Fermionic atoms in a Three Dimensional optical lattice: Observing Fermi Surfaces, Dynamics and Interactions

Michael Kölh†, Henning Moritz, Thilo Stöferle, Kenneth Günter, and Tilman Esslinger
Institute of Quantum Electronics, ETH Zürich, Hönggerberg, CH–8093 Zürich, Switzerland
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We have studied interacting and non-interacting quantum degenerate Fermi gases in a three-dimensional optical lattice. We directly image the Fermi surface of the atoms in the lattice by turning off the optical lattice adiabatically. Due to the confining potential gradual filling of the lattice transforms the system from a normal state into a band insulator. The dynamics of the transition from a band insulator to a normal state is studied and the time scale is measured to be an order of magnitude larger than the tunneling time in the lattice. Using a Feshbach resonance we increase the interaction between atoms in two different spin states and dynamically induce a coupling between the lowest energy bands. We observe a shift of this coupling with respect to the Feshbach resonance in free space which is anticipated for strongly confined atoms.

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The exploration of quantum degenerate gases of fermionic atoms is driven by the ambition to get deeper insight into long-standing problems of quantum many-body physics, such as high temperature superconductivity. Very recently, the cross-over regime between a strongly interacting two-component Fermi gas and a molecular Bose-Einstein condensate has been studied in harmonic traps [1, 2, 3, 4, 5]. These experiments mark a milestone towards the understanding of superfluidity of fermionic atoms. However, the analogy to an electron gas in a solid is limited since there the electrons experience a periodic lattice potential. The lattice structure is in fact a key ingredient for most models describing quantum many-body phenomena in materials. It has been suggested that strongly interacting fermionic atoms in optical lattices could be employed for studies of high-Tc-superconductivity [6]. Mott-insulating phases [7]. Bose condensation of fermionic particle-hole pairs [8], or interacting spin systems [9].

Here we report on an experiment bridging the gap between current ultracold atom systems and fundamental concepts in condensed matter physics. A quantum degenerate Fermi gas of atoms is prepared in the crystal structure of a three dimensional optical lattice potential created by three crossed standing laser waves. The unique control over all relevant parameters in this system allows us to carry out experiments which are not feasible with solid-state systems.

It was conceived by D. Jaksch et al. that ultracold atoms exposed to the periodic potential of an optical lattice are an almost ideal realization of a Hubbard model [10]. This model is elementary to describe the quantum physics of many electrons in a solid. It takes into account a single band of a static lattice potential and assumes the interactions to be purely local [11]. Ultracold atoms in an optical lattice give a very direct access to the underlying physics. The fundamental parameters include the tunnel coupling between adjacent lattice sites, the atom interactions and the dimensionality of the system. Previous experiments with far-detuned three dimensional optical lattices [12, 13, 14] were always carried out with bosonic atoms, and experiments with fermions were restricted to a single standing wave [15]. In the latter situation many atoms can reside in each standing wave minimum but formation of a band insulator is prevented by the weak transverse confinement. The observed inhibition of transport [16] is due to localized states and therefore differs qualitatively from the band insulator which we create in the three dimensional optical lattice.

