Int. PhD in PHYSICAL SCIENCES

Programme Code: PHYS05

Programme Outcome:

- Understanding and knowledge of physics in the classical domain.
- Understanding and knowledge of physics in the quantum domain.
- Understanding and application of statistical methods in physics
- Laboratory experience so that students are exposed to modern experimental techniques.
- Understanding of mathematical methods in their applications in diverse settings.
- Provide exposure to various specialised areas such as condensed matter, nuclear physics, atomic physics, particle physics, astrophysics and quantum information
- Introduction to methods that will be lifelong assets for careers in research and development.

Course summary matrix:

- **For theoretical courses:**

  L-T-P (per week): 2 (90 minutes each) + 1 office hour (1 hour) - 1 (90 minutes) - 0
- **For laboratory courses:**

  L-T-P (per week): 0 - 0 - 2 (4 hours each)
- **Credit Structure :**

  15 hours = 1 credit for theory courses, 30 hours = 1 credit for lab courses

DETAILED COURSE STRUCTURE

First Semester

Sr.No	Course Code	Course	Hours (L-T-P)	Credits
1	08-PHYS05-601-C	Classical Mechanics	75	5
2	08-PHYS05-602-C	Quantum Mechanics I	75	5
3	08-PHYS05-604-C	Mathematical Methods I	75	5
4	08-PHYS05-608-C	Electronics	75	5
5	08-PHYS05-601-L	Laboratory I	90	3

Second Semester

Sr.No	Course Code	Course	Hours (L-T-P)	Credits
1	08-PHYS05-606-C	Quantum Mechanics II	75	5
2	08-PHYS05-607-C	Statistical Mechanics	75	5
3	08-PHYS05-603-C	Electrodynamics	75	5
4	08-PHYS05-605-C	Numerical Methods	75	5

5	08-PHYS05-602-L	Laboratory II	90	3

Third Semester

Sr.No	Course Code	Course	Hours (L-T-P)	Credits
1	08-PHYS05-612-C	Mathematical Methods II	75	5
2	08-PHYS05-609-C	Condensed Matter Physics I	75	5
3	08-PHYS05-605-E	Quantum Information and Computation I	75	5
4	08-PHYS05-611-C	Quantum Field Theory I	75	5
5	-	MSc Thesis (year long)		10

Fourth Semester

Sr.No	Course Code	Course	Hours (L-T-P)	Credits
1	08-PHYS05-613-C	Particle Physics	75	5
2	08-PHYS05-603-E	General Relativity	75	5
3	-	Elective I	75	5
4	08-PHYS05-603-L	Laboratory III	90	3

Fifth Semester

Sr.No	Course Code	Course	Hours (L-T-P)	Credits
1	-	Elective II	75	5
2	08-PHYS05-601-PR	Project (year long)		10

3		Mini-Project I		3

Sixth Semester

Sr.No	**Course Code**	**Course**	**Hours (L-T-P)**	**Credits**
1	-	Elective III	75	5
2	-	Mini-Project II		3
3	08-PHYS04-601-R	Research Methodology & Research Publication Ethics	45	3
Total				**123**

- *MSc (Physics) shall be conferred upon completion of Semesters 1–6 (coursework ≥ UGC minimum, successful thesis submission and viva), prior to PhD registration/conversion*
- *Exit with MSc (Physics) after Semester 6 is available subject to thesis/viva and CGPA thresholds*

ELECTIVE COURSE STRUCTURE

ELECTIVE COURSES IN GENERAL PHYSICS

Sr.No	Course Code	Course	Hours (T)	Credits
1	08-PHYS04-619-E	Accretion Process in Astrophysics	75	5
2	08-PHYS08-601-E	Advanced Statistical Mechanics	75	5
3	08-PHYS08-625-E	Advanced Topics in General Relativity	75	5
4	08-PHYS04-631-E	Advanced Topics in Quantum Field Theory	75	5
5	08-PHYS04-621-E	Astronomical Data Analysis	75	5
6	08-PHYS04-617-E	Astrophysical Fluid Dynamics	75	**5**
7	08-PHYS04-606-E	Astrophysics	75	5
8	08-PHYS04-624-E	Collider Physics	75	5
9	08-PHYS04-622-E	Computational Astrophysics	75	5
10	08-PHYS08-622-E	Computational Many Body Theory I	75	5
11	08-PHYS04-616-E	Computational Many Body Theory II	75	5
12	08-PHYS08-623-E	Computational Materials Science	75	5
13	08-PHYS04-607-E	Condensed Matter Physics II	75	5
14	08-PHYS08-617-E	Correlated Electron Systems	75	5
15	08-PHYS04-608-E	Cosmology	75	5

16	08-PHYS04-627-E	Dark Matter and particle astrophysics	75	5
17	08-PHYS08-618-E	Disorder in Condensed Matter	75	5
18	08-PHYS04-626-E	Flavour Physics and CP violation	75	5
19	08-PHYS04-601-E	Fluid Mechanics	75	5
20	08-PHYS04-602-E	General Relativity	75	5
21	08-PHYS04-628-E	Grand Unified Theories	75	5
22	08-PHYS08-615-E	Introduction to Electronic Structure	75	5
23	08-PHYS08-619-E	Matter Out of Equilibrium	75	5
24	08-PHYS08-615-E	Mesoscopic Physics	75	5
25	08-PHYS04-625-E	Neutrino Physics	75	5
26	08-PHYS04-603-E	Nonlinear Dynamics	75	5
27	08-PHYS04-610-E	Particle Physics	75	5
28	08-PHYS04-623-E	Particle Physics-2	75	5
29	08-PHYS04-611-E	Quantum Field Theory II	75	5
30	08-PHYS04-604-E	Quantum Information and Computation I	75	5
31	08-PHYS04-612-E	Quantum Information and Computation II	75	5
32	08-PHYS08-620-E	Quantum Many Body Theory	75	5
33	08-PHYS04-605-E	Quantum Mechanics III	75	5

34	08-PHYS04-613-E	Quantum Optics	75	5
35	08-PHYS04-618-E	Radiative Transfer Phenomena in Astrophysics	75	5
36	08-PHYS04-620-E	Relativistic Astrophysics	75	5
37	08-PHYS04-614-E	Soft Matter	75	5
38	08-PHYS08-621-E	Spectroscopic Methods	75	5
39	08-PHYS08-624-E	String Theory I	75	5
30	08-PHYS04-629-E	String theory 2	75	5
31	08-PHYS04-630-E	Supersymmetry	75	5
32	08-PHYS08-616-E	Topological Quantum Matter	75	5
33	08-PHYS04-615-E	Ultra Cold Atoms	75	5

CORE COURSES COORDINATOR

Course	**Coordinators**	**Email**
Classical Mechanics	Prof. Anirban Basu	anirbanbasu@hri.res.in
Quantum Mechanics I		
Mathematical Methods I		
Electronics		
Laboratory I		
Quantum Mechanics II		
Statistical Mechanics		
Electrodynamics		
Numerical Methods		
Laboratory II		
Mathematical Methods II		
Condensed Matter Physics I		
Quantum Information and Communication I		
Quantum Field Theory I		
MSc Thesis (year long)		

Particle Physics		
General Relativity		
Laboratory III		

ELECTIVE COURSES COORDINATOR

Course	**Coordinators**	**Email**
Accretion Process in Astrophysics	Prof. Anirban Basu	anirbanbasu@hri.res.in
Advanced Statistical Mechanics		
Advanced Topics in General Relativity		
Advanced Topics in Quantum Field Theory		
Astronomical Data Analysis		
Astrophysical Fluid Dynamics		
Astrophysics		
Collider Physics		
Computational Astrophysics		
Computational Many Body Theory I		
Computational Many Body Theory II		
Computational Materials Science		
Condensed Matter Physics II		
Correlated Electron Systems		

Cosmology	Prof. Anirban Basu	anirbanbasu@hri.res.in
Dark Matter and particle astrophysics		
Disorder in Condensed Matter		
Flavour Physics and CP violation		
Fluid Mechanics		
Grand Unified Theories		
Introduction to Electronic Structure		
Matter Out of Equilibrium		
Mesoscopic Physics		
Neutrino Physics		
Nonlinear Dynamics		
Particle Physics-2		
Quantum Field Theory II		
Quantum Information and Computation II		
Quantum Many Body Theory		
Quantum Mechanics III		
Quantum Optics		
Radiative Transfer Phenomena in Astrophysics		
Relativistic Astrophysics		
Soft Matter		
Spectroscopic Methods		
String Theory 1		

String theory 2		
Supersymmetry		
Topological Quantum Matter		
Ultraold Atoms		

CORE COURSES

08-PHYS05-601-C: Classical Mechanics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- **A rapid review/summary of Newtonian mechanics**
- **Calculus of variations:**
  Concept of variation - Euler equation - Applications - Variation subject to constraints and Lagrange multipliers.
- **The Lagrangian formulation:**
  Generalised coordinates and velocities - The principle of least action and the Lagrange equations of motion - Extension to constrained systems.
- **Conservation laws:**
  Symmetries and Noether's theorem.
- **Integration of the Lagrange equations of motion:**
  Motion in one dimension - The two body problem, reduced mass and the equivalent one-dimensional problem - Motion in a central field - Kepler's problem - Scattering.
- **Small oscillations:**
  Free, damped and forced oscillations in one dimension - Resonance - Damped and forced oscillations - Parametric resonance.
- **Rigid body motion:**
  Angular velocity - The inertia tensor and angular momentum of a rigid body - The equations of motion-Eulerian angles - Motion of tops - Motion in a rotating frame - Coriolis force.
- **The Hamiltonian formulation:**
  Hamiltonian and Hamilton equations - Poisson brackets - Dynamics in the phase space - Hamilton-Jacobi equation - Separation of variables and solutions - Action-angle variables - Adiabatic invariants.
- **Elements of non-linear dynamics:**
  Differential equations as dynamical systems - Lyapunov exponents.

Course Outcomes:

- Acquiring knowledge of Lagrangian and Hamiltonian formulations of classical dynamics.
- Acquiring knowledge of basic concepts of classical mechanics such as general theory of conservation laws, phase space and Poisson brackets.
- Understanding the theory of rigid body motion.
- Acquiring knowledge of applications such as the central force problem, small oscillations, non-linear dynamics.

References:

1. Classical Mechanics, H Goldstein,
2. Mechanics, L D Landau and L M Lifshitz
3. Classical Dynamics, E. J. Saletan and J. V. Jose
4. Nonlinear Dynamics and Chaos, S. Strogatz

08-PHYS05-602-C: Quantum Mechanics I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- One-dimensional problems:
  harmonic oscillator, periodic potential, Kronig-Penny model;
- Three-dimensional problems:
  central force potential, the hydrogen atom, Axiomatic introduction of QN
- Angular momentum in quantum mechanics:
  raising and lowering operators, angular momentum addition, Clebsch-Gordon coefficients
- Tensor operators and Wigner-Eckart theorem
- Charged particle in an electromagnetic field:
  gauge invariance, Landau levels
- Symmetries and conservation laws in QM:
  Degeneracies, Discrete symmetries
- Time-independent perturbation theory:
  non-degenerate and degenerate cases, Stark and Zeeman effects
- Semiclassical (WKB) approximation and variational methods
- Schrodinger and Heisenberg pictures
- Time-dependent perturbation theory
- Interaction picture
- Fermi golden rule

Course Outcomes:

- Acquiring working knowledge of the basic concepts of quantum mechanics:
- states, operators and time evolution.
- Understanding of the role of symmetries in quantum mechanics.
- Understanding of the theory of angular momentum in quantum mechanics.
- Acquiring knowledge of applications such as the hydrogen atom, charged particle in a magnetic field and a particle in a periodic potential.
- Acquiring knowledge of perturbation theory in quantum mechanics and applications such as Stark and Zeeman effect.

