UMD Majorana Workshop (2205 Toll building)

Day 1: Current Status of Majorana Nanowires

Speaker		Time
Sankar	Das Sarma	8:30 (30)
Leo	Kouwenhoven	9:00(45+15)
Charlie	Marcus	10:00(45+15)
Sergey	Frolov	11:00(20+10)
Chetan	Nayak	11:30(45+15)
Lunch		12:30(90)
Roman	Lutchyn	14:00(20+10)
Chingkai	Chiu	14:30(20+10)
Tudor	Stanescu	15:00(20+10)
Jay	Sau	15:30(20+10)
Will	Cole	16:00(20+10)
Yuval	Oreg	16:30(20+10)
Ady	Stern	17:00(20+10)
End		17:30

Day 2: Future TQC in Majorana Nanowires

Speaker		Time
Jason	Alicea	8:30(30+15)
David	Clarke	9:15(30+15)
Karsten	Flensberg	10:00(20+10)
Reinhold	Egger	10:30(20+10)
Mike	Freedman	11:00(30+15)
Charlie	Marcus	11:45(30+15)
Lunch		12:30(90)
Leo	Kouwenhoven	14:00(30+15)
Discussion		14:45(165)
End		17:30

SUMMARY OF CMTC MAJORANA WORKSHOP IN COLLEGE PARK OCT 29/30, 2016

DAY 1: Current Status of Majorana Nanowires

Consensus items:

Although varying definitions of `topological' and 'trivial' were discussed, there seemed to be general agreement that alternate explanations for ZBCP that do not involve Majoranas in some way (e.g. Kondo physics) are inconsistent with the totality of the observed ZBCP behavior. This leaves open the possibility of multiple Majorana or Majorana-like modes near the wire end. One suggested mechanism for such multiple-Majorana physics was an inhomogeneous potential within the wire. Another possibility mentioned was disorder, including possibly in the parent superconductor. It was pointed out that signatures looking for bulk topological phase transition such as heat conductance and bulk gap closure could be an independent check to identify bulk topological order.

Open questions:

What governs the height, width, and line shape of the ZBCP? Temperature and dissipation were raised as possibilities. For instance, why is the peak width still of order 20 micro-eV? Is it purely a thermal or dissipative effect? How much should one worry about the fact that many of the presented experimental ZBCPs are less than a factor of 20 of the quantized Majorana value?

It was pointed out that ZBCPs in realistic nanowires could arise from multiple- nearby MZMs (essentially equivalent to an Andreev state) of non-topological origin (i.e. no non-Abelian braiding statistics) which could smoothly go over to localized MZMs with topological properties. This crossover is not easily distinguishable in tunneling experiments. Perhaps this could be the origin for the weird ZBCP line shapes seen in some experiments.

What governs the observed particle-hole asymmetry? It was suggested that this asymmetry may result from dissipative effects, and therefore, the samples observed to have better p-h symmetry (presumably with less dissipation) may be better suited for TQC. It is not clear that braiding will succeed if dissipation is strong. Interaction was also mentioned as a possibility for p-h asymmetry.

There was considerable discussion on possible source(s) for dissipation. It was generally agreed that intrinsic dissipation is not a good thing here, particularly in the context of achieving TQC. It appears that the best simulation fits to the best current experimental ZBCP data necessarily require the presence of finite dissipation on a phenomenological level since pure thermal effects lead to finite ZBCP peak height and width, but cannot explain the p-h symmetry breaking. Also, the observed ZBCP height/width is smaller/larger than that implied just by the experimental temperature.

What leads to the observed (lack of) oscillating splitting with increasing amplitude in magnetic field? One suggested mechanism was a `squeezing' effect due to level repulsion from above-gap energy levels as the bulk gap closes due to increased magnetic field. Another was the possibility of the observed splitting coming from nearby overlapping Majoranas at the wire end. The possibility of coupling through the bulk SC as a reason for suppressed MZM oscillations was mentioned and debated also. Finally, it is not known what role Coulomb interactions might play in suppressing (or enhancing) these oscillations. The generic lack of MZM oscillations in NS tunneling measurements was discussed and possible reasons suggested were multiple MZMS, large SO-coupling, disorder, dissipation, and image charge effect. Also not discussed extensively (but mentioned in the Introduction to the conference) is the lack of end-to-end correlations in the experimental Majorana wires, which may be connected with the lack of MZM oscillations.

There was a lot of discussion on the recent Copenhagen finding of topologically protected MZM oscillations in the Coulomb blockaded regime of Inas/Al nanowires. The non-increasing amplitude of these oscillations with increasing magnetic field remains a mystery in spite of considerable theoretical efforts in understanding the observation. Furthermore, it is also a mystery that in the experiment, the parity sometimes does not switch as the two peak spacings are closed, but the theoretical prediction is that parity should always switch due to the Majorana hybridization. Various possibilities were suggested including coupling through the parent superconductor, complicated trajectories through density-chemical potential landscape with increasing magnetic field, and perhaps accidental end Andreev state induced oscillations. There was a feeling that the observed nature of these oscillations (i.e. amplitude not increasing with increasing magnetic field) probably cannot be explained simply by using a magnetic field induced proximity gap which is collapsing-- in fact, such a procedure by itself produces the opposite effect of further enhancing the oscillation amplitude with increasing magnetic field.

