UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Quantum Materials

2526-1-F1703Q044

Aims

A quantum material is one whose electronic or magnetic properties are best described as having a nontrivial quantum mechanical origin, in other words materials where semi-classical approximations that do not consider the full character of the system are unable to capture the observed peculiarities.

The course presents the physical principles underlying the quantum materials properties, thus permitting to understand these materials from the basis. Several materials systems will be treated in detail: from superconductors, the prototypical example of a quantum material, to integer quantum hall effect and topological insulators, which show a strict connection of their electronic properties with topology derived invariants. For each class of materials we will briefly discuss some technological applications.

Learning Outcomes
Knowledge and understanding:
• Detailed knowledge of the basic concepts and approaches in quantum materials research.
• Understanding emergent phenomena in quantum materials
• Understanding the effects of topology and symmetries on the quantum electronic properties of materials

Applying knowledge and understanding:
• Acquisition of the ability to apply the theoretical notions covered in the course to the effective description of quantum materials.

Communication skills:
• Aquisition of written and oral communication skilles on topics related to advanced quantum physics.

Making judgements:
• The student will acquire the competence to judge which phenomena and observable of a given material can be ascribed to its emergent quantum properties.

Learning skills:

The student can extend what he has learned in the lectures to case studies not covered during the course. In particular, he can independently manage the vast literature dedicated to quantum materials.

Contents

• Introduction: Quantum materials for quantum technologies.
• Ginzburg Landau theory of Superconductors and BCS
• Integer Quantum Hall Effect
• Topology and Berry phase
• Topological invariants and physical properties

Detailed program

1) Introduction:
• quantum materials as a tool for modern quantum technologies.
• Overview of course pre-requisite, lecture contents, textbooks/literature, and assessment methods.
2) Superconductors
• Electron-phonon interaction & Cooper pairs
• Ginzburg-Landau Theory
• BCS Theory of superconductivity
• Josephson effect & SQUIDS
• Superconducting quantum bits
3) Integer Quantum Hall Effect:
• Landau Levels
• Laughlin theory of the Quantum Hall Effect
• Why 2D, disorder and localization are important
• Semiclassical percolation theory
• IQHE edge states
4) Topology:
• Berry phase, Connection and curvature
• Berry's Phase for Electrons in Crystals
• Applications of Berry's Phase: Aharonov–Bohm Effect, Polarization of Crystals, Crystal Electrons in Uniform Electric Field
• Chern Numbers
• Time-reversal and inversion symmetries: Broken Symmetry in Honeycomb Lattice
• IQHE without Landau Levels
• Topological Invariants
• Topological superconductivity

Prerequisites

Quantum mechanics and solid-state physics concepts.

Teaching form

Frontal lectures using blackboard and/or slides.
-46 hours of lectures delivered in presence.
The lectures will be given in English.

Textbook and teaching resource

Slides will be made available to the students through the present e-learning platform.

Main textbooks:
• Efthimios Kaxiras & John D. Joannopoulos (2019) Quantum Theory of Materials, Cambridge University Press. doi 10.1017/9781139030809:
• Michael Tinkham, Introduction to superconductivity, Dover ISBN 0486435032

For futher insights:
• Girvin, S., & Yang, K. (2019). Modern Condensed Matter Physics. Cambridge University Press. doi:10.1017/9781316480649
• P. G. De Gennes (1999) Superconductivity of Metals and Alloys, Westview Press, ISBN 0-7382-0101-4
• Raffaele Resta, Geometry and Topology in Electronic Structure Theory, Notes, http://www-dft.ts.infn.it/~resta/gtse/draft.pdf
• A.Bernevig with T. L. Hughes, Topological Insulators and Topological Superconductors, Princeton University Press (2013).
• János K. Asbóth, László Oroszlány, András Pályi (2016). A Short Course on Topological Insulators: Band Structure and Edge States in One and Two Dimensions. Springer

Scientific articles:
Different topics of the course are also well presented in scientific articles, such as:

• Von Klitzing K (1986) The quantized Hall effect, Reviews of Modern Physics 58, 519
• R. B. Laughlin (1981) Quantized Hall conductivity in two dimensions, Phys. Rev. B 23, 5632
• Feliciano Giustino et al (2020) The 2021 quantum materials roadmap. J. Phys. Mater. 3 042006.
• B. Keimer & J. E. Moore (2017) The physics of quantum materials. Nature Physics 13, 1045–1055.
• Hasan MZ, Kane CL (2010) Colloquium: Topological insulators. Reviews of Modern Physics, 82(4):3045–3067.
• Haldane FDM (1988) Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly", Phys Rev. Lett. 61, 2015

Semester

Second semester

Assessment method

Oral exam.
Discussion concerning the topics covered during the course.
The ability to present the topics covered in class in all their conceptual and formal aspects will be assessed,

including the derivation of the results.
No ongoing partial tests are planned.

Office hours

From Monday to Friday at any working hour (an appointment should be arranged with the teacher by email).

Sustainable Development Goals

QUALITY EDUCATION