# An Introduction to Highly Entangled States of Quantum Matter

**(7 January 2014)**

**Xiao-Gang Wen**

***Perimeter Institute for Theoretical Physics***

I plan to discuss the concept of short-range and long-range entanglement, as well as their systematics description. Many amazing properties of quantum states of matter are directly related to the pattern of many-body entanglement.

# Proximity-effect-induced Superconductivity and Cooper Pair Interference on the Surfaces of $Bi_2Se_3$ and $Bi_2Te_3$

**(7 January 2014)**

**Li Lu**

*Institute of Physics, Chinese Academy of Sciences*

It is believed that once the helical electrons on the surface/edge of a topological insulator form Cooper pairs via proximity effect, the induced superconducting state would resemble that of a spinless chiral *p*-wave superconductor [1]. We have studied the proximity-effect-induced superconductivity on the surfaces of three-dimensional topological insulator (TI) candidates $Bi_2Se_3$ or $Bi_2Te_3$ by depositing conventional *s*-wave superconductors Pb or Sn onto exfoliated single crystals of the materials. The induced superconductivity is found to spread significantly away from the interface, both along the surface direction (up to several microns) and in the depth direction (could easily penetrate a crystal of thickness ~ 100 nm) [2, 3]. By utilizing the induced superconducting surface state, we have constructed superconducting quantum interference devices and studied the interference behaviour of the Cooper pairs formed of helical electrons. Two types of interference patterns were recognized at low temperatures [3, 4]. One is conventional *s*-wave like and is identified to arise from a zero-phase loop inhabited in the bulk of $Bi_2Te_3$. The other, being identified to relate to the surface states, is anomalous for that the peak positions of the pattern are shifted away from those of a zero-phase loop, to opposite magnetic-field directions in positive and negative bias current directions [4]. The result is consistent with the picture that the Cooper pairs on the surface of $Bi_2Te_3$ have a $2\pi$ Berry phase which makes the superconductivity $p_x+ip_y$-wave-like.

**References**

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**Universal Topological Quantum Computation from A Superconductor / Abelian Quantum Hall Heterostructure**

**(8 January 2014)**

**Roger Mong**

***California Institute of Technology***

Non-Abelian anyons promise to reveal spectacular features of quantum mechanics that could ultimately provide the foundation for a decoherence-free quantum computer. The Moore-Read quantum Hall state and a (relatively simple) two-dimensional p+ip superconductor both support Ising non-Abelian anyons, also referred to as Majorana zero modes. Here we construct a novel two-dimensional superconductor in which charge-2e Cooper pairs are built from fractionalized quasiparticles, and like the Z3 Read-Rezayi state, harbors Fibonacci anyons that – unlike Ising anyons – allow for universal topological quantum computation solely through braiding.

## Wave Function and Strange Correlator of Short Range Entangled States

**(8 January 2014)**

**Cenke Xu**

***University of California, Santa Barbara***

Short range entangled states (such as integer quantum Hall states, quantum spin Hall states) can have nontrivial edge states, but their bulk spectrum must be completely trivial. We propose a general method to determine whether a SRE state is a trivial or nontrivial, based on its bulk ground state wave function. Our method is applicable to both fermion and boson SRE states.

**Equation of State for Ultracold Fermions**

**(8 January 2014)**

**Xavier Leyronas**

***Universite Pierre et Marie Curie***

The field of ultracold fermions has been rapidly growing in the last ten years. In these systems, fermionic isotopes of atoms can be in two internal states ("spin one half fermions"), like in electrons in solids. The physics of ultracold fermions is particularly rich, since one can experimentally tune the strength of the interaction, or "polarize" the system.

After a general introduction, including the presentation of the BEC-BCS crossover, I will present my work on the calculation of the equation of state in different situations. These calculations will be compared to accurate measurements on ultracold Li6 gases performed at ENS and MIT.

**Majorana Zero-modes in A Quantum Spin Hall Insulator**

**(9 January 2014)**

**Carlo Beenakker**

***Leiden University***

Topological insulators in proximity to a superconductor have been predicted to support Majorana zero-modes: midgap states with identical creation and annihilation operators and non-Abelian braiding statistics, that are presently under intense scrutiny. The conducting edge of a quantum spin Hall insulator (a quantum well with an inverted band gap) seems like an ideal system to search for these elusive particles in a transport experiment: Only a single mode propagates in each direction along the edge, unaffected by disorder since backscattering of these helical modes is forbidden by time-reversal symmetry. We discuss the prospects for the detection of Majoranas as a short-term application, and braiding as a longer term perspective.

