Workshop report:
"Topological superconductors: Materials, topological order, and quenched disorder,"
Rice University Center for Quantum Materials (RCQM), April 24–25, 2018.

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Organizers

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1 Overview

1.1 Executive Summary

Superconductivity is a remarkable phenomenon that arises from the collective motion of electrons in materials, and in particular the partnering of electrons into so-called Cooper pairs. Superconductors can conduct electric current without dissipating energy into heat, and can levitate magnets owing to their perfect diamagnetism. Since the late 1980s, much of the condensed matter physics community has focused on understanding high-temperature superconductivity, with the hope that a room-temperature superconductor could one day revolutionize power delivery.

In the last decade, an entirely new frontier of superconductivity has been revealed, that of *topological* superconductivity. Owing to a "quantum knot" in the electronic structure of the bulk, a topological superconductor is predicted to host an exotic two-dimensional fluid at the surface of the crystal. The surface fluid consists of special particles called Majorana fermions that can be viewed as the "loose ends" of the quantum knot, which unties only at the surface. As a result the physical properties of these Majorana fermions are predicted to be robustly protected from perturbations. Most importantly, the surface fluid can be manipulated with magnetic fields, which could be used to form and move "Majorana zero modes" at the surface. These zero modes are now being actively sought in laboratories across the world, and could enable fault-tolerant topological quantum computation.

Much of the effort to realize Majorana zero modes has so far focused on artificial (engineered) systems, in which heterogeneous components must be microfabricated together to create a synthetic topological superconductor. This workshop instead considered the prospects for the discovery and characterization of new, natural topological superconducting materials. Key takeaways included news of the possible experimental observation of Majorana zero modes in several different materials, a theoretical picture that might explain these observations, prospects for topological superconductivity in higher-spin materials, and the interplay of disorder and strong interactions on Majorana surface fluids. The search for materials candidates is still in its infancy, but the many remarkable theoretical predictions strongly suggest that finding bulk topological superconductors in the lab will open up many new avenues for fundamental materials research.

Topological superconductors are predicted to arise from non-s-wave pairing, a feature shared by the high temperature superconductors with the highest transition temperatures. Thus further theoretical research into topological superconductivity may also teach us something new about the still vexing problem of understanding the mechanisms behind high-temperature superconductivity. As with parallel efforts spearheaded by Google and Microsoft to realize quantum computers using engineered systems, research into topological superconductors could eventually revolutionize quantum information processing.

1.2 Scientific justification

In the past decade there has been an explosion of interest in new forms of topological matter, driven by the discoveries of topological insulators and gapless topological phases. An intense effort is now being made to employ these as platforms for topological superconductivity [1, 2, 3] and Majorana fermion zero modes (MZMs), which might enable topological quantum computation [4]. Much of the focus is on artificially engineered platforms for MZMs [3,4], usually through proximity coupling to an ordinary *s*-wave superconductor. On the other hand, the discovery of bulk 3D topological superconductors predicted theoretically [1-3] would give access to a fundamentally different type of Majorana surface states, with features not easily attainable elsewhere. In particular, they could open the door to topological quantum computation, in which quantum information is stored in the topology of a macroscopic quantum state rather than in the synthetically engineered MZMs. Despite intense efforts, we do not yet have accepted experimental realizations of such topological superconductors, although several candidate materials have been proposed and are hotly debated, that were at the center of this workshop.

Bulk topological superconductors (TSCs) should also solve the energy mismatch problem that often plagues other Dirac materials. In topological insulators as well as Dirac and Weyl semimetals, the chemical potential is typically located far from the bulk or surface Dirac point, and instead resides in the valence or conduction band. Fully gapped topological superconductors, on the other hand, are predicted to host Majorana bands of topologically protected quasiparticles at the material surface. These surface bands penetrate the bulk superconducting gap, and the chemical potential appears precisely at the Dirac point of the surface band (inside the gap), due to the particle-hole symmetry in a superconductor.

The goal of this workshop was to provide a unique opportunity for leading researchers to focus on bulk topological superconductivity in terms of materials prospects and fundamental theory and to bring together theorists and experimentalists within the rubric of this singular focus. The organizers believe that the exchange of ideas is extremely beneficial between the theorists often working on rather complex aspects of the mathematical description of topological phases, and the experimentalists striving to realize these phases in real materials.