The experiments are performed in a modified apparatus previously used to study bosonic rubidium atoms in optical lattices [14, 17]. A mixture of bosonic $^87$Rb and fermionic $^{40}$K atoms is captured in a magneto-optical trap. For magnetic trapping we optically pump the potassium atoms into the $|F = 2, m_F = 2\rangle$ hyperfine ground state, with $F$ being the total angular momentum and $m_F$ the magnetic quantum number. The mixture is evaporatively cooled using microwave radiation to selectively remove the most energetic rubidium atoms from the trap. The potassium cloud is sympathetically cooled by thermal contact with the rubidium atoms [18]. After reaching quantum degeneracy for both species with typically $6 \times 10^5$ potassium atoms at a temperature of $T/T_F = 0.32$ ($T_F = 260$ nK is the Fermi temperature of the non-interacting gas) we remove all the rubidium atoms [19]. The potassium atoms are then transferred from the magnetic trap into a crossed beam optical dipole trap whose laser beams possess a wavelength of $\lambda = 826$ nm and are focused at the position of the Fermi gas to $1/e^2$-radii of 50 $\mu$m (x-axis) and 70 $\mu$m (y-axis). The initial trapping frequencies are $\omega_x = 2 \pi \times 93$ Hz, $\omega_y = 2 \pi \times 154$ Hz and $\omega_z = 2 \pi \times 157$ Hz. When loading the optical trap we turn off the magnetic confinement in such a way that a variable homogenous magnetic field remains present. In the optical trap we
prepare a spin mixture with $(50 \pm 4)\%$ in each of the $|F = 9/2, m_F = -9/2\rangle$ and $|F = 9/2, m_F = -7/2\rangle$ spin states using a sequence of two radio frequency pulses. By lowering the depth of the optical trap on a time scale of 2 seconds we further evaporatively cool the potassium gas. This is done at a bias magnetic field of $B = 227$ G, which is well above the magnetic Feshbach resonance centered at $B_0 = 202.1$ G [1] and the s-wave scattering length between the two fermionic spin states is $a = 118 a_0$ ($a_0$ is the Bohr radius). At the end of the evaporation process we heat temperatures between $T/T_F = 0.2$ and 0.25 with $5 \times 10^4$ to $2 \times 10^5$ particles, respectively.

Prior to loading the atoms into the optical lattice we tune the magnetic field to $B = (210 \pm 0.1)$ G, such that the s-wave scattering length between the two states vanishes. Then the standing wave laser field along the vertical $z$-axis is turned on. Subsequently, the optical dipole trap along the $y$-axis is turned off and a standing wave laser field along the same axis is turned on, followed by the same procedure along the $x$-axis. In order to keep the loading of the atoms into the lattice as adiabatic as possible the intensities of the lasers are slowly increased (decreased) by modulating the laser intensity and studying the parametric heating. The calibration error is estimated to be $< 10\%$.

The potential created by the optical lattice results in a simple cubic crystal structure and the gaussian intensity profiles of the lattice beams give rise to an additional confining potential which varies with the laser intensity. As a result, the sharp edges characterizing the $T = 0$ distribution function for the quasi momentum in the homogeneous case [17] are expected to be rounded off. A quantitative picture can be obtained by considering a tight-binding Hamiltonian to describe non-interacting fermions in an optical lattice with an additional harmonic confinement [21]. At $T = 0$ the inhomogeneous system is characterized by the total atom number $N$ and by the characteristic length $\zeta$ over which the potential shift due to the harmonic confinement equals the tunnel coupling matrix element $J$. One finds $\zeta_\alpha = \sqrt{2J/m\omega_\alpha^2}$, with the frequencies of the external harmonic confinement given by $\omega_\alpha$ ($\alpha = x, y, z$). The density distribution scaled by $\zeta_\alpha$ and the momentum distribution of the atoms in the lattice only depend on the characteristic density $\rho_c = \frac{N\zeta^3}{\pi^{3/2}$$\omega_\alpha^3}$, where $d$ is the lattice spacing [2]. For a three-dimensional lattice with $20 \times 20 \times 20$ sites we have numerically calculated the characteristic density for the onset of a band insulator to be $\rho_c \approx 60$. For this value of $\rho_c$, the occupation number at the center of the trap is larger than 0.99. It has been pointed out that a fermionic band insulator in an optical lattice with confining potential constitutes a high fidelity quantum register [21].

In the experiment we probe the population within the first Brillouin zone by ramping down the optical lattice slowly enough for the atoms to stay adiabatically in the lowest band whilst quasi-momentum is approximately conserved [22]. We lower the lattice potential to zero over a timescale of 1 ms. After 1 ms we switch off the homogeneous magnetic field and allow for total of 9 ms of ballistic expansion before we take an absorption image of the expanded atom cloud. The momentum distribution obtained from these time of flight images, shown in Fig. 1 reproduces the quasi-momentum distributions of the atoms inside the lattice. With increasing characteristic density the initially circular shape of the Fermi surface develops extensions pointing towards the Bragg planes and finally transforms into a square shape completely filling the first Brillouin zone deeply in the band insulator. We have observed population of higher bands if more atoms are filled into the lattice initially. In Fig. 2 the experimental data for momentum distributions along the line with quasi-momentum $q_y = 0$ are compared to the results of numerical simulations using the same characteristic densities.

