

# Evidence for superfluidity of ultracold fermions in an optical lattice

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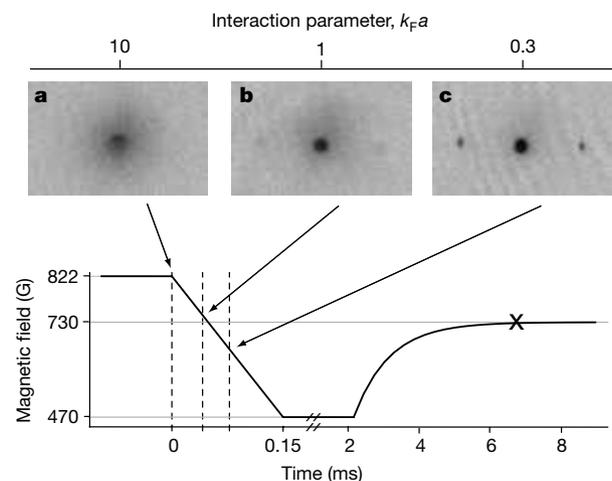
The study of superfluid fermion pairs in a periodic potential has important ramifications for understanding superconductivity in crystalline materials. By using cold atomic gases, various models of condensed matter can be studied in a highly controllable environment. Weakly repulsive fermions in an optical lattice could undergo *d*-wave pairing<sup>1</sup> at low temperatures, a possible mechanism for high temperature superconductivity in the copper oxides<sup>2</sup>. The lattice potential could also strongly increase the critical temperature for *s*-wave superfluidity. Recent experimental advances in bulk atomic gases include the observation of fermion-pair condensates and high-temperature superfluidity<sup>3–8</sup>. Experiments with fermions<sup>9–11</sup> and bosonic bound pairs<sup>12,13</sup> in optical lattices have been reported but have not yet addressed superfluid behaviour. Here we report the observation of distinct interference peaks when a condensate of fermionic atom pairs is released from an optical lattice, implying long-range order (a property of a superfluid). Conceptually, this means that *s*-wave pairing and coherence of fermion pairs have now been established in a lattice potential, in which the transport of atoms occurs by quantum mechanical tunnelling and not by simple propagation. These observations were made for interactions on both sides of a Feshbach resonance. For larger lattice depths, the coherence was lost in a reversible manner, possibly as a result of a transition from superfluid to insulator. Such strongly interacting fermions in an optical lattice can be used to study a new class of hamiltonians with interband and atom–molecule couplings<sup>14</sup>.

Previous experiments showing long-range phase coherence in Bose–Einstein condensates (BECs) and in fermion superfluids used ballistic expansion to observe the interference of two independent condensates<sup>15</sup>, vortex lattices<sup>8,16,17</sup> or interference peaks after release from an optical lattice<sup>18,19</sup>. However, for strongly interacting fermions, elastic collisions can change the momentum distribution and wash out interference peaks. For an initially superfluid cloud, such dissipative dynamics corresponds to superfluid flow faster than the critical velocity. Consistent with this expectation is the observation that a strongly interacting Fermi superfluid initially containing distinct momentum components yielded a broad diffuse cloud after expansion (Fig. 1). This issue was addressed by using a magnetic field ramp that quickly increased the detuning from a Feshbach resonance, taking the system out of the strongly interacting regime and enforcing ballistic expansion. In previous studies of strongly interacting Fermi gases, magnetic field sweeps were applied to prevent fermion pairs above the Feshbach resonance from dissociating<sup>6,7,20</sup>. In contrast, our experiment required a magnetic field sweep both above and below the Feshbach resonance to avoid elastic collisions.

