Observation of chiral currents with ultracold atoms in bosonic ladders

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Engineering optical lattices with laser-induced tunnelling amplitudes has enabled the realization of artificial magnetic fields with remarkable tunability. Here, we report on the observation of chiral Meissner currents in bosonic ladders exposed to a strong artificial magnetic field. By suddenly decoupling the individual ladders and projecting into isolated double wells, we are able to measure the currents on each side of the ladder. For large coupling strengths along the rungs of the ladder, we find a saturated maximum chiral current, which is analogous to the surface currents in the Meissner effect. Below a critical inter-leg coupling strength, the chiral current decreases in good agreement with our expectations for a vortex lattice phase. Our realization of a low-dimensional Meissner-like effect and spin–orbit coupling in one dimension opens the path to exploring interacting particles in low dimensions exposed to a uniform magnetic field.

The Meissner effect is the hallmark signature of a superconductor exposed to a magnetic field³,². For a type-II superconductor, full screening of the applied external field occurs up to a critical field \( H_{c1} \). Such a screening is the result of circular surface currents on the superconductor that generate an opposite field, cancelling the applied field. The superconductor thus acts as a perfect diamagnet in the Meissner phase. For larger field strengths \( H > H_{c1} \), however, the superconductor is not able to fully screen the applied field and an Abrikosov vortex lattice phase is formed in the system. In low-dimensional quantum systems it has been a longstanding challenge to probe analogue ideas and investigate the interplay of orbital magnetic field effects and interactions. Whereas a single one-dimensional system does not allow for any orbital magnetic field effects, a ladder system is the simplest extension where these are permitted³–⁹.

Here we report on the realization of such bosonic ladders for ultracold atoms exposed to a uniform artificial magnetic field created by laser-assisted tunnelling⁰–¹⁹. Previously, such ladders have been discussed in the context of Josephson-junction arrays³,¹⁰–¹² and more recently also for ultracold atoms exposed to an artificial gauge field³–⁹. In our experiment we can measure the probability current on either leg of the ladder and, in addition, observe the momentum distribution of the system after time-of-flight expansion. Rather than varying the external field strength, we determine the response of the system as a function of the ratio of transverse rung coupling \( K \) to coupling along the legs of the ladder \( J \) (Fig. 1). In analogy to the type-II superconductor, we find evidence for a ‘Meissner phase’ with maximum chiral currents that are determined by the applied magnetic field. Below a critical coupling strength \((K/J)\), we find a decreasing chiral current, in good agreement with our modelling of a vortex phase.

The simplest theoretical description for our system is that of non-interacting bosonic particles in an infinitely extended two-leg ladder geometry, subject to a magnetic flux \( \phi \) per plaquette. The corresponding Hamiltonian is:

\[
H = -J \sum_{\ell} \left( \hat{a}^\dagger_{\ell+1,\uparrow} \hat{a}_{\ell,\uparrow} + \hat{a}^\dagger_{\ell+1,\downarrow} \hat{a}_{\ell,\downarrow} \right) -K \sum_{\ell} \left( e^{i\phi} \hat{a}^\dagger_{\ell,\uparrow} \hat{a}_{\ell+1,\downarrow} \right) + \text{h.c.} \tag{1}
\]

Here, the operator \( \hat{a}_{\ell,\mu} \) annihilates a particle at site \( \ell \) in the left or right leg of the ladder, where \( \mu \) = (L, R). The hopping amplitude between neighbouring sites along the ladder is \( J \), \( K e^{i\phi} \) denotes the spatially dependent tunnelling amplitude between legs, and h.c. is the hermitian conjugate term. This Hamiltonian can be mapped onto a spin–orbit coupled system, where the pseudo-spin represents the legs of the ladder³–⁹. Observables that can be readily measured in the experiment, and that allow one to characterize the different phases of the system, are the gauge-independent average current on either side of the ladder \( j_\mu = N_{\text{leg}}^{-1} \sum \langle \hat{a}^\dagger_{\ell+1,\mu} a_{\ell,\mu} \rangle \) and the chiral current \( j_c = j_\uparrow - j_\downarrow \) (ref. 6). Here \( N_{\text{leg}} \) is the number of sites along the ladder and \( j_{\ell+1,\mu} \) denotes the current operator for currents flowing from site \( \ell \rightarrow \ell + 1 \).