**Aspects of Proximity-Coupled InAs/GaSb as a Platform of Majorana Fermions**

**(9 January 2014)**

**Rui Rui Du**

***Rice University***

Recent low temperature transport experiments have shown robust helical edge states in inverted InAs/GaSb quantum wells, with quantized conductance plateaus observed at temperatures well above 10 K. Several experiments show clear signals of Andreev reflection and superconductor proximity effect in s-SC contacted edge states, indicating highly transparent interface. Such experimental advances have promoted a great interest in pursuing Majorana fermions in a platform build from InAs/GaSb and s-wave superconductors. In this talk I will briefly discuss materials issues, temperature and magnetic field dependent properties of the edge modes, and on-going experiments (using either normal or superconducting contacts) on the edge states by transport and STM experiments. I will try to provide some perspective of the field.

**Majorana States by Self-organization of Magnetic Moments in A One-dimensional Conductor**

**(10 January 2014)**

**Bernd Braunecker**

***Perimeter Institute for Theoretical Physics***

The interaction between magnetic moments embedded in a one-dimensional conductor and the spins of the conduction electrons can trigger a Peierls-type transition that drives the system into an unexpected ordered phase. This phase consists of a spiral order of the magnetic moments that is inseparably bound to a helical electron density wave combining spin and charge degrees of freedom. Remarkably, the gap associated with this density wave binds only half of the conduction electron modes, while the remaining gapless modes form a helical conductor. Since induced superconductivity in a helical conductor becomes of the topological type supporting Majorana end states, such self-organized systems may offer an alternative route to Majorana states. Most notably such phases appear genuinely (at low enough temperatures) without any requirement of fine-tuning material properties or external fields.

It should be noted, however, that the helical phase results from an optimized balance of interactions between the magnetic moments and the electrons. Through the induction of superconductivity this balance is substantially perturbed. I show in this talk that nonetheless Majorana states genuinely appear. Yet the involved physics is quite complex and its understanding requires a manifestly self-consistent investigation of the mutual feedback effects between electrons and magnetic moments, and the strong renormalization of the physical parameters by electron-electron interactions. The results allow me to comment on the reachability of the ordering temperatures in semiconductor wires and magnetic adatom chains.

**Reference**

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# Theory of Superconducting Topological Insulator

**(11 January 2014)**

**Yukio Tanaka**

***Nagoya University***

Topological superconductor with time reversal symmetry is a hot topic now. Recently, topological superconducting state has been predicted in Cu doped $Bi_2Se_3$ ($Cu_xBi_2Se_3$) [1]. Point contact spectroscopy has shown a zero bias conductance peak (ZBCP) consistent with the presence of surface edge mode [2], i.e., surface Andreev bound states (SABSs) [2]. We study, i) Tunneling spectroscopy [3,6], ii) Josephson current[5], iii) Bulk properties [8] and iv) proximity effect of this system [9].

i) Tunneling spectroscopy of superconducting topological insulator [3]

We develop a theory of the tunneling spectroscopy for superconducting topological insulators (STIs), where the SABSs appear as helical Majorana fermions. We find that the SABSs in the odd-parity STIs have a structural transition in the energy dispersions. The transition [3,4] results in a variety of Majorana fermions, by tuning the chemical potential and the effective mass of the energy band. We clarify robust zero bias peaks in the tunneling conductance [3] between normal metal/STI junctions. We derive an analytical formula of the conductance of the present junction [6] which is an extension of the conductance formula of unconventional superconductors [7].

ii) Josephson effect of superconducting topological insulator [5]

We study the effect of helical Majorana fermions at the surface of odd-parity STIs on the Josephson current. The Josephson current-phase relation in an STI/*s*-wave superconductor junction shows robust $\sin(2\phi)$ owing to mirror symmetry, where $\phi$ denotes the macroscopic phase difference between the two superconductors. The maximum Josephson current in an STI/STI junction exhibits a nonmonotonic temperature dependence depending on the relative spin helicity of the two surface states.

iii) Spin susceptibility[8]