1.3 A brief description of the event and the science covered:

- The workshop took place over two days in Houston, Texas, incorporating 30 minute invited speaker talks (8 the first day, 9 the second) a poster session, and discussion sessions both days. The detailed program is included in the Appendix A below.
- Talks included the following topics
  1. Experimental evidence for nematic superconductivity in doped-Bi_2Se_3 topological superconductors [5,6].
  2. Majorana zero modes and vortices in proximitized (synthetic p+ip) surface states [7,8].
  3. Transport evidence for topological superconductivity in doped β-$PdBi_2$.
  4. STM evidence for Majorana bound states in iron-based superconductor Fe(Te, Se) [7].
  5. Josephson Junctions of Topological Crystalline Insulators.
  6. Non-*s*-wave superconductivity in YPtBi [9,10,11,12].
  7. The theory of quasiparticle Fermi surfaces for strongly paired superconductivity in semimetals [13,14].
  8. Theory talks on using Anderson (de)localization to classify topological superconductors [15], topological protection of surface states and transport signatures [16,17,18], and strongly interacting topological superconductors with surface topological order [19,20,21,22].
  9. Weyl semimetal behavior in Kondo systems [23].

Topics 1–4 dealt with the core issues of bulk materials that are either putative topological superconductors (doped-Bi_2Se_3) or superconductors with surface states due to topological band crossings [Fe(Te, Se)], and evidence for MZMs in these. Topics 6 and 7 concerned prospects for the discovery of novel forms of superconductivity (including TSC) in higher-spin compounds, which are just beginning to be explored in this context. Topic 8 dealt with many of the core theoretical issues concerning Majorana surface fluids, their stability and classification, and prospects for detection.

2 Brief overview of the invited presentations

2.1 Materials prospects for bulk topological superconductivity

A **bulk topological superconductor** (TSC) is a three-dimensional solid state system in which topologically nontrivial pairing occurs between electrons; see e.g. [15] for an overview. The topology can be characterized by an integer-valued winding number determined by the (mean-field) bulk Bogoliubov-de Gennes bandstructure, or by the character of the predicted **two-dimensional Majorana surface fluid** expected to form at the material surface. The pairing mechanism is not determined by the topology, but it is expected that strong spin-orbit coupling and/or strong correlations are important in order to achieve topological pairing. This is because simple s-wave pairing is necessarily non-topological—theoretically, one can imagine tuning the pairing strength all the way to the BEC regime. The latter is a weakly interacting gas of featureless bosonic molecules, and is not topological.

Bulk topological superconductivity differs in various respects from its lower-dimensional cousins. The 1D Kitaev wire and 2D $p+ip$ TSCs necessarily break bulk time-reversal symmetry. By contrast, fully-gapped 3D TSCs preserve time-reversal in the bulk, while nodal TSCs that break time-reversal can exhibit Weyl points and surface "Majorana arcs." The surface Majorana fluid is *gapless*, and can conduct heat and (if conserved) spin. Longitudinal transport of these is predicted to be precisely quantized [15,18] for fully-gapped, time-reversal invariant 3D TSCs, while quantized spin and/or thermal Hall conductivities are predicted for superconductors with Weyl nodes (see, e.g., [12]). Turning on a magnetic field can gap out the surface of a strong TSC, inducing an effective $p+ip$ type order. The latter supports Majorana zero modes in vortex cores.

Since the classification of topological phases does not directly aid in identifying materials candidates for topological superconductivity, the most pressing problems in this field are to

1. Confirm or refute the presence of topological superconductivity in known candidates, e.g. $Cu_xBi_2Se_3$ [24],
2. Unearth principles to guide the search for new materials.

Shingo Yonezawa (Kyoto University, Japan) presented experimental results on $Cu_xBi_2Se_3$ [5]. Based upon specific heat measurements, it is proposed that the superconducting state breaks rotational symmetry, with nematicity in the x-y plane of the sample that is not present in the normal state. This could be consistent with the E_u pairing representation; although not the strong topological scenario originally advocated by Fu and Berg [24], this state is expected to exhibit nodal superconductivity, i.e. *Dirac nodes in the paired state* (not to be confused with superconductivity in a Dirac semimetal, which could be topologically trivial or nontrivial depending on pairing details).

Open question: Is the observed nematicity really a result of superconductivity? Could it instead be a byproduct of structural distortion? Is the observed state truly gapless? We note that so far, STM studies have failed to observe a surface Majorana fluid in $Cu_xBi_2Se_3$.