For low flux values \( \phi < \phi_c \), the ground state of the Hamiltonian exhibits a Meissner phase (Fig. 2), with maximal and opposite currents along the two legs of the ladder \( |j_\mu| = (2J/h) \sin(\phi/2) \). Increasing the flux leads to increasing edge currents up to a critical flux \( \phi_c \), beyond which the current abruptly starts to decrease. At this point the system enters a vortex phase with decreasing edge currents. Such a response resembles that of the Meissner effect in a type-II superconductor and its transition into an Abrikosov vortex lattice phase³. However, in contrast to the Meissner effect, the atomic chiral currents here do not cause any back-action onto the (artificial) magnetic field because of their charge neutrality. The response of

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our system also has some similarities to the Hess–Fairbank effect, which has been discussed as a rotational analogue of the Meissner effect\(^{(2,3)}\). In that case, a neutral superfluid is placed in a rotating vessel. Below a critical angular velocity \(\omega_c\), the superfluid remains in a non-rotational state, whereas above it a vortex structure appears in the superfluid, analogous to the critical field \(H_{c1}\) in a type-II superconductor. The phase transition from the Meissner to the vortex phase in our system is characterized by a change in the band structure, where the single minimum at \(q = 0\) in the lower band splits into two minima at finite \(q\) (Fig. 1b). In our experiment we chose the following strategy to observe the transition from a Meissner to a vortex phase: rather than changing the magnetic field strength, we worked at a fixed flux and varied the rung-to-leg coupling ratio \(K/J\). As can be seen in Fig. 2a, in this case one expects to observe
an increase of the leg currents for increasing $K/J$ up to a critical coupling strength $(K/J)_c$, after which a saturation in the current occurs, signalling the transition from the vortex to the Meissner phase. In the vortex phase, the ground state wavefunction exhibits a vortex structure for the currents, whose period increases with $K/J$, and the atom density on the ladder becomes modulated with the same periodicity. In the Meissner phase, on the other hand, the size of the vortex is infinite and the density is uniform (Fig. 2b).

Our experimental set-up consists of a Bose–Einstein condensate of $^{87}$Rb atoms loaded into a three-dimensional optical lattice potential. This potential is created by a standing wave of wavelength $\lambda_y = 767$ nm along $y$ and a superposition of a short and a long standing wave of wavelengths $\lambda_x$ and $\lambda_z$, respectively along $x$. In addition, a weak standing wave with $\lambda_x = 844$ nm that does not isolate different planes is used along $z$. The resulting superlattice potential in the $x$ direction is of the form $V(x) = V_{1x} \sin^2(k_xx + \varphi/2) + V_x \sin^2(k_xx)$, where $k_i = 2\pi/\lambda_i$, $i \in \{x, l\}$. The lattice depths $V_{1x}$ and phase $\varphi$ are chosen to have an array of isolated tilted double-well potentials, where each double well corresponds to a realization of a ladder. Using the same scheme as in our previous works$^{4, 5}$, we employ a pair of far-detuned running-wave beams to induce left–right tunnelling inside each double well. This lattice configuration creates a one-dimensional array of isolated ladders in the $xy$-plane, with a total flux per plaquette $\varphi = \pi/2$ (Fig. 1a and Supplementary Information).

To reveal the presence of the chiral edge currents, we prepared the system in the ground state of the flux ladder and measured the currents on the left and right legs averaged over an array of about 20 individual ladders with an average of approximately 40 lattice sites. In the experimental sequence we loaded a Bose–Einstein condensate of about $5 \times 10^5$ atoms into the isolated flux ladders for different values of $K/J$ (see Supplementary Information for a description of the experimental sequence). To extract the currents along the legs, the wavefunction was then suddenly projected into isolated double wells along $y$ and held for a certain time $t$ in this configuration (Fig. 3a and Supplementary Information and ref. 8). During the projection we also decoupled the legs of the ladder by switching off the left–right laser-assisted tunnelling such that atoms can only tunnel within a single double well along $y$. If $J_z$ is the tunnel coupling inside each individual double well, then the averaged even–odd atom fraction oscillates according to

$$ n_{\text{even},a}(t) = n_{\text{odd},a}(t) = \left[n_{\text{even},a}(0) - n_{\text{odd},a}(0)\right] \cos(2J_z t/\hbar) - J_{\text{int}} \sin(2J_z t/\hbar) $$

