Theoretical Solid State Physics

Preliminary Outline

General goal: This course will give an overview of quantum condensed matter physics with an emphasis on *topological aspects* of solid state theory. Topology played a role in condensed matter theory at various stages but its wide-ranging importance for understanding phases of quantum matter has been fully appreciated only during the past decade or so. It is this development that led to last year's Noble Prize for David Thouless, Michael Kosterlitz, and Duncan Haldane, who are responsible for some of the early theoretical insights that have driven this field. The applications of topology to solid state theory are deeply intertwined with more conventional subjects such as band structure theory and superconductivity. The course will also include a basic introduction to these subjects.

1) Topological quantum numbers: magnetic monopoles; Landau theory of phase transitions; Ginzburg-Landau theory of superconductors; vortices as topological excitations in superconductors; Kosterlitz-Thouless transitions; Berry phases
2) Integer quantum Hall effect: Landau levels; edges states and Landauer-Büttiker theory; linear response theory; Laughlin argument; Hall conductivity as a Chern number; bosonization for edge states; skyrmions
3) Su-Schrieffer-Heeger model: band structure; end states; effective Dirac description; domain walls and midgap states; Goldstone-Wilczek currents and fractional charges; Thouless pump; boundary Green function
4) Topological insulators: time-reversal symmetry in quantum mechanics; band structure theory of solids; k.p theory; weak and strong topological insulators; gapless boundary modes; bulk-edge correspondence; topological invariants; topological crystalline insulators; higher-order topological insulators
5) Topological superconductors: BCS theory of superconductivity; Kitaev chain; spinless p+ip superconductors; Majorana modes and Majorana bound states; nonabelian statistics
6) Periodic table of topological phases: random-matrix theory; Altland-Zirnbauer symmetry classes and the tenfold way; Bott periodicity; topological invariants
7) Weyl and Dirac semimetals: Fermi arcs; chiral anomaly
8) AKLT model
9) Fractional quantum Hall effect: Laughlin wave functions; edge states; anyons; composite fermions and Chern-Simons theory
10) Toric code: ground state degeneracy; nonabelian excitations
11) Kitaev model
12) Topological quantum computation

Tutorials: Depending on the number of participants, a fraction of the tutorials will be held in the form of dice seminars. All of you will have to read an assigned research paper which will then be discussed during the tutorial section. To ensure that everyone has read and thought about the paper prior to the tutorial, the discussion leader will be randomly chosen among the students at the beginning of tutorial. The assignment may also include the task of working out certain calculations in the paper in detail. These dice seminars are an obligatory part of the course.

Literature

1) Charles Kittel, Quantum Theory of Solids, Wiley
2) Alfred Shapere, Frank Wilczek, Geometric Phases in Physics, World Scientific
3) David Thouless: Topological quantum numbers, World Scientific
4) Andrei Bernevig: Topological insulators and superconductors, Princeton University Press
5) János Asbóth, László Oroszlány, and András Pályi, A Short Course on Topological Insulators, Springer
6) Shun-Qing Shen, Topological Insulators, Springer
7) Jiannis K. Pachos, Introduction to topological quantum computation, Cambridge
8) Claudio Chamon, Mark O. Goerbig, Roderich Moessner, and Leticia F. Cugliandolo, Topological Aspects of Condensed Matter Physics: Lecture Notes of the Les Houches Summer School, Oxford 2017.
9) Bei Zeng, Xie Chen, Duan-Lu Zhou, Xiao-Gang Wen, Quantum Information Meets Quantum Matter -- From Quantum Entanglement to Topological Phase in Many-Body Systems, arXiv:1508.02595
10) M. Z. Hasan and C. L. Kane, Colloquium: Topological insulators, Rev. Mod. Phys. 82, 3045 (2010)
11) A. Bansil, Hsin Lin, and Tanmoy Das, Colloquium: Topological band theory, Rev. Mod. Phys. 88, 021004 (2016)
12) Edward Witten, Rev. Mod. Phys. 88, 035001 (2016)
13) Ching-Kai Chiu, Jeffrey C. Y. Teo, Andreas P. Schnyder, and Shinsei Ryu, Classification of topological quantum matter with symmetries, Rev. Mod. Phys. 88, 035005 (2016)
14) Xiao-Liang Qi and Shou-Cheng Zhang, Topological insulators and superconductors, Rev. Mod. Phys. 83, 1057 (2011)
15) Di Xiao, Ming-Che Chang, Qian Niu, Berry phase effects on electronic properties, Rev. Mod. Phys. 82, 1959 (2010)

Class schedule

Th April 20 class

Mo April 24 class + tutorial

Th April 27 class

Mo May 1 holiday

Th May 4 class

Mo May 8 class + tutorial

Th May 11 class

Mo May 15 class + class

Th May 18 tutorial

Mo May 22 class + tutorial

Th May 25 holiday

Mo May 29 class + tutorial

Th June 1 class

Mo June 5 holiday

Th June 8 class

Mo June 12 class + tutorial

Th June 15 class

Mo June 19 class + class

Th June 22 tutorial

Mo June 26 class + tutorial

Th June 29 class

Mo July 3 class + class

Th July 6 tutorial

Mo July 10 tutorial + tutorial

Th July 13 EXAM

Mo July 17 class + class

Th July 20 class