Condensed Matter Theory

Physics, Applied Physics, Geology and Geophysics, Mechanical Engineering
Condensed matter theory research at Yale spans a broad range of topics:

(i) **Many-body physics:**
- Number of particles is large
- Interactions among constituents can be strong

(ii) **Phases of matter:**
- Superfluidity, superconductivity
- Ferromagnetic and anti-ferromagnetic phases
- Topological phases (cannot be understood by symmetry breaking)
- Fractonic phases (beyond the standard quantum field theory framework)

(iii) **Cold atom physics:**
- Interactions between particles can be tuned
- Simulations of quantum condensed matter systems

(iv) **Quantum computation**
CMT at Yale: Physics

Nicholas Read

Steven Girvin

R. Shankar

Yoram Alhassid

Meng Cheng

Leonid Glazman
R. Shankar

Statistical and Many Body Problems
Quantum Phase Transitions
Field theory methods
Renormalization group
Interactions and Disorder
Quantum dots
Graphene + Topological insulators

Principles of Quantum Mechanics
SECOND EDITION
R. Shankar

Quantum Field Theory and Condensed Matter
An Introduction
R. Shankar
Quantum Computation and Quantum Optics of Electrical Circuits

Cavity/Circuit QED
- coupling single microwave photons to superconducting qubits
- entanglement of qubits, quantum error correction protocols
- quantum measurements/amplification/noise
- optomechanics: micromechanical cantilevers in optical cavities
Nicholas Read

Many body theory, quantum field theory, statistical mechanics

Fractional quantum Hall systems and topological phases
- non-Abelian statistics, new states of matter, connection with conformal field theory
- Majorana zero modes
- entanglement spectrum
- Hall viscosity: a non-dissipative transport coefficient
- application to topological quantum computation

Two-dimensional critical phenomena and conformal field theory
- related to integer quantum Hall effect and transport; algebraic techniques

Combinatorial optimization and complexity
- minimum spanning trees and relation to percolation
- spin glasses
- other computer science problems and quantum computation/information
One-dimensional quantum fluids (electrons, spinons, cold atoms):
- Conduction of nano-wires;
- Dynamic structure factors of spin excitations;
- Quantum liquids in optical lattices

Leonid Glazman
Quantum Many-Body Physics in Low Dimensions

Low-dimensional and mesoscopic superconductors:
- Quantum phase slips in mesoscopic superconductors;
- Physics of superconducting qubits (close collaboration with experimental groups of Michel Devoret and Rob Scholekopf)

Electron transport in topological insulators (TI):
- Electron scattering mechanisms
- Quantum effects in conduction properties
- Theory is closely related to ongoing experiments

Fig. 1: Electron tunneling spectra explained by nonlinear Luttinger liquid theory

Fig. 2: Spectrum of a fluxonium qubit, experiment and theory

Fig. 3: Tunneling between helical edge states and electron puddles in 2D TI
Meng Cheng

Quantum condensed matter theory

Quantum many-body topology
- Classifying and charactering gapped quantum states
- Topological classification of quantum evolution
- Applications to quantum information processing

Fractonic phases of matter
Phases of matter beyond standard QFT framework
- Explore new types of fracton models in 3D
- Renormalization group of fractonic phases
Quantum dots: sub-micron-scale artificial devices containing up to several thousand electrons

- Statistical regime: interplay between one-body chaos and interactions

Nanoparticles: nano-scale metallic grains.

- Their properties are different from bulk superconductors
- Competition between superconductivity and ferromagnetism

Ultra-cold atoms: fermions with a tunable contact interaction

- BEC to BCS crossover
- Unitary limit: pseudogap regime (non-Fermi liquid)?
- Strongly interacting Fermi gases in 2D
Complex and non-linear systems
- Laser theory and complex micro/nano lasers
- Quantum/wave chaos, random matrix theory
- Classical/Quantum optics in complex media
- Control of light propagation in random media
- Quantum measurement and control

Can light propagate through strong scattering opaque media? Yes, by inputting special states

Focusing and defocusing light through white paint

Theory: “Filtered” random matrix theory predicts focusing enhancement

Correlation-enhanced control of wave focusing in disordered media
Nature Physics, 2017

SLM
Interfaces between two materials:
How is the interfacial region different from either side? What do electrons do in such an asymmetric environment?

Nanoscale/low-dimensional materials
• 2D materials: synthesis, bonding, electronic & optical response, topology
• Ferroelectric surface chemistry

Electron correlation especially in transition metal oxides (many-body Green functions; slave bosons)
Vidvuds Ozolins

Theory of electronic structure & energy materials

Theory of real electronic materials
Applications in energy storage, generation and conversion

Machine learning for quantum mechanics:
• Solving the Schrödinger equation
• Localized basis for electron correlation - Wannier functions
• Deep Boltzmann machines and Convolutional Neural Nets for Quantum Monte Carlo

• Electron-phonon interactions in solids
• Transport of heat and electrical current
• Thermoelectric effect
• Exotic magnetism – spin liquids
John Wettlaufer

Applied Mathematics, Geophysics and Physics

Active Matter
Soft Materials
Surface Phase Transitions
Turbulence Stochastic Theories of Climate
Nonequilibrium Statistical Mechanics

Asymptotic Methods, Stability Theory & PDE Analysis
Lattice Boltzmann Methods

Students: Physics-Stockholm (Anthony Bonfils & Ludovico Giorgini)
Mathematics (Jonas Katona); Geophysics (Manpreet Singh)
Theoretical and Computational Studies of Soft Matter and Biological Materials
O’Hern Research Group

Current Projects:

- Crowding in cell cytoplasm
- Tissue formation in embryos
- Design of protein-protein interactions
- Jamming in granular media
- Glass-formability in metal alloys
Condensed Matter Theory at Yale

**Broad research:** From bulk systems to nanoscale physics
From mathematical foundations to numerical studies

**Other departments:** applied physics, applied mathematics, geophysics, mechanical engineering,…

**Collaborations across departments:** physics and applied physics (theory and experiment)

**Interdisciplinary research**