

Ph.D. in PHYSICAL SCIENCES

Programme Code: PHYS04

Programme Outcome:

- Manpower development with the ability to apply basic concepts and methods in physics to research problems.
- Training of manpower to take up research in frontier areas of physics
- Building human resource in carrying out R&D in physical and nuclear sciences
- Training of manpower in working in interdisciplinary subjects with physics as one of the subjects

Course summary matrix:

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

DETAILED COURSE STRUCTURE

First Semester				
Sr.No	Course Code	Course	Hours (T)	Credits
1	08-PHYS04-602-C	Mathematical Methods II	75	5
2	08-PHYS04-601-C	Quantum Field Theory I	75	5
3	-	Elective I	75	5
4	08-PHYS04-601-PR	Project I (year long)		10
Second Semester				
Sr.No	Course Code	Course	Hours (T)	Credits
1	08-PHYS04-603-C	Statistical Mechanics	75	5
2	08-PHYS04-604-C	Numerical Methods	75	5
3	-	Elective II	75	5
4	-	Elective III	75	5
5	08-PHYS04-601-R	Research Methodology & Research Publication Ethics	45	3
Third Semester				
Sr.No	Course Code	Course	Hours (T)	Credits
1	08-PHYS04-602-PR	Project II	75	5

2	-	Mini – Project	3
Total			56

Elective III Can be done in the Third Semester

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
Mathematical Methods II	Prof. Anirban Basu	anirbanbasu@hri.res.in
Quantum Field Theory I		
Statistical Mechanics		
Numerical Methods		
Research Methodology & Research Publication Ethics		

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	Prof. Anirban Basu	anirbanbasu@hri.res.in
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		
Dark Matter and particle astrophysics		
Disorder in Condensed Matter		
Flavour Physics and CP violation		
Fluid Mechanics		
General Relativity		
Grand Unified Theories		
Introduction to Electronic Structure		
Matter Out of Equilibrium		

Mesoscopic Physics	Prof. Anirban Basu	anirbanbasu@hri.res.in
Neutrino Physics		
Nonlinear Dynamics		
Particle Physics		
Particle Physics-2		
Quantum Field Theory II		
Quantum Information and Communication I		
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 I		
String theory 2		

Supersymmetry	Prof. Anirban Basu	anirbanbasu@hri.res.in
Topological Quantum Matter		
Ultra Cold Atoms		

CORE COURSES

08-PHYS04-602-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-PHYS04-601-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 nonrelativistic 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, Michael E. Peskin and Daniel V. Schroeder
2. Field Theory: A Modern Primer, Pierre Ramond
3. Quantum Field Theory, Claude Itzykson and Jean-Bernard Zuber

08-PHYS04-601-PR Project I

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

Course Details:

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

Course Outcomes:

- Ability to formulate a research problem
- Developing scientific skills to solve the problem
- Acquiring knowledge to interpret, discuss and communicate scientific results in written and oral form

08-PHYS04-603-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 H

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-PHYS04-604-C : Numerical Methods (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

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

Course Outcomes:

- Acquiring knowledge of Research Methodology & Research Publication Ethics including quantitative methods, communication skills, seminar presentation and review of research papers.
- Introduction to programming languages: F77, F90 or C.
- Acquiring knowledge of numerical linear algebra, interpolation techniques, generation and use of random numbers.
- Acquiring knowledge of numerical differentiation and integration (including Monte Carlo techniques).
- Acquiring knowledge of numerical methods to treat ODEs and PDEs: including FFT and finite difference methods, integral equations.

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-PHYS04-601-R : Research Methodology & Research Publication Ethics (75 Lecture Hrs)

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

Course Details:

- To be taught by HBNI

Course Outcomes:

- Acquiring knowledge of Research Methodology & Research Publication Ethics including quantitative methods, communication skills seminar presentation and review of research papers.
- Introduction to programming languages: F77, F90 or C.
- Acquiring knowledge of numerical linear algebra, interpolation techniques, generation and use of random numbers.
- Acquiring knowledge of numerical differentiation and integration (including Monte Carlo techniques).
- Acquiring knowledge of numerical methods to treat ODEs and PDEs: including FFT and finite difference methods, integral equations.

08-PHYS04-602-PR : Project II (75 Lecture Hrs)

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

Course Details:

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

Course Outcomes:

- Developing ability to read the literature and come up with research problems.
- Developing oneself conceptually and technically to tackle the problems.
- Acquiring skills to present the findings as a seminar.

Mini-project

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

LIST OF ELECTIVES

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:

- Acquiring the knowledge of the dynamics of fluid flow onto gravitating astrophysical objects, both within the Newtonian as well as the general relativistic framework.
- Acquiring the knowledge of mass transfer in massive binary systems.
- Understanding the physics and astrophysics of black holes and of active galactic nuclei.

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, Self-consistent 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 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. 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 thermodynamics 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

anirbanbasu@hri.res.in

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:

- Learning classical solutions and understanding their utility in quantum field theory.
- Understanding various non-perturbative techniques.
- Learning about quantum mechanical consistency conditions and resultant consistency conditions on quantum theories.
- Introducing supersymmetric theories and their phenomenological relevance.
- Learning thermal field theory techniques which have wide applications from black hole physics to condensed matter physics.

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:

- Acquiring the basic knowledge of data acquisition from archival sources.
- Familiarity of handling softwares useful to refine, mount, and analyze big data.
- Acquiring the expertise in understanding and analysing data as obtained from artificial satellites sent to space for the purpose of research in astrophysical sciences in general.

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 supernovae 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:

- Acquiring the knowledge of dynamics and kinematics of compressible fluid in general.
- Acquiring the knowledge of fluid dynamics under the influence of strong gravity.
- Acquiring the knowledge of turbulence and perturbation in the hydrodynamic and magnetohydrodynamic fluid flow.

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

08-PHYS04-606-E: Astrophysics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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 Inverse-Compton 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-hydrodynamics, 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, Bradley W. Carroll and Dale A. Ostlie
3. Principles of Astrophysical Fluid Dynamics, Cathie Clarke and Bob Carswell

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

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

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:

- Acquiring knowledge on different types of past, present, and future collider experiments and related observations and results.
- Acquiring knowledge of the substructure of protons and the PDF distribution of constituent partons that participate in the scattering at proton colliders.
- Acquiring knowledge of how jets are constructed and observed in detectors and related algorithms used for them.
- Acquiring knowledge of experimental results from past and present collider experiments and how they are interpreted against SM predictions.
- Acquiring knowledge of analysis techniques and statistics used in particle physics.

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:

- Acquiring the basic idea of large scale computing in general.
- Developing the ability of writing numerical codes required to solve time dependent ordinary and partial differential equations.
- To understand how one develops the computational codes to carry out numerical simulations in astrophysics in general.

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,
3. Lecture Notes 1997 Swiss Society of Astrophysics and Astronomy, (ed. O. Steiner and a. Gautschy) LeVeque, Mihalas, Dorfi and Muller

08-PHYS08-623-E:Computational Many Body Theory I (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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, mobility edge, finite size effects, resistivity and optical conductivity 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, implementation 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****anirbanbasu@hri.res.in****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 non-linear 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:

- Getting acquainted with exact diagonalization based Monte Carlo including path integral formulation and implementation for Holstein and double exchange models.
- Acquiring knowledge of molecular dynamics, Langevin scheme, Noise driven coupled linear oscillators and coupled nonlinear oscillators.
- Implementation of variational and quantum monte carlo and learning about Anderson impurity model and Ising representation.
- Understanding of density matrix renormalization group 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

08-PHYS08-623-E: Computational Materials Science (75 Lecture Hrs)**Coordinators: Prof. Anirban Basu****anirbanbasu@hri.res.in****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. Embedded 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 techniques 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

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, transmission function, S matrix and Green functions. Non-equilibrium Green functions and Landauer–Büttiker theory. Noise in charge transport, scattering theory of shot noise
- Spintronics: introduction to spintronics (Datta–Das spin transistor) equilibrium and non-equilibrium 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:

- Learning the skill to study low dimensional systems.
- Understanding theories which describe charge transport in mesoscopic systems.
- Acquiring knowledge of the electronic structure in low dimensional systems.
- Learning about the effects of phonons in metals and dielectric properties of insulators.
- Learning formalism necessary to study Quantum Hall systems, quantum wires and dots.
- Acquiring knowledge of correlated electron systems.
- Learning about the Mott transition, the Kondo systems, Superconductivity and magnetism.

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-PHYS08-617-E: Correlated Electron Systems (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Mott physics: electron localisation, 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, superconductivity 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 reentry, from density fluctuation to CMB fluctuations via Boltzmann transport equation, origin of the acoustic peak, origin of CMB polarisation, E and B modes

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

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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:

- Acquiring knowledge on the basics of cosmology, and the role of particle physics in the early universe.
- Acquiring knowledge to calculate the dark matter abundance in the universe, and learning about signatures of various kind of dark matter candidates in direct, indirect and collider experiments.
- Acquiring knowledge on the dynamical effect of dark matter on various celestial objects.
- Acquiring knowledge on dark matter model building and various portals that dictate the interactions between the Standard Model particles with the dark sector

References:

1. Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles, 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

anirbanbasu@hri.res.in

Course Details:

- Origin of disorder in condensed matter: point defects, alloys, grain boundaries and dislocations. Disorder in dielectric media. Distributions of disorder. Correlated and uncorrelated disorder
- Classical waves in a disordered medium: photons and phonons in disordered media, localisation effects
- Perturbation theory and disorder average: low order scattering and results for the single particle Green's function and the conductivity
- Quantum interference and localisation: coherent backscattering and its effects in different dimensions. The mobility edge. Anderson localisation 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: localised states and phonon assisted hopping, variable range hopping, Coulomb gap, experiments on insulators
- Electron–electron interaction in disordered systems: the Altshuler–Aronov theory. Combined 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 theory 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: Flavour Physics and CP violation (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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:

- Acquiring knowledge of the flavour structure of fermions in the Standard Model and how the mixings are parameterised in the mass basis w.r.t the gauge basis.
- Acquiring knowledge of the CKM matrix and its different parameterisations and their role in flavour physics.
- Acquiring knowledge of the physics of meson mixings and rare meson decays.
- Acquiring knowledge on the importance of CP violation in nature and signatures for them appearing in particle decays.
- Acquiring knowledge of the flavour models beyond the Standard Model and how they explain the observed flavour structure of the Standard Model.

References:

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

08-PHYS04-601-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 equation of motion
- Turbulence: stability of flows, instabilities, quasiperiodic flows, strange attractors, turbulent flows, jets, free shear layers, wakes, boundary layers
- Thermal Conduction in fluids: equation of heat transfer, conduction in incompressible fluid, law of heat transfer, convection, convective instability in static fluid
- Compressible flows
- Relativistic fluid dynamics: equation of motion, energy–momentum tensor, equation 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. Fluid Mechanics, P. K. Kundu, I. M. Cohen, and D. R. Dowling

08-PHYS04-602-E: General Relativity (75 Lecture Hrs)**Coordinators: Prof. Anirban Basu****anirbanbasu@hri.res.in****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; Maxwell’s equation in curved space–time
- Einstein’s 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; Gauss–Codacci 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:

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

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:

- Acquiring knowledge on the unification of forces within the Standard Model and its various limitations.
- Acquiring knowledge on the unification of forces in models beyond the Standard Model and the basics of model building on grand unification theories.
- Acquiring knowledge of the renormalization group equations in grand unification theories.
- Acquiring knowledge on the phenomenological consequences of grand unified theories in terrestrial and celestial experiments.
- Acquiring knowledge on the impact of grand unification theories on neutrino masses and how they impact neutrino sector observables.

