UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Materiali Quantistici

2223-1-F1701Q151

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 classical particles or calculations that do not consider the full character of the system do not adequately describe the electronic or magnetic properties displayed.
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.

Learning Outcomes
• 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
• Acquisition of verbal and written communication skills in advanced concepts of quantum physics.

Contents

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

Detailed program

• **Introduction**:
• quantum materials as a tool for modern quantum technologies.
• Overview of course pre-requisite, lecture contents, textbooks/literature, and assessment methods.
• **Superconductors**
• Thermodynamics: type I & II superconductors
• Electrodynamics
• Electron-phonon interaction & Cooper pairs
• Ginzburg-Landau Theory
• Josephson effect & SQUIDS
• Superconducting quantum bits
• **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
• **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

Prerequisites

Quantum mechanics and solid-state physics concepts.

Teaching form

Frontal lectures and exercise sessions using blackboard and/or slides.

Textbook and teaching resource

Slides will be made available to the students through the present e-learning platform.
Textbooks:
• P. G. De Gennes (1999) Superconductivity of Metals and Alloys, Westview Press, ISBN 0-7382-0101-4
• Efthimios Kaxiras & John D. Joannopoulos (2019) Quantum Theory of Materials, Cambridge University Press. doi 10.1017/9781139030809:
• Girvin, S., & Yang, K. (2019). Modern Condensed Matter Physics. Cambridge University Press. doi:10.1017/9781316480649
• B. I. Shklovskii & A. L. Efros (2013) Electronic Properties of Doped Semiconductors Springer. isbn:9783662024034
• Raffaele Resta, Geometry and Topology in Electronic Structure Theory, Notes, http://www-

dft.ts.infn.it/~resta/gtse/draft.pdf
• Giuseppe Grosso & Giuseppe Pastori Parravicini (2013), Solid State Physics, Academic Press. isbn:9780123850317
• 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

Students’ knowledge will be evaluated through an oral exam focusing on the topics discussed during the course.

Office hours

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

Sustainable Development Goals

INDUSTRY, INNOVATION AND INFRASTRUCTURE