Observing the drop of resistance in the flow of a superfluid Fermi gas

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The ability of particles to flow with very low resistance is characteristic of superfluid and superconducting states, leading to their discovery in the past century1,2. Although measuring the particle flow in liquid helium or superconducting materials is essential to identify superfluidity or superconductivity, no analogous measurement has been performed for superfluids based on ultracold Fermi gases. Here we report direct measurements of the conduction properties of strongly interacting fermions, observing the well-known drop in resistance that is associated with the onset of superfluidity. By varying the depth of the trapping potential in a narrow channel connecting two atomic reservoirs, we observed variations of the atomic current over several orders of magnitude. We related the intrinsic conduction properties to the thermodynamic functions in a model-independent way, by making use of high-resolution in situ imaging in combination with current measurements. Our results show that, as in solid-state systems, current and resistance measurements in quantum gases provide a sensitive probe with which to explore many-body physics. Our method is closely analogous to the operation of a solid-state field-effect transistor and could be applied as a probe for optical lattices and disordered systems, paving the way for modelling complex superconducting devices.

Over the past decade, cold atoms have emerged as a many-body system with a uniquely high level of control3. Experiments have shown that interacting atomic Fermi gases, analogous to electrons in a solid, can display superfluidity4. The equilibrium properties of such gases have been measured with increasing precision5–8 and the superfluid character of the ground state has been investigated via the response to external perturbations9 and the direct observation of vortices10, in the same way as for Bose–Einstein condensates11–13. Using new techniques to create and observe directed currents in a closed atomic circuit17 or between two large reservoirs15, it is now possible to study the transport properties of mesoscopic systems that are directly analogous to electronic devices16.

Here we investigated the conduction properties of strongly interacting fermions flowing through a quasi-two-dimensional, multimode channel, which connects two atomic reservoirs. Going beyond our previous work17, we now obtained full control over the atomic current by tuning a repulsive gate potential in the channel. The gate potential was created by an off-resonant laser beam, as illustrated in Fig. 1. In analogy with an electronic field-effect transistor, this gate potential controls the chemical potential in the channel while keeping the temperature imposed by the reservoirs unchanged. With the gate potential as a control parameter, we measured the current through the channel over a large dynamic range and related it to the observed density in the channel region. This allowed us to observe the onset of superfluid flow of strongly interacting fermions. We compared these measurements to the case of weakly interacting fermions. In our experiment, the current established in the channel was a response to the longitudinal perturbation induced by a difference in chemical potential between the two reservoirs. This is complementary to experiments probing the response of isolated atomic clouds to transverse excitation via rotation18 or shear19.

Our experiments were performed with strongly and weakly interacting quantum degenerate gases of fermionic 6Li atoms, equally populating the lowest two hyperfine states. To obtain a strongly interacting gas, the atoms were placed in a homogeneous magnetic field of 834 G where the s-wave scattering length diverges and leads to the formation of pairs, while a weakly interacting gas was studied at a field of 475 G (see Methods and Supplementary Information). The atoms were radially confined in the x–z plane by an optical dipole trap oriented along the y-axis with a 1/e2 beam radius of 22(1) μm; here and elsewhere, the value in parentheses is the 1-σ error of the last significant digit. Along the y-direction, the curvature of the magnetic field yielded a harmonic confinement with a frequency of ωy = 2π × 32(1) Hz. To engineer the reservoirs, we split the cloud into two parts using a repulsive laser beam at a wavelength of 532 nm that points along the x-direction (beam not shown in Fig. 1). The intensity profile of this beam has a holographically imprinted nodal line along the y-axis. As a result, a channel in the x–y plane was formed, which confined the atoms along the z-direction with a centre trap frequency of 2.9 kHz. The gate potential was created by another laser beam at 532 nm that was sent along the z-axis onto the channel and had a waist of 18 μm. We refer to the maximum of the repulsive potential created by this beam as the gate potential U. Along the z-axis, a high-resolution microscope objective was used for in situ absorption imaging of the atoms in the channel. The atom number in the reservoirs was measured by absorption imaging along the x-direction. By creating an atom number imbalance between the two reservoirs, we created a chemical potential bias that induced a current through the channel17.