We calculate the temperature dependence of the spin susceptibility. We propose that the pairing symmetry of a STI can be determined from measurement of the Knight shift by changing the direction of the applied magnetic field.

iv) Proximity effect [9]

We self-consistently study surface states and proximity effect. We demonstrate that, if a topologically trivial bulk s-wave pairing symmetry is realized, parity mixing of pair potential near the surface is anomalously enhanced by surface Dirac fermions, opening an additional surface gap larger than the bulk one. In contrast to classical s-wave superconductors, the resulting surface density of state hosts an extra coherent peak at the induced gap besides a conventional peak at the bulk gap but no such surface parity mixing is induced by Dirac fermions for topological odd-parity superconductors. Our calculation suggests that the simple U-shaped scanning tunneling microscope spectrum does not originate from s-wave superconductivity of $Cu_xBi_2Se_3$.

**References**

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**Hole Binding in Antiferromagnets: A DMRG Study**

**(13 January 2014)**

**Zheng-Yu Weng**

***Tsinghua University***

The binding of two holes injected in antiferromagnets is studied based on the density matrix renormalization group simulation for the t-J square ladders. It is shown that the binding strength is substantially enhanced in a spin background of short-range spin correlations as opposed to that of quasi-long-range spin correlations. However, it is further shown that such strong hole binding gets significantly diminished once phase strings are switched off. In the latter case, a coherent quasiparticle picture is restored for an unpaired single hole. By contrast, the quantum frustration of the single hole's motion due to phase strings can be effectively removed by pairing, and thus a strong binding force hidden in the kinetic energy term is revealed for the t-J model.

## Spin Pumping into the Surface State of Topological Insulators

**(14 January 2014)**

**Yoichi Ando**

***Osaka University***

In this talk, I will present the results of our recent experiment to detect the electrical response of the topological surface state to spin pumping from a nearby ferromagnet, performed in collaboration with Prof. Saito's group at Tohoku University (arXiv:1312.7091). We observed clear evidence for spin-electricity conversion which takes place as a result of the spin-momentum locking when a fixed spin polarization is pumped into the topological surface state.

I will also present the update on our experiment to address the (111) surface state of SnTe, which is a topological crystalline insulator harboring Dirac cones of two different geometries on this surface (arXiv:1305.2470 and arXiv:1312.2803).

**Measurements of Superconductivity in DMFT Simulations at the Two-particle Level**

**(14 January 2014)**

**Ziyang Meng**

***University of Toronto***

The two-particle measurements are important in the study of the phase transition in strongly correlated electron systems, various vertex functions, such as charge, magnetic and superconducting, are directly related to the corresponding susceptibilities and contain the information of the transition temperature and the properties of the developed order parameter in the symmetry broken phase. In this talk, I will present a scheme to measure and construct the non-local, two particle-particle vertex functions in the dynamic mean field theory (DMFT) simulations, where one first measures the vertex function locally on the quantum impurity, then through the help of the Parquet equation – the fact that the irreducible vertex is still reducible outside its own channel – one introduces the non-local information (momentum-dependence) into the vertex functions. Such scheme is applied to the measurement of superconducting instabilities in several strongly correlated systems: in one-band Hubbard model on square lattice, a d-wave singlet pairing instability can be clearly seen; and in the one-band Hubbard model with special van Hove Singularities, a p-wave, triplet pairing, topological superconductivity is the dominate instability.

**Can Deeply Underdoped Cuprates be Topological Superconductors?**

**(15 January 2014)**

**Dung-hai Lee**

***University of California, Berkeley***

A hallmark of the copper-oxide high temperature superconductor is the nodal d-wave pairing symmetry. According to topological consideration the nodes are stable against perturbations. It is therefore surprising that recent angle-resolved photoemission experiments on very underdoped cuprates revealed a nodeless particle-hole symmetric gap over the entire Fermi surface. Moreover this fully gapped states have been observed in compounds across several different cuprate families. In this talk I propose that this fully gapped state is a topological chiral superconductor.

