School of Physical Sciences
Jawaharlal Nehru University

Revised syllabus for the M.Sc. (Physics) programme (for students admitted during or after the academic year 2016-2017)

Semester I	Semester II
Mathematical Physics I PS 417 (3 credits)	Quantum Mechanics II PS 421 (3 credits)
Classical Mechanics PS 412 (3 credits)	Statistical Mechanics PS 429 (3 credits)
Quantum Mechanics I PS 413 (3 credits)	Electromagnetic Theory PS 423 (3 credits)
Electronics PS 425 (2 credits)	Mathematical Physics II PS 428 (2 credits)
Physics Lab I PS 415 (6 credits)	Relativistic Physics PS 424 (2 credits)
	Physics Lab II (Electronics) PS 426 (4 credits)

Semester III	Semester IV
Computational Physics PS 427 (3 credits)	Elective I (3 credits)
Condensed Matter Physics PS 511 (3 credits)	Elective II (3 credits)
Subatomic Physics PS 512 (3 credits)	Elective III (3 credits)
Atoms and Molecules PS 514 (3 credits)	Project (4 credits) PS 522
Physics Lab III PS 515 (6 credits)	

SEMESTER I

- **Mathematical Physics I (3 credits) PS 417**
- **Classical Mechanics (3 credits) PS 412**
- **Quantum Mechanics I (3 credits) PS 413**
- **Electronics (2 credits) PS 425**
- **Physics Lab I (6 credits) PS 415**

Total 17 credits

<u>PS 417 Mathematical Physics I</u> (3 credits)

Linear Vector Spaces

Linear vector spaces, dual space, inner product spaces. Linear operators, matrices for linear operators. Eigenvalues and eigenvectors. Similarity transformation, (matrix) diagonalization. Special matrices: Normal, Hermitian and Unitary matrices. Hilbert space.

Complex Analysis

Complex numbers and variables. Complex analyticity, Cauchy-Riemann conditions. Classification of singularities. Cauchy's theorem. Residues. Evaluation of definite integrals. Taylor and Laurent expansions. Analytic continuation, Gamma function, zeta function. Method of steepest descent.

Ordinary Differential Equations and Special Functions

Linear ordinary differential equations and their singularities. Sturm- Liouville problem, expansion in orthogonal functions. Series solution of second-order equations. Hypergeometric function and Bessel functions, classical polynomials. Fourier Series and Fourier Transform.

References:

1. **G.B. Arfken,** *Mathematical Methods for Physicists*, Elsevier
2. **P. Dennery and A. Krzywicki,** *Mathematics for Physicists*, Dover
3. **S.D. Joglekar,** *Mathematical Physics: Basics (Vol. I) and Advanced (Vol. II),* Universities Press
4. **A.W. Joshi,** *Matrices and Tensors in Physics*, New Age Publishers
5. **R.V. Churchill and J.W. Brown,** *Complex Variables and Applications,* McGraw-Hill
6. **P.M. Morse and H. Feshbach,** *Methods of Theoretical Physics (Vol. I & II),* Feshbach Publishing
7. **M.R. Spiegel,** *Complex Variables,* McGraw-Hill

PS 412 Classical Mechanics (3 credits)

Lagrangian and Hamiltonian Formulations of Mechanics

Calculus of variations, Hamilton's principle of least action, Lagrange's equations of motion. Symmetries and conservation laws, Noether's theorem. Hamilton's equations of motion. Phase plots, fixed points and their stabilities.

Two-Body Central Force Problem

Equation of motion and first integrals. Kepler problem. Classification of orbits. Satellites and inter-planetary orbits. Scattering in central force field.

Small Oscillations

Linearization of equations of motion. Normal coordinates. Damped and forced oscillations. Anharmonic terms, perturbation theory.

Rigid body dynamics

Rotational motion, moments of inertia, torque. Euler's theorem, Euler angles. Symmetric top. Gyroscopes and their applications.

Hamiltonian Mechanics

Canonical transformations. Poisson brackets. Hamilton-Jacobi theory, action-angle variables. Integrable system. Perturbation theory. Introduction to chaotic dynamics.