References:

1. Modern Quantum Mechanics, J. J. Sakurai and J. Napolitano
2. Introduction to Quantum Mechanics, D. J. Griffiths,
3. Principles of Quantum Mechanics, R. Shankar
4. Quantum Mechanics, Bernard Diu and Claude Cohen-Tannoudji

08-PHYS05-604-C: Mathematical Methods I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Vector Analysis:

  operations with vectors, scalar and vector fields, gradient, curl and divergence. Line, surface, and volume integrals, Curvilinear coordinate systems, Elements of tensors.
- Vector Spaces, linear transformations, scalar product and dual space, bases, linear operators, eigenvalues and eigenfunctions, unitary and hermitian operators
- Complex Analysis:

  functions of a complex variable, analytic functions, integral calculus, contour integrals, Taylor and Laurent series, singularities, residues, principal values, Riemann surfaces, conformal mapping, analytic continuation
- Ordinary differential equations:

  linear ODEs, Green functions, second order differential equations: classification of singularities and local solutions, special functions
- Elements of statistics: probability, random walk. Probability distributions.

Course Outcomes:

- Acquiring knowledge of vector spaces and its applications to various physical problems.
- Acquiring knowledge of complex analysis and its applications to various physical problems.
- Acquiring knowledge of the theory of ordinary differential equations and its applications in various physical problems.
- Acquiring basic knowledge of the theory of statistics and its applications in interpretation of data

References:

1. Mathematical Methods for Physicists, G. B. Arfken, H. J. Weber, F. E. Harris,
2. Fundamentals of Mathematical Physics, E. A. Kraut,
3. Mathematical Methods in the Physical Sciences, Mary L. Boas
4. Complex Variables and Applications, .Iames Ward Brown and Ruel V Churchill

08-PHYS05-608-C: Electronics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Circuit theory:

  lumped circuit approximation, circuit elements, Kirchhoff's current and voltage laws, resistive networks, node and loop analysis, Thevenin and Norton's theorem, time domain response of RL, RC and RLC circuits, frequency domain response, impedance, filters and transfer function.

- Analog electronics:

  discrete devices, characteristics and operation – diode, Zener diode, LED, photodiode. Simple diode circuits. Bipolar junction transistor (BJT): biasing,

- Analog electronics (continued):

  parameters, small and large signal response, amplifiers. Field effect transistors.

- Operational amplifiers:

  device properties, integrator, differentiator, RC active filter, negative and positive feedback, oscillators.

- Digital electronics:

  logic gates, truth table, multiplexer, combinatorial circuits, flip-flop, counters, programmable logic devices, microprocessors.

Course Outcomes:

- Apply fundamental principles of circuit theory and analog electronics to analyze and design basic electrical and electronic circuits involving diodes, BJTs, FETs, operational amplifiers, and passive components in time and frequency domains.
- Understand and implement digital electronic systems by analyzing logic gates, combinational and sequential circuits, and programmable logic devices for solving practical engineering problems.

References:

1. Electronic Devices and Circuit Theory, Boylestad
2. Solid State Electronic Devices, Streetman and Banerjee
3. Op-Amps and Linear Integrated Circuits, R. A. Gayakwad
4. Digital Principles and Applications, Malvino and Leach

08-PHYS05-601-L: Laboratory I (90 Lab Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Forced Oscillations-Pohl’s Pendulum:
- Coupled Pendula and Chaotic oscillator:
- Photoelectric effect:
- Normal and Anomalous Zeeman Effect:
- Michelson Interferometer:
- Mach-Zehnder Interferometer:
- Faraday Effect:
- Millikan Oil-drop Experiment:
- Electron Diffraction:
- Fine Structure

Course Outcomes:

- Performing experiments involving oscillators such as the Pohl's pendulum and chaotic oscillators.
- Performing experiments involving interferometers such as the Michelson interferometers and Mach Zehnder interferometers.
- Performing spectroscopic experiments such as the Zeeman effect.
- Performing the Millikan Oil drop experiment

References:

1. Data Reduction and Error Analysis for the Physical Sciences, R. Bevington and D. K. Robinson
2. Fundamentals of Physics, R. Resnick, D. Halliday and J. Walker
3. Concepts of Modern Physics, A. Beiser

08-PHYS05-606-C: Quantum Mechanics II (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Scattering theory and applications
- Quantum mechanics of many particles, identical particles and symmetries of the wave-function, scattering of identical particles
- Relativistic quantum mechanics, Klein-Gordon and Dirac equations and their solutions, gyromagnetic ratio of the electron, relativistic corrections to the Schrodinger equation
- Atomic physics:

  One electron atom – spin-orbit interaction, fine structure. Two electron atoms: spin wave functions, approximate handling of electron–electron repulsion. Coupling of angular momenta, multiplet structure, gyromagnetic effects. Hyperfine and nuclear quadrupole interactions.
- Molecular physics:

  Born–Oppenheimer approximation, molecular structure, rotation and vibration of diatomic molecules, hydrogen molecular ion, vibrational–rotational coupling, the effect of vibration and rotation on molecular spectra.
- Electronic structure:

  molecular orbital and valence bond theories.

Course Outcomes:

- Understand and apply mathematical techniques for describing and deeper understanding of physical systems.

References:

1. Quantum Mechanics, L. Schiff
2. Quantum Mechanics, L. D. Landau and E. Lifshitz
3. Relativistic Quantum Mechanics, Bjorken and Drell
4. Physics of Atoms and Molecules, Brandon and Joachain
5. Introduction to Atomic Spectra, J. White

08-PHYS05-607-C: Statistical Mechanics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Basics:

  phase space, distributions, notion of equilibrium, ensembles, Boltzmann distribution, partition function, calculating observables.
- Non interacting classical systems:

  few level systems, ideal gases, oscillators.
- Non interacting quantum systems:

  method of second quantisation, electrons in metals, relativistic electron systems, electrons in a strong magnetic field, lattice vibrations and phonon physics, photons, blackbody radiation, Bose condensation.
- Interacting classical systems:

  non-ideal gases, van der Waals gas, cluster expansion, classical spin models - Ising and Heisenberg, outline of exact solutions.
- Phase transitions:

  symmetry breaking and long range order, mean field approach, Landau theory, 2nd and 1st order transitions, Landau-Ginzburg functional, illustrative examples, estimate of fluctuations.

Course Outcomes:

- Acquiring knowledge of basics concepts such as phase space, distributions, notion of equilibrium, ensembles, Boltzmann distribution, partition function, calculating observables.
- Understanding of Statistical Mechanics of non-interacting classical systems:
  few level systems, ideal gases, oscillators.
- Understanding of Statistical Mechanics of non-interacting quantum systems:
  electrons in metals, relativistic electron systems, photons, blackbody radiation, Bose condensation.
- Acquiring knowledge of the basics of interacting classical systems:
  non-ideal gases, van der Waals gas, cluster expansion, classical spin models – Ising and Heisenberg, outline of exact solutions.
- A basic understanding of the theory of phase transitions.

References:

1. Fundamentals of Statistical and Thermal Physics, F. Reif
2. An Introduction to Statistical Mechanics and Thermodynamics, R. H. Swendsen
3. Statistical Mechanics of Particles, M. Kardar

08-PHYS05-603-C: Electrodynamics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Special theory of relativity and electrodynamics:

  Lorentz transformations of electromagnetic fields, Lorentz-covariant formulation of electrodynamics, gauge invariance, Maxwell equations from action principle
- Electrostatics:

  Multipole expansion, uniqueness theorem, boundary-value problems, solution of Poisson equation
- Magnetostatics:

  Magnetostatic limit of Maxwell equations and applications
- Electrodynamics of charges and fields:

  Motion of charges in external fields, electromagnetic waves in vacuum and continuous media, energy–momentum tensor, Poynting theorem
- Advanced and retarded Green functions:

  Lienard–Wiechert potentials, dipole radiation, Larmor formula, angular distribution of radiation, synchrotron radiation
- Scattering of electromagnetic waves: Rayleigh and Thomson scattering, radiation damping

Course Outcomes:

- Acquiring knowledge of special theory of relativity and its role in electromagnetism.
- Acquiring knowledge of electrostatics and magnetostatics.
- Acquiring knowledge of the theory of electromagnetic radiation.
- Acquiring knowledge of scattering of electromagnetic waves.

References:

1. Classical Electrodynamics, J. D. Jackson
2. Electrodynamics of Continuous Media, L. D. Landau, E. M. Lifshitz and L. P. Pitaevskii
3. Classical Electrodynamics, J. Schwinger

08-PHYS05-605-C: Numerical Methods (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

a. Introduction to programming languages: F77, F90 or C
b. Errors in numerical calculations.
c. Numerical linear algebra, eigenvalue and eigenvectors.
d. Interpolation techniques.
e. Generation and use of random numbers.
f. Sorting and searching.
g. Differentiation and Integration (including Monte Carlo techniques)
h. Root finding algorithms
i. Optimisation, extrema of many variable functions.
j. ODEs and PDEs: including FFT and finite difference methods, integral equations.

Course Outcomes:

- Understand and apply mathematical techniques for describing and deeper understanding of physical systems.

References:

1. Numerical Recipes, Press, Teukolsky, Vetterling and Flannery
2. Numerical Linear Algebra, Trefethen and Bau
3. Finite Difference Methods for Ordinary and Partial Differential Equations, Randall J. LeVeque
4. A First Course in Numerical Analysis, Anthony Ralston and Philip Rabinowitz
5. Computational Physics, Nicholas J. Giordano and Hisao Nakanishi

08-PHYS05-602-L: Laboratory II (90 Lab Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Coupled Oscillator Circuits:
- Thermal Equation of State and Critical point:
- Lock-in Amplifier and Signal Processing:
- OpAmps I:
  Amplifiers & Negative Feedback:
- OpAmps II:
  Limitations & Applications:
- Diodes:
  Clamps, Rectifiers, Power supplies
- Transistors I:
  Switch, Common Emitter Amplifier, Push-pull Follower
- Transistors II:
  Characteristics, Comparators, MoSFET, CMoS Inverter
- Logic Gates:
  NAND gate, OR, AND, NOT; Adder, Oscillator
- Flip-flops:
  as Memory element, Shift Register, Counters
- Microcontroller I:
  Programming to MCU, using the port for input
- Microcontroller II:
  Some Applications, Seven Segment Display

Course Outcomes:

- Laboratory Experience with Coupled Oscillator Circuits:
- Laboratory Experience with OpAmps, Diodes, Clamps, Rectifiers, Power supplies and Transistors
- Laboratory experience with Logic Gates: NAND gate, OR, AND, NOT; Adder, Oscillator
- Laboratory Experience with Flip-flops and Microcontrollers.

References:

1. Experiments in Modern Electronics, W. M. Leach and T. E. Brewer
2. Experiments in Electronics, D. Buchla
3. Books referred in Electronics Theory course

08-PHYS05-612-C: Mathematical Methods II (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Integral transforms, Fourier transforms, inversion and convolution, Laplace transforms
- Advanced topics in ODE, Partial differential equations:

  classification of second order PDEs, Laplace and Poisson equations, applications to electrostatics, Heat equation, Wave equation
- Group theory, definitions and examples of groups. Homomorphism, isomorphism and automorphism, Permutation groups
- Group representation:

  reducibility, equivalence, Schur's lemma. Lie groups and Lie algebras, SU(2) and SU(3). Representations of simple Lie algebras, SO(n), Lorentz group. Symmetries in physical systems, Young Tableau.