**Half Dirac Semimetal and Quantum Anomalous Hall Effect in Chromium Dioxide Thin Films**

**(15 January 2014)**

**Fa Wang**

***Peking University***

Chromium dioxide ($CrO_2$) is a half-metallic material, widely used in high-end data storage applications. Using first principles calculations, we show via interfacial orbital design that a novel class of half semi-metallic Dirac electronic phase emerges at the interface between $CrO_2$ and $TiO_2$ in both thin film and superlattice configurations, with four spin-polarized Dirac points in momentum-space. Taking spin-orbit coupling into account, the $CrO_2/TiO_2$ superlattice becomes a Chern insulator without external magnetic fields or additional doping. The Chern insulator state has a gap of about 43 Kelvin and Chern number 2, namely quantization of Hall conductance to $2e^2/h$.

## Berry Phase Phenomena of Non-collinear Spins

**(16 January 2014)**

**Naoto Nagaosa**

***The University of Tokyo***

Berry phase is a concept ubiquitous in many branches of physics. Especially, when the spins in magnetic systems form non-collinear configurations, the overlap integral of the wavefunctions of neighbouring spins gives the complex phase factors. This leads to the Berry connection which acts as the gauge potential. This gauge potential plays the crucial role in theories of strongly correlated electronic systems such as high temperature superconductors [1], frustrated quantum spin systems [2], anomalous Hall effect [3], and various spin textures in magnets [4].

In this talk, the physical phenomena induced by this Berry phase related to the non-collinear spins will be discussed. After the generic introduction to this subject, I will mainly focus on the recent developments on the Hall effect and topological spin textures in magnets.

### References

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**Quantum Anomalous Hall Effect: From Science Fiction to Realistic Materials**

**(16 January 2014)**

**Xi Dai**

***Chinese Academy of Sciences***

In this talk, I will introduce how we can possibly realize quantum anomalous Hall effect by material design. The first proposal is the thin film of a magnetic semi-metal EuB6, which is relatively easy for the sample growth but the energy gap is only several meV. The second proposal is the LaCoO3 thin film growing along (111) direction, where the energy gap is generated by the Coulomb interaction and can easily reach 0.1eV.

## Generalized Laughlin's Argument for Symmetry Protected Topological Phases

**(16 January 2014)**

**Shinsei Ryu**

***University of Illinois at Urbana-Champaign***

We generalize Laughlin's flux insertion argument in a way that it is applicable to topological phase protected by symmetries such as unitary on-site symmetry and parity symmetry. We formulate it as a gappability / ingappablity condition of non-chiral gapless edge theories that appear at an edge of a bulk symmetry-protected topological phase.

## Majorana Ghosts: From Topological Superconductor to the Origin of Neutrino Masses, Three Generations and their Mass Mixing

**(17 January 2014)**

**Zhengcheng Gu**

***California Institute of Technology***

Recently, Majorana's spirit returns to modern condensed matter physics, in the context of Majorana zero mode in certain classes of topological superconductors. In this talk, I investigate the topological nature of a Majorana fermion by assuming that it is made up of four Majorana zero modes. First, I show that a pair of Majorana zero modes can realize a T^4 = -1 time reversal symmetry, a P^4 = -1 parity symmetry and even a nontrivial C^4= -1 charge conjugation symmetry. Next, I propose a CPT super algebra for the Majorana fermion made up of four Majorana zero modes. Furthermore, the origin of three generations of neutrinos can be naturally explained as three distinguishable ways to form a pair of (local) complex fermions out of four Majorana zero modes. Finally, I compute the mass mixing matrix and mass ratios of the three mass eigenstates from a first principle at leading order (in the absence of CP violation and charged lepton corrections). We obtain \theta_{12} = 31.7, \theta_{23} = 45, \theta_{13} = 0 and m1=m3 = m2=m3 = 3/\sqrt{5}. We also predict the effective mass in neutrinoless double beta decay to be m_{\beta\beta}= m1/\sqrt{5}.

**Disordered Topological Superconducting Nanowires**

**(17 January 2014)**

**Michael Wimmer**

***Leiden University***

It is well-established that disorder is harmful to a topological phase in p-wave superconductors. Recently, it has been proposed to engineer a p-wave superconductor using conventional materials: a nanowire with strong spin-obrit coupling in proximity to a s-wave superconductor and in a magnetic field ("s-wave Rashba wires"), and first experimental results have been obtained.

I will discuss a simple and intuitive method to link topological properties of superconducting wires to their normal state properties. This allows to describe ensemble-averaged topological properties as well as individual systems. In particular, I will show that the effect of disorder is quite different in p-wave superconductors and s-wave Rahsba wires: While disorder is always harmful for the former, topology can be created by disorder in the latter.