Hai-Hu Wen (Nanjing University, China) presented STM studies of Bi_2Se_3 thin films on superconducting $FeTe_{0.55}Se_{0.45}$ substrates [6]. The superconductivity in the substrate presumably induces superconductivity in the Bi_2Se_3 film, via the proximity effect. The work reveals evidence for rotational symmetry in the superconducting state similar to Yonezawa, which seems to support the E_u pairing scenario. A key difference from Ref. [5] however is that rotational symmetry breaking could have a different physical origin, as superconductivity here is induced by proximity. E.g., it could arise from strain relative to the substrate.

In any case, the large superconducting gap in $FeTe_{0.55}Se_{0.45}$ allows Wen to resolve the Caroli-de Gennes-Matricon vortex core states in the Bi_2Se_3 thin films when subjected to a perpendicular magnetic field, an attribute also exploited by Hong Ding's group (described below). Wen sees evidence for Majorana zero modes in the presence of the field, identified as zero-bias peaks in the STM data.

Open question: The most important question is what is the source of the rotational symmetry breaking, and does it tell us anything about $Cu_xBi_2Se_3$? Wen also presented data on bulk $Sr_xBi_2Se_3$, indicating rotational symmetry breaking in the superconducting state. Tunneling into all of these systems in the absence of the magnetic field does not reveal evidence for a gapless Majorana fluid. In the case of the Bi_2Se_3 thin films on superconducting $FeTe_{0.55}Se_{0.45}$, this could be due to hybridization between top and bottom surfaces.

Pavan Hosur (University of Houston) discussed recent experiments carried out at the University of Houston on potassium-doped β-$PdBi_2$. This material is a "topological metal," with transport that is however dominated by trivial bands in the normal state. Doping appears to induce positive magnetoresistance at low temperatures, consistent with the Hikami-Larkin-Nagaoka model for weak antilocalization. This is possible evidence for $\mathbb{Z}_2$ topological insulator surface states being "revealed" by the potassium doping.

The material goes superconducting at $T_c = 4.4$ K. Andreev bound states (in soft point contact spectroscopy), upper critical field (in resistivity) and vortex magnetization (in SQUID magnetometry) are consistent with odd-parity superconductivity.

2.2 Majorana zero modes and synthetic 2D p+ip topological superconductivity via proximity

Since the work of Fu and Kane [25], it has been understood that bulk topological materials can provide an alternative route to topological superconductivity and Majorana zero modes, via *synthetic p+ip surface superconductivity* induced via proximity coupling. The idea is to take a $\mathbb{Z}_2$ topological insulator with a single Dirac cone at its surface, protected by time-reversal symmetry. Using an external s-wave superconductor to "proximitize" the surface leads to an effective p+ip state, which is fully gapped (irrespective of the chemical potential). This state in fact preserves time-reversal and rotational invariance, but "looks" like p+ip in terms of the canonical quantization of the surface Dirac state. In any case, further breaking time-reversal via the application of a perpendicular magnetic field can induce vortices, and Fu and Kane showed that these pin Majorana zero modes.

Pouyan Ghaemi (City University of New York) discussed Caroli-de Gennes-Matricon vortex core states in superconductors, in the presence of a Berry phase. Here, the following scenario is envisioned. One considers a topologically *trivial* s-wave bulk superconductor. In addition, however, the material is assumed to have a topological band gap (anticrossing) somewhere in the bulk bandstructure (not necessary near the Fermi energy). Then the superconducting bulk may "self-proximitize" topological insulator surface states, presuming that these survive from the topological band anticrossing all the way to the Fermi level. It is worth emphasizing that topological insulator surface states are only guaranteed to be "protected" (from disorder and interactions) within the bandgap. However, it is well-known from experiments that these surface states often persist up to energies well within the bulk conduction or valence bands, and can avoid significant hybridization with bulk states over some nonzero swath of energy.

The original context for this idea is $Cu_xBi_2Se_3$ [8]. Different from the *strong* TSC scenario envisioned in Ref. [24] and from the nematic state that seems to be favored by experiments [5,6], Ghaemi and collaborators assumed that the superconductivity observed in $Cu_xBi_2Se_3$ is in fact trivial s-wave. This can nevertheless produce a nontrivial effect if it proximitizes the topological insulator surface states spanning the valence-conduction band gap in the native Bi_2Se_3, which are known to persist well into the conduction band.

