Topologically-protected edge states, topological order, and entanglement in quantum condensed matter.

Professor F. Duncan M. Haldane
Princeton University

Topological properties of quantum states of condensed matter have become one of the most active areas of current research, driven by both theory and experiment, and the dream of using topologically-protected manipulation of entanglement for quantum information processing. I will survey some of the history of this subject, from free-electron systems with topologically-non-trivial band-structures, characterized by topological invariants and edge states, progressing to topologically-ordered correlated many-body systems, and describe how their characteristic properties (including their "quantum anomalies") can be exposed by computing their "entanglement spectrum".

Superconductor-topological insulator hybrids

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Inspired by theoretical ideas of manifestation of Majorana fermions in hybrid superconductor-topological insulator structures, we use nanofabrication, transport, and scanning SQUID measurements to probe the relevance of these ideas to experimentally-realizable systems. We find surprising patterns, but so far no clear evidence of Majoranas.

Probing strongly correlated quantum systems with single-atom resolution

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Ultracold atoms in optical lattices are a versatile tool to investigate fundamental properties of quantum many body systems. In a series of experiments performed at the Max-Planck Institute for Quantum Optics in Garching, we demonstrated how the control of such systems can be extended down to the most fundamental level of single atomic spins at specific lattice sites. Using a high-resolution optical imaging system, we were able to obtain fluorescence images of strongly interacting bosonic Mott insulators with single-atom and single-site resolution [1] and addressed the atomic spins with sub-diffraction-limited resolution [2]. In addition, we directly monitored the tunneling quantum dynamics of single atoms in the lattice, and observed quantum-correlated particle-hole pairs [3] spreading of correlations after a parameter quench [4], and the quantum dynamics of spin-impurities [5]. Our results open the path to a wide range of novel experiments from observation of strongly correlated fermionic systems, implementation of novel cooling schemes, and engineering of quantum many-body phases to quantum information processing.

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Evolution of zero bias conductance peaks in nanowires

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This talk will review experiments by our group and others on zero bias features an an experimental signature of Majorana end states in quantum wires. From our lab: In low-field studies of InAs nanowires, Andreev bound states cross evolve into a Kondo like zero bias features which continues to show a dependence on phase difference between two superconducting contacts [1]. At higher field, the splitting of zero bias peaks with applied field is periodic in field on a field scale comparable to scale set by Zeeman splitting and the induced gap in the wire [2]. Connections between these observations and other experiments as well as theory will be made. The role of electron interactions in gate defined constrictions in these systems will be emphasized. Research supported by Microsoft Project Q, the Danish National Research Foundation, Harvard Society of Fellows, the Carlsberg Foundation, the Villum Foundation, the Lundbeck Foundation, and the EU-FP7 project SE2ND (271554).

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[2] H. O. H. Churchill et al., Superconductor-nanowire devices from tunneling to the multichannel regime: Zero-bias oscillations and magnetoconductance crossover, Phys Rev. B 87, 241401 (2013).

Circuit QED: Wiring up Quantum Systems

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A revolution is underway in the construction of 'artificial atoms' out of superconducting electrical circuits. These macroscopic 'atoms' have quantized energy levels and can emit and absorb quanta of light (in this case microwave photons), just like ordinary atoms. Unlike ordinary atoms, the properties of these artificial atoms can be engineered to suit various particular applications, and they can be connected together by wires to form quantum 'computer chips.' This so-called 'circuit QED' architecture has given us the ability to test quantum mechanics in a new regime using electrical circuits and to construct rudimentary quantum computers which can perform certain tasks that are impossible on ordinary classical computers. Remarkably strong atom-photon coupling permits the realization of record Schrödinger cat states of microwave photons which likely represent the most macroscopic quantum superpositions ever created. This strong coupling may someday also permit development of topological quantum error correction circuits.

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Topological order: from long-range entanglements to an unification of light and electrons

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I review the progress in last 20 -- 30 years, during which we discovered that there are new states of matter -- topologically ordered -- that are beyond Landau symmetry breaking theory. Recently, we found that topological order is due to long-range quantum entanglement, which leads to many amazing emergent phenomena, such as fractional quantum numbers, fractional/non-Abelian statistics, and perfect conducting boundary channels. Long-range quantum entanglements can even provide a unified origin of light and electrons (or more generally, gauge interactions and Fermi statistics): light waves (gauge fields) are fluctuations of long-range entanglements, and electrons (fermions) are defects of long-range entanglements.

What is Quantum Information?

