Mobilizing Majorana fermions

Chiral Majorana fermion modes in a quantum anomalous Hall insulator-superconductor structure

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Science **357**, 294-299 (2017); arXiv:1606.05712

Recommended with a Commentary by Jason Alicea, Caltech

In condensed matter, a pair of point-like zero-energy Majorana Fermions may be generated if a conventional fermion is fragmented [Fig. 1(a)]. Such 'Majorana zero modes' have non-Abelian statistics and may be used in topological quantum computing applications. An avid experimental effort [1] is on to realize this. Moving to one higher dimension, a fermionic integer-quantum-Hall edge state can similarly split into a pair of chiral Majorana fermions [Fig. 1(b)]. Contrary to their point-like cousins, the latter are propagating degrees of freedom that closely resemble the particle-physics notion of Majorana fermions. They, too, yield interesting physics exploitable for quantum-information applications. Experimental explorations have nevertheless remained comparatively scarce.

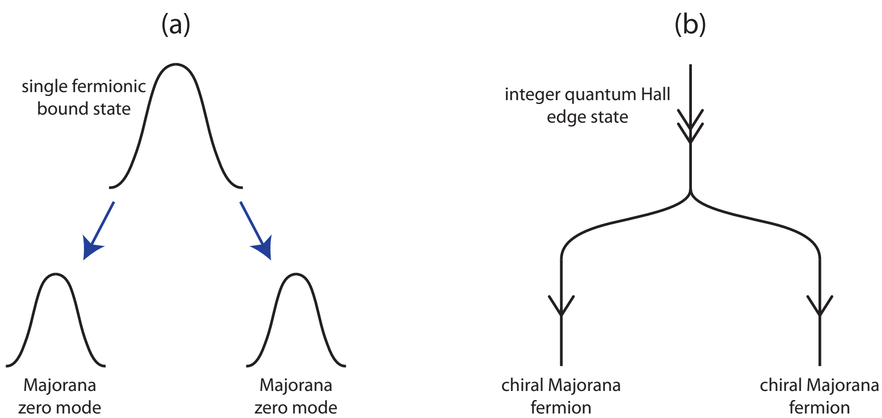

Figure 1: (a) Majorana zero modes form when a localized fermion level splits in two. (b) Chiral Majorana fermions similarly arise from fragmentation of an integer-quantum-Hall edge state.

Where to look in pursuit of chiral Majorana fermions? The (theoretically) simplest answer is a spinless 2D $p + ip$ superconductor, which hosts a single chiral Majorana edge state. Nature has not been forthcoming, however, with realizations. Helium-3 and strontium ruthenate may come close, but are neither spinless nor naturally 2D [2]. Progress instead appears to require an 'engineering' approach that bootstraps off of existing materials—similar to the strategy deployed for point-like Majorana zero modes.

Many blueprints for engineering spinless 2D $p+ip$ superconductivity have appeared over the last decade. Of interest here is the proposal from Qi, Hughes, and Zhang [3] that exploits the transition between an insulator and a $\nu = 1$ integer quantum Hall state in a 2D electron system. Qi et al. showed that upon coupling the 2D electron system to a bulk superconductor, the transition generically widens into an extended spinless 2D $p + ip$ phase; see Fig. 2(a). Prospects for implementation rose considerably with the subsequent demonstration of a quantum anomalous Hall state—which is topologically equivalent to a $\nu = 1$ phase—in magnetically doped thin-film topological insulators [4]. In currently available samples a relatively small field ~ 0.1T suffices to toggle the thin film between an insulator (driven by inter-surface tunneling) and a quantum anomalous Hall state (driven by exchange with field-polarized ferromagnetic domains). Coating the film's surface with a superconductor should then open a field-tunable window to a spinless 2D $p + ip$ phase. Importantly, the modest required field scale allows quantum-Hall physics and superconductivity to peacefully coexist.