The inset to Fig. 2a presents an example of the time evolution of the relative number imbalance between the two reservoirs, measured for strongly interacting (red) and weakly interacting (blue) fermions, using the same gate potential of U = 525(50) nK. For the strongly interacting gas, an exponential fit yielded a decay time of 0.057(7) s,

Figure 1 | Principle of the experiment. Two atomic reservoirs (source and drain) are connected by a quasi-two-dimensional conducting channel. An atom number imbalance N_{left} > N_{right} between source and drain drives an atom current through the channel, indicated by the arrows. A repulsive laser beam (gate beam) propagating along the z-axis is focused on the channel. It creates a repulsive potential with a gaussian envelope and a tunable amplitude. The lighter region in the channel indicates the reduced density due to the repulsive potential.
which is more than one order of magnitude faster than the decay time of 0.70(6) s obtained for the weakly interacting gas.

The reservoirs can be considered to be in quasi-thermal equilibrium during the entire decay, provided this process is sufficiently slow compared to the thermalization dynamics within the reservoirs. Thus we interpret the exponential decay of the imbalance as a resistance measurement through a tunable channel with resistance $R$. This is analogous to the discharge of a capacitor with a fixed capacity $C$ where the decay time is $\tau = RC$. In our system $C$ is the compressibility of the reservoirs, which remains constant as the gate potential is varied\textsuperscript{17}. The natural timescale to which we compare the decay time is provided by $\omega_y$, the frequency of the overall harmonic confinement along the $y$-axis. Therefore, we defined a dimensionless resistance $r = RC\omega_y$, which is shown in Fig. 2a as a function of the gate potential $U$. For decreasing gate potential the weakly interacting Fermi gas (blue) shows a decrease of resistance reaching a minimum value of $r \approx 35$ for zero gate potential. For high gate potentials the resistance for both interaction strengths are comparable, yet the strongly interacting gas (red) showed a much faster drop of resistance below $0.7 \mu$K. At a gate potential of $0.23(2) \mu$K the resistance differed by a factor of about 25 from the weakly interacting gas. As $r$ approaches unity (below $0.23 \mu$K) the decay time $\tau$ became equal to the timescale of the internal dynamics of the reservoirs, set by the trap frequency along the $y$-direction. In this regime, we cannot interpret our strongly interacting data sets in terms of a resistance measurement because the reservoirs do not remain in thermal equilibrium at each point in time, that is, the resistance drops below our measurement capabilities. This gives rise to deviations from the exponential decay.

In addition to the resistance, we also estimated the current through the channel using a linear fit to the initial part of the decay (see Methods). This measurement does not rely on the thermalization of the reservoirs and thus can also be applied to cases where the reservoirs are not fully in quasi-thermal equilibrium. Figure 2b shows the current $I$ as a function of the gate potential for the strongly interacting gas (red) and the weakly interacting gas (blue). Unlike the weakly interacting gas, the strongly interacting gas showed a fast increase of the current below $0.7 \mu$K. For the lowest gate potentials the current was limited by the conservation of energy. The limit was reached when the potential energy introduced by the initial imbalance was fully converted into kinetic energy, as for example in undamped dipole oscillations. It is represented by the shaded region in the inset to Fig. 2b, where we show the current in logarithmic scale. Remarkably, the observed current was very close to that limit, meaning that the strongly interacting Fermi gas flowed as if there were no constriction or gate potential at all. This is the expected behaviour of a superfluid.

Although the current depends on the atomic density in the channel, the transport properties are characterized in a density-independent way by the drift velocity. To extract this quantity, we first used high-resolution \textit{in situ} imaging to measure the atomic line density $n_{\text{line}}$ in the channel. The measured line density as a function of the gate potential is shown in the inset to Fig. 3. As expected from its higher compressibility\textsuperscript{18-20}, the strongly interacting gas reached larger line densities. For each value of the gate potential, we then divided the measured current by the corresponding line density, yielding the drift velocity.

The drift velocities as a function of gate potential are presented in Fig. 3. The drift velocity for the weakly interacting gas showed almost no variations. In contrast, the drift velocity for the strongly interacting gas increased significantly below $U = 0.7 \mu$K. This demonstrates that the large increase of the current, seen in Fig. 2, was not simply caused by the higher density of the strongly interacting gas in the channel and reveals a change in the nature of the transport process. It cannot be explained by a transition of the gas from ballistic to classical hydrodynamic behaviour because even for large gate potentials the mean free

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**Figure 2** | Conduction properties through the channel. Red and blue data points correspond to the strongly and weakly interacting gas, respectively.

(a) Dimensionless resistance $r$ as a function of gate potential $U$. The data points shown are those for which the decay is exponential. The inset to a shows a decay of the relative atom number imbalance between source and drain as a function of time with a gate potential $U = 525(50)$ nK, where $N$ is the total number of atoms and $\Delta N$ is the difference in atom number. The solid lines are exponential fits with fixed offset of 0.04 for the red curve to account for a small remaining imbalance in the reservoirs. (b) Atom current as a function of the gate potential $U$. A large increase of the current appears for the strongly interacting gas below $U = 0.7 \mu$K. The inset to b shows the atom current in logarithmic scale. The shaded region indicates the maximum current allowed by the internal dynamics of the reservoirs (see main text). The error bars show the statistical errors.

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**Figure 3** | Density-independent conduction properties through the channel. Red and blue data points correspond to strongly interacting and weakly interacting atoms, respectively. Drift velocity is plotted as a function of gate potential. The points corresponding to the three highest values of the gate potential are omitted in the weakly interacting case because the density is almost zero. The inset shows line density $n_{\text{line}}$ measured \textit{in situ} in the channel as a function of gate potential (see Methods). The error bars represent statistical errors (one standard deviation).
path remains well below the channel size. On the other hand, at low gate potentials, that is, at low $T/T_F$, where $T_F$ is the Fermi temperature, Pauli blocking of interparticle collisions in a normal gas should restore the ballistic behaviour\(^{21–23}\) (see Methods). This is in contrast to our observations, supporting our superfluidity interpretation. Whether another mechanism can lead to better conduction properties than that of a perfect ballistic conductor is unclear.

It was instructive to compare the drift velocity to characteristic velocities of the superfluid flow. A Landau-type critical velocity provides a value which is expected to be of the order of the Fermi velocity for strongly interacting fermions\(^1\). We estimated the Fermi velocity in the channel from the column density at zero gate potential, which gives about 50 mm s\(^{-1}\), twice as large as the measured drift velocity. Additionally, the creation of vortices in the fluid provided a lower critical velocity, giving rise to a finite resistance. This velocity can be roughly estimated from the channel geometry and the healing length using energetic arguments\(^{4,6}\), and yielded about 5 mm s\(^{-1}\). The observed drift velocity was significantly larger than this critical value. This would explain the low but finite resistance observed even in the superfluid state, where the decay of the number imbalance is fast but remains exponential.

We next related the conduction properties to a thermodynamic parameter by replacing the gate potential scale, which is specific to our system, by the thermodynamic potential. To this end, we used the high-resolution images of the gas in the channel, which gave us access to the equation of state\(^{4,8}\). The gas in the channel is in the crossover regime between two and three dimensions, where the equation of state naturally relates the column density $n_{\text{col}}$ to the chemical potential\(^{24,25}\) (see Methods). From the in situ absorption images of the channel for different gate potentials we obtained $n_{\text{col}}(U)$ at fixed temperature, which is imposed by the reservoirs. Integrating this relation over the known variations of the gate potential yielded the thermodynamic potential $\Omega(U) = \int V_{\text{eff}(V)} \, dV$ which would be equal to the pressure in a purely two-dimensional gas. We normalized $\Omega$ by the pressure of a two-dimensional ideal Fermi gas at zero temperature $\Omega_0 = \frac{\hbar^2}{2m} n_{\text{col}}^2 / m$ and obtained a model-independent thermodynamic scale, analogous to the three-dimensional situation discussed in ref. 8. This allowed us to convert the gate potential into a thermodynamic quantity, even though the gas in the channel was not expected to be in the universal regime\(^4\) owing to the strong confinement\(^26\), where most of the thermometry techniques cannot be applied directly\(^4,8\).