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 1, June 1981, Pages 185–385)
3. Grand Unified Theories, Graham G. Ross
4. Unification and Supersymmetry, R. N. Mohapatra

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

Course Details:

- Review of QM: variational method, 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, 4–31G, 6–31G etc., quality of basis sets, polarisation functions, spin-restricted calculations, Roothaan equations
- Spin unrestricted calculations, plane wave basis set
- Pseudopotentials and PAW in conjunction with plane waves
- Structure optimisation, Hellmann–Feynman theorem
- Simple practical applications: band structure of standard solids, metals and semiconductors, optimisation 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:

- Acquiring the knowledge of the first principle computation, methods like the H-F approximation.
- Learning the Density Functional theory, and various approximations within the formulation.
- Learning the pseudo potential method and its applications.
- Application of these methods to study the band structure of various materials

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

anirbanbasu@hri.res.in

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 Hamiltonian, dynamical solution for free and harmonically bound particles, time dependent averages, 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, transport 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 perturbation theory, Dyson equation, skeleton diagrams, Hartree and Hartree–Fock approximation
- 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

anirbanbasu@hri.res.in

Course Details:

- Basics – time, length, energy scales. Ballistic transport, Landauer–Büttiker formalism, conductance quantisation
- Diffusive transport, weak localisation, phase coherence, Aharonov–Bohm effect, general interference effects
- Quantum dots, charging effects, Coulomb blockade
- Landau levels and integer quantum Hall effect, edge states
- Non-equilibrium Green’s functions and Landauer–Büttiker 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
anirbanbasu@hri.res.in

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:

- Acquiring knowledge of how neutrinos interact in the Standard Model and important scattering cross sections of the neutrinos.
- Acquiring knowledge of the phenomena of neutrino oscillations and its propagation in vacuum and matter.
- Acquiring knowledge of neutrino nature if they are Majorana or Dirac fermions, and related observations.
- Acquiring knowledge of terrestrial sources of neutrinos and how they are observed.
- Acquiring knowledge of past, present and future neutrino experiments and how the neutrino results are interpreted.

References:

1. Fundamentals of Neutrino Physics and Astrophysics, by Giunti and Kim
2. Massive Neutrinos in Physics and Astrophysics, 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

anirbanbasu@hri.res.in

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, Poincaré–Bendixson 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 behaviour 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 non-conservative systems.
- Understanding of different kinds of perturbation theory for calculating orbits.
- Understanding of maps, fixed points, cycles and stability, bifurcations.
- Basic understanding of chaos.

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-PHYS04-610-E: Particle Physics (75 Lecture Hrs)

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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 be 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 – An Introductory Course in Modern Particle Physics, Alan Martin and Francis Halzen
4. Introduction to High Energy Physics, Donald H. Perkins
5. An Introduction to Quantum Field Theory, Michael E. Peskin and Daniel V. Schroeder

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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:

- Acquiring a more comprehensive knowledge of the Standard Model and experimental results that have helped in confirming its validity.
- Acquiring detailed knowledge of the scalar sector of SM that would help study its extensions and related constraints.
- Acquiring knowledge of existing anomalies in particle physics and related experiments.
- Acquiring basic knowledge of collider physics that would help study and analyse scattering processes at accelerator experiments.
- Acquiring knowledge on models that propose solutions to shortcomings of the SM and their phenomenology.

References:

1. An Introductory Course of Particle Physics, 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

anirbanbasu@hri.res.in

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, quantisation 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, M. Srednicki
3. Quantum Field Theory, Claude Itzykson and Jean-Bernard Zuber

08-PHYS04-604-E: Quantum Information and Communication 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: no-cloning 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:

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

References:

1. Quantum Computation and Quantum Information, M. Nielsen and I. Chuang
2. Lecture Notes of John Preskill, available at <http://www.theory.caltech.edu/preskill/ph229/>
3. Quantum Theory: Concepts and Methods, A. Peres

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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 quantum information (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.
- Acquiring the knowledge of the entanglement theory, and quantum correlations.
- Learning about the resource theory.
- Developing the understanding of quantum thermodynamics.
- Relating the quantum information systems with the condensed matter systems.

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****anirbanbasu@hri.res.in****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, Wick's 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: self-consistent 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, gaussian 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 techniques 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, A. Altland and B. Simons
2. Quantum Many-particle Systems, J. W. Negele and H. Orland
3. Introduction to Many-Body Physics, P. Coleman
4. Many-Body Quantum Theory in Condensed Matter Physics: An Introduction, H. Bruus and K. Flensberg
5. Field Theories of Condensed Matter Physics, Eduardo Fradkin

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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,
- BCS–BEC 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 of the basics of atomic spectra in single electron atoms

References:

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

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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

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

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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 of astrophysical objects

Course Outcomes:

- Acquiring the knowledge of the interaction of the radiation and matter in general.
- Acquiring the knowledge of emission of electromagnetic radiation from celestial matter and its importance in understanding the spectra emitted corresponding to the flow of matter onto astrophysical objects.
- Acquiring the knowledge of various radiative processes, Bremsstrahlung, Synchrotron, and Compton scattering - for example.

References:

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

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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:

- Acquiring knowledge of relativistic fluid dynamics and thermodynamics.
- Physics of compact astrophysical objects.
- General relativistic accretion onto astrophysical black holes.

References:

1. Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects, Stuart Shapiro and Saul Teukolsky
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

anirbanbasu@hri.res.in

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. Principles of Condensed Matter Physics, P. Chaikin and T. C. Lubensky
2. Soft Matter Physics, M. Doi
3. Soft Matter Physics: An Introduction, M. Kleman and O. D. Lavrentovich

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

Coordinators: Prof. Anirban Basu

anirbanbasu@hri.res.in

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:

- Understanding the Light matter interactions based on Interaction of electromagnetic radiation with matter.
- Conceptualization of Electron spectroscopy in atoms and molecular systems.
- Understanding Vibration and rotational spectroscopy including Raman, infrared and microwave methods for computation.
- Acquiring knowledge about probing spin states and collective effects including Mossbauer spectroscopy and understanding of solid state effects on the spectrum.

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 I (75 Lecture Hrs)

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

Course Details:

- Bosonic strings
- Light cone quantization of bosonic strings
- Introduction to 2D conformal field theories
- Vertex operators
- BRST quantisation 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. Light-cone, 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 II (75 Lecture Hrs)

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:

- Acquiring basic knowledge of supersymmetric string theory and its various formulations and quantisation techniques.
- Learning 2D superconformal field theories and using them to study superstring world sheet theory.
- Learning the relationship between the solitonic solutions and open string boundary conditions, and relation to the Ramond-Ramond charges.
- Learning advanced conformal field methods to study orbifold and orientifold geometries, and their relevance to string dualities as well as exotic higher dimensional theories and their compactifications.
- Learning about a concrete field theory-gravity correspondence and its implications. In particular, application of finite temperature version of this correspondence to black hole physics

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. Lüst and S. Theisen

08-PHYS04-630-E:Supersymmetry (75 Lecture Hrs)

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

Course Details:

- Supersymmetry algebra
- Chiral and 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:

- Introducing the concept of Bose-Fermi symmetry.
- Learning supersymmetry geometrically using superspace and understanding multiplet structure both algebraically and geometrically.
- Learning supersymmetric Quantum Field Theories including extended supersymmetry and special states saturating BPS conditions.
- Learning basics of supersymmetric version of gravity as well as in terms of curved superspace.
- Developing some understanding of phenomenological applications.

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, Z_2 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. Asbóth, L. Oroszlány and A. Pályi

08-PHYS04-615-E:Ultra Cold Atoms (75 Lecture Hrs)**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–Pitaevskii 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

Course Outcomes:

- Learning about the scales involved in the system.
- Understanding the experimental background, like trapping, optical lattices, Feshbach resonance, etc.
- Using many body methods to study phase transition, perturbation theory.
- Learning about the Bose condensation and its theoretical aspects.
- Developing the understanding of the BCS instability in sermonic system.
- Studying the quantum spin systems.

References:

1. Bose–Einstein Condensation and Superfluidity, Lev Pitaevskii and 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