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Quantum information [1] has become a popular phrase, incorporating as it does such high-profile ideas as quantum computation, quantum information processing and quantum cryptography. But what is quantum information and how does it differ from its classical counterpart? Why is it, moreover, that quantum information seems to offer possibilities thought to be impossible in the classical domain?

I shall attempt to provide some answers to and personal perspectives on these questions, starting with classical information and its remarkable link with entropy. The fundamentally new feature of quantum information is the superposition principle: a classical manifestation of a logical bit is something than can be set in either of two stable states, but a quantum bit (qubit) can exist in any superposition of two orthogonal states. The distinctive nature of quantum information and the associated technological possibilities, including quantum-secure communications, teleportation and quantum computation may all be traced back to the superposition principle. I shall illustrate this idea with a number of simple examples.

[1] S. M. Barnett, *Quantum Information* (Oxford University Press, Oxford, 2009).

How to probe edge and surface states of topological phases via transport measurements

Professor Joel Moore

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Many topological phases are distinguished by having unique metallic edge or surface states. As introduction, the bulk-edge correspondence in the quantum Hall effect is reviewed in light of some numerical and analytical progress in analyzing fractional quantum Hall states on strips and cylinders. Symmetry-protected phases such as topological insulators open up new opportunities for experiments, as the metallic edge/surface state can be destroyed by an appropriate perturbation. For the quantum spin Hall edge, this destruction maps on to the integrable non-equilibrium transport in a spinless Luttinger liquid with impurity. For 3D topological insulators, we discuss how transport experiments on a nanowire pierced by magnetic flux might provide convincing evidence of the surface state. In closing we consider junctions of 3D topological insulators with superconductors and whether there exists a 3D field theory version of the bulk-edge correspondence.

HEAVY FERMION PHYSICS: Rise of the topologies.

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(2) Department of Physics, Royal Holloway, University of London.

The electrons in Heavy fermion materials are subject to spin-orbit coupling interactions that greatly exceed their Kinetic energy. It has long been known that the spin orbit coupling stablizes new kinds of heavy fermion metals, superconductors and "Kondo insulators" against the competing state of magnetism. In this talk I will discuss the new realization that spin orbit copling can influence the ground state, changing its topology and giving rise to Topological Kondo insulators.

We'll look at samarium hexaboride, SmB6, "the worlds oldest topological insulator", a Kondo insulator discovered 45 years ago, predicted to be topological in 2011, and tentatively confirmed to be so in a series of hot new experimental studies of the past few months. I'll discuss a simple model for a topological Kondo insulator and introduce the most recent measurements, including ARPES, de Haas van Alphen and weak antilocalization that appear to support the idea that this is a strongly interacting topological insulator in which the surface conductance is carried by electrons on spin-orbit coupled Dirac cones. We'll also discuss the open unanswered questions surrounding this topic.

If time permits, we'll also talk briefly about "vortex metals": Kondo insulators with a line vortex in momentum space that causes the insulating state to become a strange semi-metal. Two of these materials, YbAlB4 and the heavy electron quasicrystal, YbAlAu suggest a possible interplay of topology and quantum criticality that poses a fascinating new challenge to our understanding of quantum matter.

Time Reversal Symmetry Breaking in Unconventional Superconductors

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In recent years the search for systems exhibiting non-Abelian statistics has intensified as possible building blocks for models of topological quantum computers. In particular, superconductors with chiral pairing have been studied, and their respective order parameters have been classified. Such systems can give rise to topological superconductors where all Bogoliubov quasiparticle excitations are gapped in the bulk whereas topologically protected chiral Majorana fermion modes exist at the edge of the system and in vortex cores. A hallmark of chiral superconductors is time reversal symmetry breaking, similar to quantum Hall effect.

In this talk we will survey current searches for topological superconductors, concentrating on several classes of systems. Our studies utilize a modified Sagnac interferometer, that can measure polar Kerr effect with resolution exceeding 10-8 rad, which is sensitive to time reversal symmetry breaking since it measures the existence of an antisymmetric contribution to the real and imaginary parts of the frequency-dependent conductivity tensor. First is Strontium ruthenate (Sr2RuO4), which is an odd-parity superconductor with odd orbital angular momentum and symmetric spin-triplet (p-wave) pairing. Discussing our studies of Sr2RuO4, we will continue to review our recent studies of the heavy fermion superconductors URu2Si2 and UPt3 and discuss their possible pairing symmetry as a result of our measurements. Finally we will discuss results on hybrid systems involving proximity effect between super conductors and magnetoc systemms.