References:

1. **H. Goldstein, C.P. Poole and J.F. Safko**, *Classical Mechanics,* Addison-Wesley
2. **N.C. Rana and P.S. Joag,** *Classical Mechanics*, Tata McGraw-Hill
3. **J.V. Jose and E.J. Saletan,** *Classical Dynamics: A Contemporary Approach,* Cambridge University Press
4. **L.D. Landau and E.M. Lifshitz,** *Mechanics,* Butterworth-Heinemann
5. **I.C. Percival and D. Richards,** *Introduction to Dynamics*, Cambridge University Press
6. **R.D. Gregory,** *Classical Mechanics,* Cambridge University Press

PS 413 Quantum Mechanics I (3 credits)

Introduction

Review of empirical basis, wave-particle duality, electron diffraction. Notion of state vector. Probability interpretation. Review and relations between approaches of Heisenberg-Born-Jordan, Schroedinger and Dirac.

Structure of Quantum Mechanics

Operators and observables, operators as matrices, significance of eigenvalues and eigenfunctions. Commutation relations. Uncertainty principle. Measurement in quantum theory.

Quantum Dynamics

Time-dependent Schrödinger equation. Stationary states and their significance. Time-independent Schrödinger equation.

Schrödinger Equation for one-dimensional systems

Free-particle, periodic boundary condition. Wave packets. Square well potential. Numerical solution of Schroedinger equation. Transmission through a potential barrier. Gamow theory of alpha-decay. Field induced ionization, Schottky barrier. Simple harmonic oscillator: solution by wave equation and operator method. Charged particle in a uniform magnetic field. Coherent states.

Spherically Symmetric Potentials

Separation of variables in spherical polar coordinates. Orbital angular momentum, parity. Spherical harmonics. Free particle in spherical polar coordinates. Spherical well. Hydrogen atom. Numerical solution of the radial equation in arbitrary potential.

References:

1. **C. Cohen-Tannoudji, B. Diu and F. Laloe,** *Quantum Mechanics (Vol. I),* Wiley
2. **L.I. Schiff,** *Quantum Mechanics,* McGraw-Hill
3. **R. Shankar,** *Principles of Quantum Mechanics,* Springer
4. **E. Merzbacher,** *Quantum Mechanics,* John Wiley and Sons
5. **A. Messiah,** *Quantum Mechanics (Vol. I),* Dover
6. **A. Das,** *Lectures on Quantum Mechanics,* Hindustan Book Agency
7. **R.P. Feynman**, *Feynman Lectures on Physics (Vol. III),* Addison-Wesley
8. **A. Levi,** *Applied Quantum Mechanics*, Cambridge Univ Press

PS 425 Electronics (2 credits)

Introduction

Survey of network theorems and network analysis, AC and DC bridges, transistors at low and high frequencies, FET.

Electronic Devices

General properties of semiconductors. Schottky diode, p-n junction, Diodes, light-emitting diodes, photo-diodes, negative-resistance devices, p-n-p-n characteristics, transistors (FET, MoSFET, bipolar).

Basic differential amplifier circuit, operational amplifier - characteristics and applications, simple analog computer, analog integrated circuits.

Digital Electronics

Gates, combinational and sequential digital systems, flip-flops, counters, multi-channel analyzer.

References:

1. **P. Horowitz and W. Hill,** *The Art of Electronics,* Cambridge University Press
2. **J. Millman and A. Grabel,** *Microelectronics,* McGraw-Hill
3. **J.J. Cathey,** *Schaum's Outline of Electronic Devices and Circuits,* McGraw-Hill
4. **M. Forrest,** *Electronic Sensor Circuits and Projects,* Master Publishing Inc
5. **W. Kleitz,** *Digital Electronics: A Practical Approach,* Prentice Hall
6. **J.H. Moore, C.C. Davis and M.A. Coplan**, *Building Scientific Apparatus,* Cambridge University Press

PS 415 Physics Laboratory I (6 credits)

1. Error analysis
2. G.M Counter
3. Experiments with microwaves
4. Resistivity of semiconductors
5. Work function of Tungsten
6. Hall effect
7. Thermal conductivity of Teflon
8. Susceptibility of Gadolinium
9. Transmission line, propagation of mechanical and EM waves
10. Measurement of e/m using Thomson method
11. Measurement of Planck's constant using photoelectric effect
12. Michelson interferometer
13. Millikan oil-drop experiment
14. Frank-Hertz experiment
15. Experiment using semiconductor laser

Note: Each student is required to perform at least 8 of the above experiments.