The theoretical calculation in [8] considered a scenario wherein the Fermi level is swept from the topological bandgap region continuously up through the conduction band, whilst trivial bulk superconductivity persists at all dopings. For doping levels close to or at the gap, the application of an external magnetic field can create vortices in proximitized surface states on opposite sides of the crystal that pin a pair of Majorana zero modes (MZMs). Since these coexist with bulk superconductivity, there must also be a vortex line linking these through the bulk. Now, as the Fermi energy is increased in this thought experiment, one would expect the MZMs to disappear by the time the surface states supporting them hybridize with the conduction band.

The surprising claim in [8] is that one can actually forget about the surface states, and focus only on the vortex line linking the two surfaces. The idea is that this is an effective 1D Kitaev wire. In its topological BCS phase, it supports MZMs at its ends, while in its trivial BEC phase, the MZMs bleed into the bulk and annihilate. Applying this picture to $Cu_xBi_2Se_3$ leads to numbers that match the hydrization energy for bulk and surface states in the conduction band.

Open question: Is this isolated vortex line picture correct in the presence of small, but nonzero hybridization with the bulk conduction band? Shouldn't we need to worry about the conduction electrons acting as a gapless bath that can dephase any qubits encoded in pairs of MZMs?

Hong Ding (Institute of Physics, Beijing, China) discussed his STM studies of the iron-based superconductor Fe(Se,Te) [7]. Like Hai-Hu Wen, Ding images Caroli-de Gennes-Matricon vortex core states, but here in the Fe(Se,Te) superconductor itself. He finds evidence for MZMs in some (but not all) vortex cores. The idea is that a $\mathbb{Z}_2$ topological band anticrossing that is well-separated from the Fermi level is giving rise to TI surface states, which are then "self-proximitized" by the trivial s-wave superconductivity in the bulk. This is the scenario articulate by Ghaemi [8], above. The topological band gap away from the Fermi energy is predicted via first-principles calculations [7].

Open question: Does the buried band gap really support surface states? A more fundamental question is do MZMs in superconducting vortices really imply "topological superconductivity"? A recent preprint by Dung-Hai Lee [26] call this into question.

2.3 Superconductivity in the half-Heusler family

In this cubic family of materials, the band structure can exhibit a so-called band inversion, with the s-like Γ_6 doublet located lower in energy than the p-like Γ_8 quadruplet (at the Γ point). The latter 4 bands can be thought of as being part of an effective

$J = 3/2$ multiplet, forming the basis of the so-called Luttinger model, developed to describe semiconductors with cubic symmetry [27]. The chemical potential typically crosses these $J = 3/2$ bands, and in some compounds, superconductivity is observed, leading to the notion of effective spin-3/2 Cooper pairing [9, 10, 13, 14, 11, 12].

Masatoshi Sato (Kyoto University, Japan) discussed theoretical prospects for high-winding number topological superconductivity in topological crystalline materials for effective $J = 3/2$ carriers [28].

Johnpierre Paglione (University of Maryland) gave an experimental overview of his group's work on the half-Heusler superconductor YPtBi [9], performed in collaboration with the theorists Agterberg (present in the audience) and Brydon [10]. The key observation is superconductivity in this hole-doped material, with a power-law dependence of the penetration depth versus temperature. This suggests non-s-wave pairing, and may indicate bulk line or point nodes.

Open question: what is the k-space structure of the superconducting order parameter? Is it, for instance, the mixed (s+p) septet pairing proposed by Brydon and Agterberg (with bulk line nodes), or does it have a different structure, for instance s+id (with Weyl nodes broadened by quenched disorder), as proposed recently by the group of Foster and Nevidomskyy [12]?

Andriy Nevidomskyy (Rice University) summarized the exhaustive theoretical treatment of various Cooper pairing scenarios that may take place in a Luttinger metal such as in YPtBi [10, 11, 12]. The main conclusion is that local (i.e. k-independent) pairing, which appears to be most natural, leads to either an s-wave or an effective d-wave pairing when projected onto the Fermi surface. In the presence of repulsive interactions, the pure s-wave is unlikely to survive, but the d-wave pairing is likely to be manifest, with either line nodes (if single d-component) or point nodes (in the case of d+id). Both scenarios would result in the power-law dependence of the density of states in the superconducting phase, consistent with the observations in YPtBi. Of these, the point nodes from the (d+id) pairing present the most interesting possibility, since these nodes come in pairs of Weyl points and are protected by a discrete $\mathbb{Z}$-valued topological invariant (the Chern number). The effect of quenched disorder on these nodes was discussed in detail, with implications for YPtBi [12].

