25SC808 Quantum Phases of Matter 3-1-0-4

Objective:

To equip graduate students with a deep understanding of superconductivity and topological phases of matter, enabling them to analyze and explore emergent quantum phenomena and their applications in modern condensed matter physics and quantum technologies.

Unit – I Fundamentals of Superconductivity

Superconducting phase transition and the onset of zero resistivity; Meissner effect and perfect diamagnetism; London equations and their implications for electromagnetic response; penetration depth and coherence length, and their roles in characterizing superconducting states.

Unit – II BCS Theory and Josephson Effect

Microscopic theory of superconductivity via the BCS framework; formation of Cooper pairs and condensation into a macroscopic quantum state; energy gap and quasiparticle excitations; Josephson tunnelling between superconductors; DC and AC Josephson effects and their role in quantum circuits and interferometry.

Unit – III Topology in Condensed Matter Physics

Introduction to the role of topology in condensed matter systems; distinction between conventional and topological phases; the impact of symmetry on topological classification; concepts of symmetry-protected topological order and the emergence of robust edge states in various physical contexts.

Unit – IV Classification Schemes and Topological Phases

Ten-Fold Way classification of topological insulators and superconductors based on time-reversal, particle-hole, and chiral symmetries; periodic table of topological phases and its connection to spatial dimensions; overview of experimentally realized topological materials; topological invariants such as the Berry phase, Berry curvature, and Chern number; quantum Hall effect as a paradigmatic topological phase; the Hofstadter model and fractal energy spectra; topological superconductors as a class of systems where superconductivity coexists with nontrivial topological order; emergence of Majorana modes in one- and two-dimensional platforms and their relevance to fault-tolerant quantum computation; Weyl and Dirac semimetals as gapless topological systems featuring linear band crossings, chiral anomalies, and Fermi arc surface states.

Unit – V Topological Models and Bulk-Boundary Correspondence

Su-Schrieffer-Heeger (SSH) model and topological phase transitions in one-dimensional lattices; Kitaev chain and realization of Majorana fermions; bulk-boundary correspondence and the connection between bulk topological invariants and protected surface or edge states; physical observables tied to topological features and their manifestation in electronic and optical experiments.

Unit – VI 2D Topological Materials and Experimental Realizations

Two-dimensional topological systems and the physics of Dirac cones in materials like graphene; Haldane model and the quantum anomalous Hall effect; Kane-Mele and half-BHZ models for spin-orbit-induced topological phases; quantum spin Hall effect and time-reversal symmetry protection; edge modes and their robustness against disorder; band inversion mechanisms; experimental realization of topological phenomena in strained semiconductors, quantum wells, and layered heterostructures using transport measurements, ARPES, and STM.

Textbooks:

1. 1. F. Ortmann, Topological Insulators: Fundamentals and Perspectives, Wiley-VCH (2015), 1st Ed.
2. 2. Ed. by G. Tkachov, Topological Insulators: The Physics of Spin Helicity in Quantum Transport, CRC press (2016), 1st Ed.
3. 3. János K. Asbóth, László Oroszlány, András Pályi, A Short Course on Topological Insulators: Band Structure and Edge States in one and two dimensions, Springer (2016), 1st Ed.
4. 4. B. Andrei Bernevig, Topological Insulators and Topological Superconductors, Princeton University Press (2013) 1st Ed.

References:

1. Aguado, R. Majorana quasiparticles in condensed matter. *Riv. Nuovo Cim.* 40, 523–593 (2017).
2. 5. A.M. Turner, V. Ashwin, Beyond band insulators: Topology of semi-metals and interacting phases, (arXiv 1301.0330(V2))

Outcomes:

CO	Course Outcomes
CO01	Understand the principles of superconductivity, including phase transitions, Meissner effect, and microscopic BCS theory.
CO02	Analyze the role of topology and symmetry in condensed matter systems using mathematical and physical frameworks.
CO03	Apply topological classification schemes, compute invariants like the Chern number, and interpret their physical consequences.
CO04	Explore model systems such as SSH, Kitaev chains, and topological superconductors to study edge states and Majorana modes.
CO05	Evaluate experimental realizations of topological phases in 2D materials through phenomena like band inversion and quantum spin Hall effect.

Evaluation Pattern:

Category	Marks
Quizzes(2)	10
Assignments(2)	20
Mid-sems(1)	30
End-sems(1)	40