BS-MS SYLLABUS

Physical Sciences

I Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
BIO 101	Introduction to Biological Sciences	3	0	1	6	3
BIO 103	General Biology Laboratory I	0	3	0	0	1
CHM 101	General Chemistry	3	0	1	6	3
CHM 103	General Chemistry Laboratory	0	3	0	0	1
CDS 101	Introduction to Computers	2	1	0	6	3
HSS 103	Basics of Communication Skills	1	0	0	2	1
MTH 101	Introduction to Mathematics	3	0	1	6	3
PHY 101	Mechanics	3	0	1	6	3
PHY 103	Mathematical Methods	1	0	1	0	1
EES 101	Introduction to Earth System Sciences	3	0	1	6	3
Total		19	07	06	38	22

II Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
BIO 102	Biochemical and Cellular basis of life	3	0	1	6	3
BIO 104	General Biology Laboratory II	0	3	0	0	1
CHM 102	Basic Inorganic Chemistry	3	0	1	6	3
CHM 104	Inorganic Chemistry Laboratory I	0	3	0	0	1
HSS 104	Oral and Written Communication	1	0	0	2	1
EES 102	Introduction to Environmental Sciences	3	0	1	6	3
MTH 102	Calculus of One Variable	3	0	1	6	3
PHY 102	Electromagnetism	3	0	1	6	3
PHY 104	General Physics Laboratory I	0	3	0	0	1
Total		16	09	05	32	19

III Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
BIO 201	Introduction to Genetics and Evolution	3	0	1	6	3
BIO 203	General Biology Laboratory III	0	3	0	0	1
CHM 211	Basic Organic Chemistry	3	0	1	6	3
CHM 213	Organic Chemistry Laboratory I	0	3	0	0	1
EES 201	Foundation of Earth Sciences: Part 1 (Introduction to Mineralogy, Petrology)	3	0	1	6	3
HSS 209	Technical Writing	2	0	0	4	2
MTH 201	Linear Algebra	3	0	1	6	3
PHY 201	Waves and Introductory Optics	3	0	1	6	3
PHY 203	General Physics Laboratory II	0	3	0	0	1
Total		17	09	05	34	20

IV Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
BIO 202	Molecular Biology and Developmental Biology	3	0	1	6	3
BIO 204	General Biology Laboratory IV	0	3	0	0	1
CHM 222	Classical Thermodynamics	3	0	1	6	3
CHM 224	Physical Chemistry Laboratory I	0	3	0	0	1
EES 202	Foundation of Earth Sciences: Part 2 (Introduction to Rock Deformation and Plate Tectonics)	3	0	1	6	3
HSS 207	Macroeconomics	1	0	0	2	1
MTH 202	Multivariable Calculus	3	0	1	6	3
PHY 202	Quantum Physics	3	0	1	6	3
PHY 204	General PHY Lab III	0	3	0	0	1
CDS 202	Information for Science and Technology	2	0	0	4	2
Total		18	09	05	36	21

V Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
PHY 301	Mathematical Methods I	3	0	0	9	4
PHY 303	Quantum Mechanics I	3	0	0	9	4
PHY 305	Classical Mechanics	3	0	0	9	4
PHY 307	Physics Laboratory I	0	6	0	3	3
*** ***	Open Elective I	3				3/4
Total		**12**				**18/19**

VI Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
PHY 302	Mathematical Methods II	3	0	0	9	4
PHY 304	Quantum Mechanics II	3	0	0	9	4
PHY 306	Statistical Mechanics	3	0	0	9	4
PHY 308	Physics Laboratory II	0	6	0	9	3
*** ***	Open Elective II	3				3/4
Total		**12**				**18/19**

VII Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
PHY 401	Electrodynamics and Special Theory of Relativity	3	0	0	9	4
PHY 403	Condensed Matter Physics	3	0	0	9	4
PHY 405	Condensed Matter Physics Laboratory	0	6	0	3	3
*** ***	Open Elective III	3				3/4
*** ***	Open Elective IV	3				3/4
Total		**12**				**17/19**

VIII Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
PHY 402	Atomic and Molecular Physics	3	0	0	9	4
PHY 404	Nuclear and Particle Physics	3	0	0	9	4
PHY 406	Nuclear Laboratory	0	6	0	3	3
*** ***	Open Elective V	3				3/4
*** ***	Open Elective VI	3				3/4
Total		**12**				**17/19**

IX Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
PHY 501	Project Work					14
*** ***	Open Elective VII	3	0	0	9	4
*** ***	Open Elective VIII	3	0	0	9	4
HSS 503	Law Relating to Intellectual Property and Patents	1	0	0	2	1
Total		**7**				**23**

X Semester

Course No.	Course Name	Lec Hr	Lab Hr	Tut Hr	SS Hr	Credit
PHY 501	Project Work					14
*** ***	Open Elective IX	3	0	0	9	4
*** ***	Open Elective X	3	0	0	9	4
HSS 504	Law Relating to Intellectual Property and Patents	1	0	0	2	1
Total		**7**				**23**

BS-MS SYLLABUS , PHYSICAL SCIENCE

PHY 101: Mechanics (3)

***Learning Objectives*:**

The course will introduce foundations of Newton's laws of mechanics and its application to many particle sytems, rotational motion, non-intertial systems. The course will also introduce the theory of special relativity.

***Course Contents*:**

Kinematics and Kinetics: Introduction, Newton's laws of motion, Frames of reference,Momentum, Momentum of system of particles, Conservation laws, Center of mass, Variable mass system, Collision in laboratory and Center of mass system and Scattering.

Oscillations: Small oscillations, damped harmonic oscillation and forced oscillation, Q factor and resonance. Rigid body motion: Rigid body, Moment of inertia, Rigid body kinematics, Rigid body kinetics, Motion of gyroscope. Non Inertial Frame: Physics in the rotating coordinate system, Fictitious force. Central force and Motion of planets and satellites. Relativity:Axioms of relativity, Lorentz transformation, length contraction, time dilation, relativistic mass energy,Doppler effect.

PHY 102: Electromagnetism (3 Credit)

***Course Contents*:**

To learn basics of modern physics including basic quantum mechanics, statistical mechanics, solid state physics and nuclear physics

***Course Contents*:**

*Electrostatics:*Coulomb's Law, Gauss's law (integral and differential form) and its applications, Electric potential, Laplace's and Poisson's equations (no solutions), Energy of a charge distribution, , Boundary conditions, Conductors, The uniqueness theorem (statement only), Method of images, Field and Potential due to dipole. Multipole expansion, Polarization in a dielectric, vectors D, P and E, linear dielectrics, force on dielectrics.

Electric currents: Line, surface and volume currents and current densities, electrical conductivity and Ohm's law, equation of continuity, energy dissipation. Motion of charged particles in electric and magnetic fields

Magnetostatics: Biot-Savart and Ampere's law, divergence and curl of B, integral and differential forms of Ampere's law, vector potential, Boundary conditions, Magnetic dipoles, Multipole expansion, magnetization in materials, H, B and M, Dia-, para- and ferro-magnetism, B and H in bar-magnet.

Electrodynamics: Electromagnetic induction, motional emf and Faraday's law, inductance and energy in magnetic field, the displacement current, Maxwell's equations.

Maxwell's equations: Wave equation, plane, spherical, cylindrical and beam like solutions of the wave equation.

Electromagnetic Wave: EM wave in vacuum and dielectrics, Poynting's theorem, Reflection, transmission, refraction of EM wave

***Suggested Books*:**

- D. J. Griffiths, *Introduction to electrodynamics 3rd Ed.*
- E. M. Purcell, *Electricity and Magnetism (Berkeley Physics course) 2nd Ed.*
- R. P. Feynman, R. B. Leighton and M. Sands, *The Feynman Lecture of Physics Vol 2.*

PHY 103: Mathematical Methods (Course credit - 1)

***Learning Objectives*:**

The course will introduce different mathematical methods commonly used in Physics.

***Course Contents*:**

Introduction to coordinate systems. Cylindrical and Spherical coordinate systems: Line, surface and volume elements, Vector Algebra. Introduction to vector calculus: Gradient, Divergence and curl of Fields, Divergence theorem, Stokes Theorem, Dirac delta function. Polar Representation of Complex number (addition, multiplication and phasor diagram). Fourier analysis (periodic and non-periodic), Inverse Fourier Transformation. Elementary introduction to tensors.

***Suggested Books:*:**

- B. Arfken and H. J. Weber, Mathematical Methods for Physicists, 6th Ed.
- P. K. Chattopadhyay, Mathematical Physics.
- M. L. Boas, Mathematical Methods in Physical Sciences.
- S. D. Joglekar, Mathematical Physics: The Basics.
- A. K. Ghatak, Mathematical Method of Physics.
- H. W. Wyld, Mathematical Methods for Physics.
- F. B. Hildebrand, Methods of Applied Mathematics.
- A. W. Joshi, Elements of Group Theory for Physicist.
- S. Hassani, Mathematical Physics.
- P. Dennery and A. Krzywicki, Mathematics for Physicists.
- J. Mathews and R. L. Walker, Mathematical Methods of Physics

PHY 104: General Physics Laboratory I (1 Credit)

***Course Contents*:**

- Gyroscope
- Determination of g by bar pendulum
- Determination of g by free fall
- Moment
- Torsional Pendulum/Pohls' pendulum
- Resonance
- Youngs' Modulus

PHY 201: Waves and Introductory Optics (3 Credit)

***Learning Objectives*:**

*Waves:***:** Wave equation, superposition of waves with same and different frequency, Lissajous figures, standing waves, Travelling wave on a string, Dispersive non dispersive beats, Wave dispersion, Propagation of sound in air. Wave hitting an interface (waves on string).

BoundaryConditions: reflection and transmission at the boundary. Impedance matching at interface.Geometrical Optics: Paraxial approximation, lens aberration, Optical systems and resolving power. Prisms and cameras. Huygens and Fermat's principle of reflection and refraction,Imaging and lenses, Ray matrix approach to Gaussian optics.Interference, Young's double slit experiment, coherence, diffraction by single slit and circular aperture, polarization.

***Suggested Books*:**

- E. Hecht, *Optics, 4th Ed.*
- *F. A. Jenkins and H. E. White, Fundamentals of Optics.*
- *Ghatak, Optics.*
- *Ghatak, An introduction to modern optics.*
- *K. K. Sharma, Optics: principles and applications.*
- *G. R. Fowles, Introduction to Modern Optics.*

PHY 202: Quantum Physics (3)

***Course Contents*:**

Double-slit experiment, Frank Hertz Experiment, Stern Gerlach experiment.

Discrete spectra and Bohr model: Review of Bohr atom model, its successes and failures.

Particle properties of waves : black body radiation, photoelectric effect, Compton effect, X-ray diffraction, pair production.

Wave properties of particle: de Broglie wavelength, wave particle duality, phase and group velocities, particle/electron diffraction, particle in a box, uncertainty principle. Schrödinger equation, linearity, superposition, operators, eigenvalues and eigenfunctions of operators,expectation values, particle in a box, finite well potential, tunnelling, harmonic oscillator.

Hydrogen atom: Setup Schrödinger equation (W/o derivation) for hydrogen atom. Analyse energy states and quantum numbers (comparison with Bohr model).

***Suggested Books*:**

- Beiser, *Concept of Modern Physics.*
- H. C. Verma, *Quantum Physics.*
- R. P. Feynman, R. B. Leighton and M. Sands, *The Feynman Lecture of Physics Vol 3.*
- H. S. Mani and G. K. Mehta: *Introduction to Modern Physics.*

PHY 203: General Physics Laboratory II (1)

***Learning Objectives*:**

The course aims to complement the theoretical knowledge gathered in PHY 201 by means of experimental demonstration.

***Course Contents*:**

- Determination of magnetic field by pair of Helmholtz coil,
- Surface tension.
- Measurement of magnetic moment by a pair of Helmholtz coil.
- Newton's Ring.
- LCR Circuit.
- Charging discharging of a capacitor.
- Electromagnetic Induction.

PHY 204: General PHY Lab III (1)

***Course Contents*:**

- Refractive index of prism by spectrometer,
- Measurement of e/m
- Electron diffraction
- Polarization of light
- Balmer series
- Planck's constant
- Frank-Hertz Experiment.

PHY 301: Mathematical Methods I (4)

***Learning Objectives*:**

The main objective of the course is to equip the students with the tools of mathematics which are required in various courses of physics curriculum.

***Course Contents*:**

Vectors analysis in curvilinear coordinates, Tensor analysis (Cartesian only)

Matrices, Eigenvalues and Eigenvectors, Transformation of matrices, Diagonalization of matrices

Review of Complex variables: Multiple valued function, branch cuts and branch points, Evaluation of integrals, saddle point method, Analytic continuation, The Gamma function, Conformal mapping

Ordinary differential equations (with constant coefficients), ODE-singular points, Methods of solutions, Legendre, Bessel, Hermite and Laguire equations and their solutions

***Suggested Books*:**

- B. Arfken and H. J. Weber, *Mathematical Methods for Physicists, 6th Ed*.
- P. K. Chattopadhyay, *Mathematical Physics*.
- M. L. Boas, *Mathematical Methods in Physical Sciences*.
- S. D. Joglekar, *Mathematical Physics: The Basics*.
- A. K. Ghatak, *Mathematical Method of Physics*.
- H. W. Wyld, *Mathematical Methods for Physics*.
- F. B. Hildebrand, *Methods of Applied Mathematics*.
- A. W. Joshi, *Elements of Group Theory for Physicist*.
- S. Hassani, *Mathematical Physics*.
- P. Dennery and A. Krzywicki, *Mathematics for Physicists*.
- J. Mathews and R. L. Walker, *Mathematical Methods of Physics.*

PHY 302: Mathematical Methods II (4)

***Prerequisite**: PHY 301: Mathematical Methods I*

Sturm-Liouville theory, Orthogonal expansions

Fourier series expansion and Fourier integrals, their use in some simple problems, Fourier and Laplace transforms.

Generalized functions: Dirac delta function

Partial Differential equations, Green's functions, Solution of Laplace and Poisson's equations, Wave equation, Integral equations

Introduction to Groups Representations, Finite Groups, Permutation Groups, Continuous Groups, Lie Algebras, Representation of Unitary and rotation group.

***Suggested Books*:**

- B. Arfken and H. J. Weber, *Mathematical Methods for Physicists, 6th Ed*.
- P. K. Chattopadhyay, *Mathematical Physics*.
- M. L. Boas, *Mathematical Methods in Physical Sciences*.
- S. D. Joglekar, *Mathematical Physics: The Basics*.
- K. Ghatak, *Mathematical Method of Physics*.
- H. W. Wyld, *Mathematical Methods for Physics*.
- F. B. Hildebrand, *Methods of Applied Mathematics*.
- W. Joshi, *Elements of Group Theory for Physicist*.
- S. Hassani, *Mathematical Physics*.
- P. Dennery and A. Krzywicki, *Mathematics for Physicists*.
- J. Mathews and R. L. Walker, *Mathematical Methods of Physics.*

PHY 303: Quantum Mechanics I (4)

***Learning Objectives*:**

The course will lay down foundations of quantum mechanics via wave-particle duality, uncertainty principle and Schrodinger's equation. Operator formalism will be developed and applied to various problems in one-dimensional potential and central potential. Particularly, hydrogen atom problem and angular momentum algebra be discussed in detail.

***Course Contents*:**

Postulates of Quantum Mechanics, Schroedinger equation. Uncertainty Principle; Probability interpretation, probability current, continuity equation; Expectation values of dynamical variables. Introduction to Dirac's notation, Hermitian and Unitary operators; Eigenvalues; Simultaneous eigenstates of commuting operators, Hilbert spaces; Classical limit – Ehrenfest's theorem.

One Dimensional Problems: Harmonic Oscillator, Creation and annihilation operators; Brief descriptions of potential step, barrier and well. Ideas of tunneling, bound states, scattering states and resonances; Dirac-delta potential

*Theory of Angular Momentum:*Orbital angular momentum and eigenvalue problem; Spherical harmonics, Spin angular momentum, addition of angular momentum.

Three dimensional problems: 3D problems in Cartesian coordinates, free particle, box potential; 3D problems in spherical coordinates; central potential; free particle in spherical coordinates; bound states in three dimensions; hydrogen atom.

Charged particle in magnetic field: Gauge invariance of Schroedinger equation; Larmor frequency; Brief discussions on normal and anomalous Zeeman effect, Landau levels.

***Suggested Books*:**

- H. C. Verma, *Quantum Physics* (Surya Publn)
- R. P. Feynman, R. B. Leighton and M. Sands, *The Feynman Lecture of Physics Vol 3* (Narosa Publ.)
- J. J. Sakurai, *Modern Quantum Mechanics* (Pearson)
- B. H. Bransden and C. J. Joachain, *Quantum Mechanics* 2nd Ed (Pearson Education)
- D. J. Griffiths, *Introduction of Quantum Mechanics*, 2nd Ed. (Pearson)
- P. A. M. Dirac, The *Principles of Quantum Mechanics*. (4th Ed. Oxford Science Publications)
- C. Cohen-Tannoudji, *Quantum Mechanics, (Vol I and II)* (John Wiley and Sons)
- R. Shankar, *Principles of Quantum Mechanics*, 2nd Ed (Springer)
- A. I. M. Rae, *Quantum Mechanics*, 4th Ed. (IOP publishing)
- E. Merzbacher, *Quantum Mechanics* , 3rd Ed. (Hamilton Printing Company)
- L. D. Landau and L. M. Lifshitz, *Quantum Mechanics Non-Relativistic Theory*. 3rd Ed. (Butterworth-Heinemann)

PHY 304: Quantum Mechanics II (4)

Prerequisite: *PHY 303 Quantum Mechanics I, PHY 301 Mathematical Methods I*

Theory of Spin: Stern-Gerlach experiment; Formulation of spin ½ states; Pauli matrices; Addition of angular momentum

Approximation Methods for Stationary States: Time Independent Perturbation Theory: Formalism; Applications to relativistic corrections ('fine structure corrections') to atom (a) Relativistic K.E, (b) Spin-Orbit couplings, (c) Darwin term; WKB method: Descriptions of tunneling Variational method: Application to He atom ground state

Time Dependent Phenomena: Formalism; Fermi's Golden rule; Adiabatic approximations; Application to matter-radiation interactions; Emissions and absorptions of photons; Selection rule for electric dipole transitions; Applications to Lasers

Scattering by a Potential: Formalism; Born approximations; Partial wave analysis

Symmetries in quantum mechanics

Relativistic Quantum Mechanics: Klein Gordon Equation; Dirac Equation; Plane wave solutions; Negative energy states; Spin; Magnetic moments; Non-relativistic limit of the Dirac equation

***Suggested Books*:**

- H. C. Verma, *Quantum Physics*.
- R. P. Feynman, R. B. Leighton and M. Sands, *The Feynman Lecture of Physics Vol 3*.
- J. J. Sakurai, *Modern Quantum Mechanics*.
- B. H. Bransden and C. J. Joachain, *Quantum Mechanics*.
- D. J. Griffiths, *Introduction of Quantum Mechanics*.
- P. A. M. Dirac, The *Principles of Quantum Mechanics*.
- C. Cohen-Tannoudji, *Quantum Mechanics, (Vol I and II)*.
- R. Shankar, *Principles of Quantum Mechanics*.
- I. M. Rae, *Quantum Mechanics*.
- E. Merzbacher, *Quantum Mechanics*.
- L. D. Landau and L. M. Lifshitz, *Quantum Mechanics Non-Relativistic Theory*.

PHY 305: Classical Mechanics (4)

***Learning Objectives*:**

The course deals with the advances concepts of mechanics. It gives a good understanding of Lagrangian mechanics, conservation principles, oscillations and waves, gravitation, central force, scattering, rigid body etc. The tools learnt in this course will be extremely useful to undersnand wide branches of physics including condensed matter, high energy physics and cosmology.

***Course Contents*:**

Review of Newtonian mechanics.
Lagrangian mechanics, generalized coordinates, calculus of variations, constraints, principle of virtual work, Lagrange's equation.

Symmetry principles, Noether theorem,
Central forces, Planetary motions, Collisions, Scattering, Small oscillations, Normal modes, Forced oscillators, Anharmonic oscillators, Perturbation theory.

Rigid body dynamics, Motion of a top.
Hamilton's equations, phase space & phase trajectories, canonical trans-formations, Poisson brackets.Hamilton- Jacobi theory.

***Suggested Books*:**

- H. Goldstein, *Classical Mechanics*.
- L. D. Landau and E. M. Lifshitz, *Mechanics*.
- R. G. Takwale and P. S. Puranik, *Introduction to Classical Mechanics*.
- K. C. Gupta, *Classical Mechanics of Particles and Rigid Bodies*.
- N. C. Rana and P. S. Joag, *Classical Mechanics*.
- C. Percival and D. Richards, *Introduction to Dynamics*.
- S. H. Strogatz, *Nonlinear Dynamics and Caos*.
- R. Hilborn, *Caos and Nonlinear Dynamics*.

