates a decreasing degeneracy for lattice sites far from the center. The reduction of the efficiency of sympathetic cooling in a tight lattice is actually not unexpected, since the bosons in the lateral lattice sites are rapidly removed by the evaporation, because of their larger Zeeman energy, and they are not very efficiently replaced through tunneling. As soon as their number drops below that of the fermions, the cooling slows down, and eventually stops when all the bosons are removed from the site.

One of the issues of the experiment was to understand whether a tight lattice would affect the stability of the degenerate mixture, since, in principle, collapse or three-body decay [14] can be favored by an increased confinement [15]. However, we were not able to observe a collapse of the mixture in the combined potential for $s=8$, even for total atom numbers approaching the critical values in 3D. Moreover, in the lattice we measured the lifetime of the Fermi gas $\tau \gtrsim 0.5$ s, limited by three-body collisions with Rb atoms, which is comparable to the one in the magnetic potential [14]. Both these observations seem to indicate that the effective density overlap of the BEC and Fermi gas in the lattice is not increased with respect to that in the magnetic potential alone. We have compared these observations with the prediction of our simple model which neglects both the axial confinement and the axial motion of the atoms along the lattice, i.e., assumes both bosons and fermions confined to quasi-2D droplets. The density distribution of both species has therefore a 2D Thomas-Fermi radial shape appropriate to the statistics [16], and a Gaussian axial shape, with rms width σ_l. For the typical atom numbers, we find that the peak density of the Fermi gas increases by approximately 5 with respect to the pure magnetic trap, while the increase of the condensate peak density is limited to approximately 1.5 by the boson-boson mean-field repulsion. The overlap of the two species in the lattice is however worse, mainly because the radius of the Fermi gas decreases by almost 50% passing from 3D to 2D, thus increasing the effect of the differential gravitational sag [9]. As an example, the radii of a BEC and a Fermi gas containing 5×10^4 atoms are 2.8 μm and 4 μm, respectively, hence comparable to the gravitational sag $\delta z = 3.6$ μm. These predictions confirm qualitatively observations both on the stability of the mixture and on the slightly reduced efficiency of the sympathetic cooling.

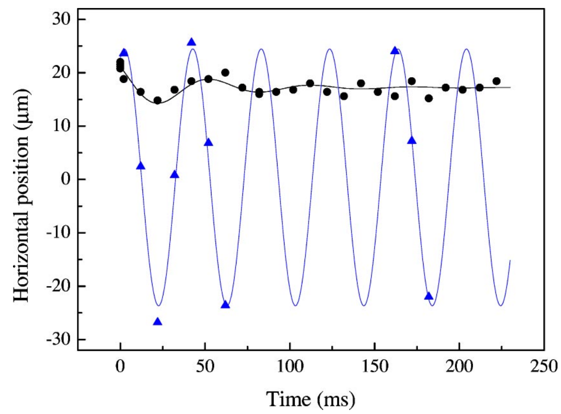

FIG. 4. Dipolar axial oscillations of a Fermi gas in the combined magnetic potential and optical lattice with $s=7.6$ (circles), and in the magnetic potential alone (triangles). The oscillations are excited by displacing the magnetic trap by 15 μm, and the position of the cloud is detected after 8 ms of ballistic expansion. In the presence of the lattice, the Fermi gas performs a strongly damped oscillation close to the equilibrium position in the magnetic trap prior to the displacement.

The different statistical natures of bosons and fermions determine also their *dynamics* in the lattice. We have studied the dipolar oscillations of either the Fermi gas or the BEC in the combined potential [17], which are induced by a sudden axial displacement of the magnetic trap. As shown in Fig. 4, the oscillation of the Fermi gas is strongly damped in presence of the tight lattice, and the center of mass of the cloud is hardly displaced from the original equilibrium position. Differently, the BEC oscillation in the lattice proceeds without damping, as originally studied in Ref. [2].

To understand these different dynamical behaviors, we can no longer neglect the axial magnetic potential. In a semiclassical picture, the atoms move under the force exerted by the harmonic magnetic potential, with the Bloch velocity dispersion $v(q)=1/\hbar\,\partial E/\partial q$ set by the lattice. The narrow quasimomentum distribution of the BEC allows an undamped dipolar oscillation, provided that q is confined to the parabolic part of the fundamental energy band in Fig. 2, which has an overall cosine shape in this tight-binding regime. This picture changes completely for the Fermi gas, because of its broad quasimomentum distribution. Already at equilibrium, i.e., before exciting the dipolar motion, most of the individual fermions oscillate along a wide section of the fundamental bands during their motion in the trap, and therefore, in general, they perform strongly nonharmonic oscillations. This single-particle behavior will clearly affect also the collective dipolar oscillation, which is likely to be damped, as it would happen in an anharmonic potential. If the atoms are no more able to perform full oscillations in the magnetic potential, one could also expect that the Fermi gas is eventually blocked to an equilibrium position far from the magnetic trap minimum, as we observe in the experiment.

To access a regime where the Fermi gas can perform dipolar oscillations with larger amplitude, one should reduce either the number of atoms, in order to have a much narrower momentum distribution, or the lattice depth, in order to have almost parabolic bands. In the experiment, we have actually observed that the oscillation amplitude of the Fermi gas grows as the lattice height is lowered. We plan to further investigate the oscillations of the Fermi gas in shallow lattices, and to make a comparison to those of a thermal cloud of bosons, to study possible effects of the statistics.

We have also studied the oscillation of the mixture of BEC and Fermi gas in the tight lattice, seeking possible interaction effects. On the BEC side, we have observed just a moderate damping due to collisions with fermions, as we have already measured in the magnetic trap [18], and no noticeable frequency shift. In contrast, in presence of the BEC, the oscillation of the Fermi gas in the lattice appears to be further reduced, and becomes no longer detectable. Future work on shallower lattices will also help to elucidate the effects of the interactions with bosons on the oscillations of the Fermi gas.

In conclusion, we have produced a Fermi gas of atoms in a 1D lattice by sympathetic cooling with bosonic atoms. The realization of quasi-2D Fermi gases in the lattice is interesting in view of achieving fermionic superfluidity, as discussed in Ref. [19]. Our results are promising also for loading the Fermi gas or the Bose-Fermi mixture in 2D or 3D lattices. These are of great interest for studies on high-T_c superfluidity [6], novel quantum phases [8], and the formation of ultracold heteronuclear molecules [20].

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