Open question: based on the theoretical predictions, can one deduce the structure of the superconducting gap in YPtBi from experimental observations? Probably not, without more experiments to search for time-reversal symmetry breaking, anomalous spin or thermal Hall effects, etc. [12].

Daniel Agterberg (University of Wisconsin, Milwaukee) spoke about the recently introduced notion of Bogoliubov Fermi surfaces [13,14], that is, the bosonic analogs of a Fermi surface formed by Bogoliubov quasiparticles in a superconductor. One could think of these surfaces as the "inflated" versions of nodal points or nodal lines, with the Lifshitz transition separating the surfaces of finite measure from the points/lines of zero measure. It is claimed that if chiral symmetry is present [i.e. if $(\mathrm{CP})^2 = 1$] then these unusual quasiparticle surfaces are topological protected by a $\mathbb{Z}_2$ invariant, making them stable against any local perturbation preserving the CP symmetry. It was pointed out that in the half-Heusler materials like YPtBi, the spatial parity symmetry (P) is absent, and therefore the topological protection no longer exists; nevertheless, the "inflated" Bogoliubov Fermi surfaces may still manifest themselves [14].

Open question: What is the role of disorder on the Bogoliubov Fermi surfaces? Do those surfaces survive the effect of strong electron interactions? In order to be observable, the value of $|\Delta|$ should presumably be *large compared to the Fermi energy* (since the inflated surfaces arise from interband mixing), and if this is the case, then the weak-coupling description of the Bogoliubov quasiparticles may be insufficient—is it?

2.4 Classification and the effects of quenched disorder

Andreas Ludwig (University of California, Santa Barbara) gave an overview of the classification scheme for fermionic topological insulators and superconductors (the latter in the mean-field picture), based on the random matrix classification of Hamiltonians and the associated periodic table developed by Ludwig and collaborators [15] (and derived independently by Kitaev). Ludwig emphasized the historical path that led them to the classification scheme, which relied upon the protection of surface states from *Anderson localization* by impurities.

Matthew Foster (Rice University) presented a summary of his group's recent work on surface states of strong topological superconductivity [12, 16, 17, 18]. He discussed evidence for the precise quantization of the surface thermal and (if conserved) spin conductivities in the presence of both quenched disorder and interactions, on the basis of calculations that treat the effects of disorder exactly [18]. These results suggest that the (electronic component of the) surface thermal conductivity could serve as a "smoking gun" for the surface Majorana fluid expected to envelope the topological bulk.

Foster then switched to results relevant to spin-3/2 topological superconductors in class DIII, the yet undiscovered solid-state

analog of the ^{3}He-B superfluid. The microscopic model can be the aforementioned Luttinger metal at a finite chemical potential, if an odd-wave pairing is present. Microscopic Eliashberg calculations by the MIT group [11] suggest that optical phonon-mediated pairing could favor this non-s-wave channel in hole-doped half-Heusler materials. Foster's group has demonstrated that while the surface states of model higher spin topological superconductors exhibit unusual features in the clean limit (such as high-order cubic dispersion), any non-magnetic impurities induce quantum interference that drives the surface to the same robust quantum criticality [16] previously predicted to occur at the surface of spin-1/2 topological superconductors [12, 17].
Open questions: Is the odd-wave pairing, to which the above applies, realized in half-Heusler materials, for instance in YPtBi? Is there experimental information available that one could compare directly with the predictions describing the robust quantum critical dirty surface, which is described by a certain 2D conformal field theory [16, 29]?

2.5 Topology and Strong Interactions

Lucasz Fidkowski (University of Washington) spoke about the *intrinsically interacting* topological (IIT) superconductors, that is superconducting phases that require interactions to be topologically non-trivial. Said differently, such topological phases do not have a free-fermion description. A recent example is an exactly solvable model proposed in Ref. [30] whose non-interacting limit is in the class D (which is known to be trivial in 3D [15]), but which is rendered topologically non-trivial by interactions. On a technical level, a certain discrete unitary symmetry (in this example, it is $\mathbb{Z}_2 \times \mathbb{Z}_4$, coupled with fermion parity) protects the topology, which is encoded in a non-trivial braiding statistics of vortex loops. Physically, this non-trivial topology manifests itself in a quantized response of the system when coupled to the appropriate gauge field (similar to how non-interacting 3D TIs have a non-trivial magneto-electric effect, protected by time-reversal symmetry). In his talk, Fidkowski pointed out that such an intrinsic interacting topological 3D phase must have a non-trivial topological order on its 2D surface; and outlined a proposal for classifying such phases by studying how the symmetry manifests itself on the surface.