When imaging the cloud along the $x$-direction we find a homogeneous filling of the band in the vertical ($z$-) direction, probably due to the change in the harmonic confinement while loading the lattice combined with the presence of gravity. This asymmetry between the horizontal $x$, $y$, and the vertical $z$-directions vanishes when the gas approaches the band insulating regime. We have

![FIG. 1: Observing the Fermi surface. Time of flight images obtained after adiabatically ramping down the optical lattice. The characteristic density increases from left to right.](image)
examined the level of adiabaticity of our loading scheme into the optical lattice by transferring the atoms from the band insulator back into the crossed beam dipole trap. There we find a temperature of $0.35 T_F$ when the initial temperature prior to loading into the lattice was $0.2 T_F$.

FIG. 2: Analysis of the density distributions. The dots are cuts through the measured density distribution for quasi momentum $q_y = 0$ after adiabatically ramping down the optical lattice. (a) Normal state with $\rho_c = 14.5$, (b) band insulator with $\rho_c = 137$, (c) band insulator with $\rho_c = 2500$. We have numerically calculated the momentum distribution function of fermions in the lowest band of a three-dimensional lattice with $20 \times 20 \times 20$ sites and characteristic lengths $z_J/d = 3.2$, $\zeta_y/d = 2.6$, $\zeta_z/d = 2.5$ ((a) and (b)) and $\zeta_y/d = 1$, $\zeta_z/d = 0.8$ (c), assuming zero temperature (solid lines). Experimental data of (c) are averaged over 5 images. Imperfect adiabaticity during the switch-off of the optical lattice may cause the rounding-off of the experimental data at the edge of the Brillouin zone in (b) and (c). The calculated momentum distribution function is scaled to match the experimental data using identical scale factors for all graphs.

We have studied the dynamic response of the non-interacting Fermi gas to a change in the characteristic density from a value deep in the band insulating regime to a value below. In the latter regime the fermions are delocalized over several sites of the optical lattice and an interference pattern is observed when the atoms are abruptly released from the lattice. The width of the interference peaks is a measure of the length scale over which the atoms are delocalized in the lattice or, equivalently, their coherence length. We change the characteristic density in situ by varying the strength of the lattice laser beams. Starting from an initial characteristic density of $\rho_c = 16$ in an optical lattice with a potential depth of $5 E_r$, we create a band insulator with a characteristic density of $\rho_c = 2700$ at a potential depth of $15 E_r$. After holding the atoms for $5$ ms we reduce the potential depth back to $5 E_r$, using an exponential ramp with duration and time constant $t_r$. This is followed by a rapid switch off of the lattice (see Fig. 3a). We measure the width of the central momentum peak in the time of flight images for different durations $t_r$ and obtain the time scales $\tau_x = (2.7 \pm 0.4) \text{ms}$ and $\tau_y = (3.8 \pm 0.3) \text{ms}$ in the x- and y-direction, respectively. This corresponds to approximately ten times the timescale for tunnelling given by $h/2\pi z J$ at a potential depth of $5 E_r$, where $z$ is the coordination number of the lattice. This non-trivial dynamics appears to be significantly slower than the time scale measured for the transition of a Mott-insulating state to a superfluid state using bosonic atoms in an optical lattice [12]. The comparatively slow dynamics of delocalization of the fermions when approaching the normal state is most likely due to Pauli blocking which prevents tunneling of atoms in regions where the lowest band is full and the atoms are well localized.