(2)

where $n_{\text{odd},a}(t) = \sum_l n_{2l+1,a}(t)$ and $n_{\text{even},a}(t) = \sum_l n_{2l,a}(t)$ are the averaged atom fractions over the individual double wells, with $n_{a,j}(t) = \langle \hat{a}_{l,a}\hat{a}_{l,j}^\dagger \rangle / \langle \hat{a}_{l,a}^\dagger \hat{a}_{l,a} \rangle$. The quantity $J_r = N_{\text{int}} \sum_l (2l+1) j_{2l+1,a}(t)$ is the normalized average of the currents on the left or right side of the ladder where the expectation value is calculated for the initial state directly after the projection. Even though the average runs only over the double wells within the projected double wells (that is, every other bond, see Fig. 3a), it is a very good approximation of the average leg currents for our system. The first oscillating term of the atom fraction in equation (2) is proportional to the initial population imbalance and should be ideally zero as a result of the averaging. The second term is proportional to the current amplitude and dominates the time evolution. Therefore, currents with opposite directions along the legs result in population oscillations in the double wells that are out of phase by $\pi$. In Fig. 3b–d the experimentally measured time evolution $n_{\text{odd},a}(t)$ for positive, negative and zero flux are shown. For $\varphi = +\pi/2$, the current flows downwards on the left leg and upwards on the right leg, yielding an even–odd oscillation of $n_{\text{odd},a}(t)$ and $n_{\text{odd},a}(t)$ with an initial phase of $\pi$ and zero, respectively. When the flux is reversed to $\varphi = -\pi/2$, the phases of $n_{\text{odd},a}(t)$ and $n_{\text{odd},a}(t)$ are also reversed. This demonstrates that the flux ladder exhibits a chiral edge current in the ground state whose chirality is reversed when inverting the direction of the flux, in agreement with the theoretical expectation. For the case without the applied artificial magnetic field ($\varphi = 0$), the wavefunction is homogeneous throughout the ladder and no chiral currents are present, leading to a vanishing oscillation.
amplitude in the double wells, as observed in the experiment (see Supplementary Information for a detailed description of the experimental sequence).

To probe the phase diagram shown in Fig. 2a, we studied the change of the chiral current amplitude when increasing the ratio $K/J$ for a constant flux $\phi = \pi/2$. On each leg of the ladder we measured $n_{\text{odd},\mu}(t)$ and fitted its amplitude $I_\mu$ and phase $\phi_\mu$ for different values of $K$ and constant $J$. To extract the chiral current, we made use of the left–right symmetry of the wavefunction density, namely, $n_{\text{even},\mu}(0) - n_{\text{odd},\mu}(0) = n_{\text{even},\mu}(0) - n_{\text{odd},\mu}(0)$, from which we obtain $j_\mu = I_\mu \propto |I_\mu - e^{i\Delta\phi}I_\mu|$, with $\Delta\phi = \phi_{\text{odd}} - \phi_{\text{even}}$. As shown in Fig. 4, in the vortex phase the chiral current increases when increasing $K/J$ up to the critical point $(K/J)_c = \sqrt{2}$ at which the system enters the Meissner phase, indicated by a saturation of the chiral current. For a comparison with theory, we fit the theoretically predicted behaviour with amplitude and offset as free fit parameters and find good agreement between theory and experiment. We also observe that when $K/J > 1$, the value of the phase difference $\Delta\phi$ is close to $\pi$. This is to be expected whenever the averaged initial population imbalance on neighbouring sites in the double well is negligible (see equation (2)) and a chiral current is present in the system. For values of $K/J < 1$, we find that $\Delta\phi$ decreases, most probably owing to the fact that smaller and smaller leg currents for decreasing $K/J$ lead to a larger effect of any possible initial population imbalance on the phase of the double-well oscillations (see equation (2)). These population differences are not perfectly averaged out over the entire system in the experiment and lead to the observed decrease in $\Delta\phi$ for small values of $K/J$. We note, however, that by subtracting the two population oscillations, as described above for the left and right leg of the ladder, we remove the oscillation term caused by the initial population imbalance and, therefore, we can still reliably determine the chiral current.

In a second series of measurements, we investigated the momentum distribution of the system along the $y$ direction after time-of-flight expansion as a function of $K/J$. In the experimentally realized gauge, each quasimomentum $q$ has two real momentum
components in the first Brillouin zone, located at \(k_y = q \pm \pi/(4d_y)\) (ref. 6). Therefore, for the Meissner phase where the lowest energy band has a single ground state at \(q = 0\), the momentum peaks are located at \(k_y = \pm \pi/(4d_y)\). In the vortex phase the energy band has two ground states at \(\pm q_{k/J}\) that depend on the ratio \(K/J\), and correspondingly four momentum peaks at \(k_y = q_{k/J} \pm \pi/(4d_y)\) and \(k_y = -q_{k/J} \pm \pi/(4d_y)\) are expected (see inset in Fig. 5). When \(K/J \ll (K/J)\), the two outer peaks at \(k_y = \pm q_{k/J} \pm \pi/(4d_y)\) vanish and the two inner peaks converge to \(k_y = 0\). To study this behaviour, we used the same experimental sequence as above, but instead of projecting into isolated double wells along \(y\), we directly released the atoms from the trap and determined the time-of-flight momentum distribution. For the Meissner phase, we observe the two expected peaks, but in the vortex phase we only observe the two inner peaks and cannot resolve the position of the outer peaks. The reason for this is that close to the critical point the two peaks at \(k_y = \pm q_{k/J} \pm \pi/(4d_y)\) are too close to each other, and the band flatness combined with the finite temperature do not allow one to resolve the two peaks. On the other hand, for \(K/J \ll (K/J)\), where we could expect to resolve them, the peaks are well separated but the outer peaks vanish. For the analysis of the momentum distributions, we therefore fitted the position of the two inner peaks and measured their relative distance as a function of \(K/J\). As can be seen in Fig. 5, we obtain a reasonable agreement with the theoretically calculated peak separation, where the small reduction in amplitude can be explained by considering the finite temperature of the system, which slightly reduces the separation of the momentum peaks, as shown by the light green shaded area. There is a twofold reason for the reduction in the separation due to finite temperature: non-zero temperature implies population of a fraction of the energy band, which means that as a result of our experimental gauge the maxima of the peaks are shifted closer to each other. The second reason is that the peaks get broader and are then more strongly affected by the Wannier envelope in the time-of-flight expansion, which also shifts the peaks to a closer position. Furthermore, we observed that near the critical point the widths of the fitted peaks have a maximum, which is consistent with the especially flat band at this critical point and with the presence of the outer peaks that cannot be resolved (Supplementary Information).

In conclusion, this work presents the demonstration of a low-dimensional Meissner-like effect and the observation of chiral Meissner edge currents for a bosonic lattice superfluid. It also demonstrates an efficient way to implement spin–orbit coupling in one-dimensional ultracold quantum gases. In future works it would be intriguing to use the recently developed high-resolution imaging to measure the lattice currents in a spatially resolved way. This would enable one to not only directly detect the vortices in the flux ladders, but also measure their full current statistics. Measuring the edge currents precisely would also open intriguing avenues for exploring their connection to the edge states of an integer quantum Hall insulator. Furthermore, one could also hope to realize new many-body phenomena in the strongly interacting limit of a Mott insulator, where the existence of chiral Mott insulators and a spin–Meissner effect for two-component systems have been predicted. Detecting the quantum fluctuations of a chiral Mott insulator would enable one to directly probe the chiral currents in this topologically highly non-trivial insulating phase.

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References

1. Meissner, W. & Ochsenfeld, R. Ein neuer Eekt bei Eintritt der Supraleitfähigkeit. Naturwissenschaften 21, 787–788 (1933).
2. Bardeen, J., Cooper, L. N. & Schriefer, J. R. Theory of superconductivity. Phys. Rev. 108, 1175–1204 (1957).
3. Orignac, E. & Giamarchi, T. Meissner effect in a bosonic ladder. Phys. Rev. B 64, 144515 (2001).
4. Petrescu, A. & Le Hur, K. Bosonic Mott insulator with Meissner currents. Phys. Rev. Lett. 111, 150601 (2013).
5. Dhar, A. et al. Bose–Hubbard model in a strong effective magnetic field: Emergence of a chiral Mott insulator ground state. Phys. Rev. A 85, 041602(R) (2012).
6. Hugel, D. & Paredes, B. Chiral ladders and the edges of Chern insulators. Phys. Rev. A 89, 023619 (2014).
7. Celi, A. et al. Synthetic gauge fields in synthetic dimensions. Phys. Rev. Lett. 112, 043001 (2014).
8. Kessler, S. & Marquardt, F. Single-site resolved measurement of the current statistics in optical lattices. Preprint at http://arXiv.org/abs/1309.3890 (2013).
9. Tokuno, A. & Georges, A. Ground states of a Bose–Hubbard ladder in an artificial magnetic field: Field-theoretical approach. Preprint at http://arXiv.org/abs/1403.0413 (2014).