PHY 306: Statistical Mechanics (4)

Prerequisite: *PHY 303: Quantum Mechanics I, PHY 301: Mathematical Methods I, PHY 309: Thermal Physics*

Motivation : Why do we need statistical mechanics ? Thermodynamic description of a system. Microscopic origin of of thermodynamic results - introduction of statistical description. Introduction and definition of ensemble. Examples of ensembles.

Phase spac: Introduction and definition of phase space. Examples. Phase space density Time average and ensemble average. Equivalence between time average and ensemble average - Postulate of statistical mechanics (Ergodic hypothesis). Liouville's equation.

Equilibrium Statistical mechanics

A. Definition.
B. Micro-canonical ensemble: Definition ,Volume of phase space, Definition of entropy, Definition of temperature, Physical interpretation of temperature. Validity of statistical description. Definition of pressure,1st law of thermodynamics. Statistical interpretation of entropy. Classical ideal gas in microcanonical ensemble. Gibbs paradox.
C. Canonical ensemble: Definition, Average in canonical ensemble, Partition function Equivalence between canonical and microcanonical ensemble average. Definition of free energy. Ideal gas in canonical ensemble.
D. Grand-canonical ensemble: Definition, Grand-canonical partition function, Definition of chemical potential, Equivalence between canonical and grand-canonical average. Ideal gas in grand canonical ensemble

Quantum statistical mechanics: Pure and mixed ensemble. Examples of pure and mixed ensemble. Quantum ensemble average. Introduction of density matrix. Properties of density matrix. Examples of density matrix. Micro-canonical ensemble, Canonical ensemble and Partition function, Grand-canonical ensemble and partition function.

Three different statistics Boltzmann statistics: Partition function for ideal Boltzmann gas. Equation of state. Bose and Fermi statics/distribution

Ideal Fermi gas: Partition function. Equation of state. High temperature fermi gas. Low temperature fermi gas. Fermi energy, fermi temperature and fermi surface. Pressure of low temperature fermi gas. Zero point pressure.

Magnetization: Dia-magnetization, Paramagnetization.

Ideal Bose gas: Partition function. Equation of state. Gas of photon - Black body radiation Lattice vibration : Specific heal, Einstein and Debye's model of specific heat.

***Suggested Books*:**

- F. Reif, *Fundamentals of Statistical and Thermal Physics*.
- R.K. Pathria, *Statistical Mechanics, 2nd Ed.*
- M. Plischke and B. Bergersen, *Equilibrium Statistical Physics*.
- J. K. Bhattacharjee, *Statistical Physics: Equilibrium and Non-Equilibrium Aspects*.
- Kerson Huang, *Statistical Mechanics*.
- S-K. Ma, *Statistical Mechanics*.

- L. D. Landau and E. M. Lifshitz, *Statistical Physics*.
- R. Kubo, M. Toda and N. Hashitsume, *Statistical Physics I and II*.
- S-K. Ma, *Modern Theory of Critical Phenomena*.

PHY 307: Physics Laboratory I (3)

***Learning Objectives*:**

The laboratory course will complement the theoretical courses in terms of experimental demonstration.

***Course Contents*:**

- Franck Hertz experiment
- Planck's constant
- Cavendish experiment
- Chua's circuit
- Ferromagnetic Hysteresis
- Atomic spectra of Iodine vapor
- Inelastic electron collision
- Millikan's oil drop experiment
- Viscosity of Newtonian and non-Newtonian liquids
- Microwave based waveguide measurement.

PHY 308: Physics Laboratory II (3)

- STM
- AFM
- Raman Spectrometer
- Characteristics of He-Ne laser.
- Fiber optics
- Spectroscopy with fibers [Ocean optics*]
- Michelson Interferometer
- Fabry Parrot Interferometer
- Optical detection of weak source using a lock-in.Laser gyroscope

PHY 309: Thermal Physics (4)

***Learning Objectives*:**

The course aims to lay down foundations of thermodynamics along with introduction to phenomenon of phase transitions and critical phenomenon.

***Course Contents*:**

Kinetic theory of gases: Statistical definition of temperature, Boltzmann function, Maxwell-Boltzmann distribution, molecular distribution, molecular effusion, mean free path and collisions, transport and thermal diffusion: viscosity, thermal conductivity and diffusion, the Prandtl number.

Review of basic thermodynamics: Thermodynamic systems: hydrostatic and non-hydrostatic, first law of thermodynamics, second law of thermodynamics, Claussius theorem, thermodynamic and statistical definition of entropy, entropy of mixing (Gibbs paradox), entropy and probability, the TdS, internal energy and heat capacity equations and their applications.

Thermodynamics in action: Entropy and information theory (Shannon's entropy), Thermodynamic potential functions and their applications, Maxwell relations, Throttling/Joule-Thomson expansion, Liquefaction of gases, adiabatic demagnetization for milli/micro Kelvin temperatures, entropy of elastic rod (rubber and wire), third law of thermodynamics and its implications, chemical potential, energy maximum and entropy minimum principle, the Gibbs-Duhem relation.

Phase transitions: Claussius-clayperon equation, stability and metastability, Le Chatelier's and Le Chatelier-Baun principle, latent heat, chemical potential and phase changes, classification/order of phase transitions, order parameter, Gibbs phase rule, colligative properties, phase transitions of single and multicomponent systems, eutectic point, Landau theory of phase transitions, universality and scaling, renormalization (introduction).

Special topics: Brownian motion and fluctuations: Brownian motion, Johnson noise, fluctuations and availability.

Non-equilibrium thermodynamics: entropy production, thermoelectricity, Osnager relations, time reveral and the arrow of time.

***Suggested Books*:**

- Concepts in Thermal Physics, by Blundell and Blundell
- Heat and Thermodynamics, by Zemansky and Dittman
- An Introduction to Thermal Physics, by D.V. Schroeder
- Thermodynamics and an Introduction to Thermostatics, by H.B. Callen
- Thermodynamics, by E. Fermi

PHY 310: Waves and Optics (4)

***Learning Objectives*:**

In this course, students will be introduced to fundamental concepts of waves and classical optics with application to interference and diffraction.

***Course Contents*:**

Maxwell's equations: Wave equation, plane, spherical and cylindrical wave solutions, beam like solution

Boundary conditions: reflection and transmission at the boundary

Propagation of light in anisotropic media

Coherence: Spatial and temporal

Polarization and double refraction, quarter and half wave plates

Geometrical optics: Paraxial approximation, lens aberrations, ray matrix approach to Gaussian optics, optical systems and resolving power

Interference: Division of wavefront (Young's double slit) and amplitudes (Newton's rings, Michelson interferometer), multiwave interference-Febry-Perot interferometer, thin optical coatings (single and multilayer), interference filters

Diffraction: Huygen-Fresnel and Kirchhoff's theories Fresnel diffraction: rectangular, circular and zone plates

Fraunhoffer diffraction: Slits (single, double) and Grating and circular aperture

Introduction to metamaterials

***Suggested Books*:**

- French, *Waves and Oscillations*
- Bajaj, N.K, *The Physics of Waves and Oscillations*
- Ghatak, *Optics*
- Jenkins and White, *Fundamentals of Optics*
- Longhurst, *Geometrical and Physical Optics*

PHY 312: Numerical Methods and Programming (4)

Approximation Methods and Errors: Truncation and round-o errors. Accuracy and precision

Roots of Equations: Bracketing Methods (false position. bisection) Iteration Methods (Newton- Raphson and secant). Systems of linear algebraic equations inversion and LU decompositon methods. Gauss elimination, matrix

Curve fitting: Least squares regression. Linear, multiple linear and nonlinear regressions. Cubic spline.

Interpolation Methods: interpolating polynomials. Newton's divided diff erence and Lagr'ange

Fourier approximation: Curve fitting with oscillatory functions Frequency and time domains. Discrete Fourier and Fast Fourier transforms

Numerical differentiation and integration: Divided difference method for differentiation. Newton-Cotes formula. Trapezoidal and Simpson's rules. Romberg and Gauss quadrature methods.

Ordinary differential equations: Euler's method and its modications Runge-Kutta methods. Boundary value and Eigenvalue problems. Partial differential equations. Finite difference equations. Elliptic equations. Laplace's equation and solutions. Parabolic equations. Solution of the heat conduction equation. Finite element method: General approach. Application to 1-dimensional and 2-dimensional problems.

Programming: Case studies in the form of problems on the topics covered in the course to be introduced as programs in suitable computer languages.

***Suggested Books*:**

- Numerical Methods for Engineering, S.C. Chapra and R.C. Canale, McGraw-Hill (1989).
- Introductory Methods of Numerical Analysis, S.S. Sastry, Prentice Hall of India (1983).
- Numerical Mathematical Analysis, J.B. Scarborough, John Hopkins (1966).
- Computer Oriented Numerical Methods, V. Rajaraman, PHI Learning Private Limited (1993)
- M.K. Jain, S.R.K. Iyengar and R.K. Jain, Numerical Methods for Scientic and Engineering Computation, Wiley Eastern (1992).

PHY 315: Theory of Relativity (4)

Pre-Einstein Relativity: Inertial and non-inertial frames; Galilean relativity; Michelson-Morley experiment; Concepts of aether

Einstein's Relativity: Postulates of the special theory of relativity; Lorentz transformations; Length contraction; Time dilations; Simultaneity; Velocity addition theorem; Aberration; Doppler effect; Mass energy relation

Algebra of Lorentz Transformations: Proper time and the light cone; Intervals; Minkowski metric; Causality; Lorentz transformations as orthogonal transformations in 4 dimensions; 4-vectors and tensors; Covariance of the equations of physics; Relativistic momentum and energy; Variation of mass with velocity

Relativistic Particle Kinematics: Kinematics of decay products of an unstable particle; Centre of momentum transformation and reaction thresholds; Transformation of scattering cross section; Momenta and energies from CM to laboratory systems

Incompleteness of Special Theory of Relativity: Non-intertial reference frames; The Equivalence Principle; Gravitational red shift and time delay; Towards General Relativity

***Suggested Books*:**

- Resnick - *Special Theory of Realtivity*
- French - *Special Theory of Realtivity*
- Edwin F. Taylor and John Archibald Wheeler - *Spacetime Physics: Introduction to Special Relativity*
- Wolfgang Rindler - *Introduction to Special Relativity*
- S. Carroll - *General Relativity*
- S. Weinberg - *Gravitation and Cosmology*

PHY 337: Integrated Physics Laboratory I (4)

***Learning Objectives*:**

The laboratory course will complement the theoretical courses in terms of experimental demonstration.

***Course Contents*:**

- Franck Hertz Experiment
- Planck's constant
- Cavendish experiment
- Chua's circuit
- Ferromagnetic Hysteresis
- Atomic Spectra of Iodine Vapor
- Inelastic electron collision
- Millikan's oil drop experiment
- Viscosity of Newtonian and non-Newtonian liquids
- Microwave based waveguide measurement
- GM Counter
- Gamma Ray Spectroscopy

PHY 338: Integrated Physics Laboratory II (3)

- STM
- AFM
- Raman Spectrometer
- Characteristic of He-Ne Laser
- Fiber Optics
- Spectroscopy with fibers
- Michelson Interferometer
- Fabry-Perot Interferometer
- Optical detection of weak source using a lock-in
- Laser gyroscope
- X-ray fluorescence
- Compton Scattering

PHY 401: Electrodynamics (4)

Prerequisites: PHY 305: Classical Mechanics, PHY 301: Mathematical Methods I, PHY 302: Mathematical Methods II

***Learning Objectives*:**

Maxwell's equations will be discussed in detail with application to physical problem relating to electromagnetic fields including electromagnetic fields in the medium. Special relativity will be studied in context of Maxwell's equations, guage invariance and radiation by accelerating charged particles.

***Course Contents*:**

Boundary problems, Formal solution with Green functions, Electric fields in matter, Boundary-Value problems with dielectrics, polarizability and susceptibility, Energy density in a dielectric, Multipole expansion.

Vector potential, Magnetic fields of a localized current distribution, Magnetic moment, Force and Torque on and energy of a localized current distribution, Boundary conditions on B and H, Boundary value problems in magnetostatics, Multipole expansion.

Maxwell equations, Gauge transformations, Green functions for the wave equation, Poynting's theorem, Tranformation properties of electromagnetic fields and sources under rotations, spatial reflections, and time reversal

Plane electromagnetic waves and wave propagation, polarization, Stokes parameters, Reflection and refraction of electromagnetic waves at a plane interface between dielectrics, wave propagation in conductors and dielectrics, dispersion, complex refractive index, waveguides

Fields and radiation of a localized oscillating source, Electric dipole fields and radiation, Linear antennas.

Scattering at long wavelengths, Rayleigh scattering

Minkowski space and four vectors, concept of four-velocity, Four acceleration and higher rank tensors, Relativistic formulation of electrodynamics, Maxwell equations in covariant form, Gauge invariance and four-potential, the action principle and electromagnetic energy momentum tensor, Liénard-Weichert potentials, Radiation from an accelerated charge, Larmor formula, bremsstrahlung and synchrotron radiation, multipole radiation, dispersion theory, radiative reaction, radiative damping.

***Suggested Books*:**

- J. D. Jackson, *Classical Electrodynamics*.
- D. J. Griffiths, *Introduction to Electrodynamics*, 3rd Ed.
- L. D. Landau and E. M. Lifschitz, *Classical Theory of Fields*.
- R. P. Feynman, R. B. Leighton and M. Sands, *The Feynman Lecture of Physics* Vol 2.
- W. K. H. Panofsky and M. Philips. *Classical Electricity and Magnetism*.
- W. R. Smythe, *Static and Dynamic Electricity*.

PHY 402: Atomic and Molecular Physics (4)

Prerequisite: PHY 304: Quantum Mechanics II

Brief review of Hydrogen atom and periodic table; Significance of four quantum numbers; Concepts of atomic orbital

One Valance Electron Atom: Review of [Orbital magnetic dipole moment; Orbital, spin and total angular momenta; Spin-orbit interaction and fine structures]; Intensity of spectral lines; General selection rules; Details of Stark, Zeeman (Normal and anomalous) and Paschenbeck effects

Many Valance Electrons Atom: Two Valance Electrons Atom: Para and ortho states and the role of Pauli's Exclusion principle, He atom, Identical particles, Slater determinant; LS and JJ coupling scheme

Approximation Methods: The Hatree-Fock method; The Thomas-Fermi model of the atom

Width and shape of spectral lines; Hyperfine structure of lines; Lamb shift; Principal of ESR with experimental setup; chemical shift

Molecules: Concept of valance and bonding; Born-Oppenheimer approximation; Hydrogen molecule – Heitler-London method

Molecular orbital and electronic configuration of diatomic molecules (H_2, C_2, O_2, NO, and CN); Vibrational structure and vibrational analysis; Frank-Condon principle; Dissociation energy; Rotational spectra; Raman spectra and influence of nuclear spin

***Suggested Books*:**

- P. W. Atkins and R. S. Friedman, *Molecular Quantum Mechanics 3rd Ed*.
- W. Demtroder, *Atoms, Molecules and Photons*.
- G. W. Woodgate, *Elementary Atomic Structure*.
- H. S. Friedrich, *Theoretical Atomic Physics*.
- R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*.
- H. E. White, *Introduction to Atomic Spectra*.
- B. H. Bransden and C. J. Joachain, *Physics of Atoms and Molecules*.
- H. G. Kuhn, *Atomic Spectra*.
- F. A. Cotton, *Chemical Applications of Group Theory*.
- C. N. Banwell, *Fundamentals of Molecular Spectroscopy*.
- G. M. Barrow, *Introduction to Molecular Spectroscopy*.
- J. M. Hollas, *Modern Spectroscopy*.
- C. A. Coulson, *Valence*.

PHY 403: Condensed Matter Physics (4)

Prerequisites: PHY 306: Statistical Mechanics

***Learning Objectives*:**

The course objective is to introduce to the student the physical properties of solids including the electrical, magnetic, optical, thermal and mechanical properties. The structure, symmetry, and bonding in solids determine the properties of solids and the goal of this course is the development of student understanding of these impacts.

***Course Contents*:**

Structure of solids, Symmetry, Unit cell, Miller indices, Simple crystal structure, Diffraction of x-rays, Reciprocal lattice, Laue equations and Bragg's law, Brillouin Zones, Atomic scattering and structure factors, Defects and dislocations.

Bonding in solids, van-der Wall and Repulsive interactions, Lennard Jones potential, Cohesive energy and compressibility, Ionic crystals, Madelung potential, Covalent crystals, Metals, atomic and ionic radii.

Vibrations of one dimensional monoatomic and diatomic chain, Normal modes and Phonons,, Phonon spectrum, Long wavelength of acoustic phonons and elastic constants, specific heat capacity, Density of states, thermal expansion and conductivity, Phonons: Vibrational Properties, normal modes, acoutic and optical phonons.

The Drude theory of metals: DC electrical conductivity of a metal; Hall effect and magnetoresistance; AC electrical conductivity of a metal and propagation of electromagnetic radiation in a metal; Thermal conductivity of a metal, The Sommerfeld theory of metals: Density of states; Fermi-Dirac distribution; Specific heat, thermal, and electrical conductivity of degenerate electron gases.

Free electron theory, Kronig-Penney Model, Crystal lattices: Bravais lattices, Periodic potential, Band theory, Tight binding, Classification of metals, insulators and semiconductors, Cellular and pseudopotential methods, Symmetry of energy bands, Density of state, Fermi surface, de Hass-van Alphen effect, Motion of electron in electric and magnetic fields, Hall Effect, Quantum Hall Effect, Magnetoresistance, Superconductivity, Meissner effect, Topological Insulators

Dia-, Para-, and Ferromagnetism, origin of magnetism, Langevin's theory of paramagnetism, Weiss Molecular theory, Ferromagnetic ordering, spin waves, magnons, ferromagnetic domains.

Bose-Einstein distribution and Bose-Einstein condensation.

***Suggested Books*:**

- L. V. Azaroff, *Introduction to Solids*.
- C. Kittel, *Introduction to Solids State Physics*.
- N. W. Ashcroft and N. D. Mermin, *Solids State Physics*.
- J. Decker, *Solids State Physics*.
- O. Madelung, *Introduction to Solid State Theory*.
- P. M. Chaikin and T. C. Lubensky, *Principles of Condensed Matter Physics*.

- H. Ibach and H. Lutz, *Solid State Physics*.
- J. Weertman and J. R. Weertman, *Elementary Dislocation Theory.*
- M. J. Buerge, *Crystal Structure Analysis*.
- J. Callaway, *Quantum Theory of solid State*.

PHY 404: Nuclear and Particle Physics (4)

Prerequisites: PHY 304: Quantum Mechanics II

Properties of nucleon-nucleon interaction, general forms of N-N potential, description of low energy neutron-proton scattering to show spin dependence of nuclear force, ground state properties of deuteron, simple considerations of deuteron using central potential.

Coumpound nucleus theory, shell model potential and shell theory, liquid drop model, electromagnetic interaction in nuclei, parity and angular momentum selection rules, internal conversion, Fermi theory of Beta decay

Nucleon emission, separation energy, alpha decay and its energy spectrum, Q-value, Gamow's theory of alpha decay, Beta decay and its energy spectrum, Need for neutrinos, Q-value of Beta decay, Gamma decay, Selection rules for gamma transitions (no derivation).

Basic interactions in nature, elementary particles, quantum numbers and conservation laws, concepts of isospin, quark flavors and colors, quark model, eightfold way, mesons and baryons, bound states and resonance states.

Feynman diagrams and interactions in the standard model, CKM matrix, neutrino mixing, introduction to decay channels, branching fractions and decay times, OZI rule.

Relativistic Kinematics, Four vectors, relativistic energy-mometum conservation and collisions. Noether's theorem, symmetries and conservation laws, discrete symmetries (CPT).

Brief review of Experimental Methods: Gas Filled counters (ionization Chamber), Scintillation counter, Spark Chambers, Cerenkov detectors, Ion Sources, Synchrotron, Introduction of Modern Colliders (LHC and RHIC), Storage Ring

***Suggested Books*:**

- S. S. M. Wong, *Introductory Nuclear Physics*.
- V. Devanathan, *Nuclear Physics*.
- B. L. Cohen, *Concepts of Nuclear Physics*.
- B. B. Srivastava, *Fundamentals of Nuclear Physics*.
- H. A. Enge, *Introduction to Nuclear Physics*.

PHY 405: Condensed Matter Physics Lab (3)

***Learning Objectives*:**

The course aims to complement the theoretical knowledge gathered in PHY 403 by means of hands on experience with experiments relating to condensed matter physics.