Our experiments used a balanced mixture of <sup>6</sup>Li fermions in the two lowest hyperfine states. Evaporative cooling produced a nearly pure fermion pair condensate that was adiabatically loaded into a

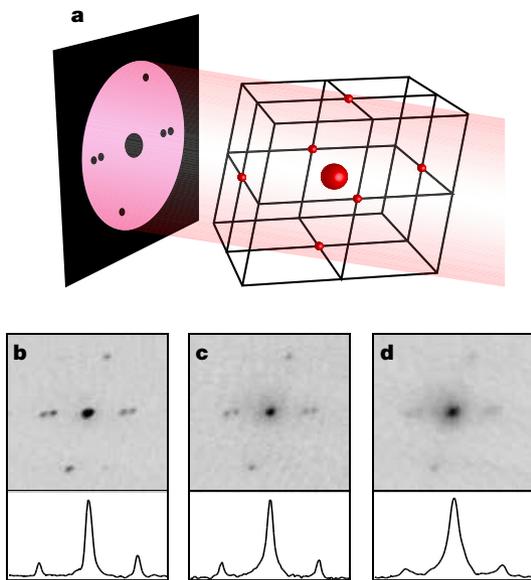
three-dimensional optical lattice. A broad Feshbach resonance centred at 834 G enabled tuning of the interatomic interactions over a wide range. On resonance, a bound molecular state becomes degenerate with the open atomic scattering channel, leading to a divergence in the scattering length *a*. Here we explore the region of strong interactions, also known as the BEC–BCS (Bardeen–Cooper–Schrieffer) crossover, in which the magnitude of the interaction parameter  $|k_F a|$  is greater than unity, and  $k_F$  is defined as the peak Fermi wavevector of a two-component non-interacting mixture of <sup>6</sup>Li atoms. In the crossover region, pairing occurs as a result of many-body interactions. Below resonance, for strong interactions, the bare two-body state has a bond length larger than the interatomic spacing and is irrelevant. In a lattice, atom pairs above and below the resonance can be confined to one lattice site<sup>11</sup>, and crossover physics may require an occupation larger than or equal to one.

The peak pair filling factor of the lattice was about unity. At this density in the bulk, the fermion pair size is on the order of  $1/k_F = 170$  nm, comparable to the lattice spacing of 532 nm. To probe the momentum distribution, we ramped the magnetic field out of the strongly interacting regime as fast as technically possible (about 150  $\mu$ s) and then turned off the confining potential. Absorption



**Figure 1 | Dissipative collisions during expansion of a strongly interacting fermionic superfluid.** The schematic shows the time sequence of the magnetic field ramp used throughout this paper. A one-dimensional optical standing wave was pulsed onto the superfluid at different magnetic fields  $B_p$  (indicated by arrows at 822 G (a), 749 G (b) and 665 G (c)) during expansion, creating particles at twice the photon recoil<sup>30</sup>. Absorption images taken at the time marked with the cross show distinct momentum peaks only at magnetic fields  $B_p \leq 750$  G, where  $k_F a \leq 1$ . At higher magnetic fields, the peaks blurred into a broad diffuse cloud as a result of the larger collision cross-section.

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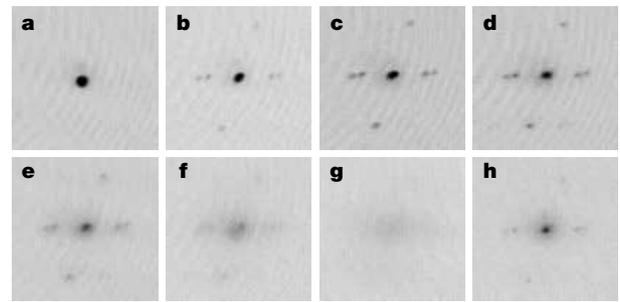
**Figure 2 | Observation of high-contrast interference of fermion pairs released from an optical lattice below and above the Feshbach resonance.** **a**, The orientation of the reciprocal lattice, also with respect to the imaging light. **b–d**, Interference peaks are observed for magnetic fields of 822 G (**b**), 867 G (**c**) and 917 G (**d**). The lattice depth for all images is  $5E_r$ , and each image is the average of three shots. The field of view is  $1 \text{ mm} \times 1 \text{ mm}$ . Density profiles through the vertical interference peaks are shown for each image.

images taken after 6.5 ms of expansion reveal sharp peaks at the reciprocal lattice vectors—the signature of long-range coherence, a strong indicator for superfluidity.

We observed these interference peaks at magnetic fields both above and below the Feshbach resonance (Fig. 2). The six first-order diffracted peaks are clearly visible around the zero momentum fraction and their positions correspond to the expected momentum quanta of  $2\hbar k_L$  carried by molecules of mass  $2m$ , where  $k_L$  is the lattice wavevector. At high magnetic fields (Fig. 2d) the visibility of the interference peaks decreased and some additional heating was observed. This degradation could be due to a higher fraction of thermal atoms as we approached the BCS limit, but it was not studied in detail.