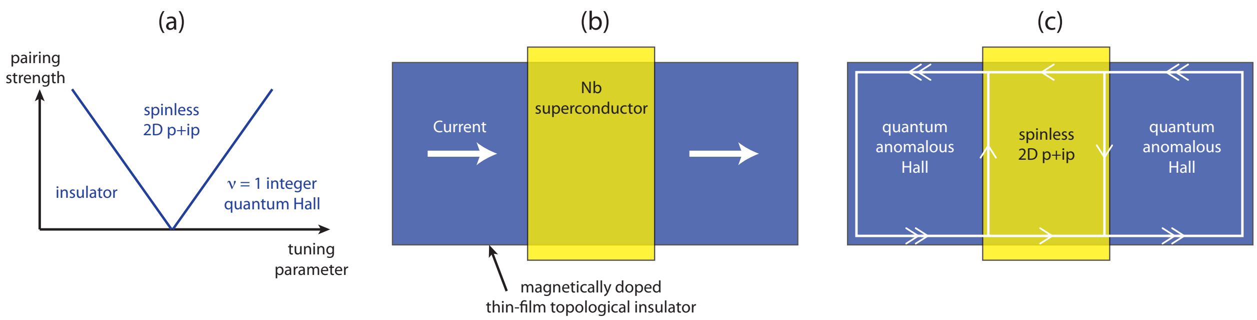

Figure 2: (a) The transition between an insulator and a $\nu = 1$ integer quantum Hall state broadens into an extended spinless 2D $p + ip$ phase upon introducing superconductivity [3]. (b) Schematic setup studied by He et al. consisting of a magnetically doped thin-film topological insulator overlayed with a superconductor in the central region. The conductance G referred to in the text corresponds to current flowing between the left and right regions. (c) Configuration where the outer regions form quantum anomalous Hall states while the middle forms a spinless 2D $p + ip$ superconductor. Note the fragmenting of the quantum Hall edge states into chiral Majorana fermions [consistent with Fig. 1(b)], which leads to a quantized conductance $G = \frac{1}{2}\frac{e^2}{h}$ as observed by He et al.

In the highlighted paper, He et al. experimentally pursue this strategy using the setup in Fig. 2(b). A niobium superconductor coats the central region of a magnetically doped thin-film topological insulator; uncoated regions to the left and right essentially serve as probing leads. Various regimes are possible depending on the applied magnetic field. Figure 2(c) shows the most interesting case wherein the 'leads' form quantum anomalous Hall states while the central region forms a spinless $p+ip$ superconductor with chiral Majorana edge states. In this regime the device's two-terminal conductance is predicted to be $G = \frac{1}{2}\frac{e^2}{h}$ [5, 6], where the crucial factor of 1/2 reflects the splintering of integer-quantum-Hall edge states into chiral Majorana fermions. Remarkably, He et al. indeed observe conductance plateaus at this value over a narrow yet discernible field interval—reproducibly and in several devices. Additional consistency checks described in the paper rule out some alternative non-Majorana-related interpretations of these measurements.

Experimental evidence of chiral Majorana fermions is certainly very exciting, though in my view most of all because they signal the onset of a long-sought $p+ip$ phase that promises further rewards. In particular, such a superconductor also provides a platform for Majorana zero modes, which in this setting bind to $h/2e$ vortices. Initial forays into vortex physics seem particularly well-suited for follow-up studies, and could provide additional sanity checks on He et al.'s findings as well as valuable comparisons with Majorana experiments in other systems. Even more ambitiously, one can pursue the robust storage and manipulation of quantum information that Majorana zero modes are predicted to underpin. It is interesting to devise experiments that probe these finer aspects of Majorana physics using schemes that are natural for the topological-insulator-based devices highlighted here.

References

[1] For a very recent overview of semiconducting-wire-based Majorana experiments, see R. M. Lutchyn, E. P. A. M. Bakkers, L. P. Kouwenhoven, P. Krogstrup, C. M. Marcus, Y. Oreg, arXiv:1707.04899.

[2] Some related discussion can be found in the March 2017 journal-club commentary by Tony Leggett.

[3] Xiao-Liang Qi, Taylor L. Hughes, Shou-Cheng Zhang, Phys. Rev. B **82**, 184516 (2010).

[4] Cui-Zu Chang, Jinsong Zhang, Xiao Feng, Jie Shen, Zuocheng Zhang, Minghua Guo, Kang Li, Yunbo Ou, Pang Wei, Li-Li Wang, Zhong-Qing Ji, Yang Feng, Shuaihua Ji, Xi Chen, Jinfeng Jia, Xi Dai, Zhong Fang, Shou-Cheng Zhang, Ke He, Yayu Wang, Li Lu, Xu-Cun Ma, Qi-Kun Xue, Science **340**, 167 (2013).

[5] S. B. Chung, X.-L. Qi, J. Maciejko, S.-C. Zhang, Phys. Rev. B **83**, 100512 (2011).

[6] J. Wang, Q. Zhou, B. Lian, S.-C. Zhang, Phys. Rev. B **92**, 064520 (2015).