SEMESTER II

- **Quantum Mechanics II (3 credits) PS 421**
- **Statistical Mechanics (3 credits) PS 429**
- **Electromagnetic Theory (3 credits) PS 423**
- **Mathematical Physics II (2 credits) PS 428**
- **Relativistic Physics (2 credits) PS 424**
- **Physics Laboratory II (Electronics) (4 credits) PS 426**

Total 17 credits

PS 421 Quantum Mechanics II (3 credits)

Symmetry in Quantum Mechanics

Symmetry operations and unitary transformations. Conservation laws. Space and time translations; rotation. Discrete symmetries: Space inversion, time reversal and charge conjugation. Symmetry and degeneracy.

Angular momentum

Rotation operator, generators of infinitesimal rotation, angular momentum algebra, eigenvalues of J^2 and J_z. Pauli matrices and spinors. Addition of angular momenta.

Identical particles

Indistinguishability, symmetric and anti-symmetric wave functions, incorporation of spin, Slater determinants, Pauli exclusion principle.

Time-independent Approximation Methods

Non-degenerate and degenerate perturbation theory. Stark effect, Zeeman effect and other examples. Variational methods. WKB approximation. Tunnelling. Numerical perturbation theory, comparison with analytical results.

Time-dependent Problems

Schrödinger and Heisenberg pictures. Time-dependent perturbation theory. Transition probability calculations, Fermi's golden rule. Adiabatic and sudden approximations. Beta decay. Interaction of radiation with matter. Einstein A and B coefficients, introduction to the quantization of electromagnetic field.

Scattering Theory

Differential scattering cross-section, scattering of a wave packet, integral equation for the scattering amplitude, Born approximation, method of partial waves, low energy scattering and bound states, resonance scattering.

References:

Same as in Quantum Mechanics I plus

1. **C. Cohen-Tannoudji, B. Diu and F. Laloe**, *Quantum Mechanics* (*Vol. II*), Wiley
2. **A. Messiah**, *Quantum Mechanics* (*Vol.II*), Dover
3. **S. Flügge**, *Practical Quantum Mechanics*, Springer
4. **J. J. Sakurai**, *Modern Quantum Mechanics*, Pearson
5. **K. Gottfried and T.-M. Yan**, *Quantum Mechanics: Fundamentals,* Springer

PS 429 Statistical Mechanics (3 credits)

Elementary Probability Theory

Binomial, Poisson and Gaussian distributions. Central limit theorem.

Review of Thermodynamics

Extensive and intensive variables. Laws of thermodynamics. Legendre transformations and thermodynamic potentials. Maxwell relations. Applications of thermodynamics to (a) ideal gas, (b) magnetic material, and (c) dielectric material.

Formalism of Equilibrium Statistical Mechanics

Phase space, Liouville's theorem. Basic postulates of statistical mechanics. Microcanonical, canonical, grand canonical ensembles. Relation to thermodynamics. Fluctuations. Applications of various ensembles. Equation of state for a non-ideal gas, Van der Waals' equation of state. Meyer cluster expansion, virial coefficients. Ising model, mean field theory.

Quantum Statistics

Fermi-Dirac and Bose-Einstein statistics.

Ideal Bose gas, Debye theory of specific heat, properties of black-body radiation. Bose-Einstein condensation, experiments on atomic BEC, BEC in a harmonic potential.

Ideal Fermi gas. Properties of simple metals. Pauli paramagnetism. Electronic specific heat. White dwarf stars.