The narrow interference peaks clearly reveal the presence of a macroscopic wavefunction possessing long-range phase coherence. The separation between the interference peaks relative to their width gives an estimate of the coherence length of about ten lattice sites. This estimate is a lower bound, because effects of finite resolution and mechanisms of residual broadening have been neglected. With unity occupation, and in the absence of any discernible background at magnetic fields near the Feshbach resonance, this implies a minimum phase space density of  $10^3$  and shows that our samples are deep in the quantum-degenerate regime. In previous studies of ultracold Bose and Fermi gases, the appearance of a condensate fraction and long-range phase coherence was shown to occur concurrently with the possibility to excite superfluid flow<sup>8,16,17,21</sup>. Superfluid hydrodynamics is usually regarded as the direct proof for superfluidity. However, all reports of superfluidity of bosons in three-dimensional optical lattices have relied solely on observations of sharp interference peaks and inferred superfluidity from the established connection between long-range coherence and superfluidity<sup>19,22</sup>. Similarly, our observations directly show long-range coherence and indirectly show superfluidity of fermion pairs in an optical lattice.

For deep lattices, breakdown of superfluid behaviour has been observed for weakly interacting BECs of different bosonic species<sup>19,23</sup>. This phase transition to the Mott-insulator state occurs when on-site interactions start to suppress atom number fluctuations and the system undergoes a transition from a delocalized superfluid



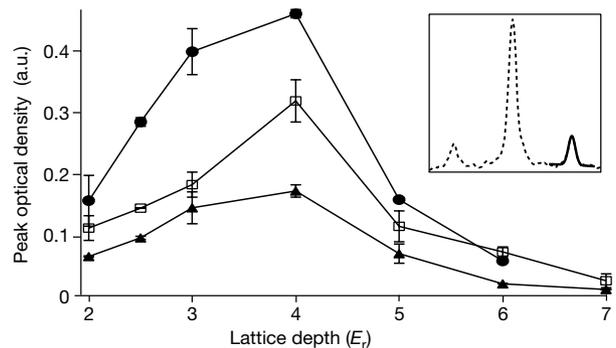
**Figure 3 | Interferograms of fermion pairs released from different lattice depths  $V_0$  at a field of 822 G.** Values of  $V_0$  are  $0E_r$  (**a**),  $2.5E_r$  (**b**),  $4E_r$  (**c**),  $5E_r$  (**d**),  $6E_r$  (**e**),  $7E_r$  (**f**),  $9E_r$  (**g**) and  $2.5E_r$  (**h**). **a–g** were taken after an adiabatic ramp up to the final  $V_0$ , whereas **h** was taken after first ramping up to  $10E_r$  before ramping down to  $2.5E_r$ .

described by a macroscopic wavefunction to a product of Wannier states tightly localized at each lattice site. Experimentally, this is manifested as a smearing of the distinct  $2\hbar k_L$  interference peaks.

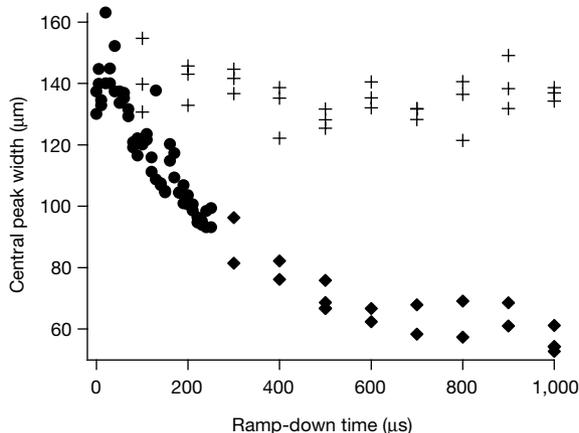
Figure 3 shows the change in the coherence properties when the lattice depth was increased. The interference peaks became more pronounced initially, because of increased modulation of the wavefunction. The interference peaks began to smear out, rapidly giving way to a featureless cloud, beyond a critical lattice depth  $V_c \approx 6E_r$ , where  $E_r = \hbar^2 k_L^2 / 4m = \hbar \times 15 \text{ kHz}$  is the recoil energy. This indicates that all phase coherence had been lost. On subsequent ramping down of the lattice, interference peaks became visible again (Fig. 3h), showing reversibility of the lattice ramp.