Course Outcomes:

- Ability to analyse phenomena using Fourier and Laplace transformation
- Ability to construct and solve higher order differential equation
- Understanding to apply Laplace and Poisson equation to electrostatics, Heat equation, Wave equation
- Understanding Group theory concepts and its application in Lie algebras

References:

1. Group Theory, P. Ramond
2. Classical Groups for Physicists, B. Wybourne
3. Group Theory for Physics, S. Sternberg
4. Methods of Mathematical Physics, R. Courant and D. Hilbert
5. Introduction to PDEs, P. J. Olver

08-PHYS05-609-C: Condensed Matter Physics I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- The building blocks - atoms to solids:

  atomic physics, Coulomb effects, crystal fields in solids, local moments and band electrons, lattice vibrations, electron-lattice coupling, electron-electron interactions.

- Structure:

  characterizing structures - crystalline/amorphous/liquids, classification of periodic structures, reciprocal space, x-ray and neutron diffraction.

- Electronic structure:

  free electrons - spectrum, density of states, thermodynamics, band electrons - nearly free electron and tight binding limits, consequences for thermodynamics and transport.

- Physics of metals:

  specific heat, susceptibility, impurity scattering, basic transport theory. Response to magnetic fields: Landau quantization, quantum Hall effect.

- Phonons:

  Debye and Einstein model, spectrum of a real lattice, thermodynamics of phonons, anharmonic effects, Debye-Waller factor.

- Magnetism:

  spin paramagnetism, itinerant-vs-localised electrons, Stoner and Heisenberg models, mean-field theory, spin waves.

- Superconductivity:

  phenomenology, pairing interaction, BCS theory, Ginzburg-Landau theory and type II superconductors.

Course Outcomes:

- Understanding of the basic building blocks of matter and methods to probe structure of materials.
- Acquiring knowledge of the physics of metals.
- Acquiring knowledge of the physics of phonons.
- Acquiring knowledge of the physics of superconductors.
- Acquiring knowledge of the physics of magnetism.

References:

1. Oxford Solid State Basics, Steven H. Simon
2. Solid State Physics, N. W. Ashcroft and N. D. Mermin
3. Introduction to Solid State Physics, C. Kittel
4. States of Matter, David Goodstein
5. Fundamentals of the Theory of Metals, A. Abrikosov

08-PHYS05-605-E: Quantum Information and Computation I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Quantum formalism:
  states, evolution, measurements.
- Multipartite quantum systems:
  description and manipulation of bipartite systems and beyond.
- Entanglement:
  quantification and detection in bipartite and multipartite systems.
- Quantum communication:
  noloning theorem, quantum teleportation, quantum dense coding, multipartite communication protocols.
- Quantum cryptography:
  essential classical cryptography, BB84, B92, Ekert, and secret sharing protocols.
- Quantum computation:
  quantum algorithms, universal gates.
- Interface of quantum information with other sciences.
- Experimental realisations.

Course Outcomes:

- Understanding of the concept of entanglement: quantification and detection in bipartite and multipartite systems.
- Acquiring knowledge of the basics of quantum communication.
- Acquiring knowledge of the basics of quantum cryptography and quantum computation.
- Acquiring knowledge of the basics of the interface of quantum information with other sciences and experimental realizations.

References:

1. Quantum Computation and Quantum Information, M. Nielsen and I. Chuang
2. Lecture notes of John Preskill (Caltech)
3. Quantum Theory: Concepts and Methods, A. Peres

08-PHYS05-611-C: Quantum Field Theory I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Non-relativistic quantum field theory:

  quantum mechanics of many particle systems; second quantisation; Schrodinger equation as a classical field equation and its quantisation; inclusion of inter- particle interactions in the first and second quantised formalism
- Irreducible representations of the Lorentz group, connection to quantum fields
- Symmetries and conservation laws:

  examples in non-relativistic and relativistic field theories; translation, rotation, Lorentz boost/Galilean transformation and internal symmetry transformations; associated conserved charges
- Free Klein-Gordon equation:

  classical action and its quantisation; spectrum; Feynman rules for computing n-point Green functions of elementary and composite operators.
- Interacting Klein-Gordon field:

  Feynman rules for computing Green functions; physical mass of the particle from the analysis of two point Green functions; S-matrix and its computation from n-point Green functions; relating S-matrix to cross-section.
- Quantisation of free Dirac fields:

  spectrum; Feynman rules
- Quantisation of free electromagnetic field:

  role of gauge invariance; gauge fixing; physical state condition; spectrum; Feynman rules
- Quantum electrodynamics:

  coupling Dirac field to electromagnetic field; gauge invariance; quantisation; Feynman rules for computing Green functions; Spectrum and S-matrix from the Green functions.

Course Outcomes:

- Acquiring knowledge of the method of second quantization for the study of many particle non-relativistic systems.
- Acquiring knowledge of the Lorentz group and its role in relativistic quantum field theory.
- Acquiring knowledge of the quantization of the Klein Gordon, Dirac and Maxwell fields.
- Acquiring knowledge of the basics of quantum electrodynamics and the study of various processes at tree level.
- Understanding of the role of gauge invariance in quantum electrodynamics.

References:

1. An Introduction to Quantum Field Theory, M. E. Peskin and D. V. Schroeder
2. Field Theory: A Modern Primer, Pierre Ramond
3. Quantum Field Theory, Itzykson and Zuber

MSc thesis

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- In this thesis, every student will to do a 1 year long project on a theoretical physics topic under the supervision of HRI faculty

08-PHYS05-613-C: Particle Physics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Experimental methods:
  fixed target and collider experiments, particle detectors.
- Role of symmetries:
  charge conjugation, parity, time reversal, isospin and SU(2), quark model and SU(3).
- Introduction to relativistic kinematics:
  Mandelstam variables, phase space, calculation of cross- sections and decay widths.
- Basics of quantum electrodynamics:
  electron-positron annihilation, electron-muon scattering, Bhabha scattering, Compton scattering.
- Deep inelastic scattering:
  Bjorken scaling, parton model, scaling violation, introduction to quantum chromodynamics and tree level processes.
- Introduction to weak interactions:
  parity violation, V-A theory, pion and muon decay, neutrino scattering.
- Standard Model:
  Glashow-Salam-Weinberg model, neutral current, physics of W, Z and Higgs, CKM mixing and CP violation.
- Neutrino physics, neutrino oscillation

Course Outcomes:

- Understanding physics of elementary particles.
- Learning about fundamental interactions in terms of gauge principle.
- Acquiring skills to carry out computation in Strong, Weak and Electromagnetic theory.
- Learning various techniques useful for particle physics phenomenology.
- Learning methods to compute physical observables which can tested in the laboratory.

References:

1. Quantum Field Theory and the Standard Model, Matthew D. Schwartz
2. Gauge Theory of Elementary Particle Physics, Ta-Pei Cheng and Ling-Fong Li
3. Quarks and Leptons, Francis Halzen and Alan Martin
4. Introduction to High Energy Physics, Donald H. Perkins
5. An Introduction to Quantum Field Theory, Peskin and Schroeder

08-PHYS05-603-E: General Theory of Relativity (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Review of Lorentz transformations and special theory of relativity.
- Tensors and their transformation laws;

  Christoffel symbol and Riemann tensor; geodesics; parallel transport along open lines and closed curves; general properties of the Riemann tensor.
- Equivalence principle and its applications:

  gravity as a curvature of space-time; geodesics as trajectories under the influence of gravitational field; generalisation to massless particles; gravitational red-shift; motion of a charged particle in curved space-time in the presence of an electric field; Maxwells equation in curved space-time.
- Einsteins equation, Lagrangian formulation, Einstein-Hilbert action.
- Schwarzschild solution:

  construction of the metric and its symmetries; motion of a particle in the Schwarzschild metric; Schwarzschild black hole; white holes and Kruskal extension of the Schwarzschild solution: construction of the metric and its symmetries; Motion of a particle in the Schwarzschild metric; precession of the perihelion; bending of light; horizon, its properties and significance.
- Precession of the perihelion; bending of light; radar echo delay.
- Initial value problem; extrinsic curvature; Gaussodacci equations;
- Linearised theory, gravitational waves, field far from a source, energy in gravitational waves, quadrupole formula
- Elementary cosmology:

  principles of homogeneity and isotropy; Friedman-Robertson-Walker metric; open, closed and flat universes; Friedman equation and stress tensor conservation, equation of state, big bang hypothesis and its successes.

Course Outcomes:

- Acquiring basic knowledge of differential geometry.
- Understanding of the equivalence principle and its applications.
- Acquiring knowledge of Einstein equation
- Acquiring knowledge of Schwarzschild solution along with applications.
- Acquiring knowledge of the theory of gravitational waves.
- Acquiring knowledge of the basics of Friedman-Robertson-Walker cosmology.

References:

1. Gravitation and Cosmology, S. Weinberg
2. A First Course in General Relativity, B. Schutz
3. Spacetime and Geometry, S. Carroll
4. Gravity, J. Hartle

08-PHYS05-603-L: Laboratory III (90 Lab Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Ferro to para-electric phase transition (or magnetic analogue)
- Raman spectroscopy
- Electron spin resonance (ESR)
- Earth’s field NMR gradient
- Bragg diffraction by microwaves
- Hall effect
- Geiger–Müller counter, counting statistics, gamma-ray absorption
- Gamma-ray spectroscopy
- STM with graphene, HOPG, gold, semiconductors and CDW
- Measurement of speed of light

Course Outcomes:

- Performing experiments to study the phase transitions and different types of detectors.
- Performing experiments to explore the Bragg's diffraction from crystals and abnormal Hall effect.
- Performing spectroscopic experiments such as the Raman spectroscopy and magnetic resonance spectroscopy.
- Exploring atomic scale imaging and electronic Density of states of solids.

References:

1. Laser Fundamentals, W. T. Silfvast
2. Elements of X-Ray Diffraction, B. D. Cullity
3. Books referred for laboratory

08-PHYS05-601-PR: Project (year long)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- In this project, every student will to do a one year long project on a theoretical physics topic under the supervision of HRI faculty

Mini–project I

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- In this semester long project, every student will to do a short project on a theoretical physics topic under the supervision of HRI faculty

Mini-project II

Coordinators: Prof. Anirban Basu

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Course Details:

- In this semester long project, every student will to do a short project on a theoretical physics topic under the supervision of HRI faculty

08-PHYS04-601-R : Research Methodology & Research Publication Ethics (45)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- To be taught by HBNI

ELECTIVE COURSES

08-PHYS04-619-E: Accretion Process in Astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Astrophysical accretion as a source of energy
- Accretion from binary systems
- Accretion discs in astrophysics at various length scales
- Accretion onto compact objects
- Accretion power and accretion disc in active galactic nuclei

Course Outcomes:

- Explain the mechanism of astrophysical accretion as a major source of energy in the universe.
- Describe accretion processes in binary systems and analyze mass transfer between stellar components.
- Interpret the structure and dynamics of accretion discs across different astrophysical length scales, from stellar to galactic systems.
- Analyze accretion onto compact objects (white dwarfs, neutron stars, black holes) and evaluate accretion power in active galactic nuclei (AGN).