References:

1. **F. Reif,** *Fundamentals of Statistical and Thermal Physics,* Levant
2. **K. Huang,** *Statistical Mechanics,* Wiley
3. **R.K. Pathria,** *Statistical Mechanics,* Elsevier
4. **D.A. McQuarrie,** *Statistical Mechanics,* University Science Books
5. **S.K. Ma,** *Statistical Mechanics,* World Scientific
6. **R.P. Feynman,** *Statistical Mechanics,* Levant
7. **D. Choudhury and D. Stauffer,** *Principles of Equilibrium Statistical Mechanics,* Wiley-VCH

PS 423 Electromagnetic Theory (3 credits)

Review of Electrostatics and Magnetostatics (2-3 weeks)

Coulomb's law, action-at-a distance vs. concept of fields, Poisson and Laplace equations, formal solution for potential with Green's functions, boundary value problems; multipole expansion; Dielectrics, polarization of a medium; Biot-Savart law, differential equation for static magnetic field, vector potential, magnetic field from localized current distributions; Faraday's law of induction; energy densities of electric and magnetic fields.

Maxwell's Equations

Maxwell's equations in vacuum. Vector and Scalar potentials in electrodynamics, gauge invariance and gauge fixing, Coulomb and Lorenz gauges. Displacement current. Electromagnetic energy and momentum. Conservation laws. Inhomogeneous wave equation and its solutions using Green's function method. Covariant formulation of Maxwell's equations (brief discussion).

Electromagnetic Waves

Plane waves in a dielectric medium, reflection and refraction at dielectric interfaces. Frequency dispersion in dielectrics and metals. Dielectric constant and anomalous dispersion. Wave propagation in one dimension, group velocity. Metallic wave guides, boundary conditions at metallic surfaces, propagation modes in wave guides, resonant modes in cavities. Dielectric waveguides. Plasma oscillations.

Radiation

EM Field of a localized oscillating source. Fields and radiation in dipole and quadrupole approximations. Antenna; Radiation by moving charges, Lienard-Wiechert potentials, total power radiated by an accelerated charge, Lorentz formula.

References:

1. **D.J. Griffiths,** *Introduction to Electrodynamics,* Prentice Hall
2. **J.D. Jackson,** *Classical Electrodynamics,* Wiley
3. **A. Das,** *Lectures on Electromagnetism,* Hindustan Book Agency
4. **J.R. Reitz, F.J. Milford and R.W. Christy,** *Foundations of Electromagnetic Theory,* Addison-Wesley
5. **W.K.H. Panofsky and M. Phillips,** *Classical Electricity and Magnetism,* Dover
6. **R.P. Feynman**, *Feynman Lectures on Physics (Vol. II),* Addison-Wesley
7. **A. Zangwill,** *Modern Electrodynamics,* Cambridge Univ Press

PS 428 Mathematical Physics II (2 credits)

Calculus of variations

Extremization problems (with and without constraints). Euler-Lagrange equations and Lagrange's multipliers. Functional derivatives for real and complex fields (with applications in classical and quantum physics). Noether's theorem.

Partial Differential Equations

Laplace and Poisson equation (with particular emphasis on solving boundary value problems in Electrostatics and Magnetostatics); Wave equation. Heat Equation. Green's function approach. Separation of variables and solution in different coordinates.

Group Theory

Definition and properties. Discrete and continuous groups. Subgroups and cosets. Products of groups.

Matrix representation of a group. (Ir)reducible reprsentations. Characters. Representations of finite groups.

Examples of continuous groups, SO(3), SU(2) and SO(n) and SU(n). Generators of SU(2) and their algebra. Representations of SU(2).

References:

1. **P. Dennery and A. Krzywicki,** *Mathematics for Physicists,* Dover
2. **S.D. Joglekar,** *Mathematical Physics: Advanced Topics (Vol. II),* Universities Press
3. **P.M. Morse and H. Feshbach,** *Methods of Theoretical Physics (Vol. I & II),* Feshbach Publishing
4. **A.W. Joshi,** *Matrices and Tensors in Physics,* New Age Publishers
5. **W.-K. Tung,** *Group Theory in Physics,* World Scientific
6. **A. Das and S. Okubo,** *Lie Groups and Lie Algebras for Physicists,* Hindustan Book Agency
7. **I. Gelfand and S. Fomin,** *Calculus of Variations,* Dover
8. **W. Yourgrau and S. Mandelstam,** *Variational Principles in Dynamics and Quantum Theory,* Dover

PS 424 Relativistic Physics (2 credits)

Special Theory of Relativity

Motivation. Postulates of special theory of relativity. Lorentz transformation. Space-time diagram. Time dilation and length contraction. Addition of velocities. Doppler effect. Paradoxes.