The drift velocity as a function of reduced thermodynamic potential is shown in Fig. 4. The strongly interacting gas (red) show a pronounced increase of drift velocity below $\Omega/\Omega_0 \approx 1$, indicating the onset of superfluidity. This illustrates the high sensitivity of transport measurements to many-body effects in strongly correlated quantum gases. For higher $\Omega/\Omega_0$ the blue and red data sets show a constant drift velocity. The inset to Fig. 4b presents the resistance as a function of $\Omega/\Omega_0$ for the strongly interacting Fermi gas. Here, we observed a very rapid decrease of the resistance for low values of $\Omega/\Omega_0$. We interpret this as the counterpart of the drop of resistance observed in superconductors. Measurements of the equation of state of a unitary Fermi gas in three dimensions have shown that the transition takes place for a critical reduced thermodynamic potential of 0.55 (ref. 8). Even though our channel is in the crossover between two and three dimensions, we observed the change in the conduction properties at around the value of the two-dimensional reduced thermodynamic potential (black dashed lines in Fig. 4).

Our experimental geometry is reminiscent of weak links in superconductors\(^1\) and the experiment probes transport in a channel that is long compared to the coherence length. The coherence length of a strongly interacting superfluid is of the order of the interparticle spacing\(^5\), which is below a few micrometres in the channel and smaller elsewhere. The length and energy scales of our experiment mean that we operate in a dissipative regime complementary to the coherent tunnelling encountered in Josephson junctions\(^27,28\). Our set-up allows the investigation of superfluidity and supercurrents in a variety of configurations by projecting a designed potential through the microscope onto the channel\(^29\). This opens the way towards the cold-atom modelling of complex, superconducting devices.

**METHODS SUMMARY**

A balanced mixture of the two lowest hyperfine states of $^6$Li is prepared by all-optical evaporation. Final temperatures are $\lesssim 0.1T_F$ (strongly interacting gas, $6.7 \times 10^4$ atoms) and approximately $0.3T_F$ (weakly interacting gas, $4.5 \times 10^4$ atoms). For the strongly interacting gas the evaporation is performed at a magnetic field of 795 G (scattering length 3,500 a$_0$, where a$_0$ is the Bohr radius), then the field is adiabatically ramped to 834 G, at the s-wave Feshbach resonance. The weakly interacting gas is cooled at 300 G, then the field is ramped to 475 G (scattering length $\approx 100a_0$). The trap frequency along the $y$-axis is $\omega_y = 2\pi \times 32(1)$ s$^{-1}$ and $\omega_y = 2\pi \times 25(1)$ s$^{-1}$ for the strongly and weakly interacting gases, respectively. To induce an atom current, we create a number imbalance between the two reservoirs by shifting the trapping potential along the $y$-direction with a magnetic field gradient of 0.25 G cm$^{-1}$. After switching off the gradient within 10 ms, we monitor the decay of the number imbalance. The number imbalance and the total atom number are obtained from absorption images along the $x$-axis. For all data, we fit a line to the first four points of a measured decay curve of the relative number imbalance. We define the current as the fitted slope times half the total number of atoms in both reservoirs at equilibrium. To measure the column density $n_{\text{col}0}$ as well as the line density at the centre of the channel for different gate potentials, we take in situ absorption images of the channel through the high-resolution microscope in the absence of current. We apply light pulses of 5 ms and a saturation of about 0.1. The local density approximation gives the equation of state\(^6\) $n_{\text{col}0}(\mu_0 - V)$, where $\mu_0$ is the chemical potential imposed by the reservoirs and $V$ is the local gate potential. Integrating this equation over the gate potential leads to the thermodynamic potential.

