Research sub-area course description (Physics)

1. Condensed Matter Physics

Crystal structure: Direct and reciprocal lattice, Brillouin zone, X-ray diffraction and crystal structure; Crystal Vibration, Phonon heat capacity, Thermal Conductivity. Free electron theory of metals: Free electron gas in three dimension, Heat capacity of electron gas, Electrical and thermal conductivity. Magnetism: Paramagnetism and diamagnetism, spontaneous magnetism, magnetic ordering. Superconductivity: Basic properties, the London equation, elements of BCS theory. Plasmonics, Defects and dislocations, Amorphous Materials, Glass transition, Liquid crystals, Phase transitions, Mean field theories.

Band Theory of Solids- Kronig and Penney Model, Direct and Indirect band gaps, Fermi energy, Density of states, Fermi-Dirac Statistics Electron Transport – P and N type doping, Drift velocity of electrons and holes in an electric field, Drift current, Drift-diffusion equations, Transport equations, Thermal excitation of carriers, PN Junction Diode and Transistors, I-V characteristics, Models for the PN junction and bipolar transistor (Quasi-static, large-signal Small-signal, low-frequency, high-frequency model, Solar cell, P-i-N diodes. Metal-semiconductor contacts and MOSFET, Low dimensional Semiconductors: Electron transport in Quantum well, 1D electron transport, III-V heterostructure, Graphene and carbon nanotube based field effect transistors,
Spin Physics: Spin Hall Effect, giant and colossal magnetoresistance based memory devices.

Crystal Defects and Non-crystalline structure: Point defect, line defect, substitutional impurity, interstitial impurity, vacancy, self interstitial, ionic defect, Hope Diamond, Schottky defect, Frenkel defect, F-center, charge neutrality, edge dislocation, screw dislocation, dislocation motion, Physical Properties of Materials: Mechanical Behaviour, Thermal Behaviour, Failure Analysis and Prevention, Phase Diagrams, Heat Treatment, Phase Transformations, Structural Materials – Metals, Ceramics and Glasses, Polymers and Composites, Nanomaterials

Thermometry, various types of temperature sensors, Cryogenic and cryogen free low temperature generation techniques. Vacuum science: Vacuum Basics, Vacuum measurement methods. Vacuum generation techniques: Mechanical and nonmechanical pumps, considerations in system design, system component and valves. Crystal growth, Sample preparation techniques, SEM, STM, AFM, low temperature techniques, magnetic measurements, neutron diffraction.

2. **Nuclear and High Energy Physics:**

Nuclear Physics: Rutherford Scattering, definition of the scattering cross section; nuclear size and mass, liquid drop model; Angular momentum and parity, magnetic and quadrupole momenta; Two-nucleon problem, the deuteron, tensor force; Neutron-proton scattering, phase-shift analysis, scattering length, spin-dependence; Isospin-formalism, exchange forces, NN potentials; nuclear shell model, spin-orbit coupling; Nuclear decay, alpha and beta-decay; quark model.

Particle Physics, QFT, String Theory: Klein-Gordon eqn. Maxwell's equation and Dirac eqn., symmetries and conservation laws,, Relativistic kinematics of collision and decay, electron-photon interaction(QED), Scalar field theory, Dirac field theory, Yang Mills field, Interactions, Quantum Electrodynamics, Spontaneous symmetry breaking, Abelian-Higgs model, QCD, Renormalization group, Anomalies, non-perturbative configurations, instantons, Lattice gauge theories. Lie groups (U(1),SU(2),SU(3)) and algebra, Electro-weak interaction, phenomenology of QCD, Higgs mechanism, Supersymmetry and Supersymmetric field theory, Perturbative & non-perturbative aspects of string theory, Conformal field theory, Aspects of differential geometry, Topological field theory, Elements of group theory and representations. Differential geometry, calculus of variations

Numerical methods for solving ODE's, PDE's; Monte-carlo methods; Molecular dynamics simulations; Numerical methods for finding eigenvalues and eigenvectors; Numerical methods for solving linear and nonlinear equations; Numerical interpolation and integration; Fourier transforms.