Open questions: Despite the mathematical beauty of the underlying theory (with its connection to topological quantum field theories and the mathematical subject of group extensions), is there a way to experimentally interrogate the proposed IIT phases to demonstrate the non-trivial topology? For instance, are there examples of IIT phases where the hypothesized quantized response could be measured in an experiment?

3 Outcomes of the Workshop

3.1 The emergence of any potential research collaborations:

- A new theory collaboration between Matthew Foster (Rice) and Pavan Hosur (University of Houston) may emerge with respect to the effects of finite surface state depth in topological phases.
- A new theory collaboration involving Fiona Burnell (U. Minnesota), Lukasz Fidkowski (U. Washington) and Andriy Nevidomskyy (Rice) may emerge concerning the classification of symmetry-enriched topological phases.
- A recently established experiment-theory collaboration among Silke Buhler-Paschen (TU Wienna), Jun Kono (Rice) and Qimiao Si (Rice) was further boosted by this workshop.
- The significant overlap between the theoretical ideas of Pouyan Ghaemi (CUNY) on the vortex states in the bulk of a topological superconductor and the experiments from Hong Ding's group (IOP, Beijing) may lead to future interactions between these groups.
- The workshop has strengthened the burgeoning collaboration between the local organizers Pavan Hosur (U. Houston), Matthew Foster (Rice) and Andriy Nevidomskyy (Rice), who seek to better understand the behavior of the "Majorana arcs" on the surface of a topological Weyl superconductor, in particular how these arcs are affected by disorder and overlap with the gapless bulk states.

3.2 Big questions, theoretical and materials prospects

As a result of the discussions that took place during the workshop, the emerging consensus is that more work is needed in order to realize, and unequivocally confirm, the existence of a *bulk three-dimensional* topological superconductivity in a real material. Part of the difficulty is that the odd-wave pairing required for the non-trivial topology of the wavefunction is very fragile, and in almost all known examples the p-wave or f-wave order parameter has nodes, meaning that the bulk superconducting gap does not vanish everywhere in the **k**-space, as it ought to in order for a strong topological invariant to emerge. The difficulty lies also in the fact that few experimental probes are suitable to detect the topological signatures at the energies and temperatures suitably below that of the superconducting T_c, which is of the order of 1 K. In particular, angle-resolved photoemission spectroscopy (and laser-ARPES) does not have sufficient energy resolution as of present; scanning tunneling microscopy (STM) on the other hand, may probe the energy structure of the vortex core, however the reality is that Caroli-de Gennes-Matricon vortex core states often lie at such low energies that they are very difficult to distinguish from the true zero-energy Majorana bound states. Perhaps the most promising experimental techniques for unveiling the strong topological superconductivity in the bulk are based on heat transport – both thermal Hall effect and longitudinal thermal conductivity are expected to have quantized values due to the topological contribution from the surface Majorana fluid. These experiments are however very demanding, especially given the low-T_c of the candidate superconducting materials.

A number of outstanding theoretical and experimental questions remain in the field, and these are summarized below:

- Perhaps the most pressing issue is that there is still no *bona fide* solid-state analog of ^{3} He-B, i.e. a true bulk topological superconductor. This could be due to the fragility of p-wave pairing, although the septet scenario proposed by Agterberg and Brydon for YPtBi (if confirmed) could be a very exotic, gapless exception [9, 10].
- The original logic of the Fu and Berg paper [24] still stands, in the sense that local pairings in a Dirac semimetal can give rise to p-wave pairing when projected to the Fermi surface. Thus more effort should perhaps be devoted to evaluating superconductivity in doped Dirac semimetals.
- A (vastly) more pessimistic take could be that there is some inherent problem to stabilizing Majoranas, be they zero modes, edge states, or surface states. This could be the reason that Majorana edge and surface fluids have not been detected in Sr_2RuO_4 or $Cu_xBi_2Se_3$. A few theoretical works have called into question the reality of Majorana zero modes outside of the universally applied Bogoliubov-de Gennes framework [31]. Could this also have implications for the 2D surface fluid of ^{3}He-B?
- More work is needed to understand precisely what zero-energy Caroli-de Gennes-Matricon vortex core states mean, i.e. whether these imply topological superconductivity or not [26].
- On a completely separate note, progress made in understanding the effects of disorder on bulk topological superconductor surface states may shed light on the still poorly-understood (logarithmic) conformal field theories believed to describe the spin and integer quantum Hall plateau transitions in 2D [16]. In fact, a recent paper by Zirnbauer [32] claims that the integer quantum Hall plateau transition corresponds precisely to a zero-energy surface state of a class AIII topological superconductor with winding number 4. These questions were extensively discussed amongst various experts (Ilya Gruzberg, Ferdinand Evers, Alexander Mirlin, Victor Gurarie, Matthew Foster and others) at the recent workshop "Anderson Localization and Interactions," held at the Max Planck Institute for the Physics of Complex Systems, September 24-28, 2018. The consensus view is that much additional work is necessary to understand these connections.

3.3 Connections to NSF's Quantum Leap big idea

The major emphasis of the NSF's Quantum Leap big idea is "exploiting quantum mechanics to observe, manipulate, and control the behavior of particles and energy at atomic and subatomic scales, resulting in next-generation technologies for sensing, computing, modeling, and communicating" [33]. Research into bulk topological superconductivity could identify materials candidates, clarify the role of topological protection in defining the key physical properties of bulk and surface states, and lead to new proposals for topologically-based quantum devices (not necessarily tied to quantum computation). In addition, any strong (fully gapped) 3D topological superconductor will support a 2D gapless Majorana fluid at its boundary. The application of an external magnetic field can gap the surface, except for localized zero modes isolated in the cores of vortices that pierce the surfaces. These Majorana zero modes could be employed in topological quantum computation [4], using braiding operations to carry out topologically protected quantum gates. In this sense, bulk topological superconductivity is an ideal platform for topological quantum computation, since the needed ingredients (Majorana fermions) should be "automatically" realized at the material boundary [1, 2, 3].

As mentioned in the introduction, topological superconductivity requires non-s-wave pairing. This attribute is shared by the high-Tc cuprate superconductors, and possibly many other exotic superconductors. Theoretical research into topological superconductivity may provide new insights into the problem of robust pairing that survives to high temperatures. It may also reveal new experimental probes or signatures that may have been previously missed or misinterpreted in studies of strongly correlated superconductors, such as heavy fermion compounds. The recent identification of the heavy fermion compound SmB_6 as a heavy fermion topological insulator is an example of how topology has led to a successful reinterpretation of old experimental data.

APPENDIX A: Workshop Program

RCQM Spring Workshop "Topological superconductors: Materials, topological order, and quenched disorder"

Workshop Information

Topological superconductors: Materials, topological order, and quenched disorder

Location: Rice University, Houston, Texas. Dell Butcher Hall, Room 180

Dates: April 24-25, 2018

Registration is Closed - You may register on sight at the check in desk

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Rational:

In the past decade there has been an explosion of interest in new forms of topological matter, driven by the discoveries of topological insulators and gapless topological phases. An intense effort is now being made to employ these as platforms for topological superconductivity. The discovery of bulk 3D topological superconductors would carry the promise of exotic quantum phenomena on their surface, in the form of so-called Majorana surface states. Several candidate materials have been proposed and are currently being measured and hotly debated.

The discovery of bulk topological superconducting materials could open the door to topological quantum computation, in which quantum information is stored in the topology of a macroscopic quantum state. Much experimental and theoretical effort has been invested by major companies to realize topological quantum computing in artificial (engineered) systems, but many technical barriers remain to be solved. Bulk topological superconductors could solve these problems “automatically” through a physical realization of the needed topology, if a suitable host material is found. The time is ripe for a small, intensive conference hosting both experimentalists and theorists to discuss prospects for bulk topological superconductivity. The conference will emphasize materials and existing experiments, as well as fundamental theoretical advances that link topological superconductors to the well-known quantum Hall effect in 2D. The workshop will address these key unsolved problems and by bringing together experts from different communities, will help advance the research frontier.