Figure 5 | Relative position of the momentum peaks. Experimental peak separation between inner peaks as a function of \(K/J\) fitted from the time-of-flight images. Each point corresponds to an average of 5–40 individual measurements and the error bars are the standard deviations. The solid line is the theoretically calculated peak separation, where there is no free parameter. The light green shaded area shows the peak separation calculated for a system with a density of 25 particles per single site of the ladder and for a temperature range from 10 nK to 30 nK (Supplementary Information). The inset shows the expected momentum distribution along \(y\) as a function of \(K/J\), and the black circles highlight the measured peak separation.
10. Goldman, N., Juzeliūnas, G., Öhberg, P. & Spielman, I. B. Light-induced gauge fields for ultracold atoms. Preprint at http://arXiv.org/abs/1308.6533 (2013).

11. Jakšch, D. & Zoller, P. Creation of effective magnetic fields in optical lattices: The Hofstadter butterfly for cold neutral atoms. New J. Phys. 5, 56 (2003).

12. Gerbier, F. & Dalibard, J. Gauge fields for ultracold atoms in optical superlattices. New J. Phys. 12, 033007 (2010).

13. Kolovsky, A. Creating artificial magnetic fields for cold atoms by photon-assisted tunneling. Europhys. Lett. 93, 20003 (2011).

14. Aidelsburger, M. et al. Experimental realization of strong effective magnetic fields in an optical lattice. Phys. Rev. Lett. 107, 255301 (2011).

15. Aidelsburger, M. et al. Realization of the Hofstadter Hamiltonian with ultracold atoms in optical lattices. Phys. Rev. Lett. 111, 185301 (2013).

16. Miyake, H. et al. Realizing the Harper Hamiltonian with laser-assisted tunneling in optical lattices. Phys. Rev. Lett. 111, 185302 (2013).

17. Jiménez-García, K. et al. Peierls substitution in an engineered lattice potential. Phys. Rev. Lett. 108, 225303 (2012).

18. Struck, J. et al. Tunable gauge potential for neutral and spinless particles in driven optical lattices. Phys. Rev. Lett. 108, 225304 (2012).

19. Juzeliūnas, G. & Öhberg, P. Creation of an effective magnetic field in ultracold atomic gases using electromagnetically induced transparency. Opt. Spectrosc. 99, 357–361 (2005).

20. Kardar, M. Josephson-junction ladders and quantum fluctuations. Phys. Rev. B 33, 3125–3128 (1986).

21. Granato, E. Phase transitions in Josephson-junction ladders in a magnetic field. Phys. Rev. B 42, 4797–4799 (1990).

22. Denniston, C. & Tang, C. Phases of Josephson junction ladders. Phys. Rev. Lett. 75, 3930–3933 (1995).

23. Nishiya, Y. Finite-size-scaling analyses of the chiral order in the Josephson-junction ladder with half a flux quantum per plaquette. Eur. Phys. J. B 17, 295–299 (2000).

24. Hess, G. B. & Fairbank, W. M. Measurements of angular momentum in superfluid helium. Phys. Rev. Lett. 19, 216–218 (1967).

25. 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).

26. Trotzky, S. et al. Probing the relaxation towards equilibrium in an isolated strongly correlated one-dimensional Bose gas. Nature Phys. 8, 325–330 (2012).

27. Killi, M., Trotzky, S. & Paramekanti, A. Anisotropic quantum quench in the presence of frustration or background gauge fields: A probe of bulk currents and topological chiral edge modes. Phys. Rev. A 86, 063632 (2012).

28. Sebby-Strabley, J., Anderlini, M., Jessen, R. S. & Porto, J. V. Lattice of double wells for manipulating pairs of cold atoms. Phys. Rev. A 73, 033605 (2006).

29. Bakr, W. et al. Probing the superfluid-to-Mott-insulator transition at the single-atom level. Science 329, 547–550 (2010).

30. Sherson, J. et al. Single-atom-resolved fluorescence imaging of an atomic Mott insulator. Nature 467, 68–72 (2010).

31. Fisher, M., Weichman, P., Grinstein, G. & Fisher, D. S. Boson localization and the superfluid–insulator transition. Phys. Rev. B 40, 546–570 (1989).

32. Greiner, M. et al. Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms. Nature 415, 39–44 (2002).

33. Zaletel, M. P., Parameswaran, S. A., Rüegg, A. & Altman, E. Chiral Bosonic Mott insulator on the frustrated triangular lattice. Phys. Rev. B 89, 155142 (2014).

34. Endres, M. et al. Observation of correlated particle–hole pairs and string order in low-dimensional Mott insulators. Science 334, 200–203 (2011).

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Author contributions
M. Atala, M. Aidelsburger, M.L. and J.T.B. performed the experiment and analysed the data. I.B. and B.P. devised and supervised the project. All authors contributed to the writing of the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.