We investigate the interacting regime in the lattice starting from a non-interacting gas deep in a band insulator with $V_x = 12 E_r$ and $V_y = V_z = 18 E_r$ and corresponding trapping frequencies of $\omega_x = 2 \pi \times 50 \text{kHz}$ and $\omega_y = \omega_z = 2 \pi \times 62 \text{kHz}$ in the individual minima. A short radio-frequency pulse is applied to transfer all atoms from the $|F = 9/2, m_F = -7/2 \rangle$ into the $|F = 9/2, m_F = -5/2 \rangle$ state, with the atoms in the $|F = 9/2, m_F = -9/2 \rangle$ remaining unaffected. We ramp the magnetic field with an inverse sweep rate of $12 \mu \text{s/G}$ to different final values around the Feshbach resonance (see Fig. 4a) located at $B = 224 \text{G}$ [23]. The sweep across the Feshbach resonance goes from the side of repulsive interactions towards the side of attractive interactions. When using this direction of the sweep there is no adiabatic conversion to molecules. After turning

FIG. 3: Restoring phase coherence. (a) Control sequence for the depth of the optical lattice. (b) Pseudocolor image of the momentum distribution after releasing the atoms from the initial optical lattice of $5 E_r$ and $7 \text{ms}$ ballistic expansion. It reveals the central momentum peak and the matter wave interference peaks at $\pm 2 h k$. The data are averaged over 5 repetitive measurements. (c) Width of the central momentum peak obtained from Gaussian fits to the atomic density data using identical scale factors for all graphs.
FIG. 4: Interaction-induced transition between Bloch bands. (a) Transferring fermions into higher bands using a sweep across the Feshbach resonance (filled symbols). The inverse magnetic field sweep rate is $12 \mu$s/G. The line shows a sigmoidal fit to the data. The open symbols show a repetition of the experiment with the atoms prepared in the spin states $|F = 9/2, m_F = -9/2\rangle$ and $|F = 9/2, m_F = -7/2\rangle$ where the scattering length is not sensitive to the magnetic field. The magnetic field is calibrated by rf spectroscopy between Zeeman levels. Due to the rapid ramp the field lags behind its asymptotic value and the horizontal error bars represent this deviation. (b) Fraction of atoms in higher bands for a final magnetic field of 233 G for different magnetic field sweep rates. The vertical error bars show the statistical error of 4 repetitive measurements. (c) Momentum distribution for a final magnetic field of $B = 233$ G and a $12 \mu$s/G sweep rate. Arrows indicate the atoms in the higher bands.

off the optical lattice adiabatically and switching off the magnetic field we measure the momentum distribution. To see the effect of the interactions we determine the fraction of atoms transferred into higher bands. For final magnetic field values well above the Feshbach resonance we observe a significant increase in the number of atoms in higher bands along the weak axis of the lattice, demonstrating an interaction-induced coupling between the lowest bands. Since the s-wave interaction is changed on a time scale short compared to the tunnelling time between adjacent potential minima we may regard the band insulator as an array of harmonic potential wells. It has been shown that increasing the s-wave scattering length for two particles in a harmonic oscillator shifts the energy of the two-particle state upwards until the next oscillator level is reached [24]. In our case this leads to a population of higher energy bands. The fraction of atoms transferred could be limited by the number of doubly occupied lattice sites and tunnelling in the higher bands. The number of doubly occupied sites could be measured by studying the formation of molecules in the lattice. In addition, we observe a shift of the position of the Feshbach resonance from its value in free space to larger values of the magnetic field (see Fig. 4(b)), which has been predicted for tightly confined atoms in an optical lattice [25]. This mechanism for a confinement induced resonance is related to the phenomenon predicted for one-dimensional quantum gases [26] which has as yet escaped experimental observation. For a quantitative description of this strongly interacting Fermi gas on a lattice a multi-band Hubbard model could be considered but these are even in the static case notoriously difficult or even impossible to solve with present methods [27].

In conclusion we have created a fermionic many-particle quantum system on a lattice. We have demonstrated the dynamic control over the parameters of the system such as filling and interactions which is not feasible in solid state systems. For the non-interacting static regime we find good agreement between our measurements and a theoretical model. Both the dynamic measurements and the strongly interacting cases pose challenges for the present theoretical understanding of many-particle fermionic systems on optical lattices.

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