Speakers:

(A) Theorists

1. Andreas Ludwig (UCSB)
2. Daniel Agterberg (U Wisc Milwaukee)
3. Lukasz Fidkowski (University of Washington)
4. Masaki Oshikawa (University of Tokyo)
5. Masatoshi Sato (Kyoto University)
6. Pouyan Ghaemi (CUNY)
7. Fiona Burnell (University of Minnesota)

(B) Experimentalists

1. Johnpierre Paglione (U Maryland, co-organizer)
2. Hai-Hu Wen (Nanjing University)
3. Vidya Madhavan (UIUC)
4. Hong Ding (IOP, Beijing)
5. Shingo Yonezawa (Kyoto University)
6. Jimmy Williams (University of Maryland, College Park)
7. Silke Paschen (TU Wien)

Tuesday Morning, April 24

8:45 Welcome address: Matthew Foster

Session I: Candidate 3D Topological Superconductors

9:00 Shingo Yonezawa (Kyoto University)
Nematic superconductivity in doped-Bi2Se3 topological superconductors

9:30 Pouyan Ghaemi (CUNY)
Interplay of the surface and bulk topological superconductivity in doped topological insulators

10:00 Hai-Hu Wen (Nanjing U.)
Evidence of Nematic Superconductivity in Bi2Te3 Thin Film Deposited on FeTe0.55Se0.45

10:30 --- coffee break ---

Session II: Topological Superconductivity in Weyl semimetals

11:00 Pavan Hosur (U. Houston)
Transport evidence for topological superconductivity in doped beta-PdBi2

11:30 Vidya Madhavan (UIUC)
STM studies of Superconductivity in Weyl semimetals

Lunch and informal discussions (12:00 – 1:30pm)

Tuesday Afternoon, April 24

Session III: Surface Topological Superconductivity and Crystalline TIs

1:30 Hong Ding (IOP, Beijing, China)
Majorana bound state in iron-based superconductor Fe(Te, Se)

2:00 Masatoshi Sato (Kyoto University, Japan)
Topological Crystalline Materials of J=3/2 Electrons:
Antiperovskite, Dirac points, and High Winding Topological Superconductivity

2:30 Jimmy Williams (U. Maryland)
Josephson Junctions of Topological Crystalline Insulators

3:00 --- coffee break ---

3:30 – 5:15pm: Discussion Session I

5:15 - 6:00pm: Reception

6:00 Invited Speakers and External Poster Presenters Board Bus

6:30 Workshop Dinner (Invited Speakers/RCQM Faculty)

Wednesday Morning, April 25

Session IV: Topological Superconductivity in half-Heuslers & other Weyl semimetals

9:00 Johnpierre Paglione (U. Maryland)
High-spin superconductivity in topological half-Heusler semimetals

9:30 Andriy Nevidomskyy (Rice)
Pairing of effective spin-3/2 carriers: interplay of topology & disorder

10:00 Daniel Agterberg (U. Wisconsin, Milwaukee)
Topologically protected Bogoliubov Fermi surfaces

10:30 --- coffee break ---

Session V: Classification and Effects of Quenched Disorder

11:00 Andreas Ludwig (UCSB)
Disorder as a Tool to Classify Topological Insulators and Superconductors

11:30 Matthew Foster (Rice)
Quantized surface transport and universal criticality in dirty bulk topological superconductors:
A 3D analog of the integer quantum hall effect?

Lunch/Informal discussions & Poster Session (12:00 – 1:30pm)

Wednesday Afternoon, April 25

Session VI: Topology & Strong Interactions

1:30 Lukasz Fidkowski (U. Washington)
Strongly interacting topological superconductors beyond the band classification

2:00 Masaki Oshikawa (University of Tokyo, Japan)
Orbital Angular Momentum and Current Distribution in Two Dimensional Chiral Superfluids

2:30 --- coffee break ---

3:00 Silke Paschen (TU Vienna)
Weyl semimetal behavior in Kondo systems

3:30 Fiona Burnell (U. Minnesota)
Microscopic analysis of superconducting instabilities in NbSe2 and MbS2

3:30 – 5:00pm: Discussion session II

5:00 pm – Meeting adjourned

Organizers' Information

Organizers: Matthew Foster (Assistant Professor, Rice University, matthew.foster@rice.edu), Andriy Nevidomskyy (Associate Professor, Rice University, nevidomskyy@rice.edu), Johnpierre Paglione (Professor, University of Maryland, paglione@umd.edu), Pavan Hosur (Assistant Professor, University of Houston, pavanhosur@gmail.com)

Special Thanks to our Event Sponsors:

Location: Rice University

Date: April 24, 2018, midnight - April 25, 2018, 11:59 p.m.

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