Four-vectors, contra- and covariant vectors. Coordinate, velocity and momentum four-vectors.

Tensors. Electromagnetic field tensor. Maxwell's equations in tensor notation. Transformation of electromagnetic field. Relativistic dynamics of charged particles in electromagnetic field with special emphasis on particle accelerators. Relativistic Lagrangian of charged particles in electromagnetic fields.

Relativistic Quantum Mechanics

Klein-Gordon equation and its plane wave solution.

Dirac matrices. Dirac equation. Plane wave solutions, intrinsic spin and magnetic moment. Antiparticles.

Dirac equation for the hydrogen atom. Spin-orbit coupling and fine structure.

References:

1. **H. Goldstein C.P. Poole and J.F. Safko,** *Classical Mechanics,* Addison-Wesley
2. **A.P. French,** *Special Relativity,* W.W. Norton
3. **E.F. Taylor and J.A. Wheeler,** *Spacetime Physics: Introduction to Special Relativity,* W.H. Freeman
4. **W. Rindler,** *Introduction to Special Relativity,* Oxford University Press
5. **J.D. Jackson,** *Classical Electrodynamics,* Wiley
6. **L. Schiff,** *Quantum Mechanics*, McGraw-Hill
7. **B.H. Bransden and C.J. Joachain,** *Quantum Mechanics,* Pearson
8. **D. Styer,** *Relativity for the Questioning Mind,* Johns Hopkins Univ Press

PS 426 Physics Laboratory II (Electronics) (4 credits)

1. Circuit analysis using Thevenin's theorem and Kirchhoff's law.
2. Characteristics of diode, BJT, FET, FET-switch
3. Analysis of feedback circuits
4. Differential amplifier and current mirror circuits
5. Characteristics of OPAMP and Trigger circuit
6. Digital electronics

SEMESTER III

- **Computational Physics (3 credits) PS 427**
- **Condensed Matter Physics (3 credits) PS 511**
- **Subatomic Physics (3 credits) PS 512**
- **Atoms and Molecules (3 credits) PS 514**
- **Physics Lab III (6 credits) PS 515**

Total 18 credits

PS 427 Computational Physics (3 credits)

Overview

Computer organization, hardware, software. Scientific programming in FORTRAN and/or C, C++. Introduction to Mathematica and/or Matlab

Numerical Techniques

Sorting, interpolation, extrapolation, regression, numerical integration, quadrature, random number generation, linear algebra and matrix manipulations, inversion, diagonalization, eigenvectors and eigenvalues, integration of initial-value problems, Euler, Runge-Kutta, and Verlet schemes, root searching, optimization.

Simulation Techniques

Monte Carlo methods, molecular dynamics, simulation methods for the Ising model and atomic fluids, simulation methods for quantum-mechanical problems, time-dependent Schrödinger equation. Langevin dynamics simulation.

References:

1. **V. Rajaraman**, *Computer Programming in Fortran 77,* Prentice Hall
2. **W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling**, *Numerical Recipes: The Art of Scientific Computing,* Cambridge University Press
3. **H.M. Antia**, *Numerical Methods for Scientists and Engineers,* Hindustan Book Agency
4. **D.W. Heermann**, *Computer Simulation Methods in Theoretical Physics,* Springer
5. **H. Gould and J. Tobochnik**, *An Introduction to Computer Simulation Methods,* Addison-Wesley
6. **J.M. Thijssen**, *Computational Physics,* Cambridge University Press

PS 511 Condensed Matter Physics (3 credits)

Metals

Drude theory, DC conductivity, Hall effect and magneto-resistance, AC conductivity, thermal conductivity, thermo-electric effects, Fermi-Dirac distribution, thermal properties of an electron gas, Wiedemann-Franz law, critique of free-electron model.