3. **Optics and Spectroscopy**

Maxwell's equations, wave equation for electromagnetic radiation, light waves in matter, paraxial optics, matrix methods, two and multiple beam interference, Fresnel & Fraunhoffer diffraction, temporal & spatial coherence, image formation, polarization, crystal optics, lasers, holography, fiber optics, Nonlinear Optics, Quantum Optics

Interaction of matter with radiation, transition rates, dipole approximation, Einstein coefficients, angular momentum and selection rules, line intensities and line shapes, Doppler effect, Alkali spectra, fine structure, LS coupling, jj-coupling, Zeeman effect, Paschen-Back effect, Stark effect, hyperfine structure, rotational and vibrational spectra of diatomic and polyatomic molecules, Raman Spectroscopy, electronic spectroscopy of molecules, Nuclear Magnetic Resonance spectroscopy, Electron Spin Resonance spectroscopy.

4. **Theoretical Physics**

Vectors and tensors, linear operators- eigenvalues and eigenstates. Discrete and continuous spectra. Delta function (and other distributions). Inverse operator and Green functions.

Group theory: Cayley's theorem, Langrange's theorem, invariant subgroups, construction of group representations, character of group representation,Schur's lemmas, orthogonality relations, irreducible representation, adjoint representations, reduction of Kronecker products(C-G series), point symmetry groups, Continuous groups, infinitesimal transformations, structure constants, Lie algebras, Linear representation of Lie groups, irreducible representations of Lie groups and Lie algebras, Multivalued representation, Universal covering group, representations of rotation group(2-d&3-d), Irreducible representations of SU(n), U(n),Sp(n). Partial differential equations: Laplace equation, wave equation, And heat flow, Special functions: Gamma functions, Bessel functions and its variants, Legendre functions, Hermite functions, Hypergeometric functions, Confluent hypergeometric functions, Laguerre functions, Integral transforms: Fourier and Laplace transform.

Constraints and generalized coordinates, Lagrange's equation of motion, calculus of variation and principle of least action, central force motion, kinematics of rigid body motion, rigid body equations of motion, heavy symmetrical top, Hamilton's equations of motion, canonical transformations.

Fundamental concepts (Stern-Gerlach experiments, bra-ket vectors), Quantum Dynamics(Schrodinger and Heisenberg picture, Simple Harmonic Oscillator) Angular momentum(spin ½ system, angular momentum addition), Symmetry in Quantum Mechanics(conservation laws, continuous and discrete symmetries), Time-Independent perturbation theory: nondegenerate and degenerate cases, Zeeman effect and Stark effect, Time-dependent potential, the interaction picture, Identical particles, Scattering

Macro and Micro-states , Phase space, Liouville's theorem, Microcanonical ensemble, Equipartition & Virial theorems, Canonical ensemble, a system of harmonic oscillators, Paramagnetism, Bose-Einstein and Fermi-Dirac statistics, Black-Body radiation, Specific heat, Bose-Einstein condensation.

Electric potential of charge distribution, potential of dipole, Dielectric, Electric displacement, Magneto statics, Vector potential, magnetization, bound currents, Ampere’s law in magnetic material, Faraday’s law, induced electric field, Energy in magnetic field, Maxwell's equations in free space and media. Poynting theorem, Conservation of momentum and angular momentum, plane waves, propagation in linear media, absorption and dispersion, Potential formulation of electrodynamics, Gauge transformations, Retarded potentials, Lienard-Wiechert potential, field of moving point charge, Electric dipole radiation, magnetic dipole radiation, power radiated by point charge, radiation reaction.

5. Quantum Physics

Wave-particle duality, notion of state vector and its probability interpretation, Dirac’s bra-ket notation, operators and observables, generalized uncertainty principle, Time-independent / dependent Schrödinger equation, Schrödinger and Heisenberg pictures, Particle in a square well potential, transmission through a potential barrier, simple harmonic oscillator by wave equation and operator methods, Separation of variables in spherical polar coordinates, orbital angular momentum, spherical harmonics, hydrogen atom, Rotation operators, angular momentum algebra, spinors and Pauli matrices, addition of angular momenta. Time-independent Non-degenerate/ degenerate perturbation theory, variational methods, WKB method, Time-dependent perturbation theory, Fermi’s golden rule, Differential cross-section, partial wave analysis, The Born approximation.

Atomic and Molecular Physics: Interaction of matter with radiation, transition rates, dipole approximation, Einstein coefficients, angular momentum and selection rules, line intensities and line shapes, Doppler effect, Alkali spectra, fine structure, LS coupling, jj-coupling, Zeeman effect, Paschen-Back effect, Stark effect, hyperfine structure, rotational and vibrational spectra of diatomic and polyatomic molecules, Raman Spectroscopy, electronic spectroscopy of molecules, Nuclear Magnetic Resonance spectroscopy, Electron Spin Resonance spectroscopy.