We repeated this sequence for a wide range of initial magnetic fields, both above and below the resonance, and observed the same marked change in the interference pattern. Figure 4 displays the peak optical density of the interference peaks for different lattice depths at representative fields. Across all fields, the sharp decrease in peak optical density occurred between  $5E_r$  and  $6E_r$ . A further increase in the magnetic field resulted in decreasing overall visibility, until interference peaks could no longer be observed regardless of lattice depth.

The loss of phase coherence with increasing lattice depth is consistent with the qualitative description of the superfluid to Mott-insulator transition. However, the usual single-band description is no longer applicable, because in the strong-coupling regime the on-site interaction strength should be comparable to the band gap  $\hbar\omega$ , where  $\omega$  is the onsite trap frequency. Furthermore, Pauli blocking forbids the multiple occupation of the lowest state of an



**Figure 4 | Peak optical density of interference peaks for increasing lattice depths at different magnetic fields.** Values of magnetic fields are 842 G (filled circles), 892 G (open squares) and 942 G (filled triangles). Peak optical densities were estimated from fits to the peaks, including background subtraction. The inset shows a sample density profile of the central and one pair of interference peaks (dotted line), with a bimodal fit to one side peak (solid line). Each point is the average of three different images with six interference peaks per image. Error bars show s.d.



**Figure 5 | Restoring coherence from a deep lattice.** The width of the central peak is used as a measure of phase coherence after an adiabatic ramp up to  $8E_F$ , followed by a fast ramp down to  $2.5E_F$  at a fixed magnetic field of 822 G. Filled circles were extracted with the use of a gaussian fit, and diamonds with a bimodal fit. Also plotted for comparison is the gaussian width of the central peak for a dephased sample, in which a field gradient was applied during the ramp up of the lattice (crosses). All points were taken for 6.5 ms time of flight.

individual lattice site by identical fermions, and modification of the single-particle tunnelling rate is expected as a result of virtual pair-breaking transitions<sup>14</sup>. One may still be tempted to use the standard bosonic Hubbard model and estimate the critical lattice depth  $V_c$  for an assumed value of onsite interaction energy  $U = \hbar\omega$  and non-interacting, single-particle tunnelling  $J$ , but the obtained  $V_c \approx 3E_F$  is significantly smaller than our observation, which is in turn much smaller than the  $V_c > 10E_F$  observed for weakly interacting atomic BECs<sup>19,23</sup>. Together with the observed insensitivity of  $V_c$  to the magnetic field, this shows that models based on weak interactions are inadequate.

Figure 3h shows the reversibility of the transition from a long-range coherent state to a state without strong coherence. We now study the timescale for this recoherence, by analogy with similar measurements performed across the transition from superfluid to Mott insulator in atomic BECs<sup>19</sup>. Figure 5 shows that phase coherence was restored on a submillisecond timescale, on the order of the single-particle tunnelling time of about 500  $\mu\text{s}$  (for a shallow lattice of  $2.5E_F$ ). When the same lattice ramp sequence was applied to a superfluid that had been dephased by a magnetic field gradient<sup>19</sup>, the system did not regain phase coherence on the timescales that we probed. Evaporative cooling is therefore negligible during this time. The short recoherence time of the condensate is evidence that the system stayed in its ground state or at least in a low-entropy state when the lattice was ramped up.

Figure 5 also provides evidence that the system could not recohere during the 150- $\mu\text{s}$  magnetic field ramp. In Fig. 3h, the central peak is well fitted by a bimodal distribution with a width of 35  $\mu\text{m}$ , in clear contrast to the gaussian width of 105  $\mu\text{m}$  obtained from Fig. 5 after 150  $\mu\text{s}$ . We therefore conclude that the observed interference patterns in Fig. 1 reflect the coherence of the cloud at the initial magnetic field, in the strongly interacting regime.