Crystal Lattices

Bravais lattice, symmetry operations and classification of Bravais lattices, common crystal structures, reciprocal lattice, Brillouin zone, X-ray diffraction, Bragg's law, Von Laue's formulation, diffraction from non-crystalline systems.

Classification of Solids

Band classifications, covalent, molecular and ionic crystals, nature of bonding, cohesive energies, hydrogen bonding.

Electron States in Crystals

Periodic potential and Bloch's theorem, weak potential approximation, energy gaps, Fermi surface and Brillouin zones, Harrison construction, level density. Motion of electrons in optical lattices.

Electron Dynamics

Wave packets of Bloch electrons, semi-classical equations of motion, motion in static electric and magnetic fields, theory of holes.

Lattice Dynamics

Failure of the static lattice model, harmonic approximation, vibrations of a one-dimensional lattice, one-dimensional lattice with basis, models of three-dimensional lattices, quantization of vibrations, Einstein and Debye theories of specific heat, phonon density of states, neutron scattering.

Semiconductors

General properties and band structure, carrier statistics, impurities, intrinsic and extrinsic semiconductors, equilibrium fields and densities in junctions, drift and diffusion currents.

Magnetism

Diamagnetism, paramagnetism of insulators and metals, ferromagnetism, Curie-Weiss law, introduction to other types of magnetic order.

Superconductors

Phenomenology, review of basic properties, thermodynamics of superconductors, London's equation and Meissner effect, Type-I and Type-II superconductors.

References:

1. **C. Kittel,** *Introduction to Solid State Physics,* Wiley
2. **N.W. Ashcroft and N.D. Mermin,** *Solid State Physics,* Brooks/Cole
3. **J.M. Ziman,** *Principles of the Theory of Solids,* Cambridge University Press
4. **A.J. Dekker,** *Solid State Physics,* Macmillan
5. **G. Burns,** *Solid State Physics,* Academic Press
6. **M.P. Marder,** *Condensed Matter Physics,* Wiley

PS 512 Subatomic Physics (3 credits)

Nuclear Physics

Discovery of the nucleus, Rutherford scattering. Scattering cross-section, form factors. Kinematics of (non-)relativistic scattering. Properties of nuclei: size, mass, charge, angular momentum, magnetic moment, parity, quadrupole moment. Charge and mass distribution.

Mass defect, binding-energy statistics, Bethe-Weiszacker mass formula. Magic numbers, shell model, parity and magnetic moment.

Nuclear stability: alpha, beta and gamma decay. Tunnelling theory of alpha decay, Fermi theory of beta decay. Parity violation. Fission and fusion. Nuclear reaction.

Nuclear force. Nuclear reaction. Deuteron, properties of nuclear potentials. Yukawa's hypothesis.

Particle Physics

Discovery of elementary particles in cosmic rays. Muon, meson and strange particles. Isospin and strangeness.

Accelerators and detectors.

Quark hypothesis, flavour and colour. Meson and Baryon octets. Gellmann-Nishijima formula. Discovery of J/psi, charm quark. Families of leptons and quarks. Bottom and top quarks.

Gauge symmetry and fundamental forces. Weak interaction, W and Z bosons, Higgs mechanism and spontaneous symmetry breaking. Higgs particle. Gluons and strong interaction.

Neutrino oscillations, CP violation.

References:

1. **B.L. Cohen**, *Concepts of Nuclear Physics,* Tata McGraw Hill
2. **W.N. Cottingham and D.A. Greenwood,** *An introduction to Nuclear Physics,* Cambridge University Press
3. **I. Kaplan,** *Nuclear Physics,* Addison-Wesley
4. **B.R. Martin,** *Nuclear and Particle Physics*, Wiley
5. **A. Das and T. Ferbel,** *Introduction to Nuclear and Particle Physics,* World Scientific
6. **B. Povh, K. Rith, C. Scholtz and F. Zetsche,** *Particles and Nuclei,* Springer

7. **G.D. Coughlan and J.E. Dodd**, *The Ideas of Particle Physics,* Cambridge University Press
8. **D. Griffiths,** *Introduction to Elementary Particles,* Wiley
9. **D.H. Perkins,** *Introduction to High Energy Physics,* Cambridge University Press

<u>PS 514 Atoms and Molecules</u> (3 credits)

Many-electron Atoms

Review of H and He atom, ground state and first excited state, quantum virial theorem. Determinantal wave function. Thomas-Fermi method, Hartree and Hartree-Fock method, density functional theory. Periodic table and atomic properties: ionization potential, electron affinity, Hund's rule.