***Course Contents*:**

- Lattice dynamics
- Abbe refractometer
- Curie Temperature
- Dielectric constant
- Thermal expansion of quartz crystal
- Hall effect
- Thin film preparation and thickness measurement
- Raman effect
- Interfacing a multimeter through GPIB
- X-ray diffraction
- Electro-optic effect (Kerr effect)
- Fabry-Perot and Mach-Zender Interferometer
- Fiber Optics (Estimation of numerical aperture, bending loss)
- Holography

PHY 406: Nuclear Laboratory (3)

- Half life and radioactive equilibrium
- Balmer series/Determination of Rydberg's constant
- GM counter.
- Gamma - Ray Spectroscopy Using NaI (Tl) detector.
- Alpha Spectroscopy with Surface Barrier Detector.
- Determination of the range and energy of alpha partcles using spark counter.
- Study of gamma ray absorption process.
- X-Ray Fluorescence.
- Neutron Activation Analysis Measurement of the Thermal Neutron Flux.
- To Study the Solid State Nuclear Track Detector.
- Fission Fragment Energy Loss Measurements from Cf252.
- Gamma - Gamma Coicidence studies.
- Compton Scattering: Energy Determination.
- Compton Scattering: Cross-Section Determination.
- Determination of energy of mu-mesons in pi-decay using Nuclear Emulsion Technique.
- Identification of particles by visual range in Nuclear Emulsion.
- Study of Rutherford Scattering.

PHY 407: Many body physics

Second quantization. Many-body models and quantum phase transitions: (a) Bose-Hubbard model and superfluid to Mott insulator transition, (b) Ising model in presence of a transverse field. Feynman path integral. Green's function at zero temperature and finite temperature (Matsubara formalism). Bose-Einstein condensation and superfluidity. Superconductivity & BCS Theory..

***References*:**

- Many-Particle Physics by *G. D. Mahan*
- Condensed Matter Field Theory by *A. Atland and B. Simons*

Prerequisites:

- PHY 301, PHY 302, PHY 303, PHY 304, PHY 306

PHY 409: Thermal Physics (4)

Kinetic theory of gases: Statistical definition of temperature, Boltzmann function, Maxwell-Boltzmann distribution, molecular distribution, molecular effusion, mean free path and collisions, transport and thermal diffusion: viscosity, thermal conductivity and diffusion, the Prandtl number.

Review of basic thermodynamics: Thermodynamic systems: hydrostatic and non-hydrostatic, first law of thermodynamics, second law of thermodynamics, Claussius theorem, thermodynamic and statistical definition of entropy, entropy of mixing (Gibbs paradox), entropy and probability, the TdS, internal energy and heat capacity equations and their applications.

Thermodynamics in action: Entropy and information theory (Shannon's entropy), Thermodynamic potential functions and their applications, Maxwell relations, Throttling/Joule-Thomson expansion, Liquefaction of gases, adiabatic demagnetization for milli/micro Kelvin temperatures, entropy of elastic rod (rubber and wire), third law of thermodynamics and its implications, chemical potential, energy maximum and entropy minimum principle, the Gibbs-Duhem relation.

Phase transitions: Claussius-clayperon equation, stability and metastability, Le Chatelier's and Le Chatelier-Baun principle, latent heat, chemical potential and phase changes, classification/order of phase transitions, order parameter, Gibbs phase rule, colligative properties, phase transitions of single and multicomponent systems, eutectic point, Landau theory of phase transitions, universality and scaling, renormalization (introduction).

Special topics: Brownian motion and fluctuations: Brownian motion, Johnson noise, fluctuations and availability.

Non-equilibrium thermodynamics: entropy production, thermoelectricity, Osnager relations, time reveral and the arrow of time.

***Suggested Books*:**

- Concepts in Thermal Physics, by Blundell and Blundell
- Heat and Thermodynamics, by Zemansky and Dittman
- An Introduction to Thermal Physics, by D.V. Schroeder
- Thermodynamics and an Introduction to Thermostatics, by H.B. Callen
- Thermodynamics, by E. Fermi

PHY 411: Nonlinear Dynamics and Chaos (4)

Prerequisites: PHY 305: Classical Mechanics, PHY 301: Mathematical Methods I

***Learning Objectives*:**

This course introduces fundamental concepts of dynamical systems, dynamical flows, non-linearity and chaos.

***Course Contents*:**

Introduction to Dynamical Systems: Overview, Examples and Discussion

One-dimensional flows: Flows on the line, Fixed points and stability, Population growth, Linear stability analysis, Saddle-node, Transcritical and Pitchfork bifurcations, Flow on the circle

Two-dimensional flows: Linear system: Definitions and examples, Phase portraits, Fixed points and linearization, Limit cycles, Poincare-Bendixson theorem, Lienard systems, Bifurcations revisited: Saddle-node, Transcritical and Pitchfork bifurcations, Hopf bifurcations, Oscillating chemical reactions, Poincare maps, Global bifurcation of cycles, Coupled Oscillators and Quasiperiodicity

Chaos: Lorenz equations: Properties of Lorenz equation, Lorenz Map; One-dimensioanl map: Fixed points, Logistic map, Liapunov exponent, Fractals: Countable and Uncountable Sets, Cantor Set, Dimension of Self-Similar Fractals, Box dimension, Pointwise and Correlation Dimensions; Strange Attractors: Baker’s map, Henon map Chaos in Hamiltonian systems

***Suggested Books*:**

- Steven H. Strogatz, *Nonlinear Dynamics and Chaos with Applications to Physics, Biology, Chemistry and Engineering*
- Edward Ott, *Chaos in dynamical systems (Cambridge University Press)*
- R. C. Hilborn, *Chaos and Nonlinear Dynamics (Cambridge Univ. Press. 1994)*
- M. Lakshmanan and S. Rajasekar, *Nonlinear dynamics: Integrability Chaos and Patterns (Springer)*

PHY 412: Computational Physics (4)

Prerequisites: *PHY 305: Classical Mechanics, PHY 306: Statistical Mechanics, Numerical Methods*

*Introduction:*Computer simulations and problems in material science, Numerical methods and programming in Fortran 90/95, A brief review of classical mechanics and statistical mechanics, Quantum mechanics as a starting point.

Monte Carlo simulations: Importance sampling and the metropolis method, basic Monte Carlo algorithm, trial moves, random number generators, estimators. Applications and hands-on sessions–solid-liquid phase-transition in the Lennard-Jones fluid and the magnetic transition in the Ising model. Advanced applications–Monte Carlo in various ensembles, Kinetic Monte Carlo, Monte Carlo methods for rigid molecules and polymers.

Molecular Dynamics: The basic idea of MD, numerical integration of equations of motion – Verlet and velocity Verlet algorithms, classical force-fields – bonded and non-bonded interactions, parameterization of force-fields. Applications and hands-on sessions – determining the diffusion constant and radial distribution functions of a Lennard-Jones fluid using an Anderson thermostat, end-to-end distance and radius of gyration of a solvated polymer using bead-spring model. Advanced applications – MD in various ensembles – thermostats and baro-stats, constrained MD.

Some Tricks of the trade: Neighbour lists, Multiple time step methods, How to handle long-range forces

Advanced techniques: Biased Monte Carlo Schemes, Rare Event, Brownian dynamics, Dissipative particle dynamics

***Suggested Books*:**

- D. Frenkel and B. Smit, *Understanding Molecular Simulations* (ed. 2)
- A. R. Leach, *Molecular Modeling*
- M. P. Allen and D. J. Tildesley, *Computer Simulation of Liquids*
- J. M. Thijssen, *Computational Physics*
- T. Pang, *An introduction to computational physics*
- V. Rajaraman, *Computer Programming in Fortran 90 and 95*

PHY 413: Introduction to Astronomy and Astrophysics (4)

Introduction: Brief overview of the universe: Solar system and beyond.

Motions in the Sky: the Celestial Sphere, Coordinate Systems, the Ecliptic, Precission of the Equinoxes, proper motion.

Brightness measurements: Flux and UVB system, apparent and absolute magnitudes. Velocity and distance measurements.

Radiative processes in astrophysics: Radiative transfer, Blackbody radiation, Einstein coefficients, Bremsstrahlung, Cylotron & Synchrotron radiation, Thomson & Compton scattering, inverse Compton scattering

Physics of stars: stellar structure and composition, evolution, compact stellar Objects

Interstellar medium: composition, radiative heating and cooling, ISM phases, HII regions

The Milky Way: Structure, kinematics, differential rotation, oort's constant

Normal galaxies: Morphological classification of galaxies, spiral and elliptical galaxies, density wave theory of spiral structure, Galactic dynamics, stellar relaxation, dynamical friction, rotation curves and dark matter, galaxy clusters, gravitational lensing

Active galaxies: active galactic nuclei, classification, unified model of AGN, quasar absorption lines

Cosmology: High redshift universe, CMBR, structure formation

***Suggested Books*:**

- Binney, J. and Tremaine, S., *Galactic Dynamics*
- L. Sparke and J. S. Gallagher, *Galaxies in the Universe: An Introduction*
- B.W.Carrol and D.A.Ostlie, *An Introduction to Modern Astrophysics*
- Rybicki, G.B. and Lightman, A.P., *Radiative Processes in Astrophysics*
- J. E. Dyson and D. A. Williams, *The physics of the interstellar medium*
- Bohm-Vitense, Erika, *Introduction to Stellar Astrophysics. vol 3 stellar structure and evolution*

PHY 414: Advanced Condensed Matter Physics (4)

Prerequisite: PHY 403: Condensed Matter Physics

Review of basic postulates of magnetism, direct and indirect exchange interaction, Zener-double exchange interactions, super-exchange interactions, ferro-, antiferro-, ferri-magnetism, spin glasses.

Oxide based modern magnetic materials: Ferrites and magnetic technology based on it, Giant magnetoresistance: Exchange in magnetic multilayers; Colossal magnetoresistance materials, charge- and orbital-ordering, phase-separation; electric, magnetic and photo control of physical properties.

Dilute magnetic semiconductors, Introduction to spin electronics and technology based on it. Thin film technology of magnetic materials.

Review of basic postulates of superconductivity, High temperature supercondtivity, Josephson junctions, SQUID magnetometer, recent advances in superconductors: MgB2, Fe-based superconductors, *etc*.

Ferroelectricity, Multiferroicity, magnetoelectricity

Introduction to nanotechnology and nanoscience: Carbon nanotubes and fullerenes.

***Suggested Books*:**

- Fundamental of Magnetism: Mathias Getzlaff
- Solids State Physics: Ashcroft and Mermin.
- Introduction to Solid State Physics: Madelung.
- Principles of Condensed Matter Physics: Chaikin and Lubensky.
- Solid State Physics – An Introduction to Theory and Experiment: Ibach and Lutz.
- Quantum Theory of solid State: Callaway.
- Introduction to Magnetic Materials: B. D. Cullity
- Magnetic Materials: Fundamentals and Device Applications : Nicola A. Spaldin

PHY 415: Quantum Field Theory-I (4)

Prerequisite: *PHY 305: Classical Mechanics, PHY 302: Mathematical Method-II, PHY 304: Quantum Mechanics-II, Special Theory of Relativity*

Classical Field Theory: Introduction; Lagrangian Field Theory; Lorentz Invariance; Noether's Theorem and Conserved Currents; Hamiltonian Field Theory.

Canonical Quantization: The Klein-Gordon Equation, The Simple Harmonic Oscillator, Free Quantum Fields, Vacuum Energy, Particles, Relativistic Normalization, Complex Scalar Fields, The Heisenberg Picture, Causality and Propagators, Applications, Non-Relativistic Field Theory

Interacting Fields: Types of Interaction, The Interaction Picture, Dyson's Formula, Scattering, Wick's Theorem, Feynman Diagrams, Feynman Rules, Amplitudes, Decays and Cross Sections, Green's Functions, Connected Diagrams and Vacuum Bubbles, Reduction Formula

The Dirac Equation: The Lorentz Group, Clifford Algebras, The Spinor Representation, The Dirac Lagrangian, Chiral Spinors, The Weyl Equation, Parity, Majorana Spinors, Symmetries and Currents, Plane Wave Solutions.

Quantizing the Dirac Field: Spin-Statistics Theorem, Fermionic Quantization, Fermi-Dirac Statistics, Propagators, Particles and Anti-Particles, Dirac's Hole Interpretation, Feynman Rules.

Quantum Electrodynamics: Gauge field, Gauge Invariance, Quantization, Inclusion of Matter - QED, Lorentz Invariant Propagators; Feynman Rules; QED Processes.

***Suggested Books*:**

- Peskin, Michael E., and Daniel V. Schroeder. An Introduction to Quantum Field Theory. Boulder, CO: Westview Press, 1995. ISBN: 9780201503975.
- Quantum Field Theory by Ryder
- Quantum Field Theory Part 1 by Steven Weinberg

PHY 416: General Theory of Relativity (4)

Review of special theory of relativity

Mathematical aspects: Tensor algebra, Transformation of coordinates, Lie derivative, covariant derivative, affine connections, Riemann tensor, Curvature tensior

Inertial frames, Gravitational mass and inertial mass, Equivalance principle: weak form, strong form, Principle of general covariance

Field equations in general relativity: Geodesic deviation, Vacuum Einstein equations.

Action formulation of GTR

Solution of Einstein equations: Tests of GTR, Black holes, Schwarzschild black hole

Penrose diagram of Schwarzschild black hole.

Cosmology: FRW Universe.

***Suggested Books*:**

- Spacetime and Geometry: An Introduction to General Relativity by Sean Carroll
- General Relativity by Robert M. Vald
- Gravity: An Introduction to Einstein;s General Relativity by James B. Hartle
- Gravitation and Cosmology: by Steven Weinberg

PHY 417: Soft Condensed Matter (4)

Introduction and Overview: What is soft condensed matter, forces, energies and timescales in soft condensed matter.

Colloids: A single colloidal particle in a liquid (Stoke's law and Brownian motion), forces between colloidal particles (Van der Waals, electrostatic double layer, stearic, depletion interaction), stability and phase behaviour of colloids (hard sphere, long ranged repulsion, weakly attractive, strongly attractive), flow in concentrated dispersions.

Polymers: Polymeric materials, freely jointed chains and its Gaussian limit, real polymer chains, excluded volume, theta temperature, viscoelastic behaviour of polymers, linear viscoelasticity, time-temperature superposition, entanglements, tube model and theory of reptation.

Liquid Crystals: Types of liquid crystals, characteristics and identification of liquid crystal phases, nematic/isotropic transition, rigidity and elastic constants of a nematic liquid crystal, boundary effects, disinclination, dislocation and other topological defects, polymer liquid crystals.

Amphiphiles: Self-assembled phases in solutions of amphiphilic molecules, spherical micelles and critical micelle concentration, cylindrical micelles, bilayers and vesicles, phase behaviour of concentrated amphiphile solutions, complex phases in surfactant solutions and microemulsions.

Biological Soft Matter: DNA (structure, condensation), proteins (structure, folding, crystallization), membranes (lipid membranes, instabilities).

Experimental Techniques in Soft Matter: Rheology (shear rheometry, microrheology), light scattering (dynamic light scattering, static light scattering), microscopy (optical microscopy, video microscopy and particle tracking).

***Suggested Books*:**

- Richard A. L. Jones, Soft Condensed Matter, Oxford University Press.
- Ian W. Hamley, Introduction to Soft Matter: Synthetic and Biological Self-Assembling Materials, John Wiley & Sons.
- Thomas A. Witten and Philip A. Pincus, Structured Fluids: Polymers, Colloids and Surfactants, Oxford University Press.

PHY 418: Numerical Methods and Programming (4)

Approximation Methods and Errors: Truncation and round-o errors. Accuracy and precision

Roots of Equations: Bracketing Methods (false position. bisection) Iteration Methods (Newton- Raphson and secant). Systems of linear algebraic equations inversion and LU decompositon methods. Gauss elimination, matrix

Curve fitting: Least squares regression. Linear, multiple linear and nonlinear regressions. Cubic spline.

Interpolation Methods: interpolating polynomials. Newton's divided diff erence and Lagr'ange

Fourier approximation: Curve fitting with oscillatory functions Frequency and time domains. Discrete Fourier and Fast Fourier transforms

Numerical differentiation and integration: Divided difference method for differentiation. Newton-Cotes formula. Trapezoidal and Simpson's rules. Romberg and Gauss quadrature methods.

Ordinary differential equations: Euler's method and its modications Runge-Kutta methods. Boundary value and Eigenvalue problems. Partial differential equations. Finite difference equations. Elliptic equations. Laplace's equation and solutions. Parabolic equations. Solution of the heat conduction equation. Finite element method: General approach. Application to 1-dimensional and 2-dimensional problems.

Programming: Case studies in the form of problems on the topics covered in the course to be introduced as programs in suitable computer languages.

***Suggested Books*:**

- Numerical Methods for Engineering, S.C. Chapra and R.C. Canale, McGraw-Hill (1989).
- Introductory Methods of Numerical Analysis, S.S. Sastry, Prentice Hall of India (1983).
- Numerical Mathematical Analysis, J.B. Scarborough, John Hopkins (1966).
- Computer Oriented Numerical Methods, V. Rajaraman, PHI Learning Private Limited (1993)
- M.K. Jain, S.R.K. Iyengar and R.K. Jain, Numerical Methods for Scientic and Engineering Computation, Wiley Eastern (1992).

PHY 419: Experimental Techniques (4)

Basics of vacuum technique: vacuum generation, gauging

Cryogenics: generation of low temperature and it measurements Structure and composition analysis by x-ray and electron diffraction based techniques: X-Ray Diffraction, Energy dispersive X-Ray (EDX), Transmission electron microscopy (TEM), X-Ray Fluorescence (XRF)

Electronic structure of Solids: X- ray and ultraviolet photoemission spectroscopy, angle resolved photo-emission spectroscopy, auger electron spectroscopy, and x-ray absorption techniques

Radiation and particle detectors: gas detectors, scintillators detectors and semiconductor detectors Thin film, polycrystalline and single crystal sample preparation techniques

Magnetometry and electrotransport : ac and dc magnetization techniques, two-probe and four probe resistivity measurements, magnetoresistance, Hall, thermal conductivity, thermopower, and heat capacity

Ultrafast spectroscopy: transient absorption, two photon absorption and terahertz spectroscopy Neutron and Muons in condensed matter

***Suggested Books*:**

- Scientific foundations of vacuum technique by Saul Dushman
- Experimental Techniques in Low-Temperature Physics by Guy White, Philip J. Meeson
- Elements of X Ray Diffraction by B. D. Cullity
- Physical Principles of Electron Microscopy: An Introduction to TEM, SEM, and AEM by R.F. Egerton
- Handbook of thin-film deposition processes and techniques: principles, methods, equipment, and applications by Klaus K. Schuegraf
- Crystal Growth Technology by Kullaiah Byrappa, Tadashi Ohac
- Photoelectron Spectroscopy by Principles and Applications Stefan Hüfner
- Introduction to Magnetic Materials by B. D. Cullity
- Terahertz Optoelectronics by Kiyomi Sakai
- X-Rays, Neutrons and Muons by Walter E. Fischer, Rudolf Morf

PHY 421: Quantum Field Theory II (4)

Prerequisite: PHY 415/615: Quantum Field Theory-I

Introduction: Why should we study “Path integral quantization”?

Review of path integral formulation of quantum mechanics

Path integral formulation of interacting scalar field theory: Correlation functions, Feynman Rules, Functional derivatives, Generating functional.

Path integral for Fermion fields: Anti commutating numbers, the Dirac propogator, Generating functional.

Path inegral for QED.

Non-abelian gauge theories and quantization: Gauge invariance, Yang-Mills action, Feynman rules, Faddeev-Popov ghost fields, BRST.

UV divergences and renormalization: explicit one loop renormalization for interacting gauge theory.

RG: calculation of beta function.

Spontaneous symmetry breaking: Goldstone boson, Higgs mechanism.

Standard model (GSW model, the Lagrangian, different gauge groups, representations and transformation of different fields, Higgs mechanism).

***Suggested Books*:**

- An introduction to QFT by Peskin and Schroeder
- Quantum Field Theory by Ryeder
- A First Book of QFT by Lahiri and Pal
- QFT: A modern Introduction by M. Kaku
- Relativistic QFT by Bjorken and Drell
- Gauge theory and elementary particle physics by Cheng & Lee
- Quarks and Leptons: An Introductory Course in Modern Particle Physics by Halzen and Martin

PHY 423: Non-adiabatic Interactions in Physics, Chemistry and Biology (4)

The Born-Oppenheimer Approach – The Time Independent Framework: (a) The Adiabatic Representation; (b) The Diabatic Representation

Mathematical Introduction: (a) The Hilbert Space and the Curl-Div Equations; (b) First Order Differential Equations along contours; (c) Abelian and non-Abelian Systems.

The Adiabatic-Diabatic Transformation (ADT). On the Single-valuedness of the newly formed Diabatic Potentials and the Quantization of the Born-Oppenheimer (BO) non-adiabatic coupling (NAC) matrix. Singularities, Poles and Seams characterizing the BO-NAC terms.

Molecular Fields as formed by Lorentz Wave-Equations.

The Jahn-Teller Model, The Renner-Teller model, the mixed Jahn-Teller/Renner-Teller model. The Privileged ADT phase and the corresponding Topological (Berry/Longuet-Higgins) phase.

The Extended Born-Oppenheimer Equation including Symmetry

The Born-Oppenheimer Approach – The Time Dependent Framework (emphasizing Field-dependent non-Adiabatic Coupling terms).

The interaction between molecular systems and electromagnetic fields: (a) The Classical treatment of the field (b) The Quantum treatment of the Field (based on Fock states).