**Topological Superconductivity at Type-II Van Hove Singularity**

**(17 January 2014)**

**Hong Yao**

***Tsinghua University***

We study unconventional superconductivity induced by weak repulsive interactions in 2D electronic systems at Van Hove singularity (VHS) where density of states is logarithmically divergent. We define two types of VHS. For systems at type-I VHS, weak repulsive interactions generically induce unconventional singlet pairing. However and more interestingly, for type-II VHS renormalization group (RG) analysis shows that weak repulsive interactions favor triplet pairing (e.g. p-wave) when the Fermi surface is not sufficiently nested. For type-II VHS systems respecting tetragonal symmetry, topological superconductivity (either chiral p+ip pairing or time-reversal invariant Z2 p+ip pairing) occurs generally. We shall also discuss relevance of our study to materials including recently discovered superconductors La_{1-x}O_xFBiS_2 which can be tuned to type-II VHS by doping.

## Fractional Quantized Hall Effect and Phase Transitions in the Lowest Landau Level of Single-layer Graphene

**(20 January 2014)**

**Bertrand Halperin**

***Harvard University***

Experiments have seen many fractional quantized Hall states in the zeroth Landau level of graphene; i.e., for fractions in the range $-2 < \nu < 2$. However, there are some striking differences between observations in the wings of the Landau level ($|\nu| > 1$) and the center portion ($|\nu| < 1$). I will present experimental data from the Harvard group that shows these differences, and I will discuss our theoretical explanation [1,2]. In the center region, we see quantized Hall states at a large number of fractions with odd denominator, and also see phase transitions, as a function of magnetic field or electron density, at fixed filling fraction, similar to effects seen in GaAs quantum wells. In the outer portion of the Landau level, fractions with odd numerator seem to be missing, and the phase transitions are not observed. We argue that these differences can be largely understood as a consequence of the effects of interaction terms in the Hamiltonian that violate the SU(2) valley symmetry of the simplest model Hamiltonian, which have different effects in the wings and in the center of the Landau level. I shall also discuss some experimental results on bilayer graphene.

**References**

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**Quantum Reality**

**(20 January 2014: IAS Distinguished Lecture)**

**Sankar Das Sarma**

***University of Maryland***

Quantum mechanics, the underlying microscopic theory of our existence governing the behavior of the physical world, is the crowning success of human intellect. It is astonishingly successful – no experiment contradicts the predictions of the theory, and the theory has been explicitly verified to be correct to a precision better than 1 part in a trillion. In the past 60 years, developments of quantum theory have led to the modern technology that has revolutionized the world through applications such as transistors, lasers, integrated circuits, and magnetic discs. Despite this great success we really do not understand the quantum theory in an intuitive manner because quantum laws are so radically different from the classical laws of physics. The dichotomy that the modern world is quantum, but the precise meaning of the quantum remains elusive, disturbed the stalwarts of physics such as Einstein, Schrodinger, and Feynman, and continues to baffle physicists even today. This lecture will explore this curious state of affairs, highlighting the numerous quantum based ideas and applications which underpin our modern world and the sublime strangeness of the theory which completely eludes our intuition. Connection will be made to some of the most exciting recent developments such as quantum computation which is bridging the gap between the 'weird' microscopic laws of the quantum world and some real life problems in our everyday world such as code breaking and database search.

**Topology and Geometry in Condensed Matter Quantum Physics: general thoughts and some examples**

**(21 January 2014)**

**Duncan Haldane**

***Princeton University***

The Gauss-Bonnet sum rule relating integrated Gaussian curvature and Euler characteristic of 2-manifolds is the original relation of geometry and topology, later generalized to the relation between integrated Abelian Berry curvature and first Chern class (and then to higher-dimensional generalizations), which have become central to modern theories of topological states of condensed matter. The choice of which curvature to use in this relation is not always as obvious as it appears at first sight, since all non-singular curvature function integrate to the same topological invariant. This is a significant observation in both the case of Bloch state Berry curvature, and fractional quantum Hall fluid Gaussian curvature. I will illustrate the relation of topology and geometry with two examples: "Fermi-arc" edge states of "topological metals" and Weyl semimetals (including the anomalous Hall effect), and the "guiding-center metric" and Hall viscosity in the fractional QHE.