Molecular Quantum Mechanics

Hydrogen molecular ion (numerical solution), hydrogen molecule, Heitler-London method, molecular orbital, Born-Oppenheimer approximation, bonding, directed valence. LCAO.

Atomic and Molecular Spectroscopy

Fine and hyperfine structure of atoms, electronic, vibrational and rotational spectra for diatomic molecules, role of symmetry, selection rules, term schemes, applications to electronic and vibrational problems. Raman spectroscopy.

Second Quantization

Basis sets for identical-particle systems, number space representation, creation and annihilation operators, representation of dynamical operators and the Hamiltonian, simple applications.

Interaction of Atoms with Radiation

Atoms in an electromagnetic field, absorption and induced emission, spontaneous emission and line-width, Einstein A and B coefficients, density matrix formalism, two-level atoms in a radiation field.

References:

1. **B.H. Bransden and C.J. Joachain,** *Physics of Atoms and Molecules,* Pearson
2. **I.N. Levine,** *Quantum Chemistry,* Prentice Hall
3. **L.D. Landau and E.M. Lifshitz,** *Quantum Mechanics,* Pergamon Press
4. **M. Karplus and R.N. Porter,** *Atoms and Molecules: An Introduction for Students of Physical Chemistry,* W.A. Benjamin
5. **P.W. Atkins and R.S. Friedman,** *Molecular Quantum Mechanics,* Oxford University Press
6. **W.A. Harrison,** *Applied Quantum Mechanics,* World Scientific
7. **C.J. Foot,** *Atomic Physics,* Oxford Univ Press
8. **G. Woodgate,** *Elementary Atomic Structure,* Oxford Univ Press

PS 515 Physics Laboratory III (6 credits)

1. Electron spin resonance
2. Faraday rotation and Kerr effect
3. Study of interfacial tension and viscosity of liquid
4. Reaction kinetics by spectrometer and conductivity
5. Experiment with Raman spectrometer
6. Propagation of ultrasonic waves in liquid and solid
7. Experiment with solar cell
8. Dielectric constant of ice and ferroelectric transition of $BaTiO_3$
9. Zeeman effect
10. Study of superconducting properties in high-T_c superconductor
11. Scanning tunnelling microscopy
12. Experiment with liquid using UV spectroscopy

Note: Each student is required to perform at least 8 of the above experiments.

SEMESTER IV

- **PS 522 Project (4 credits)**
  (There will be mid-term evaluation of the project)

In addition to the Project, a student has to choose any three among the following electives, each of 3 credits. Courses actually offered in a given semester will depend on the interests of the students and on the availability of instructors.

- **Advanced Statistical Mechanics (PS 520)**
- **Astrophysics, Gravitation & Cosmology (PS 523)**
- **Quantum Field Theory (PS 524)**
- **Biophysics (PS 525)**
- **Laser Physics (PS 526)**
- **Advanced Condensed Matter Physics (PS 527)**
- **Nonlinear Dynamics (PS 528)**
- **Theory of Soft Condensed Matter (PS 529)**
- **Modern Experiments of Physics (PS 530)**

Total 13 credits

PS 520 Advanced Statistical Mechanics (3 credits)

Phase Transitions and Critical Phenomena

Thermodynamics of phase transitions, metastable states, Van der Waals' equation of state, coexistence of phases, Landau theory, critical phenomena at second-order phase transitions, spatial and temporal fluctuations, scaling hypothesis, critical exponents, universality classes.

Mean Field Theory

Ising model, mean-field theory, exact solution in one dimension, renormalization in one dimension.

