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Thomas Klein Kvorning

Topological Quantum Matter

A Field Theoretical Perspective

Doctoral Thesis accepted by
Stockholm University, Stockholm, Sweden

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Supervisor's Foreword

The notion of topological states of matter dates back to the discovery of the quantum Hall liquids in the early 1980s. The term topological order was introduced by X.-G. Wen in the early 1990s to characterize those topological phases that support quasiparticles with fractional quantum numbers, the archetypical example being the anyons in the fractional quantum Hall liquids, that carry a fraction of the unit electric charge. The existence of these exotic particles was predicted by R. Laughlin, and the fractional charge was later observed in several experiments. Another important property of topologically ordered states is the gapless modes that are present at the boundaries of a sample. If the bulk is two dimensional, these states are found at the edges, and in the quantum Hall effect, it is these edge modes that are responsible for the quantized current response.

In 2007, the first topological insulators were discovered. These states are quite similar to the integer quantum Hall liquids in that they do not support fractional quasiparticles, but just as the topologically ordered states they support gapless modes at the boundaries between states with different topological properties. These topological, but not topologically ordered, phases are now referred to as symmetry protected, phases, since they are distinct only as long as certain symmetries are present. As opposed to the topologically ordered states, which are always interacting, the essence of a symmetry protected topological state can be captured by a model of noninteracting fermions.

The symmetry protected topological phases do not only include topological insulators but also certain superconductors, as long as one neglects the fluctuations in the electromagnetic field. A particularly interesting class of topological superconductors are those referred to as chiral. In these super conductors the Cooper pairs, which are loosely bound states of two electrons, carry an orbital angular momentum, which in a two-dimensional system to good approximation can be considered as perpendicular to the surface where the electrons move. If this surface is curved, one realizes the archetypical situation for a quantum mechanical Berry phase, which turns out to have interesting consequences for the electromagnetic response. The situation becomes even more interesting if one specializes in topological chiral superconductors where the electron pairing takes place in an odd angular momentum channel such as p or f. In this case, the edge states are very peculiar—they are so-called Majorana fermions which in a sense can be thought of as half fermions. These Majorana modes also occur at vortices in the bulk of the superconductor, and are of great current interest since they can in principle be used as robust carriers of quantum information.

It was later realized that topological states of matter were already known prior to the proper recognition of their special properties. It was shown that ordinary superconductors are topologically ordered when one includes the effects of electromagnetic fluctuations, and also that certain spin-chains, introduced by F.D.M. Haldane in 1983, are in fact examples of symmetry protected topological states.

All of these very topical subjects—topologically ordered, and symmetry protected topological phases, superconductors and Majorana modes—are covered in the Ph.D. thesis, Topological quantum matter—a field theoretical perspective, written by Dr. Thomas Klein Kvorning. I believe that the way this thesis is written makes it suitable as an introduction to field for those who strive for a deeper understanding of the theoretical description of topological phases. Many elementary treatments focus on specific lattice Hamiltonians representative of some specific symmetry protected topological states. Given such a Hamiltonian, one can do computer simulations and calculate, for instance, various properties of the edge states. This is often a very fruitful endeavor since, by choosing realistic lattices and geometries, there is often a direct connection to experiments. However, to get a deeper perspective on topological matter, computations are not enough. One must understand what characteristics are "topological" and which are not. To do so, the notion of topological quantum numbers and topological field theory is essential. The latter are special quantum field theories that are insensitive to details of the interaction between the electrons, and which encode all the topological information. Thomas' thesis provides an excellent introduction to the field theoretic description of various topological phases, and in appendices, he summarizes the required mathematics to make the text self-contained. It should be accessible to students with basic knowledge of quantum field theory and condensed matter physics, and could also be used by more senior condensed matter physicists who want a concise introduction to field theory methods for topological matter.

I write this as Dr. Klein Kvorning's supervisor, and I take the opportunity to say that it has been a pleasure to work closely with Thomas, and I have also very much enjoyed the collaboration we both had with Prof. Cristiane Morias Smith and Dr. Anton Quelle at the University of Utrecht.

Stockholm, Sweden Prof. Thors Hans Hansson
June 2018

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I am a student at Stockholm University, but I have also been part of the condensed matter group at UIUC. I had a great experience in Illinois, thanks to all of you that I met to work and socialize with—not least you, AtMa, Xueda, and Apoorv. Thank you!

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Emma J., you and I have been friends long before we shared office, but during our studies you have become family. You are the sunshine of my life, sometimes even outside the office.

Emma W., during my Ph.D. studies, you have become one of my closest friends. You have also helped me with many things related to my studies. One of those things is that you have corrected my grammar and spelling throughout this thesis, and done so on short notice whenever I needed! You have also supported me and encouraged me—always! I remember when I started as a Ph.D. student: then you invited me to your home, we baked bread, and you gave a pep talk.

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Finally, I would like to say that I dreaded writing the main text of this thesis. I usually get in a very bad mood by deadlines and stress. At the same time, it has been a very turbulent period in my life, with many opportunities to have my spirit destroyed. That has not happened. This year has been one of the absolutely happiest in my entire life, and that is because of you, Josefin. You have given me so much support and helped me overcome the problems I encountered.

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