References:

1. Accretion Power in Astrophysics, J. Frank, A. King and D. Raine
2. Extreme Environment Astrophysics, Ulrich Kolb
3. Black-Hole Accretion Disks - Towards a New Paradigm, S. Kato, J. Fukue and S. Mineshige

08-PHYS08-601-E: Advanced Statistical Mechanics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Critical phenomena:

  Liquid-gas transition and Van der Waals equation of state, Classical spin systems, Transfer matrix for one dimensional systems, Order parameters, Mean field approach, Landau theory, Universality, Critical exponents, Scaling hypothesis, Estimating fluctuations
- Renormalisation:

  Hubbard-Stratanovich transformation and the Ginzburg-Landau-Wilson functional, Selfonsistent approximation, Basic ideas of renormalisation group, Real space RG in one and two dimensions, Spherical limit, Wilsonian RG and ε-expansion, Field theoretic RG, Two dimensions and BKT transition
- Equilibrium dynamics:

  Conserved and broken symmetry variables, Hydrodynamic approach, Dynamical critical phenomena
- (Extra module: one of the following two):
- Non-equilibrium phenomena:

  Fluctuation-dissipation, Linear response, Kubo formula, Langevin and Fokker-Planck descriptions
- Stochastic thermodynamics:

  Non-equilibrium work theorems (Jarzynski, Crooks, …), Non- equilibrium steady-states, Stochastic heat engines, Examples from colloidal systems and molecular motors

Course Outcomes:

- Acquiring knowledge of the basics of Critical phenomena.
- Understanding of the notion of Renormalization in statistical mechanics.
- Understanding of the basics of Equilibrium dynamics: Conserved and broken symmetry variables, Hydrodynamic approach, Dynamical critical phenomena.
- Acquiring basic knowledge of Nonequilibrium phenomena and stochastic thermodynamics.

References:

1. Statistical Mechanics of Fields, M. Kardar
2. Lectures on Phase Transitions and the Renormalisation Group, N. Goldenfeld
3. Elements of Nonequilibrium Statistical Mechanics, V. Balakrishnan

08-PHYS08-625-E: Advanced Topics in General Relativity (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Penrose diagrams.
- Hypersurface geometry.
- Initial value problem in general relativity.
- Aspects of black hole physics: black hole thermodyanmics and models of collapse.
- Brief survey of singularity theorems.
- Gravitational waves.

Course Outcomes:

- Learning conformal techniques and learning diagrammatic depiction of geometries.
- Learning about embedded surfaces, family of surfaces, and constant mean curvature.
- Understanding the evolution of the Cauchy data given on a suitable initial hypersurface.
- Learning thermodynamics of black holes and studying the models leading to formation of black holes.
- Acquiring understanding of geodesic congruences, geodesic incompleteness and proving singularity theorems using the Raychaudhuri equation.

References:

1. Gravitation, C. W. Misner, K. S. Thorne and J. A. Wheeler
2. General Relativity, R. M. Wald

08-PHYS04-631-E: Advanced Topics in Quantum Field Theory (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Solitons in scalar and gauge theories
- Monopoles and instantons
- Large N: soluble models and applications in QCD
- Anomalies: global and gauge
- Introduction to supersymmetric field theories (including brief discussion of phenomenological applications)
- Aspects of finite temperature field theory

Course Outcomes:

- Understand the role of solitons in scalar and gauge field theories, including monopoles and instantons, and explain their physical significance
- Analyze the large-N limit, study soluble models, and discuss their applications in quantum chromodynamics (QCD).
- Explain the origin and implications of global and gauge anomalies in quantum field theories.
- Describe the basic structure of supersymmetric field theories and finite temperature field theory, including their key theoretical and phenomenological applications.

References:

1. Aspects of Symmetry: Selected Erice Lectures, S. Coleman
2. An Introduction to Quantum Field Theory, M. E. Peskin and D. V. Schroeder
3. Supersymmetry and Supergravity, J. Wess and J.Bagger
4. Finite Temperature Field Theory, A. K. Das

08-PHYS04-621-E: Astronomical Data Analysis (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Overview of data analysis in astronomy
- Types of astronomical data- images, catalogues, spectra, polarization, time-series
- Recapitulation of basic statistics - sources of error. Probability distributions. Bayes' theorem
- Data acquisition - sampling. Fourier methods
- Parameter estimation - model fitting
- Astronomical data archives. VO tools for analysis of archived data

Course Outcomes:

- Understand the fundamentals of data analysis in astronomy and identify different types of astronomical data such as images, catalogues, spectra, polarization, and time-series.
- Apply basic statistical concepts, including error analysis, probability distributions, and Bayes' theorem, to interpret astronomical data.
- Analyze data acquisition techniques such as sampling and Fourier methods, and perform parameter estimation through model fitting.
- Utilize astronomical data archives and Virtual Observatory (VO) tools for accessing and analyzing archived observational data.

References:

1. High Energy Astrophysics, Malcolm S. Longair
2. Astronomy Methods: A Physical Approach to Astronomical Observations, Hale Bradt

08-PHYS04-617-E: Astrophysical Fluid Dynamics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Transition from the microscopic theory of matter to the fluid properties, equivalence of the Boltzmann equation with the Navier Stokes equation
- Blast waves and shock waves in compressible fluid under the influence of strong gravity, application to the theory of supernova and other large scale astrophysical explosions in the universe
- Various instabilities. Theory of turbulence
- Time dependent perturbation of fluid under strong gravity and the stability analysis of various fluid structures in astrophysics
- Detailed study of magneto-hydrodynamics

Course Outcomes:

- Understand the transition from microscopic descriptions of matter to macroscopic fluid behavior, including the connection between the Boltzmann equation and the Navier–Stokes equations.
- Analyze blast waves and shock waves in compressible fluids under strong gravitational fields, and apply these concepts to supernovae and large-scale astrophysical explosions.
- Explain various fluid instabilities and the fundamental theory of turbulence in astrophysical contexts.
- Perform stability analysis of time-dependent perturbations in self-gravitating fluids and evaluate the behavior of astrophysical fluid structures.
- Apply the principles of magneto-hydrodynamics (MHD) to study the dynamics of magnetized astrophysical plasmas.

References:

1. Principles of Astrophysical Fluid Dynamics, Cathie Clarke, Bob Carswell, R. F. Carswell
2. The Physics of Fluids and Plasmas An Introduction for Astrophysicists, Arnab Rai Choudhuri
3. Principles of Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas, J. P. Hans Goedbloed and Stefaan Poedts
4. Modern Fluid Dynamics for Physics and Astrophysics, O. Regev, O. M. Umurhan, P. Yecko

PHYS08-606-E: Astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Introduction to celestial objects, coordinates and the concept of time. Radiation transfer. Equations of radiation transfer, Black-body/thermal radiation, Opacity and optical depth, solutions of the radiation transfer equations in limiting cases, Rosseland mean opacity.
- Thermal Bremsstrahlung emission, synchrotron emission. Self-absorption and the emergent spectrum. Thomson scattering. Compton and Inverseompton scattering. Scattering in a region with magnetic field, Faraday rotation Introduction to fluid dynamics. Convection instability and transfer of energy from cores of stars. Supersonic motion, shocks.
- Introduction to Magneto-hydro dynamics, flux freezing, Generation and amplification of magnetic fields in astrophysical situations.
- Stellar structure. Mass-radius relation for main sequence stars, Minimum and maximum mass for nucleosynthesis, Hertzsprung-Russell diagram, Evolution of a star on the HR diagram. Novae and Supernovae, End points of stellar evolution. Inter-stellar medium. Phases of interstellar medium. Thermal, photoionisation, chemical and pressure equilibrium, Star formation, feedback and the evolution of ISM.
- Orbits around massive bodies, Tidal disruption, restricted 3 body problem, Roche limit. Orbits in external potentials, potential-density pairs. An overview of models for galaxies. Accretion of matter on to a point mass, spherical accretion, Eddington limit.
- Introduction to Cosmology, Friedmann models, equations. Hubble’s law. A brief overview of the thermal history of the universe.

Course Outcomes:

- Learning about magnetohydrodynamics with applications to Astrophysical systems.
- Study of stellar structure and developing detailed understanding of structure of stars.
- Developing understanding of the models of galaxies.
- Acquiring knowledge of the accretion of matter due to a point mass.
- Developing introductory understanding of cosmology.

References:

1. Astronomy: A Physical Perspective, Marc L. Kutner
2. An Introduction to Modern Astrophysics, Carroll and Ostlie
3. Principles of Astrophysical Fluid Dynamics, Clarke and Carswell

08-PHYS04-624-E: Collider Physics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Introduction to colliders and its types, e+e-colliders, hadron colliders, LEP, Tevatron, Large
- Hadron Collider
- Particle kinematics, collider observables
- Parton distribution functions, parton model, parametrization of quark distributions, parton model for hadron-hadron collisions, gluon distribution, fragmentation functions
- Jets, jet characteristics, quark jets, gluon jets, jet clustering algorithms
- Review of Standard Model, particle searches at colliders, weak boson production and decay, two-jet production, multi-jet production.
- Statistics and analysis, Monte Carlo simulations, event generators, introduction to HEP tools, brief introduction to machine learning methods

Course Outcomes:

- Understand the principles of particle colliders, including electron–positron and hadron colliders, and explain key collider observables and particle kinematics.
- Apply the parton model, parton distribution functions, and fragmentation functions to analyze hadron–hadron collision processes.
- Analyze jet formation, distinguish quark and gluon jets, and utilize jet clustering algorithms in collider data studies.
- Interpret Standard Model processes at colliders, including weak boson production and multi-jet events, and apply statistical methods, Monte Carlo simulations, and modern HEP computational tools (including introductory machine learning techniques) for data analysis.

References:

1. Collider Physics, V. Barger and R. J. N. Phillips
2. Collider Physics within the Standard Model, G. Altarelli
3. Statistical Analysis Techniques in Particle Physics, I. Narsky and F.C. Porter

08-PHYS04-622-E: Computational Astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Introduction to computational astrophysics
- The N-body problem. Numerical algorithms
- Integrators for solving time-dependent nonlinear partial differential equations
- Particle and mesh related approaches. Numerical stochastic techniques
- Scopes of robust computational packages. Parallel computing
- Applications to astrophysical systems

Course Outcomes:

- Understand the foundations of computational astrophysics and the formulation of the N-body problem in astrophysical systems.
- Apply numerical algorithms and integrators to solve time-dependent nonlinear ordinary and partial differential equations.
- Implement particle-based, mesh-based, and stochastic numerical techniques in modeling astrophysical phenomena.
- Utilize robust computational packages and parallel computing methods for large-scale simulations and analyze their applications to diverse astrophysical systems.

References:

1. Numerical Methods in Astrophysics: An Introduction, Peter Bodenheimer, Gregory P. Laughlin, Tomasz Plewa, Michal Rozycka and Harold W. Yorke
2. Computational Methods for Astrophysical Fluid Flows: Saas-Fee Advanced Course 27, Lecture Notes 1997 Swiss Society of Astrophysics and Astronomy, (ed. O. Steiner and A. Gautschy) LeVeque, Mihalas, Dorfi and Muller

PHYS08-622-E: Computational Many Body Theory I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Free electrons in periodic structures:

  single band tight binding models in one, two and three dimensions, square, triangular and hexagonal lattices. Fermi surface and density of states. Multiband models. Spin-orbit coupling. Response functions of the free system, incipient instabilities.
- Disordered electrons:

  models with potential and hopping disorder, inverse participation ratio, maps of eigenfunctions, nobility edge, finite size effects, resistivity and optical con- ductivity using the Kubo formula. Disorder averaging.
- Effect of an orbital magnetic field, Landau levels, role of disorder.
- Mean field theory:

  implementing iterative consistency in a particle number conserving model. Competing phases.
- Bogoliubov-de Gennes schemes:

  spectrum and observables for a given pairing field, im- plementation of consistency, iterative scheme in the presence of disorder. Computing local observables.
- Classical Monte Carlo for spin models: the Ising, XY and Heisenberg models on the square and triangular lattice, structure factor and energy, finite size effects.

Course Outcomes:

- Understanding of free electrons in periodic structures along with the multiband models, effect of spin orbit coupling and response functions.
- Getting acquainted with the disordered electrons and disorder averaging with a special focus on Kubo formula along with role of disorder and Landau Levels.
- Acquiring knowledge about mean field theory and Bogoliubov-de Gennes schemes and computation of local observables.
- Conceptualization of classical monte carlo for spin models like Ising, Heisenberg models on the square and triangular lattice.

References:

1. Monte Carlo Methods in Statistical Physics, M. Newman, G. Barkema
2. An introduction to computer simulation methods, H. Gould, J. Tobochnik, W. Christian
3. Computational Physics, P. O. J. Scherer

08-PHYS04-616-E: Computational Many Body Theory II (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Exact diagonalization based Monte Carlo:

  path integral formulation, implementation for the Holstein and double exchange models. Thermal averaging, locating phase transitions, distribution of observables

- Molecular dynamics:

  Hamiltonian dynamics for single degree of freedom, linear and nonlinear models. Langevin scheme for a classical particle in a harmonic potential, match with analytic results, double well potential, Kramers escape problem. Noise driven coupled linear oscillators. Coupled nonlinear oscillators. Langevin equation for classical fields coupled to electrons Self consistent diagrammatic schemes: iterative perturbation theory for impurity models, fluctuation exchange schemes, Migdal-Eliashberg

- Exact diagonalization and Lanczos:

  setting up the many particle states for the Hubbard and S=1/2 Heisenberg models. Computing matrix elements. ED on small finite geometries. Computing spectral functions. Lanczos implementation for the ground and excited states, spectral functions

- Variational MC for ground states:

  determination of variational parameters by Monte Carlo minimization of energy. Projected wave functions for correlated superconducting states

- Quantum Monte Carlo for fermions:

  implementing determinantal Monte Carlo for the symmetric Anderson impurity model, Ising representation. Lattice models, the sign problem

- Special topics:

  Monte Carlo for bosons, density matrix renormalization group and its 2D variants, dynamical mean field theory

Course Outcomes:

- Develop understanding of exact diagonalization–based Monte Carlo methods, including path integral formulation, implementation for model Hamiltonians, thermal averaging, and identification of phase transitions.
- Apply molecular dynamics and Langevin techniques to linear and nonlinear systems, analyze stochastic dynamics, and connect numerical results with analytical predictions.
- Implement exact diagonalization and Lanczos algorithms for many-body systems (e.g., Hubbard and Heisenberg models), and compute ground states, excited states, and spectral functions.
- Utilize advanced computational many-body techniques such as variational Monte Carlo, determinantal quantum Monte Carlo, and self-consistent diagrammatic schemes, while understanding challenges like the fermion sign problem and extensions to modern methods including DMRG and dynamical mean field theory.

References:

1. Lectures on electron correlation and magnetism, P. Fazekas
2. Computational Many-Particle Physics, H. Fehske et al
3. Understanding Molecular Simulation: From Algorithms to Applications, D. Frenkel, B. Smit
4. U. Schollwock, Rev. Mod. Phys. 77, 259 (2005) 277

PHYS08-623-E: Computational Materials Science (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Introduction:
  Basic ideas of modeling and simulation. Length, time, and energy scales in materials.
- Computational techniques:
  Monte Carlo Methods: Metropolis sampling and Monte Carlo integration, Ensemble averages.
- Molecular dynamics:
  MD in different ensembles, idea of thermostat, Nose-Hoover and Nose-Hoover chain thermostats.
- Optimization techniques:
  Gradient-based methods, conjugate gradient method.
- Atomistic model/simulation of molecules and materials.
- Interatomic potentials:
  Motivation, Lennard-Jones, Morse, Tersoff etc. potentials. Em- bedded atom potentials.First principles approach: Basic ideas of Hartree-Fock and density functional theory.
- Application of the above computational techniques in atomistic systems using interatomic potential and first principles.
- Materials:
  Applications of the above techniques and ideas to real materials. Structure optimization of molecules and solids. Electronic and magnetic properties of crystalline solids. Defect properties. Properties of solid surfaces, and two-dimensional materials. Electronic and magnetic properties of molecules and clusters.
- Possible advanced topics:
  Evolutionary (genetic) algorithm and Monte Carlo based tech- niques for optimization. Application to structure optimization. Reactive force fields. Functionalizing materials for target applications such as catalysis, sensing. Adsorption of molecules and clusters on surfaces, their applications.
- Length and time scales which can be addressed by the methods discussed. Elementary ideas about methods to treat longer length and time scales: Kinetic Monte Carlo, Cellular automata, Phase field models. Multi-scale modeling.

Course Outcomes:

- Conceptualization of length, time and energy scales materials modelling and simulation.
- Learning cutting edge computational techniques like Monte Carlo methods, Metropolis algorithm, different thermostats and various optimization techniques.
- Understanding the fundamental concept of Hartree Fock and Density Functional Theory along with Interatomic potentials.
- Implementation of electronic structure theory in investigating electronic and magnetic properties of bulk, surface and two dimensional materials.
- Learning genetic algorithm, kinetic monte carlo, phase field modeling and multi scale modeling.

References:

1. Computational Materials Science, An Introduction, June Gunn Lee
2. Introduction to Computational Materials Science: Fundamentals to Applications, Richard LeSar

08-PHYS04-607-E: Condensed Matter Physics II (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

Any two of the four topics to be covered:

- Part A: Mesoscopics and spintronics
  - Foundation:
    low dimensional systems: quantum Wells, wires and quantum dots, 1D and 2D heterostructures, coupled wells and superlattices
  - Charge Transport:
    transmission and its relation to conductance, Landauer theory, trans19 mission function, S matrix and Green functions. Non-equilibrium Green functions and Landauer-Buttiker theory. Noise in Charge transport, scattering theory of shot noise
  - Spintronics:
    introduction to spintronics.(Datta-Das spin transistor) equilibrium and nonequilibrium spin currents, spin Hall effect, coupled charge and spin transport, TMR, spin shot noise, entanglement generation and its detection

- Part B: Electronic structure
  - Physics in low dimensions:
    surface states, reconstructions, adsorption, atomic wires and clusters
  - Electron-electron interactions:
    Hartree-Fock approximation, electron gas, density functional theory
  - Anharmonic effects in crystals:
    thermal expansion, lattice thermal conductivity, umklapp processes
  - Phonons in metals:
    Kohn anomaly, dielectric constant, temperature dependence of electrical resistivity Dielectric properties of insulators. Plasmons, magnons etc

- Part C: Mesoscopics and interacting systems
  - Quantum Hall effect
  - Quantum dots and quantum wires, Kondo effect
  - Fermi liquid theory and non Fermi liquids
  - Bosonization and Luttinger liquids
  - Quantum spin systems

- Part D: Correlated electrons
  - Mott physics:
    electron localisation, magnetic order, doped phase, physics in the cuprates
  - Kondo systems:
    physics of the single impurity, dense systems Kondo and Anderson lattice, heavy fermions, quantum criticality

- Metallic magnets:

  ferromagnetism in strongly repulsive systems, the transition metals, spin-fermion systems, the double exchange model, the classical Kondo lattice
- Electron-phonon coupling:

  the classical theory, polaron formation, many electron systems, polaron ordering, physics in the manganites
- Superconductivity:

  the BCS-BEC crossover, superconductivity in repulsive systems, competition with magnetism, effect of disorder

Course Outcomes:

- Develop a strong conceptual understanding of low-dimensional and correlated electronic systems, including quantum transport, electronic structure, and interaction-driven phenomena.
- Apply theoretical frameworks such as Landauer formalism, Green's function techniques, Hartree–Fock and density functional theory, and many-body approaches to analyze mesoscopic and condensed matter systems.
- Analyze emergent phenomena such as quantum Hall effect, Kondo physics, Mott localization, spin transport, superconductivity, and electron–phonon coupling in realistic materials.
- Interpret experimental signatures and transport properties of interacting electron systems, including charge, spin, and collective excitations in low-dimensional and strongly correlated materials.

References:

1. Electronic Structure: Basic Theory and Practical Methods, Richard M. Martin
2. Introduction to mesoscopic physics, Y. Imry
3. Correlated electron systems, V. J. Emery (Ed)

08-PHYS04-617-E: Correlated Electron Systems (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Mott physics:

  electron localization, magnetic order, doped phase, physics in the cuprates.
- Kondo systems:

  physics of the single impurity Anderson model, dense systems, Kondo and Anderson lattice, heavy fermions, quantum criticality.
- Metallic magnets:

  ferromagnetism in strongly repulsive systems, the transition metals, spin-fermion systems, the double exchange model, the classical Kondo lattice.
- Electron-phonon coupling:

  the classical theory, polaron formation, quantum theory of the ground state, many electron systems, polaron ordering, physics in the manganites.
- Superconductivity:

  BCS and Migdal-Eliashberg theory, the BCS-BEC crossover, super- conductivity in repulsive systems, competition with magnetism, effect of disorder.

Course Outcomes:

- Understanding the physics of Mott insulating systems ranging from electron localization to the physics of the Cuprates.
- Acquiring knowledge about the Kondo impurity and lattice models and the resulting heavy fermion physics.
- Understanding the origin of quantum magnetism in various settings.
- Acquiring knowledge about electron-phonon coupled systems and particularly the physics of polarons in these systems.
- Acquiring a sophisticated understanding of various facets of superconductivity.

References:

1. Lecture notes on electron correlation and magnetism, P. Fazekas
2. Correlated electron systems, V. J. Emery (Ed)
3. Quantum field theory in strongly correlated electron systems, N. Nagaosa

08-PHYS04-608-E: Cosmology (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Friedman-Robertson-Walker metric, Friedman equation and stress tensor conservation, equation of state: matter, radiation, cosmological constant, experimental evidence for dark matter and dark energy.
- Age of the universe, cosmological horizon, expansion rate.
- Thermal history of the universe, formation of hydrogen and origin of CMBR, decoupling of neutrinos, nucleosynthesis, recombination.
- The horizon problem, possible resolution via inflation, slow roll condition and slow roll parameters, reheating, inflationary origin of density perturbation.
- Early history, electroweak baryogenesis via leptogenesis, dark matter.
- Theory of cosmological perturbations: gauge invariant scalar and tensor perturbations, spectral index, ratio of tensor to scalar fluctuation and Lyth bound, transition from quantum to classical perturbation: horizon exit and re-entry, from density fluctuation to CMB fluctuations via Boltzmann transport equation, origin of the acoustic peak, and origin of CMB polarisation, E and B modes.

Course Outcomes:

- Learning about the cosmological model, the cosmological constant and the dark matter.
- Developing the understanding of the thermal history of the universe and its imprints on CMB.
- Understanding the horizon problem and its resolution by inflation.
- Acquiring the knowledge of the theory of cosmological perturbations.
- Studying the implications of the cosmological perturbation on the structure formation.

References:

1. Cosmology, S. Weinberg,
2. Modern cosmology, S. Dodelson

08-PHYS04-627-E: Dark Matter and particle astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Review of cosmology basics
- Dark matter relics and their density
- WIMPS, indirect and direct searches for dark matter
- Collider Searches for dark matter
- Supernova physics
- Ultra-high energy neutrinos
- Portals to dark matter

Course Outcomes:

- Develop a foundational understanding of modern cosmology and the role of dark matter in the evolution of the Universe.
- Analyze the production mechanisms of dark matter relics and calculate their present-day density.
- Evaluate experimental strategies for dark matter detection, including direct searches, indirect searches, and collider-based approaches.
- Explain the connection between supernova physics, ultra-high energy neutrinos, and portal models in probing physics beyond the Standard Model.

References:

1. Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles, by Georg Raffelt
2. Lectures on DM arXiv: 1603.03797
3. TASI lectures on dark matter models and direct detection, Tongyan Lin, arXiv: 1904.07915
4. Other supplementary materials: Recent arXiv papers and lectures as decided by the instructor

08-PHYS08-618-E: Disorder in Condensed Matter (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Origin of disorder in condensed matter:

  point defects. alloys, grain boundaries and dislo- cations. Disorder in dielectic media. Distributions of disorder. Correlated and uncorrelated disorder.
- Classical waves in a disordered medium:

  photons and phonons in disordered media, localization effects.
- Perturbation theory and disorder average:

  low order scattering and results for the single particle Green's function and the conductivity.
- Quantum interference and localization:

  coherent backscattering and its effects in different dimensions. The mobility edge. Anderson localization effects in three dimensions. Scaling theory of the metal-insulator transition. Experimental survey.
- Phase breaking effects:

  effect of inelastic scattering, spin flips and spin-orbit coupling. The effect on conductivity and magnetoresistance.
- Hopping conduction:

  localized states and phonon assisted hopping, variable range hop- ping, coulomb gap, experiments on insulators.
- Electron-electron interaction in disordered systems:

  the Altshuler-Aronov theory. Com- bined effects of interaction and disorder on density of states and transport properties.
- Special topics:

  percolation theory, self consistent theory of localisation, typical medium theory, spin glasses, Anderson-Mott problem.

Course Outcomes:

- Understanding the origin and distribution of disorder in condensed matter including the concept of grain boundaries, point defects and dislocation.
- Acquiring knowledge of classical waves in a disordered medium and perturbation theory including single particle Green's function and the conductivity
- Understanding quantum interference and localization along with Anderson localization effects and Scaling theory of metal-insulator transition
- Conceptualization of Electron-electron interaction in disordered systems, percolation the- ory and spin glasses along with Anderson-Mott problem.

References:

1. Electronic processes in non crystalline materials, N. Mott and E. A. Davis
2. Electrons and disorder in solids: V. F. Gantmakher
3. Electron-electron interactions in disordered systems: A. L. Efros and M. Pollak

08-PHYS04-626-E: Flavor Physics and CP violation (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- The discrete symmetries of the Standard Model, C, P and T symmetries, CP and CPT transformations
- Flavour structure of the Standard Model, lepton masses and mixing, quark masses and mixing, running masses
- Flavour changing neutral currents, CKM matrix and measuring its observables
- Meson mixings and mixing parameters, Kaon and B-physics, rare K and B decays
- CP Violation, CPV in decays, minimal flavour violation
- Flavour physics beyond the Standard Model

Course Outcomes:

- Understand the discrete symmetries of the Standard Model (C, P, T, CP, and CPT) and analyze their theoretical and experimental implications.
- Explain the flavour structure of the Standard Model, including quark and lepton masses, mixing matrices, and the renormalization group evolution of masses.
- Analyze flavour changing neutral currents, meson mixing phenomena (K and B systems), rare decays, and the determination of CKM observables.
- Evaluate mechanisms of CP violation and explore extensions of flavour physics beyond the Standard Model, including minimal flavour violation frameworks.

References:

1. CP Violation. Authors: I.I. Bigi, A.I. Sanda
2. CP Violation. Authors: G.C. Branco, L. Lavoura and J.P. Silva

08-PHYS04-602-E: Fluid Mechanics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Ideal Fluids:

  Euler equation, hydrostatics, Bernoulli equation, conservation laws, incompressible fluids, waves, irrotational flows, inviscid fluids and vorticity
- Viscous Fluids:

  Viscosity, Navier-Stokes equation, Reynolds number, laminar flow, exact solution to the eq. of motion.
- Turbulence:

  Stability of flows, instabilities, quasi-periodic flows, Strange attractors, turbulent flows, jets, free shear layers, wakes, boundary layers
- Thermal Conduction in fluids:

  eq. of heat transfer, conduction in incompressible fluid, law of heat transfer, convection, convective instability in static fluid
- Compressible flows
- Relativistic Fluid dynamics:

  eq. of motion, energy-momentum tensor, eq. for flow with viscosity and thermal conduction.

Course Outcomes:

- Acquiring knowledge of the basic concepts in the study of ideal fluids: Euler equation, hydrostatics, Bernoulli equation, conservation laws, incompressible fluids, waves, irrotational flows, inviscid fluids and vorticity.
- Study of viscous fluids.
- Acquiring knowledge of the basic topics in the theory of turbulence.
- Understanding of Thermal Conduction in fluids.
- Acquiring basic knowledge of Relativistic Fluid dynamics.

References:

1. Fluid Mechanics, L. D. Landau and E. M. Lifshitz,
2. An Introduction to Fluid Dynamics, G. K. Batchelor,
3. Relativistic Fluid Dynamics, A. Anile and Y. Choquet-Bruhat.

08-PHYS04-628-E: Grand Unified Theories (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Motivation and introduction, Standard Model and its limitations
- Gauge symmetries, Standard Model of particle physics, unification of SM forces
- Grand unified Theories, the Gauge group SU(n), Georgi Glashow Model, SU(5) and SO(10)
- Implications of unification, proton decay, fermion masses, renormalization group equations, baryon number
- GUT phenomenology, massive neutrinos

Course Outcomes:

- Understand the motivation for physics beyond the Standard Model and identify its theoretical and phenomenological limitations.
- Explain the role of gauge symmetries in the Standard Model and the concept of force unification through larger gauge groups.
- Analyze the structure of Grand Unified Theories (GUTs), including SU(N) groups and specific models such as SU(5) and SO(10), and their implications for fermion masses and symmetry breaking.
- Evaluate phenomenological consequences of unification, including proton decay, baryon number violation, renormalization group evolution, and the origin of massive neutrinos.

References:

1. Group theory for unified model building, R. Slansky (Physics Reports Volume 79, Issue 1, December 1981, Pages 1-128)
2. Grand unified theories and proton decay, P. Langacker (Physics Reports Volume 72, Issue 4, June 1981, Pages 185-385)
3. Grand Unified Theories, Graham G. Gross
4. Unification and Supersymmetry, R.N. Mohapatra

08-PHYS08-615-E: Introduction to Electronic Structure (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Review of QM variational methods, identical particles, many-fermion wave functions. First-principles Hamiltonian and Born–Oppenheimer approximation.
- Treating electron–electron interactions:

  Hartree–Fock approximation, exchange energy, correlation energy.
- Density functional theory:

  Thomas–Fermi method, Hohenberg–Kohn theorems, Levy constrained search formulation, Kohn–Sham formulation, exchange–correlation energy, LDA and GGA functionals, spin density functional theory.
- Solution of the Kohn–Sham equations, basis sets – LCAO: STO-NG, 3-21G, 6-31G, etc.; quality of basis sets, polarization functions, spin-restricted calculations, Roothaan equations.
- Spin-unrestricted calculations, plane-wave basis set.
- Pseudopotentials and PAW in conjunction with plane waves.
- Structure optimization, Hellmann–Feynman theorem.
- Simple practical applications: band structure of standard solids, metals, and semiconductors; optimization of lattice constants, cohesive energies, and other simple properties.
- Possible advanced topics: hybrid functionals, van der Waals interactions, density functional perturbation theory, phonon band structure, electron–phonon coupling, CI, CCSD methods, QMC.

Course Outcomes:

- Students will be able to understand and apply first-principles quantum mechanical methods—including Hartree–Fock and Density Functional Theory—to model electron–electron interactions, construct many-electron wavefunctions, and solve the Kohn–Sham equations using appropriate basis sets and approximations.
- Students will be able to perform and analyze computational simulations of materials, such as structure optimization, band structure calculations, and evaluation of basic solid-state properties, while gaining exposure to advanced electronic structure methods and modern extensions of DFT.

References:

1. Electronic Structure: Basic Theory and Practical Methods — Richard M. Martin
2. Electronic Structure Calculations for Solids and Molecules — Jorge Kohanoff
3. Methods of Electronic Structure Theory — Henry F. Schaefer
4. Electronic Structure and the Properties of Solids — Walter A. Harrison

08-PHYS08-619-E: Matter Out of Equilibrium (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

A. Classical problems

- Recapitulation of equilibrium:

  Boltzmann distribution, ensemble average, solution of a few model problems.
- Langevin equation:
- the physical argument, derivation from a system plus bath Hamilto- nian, dynamical solution for free and harmonically bound particles, time dependent aver- ages, distribution functions. decay of metastable states - Kramers escape.
- Fokker-Planck equations: derivation from the Langevin equation, solution for free and harmonically bound particle, the Smoluchowski equation,
- Kinetic equations: the BBGKY hierarchy, the Boltzmann equation for dilute gases, trans- port coefficients, approach to equilibrium.

B. Quantum problems:

- Recapitulation of equilibrium Green's functions and diagrammatic theory. Real time dynamics at equilibrium.
- Schwinger-Keldysh formalism: the Keldysh contour, contour ordered Green's functions, Wick's theorem, Feynman rules, diagrammatics, particles in a time dependent field.
- Interacting systems: electron-phonon and electron-electron interaction, low order pertur- bation theory, Dyson equation, skeleton diagrams, Hartree and Hartree-Fock approxima- tion.
- Examples: nonlinear electrical conduction, response to strong harmonic perturbation.

Course Outcomes:

- Acquiring knowledge about classical approaches to non-equilibrium statistical mechanics like the Langevin equation and the Fokker-Planck equations.
- Understanding kinetic equations like the Boltzmann equation and employing it to study the approach to equilibrium.
- Acquiring knowledge about the Schwinger-Keldysh approach to study real time quantum dynamics.
- Acquiring knowledge about Field-theoretic techniques to study interacting non-equilibrium quantum systems.

References:

1. Non-equilibrium statistical mechanics, R. Zwanzig
2. Handbook of stochastic methods, C. W. Gardiner
3. Quantum field theory of non-equilibrium states, J. Rammer
4. Field theory of non-equilibrium systems, A. Kamenev

08-PHYS08-615-E: Mesoscopic Physics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Basics - time, length, energy scales. Ballistic transport, Landauer- Buttiker formalism, conductance quantization.
- Diffusive transport, weak localisation, phase coherence, Aharanov- Bohm effect, general interference effects.
- Quantum dots, charging effects, Coulomb blockade.
- Landau levels and integer quantum Hall effect, edge states.
- Non-equilibrium Greens functions and Landauer-Buttiker theory.
- Quantum wires, bosonisation, 1D Luttinger liquid physics including edge physics.
- Spintronics, Datta-Das spin transistor, spin currents and its detection.
- Noise, Nyquist-Johnson noise and shot noise.
- Mesoscopic superconductivity, Josephson effect.

Course Outcomes:

- Acquiring knowledge about electronic and spin transport in various mesoscopic systems.
- Understanding the integer quantum hall and spin-hall effects.
- Understanding the theory of Luttinger liquids and the technique of Bosonisation to study one-dimensional quantum systems like quantum wires.
- Acquiring knowledge about various applications of mesoscopic systems such as spintronics and mesoscopic superconductivity.

References:

1. Electronic transport in mesoscopic systems, Supriyo Datta
2. Introduction to mesoscopic physics, Y. Imry
3. Mesoscopic phenomena in solids, edited by B. L. Altshuler, P. A. Lee and W. R. Webb
4. Quantum physics in one dimension, T. Giamarchi

08-PHYS04-625-E: Neutrino Physics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Neutrino interactions in the Standard Model at low and high energies
- Neutrino cross sections
- Neutrino oscillation in vacuum and matter, MSW effect
- Dirac and Majorana neutrinos
- UHE neutrinos, solar, atmospheric and supernova neutrinos
- Present and future neutrino experiments and their status

Course Outcomes:

- Understand neutrino interactions within the Standard Model at both low and high energies, and compute relevant neutrino cross sections.
- Analyze neutrino oscillations in vacuum and matter, including the Mikheyev–Smirnov–Wolfenstein (MSW) effect.
- Distinguish between Dirac and Majorana neutrinos and evaluate their theoretical and experimental implications.
- Interpret observations of solar, atmospheric, supernova, and ultra-high-energy neutrinos, and assess the objectives and status of current and future neutrino experiments.

References:

1. Fundamentals of Neutrino Physics and Astrophysics, by Giunti and Kim
2. Massive Neutrinos in Physics and Asrtophysics, by Mohapatra and Pal
3. Other supplementary materials: Recent papers and lectures from arXiv and other materials as decided by the instructor

08-PHYS04-603-E: Nonlinear Dynamics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Long-time behaviour of the solutions of a system of ordinary nonlinear differential equations, fixed points and their classification according to stability.
- Periodic orbit for conservative systems, periodic orbits for dissipative systems (limit cycles) and their stability, Bifurcations and centre manifolds.
- Different kinds of perturbation theory for calculating periodic orbits, Renormalisation group aided perturbation theory, Poincare Bendixon theorem, chaos and strange attractors.
- Maps, fixed points, cycles and stability, bifurcations, period doubling, intermittency and quasi periodicity, universal behavior at the onset of chaos, renormalization group and scaling behaviour.
- Partial differential equations, patterns, Galerkin truncations and reduction to dynamical systems.

Course Outcomes:

- Acquiring knowledge of long time behavior of the solutions of a system of ordinary nonlinear differential equations, fixed points and their classification according to stability.
- Acquiring knowledge of the nature of orbits for conservative and nonconservative systems.
- Understanding of maps, fixed points, cycles and stability, bifurcations.
- Basic understanding of chaos.
- Understanding of different kinds of perturbation theory for calculating orbits.

References:

1. Universality in Chaos, P. Cvitanovic
2. Chaos and Nonlinear Dynamics, R. Hilborn
3. Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering, Steven H. Strogatz
4. Nonlinear Ordinary Differential Equations, D. W. Jordan and P. Smith

08-PHYS04-623-E: Particle Physics-2 (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Review of the Standard Model (SM) and gauge theories of particle physics Higgs physics and phenomenology
- C, P, T symmetries and the CPT theorem
- Anomalies
- Topics in electroweak physics.
- Topics in collider physics
- Topics in neutrino physics
- Selected topics in physics beyond the Standard Model.

Course Outcomes:

- Develop a comprehensive understanding of the Standard Model and gauge theories, including Higgs physics and its phenomenological implications.
- Analyze discrete symmetries (C, P, T) and the CPT theorem, and understand the role of anomalies in quantum field theories.
- Apply theoretical concepts to key areas of electroweak, collider, and neutrino physics, interpreting relevant experimental observations.
- Evaluate selected extensions beyond the Standard Model and assess their theoretical motivations and phenomenological consequences.

References:

1. An Introductory Course of Particle Physics, by Palash Pal
2. Gauge Theories Of The Strong, Weak, And Electromagnetic Interactions, Chris Quigg
3. Other supplementary materials: Recent papers and lectures from arXiv and other materials as decided by the instructor

08-PHYS04-611-E: Quantum Field Theory II (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Path integrals for scalar and fermionic fields: generating functional, Feynman rules, loop diagrams.
- Renormalisation of scalar and Yukawa theories: power counting, regularisation, renormalisable and non-renormalisable theories, Green functions at 1 loop of some prototypical theories, basics of renormalisation group (running coupling), 1PI effective actions.
- Spontaneous symmetry breaking and Goldstone's theorem.
- Path integrals for the Maxwell field, gauge fixing.
- Renormalisation of QED: 1 loop diagrams, Landau pole.
- Non-abelian Gauge Theories: Classical theory of non-abelian gauge theories, Quantization of non-abelian gauge theories by path integral methods, Non-abelian gauge theories at one loop and asymptotic freedom, Spontaneous symmetry breaking in non-abelian gauge theories.

Course Outcomes:

- Understanding the Path Integral formulation of quantum field theory.
- Acquiring the knowledge of the regularisation methods and the renormalisation.
- Developing the understanding of spontaneous symmetry breaking and its implications
- Learning the non-abelian gauge theories and their quantisation.
- Learning the renormalisation of the nonabelian gauge theories both in the symmetric and symmetry broken phase

References:

1. An introduction to Quantum Field Theory, M. E. Peskin and D. V. Schroeder,
2. Quantum Field Theory, C. Itzykson and J-B Zuber,
3. Quantum Field Theory: A Modern Primer, P. Ramond.

08-PHYS04-612-E: Quantum Information and Computation II (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- General evolution and Decoherence theory.
- Master equations (Markovian and Non-Markovian, Various measure of non markovianity).
- Advanced entanglement theory (GM, GGM, newly proposed measures etc).
- Quantum Correlation beyond Entanglement (Quantum Discord, Geometric discord, Work-Deficit etc).
- Resource theory in QI (Entanglement, Quantum Coherence, Reference Frame, Asymmetry etc).
- Quantum Thermodynamics.
- Advanced topics in quantum channels.
- Quantum information and condensed matter systems.

Course Outcomes:

- Learning the concept of decoherence.
- Understanding the Markovian vs non- Markovian processes and their master equations.
- Learning about the resource theory.
- Developing the understanding of quantum thermodynamics.
- Relating the quantum information systems with the condensed matter systems.
- Acquiring the knowledge of the entanglement theory, and quantum correlations.

References:

1. The Theory of Open Quantum Systems, Heinz-Peter Breuer and Francesco Petruccione
2. Ultracold atomic gases in optical lattices: mimicking condensed matter physics and beyond, M. Lewenstein, A. Sanpera, V. Ahufinger, B. Damski, A. Sen(De), and U. Sen
3. Entanglement in many-body systems, Luigi Amico, Rosario Fazio, Andreas Osterloh, and Vlatko Vedral

08-PHYS08-620-E: Quantum Many Body Theory (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Basics: second quantisation, the many body Hilbert space, few particle problems. Green
- functions: formal definition, Lehmann representation, calculation for quadratic problems, expression of observables in terms of Green functions. Finite temperature: the imaginary time formulation, analytic continuation.
- Perturbation theory: the interaction representation, Wicks theorem, low order expansion and diagrammatic representation, Dyson equation and self-energy, vertex functions and Bethe-Salpeter equation, explicit calculations in the Anderson impurity model.
- Resummations: random phase approximation in the electron gas, ladder summation in dilute hardcore systems, Hartree-Fock and higher order conserving approximations.
- Long range order: selfonsistent calculations for broken symmetry phases, static mean field and dynamical calculations, Nambu formulation and Eliashberg theory. Goldstone modes in the ordered phase - metallic antiferromagnets and superconductivity,
- Functional integral methods: representing the partition function, bosons and fermions, quadratic integrals, Hubbard-Stratonovich decomposition of interactions, saddle point, gaus- sian fluctuations, beyond the Gaussian theory, Ginzburg-Landau expansions.

Course Outcomes:

- Acquiring knowledge about second quantisation and Green functions.
- Acquiring knowledge about many-body perturbation theory as well as resummation tech- niques like the Random Phase Approximation.
- Understanding long range order in various settings using field-theoretic methods
- Acquiring knowledge about functional integral methods such as the Hubbard-Stratonovich decomposition and employing it to study interacting quantum systems.

References:

1. Condensed Matter Field Theory by A. Altland and B. Simons
2. Quantum Many-particle Systems by J. W. Negele and H. Orland
3. Introduction to Many-Body Physics by P. Coleman
4. Many-Body Quantum Theory in Condensed Matter Physics: An Introduction by H. Bruus and K. Flensberg
5. Field Theories of Condensed Matter Physics by Eduardo Fradkin

08-PHYS04-605-E: Quantum Mechanics III (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Atomic physics:
  One electron atoms - spin-orbit interaction, fine structure, Lamb shift, Zeeman effect, Stark effect
- Two electron atoms:
  spin wave functions, approximate handling of electron-electron repulsion. Coupling of angular momenta, multiplet structure, gyromagnetic effects. Hyperfine and nuclear quadrupole interactions
- Many electron atoms:
  central field approximation, Thomas-Fermi and Hartree-Fock methods
- Molecular physics:
  Born-Oppenheimer approximation, molecular structure, rotation and vibration of diatomic molecules, hydrogen molecular ion, vibrational-rotational coupling, effect of vibration and rotation on molecular spectra. Electronic structure- molecular orbital and valence bond theories
- Atoms and light:
  transition rates, dipole approximation, Einstein coefficients, radiative damping, optical absorption, ac Stark effect
- Cold atoms:
  Doppler cooling, magneto-optical trap, ion traps, dipole force, evaporative cooling, optical lattice
- Collective effects:
  Feshbach tuning of interactions, Bose condensation of alkali atoms, BCSBEC crossover, the unitary Fermi gas. Imaging cold atoms
- Computing with atoms:
  qubits and their properties, entanglement, quantum logic gates, decoherence and error correction

Course Outcomes:

- Acquiring knowledge about second quantisation and Green functions.
- Acquiring knowledge about many-body perturbation theory as well as resummation tech- niques like the Random Phase Approximation.
- Understanding long range order in various settings using field-theoretic methods
- Acquiring knowledge about functional integral methods such as the Hubbard-Stratonovich decomposition and employing it to study interacting quantum systems.

References:

1. Physics of Atoms and Molecules, Brandon and Joachain
2. Introduction to Atomic Spectra, J. White

08-PHYS04-613-E: Quantum Optics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Outcomes:

- Learning about the coherent states, squeezed states and atom-photon interaction.
- Acquiring the knowledge of coherence and developing the quantum theory of atom-photon interaction.
- Developing the understanding of the quantum theory of dissipation.
- Understanding the quantum information in continuous variable systems.
- Learning the quantum state engineering.
- Learning about the cavity QED.

Course Details:

- Introduction: Quantization of the electromagnetic field, Fock states, coherent states, squeezed states, basic atom-photon interaction, density-matrix formalism.
- Theory of coherence; Semiclassical theory of atom-photon interaction.
- Quantum theory of atom-photon interaction.
- Quantum theory of dissipation.
- Quantum information in continuous variable systems; Quantum state engineering.
- Quantum operations based on beam splitters, mirrors, squeezing and homodyne and heterodyne measurements and nonlinear operations such as parametric down converters.
- Photon addition and subtraction operations; Elements of cavity QED.

References:

1. Quantum Optics: An Introduction, M. Fox
2. Optical Coherence and Quantum Optics, L. Mandel, E. Wolf
3. Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light, G. Grynberg, A. Aspect, C. Fabre

08-PHYS04-618-E: Radiative Transfer Phenomena in Astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- General overview of the field. The Einstein coefficient. Scattering and random walk. Rosseland and Eddington approximation, two stream approximation. Basic theory of radiation, fields
- Bremsstrahlung
- Synchrotron radiation and radio astronomy
- Compton scattering and astrophysical spectra
- General theory of radiative transition. Line broadening and its manifestation in spectra emerging from or the vicinity from astrophysical objects

Course Outcomes:

- Develop a foundational understanding of radiative processes in astrophysics, including Einstein coefficients, scattering mechanisms, random walk, and key approximations such as Rosseland, Eddington, and two-stream methods.
- Explain and derive the physical principles of major radiation mechanisms such as bremsstrahlung, synchrotron radiation, and Compton scattering, and relate them to observed astrophysical spectra.
- Analyze radiative transitions and line formation processes, including mechanisms of line broadening and their observational signatures in astrophysical environments.
- Interpret multi-wavelength astronomical observations (including radio and high-energy regimes) using theoretical models of radiation and radiative transfer.

References:

1. Radiative Processes in Astrophysics, George B. Rybicki and Alan P. Lightman
2. An Introduction to Radiative Transfer: Methods and Applications in Astrophysics, Annamaneni Peraiah

08-PHYS04-620-E: Relativistic Astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

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Course Details:

- Elements of special and general relativistic fluid dynamics and thermodynamics. Astronomical Data Analysis
- Extended body in general relativity. Rotation in general relativity
- Dynamics and thermodynamics of non-self gravitating matter in curved space-time
- Black hole astrophysics

Course Outcomes:

- Develop a conceptual and mathematical understanding of special and general relativistic fluid dynamics and thermodynamics, with applications to astrophysical systems.
- Analyze the motion and properties of extended bodies and rotational effects within the framework of general relativity.
- Apply relativistic dynamics and thermodynamics to non-self-gravitating matter evolving in curved space-time.
- Interpret key phenomena in black hole astrophysics using principles of relativistic gravity and high-energy astrophysical processes.

References:

1. Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects, StuartShapiro and Saul Tuekolsky
2. Black Hole Physics: Basic Concepts and New Developments, V. Frolov and I. Novikov
3. Gravitation: Misner, Thorne and Wheeler

08-PHYS04-614-E: Soft Matter (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Forces, energies and timescales in soft matter, van der Waals force, hydrophobic and hydrophilic interactions. Basic phenomenology of liquid crystals, polymers, membranes, colloidal systems. Phase behaviour, diffusion and flow, viscoelasticity.
- Order parameter, phase transitions: mean-field theory and phase diagrams, elasticity, stability, metastability, interfaces.
- Colloidal systems: Poisson-Boltzmann theory, DLVO theory, sheared colloids, stability of colloidal systems, measurement of interaction.
- Polymers: model systems, chain statistics, polymers in solutions and in melts, flexibility and semi-flexibility, distribution functions, self-avoidance, rubber elasticity, viscoelasticity, reptation ideas.
- Membranes: fluid vs. solid membranes, energy and elasticity, surface tension, curvature, de Gennes-Taupin length, brief introduction to shape transitions.
- Experimental tools and numerical approaches: Stokes limit, Rouse and Zimm Model for polymers, membranes, relaxation, computational studies, multiscale modelling.

Course Outcomes:

- Learning about what scales are involved in soft matter.
- Studying the phase transition using various techniques.
- Understanding the colloidal systems.
- Developing the intuition about polymers and membranes.
- Learning about the experimental methods.

References:

1. Soft Matter Physics, M. Kleman and O. D. Lavrentovich,
2. Principles of Condensed Matter Physics, P. Chaikin and T. C. Lubensky (Cambridge),
3. Soft Matter Physics, Ed, M. Daoud and C. E. Williams,

08-PHYS08-621-E: Spectroscopic Methods (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Probes for matter on different energy and spatial scales.
- Interaction of electromagnetic radiation with matter; correlation functions in classical and quantum matter, point group symmetries and selection rules.
- Electron spectroscopy in atoms and molecules: single- and many-electron atoms, simple molecules, vibronic transitions.
- Vibrational and rotational spectroscopy: infrared, Raman and microwave methods; computing the spectrum of simple atomic and molecular systems.
- Probing spin states: electron spin resonance and nuclear magnetic resonance, Mössbauer spectroscopy, spectra of magnetic ions, solid-state effects on the spectrum.
- Probe of collective effects: X-ray and neutron scattering from condensed matter, static structure and dynamical correlations, effect of phonons on lattice dynamical structure factor, dynamical magnetic structure factor from ferro- and antiferromagnetic spin waves, diffuse magnetic scattering, dynamics of classical liquids.
- Extended electronic states: angle-resolved photoemission spectroscopy, computing the spectrum for weakly correlated electron systems.
- Ultrafast dynamics: control and probe of chemical reactions via femtosecond spectroscopy.

Course Outcomes:

- Understand how different experimental probes interact with matter across energy and length scales, including electromagnetic radiation, particles, and collective excitations, and will be able to analyze electronic, vibrational, rotational, spin, and collective phenomena using appropriate spectroscopic techniques.
- Develop the ability to interpret and compute spectra from atoms, molecules, solids, and liquids, and apply modern techniques such as scattering methods, photoemission spectroscopy, and ultrafast spectroscopy to study electronic structure, magnetism, and dynamical processes in matter.

References:

1. Introduction to Spectroscopy — Donald L. Pavia, Gary M. Lampman, and George S. Kriz;
2. Molecular Spectroscopy — Jeanne L. McHale;
3. Modern Spectroscopy — J. M. Hollas;
4. Infrared and Raman Spectroscopy — P. J. Larkin.

08-PHYS08-624-E: String Theory 1 (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
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Course Details:

- Bosonic strings.
- Light cone quantization of bosonic strings.
- Introduction to two dimensional conformal field theories.
- Vertex operators.
- BRST quantization of bosonic strings.
- Tree level and one loop amplitudes in bosonic strings.
- Compactifications, Kaluza Klein and winding modes.
- T duality.
- D branes.

Course Outcomes:

- Acquiring basic knowledge of bosonic string theory.
- Learning different quantisation techniques, e.g. Lightone, covariant, BRST.
- Learning 2D conformal field theories and using them to study string world-sheet theory.
- Learning to evaluate tree and loop amplitudes in string theory.
- Learning compactification methods, duality symmetries of these compactifications, as well as studying solitonic solutions of string theory.

References:

1. A first course in string theory, B. Zwiebach
2. String theory. Vol. 1: An introduction to the bosonic string, J.Polchinski

08-PHYS04-629-E: String theory 2 (75Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Superstrings
- Quantization of superstrings
- Two dimensional superconformal theories
- Superstring amplitudes
- D branes and Ramond-Ramond fields
- Orbifolds and orientifolds
- String dualities, M theory and F Theory
- The AdS/CFT correspondence
- AdS/CFT at finite temperature
- Calabi-Yau compactifications
- Construction of semi-realistic models of particle physics

Course Outcomes:

- Develop a foundational understanding of superstring theory, including quantization, two-dimensional superconformal field theories, and the computation of string amplitudes.
- Analyze the role of D-branes, Ramond–Ramond fields, orbifolds, and orientifolds in the construction of consistent string backgrounds.
- Explain string dualities, M-theory, F-theory, and the AdS/CFT correspondence, including applications at finite temperature.
- Evaluate mechanisms of compactification (such as Calabi–Yau manifolds) and explore the construction of semi-realistic particle physics models from string theory.

References:

1. A first course in string theory, B. Zwiebach
2. String theory. Vol. 2: Superstring theory and beyond, J.Polchinski
3. Basic concepts of string theory, R. Blumenhagen, D. Lust and S.Theisen

08-PHYS04-630-E: Supersymmetry

(75Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Supersymmetry algebra
- Chiral, vector superfields and FI terms
- Superspace
- Quantum corrections in supersymmetric theories
- Theories with extended supersymmetry.
- BPS states
- Introduction to supergravity
- Phenomenological applications: the MSSM and cosmological implications.

Course Outcomes:

- Develop a clear understanding of supersymmetry algebra, superspace formulation, and the construction of chiral and vector superfields including Fayet–Iliopoulos terms.
- Analyze quantum corrections in supersymmetric theories and examine the structure of theories with extended supersymmetry and BPS states.
- Understand the basic framework of supergravity and its relation to local supersymmetry.
- Evaluate phenomenological applications of supersymmetry, including the Minimal Supersymmetric Standard Model (MSSM) and its implications for particle physics and cosmology.

References:

1. Supersymmetry and supergravity, J. Wess and J. Bagger
2. Weak scale supersymmetry: From superfields to scattering events, H. Baer and X. Tata

08-PHYS08-616-E: Topological Quantum Matter (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Berry curvature and Berry phase, two level systems.
- Landau levels and integer quantum Hall effect.
- Graphene and other Dirac materials.
- Unitary and anti-unitary symmetries, discrete symmetries, parity, inversion, time-reversal invariance and Kramers theorem.
- Basic ideas of topological invariants, winding numbers, Chern numbers, Z2 quantum numbers.
- Topological band theory and topological insulators, bulk states and surface states, toy models to realistic models.
- Bogoliubov-de Gennes formalism and topological superconductors, Kitaev model and Majorana modes.
- Weyl semimetals, surface states and Fermi arcs.

Course Outcomes:

- Acquiring knowledge about Berry phase and its application in characterising topological phenomena like the Integer quantum hall effect.
- Understanding various unitary and anti-unitary symmetries and their consequences for topological phases of matter like quantum spin-hall insulators.
- Acquiring knowledge about various topological invariants like Chern numbers and their connections to edge and surface states.
- Acquiring knowledge about recent progress in topological matter including topological superconductors, Kitaev models, and Weyl semimetals.

References:

1. Topological insulators and topological superconductors, Andrei Bernevig
2. Topological insulators : Dirac equation in condensed matter, S. Q. Shen
3. A short course on topological insulators, J. K. Asboth, L. Oroszlany, A. Palyi

08-PHYS04-615-E: Ultracold Atoms

(75Hrs)

Coordinators: Prof. Anirban Basu
anirbanbasu@hri.res.in

Course Details:

- Spatial, time, and energy scales in cold atom physics.
- Experimental background: trapping and cooling, Feshbach resonance, optical lattices, cold atom spectroscopies.
- Basic theory: many particle physics, mean field theory, phase transitions, perturbation theory.
- Continuum bosons: bosons in free space, weak interactions, Bogoliubov theory, BEC in trapped systems, Gross-Pitaevski equation.
- Continuum fermions: fermions in free space, trapped fermions, Fermi liquid theory, weak attraction - BCS instability, strong attraction - BEC of pairs, the unitary Fermi gas, Stoner instability.
- Optical lattices: Hubbard model - Bose/Fermi cases, superfluid-Mott transition for repulsive bosons, BCS-BEC crossover for attractive fermions, Mott transition in repulsive fermions.
- Spin systems: quantum, $S = 1/2$, magnetism on unfrustrated and frustrated lattices. Entanglement in many body systems: pure states, mixed states, area laws, tensor network states.
- Special topics: population imbalance, Anderson localisation, gauge fields, quench dynamics.
- The course combines elements of atomic physics with many body theory to model collective phenomena in cold atomic gases. The students would learn of the application of quantum statistical mechanics and many body theory in the context of interacting Bose and Fermi gases.

Course Outcomes:

- Learning about the coherent states, squeezed states and atom-photon interaction.
- Acquiring the knowledge of coherence and developing the quantum theory of atom-photon interaction.
- Developing the understanding of the quantum theory of dissipation.
- Understanding the quantum information in continuous variable systems.
- Learning the quantum state engineering.
- Learning about the cavity QED.

References:

1. Bose–Einstein Condensation and Superfluidity, Lev Pitaevskii, Sandro Stringari
2. Many-body physics with ultracold gases, Immanuel Bloch, Jean Dalibard, and Wilhelm Zwerger
3. Quantum information with Rydberg atoms, M. Saffman, T. G. Walker, and K. Mølmer
4. Ultracold atomic gases in optical lattices: mimicking condensed matter physics and beyond, M. Lewenstein, A. Sanpera, V. Ahufinger, B. Damski, A. Sen(De), and U. Sen