**Defects in Abelian Topologically Ordered States**

**(21 January 2014)**

**Xiao-liang Qi**

***Stanford University***

Point-like and line-like defects in topologically ordered states can be used to probe the properties of the state. In particular, non-Abelian point-like defects can be realized even in an Abelian topologically ordered state. The point defects support “parafermion zero modes” which are generalizations of the Majorana zero modes. In this talk, I will discuss the characterization of topological defects in topologically ordered states, and its realization in experimentally accessible fractional quantum Hall systems.

**Transport Properties of Magnetically Doped Topological Insulator Thin Films**

**(21 January 2014)**

**Yayu Wang**

***Tsinghua University***

Topological insulators (TIs) are novel quantum materials with topologically nontrivial band structure induced by strong spin-orbit coupling. Breaking the time reversal symmetry (TRS) in TIs has been predicted to create a variety of exotic topological magnetoelectric effects such as image magnetic monopole and quantized anomalous Hall effect. In this talk we report transport studies of magnetically doped TI ultrathin films grown by molecular beam epitaxy (MBE), aiming to reveal the unique properties of the topological surface states and realize the quantum anomalous Hall effect.

In the $Bi_2Se_3$ films doped with Cr, we found a systematic crossover from weak antilocalization to weak localization induced by magnetic doping. We show that the evolution of the localization behavior indicates the transformation of the system from a topologically nontrivial TI to a topologically trivial dilute magnetic semiconductor. In a new ternary TI system $(Bi_{1-x}Sb_x)_2Te_3$ with depleted bulk carriers, Cr dopants induce a long-range ferromagnetic ordering. More interestingly, the ferromagnetism exists both in the presence of hole- and electron-type Dirac fermions with widely varied carrier concentrations. The carrier-independent ferromagnetism in TIs is consistent with the Van Vleck mechanism mediated by the band electrons. This picture is further supported by recent observations of a topology-driven magnetic quantum phase transition, in which ferromagnetic ordering is strongly favored by the nontrivial bulk band topology. More recently, we have experimentally observed the quantum anomalous Hall effect, i.e., the quantum Hall effect without a magnetic field, in magnetic Tis.

**Engineering Non-abelian Defects beyond Majorana Fermions**

**(22 January 2014)**

**Ady Stern**

***Weizmann Institute of Science***

I will review several recent constructions proposed for the creation of non-abelian defects whose physics is richer than that of Majorana fermions. I will describe the ground state degeneracy that they lead to, the unitary transformations associated with their braiding, and the possible outcomes of their coupling.

## A New Application of Non-Abelian Anyons: Exotic Circuit Elements from Majorana (And Other) Zero-modes

**(22 January 2014)**

**Jason Alicea**

***California Institute of Technology***

Heterostructures formed by quantum Hall systems and superconductors can support Majorana fermion zero-modes and more exotic 'parafermionic' generalizations. In this talk I will describe how probing such zero-modes using quantum Hall edge states (rather than a conventional lead) yields striking non-local transport signatures that pave the way towards a variety of novel circuit elements. Examples include superconducting current and voltage mirrors, transistors for fractional charge, and 'flux capacitors'. These unusual circuits not only provide a means of detecting the zero-modes, but also reveal a new potential application of non-Abelian anyons apart from topological quantum computation.

**Parity Effects and Crossed Andreev Noise in Transport through Majorana Wires**

**(22 January 2014)**

**Bernd Rosenow**

***University of Leipzig***

One of the defining properties of a topologically ordered state is the ground state degeneracy on surfaces with nonzero genus. In semiconductor-superconductor hybrid structures, a phase transition between regular and topologically nontrivial superconductivity is expected as a function of chemical potential or magnetic field strength. The difference in ground state degeneracies of the two phases is reflected in the parity and magnetic flux dependence of nonlinear Coulomb blockade transport through a ring shaped structure. In particular, the $h/e$ flux periodicity found in the topologically nontrivial phase is related to the recently predicted $4\pi$-periodicity of the Josephson current across a junction formed by two topological superconductors.