Quantum Optics: Quantization of the EM field, Flock space representation, thermal fields, coherent states and squeezed states, quantum coherence functions and interferometry, single photon experiments, emission and absorption of radiation by atoms

Quantum Information and computation: quantum bits (qubits), quantum parallelism, teleportation etc. Basic ideas of quantum systems, two-state systems, evolution of states, superposition, entanglement, quantum measurement, decoherence. Basic ideas of computation theories and models, computational resources, complexity. Quantum Gates: single qubit, multiple qubit gates, controlled gates, universal gates, measurement. Quantum algorithms, Deutsch', Shor's and Grover's Algorithms, quantum circuits. Quantum Fourier Transform and applications, Quantum Search Algorithm. Physical Implementation of quantum computation. Characteristics of quantum information, Compression and transmission of quantum information, quantum noise, error-correction, coding and cryptography, complexity, fault-tolerant computation.

Numerical methods for solving ODE's, PDE's; Monte-Carlo methods; Molecular dynamics simulations; Numerical methods for finding eigenvalues and eigenvectors; Numerical methods for solving linear and nonlinear equations; Numerical interpolation and integration; Fourier transforms.

6. Astrophysics and Cosmology

Observational Astronomy: Celestial Sphere, Astronomical Coordinate Systems, Geographical Coordinates, Horizon System, Equatorial System, Diurnal Motion of the Stars, and Measurement of Time

Cosmology: Tensors, Affine connection, covariant derivative, geodesics, Ricci scalar, Riemann tensor and Einstein equation, Friedman-Robertson-Walker metric, Standard Model of Cosmology, Cosmological Microwave Background (CMB) spectrum, Role of Dark Matter and Dark Energy.

Astrophysics of Stars & Galaxies & Early Universe: Gravity in Astrophysics: Virial Theorem, System in Thermodynamic Equilibrium, Radiative Transfer, And Local Equilibrium. The Sun & the Solar System: Solar Atmosphere, Solar Activity, Magnetohydrodynamics, The Solar Family, Hydrostatic Equilibrium in stars, HR Diagram. Stars: Star formation (Molecular cloud, Jeans criterion), birth and death of stars, supernova, compact stars.

Review of special theory of relativity, Gravity as geometry, descriptions of curved space-time, tensor analysis, geodesic equations, affine connections, parallel transport, Riemann and Ricci tensors, Einstein’s equations, Schwarzschild solution, classic tests of general theory of relativity, mapping the universe, Friedmann-Robertson-Walker (FRW) cosmological model, Friedmann equation and the evolution of the universe, thermal history of the early universe, shortcomings of standard model of cosmology, theory of inflation, cosmic microwave background radiations (CMBR), baryogenesis, dark matter & dark energy.

Numerical methods for solving ODE's, PDE's; Monte-Carlo methods; Molecular dynamics simulations; Numerical methods for finding eigenvalues and eigenvectors; Numerical methods for solving linear and nonlinear equations; Numerical interpolation and integration; Fourier transforms.

7. Semiconductor Physics

Crystal structure and growth of semiconductor, Elementary quantum physics, Energy bands in solids, Charge carriers in semiconductors, Carrier Transport Phenomena, Non-equilibrium excess carriers in semiconductors, Continuity equation (includes setting up and solving for various boundary conditions), Fabrication of p-n junctions, equilibrium conditions, forward and reverse biased junctions, metal-semiconductor junctions, Bipolar junction transistors, Field effect transistors (JFET,MOSFET), Optoelectronic Devices (varactor diode, solar cell, LEDs, Tunnel diode, etc). IC Fabrication: Fabrication technology, Nanoscience and Nanotechnology

8. Nonlinear science and Complex systems

Phase plane analysis, Local Bifurcations in maps & differential equations, Global Bifurcations, Chaotic Dynamics, Fractals, Strange Attractors, Relaxation oscillations; Application of Bifurcation analysis to various systems; Time series analysis; Hamiltonian systems; Quantum chaos

Synchronization of periodic oscillators by periodic forces, synchronization of interacting systems with and without noise, synchronization of chaotic systems. Nonlinear dynamics in various systems - biological, social, economic, etc.

Statistical physics of complex networks: Phase transitions and disorder in complex systems; Non-linear modeling techniques – Neural networks, Genetic Algorithms, Fuzzy logic; Complex adaptive systems, self-organized Criticality.