Nonequilibrium Statistical Mechanics

Systems out of equilibrium, kinetic theory of a gas, approach to equilibrium and the H-theorem, Boltzmann equation and its application to transport problems, master equation and irreversibility, simple examples, ergodic theorem.

Brownian motion, Langevin equation, fluctuation-dissipation theorem, Einstein relation, Fokker-Planck equation.

Correlation Functions

Time correlation functions, linear response theory, Kubo formula, Onsager relations.

Coarse-grained Models

Hydrodynamics, Navier-Stokes equation for fluids, simple solutions for fluid flow, conservation laws and diffusion.

References:

1. **K. Huang,** *Statistical Mechanics,* Wiley
2. **R.K. Pathria,** *Statistical Mechanics,* Elsevier
3. **E.M. Lifshitz and L.P. Pitaevskii,** *Physical Kinetics,* Pergamon Press
4. **D.A. McQuarrie,** *Statistical Mechanics,* University Science Books
5. **L.P. Kadanoff,** *Statistical Physics: Statistics, Dynamics and Renormalization,* World Scientific
6. **P.M. Chaikin and T.C. Lubensky,** *Principles of Condensed Matter Physics,* Cambridge University Press

PS 523 Astrophysics, Gravitation & Cosmology (3 credits)

General Theory of Relativity

Brief review of special theory of relativity, geometry of Minkowski spacetime. Curvilinear coordinates, covariant differentiation and connection. Curved space and curved spacetime. Contravariant and covariant indices. Metric tensor. Christoffel connection. Geodesics. Riemann, Ricci and Scalar curvature.

Principle of equivalence. Einstein equations in vacuum. Spherically symmetric solution, Schwarzschild geometry. Timelike and lightlike trajectories. Perihelion precession, bending of light in a gravitational field. Apparent singularity of the horizon, Eddington-Finkelstein and Kruskal-Szekeres coordinates. Penrose diagram.

Energy-momentum tensor and Einstein equations. Weak field approximation, gravitational waves.

Physics of the Universe

Large scale homogeneity and isotropy of the universe. Expanding universe and Hubble’s law. FRW metric and Friedmann’s equations. Equations of state for matter (nonrelativistic dust), radiation and cosmological constant. Behaviour of scale factor for radiation, matter and cosmological constant domination. Big bang cosmology. Thermal history of the universe. Cosmic microwave background radiation and its anisotropy. Inflationary paradigm.

Astrophysics

Measuring distance and the astronomical ladder. Stellar spectra and structure, Hertzsprung-Russell diagram. Einstein equations for the interior of a star. Stellar evolution, nucleosynthesis and formation of elements. Main sequence stars, white dwarves, neutron stars, supernovae, pulsars and quasars.

References:

1. **B. Schutz,** *A First Course in General Relativity,* Cambridge Univ Press
2. **S. Carroll,** *Spacetime and Geometry,* Pearson
3. **S. Weinberg,** *Gravitation and Cosmology,* Wiley
4. **J.V. Narlikar,** *An Introduction to Relativity,* Cambridge Univ Press
5. **J. Hartle,** *Gravity,* Pearson
6. **J.V. Narlikar,** *An Introduction to Cosmology,* Cambridge Univ Press
7. **D. Maoz,** *Astrophysics in a Nutshell,* Princeton University Press
8. **A. Rai Choudhuri,** *Astrophysics for Physicists,* Cambridge Univ Press
9. **T. Padmanabhan,** *An Invitation to Astrophysics,* World Scientific

PS 524 Quantum Field Theory (3 credits)

Examples of classical fields, vibrating string and electromagnetic field. Canonical coordinates and momenta, Lagrangian and Hamiltonian formulation.

Relativistic scalar field and Klein-Gordon equation. Canonical quantization. Space of states, Fock space, vacuum states and excitations. Complex scalar field.

Noether theorem. Internal symmetries. Spacetime translations and energy-momentum tensor. Elementary excitations and particles.

Lorentz and Poincare symmetry. Spinor and vector fields.

Correlators of free scalar field. Retarded, advanced Green functions, Feynman propagator. Coupling to external source and partition function. