in the region of overlapping orders, the superconducting critical temperature T_c is higher for Ca-doped crystals than for undoped samples, suggesting that ferroelectricity may boost T_c.

The possible role of ferroelectric quantum fluctuations on superconductivity in $SrTiO_3$ has recently been discussed by Jonathan Edge and colleagues[5]. The general idea is that close to a quantum critical point, where different phases compete, one is left with low-energy excitations. Any residual interactions may then drive the system to a superconducting state. For $SrTiO_3$, Ca-doping, ^{18}O substitution or straining the lattice brings the system closer to ferroelectricity — and hence closer to a quantum critical point.

For $SrTiO_3$, the picture proposed by Edge *et al.* is that superconductivity appears in the underdoped regime when the Fermi surface forms and disappears in the overdoped regime when one is moving away from quantum criticality. The prediction for ^{18}O-substituted $SrTiO_3$ is that T_c should be higher with a maximum critical temperature shifted to lower doping as compared to ^{16}O-$SrTiO_3$. Recent experiments[6] indeed seem to point to a higher T_c for O_{18}-$SrTiO_3$.

Doping reduces the height of the barrier separating the two free-energy minima and thus promotes quantum fluctuations that rapidly destroy the ferroelectric-like state. As found by Rischau *et al.*, the coexistence of superconductivity and ferroelectricity is indeed restricted to a small region at low doping levels. In this region, the material is a superconductor with broken spatial inversion symmetry — a special class of superconductors that have attracted a lot of attention and whose order parameter should display a non-trivial symmetry[7].

Finally, what about the celebrated $LaAlO_3/SrTiO_3$ system? At its interface, superconductivity has been observed with a dome-shaped phase diagram[8], which is, however, different that of bulk-doped $SrTiO_3$ (ref. 9). Is the $LaAlO_3/SrTiO_3$ phase diagram modified and/or is T_c enhanced if ^{18}O-$SrTiO_3$ or Ca-doped $SrTiO_3$ are used? What about the breaking of inversion symmetry, also observed at the $LaAlO_3/SrTiO_3$ interface, and its impact on superconductivity? Further experiments on the $LaAlO_3/SrTiO_3$ interface and doped $SrTiO_3$ crystals will hopefully soon answer some of the fascinating questions raised by the findings of Rischau and colleagues. ❒

Marc Gabay is at the Laboratoire de Physique des Solides, Université Paris-Sud 11, Université Paris Saclay, CNRS UMR 8502, 91405 Orsay Cedex, France. Jean-Marc Triscone is in the Department of Quantum Matter Physics, University of Geneva, 1211 Geneva 4, Switzerland.
e-mail: marc.gabay@u-psud.fr; jean-marc.triscone@unige.ch

References

1. Rischau, C. W. *et al. Nat. Phys.* **13,** 643–649 (2017).
2. Anderson, P. W. & Blount, E. I. *Phys. Rev. Lett.* **14,** 217–219 (1965).
3. Rödel, T. C. *et al. Adv. Mater.* **28,** 1976–1980 (2016).
4. Kim, T. H. *et al. Nature* **533,** 68–72 (2016).
5. Edge, J. M., Kedem, Y., Aschauer, U., Spaldin, N. A. & Balatsky, A. V. *Phys. Rev. Lett.* **115,** 247002 (2015).
6. Stucky, A. *et al. Sci. Rep.* **6,** 37582 (2016).
7. Sigrist, M. & Ueda, K. *Rev. Mod. Phys.* **63,** 239–311 (1991).
8. Caviglia, A. D. *et al. Nature* **456,** 624–627 (2008).
9. Gariglio, S., Gabay, M. & Triscone, J.-M. *APL Mater.* **4,** 060701 (2016).

Published online: 17 April 2017

SUPERCONDUCTIVITY

When Andreev meets Hall

A device with superconducting contacts connected to graphene in the quantum Hall regime hints at a novel Andreev scattering mechanism.

Gleb Finkelstein and François Amet

Superconductivity and the quantum Hall (QH) effect are two prominent paradigms of condensed-matter physics that have long been viewed as mutually exclusive. Indeed, the QH effect requires high magnetic fields, which break the time-reversal symmetry essential for the superconducting Cooper pairing. However, recent works showed that high-mobility heterostructures can be contacted by superconducting alloys capable of withstanding high magnetic fields[1–5]. Writing in *Nature Physics*, Gil-Ho Lee and co-workers[6] describe transport measurements of graphene samples encapsulated in boron nitride and contacted by superconducting niobium nitride. In the QH regime, the bulk of the sample is insulating, and charge transport is mediated by carriers confined to narrow edge channels. These edge states are chiral: charge carriers circle around the device in one direction. The authors found that driving a current along a chiral edge to a narrow grounded superconducting contact causes a voltage of an opposite sign to develop at the normal contact connected downstream along the same edge (Fig. 1a).

This result can be explained by the Andreev mechanism: due to the pairing gap, a single electron cannot enter a superconductor and has to be reflected as a hole, while a Cooper pair is transferred to the superconductor (Fig. 1a). Clarke *et al.*[7] and Lindner *et al.*[8] predicted that when the superconducting contact is very narrow, a 'crossed Andreev conversion' can occur, in which the hole emerges on the other side of the contact from the incoming electron. In the QH regime, the hole should then propagate along the chiral edge to the next contact, causing it to develop a voltage of opposite sign. Lee and colleagues indeed observed this negative signal on the downstream contact, and found that it vanishes exponentially with the width of the superconducting contact and disappears above about 200 nm, when the superconducting contact is too wide compared to the superconducting coherence length. As expected, this signal gradually disappears if either the temperature approaches the critical value of the superconductor or the incident electron energy eV approaches the superconducting gap Δ.

Interestingly, this signal appears to persist at large magnetic fields, where exchange interactions are sufficient to break the fourfold spin and valley degeneracy of the zeroth Landau level. At filling factor $\nu = 1$ in particular, QH edge states are spin polarized. In this regime, Majorana zero modes were predicted[7,8] to form in a number of similar quasi-one-dimensional geometries, such as thin superconducting contacts, or narrow trenches etched into the QH material and partially filled with a superconducting metal (Fig. 1b). Here the counter-propagating spin-polarized edge channels across the trench will be coupled by crossed Andreev reflections, which results in the formation of a topologically non-trivial gapped state. This situation is analogous to that of hybrid superconducting devices made of semiconducting wires with a large spin–orbit interaction[9]. Similar to the nanowire case, the end points of the topologically non-trivial region are expected to host Majorana zero modes.

Narrow one-dimensional superconducting contacts to a QH state (Fig. 1b) may offer some advantages over alternative methods for creating Majorana zero modes in semiconducting systems with spin–orbit interaction. Indeed, this scheme does not require precise and sample-specific tuning of the chemical potential and magnetic field — once an external magnetic field is applied within the right range, $\nu = 1$ will be reached everywhere in the sample, allowing straightforward fabrication of multiple copies of the system. Despite the naturally expected mesoscopic variations, the topological properties of all these copies should be identical. Furthermore, the great appeal of the QH platform is the versatility of the edge states, which can be rerouted using well-established gating techniques. This flexibility makes the QH platform attractive for attempting to create, couple and manipulate the Majorana zero modes for the purpose of topological quantum computation.

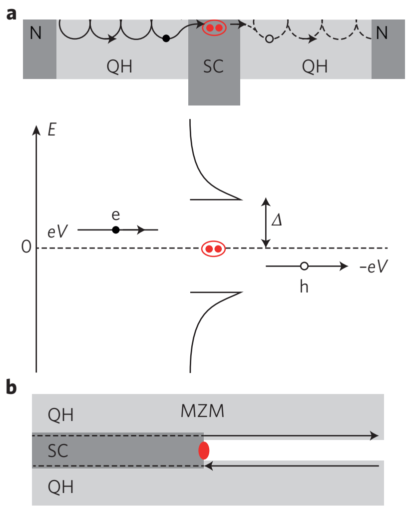

Figure 1 | Crossed Andreev conversion mechanism. **a**, An incoming electron (e) edge state, emitted by a normal contact (N) with energy $E = eV$, cannot enter the superconductor (SC) if eV is less than the pairing gap Δ. However, if the SC contact is narrow, the electron may be converted into a hole (h) with energy $-eV$, while a Cooper pair (red) at zero energy is absorbed by the superconductor. **b**, Spin-polarized edge states on both sides of a trench are gapped by crossed Andreev reflections across the superconductor. The gap closes at the end of the SC electrode which results in a Majorana zero mode (MZM; red).

At even higher field, similar device geometries in the fractional QH regime should host parafermions, which can be thought of as generalizations of the Majorana zero modes for the case of a fractional quasiparticle charge[10,11]. Detecting their signatures will be very challenging, but concrete strategies for such measurements have already been proposed[12]. Looking even further into the possible future of this field, combining superconductivity with the conventional (Abelian) fractional QH states may enable universal quantum computation[10,11]. ❐

Gleb Finkelstein is in the Department of Physics at Duke University, Durham, North Carolina 27708, USA. François Amet is in the Department of Physics and Astronomy at Appalachian State University, Boone, North Carolina 28608, USA.
e-mail: gleb@phy.duke.edu; ametf@appstate.edu

References

1. Wan, Z. *et al. Nat. Commun.* **6,** 8426 (2015).
2. Calado, V. E. *et al. Nat. Nanotech.* **10,** 761–764 (2015).
3. Ben Shalom, M. *et al. Nat. Phys.* **12,** 318–322 (2016).
4. Amet, F. *et al. Science* **352,** 966–969 (2016).
5. Efetov, D. K. *et al. Nat. Phys.* **12,** 328–332 (2016).
6. Lee, G.-H. *et al. Nat. Phys.* **13,** 689–694 (2017).
7. Clarke, D. J., Alicea, J. & Shtengel, K. *Nat. Commun.* **4,** 1348 (2013).
8. Lindner, N. H., Berg, E., Refael, G. & Stern, A. *Phys. Rev. X* **2,** 041002 (2012).
9. Beenakker, C. W. J. *Annu. Rev. Condens. Matter Phys.* **4,** 113–136 (2013).
10. Nayak, C., Simon, S. H., Stern, A., Freedman, M. & Das Sarma, S. *Rev. Mod. Phys.* **80,** 1083–1159 (2008).
11. Mong, R. S. K. *et al. Phys. Rev. X* **4,** 011036 (2014).
12. Cheng, M. & Lutchyn, R. M. *Phys. Rev. B* **92,** 134516 (2015).

HIGH-HARMONIC GENERATION

The bright side of downsizing

The shorter the antenna, the higher the frequency — so what happens when nanoantennas hit optical frequencies? One answer may lead to high-harmonic generation without the need for high-powered lasers.

Alexandra Landsman

In the late 1880s, Heinrich Hertz invented the first antenna in a series of experiments designed to definitively prove Maxwell's theory of electromagnetism. The pair of metre-long copper wires radiated at a frequency of around 50 MHz — forming the prototype for latter-day television transmitters. But antenna size scales inversely with the frequency of resonant light. And once we reach the nanoscale, downsizing can invoke additional effects associated with the optical frequency range. Now, writing in *Nature Physics*, Giulio Vampa and colleagues[1] have used an array of nanoscale antennas to magnify infrared laser light — providing a route to generating high-order harmonics using relatively weak lasers.

High-harmonic generation is typically produced using atoms of noble gas and high-intensity, ultrafast laser pulses[2]. The basic physics involves strong-field atomic ionization, followed by recombination, whereby the electron is driven back into the parent atom by the strong laser field and emits a harmonic at the multiple of the infrared laser frequency. A coherent combination of such high harmonics leads to an extreme-ultraviolet pulse of attosecond duration — the shortest flashes of light