**Full Methods** and any associated references are available in the online version of the paper.

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1. Leggett, A. J. Quantum Liquids: Bose Einstein Condensation and Cooper Pairing in Condensed-Matter Systems (Oxford University Press, 2006).
2. van Delft, D. & Kes, P. The discovery of superconductivity. *Phys. Today* **63**, 38–43 (2010).
3. Bloch, I., Dalibard, J. & Zwerger, W. Many-body physics with ultracold gases. *Rev. Mod. Phys.* **80**, 885–964 (2008).
4. Giorgini, S., Pitaevskii, L. P. & Stringari, S. Theory of ultracold atomic Fermi gases. *Rev. Mod. Phys.* **80**, 1215–1274 (2008).
5. Luo, L., Clancy, B., Joseph, J., Kinast, J. & Thomas, J. E. Measurement of the entropy and critical temperature of a strongly interacting Fermi gas. *Phys. Rev. Lett.* **98**, 080402 (2007).
6. Horikoshi, M., Nakajima, S., Ueda, M. & Mukaiyama, T. Measurement of universal thermodynamic functions for a unitary Fermi gas. Science 327, 442–445 (2010).
7. Nascimbène, S., Navon, N., Jiang, K. J., Chevy, F. & Salomon, C. Exploring the thermodynamics of a universal Fermi gas. Nature 463, 1057–1060 (2010).
8. Ku, M. J. H., Sommer, A. T., Cheuk, L. W. & Zwierlein, M. W. Revealing the superfluid lambda transition in the universal thermodynamics of a unitary Fermi gas. Science 335, 563–567 (2012).
9. Miller, D. E. et al. Critical velocity for superfluid flow across the BEC-BCS crossover. Phys. Rev. Lett. 99, 070402 (2007).
10. Zwierlein, M. W., Abo-Shaeer, J. R., Schirotzek, A., Schunck, C. H. & Ketterle, W. Vortices and superfluidity in a strongly interacting Fermi gas. Nature 435, 1047–1051 (2005).
11. Madison, K. W., Chevy, F., Wohleben, W. & Dalibard, J. Vortex formation in a stirred Bose-Einstein condensate. Phys. Rev. Lett. 84, 806–809 (2000).
12. Matthews, M. R. et al. Vortices in a Bose-Einstein condensate. Phys. Rev. Lett. 83, 2498–2501 (1999).
13. Raman, C. et al. Evidence for a critical velocity in a Bose-Einstein condensed gas. Phys. Rev. Lett. 83, 2502–2505 (1999).
14. Burger, S. et al. Superfluid and dissipative dynamics of a Bose-Einstein condensate in a periodic optical potential. Phys. Rev. Lett. 86, 4447–4450 (2001).
15. Amo, A. et al. Superfluidity of polaritons in semiconductor microcavities. Nature Phys. 5, 805–810 (2009).
16. Ramanathan, A. et al. Superflow in a toroidal Bose-Einstein condensate: an atom circuit with a tunable weak link. Phys. Rev. Lett. 106, 130401 (2011).
17. Brantut, J.-P., Meineke, J., Stadler, D., Krinner, S. & Esslinger, T. Conduction of ultracold Fermions through a mesoscopic channel. Science 337, 1069–1071 (2012).
18. Seaman, B. T., Kraemer, M., Anderson, D. Z. & Holland, M. J. Atomtronics: Ultracoldatom analogs of electronic devices. Phys. Rev. A 75, 023615 (2007).
19. Cao, C. et al. Universal quantum viscosity in a unitary Fermi gas. Science 331, 58–61 (2011).
20. Bartenstein, M. et al. Crossover from a molecular Bose-Einstein condensate to a degenerate Fermi gas. Phys. Rev. Lett. 92, 120401 (2004).
21. Sommer, A., Ku, M., Roati, G. & Zwierlein, M. W. Universal spin transport in a strongly interacting fermi gas. Nature 472, 201–204 (2011).
22. Enss, T., Haussmann, R. & Zwerger, W. Viscosity and scale invariance in the unitary Fermi gas. Ann. Phys. 326, 770–796 (2011).
23. Bruun, G. M. Shear viscosity and spin-diffusion coefficient of a twodimensional Fermi gas. Phys. Rev. A 85, 013636 (2012).
24. Orel, A. A., Dyke, P., Delehaye, M., Vale, C. J. & Hu, H. Density distribution of a trapped two-dimensional strongly interacting Fermi gas. N. J. Phys. 13, 113032 (2011).
25. Dyke, P. et al. Crossover from 2D to 3D in a weakly interacting Fermi gas. Phys. Rev. Lett. 106, 105304 (2011).
26. Petrov, D. S. & Shlyapnikov, G. V. Interatomic collisions in a tightly confined Bose gas. Phys. Rev. A 64, 012706 (2001).
27. Albiez, M. et al. Direct observation of tunneling and nonlinear self-trapping in a single bosonic Josephson junction. Phys. Rev. Lett. 95, 010402 (2005).
28. LeBlanc, L. J. et al. Dynamics of a tunable superfluid junction. Phys. Rev. Lett. 106, 025302 (2011).
29. Zimmermann, B., Muller, T., Meineke, J., Esslinger, T. & Moritz, H. High-resolution imaging of ultracold fermions in microscopically tailored optical potentials. N. J. Phys. 13, 045007 (2011).

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METHODS

Cloud preparation. A quantum degenerate Fermi gas is prepared by all-optical evaporation of a balanced mixture of the two lowest hyperfine states of $^6$Li. Evaporation is performed at a magnetic field of 795 G (where the scattering length is $3,500a_0$, and $a_0$ is the Bohr radius) down to a trap depth of 880 nK. This produces a Bose–Einstein condensate of molecules. Then the trap depth is increased to 2.6 μK in order to stop the evaporation, and the magnetic field is adiabatically ramped up to 834 G, where the broad $s$-wave Feshbach resonance is positioned. The curvature of this Feshbach field sets the trap frequency along the $y$-axis at $\omega_y = 2\pi \times 32(1)$ Hz. We obtain a strongly interacting Fermi gas of about $6.7 \times 10^4$ atoms with a temperature $T \leq 0.17T_F$, where $T_F$ is the Fermi temperature. We determine the chemical potential ($\mu = 0.8 \mu K$) of the strongly interacting gas by measuring the size of the cloud in the trap. The weakly interacting Fermi gas is prepared using the same evaporation ramp at a magnetic field of 300 G. The magnetic field is then ramped up adiabatically to 475 G ($\omega_y = 2\pi \times 25(1)$ Hz) where the scattering length is $-100a_0$. This yields atom numbers of about $4.5 \times 10^3$ at $T = 0.37T_F$. We keep the scattering length at a small but finite value to ensure that the reservoirs remain at equilibrium during the measurement.

Current generation and measurement. During evaporative cooling we create a number imbalance between the two reservoirs by having the trapping potential shifted along the $y$-direction, away from the centre position of the channel. The shift is created using a magnetic field gradient of $0.25$ G cm$^{-1}$ along the $y$-axis. Restoring the symmetry of the potential in $10$ ms creates an atom number imbalance in the symmetric trapping configuration. This leads to a potential imbalance, inducing the atom current. To infer the atom number imbalance, as well as the total atom number, the number of atoms in each reservoir is measured by absorption imaging along the $x$-axis. This is done for variable time delays. Each measurement is repeated three times and averaged to reduce the noise. In addition to the exponential fit, we fit a line to the first four points of a measured decay curve of the relative number imbalance. We define the current $I$ as the fitted slope multiplied by half the total atom number in both reservoirs at equilibrium. For the case where the decay is exponential we checked that fitting a line and an exponential gives the thermodynamic scale that is used for Fig. 4.

Equilibrium density of the gas. In the absence of current, we take in situ absorption images of the cloud through the high-resolution microscope. We use light pulses of 5 μs with an intensity of about 0.1 of the saturation intensity. We extract the line density of the cloud by counting the total number of atoms in a region of $18$ μm along the $y$-axis at the centre of the channel, over which the trap frequency along the $y$-axis varies by less than $10\%$. The variations of column density along the $x$-axis are measured by counting the atom number in patches of length 18 μm in the $y$-direction, and 2.4 μm in the $x$-direction. From the known waist of the dipole trap---$22(1)$ μm---we infer that the change of chemical potential within one of those patches is lower than $13.7\%$. All in situ pictures are averaged $20$ times to reduce the noise. In addition, the gate beam profile is directly imaged through the same optical system, yielding a map of the gate potential.