We have shown long-range phase coherence of fermion pairs in an optical lattice in the BEC–BCS crossover region by observing sharp interference peaks during ballistic expansion. This indicates that we have achieved *s*-wave pairing and superfluidity in a lattice potential. Further studies will reveal how the pair wavefunction is affected by confinement<sup>24</sup>, and whether the lattice shifts the BEC–BCS crossover away from the Feshbach resonance<sup>25</sup>. The loss of coherence during the lattice ramp up and the rapid recoherence are characteristic of a Mott insulator. However, definitive proof will require a

better understanding of the unitarity-limited interactions in such a Fermi system. Recent theoretical work<sup>14,26</sup> predicts that strongly interacting fermions in an optical lattice feature multiband couplings and next-neighbour interactions and can realize the important *t*–*J* and magnetic XXZ models of condensed-matter theory. This demonstrates that such atomic systems are an ideal laboratory for the exploration of novel condensed-matter physics.

## METHODS

Clouds of superfluid fermion pairs were created in a new experimental setup<sup>27,28</sup> by using techniques similar to those described elsewhere<sup>8</sup>. In brief, a combination of laser cooling and sympathetic cooling of spin-polarized fermions by bosonic  $^{23}\text{Na}$  was followed by a spin transfer to create a two-component Fermi gas, allowing further cooling through direct evaporation of the fermions. As the fermions cooled, they formed pairs that Bose-condensed.

Estimates of the scattering length, and hence the interaction parameter, from the magnetic field were obtained with  $a(B) = -1,405a_0[1 + 300/(B - 834)][1 + 0.0004(B - 834)]$  (ref. 29), where  $B$  is measured in gauss and  $a_0$  is the Bohr radius. The calibration of the magnetic field in our system had an uncertainty of about 5 G.

Evaporation was performed at a magnetic field of 822 G, at which strong interactions permitted efficient evaporation. An estimated average final number of  $N \approx 2 \times 10^5$   $^6\text{Li}$  pairs and harmonic trapping frequencies of  $\nu_{x,y,z} = (270,340,200)$  Hz gave a trap depth of 1.7  $\mu\text{K}$  and a Fermi energy of  $E_F = k_B \times 1.4 \mu\text{K}$ , where  $E_F = \hbar\bar{\omega}(6N)^{1/3}$  and  $\bar{\omega}$  is the average trapping frequency. After evaporation, the magnetic field was brought to a desired value  $B_0$  in 20 ms and the condensate was allowed to equilibrate for a further 200 ms. Before ramping to values of  $B_0$  on the BCS side, we also recompressed the optical trap to (340,440,270) Hz and 2.2  $\mu\text{K}$  depth in 100 ms to accommodate the larger Fermi clouds above the resonance<sup>7</sup>.

A three-dimensional optical lattice was formed from three optical standing waves, oriented such that the resulting unit cell had a sheared cubic structure, with one axis tilted about  $20^\circ$  from the normal for reasons of optical access (see Fig. 1a)<sup>23</sup>. The incident laser beams were focused down to the condensate with waists of about 90  $\mu\text{m}$ , then retroreflected and overlapped at the condensate to generate the standing-wave potentials. All lattice light was derived from a 1,064-nm single-frequency fibre laser, and each beam was detuned by tens of MHz with respect to the others to eliminate interference between different beams.

The lattice potential was imposed on the condensate by adiabatically increasing the intensity of the laser beams to a variable final value  $V_0$ . The calibration of  $V_0$  had an uncertainty of about 20%. A simple linear ramp with a constant rate  $dV_0/dt$  of  $0.5E_F \text{ ms}^{-1}$  was used unless otherwise specified. This satisfies the inter-band adiabaticity condition of  $dV_0/dt \ll 16E_F^2/\hbar$ .

Ballistic expansion for the detection of the different momentum components was provided by a magnetic field sequence (shown in Fig. 1) that quickly brought the system out of the strongly interacting regime when all confinement was switched off. During the magnetic field ramp of about 150  $\mu\text{s}$ , the lattice potential was kept on. The first 2 ms of expansion took place at 470 G, at which the molecules are tightly bound, before the field was ramped back up to 730 G in the next 4.5 ms, at which the weakly bound molecules strongly absorb light near the atomic resonance line and could be observed by absorption imaging. The specific magnetic field sequence was chosen to minimize collisions within technical capabilities.

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