If time allows various subjects related to Quantum Reactive Scattering Theory will be introduced. Among other things the concept of arrangement channels and decoupling of arrangement channels employing Absorbing Boundary conditions will be discussed.

***Suggested Books*:**

- M. Baer and C-Y. Ng, (eds), State-Selected and State-to-State Ion-Molecule Reaction Dynamics. Ser. Advances of Chemical Physics, Vol. 82, Part 2, John Wiley, Hoboken, N.J. (1992)
- M. Baer and G.D. Billing (eds), The Role of Degenerate States in Chemistry, Ser. Advances of Chemical Physics, Vol. 124; John Wiley, Hoboken, N.J. (2002)
- W. Domcke, D.R. Yarkony and H. Koeppel, Conical Intersections, Advances Series In Physical Chemistry Vol. 15 (World Scientific, Hong-Kong (2004).
- Farad. Discussions, Non-Adiabatic Effects in Chemical Dynamics, Vol. 127 (R.S.C.), University Oxford, (2004)
- M. Baer, Beyond Born-Oppenheimer: Electronic Nonadiabatic Coupling Terms and Conical Intersections, Wiley Interscience, Hoboken, N.J., (2006).
- G.C. Schatz and M. A. Ratner, Quantum Mechanics in Chemistry, Prentice-Hall, Englwood Cliffs (1993)
- J.D. Jackson, Classical Electrodynamics, 2nd Edition, John Wiley, New York (1975)
- J. Z. H. Zhang, Theory and Application of Quantum Molecular Dynamics, World Scientific, Hong-Kong (1999)

PHY 424: Defects in Materials (4 Credit)

***Course Content*:**

Brief introduction to perfect crystals including lattice geometry, point group, space group and crystal structures.

Defect classification in crystalline systems - Point defects in metallic ionic and covalent crystals equilibrium and non-equilibrium defects dislocations, continuum and atomistic theory, dislocations in different lattices, dislocation reactions, interaction and multiplication of dislocations, dislocation sources, glide, cross slip, climb - Stacking faults, twinning - Grain boundaries, angle and high angle boundaries, special boundaries, ledges, inter-phase boundaries.

Defect interactions - interaction between point defects and dislocations, interaction between precipitates and dislocations.

Brief overview of role of defects in controlling optical, electrical, magnetic, semiconducting and superconducting properties of materials.

Brief introduction to techniques for characterization of defects.

References:

- W.D. Kingery, H.K. Bowen and D.R. Uhlmann.: Introduction to Ceramics, 2nd ed., *John Wiley and Sons, 1976*
- A. C. Damask and G. J. Dienes: Point Defects in Metals, 1st ed., *Gordon and Breach, 1963*
- D. Hull and D. J. Bacon: Introduction to dislocations, 4th ed., *Butterworth-Heinemann, 2001*
- D.A. Porter and K.E. Easterling: Phase Transformation in Metals and Alloys, 2nd ed. *Chapman and Hall, 1992*

Prerequisites: Condensed Matter Physics, Thermodynamics

PHY 425: Quantum Information Theory (4)

Probabilities

Classical Information theory

Review of quantum mechanics

Bits to Qubits

Quantum states: mixed states, multipartite states, superposition and entanglement

Quantum measurements

Quantum dynamics, open and closed dynamics

The circuit model

Quantum entropy and quantum correlations

Elements of quantum computing

***Suggested Books*:**

- M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information
- J.Preskill, Quantum Information and Quantum Computation, Available online (Caltech)
- J. J. Sakurai, Modern quantum mechanics Addison-Wesley (1994)

PHY 426: Piezoelectric Material Fundamentals and Applications (4 Credit)

***Course Content*:**

Crystallography: General principles, Rochelle salt, alpha and beta quartz, stereographic projection.

Crystal Elasticity: Introduction, primary and secondary effects, thermodynamic potential, stress and strain, compressibility, adiabatic constants, transformation of components of stress and strain, general equations, specialization of certain groups.

Vibrations of crystals: normal modes, longitudinal vibrations, equivalent system with single degree of freedom, harmonics, various types of vibrations.

Principle of Piezoelectricity: Fundamental equations, piezoelectric classes, electrostriction, thermodynamic formulations of piezoelectric theory.

Measurements of piezoelectric effects: orientation and electrodes, compression, shear, torsion, measurements of piezoelectric constant, dynamic measurements and applications of piezoelectric materials such as sensors, actuators, motors, etc.

***References*:**

- Piezoelectricity by W. G. Cady, volume one, Dover publication, 1973
- Advanced Piezoelectric Materials: Science and Technology, Kenji Uchino, A volume in Woodhead Publishing Series in Electronic and Optical Materials, 2010
- Piezoelectric Ceramics, Bernard Jaffe, Elsevier, 2012
- Principle and applications of ferroelectrics and related materials, M.E. Lines and A. M. Glass, Oxford classic text, 2009
- Introduction to Ceramics, 2nd Edition, W. D. Kingery, H. K. Bowen, D. R. Uhlmann, Wiley
- Electroceramics: Materials, Properties, Applications, by A. J. Moulson and J. M. Herbert, Wiley

Prerequisites:Condensed Matter Physics, Thermodynamics

PHY 427: Quantum Engineerring (4)

Prerequisite: PHY 303: Quantum Mechanics-I
PHY 304: Quantum Mechanics-II

Quantum confined semiconductors –physics and devices

Introduction to semiconductors; electrons and phonons in quantum wells, quantum wires, and quantum dots. Quantum well diode lasers, inter-sub-band transitions and detectors based on them, excitons in quantum wells and self-electro-optic-effect devices, quantum dots for quantum computing.

Laser cooling and trapping of ions and their use in quantum information processing: Laser cooling, Paul ion trap, other ion traps, coherent light atom interaction, quantum computing with trapped ions.

Superconducting systems for quantum information processing, Josephson effect, Phase qubits and flux qubits, circuits, examples

***Suggested Books*:**

- P.Yeh and M.Cardona, Fundamentals of semiconductors, Springer(2008)
- DAB Miller, Quantum Mechanics for scientists and engineers Cambridge Univ Press(2008);
- Paul Harrison ,Quantum Wells, Wires and Dots: Theoretical and Computational Physics of semiconductor nanostructures, Wiley(2011),
- B.R. Nag, Physics of Quantum Well Devices, Springer(2001))
- Joachim Stolze, Dieter Suter Quantum Computing: A Short Course from Theory to Experiment, Wiley (2007)
- Henry O. Everitt,ed, Experimental Aspects of Quantum Computing Springer(2005);
- L.-M. Duan and C. Monroe, Rev. Mod. Phys. 82, 1209 (2010)
- AM Zagoskin Quantum Engineering: Theory and Design of Quantum Coherent Structures Cambridge University Press (2011)

PHY 429: Introduction to High Energy Physics (4)

Prerequisite: PHY 202: Electronics; PHY 303: Quantum Mechanics I; PHY304: Quantum Mechanics I

***Learning Objectives*:**

The objective of the course is to introduce the students to the field of high energy physics where a lot of exciting research is taking place.

***Course Contents*:**

Introduction to Particles and Interactions, Feynman Diagrams, Conservation Laws, Relativistic Kinematics of Particle Interactions, Strong Interactions, Weak Interactions, Electroweak Theory, Higgs Boson, Neutrinos.

Accelerators in High Energy Physics, Principles of Particle Radiation Detection and Measurement, Particle Detectors – Scintillation Detectors, Gas Detectors, Semiconductor Detectors.

***Suggested Books*:**

- Introduction to High Energy Physics - Donald Perkins
- Introduction to Elementary Particles - David Griffiths
- Radiation Detection and Mesurement - G. F. Knoll

PHY 431: Open quantum systems and quantum thermodynamics

Open quantum systems: Density matrix formalism. Quantum entropies: (i) Von Neumann entropy (ii) Relative entropy. Time evolution in closed and open quantum systems; Unitary dynamics; Markovian dynamics: (i) Completely positive maps, (ii) Microscopic derivations; Non-Markovian dynamics, (i) Integro-Differential Models, (ii) Time-Convolutionless Forms. Jaynes-Cummings model. The Caldeira-Leggett model Quantum thermodynamics: The laws of thermodynamics in the quantum regime. Heat and work in the quantum regime. Quantum thermal machines and the Carnot limit, (i) Stroke thermal machines, (ii) Continuous thermal machines. Quantum Maxwell demon.

***References*:**

- A. Rivas and S. F. Huelga *(2011)* Open Quantum Systems: An Introduction (Berlin: Springer).
- H. P. Breuer and F. Petruccione *(2002)* The Theory of Open Quantum Systems (Oxford: Oxford University Press).
- D. Gelbwaser-Klimovsky, W. Niedenzu and G. Kurizki, Thermodynamics of Quantum Systems Under Dynamical Control, Advances in Atomic, Molecular, and Optical Physics *64, 329 (2015)*.
- R. Kosloff and Y. Rezek, The Quantum Harmonic Otto Cycle, Entropy *(2017), 19,136.*
- R. Alicki, The quantum open system as a model of the heat engine, J. Phys. A: Math. Gen., *12, L103 (1979)*.
- F. Binder, L. A. Correa, C. Gogolin, J. Anders, and G. Adesso (eds.), Thermodynamics in the quantum regime-Recent Progress and Outlook, (Springer International Publishing), 2018.

Prerequisites:

- PHY 301, PHY 302, PHY 303, PHY 304, PHY 306

PHY 434: Advanced Statistical Mechanics (4)

***Learning Objectives*:**

This course is about theoretical understanding of the various phases of matter using statistical mechanics. Phase transitions of the first order and second order will be discussed using phenomenological model and renormalization group approach. This course will also introduce non-equilibrium statistical mechanics.

***Course Contents*:**

Revision of statistical mechanics, Thermodynamics of various ensembles, General properties of partition function, Lee-Young theorem.

Thermodynamics of phase transitions, metastable states, First and second order transitions, phenomenology of liquid-gas and paramagnetic-ferromagnetic transition, Van der Waals' equation of state critical point exponent.

Classical mean field theories, mean field theory for Ising model, Landau theory. Setting up the transfer matrix, Calculation of free energy and correlation functions, Results of Ising model in one and two dimensions.

Critical phenomena at second-order phase transitions, spatial and temporal fluctuations, scaling hypothesis, critical exponents, and universality classes. Ginzburg-Landau free-energy functional, momentum-space renormalization group.

Systems out of equilibrium, kinetic theory of a gas, approach to equilibrium and the H-theorem, Boltzmann equation and its application to transport problems. Brownian motion, Langevin equation, fluctuation-dissipation theorem, Einstein relation, Fokker-Planck equation.

***Suggested Books*:**

- K. Huang, Statistical Mechanics.
- R.K. Pathria, Statistical Mechanics.
- E.M. Lifshitz and L.P. Pitaevskii, Physical Kinetics.
- D.A. McQuarrie, Statistical Mechanics.
- L.P. Kadanoff, Statistical Physics: Statistics, Dynamics and Renormalization.
- P.M. Chaikin and T.C. Lubensky, Principles of Condensed Matter Physics.
- H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena

PHY 435: Application of Group Theory in Physics

Symmetries and group theory.
Finite and Discrete groups: Representation; Vibration modes, Selection rules, Lattice symmetries, Band structure.
Continuous groups: Lie groups and Lie algebras, Representation, Roots and Weights, Dynkin diagrams, SU(2), SO(3), SU(3).

***References*:**

- A. Zee, Group Theory in a Nutshell for Physicists
- Palash B. Pal, A Physicist's Introduction to Algebraic Structures
- P. Ramadevi and Varun Dubey, Group Theory for Physicists: With Applications
- H. Georgi, Lie Algebras in Particle Physics
- M. Hamermesh, Group Theory and its Applications to Physical Problems
- J. F. Cornwell, Group Theory in Physics, Vol. I & II
- 7. S. Mukhi and N. Mukunda, Introduction to Topology, Differential Geometry and Group Theory for Physicists

Prerequisites:

- PHY 304

PHY 436: Fundamentals of Semiconductor (3)

Pre-requisites:

Condensed matter Physics, Quantum Mechanics, Electrodynamics and Statistical mechanics

***Learning Objectives*:**

Students will learn about the following specific topics: Bandgaps, Effective masse, Electrons and holes, the Fermi function, Intrinsic carrier density, Doping and carrier concentrations, Carrier transport, Generation-recombination, Quasi-Fermi levels, Energy band diagrams

***Course Contents*:**

Introduction to semiconductors: Crystalline, polycrystalline, and amorphous semiconductors, Material properties, Crystal structure and Crystal growth, energy bands, Fundamentals of band structure, Fermi Dirac distribution, Density of states Doping: Carrier concentration (temperature dependence), Carrier scattering and mobility, Equilibrium and Non Equilibrium (addition) carrier concentrationConcepts of drift, diffusion and Recombination generation

***Suggested Books*:**

- Semiconductor Physics and Devices by Donald A. Neamen
- Advanced semiconductor fundamentals by Robert F Pierret

PHY 437: Semiconductor Device Physics (3)

Pre-requisites:

Condensed matter Physics, Quantum Mechanics, Electrodynamics, Statistical mechanics, Fundamentals of semiconductor physics

***Learning Objectives*:**

Students will learn about the following specific topics:

- PN Junction
- PN Junction IV characteristics, DC and AC response
- Compound semiconductors and bandgap tuning
- Optical properties of semiconductors
- Optoelectronic devices
- Metal semiconductor and Metal oxide semiconductor junctions
- Modern semiconductors: Perovskites, Molecular Semiconductors, 2D semiconductors

***Course Contents*:**

Introduction to carrier action-drift, diffusion, Recombination-Generation and Equations of state, PN Junction diodes, PN diode I-V characteristics, PN diode Admittance and transient response, Schottky diode,Compound semiconductors and heterojunctions, Band gap tuning, Optical properties of materials, Optoelectronic diode devices: Photodiode, Solar cell and LED Metal semiconductor and Metal oxide Semiconductor junctions Modern Semiconductors- Perovskite Optoelectronics and Molecular semiconductor optoelectronics, 2D semiconductors

***Suggested Books*:**

- Semiconductor device fundamentals by Robert F Pierret
- Physics of semiconductor devices by Simon M Sze and Kwok k Ng

PHY 438: Spintronics: Fundamentals and Applications (4)

***Prerequisites*:**Condensed matter and/or Magnetism or Magnetic Materials

***Course Contents*:**

History and overview of spin electronics; Classes of magnetic materials; The early history of spin; Quantum Mechanics of spin; The Bloch sphere; Spin-orbit Interaction.

Exchange interaction; Spin relaxation mechanisms; spin relaxation in a quantum dots; The spin Galvanic effect; Basic electron transport; Spin-dependent transport; Spin dependent tunneling; Andreev Reflection at ferromagnet and Superconductor interfaces; Spintransfer torques.

Spin-transfer drive magnetic dynamics; Current-driven switching of magnetization and domain wall motion; Domain wall scattering and Current Induced switching in ferromagnetic wires; Spin injection, spin accumulation, and spin current, Spin hall effect, Silicon based spin electronic devices.

Spin LEDs: Fundamental and applications, Spin photoelectronic devices based on Heusler alloy, Electron spin filtering, Materials for spin electronics, Nanostructures for spin electronics, Deposition techniques, micro and nanofabrication techniques.

Spin-Valve and spin-tunneling devices: Read Heads, MRAMS, Field Sensors, Spintronic Biosensors, Spin transistors, Quantum Computing with spins.

***Suggested Books*:**

- S. Bandyopadhyay, M. Cahay, Introduction to Spintronics, CRC Press, 2008.
- M. Johnson, Magnetoelectronics, Academic Press 2004.
- D. J. Sellmyer, R. Skomski, Advanced Magnetic Nanostructures, Springer, 2006.
- S. Maekawa, Concepts in Spin Electronics, Oxford University Press, 2006.
- D.D. Awschalom, R.A. Buhrman, J.M. Daughton, S.V. Molnar, and M.L. Roukes, Spin Electronics, Kluwer Academic Publishers, 2004.
- Y.B. Xu and S.M.Thompson, Spintronic Materials and Technology, Taylor& Francis, 2006.

PHY 439: Magnetic Materials Fundamentals and Applications

Magnetostatics; Introduction, Magnetic poles, Magnetic moment, Magnetic dipoles,Magnetic effects of currents,Magnetization curves and hysteresis loops.
Experimental methods: Field production, Measurement of field strength, Instruments for measuring Magnetization.
Types of magnetism: Diamagnetism and paramagnetism, Ferromagnetism, Antiferromagnetism, Ferrimagnetism.
Magnetic domains: Domain wall structure, Domain wall motion, Magnetization by rotation, Effect of plastic deformation.
Magnetic anisotropy: Anisotropy in cubic crystals, Anisotropy in hexagonal crystals, Shape anisotropy.
Nanostructured Magnetic materials: Amorphous magnets, Single domain versus multidomain behavior, Coercivity of fine particles, Superparamagnetism, Magnetic thin films.
Types of magnetic materials: Soft magnetic materials, Amorphous and nanocrystalline soft magnetic materials, Hard magnetic materials and their applications.
Magnetic materials for applications: Applications of soft and hard magnetic materials,magnetocaloric materials and systems. Magnetic data storage, spin electronics, magnonics.
Magnet-polymer composites for sensing, actuation and self-healing.

***References*:**

- Magnetism and Magnetic Materials by *J. M. D. Coey*, Cambridge University Press, *2010*, Cambridge , UK
- Introduction to Magnetic Materials by *B. D. Cullity & C.D. Graham*, 2nd ed, Wiley international, *2009*, Hoboken, NJD. Jiles,
- Introduction to magnetism and magnetic materials by Jiles, *Taylor and Francis*, CRC Press *1998*.
- Magnetism in Condensed Matter by *Stephen Blundell*, Oxford University Press *(2001).*

Prerequisites:

- Condensed matter physics, Thermal Physics, Statistical mechanics, Quantum Physics

PHY 440: Superconductivity and Quantum Liquids

Physical properties of superconductors, London theory, vortices in type-II superconductors, vortex dynamics, Bean's model, Josephson transitions, quantum interference, SQUID, Ginzburg-Landau theory, BCS theory, applications of superconductivity, introduction to different types of quantum fluids (superfluid helium and Bose-Einstein condensate).

***References*:**

- Superfluidity and superconductivity by *D.R. Tilley*, CRC Press; 1st edition, *1990.*
- Superconductivity, Superfluids and Condensates by *James F. Annett,* OUP Oxford; Illustrated edition, *2004*
- Introduction to superconductivity by *Michael Tinkham, Dover publication, 2004*.

Prerequisites:

- Condensed matter physics, Thermal Physics, Statistical mechanics, Quantum Physics, Mathematical Physics

PHY 441: Dielectric material fundamentals and applications

Course Content:

Dielectric polarization. Dielectric relaxation. Dielectric loss. Dielectric spectroscopy. Capacitors and insulators. Dielectric breakdown. Aging. Piezoelectric effect. Piezoelectric ceramics and polymers, Coupling of thermal, mechanical and electrical properties, Electrostriction, Ferroelectricity, Ferroelectric and ferroelastic domains, Applications of piezoelectric and ferroelectric materials. Selected topics in multiferroic materials, Pyroelectricity and pyroelectric materials and devices.

***Suggested Books*:**

- Dielectric phenomena in solids by Kwan Chi Kao, Elsevier academic press, 2004.
- Principle and applications of ferroelectrics and related materials, M.E. Lines and A.M. Glass, Oxford classic text, 2009.
- Principles of Electronic Ceramics, by L. L. Hench and J. K. West, Wiley
- Introduction to Ceramics, 2nd Edition, W. D. Kingery, H. K. Bowen, D. R. Uhlmann, Wiley
- Electroceramics: Materials, Properties, Applications, by A. J. Moulson and J. M.Herbert, Wiley.

Perquisites: Condensed matter physics, Thermal Physics, Statistical mechanics, Quantum Physics, Mathematical Physics

PHY 442: Physics of the strongly interacting matter produced in relativistic heavy ion collisions (4)

***Prerequisites*:**Quantum Mechanics I and II, Statistical Mechanics

***Course Contents*:**

Thermodynamics: QCD thermodynamics and phase diagram, QCD critical point; Approximating QCD medium as relativistic gas (hadrons, quarks and gluons) and its statistical and thermodynamic properties; MIT Bag model, Hagedorn gas

Relativistic Kinematics: four vectors notation, rapidity variables, pseudo-rapidity variables, light cone variables, relativistic invariants

Collision Dynamics: initial state of nuclear collisions, fluid dynamical evolution, kinetic transport model, freeze-out and particle production; Medium transport coefficients

Critical dynamics and its signature in different observables and comparison to model

A general overview of an experimental setup

 (a) Particle detection Technique
Passage of radiation through matter: Interaction of heavy charged particles, neutrons, gamma rays, and relativistic particles
 (b) Detectors in Particle Physics : Gas detectors, scintillation counters, solid state detectors

Search for QGP and relevant experimental observablesCollective flow, Heavy-flavor , Strangeness enhancement, Jet quenching, J/Ψ suppression,Light matter and antimatter production

DATA Analysis techniques (Monte-Carlo Method, Event Generators)

***Suggested Books*:**

- Hadrons and QGP by Letterssier and Rafelski.
- Introduction to High Energy Heavy Ion Collisions by C. Y. Wong.
- Phenomenology of Ultra Relativistic Heavy Ion Collisions by W Florkowski.
- Ultra relativistic heavy ion collisions by R. Vogt.
- Introduction to relativistic heavy ion collisions, by L. P. Csernai.
- A Short Course On Relativistic Heavy Ion Collision by A. K. Chaudhuri.
- Extreme states of matter in strong interaction physics by Helmut Satz.
- Relativistic Hydrodynamics by L. Rezzolla and O. Zanotti.
- Research Reports in Physics, Quark Gluon Plasma, Invited lectures of Winter School, Published by Springer Verlag, Editors - B. Sinha, S. Pal and S. Raha.
- The Physics of Quark Gluon Plasma, Introductory lectures, Lecture Notes in Physics 785, Publisher - Springer, Editor - S. Sarkar, H. Satz and B. Sinha.
- Quark Gluon Plasma - From big bang to little bang, K. Yagi, T. Hatsuda, Y. Miake, Cambridge Monograms on Particle Physics, Nuclear Physics and Cosmology.
- Quark Gluon Plasma: Theoretical Foundations, An annotated reprint collection - J. Kapusta, B. Muller and J. Rafelski, Publisher - Elsevier Science.