Thermodynamic potential. For each power setting of the gate beam, the in situ column density along the $x$-axis is processed in seven patches to yield a set of curves $n_{\text{sat}}(V)$, where $V$ is the local gate potential in the corresponding patch. In the local density approximation, these curves belong to the same equation of state (because the confinement along the $z$-axis is the same in all patches). The curves are combined using the hypothesis that regions having the same column density have the same chemical potential, giving the equation of state $n_{\text{sat}}(V_0 - V)$. Here $V_0$ is the unknown chemical potential imposed by the reservoirs. Integrating this equation of state from $V$ to the largest gate potential (for which density is zero) gives the thermodynamic potential as a function of $U$ for a fixed (but unknown) temperature. By normalizing the thermodynamic potential to that of an ideal two-dimensional Fermi gas with the same column density, we obtain the thermodynamic scale that is used for Fig. 4.

Confinement-dominated regime in the channel. Inside the reservoirs, the size of the superfluid pairs on the Feshbach resonance is $2.6/k_{s0} = 0.6$ μm (ref. 30). This length scale is of the order of the size of the ground state of the harmonic oscillator for atoms in the channel, $\sqrt{\hbar/(m\omega_z)} = 0.8$ μm. Therefore, even for the lowest gate potentials, we expect the pairing mechanism in the channel to be influenced by the confinement. As the gate potential is increased, the density in the channel decreases, so the expected pair size, being inversely proportional to the Fermi wavevector on the Feshbach resonance, increases, and the gas acquires a more and more pronounced two-dimensional character.

Hydrodynamic behaviour of the strongly interacting Fermi gas. We estimate the mean free path between collisions for the gas at a magnetic field of 834 G and compare it to the length of the channel to evaluate the hydrodynamic character of the strongly interacting gas. We first consider the limit of low density, that is, large $T/T_F$, at high gate potential. Using a two-dimensional ansatz for the gas at high gate potential and following ref. 26, we estimate the collision rate $\Omega = h n_{\text{3D}}|f|^2/m$ from the scattering amplitude $f$, which depends only on the two-dimensional density $n_{\text{3D}}$ (via the Fermi energy) and the confinement when the three-dimensional scattering length diverges. The mean free path is given by the Fermi velocity divided by the collision rate, yielding $l \leq 2$ μm for $n_{3D} > 0.01 \mu m^{-2}$. With our channel length of around 20 μm, the gas is hydrodynamic down to the lowest observed densities. In the opposite limit of low gate potentials and high density, Pauli blocking of collisions is expected to increase the mean free path in a classical hydrodynamic gas, eventually making the gas ballistic. We assume the gas to be in the three-dimensional regime, which yields the unitarity-limited scattering cross-section given by $\sigma = 4\pi/k_{\text{F}}^2$, with $k_{\text{F}}$ the Fermi wavevector. The mean free path is given by $l = 1/\sigma n_{\text{3D}}$ with $n_{\text{3D}}$ the three-dimensional density. This yields $l = 1$ μm for $n_{\text{3D}} = 2$ μm$^{-2}$. Pauli blocking, however, reduces the scattering cross-section proportional to $(T/T_F)^2 \geq 0.01$ (ref. 31) for our case, leading to a mean free path of the order of the channel size or even larger.

30. Schunck, C. H., Shin, Y.-i., Schirotzek, A. & Ketterle, W. Determination of the fermion pair size in a resonantly interacting superfluid. Nature 454, 739–743 (2008).

31. O’Hara, K. M., Hemmer, S. L., Gehm, M. E., Granade, S. R. & Thomas, J. E. Observation of a strongly interacting degenerate Fermi gas of atoms. Science 298, 2179–2182 (2002).