Why is the gap consistently softer in the region where ZBCPs are observed? Is this observed softness purely due to the width of the observed zero-bias peak (often comparable to the induced gap) or are there additional soft modes (e.g. from disorder- or inhomogeneity-induced fermionic states)? It was pointed out that there is no obvious gap region in many of the experimentally topological regimes (i.e. with ZBCP) - rather a minimum between two peaks. Other suggested possibilities included Griffiths physics or superconductor-induced disorder.

The effect of the orientation of the applied magnetic on the existence (or not) of the ZBCP still remains a somewhat open experimental issue, perhaps because of orbital effects of the applied field.

What is the full role of orbital effects in this system? One suggestion was an anisotropic g-factor. Simulations including full 8-band Kohn-Luttinger model may be necessary to understand quantitative details.

What is the best/most practical signature of a bulk gap closure? Suggestions ranged from thermal conductance measurements to ARPES. Can a trijunction be used to probe the bulk spectrum?

All experiments to date have been conducted in wires for which the proximitized region is around a micron in length or smaller. Finite-size effects (both on the topological phase transition and the Majoranas themselves) may still be quite significant in such systems, putting one in a somewhat murky regime where topological and trivial physics remains rather smoothly connected. It could be that some of the outstanding issues would be resolved by going to significantly longer wires. Doing so will certainly be necessary anyway for longer-term applications (e.g. for TQC applications discussed on Day 2 which would eventually need long wires keeping the end MZMs far from each other). On the other hand, longer wires are more susceptible to inhomogeneous potential and disorder effects (both intrinsic disorder in the wire and SC-induced disorder) possibly leading to problems, so the situation is not completely clear. Perhaps experiments should be carried out both in much longer and much shorter wires to discern various issues.

Day 2: Future TQC in Majorana nanowires

<u>Consensus items:</u>

Even if `Fusion' and 'Braiding' experiments do not succeed in producing results consistent with non-Abelian Ising anyons, they can provide valuable information characterizing the nanowire systems that is unavailable from conductance measurements into the wire ends. For instance, the 'Fusion'-type experiment may be able to constrain the value of the Majorana splitting further than transport experiments by varying the time taken to cut the system with a tunnel barrier. Cutting speeds slow on the scale of the splitting produce deterministic results, while those fast compared with the splitting produce probabilistic results. There was a definite consensus that such fusion/braiding/qubit experiments should now begin in earnest even if not all the questions for Day 1 are answered yet.

Experimentalists have requested `User Manual' summaries for device proposals as the devices and the experimental protocols are becoming increasingly complex.

There appears to be tentative experimental consensus toward moving forward with a box-qubit-like device. Advantages include having all nanowires colinear and avoiding complications associated with complex Josephson junction engineering. Challenges include engineering phase coherence in the `reference' arms or in any wires required to run perpendicular to the nanowires. One disadvantage of box qubits over transmon based proposals is that the range of distance over which qubits can be entangled through a single measurement is expected to be shorter.

If Majorana-based qubits reach the same level of stability as other superconducting qubits, but do not have much greater stability, it may still be advantageous to replace SC qubits with MZM based ones in a surface code implementation due to the ease with which stabilizer operators may be measured in an arrangement of MZM qubits. This seems to be still some time in the future.

Significant materials/modeling challenges remain in building working MZM-based TQC elements. There is a serious need for experiment/theory/modeling to work together here.

As a matter of nomenclature, ‘teleportation’ was deemed an inaccurate portrayal of the process of hopping one electron onto a TSC region at one MZM and another off the TSC region near a second MZM. Single electron coherent transport (SECT) was suggested as a replacement for ‘teleportation’ in this context.

Open questions:

If dissipation broadening is of order 200mK, as may be indicated by particle-hole asymmetry in tunneling measurements, will braiding work?

How long does it take to measure a qubit in each proposed measurement scheme (quantum dot/resonator setups, conductance measurements, etc.). How susceptible is each scheme to an error in the Hamiltonian or environmental decoherence?

How should the Josephson microwave measurements be interpreted? Why is no bulk gap closure observed and only an ordinary Andreev state observed (is it possibly connected with multiple MZM story discussed on Day 1)?

When an additional symmetry is introduced, such as time-reversal symmetry or reflection combined with time-reversal symmetry, the symmetry class is changed. The 1D superconducting chain can host multiple Majorana bound states on one end protected by the additional symmetry. Observing these multiple states without breaking the symmetry in an experiment is still an open question. Will braiding work at all in this situation, or in other words, can fusion/braiding help answer these questions?