PHY 445: Emerging Memory Devices and Technologies

Si technology-based memory concepts: Fundamentals of MOSFET devices, dynamic random-access memory (DRAM), basic operation, integration aspects, high k dielectrics in DRAM, stability and reliability issues, Flash memory, 3-D and embedded flash memory technologies and challenges.

Future non-volatile memory concepts:

Resistive switching memory (RRAM): classification of RRAM types, resistive switching mechanisms, electrochemical metallization systems/CBRAM, valence change systems, thermochemical systems, scaling potentials and architectures, stability and reliability issues, present status and future challenges, etc.

Phase change memory (PCM): Phase change materials and thin film properties, requirements, principle of phase change memory, phase change memory devices and integration, scaling properties, stability and reliability issues, present status and future challenges, etc.

Magnetoresistive memory (MRAM): Anisotropies, Interlayer exchange coupling, giant magnetoresistance, tunnel magneto resistance, spin transfer-torque (STT-RAM), racetrack memory, spin transistor, implementation of MRAM devices, magnetic hard discs, stability and reliability issues, etc.

Ferroelectric memory (FeRAM) and ferroelectric transistor (FeFET): Basics of ferroelectric phenomena, ferroelectric materials and thin film properties, FeRAM circuit design, thin film integration, failure mechanism, future challenges.

Other emerging memory concepts such as molecular, nanowires, quantum dots and polymers based memory devices and unconventional applications of these memory devices.

***References*:**

- Nanoelectronics and Information Technology: Advanced Electronic Materials and Novel Devices by *Rainer Waser. Wiley VCH; 2nd, (2005)*
- *Y. Nishi and Magyari-Kope,* “Advances in non-volatile memory and storage technology,” Woodhead Publishing *(2019).*
- Semiconductor physics and devices, *S M Sze, Wiley VCH; 3 rd ed. (2021)*

Prerequisites:

- Quantum mechanics, Electronics and Condensed matter physics.

PHY 504: Magnetism and Superconductivity (4)

Prerequisite: PHY 304: Quantum Mechanics-II

Magnetism: Orbital and spin magnetism without interactions; Exchange interactions; Ferromagnetism, antiferromagnetism, ferrimagnetism, helical order and spin glasses; Measurement of magnetic order; Broken symmetry, Landau theory of ferromagnetism, Heisenberg and Ising model, consequences of broken symmetry, phase transitions and spin waves; Domains and the magnetization process; Itinerant magnetism of metals; Giant, colossal and tunneling magneto resistance; Nuclear magnetic resonance and technological aspects of magnetic materials.

Superconductivity: Properties of conventional (low temperature) superconductors, Meisnner-Ochsenfeld effect, perfect diamagnetism, London and Pippard equation; Type I superconductors and type II superconductors, vortex state, critical fields, interaction of vortices, magnetic properties, surface superconductivity; Ginzburg-Landau theory; BCS theory of superconductivity- electron-phonon interaction, ground state of the superconductor, spectrum of elementary excitations, tunnel effects and measurement of the energy gap; Josephson effect and the quantum interferometers; High Temperature superconductivity.

***Suggested Books*:**

- S. Blundell, Magnetism in Condensed Matter, Oxford (2001).
- J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge (2010)
- Aharoni, Introduction to the Theory of Ferromagnetism, Oxford (2001)
- M. Tinkham, Introduction to Superconductivity, McGraw-Hill (1996)
- J. F. Annett, Superconductivity, Superfluids and Condensates, Oxford (2004)
- T. P. Sheahen, Introduction to High- Temperature Superconductivity, Plenum (1994)

PHY 505: Advanced Topics in Condensed Matter Physics (4)

***Pre-requisites**: PHY 403 : Condensed Matter Physics*

***Learning Objectives*:**

This course aims to provide a blend of theoretical background with experimental observations covering the *recent trends in condensed matter physics*.

Initially, some basic concepts of condensed matter physics will be revised. This will be followed by the current trends in condensed matter physics covering special topics, such as; oxide electronics, emergent phenomena at the oxide interfaces and heterostructures. Later, novel properties of 2D materials (graphene and transition metal dichalcogenides (TMDCs)) will also be discussed.

An important goal of this course is to prepare the participants to know when to be surprised – that is - how/when do you know you have discovered a new species or something remarkably new?

***Course Contents*:**

Review of basic concepts: Free electron and tightly bound electrons, electron-electron interaction, band structure, Bloch electrons and transport phenomena, metal-insulator transition, semiconductors and dilute magnetic semiconductors, magnetism and superconductivity; phonons, quasi-particle couplings (electron-phonon, spin-phonon).

Recent trends in condensed matter physics:

(a) Oxide electronics: Novel properties of complex oxides; oxide thin films, interfaces and heterostructures; emergent phenomena at the interfaces - two dimensional electron gas, magnetism, superconductivity; experimental techniques to grow and probe interfaces / heterostructures; experimental observations and relevant theoretical models; etc.

(b) 2D materials: Graphene and TMDCs; lattice structure and band diagram; lattice vibrations, Landau levels; novel electronic, optical and magnetic properties as well as superconductivity.

***Suggested Books*:**

- Solid State Physics by Ashcroft & Mermin (Harcourt College Publishers).
- Condensed Matter Physics by Michael P. Marder (Wiley-Interscience Publications).
- Emergent phenomena at oxide interfaces, Nature Materials vol-11, pp-103, 2012 (and reference therein).
- Two-Dimensional Electron Gases at Complex Oxide Interfaces, Annual Review of Materials Research vol-44, pp-151, 2014 (and reference therein).
- Grahene-like Two-Dimensional Materials, Chemical Review vol-113, pp-3766, 2013 (and reference therein).
- Graphene vs MoS2, arXiv:1408.0437v1 (and reference therein).
- Beyond Graphene: Progress in Novel Teo-Dimensional Materials and van der Waals Solids, Annual Review of Materials Research vol-45, pp-1, 2015 (and reference therein).
- MoS2: Materials, Physics and Devices; Zhiming M. Wang (Editor), Lecture Notes in Nanoscale Science and Technology 21 (Springer, 2014).

PHY 506: Advanced Topics in Theoretical Condensed Matter Physics (4)

Prerequisite: PHY 303: Quantum Mechanics-I
PHY 304: Quantum Mechanics-II

***Learning Objectives*:**

Current trends in condensed matter physics will be discussed in this course. Some of the topics to be taught include topological insulators, topological superconductors, quantum hall effect and phase transitions.

***Course Contents*:**

Second quantization for bosons and fermions.

Lattice vibrations: waves and phonons in graphene. Different bending modes of graphene, Landau levels, oscillations of magnetization (de Haas van Alphen), diamagnetism Landau and magnetic susceptibility of electron gas in graphene.

Graphene: band structure and Dirac spectrum.

Various generalizations: bilayer graphene, edge modes in ribbons, The birth of topological insulators, Berry phase, topological indices, Topological order and the quantum spin hall effect, Addiabatìc transport.

***Suggested Books*:**

- Condensed Matter Field Theory, Altland and Simon
- Physical properties of carbon nanotubes, R. Saito

PHY 510: Cosmology (4)

Prerequisite: PHY 416: General Theory of Relativity

Brief introduction of cosmological distant scales - Astronomy and cosmology, galaxies, radio sources, Quasars, coordinate systems, Hubble expansion Brief review of general theory of relativity:

Relativity to Cosmology: Einstein field equation, luminosity distance, horizon and hubble radius, angular size redshift relation.

Relics of big-bang: radiation dominated universe, thermodynamical treatment of early universe, nucleosynthesis, cosmic microwave background addition,.

Problems with standard big-bang theory: inflationary paradigm, Formation of large scale structure of universe

Theory of Cosmic microwave background radiation

***Suggested Books*:**

- Modern Csmology, Scott Dodelson, Academic Press
- An Introduction to Modern Cosmology, J. V. Narlikar, Cambridge University Press
- Physical Cosmology, P.J.E. Peebles, Princeton Series in Physics
- Cosmological Physics , J. A Peacock, Cambridge Astrophysics
- Gravitation and cosmology: principles and applications of the general theory of relativity, Steven Weinberg, John Wiley & Sons, In

PHY 513: Introduction to Astronomy and Astrophysics (4)

Introduction: Brief overview of the universe: Solar system and beyond.

Motions in the Sky: the Celestial Sphere, Coordinate Systems, the Ecliptic, Precission of the Equinoxes, proper motion.

Brightness measurements: Flux and UVB system, apparent and absolute magnitudes. Velocity and distance measurements.

Radiative processes in astrophysics: Radiative transfer, Blackbody radiation, Einstein coefficients, Bremsstrahlung, Cylotron & Synchrotron radiation, Thomson & Compton scattering, inverse Compton scattering

Physics of stars: stellar structure and composition, evolution, compact stellar Objects

Interstellar medium: composition, radiative heating and cooling, ISM phases, HII regions

The Milky Way: Structure, kinematics, differential rotation, oort's constant

Normal galaxies: Morphological classification of galaxies, spiral and elliptical galaxies, density wave theory of spiral structure, Galactic dynamics, stellar relaxation, dynamical friction, rotation curves and dark matter, galaxy clusters, gravitational lensing

Active galaxies: active galactic nuclei, classification, unified model of AGN, quasar absorption lines

Cosmology: High redshift universe, CMBR, structure formation

***Suggested Books*:**

- Binney, J. and Tremaine, S., *Galactic Dynamics*
- L. Sparke and J. S. Gallagher, *Galaxies in the Universe: An Introduction*
- B.W.Carrol and D.A.Ostlie, *An Introduction to Modern Astrophysics*
- Rybicki, G.B. and Lightman, A.P., *Radiative Processes in Astrophysics*
- J. E. Dyson and D. A. Williams, *The physics of the interstellar medium*
- Bohm-Vitense, Erika, *Introduction to Stellar Astrophysics. vol 3 stellar structure and evolution*

PHY 519: Experimental Techniques (4)

Basics of vacuum technique: vacuum generation, gauging

Cryogenics: generation of low temperature and it measurements Structure and composition analysis by x-ray and electron diffraction based techniques: X-Ray Diffraction, Energy dispersive X-Ray (EDX), Transmission electron microscopy (TEM), X-Ray Fluorescence (XRF)

Electronic structure of Solids: X- ray and ultraviolet photoemission spectroscopy, angle resolved photo-emission spectroscopy, auger electron spectroscopy, and x-ray absorption techniques

Radiation and particle detectors: gas detectors, scintillators detectors and semiconductor detectors Thin film, polycrystalline and single crystal sample preparation techniques

Magnetometry and electrotransport : ac and dc magnetization techniques, two-probe and four probe resistivity measurements, magnetoresistance, Hall, thermal conductivity, thermopower, and heat capacity

Ultrafast spectroscopy: transient absorption, two photon absorption and terahertz spectroscopy Neutron and Muons in condensed matter

***Suggested Books*:**

- Scientific foundations of vacuum technique by Saul Dushman
- Experimental Techniques in Low-Temperature Physics by Guy White, Philip J. Meeson
- Elements of X Ray Diffraction by B. D. Cullity
- Physical Principles of Electron Microscopy: An Introduction to TEM, SEM, and AEM by R.F. Egerton
- Handbook of thin-film deposition processes and techniques: principles, methods, equipment, and applications by Klaus K. Schuegraf
- Crystal Growth Technology by Kullaiah Byrappa, Tadashi Ohac
- Photoelectron Spectroscopy by Principles and Applications Stefan Hüfner
- Introduction to Magnetic Materials by B. D. Cullity
- Terahertz Optoelectronics by Kiyomi Sakai
- X-Rays, Neutrons and Muons by Walter E. Fischer, Rudolf Morf

PHY 523: Non-adiabatic Interactions in Physics, Chemistry and Biology (4)

The Born-Oppenheimer Approach – The Time Independent Framework: (a) The Adiabatic Representation; (b) The Diabatic Representation

Mathematical Introduction: (a) The Hilbert Space and the Curl-Div Equations; (b) First Order Differential Equations along contours; (c) Abelian and non-Abelian Systems.

The Adiabatic-Diabatic Transformation (ADT). On the Single-valuedness of the newly formed Diabatic Potentials and the Quantization of the Born-Oppenheimer (BO) non-adiabatic coupling (NAC) matrix. Singularities, Poles and Seams characterizing the BO-NAC terms.

Molecular Fields as formed by Lorentz Wave-Equations.

The Jahn-Teller Model, The Renner-Teller model, the mixed Jahn-Teller/Renner-Teller model. The Privileged ADT phase and the corresponding Topological (Berry/Longuet-Higgins) phase.

The Extended Born-Oppenheimer Equation including Symmetry

The Born-Oppenheimer Approach – The Time Dependent Framework (emphasizing Field-dependent non-Adiabatic Coupling terms).

The interaction between molecular systems and electromagnetic fields: (a) The Classical treatment of the field (b) The Quantum treatment of the Field (based on Fock states).

If time allows various subjects related to Quantum Reactive Scattering Theory will be introduced. Among other things the concept of arrangement channels and decoupling of arrangement channels employing Absorbing Boundary conditions will be discussed.

***Suggested Books*:**

- M. Baer and C-Y. Ng, (eds), State-Selected and State-to-State Ion-Molecule Reaction Dynamics. Ser. Advances of Chemical Physics, Vol. 82, Part 2, John Wiley, Hoboken, N.J. (1992)
- M. Baer and G.D. Billing (eds), The Role of Degenerate States in Chemistry, Ser. Advances of Chemical Physics, Vol. 124; John Wiley, Hoboken, N.J. (2002)
- W. Domcke, D.R. Yarkony and H. Koeppel, Conical Intersections, Advances Series In Physical Chemistry Vol. 15 (World Scientific, Hong-Kong (2004).
- Farad. Discussions, Non-Adiabatic Effects in Chemical Dynamics, Vol. 127 (R.S.C.), University Oxford, (2004)
- M. Baer, Beyond Born-Oppenheimer: Electronic Nonadiabatic Coupling Terms and Conical Intersections, Wiley Interscience, Hoboken, N.J., (2006).
- G.C. Schatz and M. A. Ratner, Quantum Mechanics in Chemistry, Prentice-Hall, Englwood Cliffs (1993)
- J.D. Jackson, Classical Electrodynamics, 2nd Edition, John Wiley, New York (1975)
- J. Z. H. Zhang, Theory and Application of Quantum Molecular Dynamics, World Scientific, Hong-Kong (1999)

PHY 524: Defects in Materials (4 Credit)

***Course Content*:**

Brief introduction to perfect crystals including lattice geometry, point group, space group and crystal structures.

Defect classification in crystalline systems - Point defects in metallic ionic and covalent crystals equilibrium and non-equilibrium defects dislocations, continuum and atomistic theory, dislocations in different lattices, dislocation reactions, interaction and multiplication of dislocations, dislocation sources, glide, cross slip, climb - Stacking faults, twinning - Grain boundaries, angle and high angle boundaries, special boundaries, ledges, inter-phase boundaries.

Defect interactions - interaction between point defects and dislocations, interaction between precipitates and dislocations.

Brief overview of role of defects in controlling optical, electrical, magnetic, semiconducting and superconducting properties of materials.

Brief introduction to techniques for characterization of defects.

***References*:**

- W.D. Kingery, H.K. Bowen and D.R. Uhlmann.: Introduction to Ceramics, 2nd ed., *John Wiley and Sons, 1976*
- A. C. Damask and G. J. Dienes: Point Defects in Metals, 1st ed., *Gordon and Breach, 1963*
- D. Hull and D. J. Bacon: Introduction to dislocations, 4th ed., *Butterworth-Heinemann, 2001*
- D.A. Porter and K.E. Easterling: Phase Transformation in Metals and Alloys, 2nd ed. *Chapman and Hall, 1992*

Prerequisites: Condensed Matter Physics, Thermodynamics

PHY 526: Piezoelectric Material Fundamentals and Applications (4 Credit)

***Course Content*:**

Crystallography: General principles, Rochelle salt, alpha and beta quartz, stereographic projection.

Crystal Elasticity: Introduction, primary and secondary effects, thermodynamic potential, stress and strain, compressibility, adiabatic constants, transformation of components of stress and strain, general equations, specialization of certain groups.

Vibrations of crystals: normal modes, longitudinal vibrations, equivalent system with single degree of freedom, harmonics, various types of vibrations.

Principle of Piezoelectricity: Fundamental equations, piezoelectric classes, electrostriction, thermodynamic formulations of piezoelectric theory.

Measurements of piezoelectric effects: orientation and electrodes, compression, shear, torsion, measurements of piezoelectric constant, dynamic measurements and applications of piezoelectric materials such as sensors, actuators, motors, etc.

***References*:**

- Piezoelectricity by W. G. Cady, volume one, Dover publication, 1973
- Advanced Piezoelectric Materials: Science and Technology, Kenji Uchino, A volume in Woodhead Publishing Series in Electronic and Optical Materials, 2010
- Piezoelectric Ceramics, Bernard Jaffe, Elsevier, 2012
- Principle and applications of ferroelectrics and related materials, M.E. Lines and A. M. Glass, Oxford classic text, 2009
- Introduction to Ceramics, 2nd Edition, W. D. Kingery, H. K. Bowen, D. R. Uhlmann, Wiley
- Electroceramics: Materials, Properties, Applications, by A. J. Moulson and J. M. Herbert, Wiley

Prerequisites:Condensed Matter Physics, Thermodynamics

PHY 527: Quantum Engineerring (4)

Prerequisite: PHY 303: Quantum Mechanics-I
PHY 304: Quantum Mechanics-II

Quantum confined semiconductors –physics and devices

Introduction to semiconductors; electrons and phonons in quantum wells, quantum wires, and quantum dots. Quantum well diode lasers, inter-sub-band transitions and detectors based on them, excitons in quantum wells and self-electro-optic-effect devices, quantum dots for quantum computing.

Laser cooling and trapping of ions and their use in quantum information processing: Laser cooling, Paul ion trap, other ion traps, coherent light atom interaction, quantum computing with trapped ions.

Superconducting systems for quantum information processing, Josephson effect, Phase qubits and flux qubits, circuits, examples

***Suggested Books*:**

- P.Yeh and M.Cardona, Fundamentals of semiconductors, Springer(2008)
- DAB Miller, Quantum Mechanics for scientists and engineers Cambridge Univ Press(2008);
- Paul Harrison ,Quantum Wells, Wires and Dots: Theoretical and Computational Physics of semiconductor nanostructures, Wiley(2011),
- B.R. Nag, Physics of Quantum Well Devices, Springer(2001))
- Joachim Stolze, Dieter Suter Quantum Computing: A Short Course from Theory to Experiment, Wiley (2007)
- Henry O. Everitt,ed, Experimental Aspects of Quantum Computing Springer(2005);
- L.-M. Duan and C. Monroe, Rev. Mod. Phys. 82, 1209 (2010)
- AM Zagoskin Quantum Engineering: Theory and Design of Quantum Coherent Structures Cambridge University Press (2011)

PHY 531: Special Topics in Theoretical Physics (4)

- Course title and contents will be dynamic and change year to year according to emerging interesting areas in theoretical physics. Course content will be approved by Academic Senate upon recommendation from DUGC and DPGC.

PHY 534: Advanced Statistical Mechanics (4)

Prerequisites (Desirable): *PHY 306 : Statistical Mechanics*

***Learning Objectives*:**

This course is about theoretical understanding of the various phases of matter using statistical mechanics. Phase transitions of the first order and second order will be discussed using phenomenological model and renormalization group approach. This course will also introduce non-equilibrium statistical mechanics.

***Course Contents*:**

Revision of statistical mechanics, Thermodynamics of various ensembles, General properties of partition function, Lee-Young theorem.

Thermodynamics of phase transitions, metastable states, First and second order transitions, phenomenology of liquid-gas and paramagnetic-ferromagnetic transition, Van der Waals' equation of state critical point exponent.