In nanowires of finite length, topologically non-trivial superconductivity is expected to give rise to Majorana bound states at the ends of the wire. The non-locality of Majorana bound states opens the possibility of crossed Andreev reflection with nonlocal shot noise, due to the injection of an electron into one end of the superconductor followed by the emission of a hole at the other end.

When coupling the end states to leads via quantum dots with resonant levels, in the space of energies of the two resonant quantum dot levels we find a four peaked clover-like pattern for the strength of noise due to crossed Andreev reflection, distinct from the single ellipsoidal peak found in the absence of Majorana bound states.

**Majorana Fermions in Spinful Crystalline Superconductors**

**(23 January 2014)**

**Masatoshi Sato**

***Nagoya University***

I discuss recent ideas on realization of Majorana fermions in spinful superconductors. Whereas spinless superconductors naturally host Majorana fermions, spinful superconductors often realize only Dirac fermions because of spin degeneracy. I will discuss how symmetries specific to crystal structures may stabilize Majorana fermions, and apply the ideas to various unconventional superconductors.

**Interacting Electron Topological Insulators - Beyond Band Theory**

**(23 January 2014)**

**Andrew Potter**

***University of California, Berkeley***

It is often implicitly assumed that if the surface of a 3D topological insulator (TI) preserves both charge-conjugation and time-reversal symmetries symmetries then it must be gapless. However, this is true only in the absence of interactions. Sufficiently strong interactions can produce a TI surface that is both gapped and symmetry preserving, but which has intrinsic 2D topological order. This surface topological order provides a finger-print of the 3D bulk phase, and provides a non-perturbative tool that can be used to completely classify interacting 3D TI phases protected by time-reversal and charge-conservation symmetries. In addition to the well-known topological band-insulator, there are 6 distinct new 3D TI phases enabled by interactions that cannot be realized as non-interacting band-insulators.

**Gapped Symmetric Surfaces of Symmetry-protected Topological States**

**(23 January 2014)**

**Chong Wang**

***Massachusetts Institute of Technology***

It turns out that the surface of the 3D topological insulator can be both gapped and symmetry-preserving, at the expense of having non-abelian topological order on the surface. I will also describe bosonic analogs of topological insulators in 3D, with abelian topological orders on their surfaces. If time permits, I will also mention the corresponding results on 3D topological superconductors.

**Defects with Character: Zero-Energy Majorana Modes in Condensed-Matter Systems**

**(24 January 2014: IAS Distinguished Lecture)**

**Bertrand Halperin**

***Harvard University***

Theory predicts the existence of some peculiar phases of quantum condensed matter systems, which have multiple degrees of freedom with very low energy, when localized "defects" are introduced. The speaker will focus on a class of these phases where each defect has half of a conventional degree of freedom, and the defects may be considered as sites for localized zero-energy states of a "Majorana fermion". Such defects would also exhibit the intriguing property of "non-Abelian statistics", that is, if various defects can be moved around each other, or if two identical defects can be interchanged, the result is a unitary transformation on the quantum mechanical state that depends on the order in which operations are performed but is insensitive to many other details.

In this talk, the speaker will try to explain these various concepts and discuss the attempts to realize them in condensed matter systems.

**Twist Defects in Topological Systems with Anyonic Symmetries**

**(27 January 2014)**

**Jeffrey Teo**

***University of Illinois at Urbana-Champaign***

Anyonic symmetries relabel quasiparticles of a (2+1)D topological phase that leaves the braiding and exchange information unchanged. Twist defects are topological point defects of a topological phase and are vortices of anyonic symmetries. These classical twist defects together with the quantum anyons in the underlying topological system form a richer structure. We provide a framework describing the fusion and braiding statistics of these semi-classical defect-anyon composites in abelian bosonic topological phases.

**A Memory of Majorana Fermions through Quantum Quench**

**(27 January 2014)**

**Ming-Chiang Chung**

***National Chung Hsing University***

We study the sudden quench of a one-dimensional p-wave superconductor through its topological signature in the entanglement spectrum. The long-time evolution of the system and its topological characterization depend on a pseudomagnetic field $\boldsymbol{R}_{\text{eff}}(k)$, which connects both the initial and the final Hamiltonians, hence exhibiting a memory effect. In particular, we explore the robustness of the Majorana zero-mode associated with the entanglement cut in the topologically nontrivial phase and identify the parameter space in which the mode can be remembered in the infinite-time limit.