Classical mean field theories, mean field theory for Ising model, Landau theory. Setting up the transfer matrix, Calculation of free energy and correlation functions, Results of Ising model in one and two dimensions.

Critical phenomena at second-order phase transitions, spatial and temporal fluctuations, scaling hypothesis, critical exponents, and universality classes. Ginzburg-Landau free-energy functional, momentum-space renormalization group.

Systems out of equilibrium, kinetic theory of a gas, approach to equilibrium and the H-theorem, Boltzmann equation and its application to transport problems. Brownian motion, Langevin equation, fluctuation-dissipation theorem, Einstein relation, Fokker-Planck equation.

***Suggested Books*:**

- K. Huang, Statistical Mechanics.
- R.K. Pathria, Statistical Mechanics.
- E.M. Lifshitz and L.P. Pitaevskii, Physical Kinetics.
- D.A. McQuarrie, Statistical Mechanics.
- L.P. Kadanoff, Statistical Physics: Statistics, Dynamics and Renormalization.
- P.M. Chaikin and T.C. Lubensky, Principles of Condensed Matter Physics.
- H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena

PHY 538: Spintronics: Fundamentals and Applications (4)

***Prerequisites*:**Condensed matter and/or Magnetism or Magnetic Materials

***Course Contents*:**

History and overview of spin electronics; Classes of magnetic materials; The early history of spin; Quantum Mechanics of spin; The Bloch sphere; Spin-orbit Interaction.

Exchange interaction; Spin relaxation mechanisms; spin relaxation in a quantum dots; The spin Galvanic effect; Basic electron transport; Spin-dependent transport; Spin dependent tunneling; Andreev Reflection at ferromagnet and Superconductor interfaces; Spintransfer torques.

Spin-transfer drive magnetic dynamics; Current-driven switching of magnetization and domain wall motion; Domain wall scattering and Current Induced switching in ferromagnetic wires; Spin injection, spin accumulation, and spin current, Spin hall effect, Silicon based spin electronic devices.

Spin LEDs: Fundamental and applications, Spin photoelectronic devices based on Heusler alloy, Electron spin filtering, Materials for spin electronics, Nanostructures for spin electronics, Deposition techniques, micro and nanofabrication techniques.

Spin-Valve and spin-tunneling devices: Read Heads, MRAMS, Field Sensors, Spintronic Biosensors, Spin transistors, Quantum Computing with spins.

***Suggested Books*:**

- S. Bandyopadhyay, M. Cahay, Introduction to Spintronics, CRC Press, 2008.
- M. Johnson, Magnetoelectronics, Academic Press 2004.
- D. J. Sellmyer, R. Skomski, Advanced Magnetic Nanostructures, Springer, 2006.
- S. Maekawa, Concepts in Spin Electronics, Oxford University Press, 2006.
- D.D. Awschalom, R.A. Buhrman, J.M. Daughton, S.V. Molnar, and M.L. Roukes, Spin Electronics, Kluwer Academic Publishers, 2004.
- Y.B. Xu and S.M.Thompson, Spintronic Materials and Technology, Taylor& Francis, 2006.

PHY 542: Physics of the strongly interacting matter produced in relativistic heavy ion collisions (4)

***Prerequisites*:**Quantum Mechanics I and II, Statistical Mechanics

***Course Contents*:**

Thermodynamics: QCD thermodynamics and phase diagram, QCD critical point; Approximating QCD medium as relativistic gas (hadrons, quarks and gluons) and its statistical and thermodynamic properties; MIT Bag model, Hagedorn gas

Relativistic Kinematics: four vectors notation, rapidity variables, pseudo-rapidity variables, light cone variables, relativistic invariants

Collision Dynamics: initial state of nuclear collisions, fluid dynamical evolution, kinetic transport model, freeze-out and particle production; Medium transport coefficients

Critical dynamics and its signature in different observables and comparison to model

A general overview of an experimental setup

 (a) Particle detection Technique
Passage of radiation through matter: Interaction of heavy charged particles, neutrons, gamma rays, and relativistic particles
 (b) Detectors in Particle Physics : Gas detectors, scintillation counters, solid state detectors

Search for QGP and relevant experimental observablesCollective flow, Heavy-flavor , Strangeness enhancement, Jet quenching, J/Ψ suppression,Light matter and antimatter production

DATA Analysis techniques (Monte-Carlo Method, Event Generators)

***Suggested Books*:**

- Hadrons and QGP by Letterssier and Rafelski.
- Introduction to High Energy Heavy Ion Collisions by C. Y. Wong.
- Phenomenology of Ultra Relativistic Heavy Ion Collisions by W Florkowski.
- Ultra relativistic heavy ion collisions by R. Vogt.
- Introduction to relativistic heavy ion collisions, by L. P. Csernai.
- A Short Course On Relativistic Heavy Ion Collision by A. K. Chaudhuri.
- Extreme states of matter in strong interaction physics by Helmut Satz.
- Relativistic Hydrodynamics by L. Rezzolla and O. Zanotti.
- Research Reports in Physics, Quark Gluon Plasma, Invited lectures of Winter School, Published by Springer Verlag, Editors - B. Sinha, S. Pal and S. Raha.
- The Physics of Quark Gluon Plasma, Introductory lectures, Lecture Notes in Physics 785, Publisher - Springer, Editor - S. Sarkar, H. Satz and B. Sinha.
- Quark Gluon Plasma - From big bang to little bang, K. Yagi, T. Hatsuda, Y. Miake, Cambridge Monograms on Particle Physics, Nuclear Physics and Cosmology.
- Quark Gluon Plasma: Theoretical Foundations, An annotated reprint collection - J. Kapusta, B. Muller and J. Rafelski, Publisher - Elsevier Science.

PHY 601: Advanced Mathematical Methods for Physics (4)

***Learning Objectives*:**

The main objective of the course is to equip the students with the tools of mathematics which are required for graduate courses and physics research.

***Course Contents*:**

Vector space and matrices, linear independence, bases dimensionality, Inner product, tensors, parallel transport, linear transformation matrices, inverse, orthogonal and unitary matrices, independent element of a matrix, Eigen values and Eigen vectors, diagonalization.

Theory of complex variables, Cauchy- Riemann condition, analytic functions, Cauchy's theorem, Cauchy integral formula, Laurent series, singularities, branch points and cuts, residue theorem, contour integration, evaluation of definite integrals, method of steepest descent.

Ordinary differential equations, second order linear ODEs with variable coefficients, Solution by series expansion, non-homogeneous differential equations and solution by the method of Green's functions with applications. Eigenvalue methods, up to Strum-Liouville systems. Special functions, Legendre, Bessel, Hermite and Laguerre functions with their physical applications, generating functions, orthogonality conditions, recursion relations, Legendre, Bessel, Hermite, Laguire equations and their solutions. Fourier integral and transforms, inversion theorem, Fourier transform of derivatives, convolution theorem.

Partial differential equations, Solution of Laplace and Poisson's equations, Wave equation

Introduction to Groups, Representations, Finite Groups, Permutation Groups, Continuous Groups, Lie algebras.

***Suggested Books*:**

- B. Arfken and H. J. Weber, Mathematical Methods for Physicists, 6th Ed.
- P. K. Chattopadhyay, Mathematical Physics.
- M. L. Boas, Mathematical Methods in Physical Sciences.
- S. D. Joglekar, Mathematical Physics: The Basics.
- A. K. Ghatak, Mathematical Method of Physics.
- F. B. Hildebrand, Methods of Applied Mathematics.
- A. W. Joshi, Elements of Group Theory for Physicist.
- S. Hassani, Mathematical Physics.
- P. Dennery and A. Krzywicki, Mathematics for Physicists.
- J. Mathews and R. L. Walker, Mathematical Methods of Physics.

PHY 602: Advanced Classical Mechanics (4)

Review of Classical Mechanics

Variational principles- Lagrange's equation and its application,

Hamilton's equation of motion

Perturbation theory

Hamilton Jacobi theory

Poisson's bracket in Classical Mechanics and its transition to quantum mechanics

Classical field theory

***Suggested Books*:**

- Classical Mechanics, John R. Taylor, University science books, 2004
- Mechanics (Volume 1), Landau and Lifshtz, Butterworth-Heinemann (1976), Ed. 3
- Analytical Mechanics, Fowels and Cassiday, Thompson Books (2004) Ed. 7
- Classical Mechanics, Herbert Golstein, Pearson (2011), Ed .3

PHY 603: Advanced Quantum Mechanics (4)

***Learning Objectives*:**

The course will be a review of foundations of quantum mechanics along with some advanced topics like approximation methods in quantum mechanics, atomic and molecular theory, time-dependent perturbation theory and scattering theory.

***Course Contents*:**

Review of Quantum Mechanics Postulates of quantum mechanics, operator methods, matrix representations, time-dependence, symmetry : Unitary operators: translations in space, translation in time (evolution). Rotations, reflections and parity. Conservation laws.

Solutions to the Schrodinger equation in one dimension. Angular momentum and spin.

Charged particles in electromagnetic fields Hamiltonian for a charged spinless particle in an electromagnetic field. Gauge transformations and gauge nvariance. Aharonov-Bohm effect; Free electron in a uniform magnetic field: Landau levels.

Approximate Methods: Time-independent perturbation theory, first and second order expansion; Degenerate perturbation theory; Stark effect; nearly free electron model. Variational method: ground state energy and eigenfunctions; excited states. The WKB method: bound states and barrier penetration.

Atomic and molecular structure: Revision of the Hydrogen atom. Fine structure: relativistic corrections; spin-orbit coupling; hyperfine structure. Zeeman effects; diamagnetic hydrogen. Multi-electron atoms: central field approximation; LS coupling; Hund's rules. Born-Oppenheimer approximation; H_2+ ion; molecular orbitals; H_2 molecule; ionic and covalent bonding.

Time-dependent perturbation theory: Two-level system, Rabi oscillations, Magnetic resonance. Perturbation series, Fermi's Golden rule, scattering and Born approximation. Radiative transitions, dipole approximation, stimulated emission and absorption, spontaneous emission, Einstein's A and B coefficients, selection rules; Cavity rate equations and lasers.

Scattering by a Potential: Formalism; Born approximations; Partial wave analysis Relativistic Quantum Mechanics Klein-Gordan and Dirac equations and their solutions. Chirality and helicity.

***Suggested Books*:**

- Quantum Physics, S. Gasiorowicz
- Quantum Mechanics: Non-Relativistic Theory, Volume 3, L. D. Landau and L. M. Lifshitz
- The Physics of Atoms and Quanta, H. Haken and H. C. Wolf Quantum Mechanics, F. Schwabl
- Principles of Quantum Mechanics, R. Shankar
- Problems in Quantum Mechanics, G. L. Squires
- Quantum Mechanics: A New Introduction, K. Konishi and G. Paffuti
- Quantum Mechanics, F. SchwablQuantum Mechanics, C. Cohen-Tannoudji, B.D. Franck Laloe

PHY 604: Statistical Mechanics (4)

Prerequisite*: PHY 303: Quantum Mechanics I, PHY 301: Mathematical Methods I, PHY 309: Thermal Physics*

Motivation : Why do we need statistical mechanics ? Thermodynamic description of a system. Microscopic origin of of thermodynamic results - introduction of statistical description. Introduction and definition of ensemble. Examples of ensembles.

Phase spac: Introduction and definition of phase space. Examples. Phase space density Time average and ensemble average. Equivalence between time average and ensemble average - Postulate of statistical mechanics (Ergodic hypothesis). Liouville's equation.

Equilibrium Statistical mechanics

A. Definition.
B. Micro-canonical ensemble: Definition ,Volume of phase space, Definition of entropy, Definition of temperature, Physical interpretation of temperature. Validity of statistical description. Definition of pressure,1st law of thermodynamics. Statistical interpretation of entropy. Classical ideal gas in microcanonical ensemble. Gibbs paradox.
C. Canonical ensemble: Definition, Average in canonical ensemble, Partition function Equivalence between canonical and microcanonical ensemble average. Definition of free energy. Ideal gas in canonical ensemble.
D. Grand-canonical ensemble: Definition, Grand-canonical partition function, Definition of chemical potential, Equivalence between canonical and grand-canonical average. Ideal gas in grand canonical ensemble

Quantum statistical mechanics: Pure and mixed ensemble. Examples of pure and mixed ensemble. Quantum ensemble average. Introduction of density matrix. Properties of density matrix. Examples of density matrix. Micro-canonical ensemble, Canonical ensemble and Partition function, Grand-canonical ensemble and partition function.

Three different statistics Boltzmann statistics: Partition function for ideal Boltzmann gas. Equation of state. Bose and Fermi statics/distribution

Ideal Fermi gas: Partition function. Equation of state. High temperature fermi gas. Low temperature fermi gas. Fermi energy, fermi temperature and fermi surface. Pressure of low temperature fermi gas. Zero point pressure.

Magnetization: Dia-magnetization, Paramagnetization.

Ideal Bose gas: Partition function. Equation of state. Gas of photon - Black body radiation Lattice vibration : Specific heal, Einstein and Debye's model of specific heat.

Suggested Books**:**

- F. Reif, *Fundamentals of Statistical and Thermal Physics*.
- R.K. Pathria, *Statistical Mechanics, 2nd Ed.*
- M. Plischke and B. Bergersen, *Equilibrium Statistical Physics*.
- J. K. Bhattacharjee, *Statistical Physics: Equilibrium and Non-Equilibrium Aspects*.
- Kerson Huang, *Statistical Mechanics*.
- S-K. Ma, *Statistical Mechanics*.

- L. D. Landau and E. M. Lifshitz, *Statistical Physics*.
- R. Kubo, M. Toda and N. Hashitsume, *Statistical Physics I and II*.
- S-K. Ma, *Modern Theory of Critical Phenomena*.

PHY 605: Electrodynamics (4)

Prerequisites: PHY 305: Classical Mechanics, PHY 301: Mathematical Methods I, PHY 302: Mathematical Methods II

Boundary problems, Formal solution with Green functions, Electric fields in matter, Boundary-Value problems with dielectrics, polarizability and susceptibility, Energy density in a dielectric, Multipole expansion.

Vector potential, Magnetic fields of a localized current distribution, Magnetic moment, Force and Torque on and energy of a localized current distribution, Boundary conditions on B and H, Boundary value problems in magnetostatics, Multipole expansion.

Maxwell equations, Gauge transformations, Green functions for the wave equation, Poynting's theorem, Tranformation properties of electromagnetic fields and sources under rotations, spatial reflections, and time reversal

Plane electromagnetic waves and wave propagation, polarization, Stokes parameters, Reflection and refraction of electromagnetic waves at a plane interface between dielectrics, wave propagation in conductors and dielectrics, dispersion, complex refractive index, waveguides

Fields and radiation of a localized oscillating source, Electric dipole fields and radiation, Linear antennas.

Scattering at long wavelengths, Rayleigh scattering

Minkowski space and four vectors, concept of four-velocity, Four acceleration and higher rank tensors, Relativistic formulation of electrodynamics, Maxwell equations in covariant form, Gauge invariance and four-potential, the action principle and electromagnetic energy momentum tensor, Liénard-Weichert potentials, Radiation from an accelerated charge, Larmor formula, bremsstrahlung and synchrotron radiation, multipole radiation, dispersion theory, radiative reaction, radiative damping.

***Suggested Books*:**

- J. D. Jackson, *Classical Electrodynamics*.
- D. J. Griffiths, *Introduction to Electrodynamics*, 3rd Ed.
- L. D. Landau and E. M. Lifschitz, *Classical Theory of Fields*.
- R. P. Feynman, R. B. Leighton and M. Sands, *The Feynman Lecture of Physics* Vol 2.
- W. K. H. Panofsky and M. Philips. *Classical Electricity and Magnetism*.
- W. R. Smythe, *Static and Dynamic Electricity*.

PHY 606: Atomic and Molecular Physics (4)

Prerequisite: PHY 304: Quantum Mechanics II

Brief review of Hydrogen atom and periodic table; Significance of four quantum numbers; Concepts of atomic orbital

One Valance Electron Atom: Review of [Orbital magnetic dipole moment; Orbital, spin and total angular momenta; Spin-orbit interaction and fine structures]; Intensity of spectral lines; General selection rules; Details of Stark, Zeeman (Normal and anomalous) and Paschenbeck effects

Many Valance Electrons Atom: Two Valance Electrons Atom: Para and ortho states and the role of Pauli's Exclusion principle, He atom, Identical particles, Slater determinant; LS and JJ coupling scheme

Approximation Methods: The Hatree-Fock method; The Thomas-Fermi model of the atom

Width and shape of spectral lines; Hyperfine structure of lines; Lamb shift; Principal of ESR with experimental setup; chemical shift

Molecules: Concept of valance and bonding; Born-Oppenheimer approximation; Hydrogen molecule – Heitler-London method

Molecular orbital and electronic configuration of diatomic molecules (H_2, C_2, O_2, NO, and CN); Vibrational structure and vibrational analysis; Frank-Condon principle; Dissociation energy; Rotational spectra; Raman spectra and influence of nuclear spin

***Suggested Books*:**

- P. W. Atkins and R. S. Friedman, *Molecular Quantum Mechanics 3rd Ed*.
- W. Demtroder, *Atoms, Molecules and Photons*.
- G. W. Woodgate, *Elementary Atomic Structure*.
- H. S. Friedrich, *Theoretical Atomic Physics*.
- R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*.
- H. E. White, *Introduction to Atomic Spectra*.
- B. H. Bransden and C. J. Joachain, *Physics of Atoms and Molecules*.
- H. G. Kuhn, *Atomic Spectra*.
- F. A. Cotton, *Chemical Applications of Group Theory*.
- C. N. Banwell, *Fundamentals of Molecular Spectroscopy*.
- G. M. Barrow, *Introduction to Molecular Spectroscopy*.
- J. M. Hollas, *Modern Spectroscopy*.
- C. A. Coulson, *Valence*.

PHY 607: Many body physics

Second quantization. Many-body models and quantum phase transitions: (a) Bose-Hubbard model and superfluid to Mott insulator transition, (b) Ising model in presence of a transverse field. Feynman path integral. Green's function at zero temperature and finite temperature (Matsubara formalism). Bose-Einstein condensation and superfluidity. Superconductivity & BCS Theory..

***References*:**

- Many-Particle Physics by *G. D. Mahan*
- Condensed Matter Field Theory by *A. Atland and B. Simons*

Prerequisites:

- PHY 301, PHY 302, PHY 303, PHY 304, PHY 306

PHY 611: Nonlinear Dynamics and Chaos (4)

Prerequisites: PHY 305: Classical Mechanics, PHY 301: Mathematical Methods I

***Learning Objectives*:**

This course introduces fundamental concepts of dynamical systems, dynamical flows, non-linearity and chaos.

***Course Contents*:**

Introduction to Dynamical Systems: Overview, Examples and Discussion

One-dimensional flows: Flows on the line, Fixed points and stability, Population growth, Linear stability analysis, Saddle-node, Transcritical and Pitchfork bifurcations, Flow on the circle

Two-dimensional flows: Linear system: Definitions and examples, Phase portraits, Fixed points and linearization, Limit cycles, Poincare-Bendixson theorem, Lienard systems, Bifurcations revisited: Saddle-node, Transcritical and Pitchfork bifurcations, Hopf bifurcations, Oscillating chemical reactions, Poincare maps, Global bifurcation of cycles, Coupled Oscillators and Quasiperiodicity

Chaos: Lorenz equations: Properties of Lorenz equation, Lorenz Map; One-dimensioanl map: Fixed points, Logistic map, Liapunov exponent, Fractals: Countable and Uncountable Sets, Cantor Set, Dimension of Self-Similar Fractals, Box dimension, Pointwise and Correlation Dimensions; Strange Attractors: Baker's map, Henon map Chaos in Hamiltonian systems

***Suggested Books*:**

- Steven H. Strogatz, *Nonlinear Dynamics and Chaos with Applications to Physics, Biology, Chemistry and Engineering*
- Edward Ott, *Chaos in dynamical systems (Cambridge University Press)*
- R. C. Hilborn, *Chaos and Nonlinear Dynamics (Cambridge Univ. Press. 1994)*
- M. Lakshmanan and S. Rajasekar, *Nonlinear dynamics: Integrability Chaos and Patterns (Springer)*

PHY 612: Computational Physics (4)

Prerequisites: *PHY 305: Classical Mechanics, PHY 306: Statistical Mechanics, Numerical Methods*

*Introduction:*Computer simulations and problems in material science, Numerical methods and programming in Fortran 90/95, A brief review of classical mechanics and statistical mechanics, Quantum mechanics as a starting point.

Monte Carlo simulations: Importance sampling and the metropolis method, basic Monte Carlo algorithm, trial moves, random number generators, estimators. Applications and hands-on sessions–solid-liquid phase-transition in the Lennard-Jones fluid and the magnetic transition in the Ising model. Advanced applications–Monte Carlo in various ensembles, Kinetic Monte Carlo, Monte Carlo methods for rigid molecules and polymers.

Molecular Dynamics: The basic idea of MD, numerical integration of equations of motion – Verlet and velocity Verlet algorithms, classical force-fields – bonded and non-bonded interactions, parameterization of force-fields. Applications and hands-on sessions – determining the diffusion constant and radial distribution functions of a Lennard-Jones fluid using an Anderson thermostat, end-to-end distance and radius of gyration of a solvated polymer using bead-spring model. Advanced applications – MD in various ensembles – thermostats and baro-stats, constrained MD.

Some Tricks of the trade: Neighbour lists, Multiple time step methods, How to handle long-range forces

Advanced techniques: Biased Monte Carlo Schemes, Rare Event, Brownian dynamics, Dissipative particle dynamics

***Suggested Books*:**

- D. Frenkel and B. Smit, *Understanding Molecular Simulations* (ed. 2)
- A. R. Leach, *Molecular Modeling*
- M. P. Allen and D. J. Tildesley, *Computer Simulation of Liquids*
- J. M. Thijssen, *Computational Physics*
- T. Pang, *An introduction to computational physics*
- V. Rajaraman, *Computer Programming in Fortran 90 and 95*

PHY 613: Ultrafast Optics and Spectroscopy (4)

Basics laser theory: Einstein coefficient and light amplification, laser rate equations, cavity modes, transverse and longitudinal mode selection, coherence properties.

Ultrashort pulse generation: Active and passive mode-locking, mode-locking using optical Kerr Effect.

Ultrafast-pulse measurement methods: Electric field auto-correlations and power spectrum, Intensity autocorrelations, frequency resolved optical gating (FROG).

Manipulation of ultrashort pulses: Pulse shaping techniques.

Ultrafast time-resolved spectroscopy: Forced wave equations, second harmonic generation, Propagation equation for nonlinear refractive index media, nonlinear Schrodinger equation, self-phase modulation, modulation instability and solitons.

Ulatrafast time-resolved spectroscopy: Degenerate and non-degenerate pump-probe transmission measurements, stimulated Raman scattering.

Terahertz electromagnetic radiations: THz generation and detection, THz time domain spectroscopy and imaging.

Introduction to atto-second science.

***Suggested Books*:**

- Ultrafast Optics by Andrew Weiner
- Laser Spectroscopy edited by Peter Hanna Ford
- Laser Theory and Applications by K. Thyagarajan and A. K. Khatak
- Ultrafast Optics edited by Rick Trebino and Jeff Squier

PHY 614: Advanced Condensed Matter Physics (4)

Prerequisite: PHY 403: Condensed Matter Physics

Review of basic postulates of magnetism, direct and indirect exchange interaction, Zener-double exchange interactions, super-exchange interactions, ferro-, antiferro-, ferri-magnetism, spin glasses.

Oxide based modern magnetic materials: Ferrites and magnetic technology based on it, Giant magnetoresistance: Exchange in magnetic multilayers; Colossal magnetoresistance materials, charge- and orbital-ordering, phase-separation; electric, magnetic and photo control of physical properties.

Dilute magnetic semiconductors, Introduction to spin electronics and technology based on it. Thin film technology of magnetic materials.

Review of basic postulates of superconductivity, High temperature supercondtivity, Josephson junctions, SQUID magnetometer, recent advances in superconductors: MgB2, Fe-based superconductors, *etc*.

Ferroelectricity, Multiferroicity, magnetoelectricity

Introduction to nanotechnology and nanoscience: Carbon nanotubes and fullerenes.

***Suggested Books*:**

- Fundamental of Magnetism: Mathias Getzlaff
- Solids State Physics: Ashcroft and Mermin.
- Introduction to Solid State Physics: Madelung.
- Principles of Condensed Matter Physics: Chaikin and Lubensky.
- Solid State Physics – An Introduction to Theory and Experiment: Ibach and Lutz.
- Quantum Theory of solid State: Callaway.
- Introduction to Magnetic Materials: B. D. Cullity
- Magnetic Materials: Fundamentals and Device Applications : Nicola A. Spaldin

PHY 615: Quantum Field Theory-I (4)

Prerequisite: *PHY 305: Classical Mechanics, PHY 302: Mathematical Method-II, PHY 304: Quantum Mechanics-II, Special Theory of Relativity*

***Learning Objectives*:**

The course aims at introducing basic concepts of relativistic quantum theory knows as quantum field theory. Course fill focus on quantization of scalar and spinor fields and calculation of cross-sections using Feynman diagram techniques.

***Course Contents*:**

Classical Field Theory: Introduction; Lagrangian Field Theory; Lorentz Invariance; Noether's Theorem and Conserved Currents; Hamiltonian Field Theory.

Canonical Quantization: The Klein-Gordon Equation, The Simple Harmonic Oscillator, Free Quantum Fields, Vacuum Energy, Particles, Relativistic Normalization, Complex Scalar Fields, The Heisenberg Picture, Causality and Propagators, Applications, Non-Relativistic Field Theory

Interacting Fields: Types of Interaction, The Interaction Picture, Dyson's Formula, Scattering, Wick's Theorem, Feynman Diagrams, Feynman Rules, Amplitudes, Decays and Cross Sections, Green's Functions, Connected Diagrams and Vacuum Bubbles, Reduction Formula

The Dirac Equation: The Lorentz Group, Clifford Algebras, The Spinor Representation, The Dirac Lagrangian, Chiral Spinors, The Weyl Equation, Parity, Majorana Spinors, Symmetries and Currents, Plane Wave Solutions.

Quantizing the Dirac Field: Spin-Statistics Theorem, Fermionic Quantization, Fermi-Dirac Statistics, Propagators, Particles and Anti-Particles, Dirac's Hole Interpretation, Feynman Rules.

Quantum Electrodynamics: Gauge field, Gauge Invariance, Quantization, Inclusion of Matter - QED, Lorentz Invariant Propagators; Feynman Rules; QED Processes.

***Suggested Books*:**

- Peskin, Michael E., and Daniel V. Schroeder. An Introduction to Quantum Field Theory. Boulder, CO: Westview Press, 1995. ISBN: 9780201503975.
- Quantum Field Theory by Ryder
- Quantum Field Theory Part 1 by Steven Weinberg

PHY 616: General Theory of Relativity (4)

Review of special theory of relativity

Mathematical aspects: Tensor algebra, Transformation of coordinates, Lie derivative, covariant derivative, affine connections, Riemann tensor, Curvature tensior

Inertial frames, Gravitational mass and inertial mass, Equivalance principle: weak form, strong form, Principle of general covariance

Field equations in general relativity: Geodesic deviation, Vacuum Einstein equations.

Action formulation of GTR

Solution of Einstein equations: Tests of GTR, Black holes, Schwarzschild black hole

Penrose diagram of Schwarzschild black hole.

Cosmology: FRW Universe.

***Suggested Books*:**

- Spacetime and Geometry: An Introduction to General Relativity by Sean Carroll
- General Relativity by Robert M. Vald
- Gravity: An Introduction to Einstein;s General Relativity by James B. Hartle
- Gravitation and Cosmology: by Steven Weinberg

PHY 617: Soft Condensed Matter (4)

Introduction and Overview: What is soft condensed matter, forces, energies and timescales in soft condensed matter.

Colloids: A single colloidal particle in a liquid (Stoke's law and Brownian motion), forces between colloidal particles (Van der Waals, electrostatic double layer, stearic, depletion interaction), stability and phase behaviour of colloids (hard sphere, long ranged repulsion, weakly attractive, strongly attractive), flow in concentrated dispersions.

Polymers: Polymeric materials, freely jointed chains and its Gaussian limit, real polymer chains, excluded volume, theta temperature, viscoelastic behaviour of polymers, linear viscoelasticity, time-temperature superposition, entanglements, tube model and theory of reptation.

Liquid Crystals: Types of liquid crystals, characteristics and identification of liquid crystal phases, nematic/isotropic transition, rigidity and elastic constants of a nematic liquid crystal, boundary effects, disinclination, dislocation and other topological defects, polymer liquid crystals.

Amphiphiles: Self-assembled phases in solutions of amphiphilic molecules, spherical micelles and critical micelle concentration, cylindrical micelles, bilayers and vesicles, phase behaviour of concentrated amphiphile solutions, complex phases in surfactant solutions and microemulsions.

Biological Soft Matter: DNA (structure, condensation), proteins (structure, folding, crystallization), membranes (lipid membranes, instabilities).

Experimental Techniques in Soft Matter: Rheology (shear rheometry, microrheology), light scattering (dynamic light scattering, static light scattering), microscopy (optical microscopy, video microscopy and particle tracking).

***Suggested Books*:**

- Richard A. L. Jones, Soft Condensed Matter, Oxford University Press.
- Ian W. Hamley, Introduction to Soft Matter: Synthetic and Biological Self-Assembling Materials, John Wiley & Sons.
- Thomas A. Witten and Philip A. Pincus, Structured Fluids: Polymers, Colloids and Surfactants, Oxford University Press.

PHY 619: Experimental Techniques (4)

Basics of vacuum technique: vacuum generation, gauging

Cryogenics: generation of low temperature and it measurements Structure and composition analysis by x-ray and electron diffraction based techniques: X-Ray Diffraction, Energy dispersive X-Ray (EDX), Transmission electron microscopy (TEM), X-Ray Fluorescence (XRF)

Electronic structure of Solids: X- ray and ultraviolet photoemission spectroscopy, angle resolved photo-emission spectroscopy, auger electron spectroscopy, and x-ray absorption techniques

Radiation and particle detectors: gas detectors, scintillators detectors and semiconductor detectors Thin film, polycrystalline and single crystal sample preparation techniques

Magnetometry and electrotransport : ac and dc magnetization techniques, two-probe and four probe resistivity measurements, magnetoresistance, Hall, thermal conductivity, thermopower, and heat capacity

Ultrafast spectroscopy: transient absorption, two photon absorption and terahertz spectroscopy Neutron and Muons in condensed matter

***Suggested Books*:**

- Scientific foundations of vacuum technique by Saul Dushman
- Experimental Techniques in Low-Temperature Physics by Guy White, Philip J. Meeson
- Elements of X Ray Diffraction by B. D. Cullity
- Physical Principles of Electron Microscopy: An Introduction to TEM, SEM, and AEM by R.F. Egerton
- Handbook of thin-film deposition processes and techniques: principles, methods, equipment, and applications by Klaus K. Schuegraf
- Crystal Growth Technology by Kullaiah Byrappa, Tadashi Ohac
- Photoelectron Spectroscopy by Principles and Applications Stefan Hüfner
- Introduction to Magnetic Materials by B. D. Cullity
- Terahertz Optoelectronics by Kiyomi Sakai
- X-Rays, Neutrons and Muons by Walter E. Fischer, Rudolf Morf

PHY 620: Magnetism and Superconductivity (4)

Prerequisite: PHY 304: Quantum Mechanics-II

Magnetism: Orbital and spin magnetism without interactions; Exchange interactions; Ferromagnetism, antiferromagnetism, ferrimagnetism, helical order and spin glasses; Measurement of magnetic order; Broken symmetry, Landau theory of ferromagnetism, Heisenberg and Ising model, consequences of broken symmetry, phase transitions and spin waves; Domains and the magnetization process; Itinerant magnetism of metals; Giant, colossal and tunneling magneto resistance; Nuclear magnetic resonance and technological aspects of magnetic materials.

Superconductivity: Properties of conventional (low temperature) superconductors, Meisnner-Ochsenfeld effect, perfect diamagnetism, London and Pippard equation; Type I superconductors and type II superconductors, vortex state, critical fields, interaction of vortices, magnetic properties, surface superconductivity; Ginzburg-Landau theory; BCS theory of superconductivity- electron-phonon interaction, ground state of the superconductor, spectrum of elementary excitations, tunnel effects and measurement of the energy gap; Josephson effect and the quantum interferometers; High Temperature superconductivity.

***Suggested Books*:**

- S. Blundell, Magnetism in Condensed Matter, Oxford (2001).
- J. M. D. Coey, Magnetism and Magnetic Materials, Cambridge (2010)
- Aharoni, Introduction to the Theory of Ferromagnetism, Oxford (2001)
- M. Tinkham, Introduction to Superconductivity, McGraw-Hill (1996)
- J. F. Annett, Superconductivity, Superfluids and Condensates, Oxford (2004)
- T. P. Sheahen, Introduction to High- Temperature Superconductivity, Plenum (1994)

PHY 622: Advanced Topics in Theoretical Condensed Matter Physics (4)

Prerequisite: PHY 303: Quantum Mechanics-I
PHY 304: Quantum Mechanics-II

***Learning Objectives*:**

Current trends in condensed matter physics will be discussed in this course. Some of the topics to be taught include topological insulators, topological superconductors, quantum hall effect and phase transitions.

***Course Contents*:**

Second quantization for bosons and fermions.

Lattice vibrations: waves and phonons in graphene. Different bending modes of graphene, Landau levels, oscillations of magnetization (de Haas van Alphen), diamagnetism Landau and magnetic susceptibility of electron gas in graphene.

Graphene: band structure and Dirac spectrum.

Various generalizations: bilayer graphene, edge modes in ribbons, The birth of topological insulators, Berry phase, topological indices, Topological order and the quantum spin hall effect, Addiabatìc transport.

***Suggested Books*:**

- Condensed Matter Field Theory, Altland and Simon
- Physical properties of carbon nanotubes, R. Saito

PHY 623: Non-adiabatic Interactions in Physics, Chemistry and Biology (4)

The Born-Oppenheimer Approach – The Time Independent Framework: (a) The Adiabatic Representation; (b) The Diabatic Representation

Mathematical Introduction: (a) The Hilbert Space and the Curl-Div Equations; (b) First Order Differential Equations along contours; (c) Abelian and non-Abelian Systems.

The Adiabatic-Diabatic Transformation (ADT). On the Single-valuedness of the newly formed Diabatic Potentials and the Quantization of the Born-Oppenheimer (BO) non-adiabatic coupling (NAC) matrix. Singularities, Poles and Seams characterizing the BO-NAC terms.

Molecular Fields as formed by Lorentz Wave-Equations.

The Jahn-Teller Model, The Renner-Teller model, the mixed Jahn-Teller/Renner-Teller model. The Privileged ADT phase and the corresponding Topological (Berry/Longuet-Higgins) phase.

The Extended Born-Oppenheimer Equation including Symmetry

The Born-Oppenheimer Approach – The Time Dependent Framework (emphasizing Field-dependent non-Adiabatic Coupling terms).

The interaction between molecular systems and electromagnetic fields: (a) The Classical treatment of the field (b) The Quantum treatment of the Field (based on Fock states).

If time allows various subjects related to Quantum Reactive Scattering Theory will be introduced. Among other things the concept of arrangement channels and decoupling of arrangement channels employing Absorbing Boundary conditions will be discussed.

***Suggested Books*:**

- M. Baer and C-Y. Ng, (eds), State-Selected and State-to-State Ion-Molecule Reaction Dynamics. Ser. Advances of Chemical Physics, Vol. 82, Part 2, John Wiley, Hoboken, N.J. (1992)
- M. Baer and G.D. Billing (eds), The Role of Degenerate States in Chemistry, Ser. Advances of Chemical Physics, Vol. 124; John Wiley, Hoboken, N.J. (2002)
- W. Domcke, D.R. Yarkony and H. Koeppel, Conical Intersections, Advances Series In Physical Chemistry Vol. 15 (World Scientific, Hong-Kong (2004).
- Farad. Discussions, Non-Adiabatic Effects in Chemical Dynamics, Vol. 127 (R.S.C.), University Oxford, (2004)
- M. Baer, Beyond Born-Oppenheimer: Electronic Nonadiabatic Coupling Terms and Conical Intersections, Wiley Interscience, Hoboken, N.J., (2006).
- G.C. Schatz and M. A. Ratner, Quantum Mechanics in Chemistry, Prentice-Hall, Englwood Cliffs (1993)
- J.D. Jackson, Classical Electrodynamics, 2nd Edition, John Wiley, New York (1975)
- J. Z. H. Zhang, Theory and Application of Quantum Molecular Dynamics, World Scientific, Hong-Kong (1999)

PHY 624: Defects in Materials (4 Credit)

***Course Content*:**

Brief introduction to perfect crystals including lattice geometry, point group, space group and crystal structures.

Defect classification in crystalline systems - Point defects in metallic ionic and covalent crystals equilibrium and non-equilibrium defects dislocations, continuum and atomistic theory, dislocations in different lattices, dislocation reactions, interaction and multiplication of dislocations, dislocation sources, glide, cross slip, climb - Stacking faults, twinning - Grain boundaries, angle and high angle boundaries, special boundaries, ledges, inter-phase boundaries.

Defect interactions - interaction between point defects and dislocations, interaction between precipitates and dislocations.

Brief overview of role of defects in controlling optical, electrical, magnetic, semiconducting and superconducting properties of materials.

Brief introduction to techniques for characterization of defects.

References:

- W.D. Kingery, H.K. Bowen and D.R. Uhlmann.: Introduction to Ceramics, 2nd ed., *John Wiley and Sons, 1976*
- A. C. Damask and G. J. Dienes: Point Defects in Metals, 1st ed., *Gordon and Breach, 1963*
- D. Hull and D. J. Bacon: Introduction to dislocations, 4th ed., *Butterworth-Heinemann, 2001*
- D.A. Porter and K.E. Easterling: Phase Transformation in Metals and Alloys, 2nd ed. *Chapman and Hall, 1992*

Prerequisites: Condensed Matter Physics, Thermodynamics

PHY 625: Quantum Information Theory (4)

Probabilities

Classical Information theory

Review of quantum mechanics

Bits to Qubits

Quantum states: mixed states, multipartite states, superposition and entanglement

Quantum measurements

Quantum dynamics, open and closed dynamics

The circuit model

Quantum entropy and quantum correlations

Elements of quantum computing

***Suggested Books*:**

- M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information
- J.Preskill, Quantum Information and Quantum Computation, Available online (Caltech)
- J. J. Sakurai, Modern quantum mechanics Addison-Wesley (1994)

PHY 626: Piezoelectric Material Fundamentals and Applications (4 Credit)

***Course Content*:**

Crystallography: General principles, Rochelle salt, alpha and beta quartz, stereographic projection.

Crystal Elasticity: Introduction, primary and secondary effects, thermodynamic potential, stress and strain, compressibility, adiabatic constants, transformation of components of stress and strain, general equations, specialization of certain groups.

Vibrations of crystals: normal modes, longitudinal vibrations, equivalent system with single degree of freedom, harmonics, various types of vibrations.

Principle of Piezoelectricity: Fundamental equations, piezoelectric classes, electrostriction, thermodynamic formulations of piezoelectric theory.

Measurements of piezoelectric effects: orientation and electrodes, compression, shear, torsion, measurements of piezoelectric constant, dynamic measurements and applications of piezoelectric materials such as sensors, actuators, motors, etc.

***References*:**

- Piezoelectricity by W. G. Cady, volume one, Dover publication, 1973
- Advanced Piezoelectric Materials: Science and Technology, Kenji Uchino, A volume in Woodhead Publishing Series in Electronic and Optical Materials, 2010
- Piezoelectric Ceramics, Bernard Jaffe, Elsevier, 2012
- Principle and applications of ferroelectrics and related materials, M.E. Lines and A. M. Glass, Oxford classic text, 2009
- Introduction to Ceramics, 2nd Edition, W. D. Kingery, H. K. Bowen, D. R. Uhlmann, Wiley
- Electroceramics: Materials, Properties, Applications, by A. J. Moulson and J. M. Herbert, Wiley

Prerequisites:Condensed Matter Physics, Thermodynamics

PHY 627: Quantum Engineerring (4)

Prerequisite: PHY 303: Quantum Mechanics-I
PHY 304: Quantum Mechanics-II

Quantum confined semiconductors –physics and devices

Introduction to semiconductors; electrons and phonons in quantum wells, quantum wires, and quantum dots. Quantum well diode lasers, inter-sub-band transitions and detectors based on them, excitons in quantum wells and self-electro-optic-effect devices, quantum dots for quantum computing.

Laser cooling and trapping of ions and their use in quantum information processing: Laser cooling, Paul ion trap, other ion traps, coherent light atom interaction, quantum computing with trapped ions.

Superconducting systems for quantum information processing, Josephson effect, Phase qubits and flux qubits, circuits, examples

***Suggested Books*:**

- P.Yeh and M.Cardona, Fundamentals of semiconductors, Springer(2008)
- DAB Miller, Quantum Mechanics for scientists and engineers Cambridge Univ Press(2008);
- Paul Harrison ,Quantum Wells, Wires and Dots: Theoretical and Computational Physics of semiconductor nanostructures, Wiley(2011),
- B.R. Nag, Physics of Quantum Well Devices, Springer(2001))
- Joachim Stolze, Dieter Suter Quantum Computing: A Short Course from Theory to Experiment, Wiley (2007)
- Henry O. Everitt,ed, Experimental Aspects of Quantum Computing Springer(2005);
- L.-M. Duan and C. Monroe, Rev. Mod. Phys. 82, 1209 (2010)
- AM Zagoskin Quantum Engineering: Theory and Design of Quantum Coherent Structures Cambridge University Press (2011)

PHY 628: Advanced Topics in Condensed Matter Physics (4)

Pre-requisites: *PHY 607 : Condensed Matter Physics*

***Learning Objectives*:**

This course aims to provide a blend of theoretical background with experimental observations covering the *recent trends in condensed matter physics*.

Initially, some basic concepts of condensed matter physics will be revised. This will be followed by the current trends in condensed matter physics covering special topics, such as; oxide electronics, emergent phenomena at the oxide interfaces and heterostructures. Later, novel properties of 2D materials (graphene and transition metal dichalcogenides (TMDCs)) will also be discussed.

An important goal of this course is to prepare the participants to know when to be surprised – that is - how/when do you know you have discovered a new species or something remarkably new?

***Course Contents*:**

Review of basic concepts: Free electron and tightly bound electrons, electron-electron interaction, band structure, Bloch electrons and transport phenomena, metal-insulator transition, semiconductors and dilute magnetic semiconductors, magnetism and superconductivity; phonons, quasi-particle couplings (electron-phonon, spin-phonon).

Recent trends in condensed matter physics:

(a) Oxide electronics: Novel properties of complex oxides; oxide thin films, interfaces and heterostructures; emergent phenomena at the interfaces - two dimensional electron gas, magnetism, superconductivity; experimental techniques to grow and probe interfaces / heterostructures; experimental observations and relevant theoretical models; etc.

(b) 2D materials: Graphene and TMDCs; lattice structure and band diagram; lattice vibrations, Landau levels; novel electronic, optical and magnetic properties as well as superconductivity.

***Suggested Books*:**

- Solid State Physics by Ashcroft & Mermin (Harcourt College Publishers).
- Condensed Matter Physics by Michael P. Marder (Wiley-Interscience Publications).
- Emergent phenomena at oxide interfaces, Nature Materials vol-11, pp-103, 2012 (and reference therein).
- Two-Dimensional Electron Gases at Complex Oxide Interfaces, Annual Review of Materials Research vol-44, pp-151, 2014 (and reference therein).
- Grahene-like Two-Dimensional Materials, Chemical Review vol-113, pp-3766, 2013 (and reference therein).
- Graphene vs MoS2, arXiv:1408.0437v1 (and reference therein).
- Beyond Graphene: Progress in Novel Teo-Dimensional Materials and van der Waals Solids, Annual Review of Materials Research vol-45, pp-1, 2015 (and reference therein).
- MoS2: Materials, Physics and Devices; Zhiming M. Wang (Editor), Lecture Notes in Nanoscale Science and Technology 21 (Springer, 2014).

PHY 629: Introduction to High Energy Physics (4)

***Learning Objectives*:**

The objective of the course is to introduce the students to the field of high energy physics where a lot of exciting research is taking place.

***Course Contents*:**

Introduction to Particles and Interactions, Feynman Diagrams, Conservation Laws, Relativistic Kinematics of Particle Interactions, Strong Interactions, Weak Interactions, Electroweak Theory, Higgs Boson, Neutrinos.

Accelerators in High Energy Physics, Principles of Particle Radiation Detection and Measurement, Particle Detectors – Scintillation Detectors, Gas Detectors, Semiconductor Detectors.

***Suggested Books*:**

- Introduction to High Energy Physics - Donald Perkins
- Introduction to Elementary Particles - David Griffiths
- Radiation Detection and Mesurement - G. F. Knoll

PHY 630: Cosmology (4)

Prerequisite: PHY 416: General Theory of Relativity

Brief introduction of cosmological distant scales - Astronomy and cosmology, galaxies, radio sources, Quasars, coordinate systems, Hubble expansion Brief review of general theory of relativity:

Relativity to Cosmology: Einstein field equation, luminosity distance, horizon and hubble radius, angular size redshift relation.

Relics of big-bang: radiation dominated universe, thermodynamical treatment of early universe, nucleosynthesis, cosmic microwave background addition,.

Problems with standard big-bang theory: inflationary paradigm, Formation of large scale structure of universe

Theory of Cosmic microwave background radiation

***Suggested Books*:**

- Modern Csmology, Scott Dodelson, Academic Press
- An Introduction to Modern Cosmology, J. V. Narlikar, Cambridge University Press
- Physical Cosmology, P.J.E. Peebles, Princeton Series in Physics
- Cosmological Physics, J. A Peacock, Cambridge Astrophysics
- Gravitation and cosmology: principles and applications of the general theory of relativity, Steven Weinberg, John Wiley & Sons, In

PHY 631: Open quantum systems and quantum thermodynamics

Open quantum systems: Density matrix formalism. Quantum entropies: (i) Von Neumann entropy (ii) Relative entropy. Time evolution in closed and open quantum systems; Unitary dynamics; Markovian dynamics: (i) Completely positive maps, (ii) Microscopic derivations; Non-Markovian dynamics, (i) Integro-Differential Models, (ii) Time-Convolutionless Forms. Jaynes-Cummings model. The Caldeira-Leggett model Quantum thermodynamics: The laws of thermodynamics in the quantum regime. Heat and work in the quantum regime. Quantum thermal machines and the Carnot limit, (i) Stroke thermal machines, (ii) Continuous thermal machines. Quantum Maxwell demon.

***References*:**

- A. Rivas and S. F. Huelga *(2011)* Open Quantum Systems: An Introduction (Berlin: Springer).
- H. P. Breuer and F. Petruccione *(2002)* The Theory of Open Quantum Systems (Oxford: Oxford University Press).
- D. Gelbwaser-Klimovsky, W. Niedenzu and G. Kurizki, Thermodynamics of Quantum Systems Under Dynamical Control, Advances in Atomic, Molecular, and Optical Physics *64, 329 (2015)*.
- R. Kosloff and Y. Rezek, The Quantum Harmonic Otto Cycle, Entropy *(2017), 19,136.*
- R. Alicki, The quantum open system as a model of the heat engine, J. Phys. A: Math. Gen., *12, L103 (1979)*.
- F. Binder, L. A. Correa, C. Gogolin, J. Anders, and G. Adesso (eds.), Thermodynamics in the quantum regime-Recent Progress and Outlook, (Springer International Publishing), 2018.

Prerequisites:

- PHY 301, PHY 302, PHY 303, PHY 304, PHY 306

PHY 634: Advanced Statistical Mechanics (4)

***Learning Objectives*:**

This course is about theoretical understanding of the various phases of matter using statistical mechanics. Phase transitions of the first order and second order will be discussed using phenomenological model and renormalization group approach. This course will also introduce non-equilibrium statistical mechanics.

***Course Contents*:**

Revision of statistical mechanics, Thermodynamics of various ensembles, General properties of partition function, Lee-Young theorem.

Thermodynamics of phase transitions, metastable states, First and second order transitions, phenomenology of liquid-gas and paramagnetic-ferromagnetic transition, Van der Waals' equation of state critical point exponent.

Classical mean field theories, mean field theory for Ising model, Landau theory. Setting up the transfer matrix, Calculation of free energy and correlation functions, Results of Ising model in one and two dimensions.

Critical phenomena at second-order phase transitions, spatial and temporal fluctuations, scaling hypothesis, critical exponents, and universality classes. Ginzburg-Landau free-energy functional, momentum-space renormalization group.

Systems out of equilibrium, kinetic theory of a gas, approach to equilibrium and the H-theorem, Boltzmann equation and its application to transport problems. Brownian motion, Langevin equation, fluctuation-dissipation theorem, Einstein relation, Fokker-Planck equation.

***Suggested Books*:**

- K. Huang, Statistical Mechanics.
- R.K. Pathria, Statistical Mechanics.
- E.M. Lifshitz and L.P. Pitaevskii, Physical Kinetics.
- D.A. McQuarrie, Statistical Mechanics.
- L.P. Kadanoff, Statistical Physics: Statistics, Dynamics and Renormalization.
- P.M. Chaikin and T.C. Lubensky, Principles of Condensed Matter Physics.
- H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena

PHY 635: Application of Group Theory in Physics

Symmetries and group theory.
Finite and Discrete groups: Representation; Vibration modes, Selection rules, Lattice symmetries, Band structure.
Continuous groups: Lie groups and Lie algebras, Representation, Roots and Weights, Dynkin diagrams, SU(2), SO(3), SU(3).

***References*:**

- A. Zee, Group Theory in a Nutshell for Physicists
- Palash B. Pal, A Physicist's Introduction to Algebraic Structures
- P. Ramadevi and Varun Dubey, Group Theory for Physicists: With Applications
- H. Georgi, Lie Algebras in Particle Physics
- M. Hamermesh, Group Theory and its Applications to Physical Problems
- J. F. Cornwell, Group Theory in Physics, Vol. I & II
- 7. S. Mukhi and N. Mukunda, Introduction to Topology, Differential Geometry and Group Theory for Physicists

Prerequisites:

- PHY 304

PHY 636: Fundamentals of Semiconductor (3)

***Pre-requisites:*:**

Condensed matter Physics, Quantum Mechanics, Electrodynamics and Statistical mechanics

***Learning Objectives*:**

Students will learn about the following specific topics: Bandgaps, Effective masse, Electrons and holes, the Fermi function, Intrinsic carrier density, Doping and carrier concentrations, Carrier transport, Generation-recombination, Quasi-Fermi levels, Energy band diagrams

***Course Contents*:**

Introduction to semiconductors: Crystalline, polycrystalline, and amorphous semiconductors, Material properties, Crystal structure and Crystal growth, energy bands, Fundamentals of band structure, Fermi Dirac distribution, Density of states
Doping: Carrier concentration (temperature dependence), Carrier scattering and mobility, Equilibrium and Non Equilibrium (addition) carrier concentrationConcepts of drift, diffusion and Recombination generation

***Suggested Books*:**

- Semiconductor Physics and Devices by Donald A. Neamen
- Advanced semiconductor fundamentals by Robert F Pierret

PHY 637: Semiconductor Device Physics (3)

Pre-requisites:

Condensed matter Physics, Quantum Mechanics, Electrodynamics, Statistical mechanics, Fundamentals of semiconductor physics

***Learning Objectives*:**

Students will learn about the following specific topics:

- PN Junction
- PN Junction IV characteristics, DC and AC response
- Compound semiconductors and bandgap tuning
- Optical properties of semiconductors
- Optoelectronic devices
- Metal semiconductor and Metal oxide semiconductor junctions
- Modern semiconductors: Perovskites, Molecular Semiconductors, 2D semiconductors

***Course Contents*:**

Introduction to carrier action-drift, diffusion, Recombination-Generation and Equations of state, PN Junction diodes, PN diode I-V characteristics, PN diode Admittance and transient response, Schottky diode,Compound semiconductors and heterojunctions, Band gap tuning, Optical properties of materials, Optoelectronic diode devices: Photodiode, Solar cell and LED Metal semiconductor and Metal oxide Semiconductor junctions Modern Semiconductors- Perovskite Optoelectronics and Molecular semiconductor optoelectronics, 2D semiconductors

***Suggested Books*:**

- Semiconductor device fundamentals by Robert F Pierret
- Physics of semiconductor devices by Simon M Sze and Kwok k Ng

PHY 638: Spintronics: Fundamentals and Applications (4)

***Prerequisites*:**Condensed matter and/or Magnetism or Magnetic Materials

***Course Contents*:**

History and overview of spin electronics; Classes of magnetic materials; The early history of spin; Quantum Mechanics of spin; The Bloch sphere; Spin-orbit Interaction.

Exchange interaction; Spin relaxation mechanisms; spin relaxation in a quantum dots; The spin Galvanic effect; Basic electron transport; Spin-dependent transport; Spin dependent tunneling; Andreev Reflection at ferromagnet and Superconductor interfaces; Spintransfer torques.

Spin-transfer drive magnetic dynamics; Current-driven switching of magnetization and domain wall motion; Domain wall scattering and Current Induced switching in ferromagnetic wires; Spin injection, spin accumulation, and spin current, Spin hall effect, Silicon based spin electronic devices.

Spin LEDs: Fundamental and applications, Spin photoelectronic devices based on Heusler alloy, Electron spin filtering, Materials for spin electronics, Nanostructures for spin electronics, Deposition techniques, micro and nanofabrication techniques.

Spin-Valve and spin-tunneling devices: Read Heads, MRAMS, Field Sensors, Spintronic Biosensors, Spin transistors, Quantum Computing with spins.

***Suggested Books*:**

- S. Bandyopadhyay, M. Cahay, Introduction to Spintronics, CRC Press, 2008.
- M. Johnson, Magnetoelectronics, Academic Press 2004.
- D. J. Sellmyer, R. Skomski, Advanced Magnetic Nanostructures, Springer, 2006.
- S. Maekawa, Concepts in Spin Electronics, Oxford University Press, 2006.
- D.D. Awschalom, R.A. Buhrman, J.M. Daughton, S.V. Molnar, and M.L. Roukes, Spin Electronics, Kluwer Academic Publishers, 2004.
- Y.B. Xu and S.M.Thompson, Spintronic Materials and Technology, Taylor& Francis, 2006.

PHY 639: Magnetic Materials Fundamentals and Applications

Magnetostatics; Introduction, Magnetic poles, Magnetic moment, Magnetic dipoles,Magnetic effects of currents,Magnetization curves and hysteresis loops.
Experimental methods: Field production, Measurement of field strength, Instruments for measuring Magnetization.
Types of magnetism: Diamagnetism and paramagnetism, Ferromagnetism, Antiferromagnetism, Ferrimagnetism.
Magnetic domains: Domain wall structure, Domain wall motion, Magnetization by rotation, Effect of plastic deformation.
Magnetic anisotropy: Anisotropy in cubic crystals, Anisotropy in hexagonal crystals, Shape anisotropy.
Nanostructured Magnetic materials: Amorphous magnets, Single domain versus multidomain behavior, Coercivity of fine particles, Superparamagnetism, Magnetic thin films.
Types of magnetic materials: Soft magnetic materials, Amorphous and nanocrystalline soft magnetic materials, Hard magnetic materials and their applications.
Magnetic materials for applications: Applications of soft and hard magnetic materials,magnetocaloric materials and systems. Magnetic data storage, spin electronics, magnonics.
Magnet-polymer composites for sensing, actuation and self-healing.

***References*:**

- Magnetism and Magnetic Materials by *J. M. D. Coey*, Cambridge University Press, *2010*, Cambridge , UK
- Introduction to Magnetic Materials by *B. D. Cullity & C.D. Graham*, 2nd ed, Wiley international, *2009*, Hoboken, NJD. Jiles,
- Introduction to magnetism and magnetic materials by Jiles, *Taylor and Francis*, CRC Press *1998*.
- Magnetism in Condensed Matter by *Stephen Blundell*, Oxford University Press *(2001).*

Prerequisites:

- Condensed matter physics, Thermal Physics, Statistical mechanics, Quantum Physics

PHY 640: Superconductivity and Quantum Liquids

Physical properties of superconductors, London theory, vortices in type-II superconductors, vortex dynamics, Bean's model, Josephson transitions, quantum interference, SQUID, Ginzburg-Landau theory, BCS theory, applications of superconductivity, introduction to different types of quantum fluids (superfluid helium and Bose-Einstein condensate).

References:

- Superfluidity and superconductivity by *D.R. Tilley*, CRC Press; 1st edition, *1990.*
- Superconductivity, Superfluids and Condensates by *James F. Annett,* OUP Oxford; Illustrated edition, *2004*
- Introduction to superconductivity by *Michael Tinkham, Dover publication, 2004*.

Prerequisites:

- Condensed matter physics, Thermal Physics, Statistical mechanics, Quantum Physics, Mathematical Physics

PHY 641: Dielectric material fundamentals and applications

Course Content:

Dielectric polarization. Dielectric relaxation. Dielectric loss. Dielectric spectroscopy. Capacitors and insulators. Dielectric breakdown. Aging. Piezoelectric effect. Piezoelectric ceramics and polymers, Coupling of thermal, mechanical and electrical properties, Electrostriction, Ferroelectricity, Ferroelectric and ferroelastic domains, Applications of piezoelectric and ferroelectric materials. Selected topics in multiferroic materials, Pyroelectricity and pyroelectric materials and devices.

Suggested Books:

- Dielectric phenomena in solids by Kwan Chi Kao, Elsevier academic press, 2004.
- Principle and applications of ferroelectrics and related materials, M.E. Lines and A.M. Glass, Oxford classic text, 2009.
- Principles of Electronic Ceramics, by L. L. Hench and J. K. West, Wiley
- Introduction to Ceramics, 2nd Edition, W. D. Kingery, H. K. Bowen, D. R. Uhlmann, Wiley
- Electroceramics: Materials, Properties, Applications, by A. J. Moulson and J. M.Herbert, Wiley.

Perquisites: Condensed matter physics, Thermal Physics, Statistical mechanics, Quantum Physics, Mathematical Physics

PHY 642: Physics of the strongly interacting matter produced in relativistic heavy ion collisions (4)

***Prerequisites*:**Quantum Mechanics I and II, Statistical Mechanics

***Course Contents*:**

Thermodynamics: QCD thermodynamics and phase diagram, QCD critical point; Approximating QCD medium as relativistic gas (hadrons, quarks and gluons) and its statistical and thermodynamic properties; MIT Bag model, Hagedorn gas

Relativistic Kinematics: four vectors notation, rapidity variables, pseudo-rapidity variables, light cone variables, relativistic invariants

Collision Dynamics: initial state of nuclear collisions, fluid dynamical evolution, kinetic transport model, freeze-out and particle production; Medium transport coefficients

Critical dynamics and its signature in different observables and comparison to model

A general overview of an experimental setup

 (a) Particle detection Technique
Passage of radiation through matter: Interaction of heavy charged particles, neutrons, gamma rays, and relativistic particles
 (b) Detectors in Particle Physics : Gas detectors, scintillation counters, solid state detectors

Search for QGP and relevant experimental observablesCollective flow, Heavy-flavor , Strangeness enhancement, Jet quenching, J/Ψ suppression,Light matter and antimatter production

DATA Analysis techniques (Monte-Carlo Method, Event Generators)

***Suggested Books*:**

- Hadrons and QGP by Letterssier and Rafelski.
- Introduction to High Energy Heavy Ion Collisions by C. Y. Wong.
- Phenomenology of Ultra Relativistic Heavy Ion Collisions by W Florkowski.
- Ultra relativistic heavy ion collisions by R. Vogt.
- Introduction to relativistic heavy ion collisions, by L. P. Csernai.
- A Short Course On Relativistic Heavy Ion Collision by A. K. Chaudhuri.
- Extreme states of matter in strong interaction physics by Helmut Satz.
- Relativistic Hydrodynamics by L. Rezzolla and O. Zanotti.
- Research Reports in Physics, Quark Gluon Plasma, Invited lectures of Winter School, Published by Springer Verlag, Editors - B. Sinha, S. Pal and S. Raha.
- The Physics of Quark Gluon Plasma, Introductory lectures, Lecture Notes in Physics 785, Publisher - Springer, Editor - S. Sarkar, H. Satz and B. Sinha.
- Quark Gluon Plasma - From big bang to little bang, K. Yagi, T. Hatsuda, Y. Miake, Cambridge Monograms on Particle Physics, Nuclear Physics and Cosmology.
- Quark Gluon Plasma: Theoretical Foundations, An annotated reprint collection - J. Kapusta, B. Muller and J. Rafelski, Publisher - Elsevier Science.

PHY 645: Emerging Memory Devices and Technologies

Si technology-based memory concepts: Fundamentals of MOSFET devices, dynamic random-access memory (DRAM), basic operation, integration aspects, high k dielectrics in DRAM, stability and reliability issues, Flash memory, 3-D and embedded flash memory technologies and challenges.

Future non-volatile memory concepts:

Resistive switching memory (RRAM): classification of RRAM types, resistive switching mechanisms, electrochemical metallization systems/CBRAM, valence change systems, thermochemical systems, scaling potentials and architectures, stability and reliability issues, present status and future challenges, etc.

Phase change memory (PCM): Phase change materials and thin film properties, requirements, principle of phase change memory, phase change memory devices and integration, scaling properties, stability and reliability issues, present status and future challenges, etc.

Magnetoresistive memory (MRAM): Anisotropies, Interlayer exchange coupling, giant magnetoresistance, tunnel magneto resistance, spin transfer-torque (STT-RAM), racetrack memory, spin transistor, implementation of MRAM devices, magnetic hard discs, stability and reliability issues, etc.

Ferroelectric memory (FeRAM) and ferroelectric transistor (FeFET): Basics of ferroelectric phenomena, ferroelectric materials and thin film properties, FeRAM circuit design, thin film integration, failure mechanism, future challenges.

Other emerging memory concepts such as molecular, nanowires, quantum dots and polymers based memory devices and unconventional applications of these memory devices.

***References*:**

- Nanoelectronics and Information Technology: Advanced Electronic Materials and Novel Devices by *Rainer Waser. Wiley VCH; 2nd, (2005)*
- *Y. Nishi and Magyari-Kope,* “Advances in non-volatile memory and storage technology,” Woodhead Publishing *(2019).*
- Semiconductor physics and devices, *S M Sze, Wiley VCH; 3 rd ed. (2021)*

Prerequisites:

- Quantum mechanics, Electronics and Condensed matter physics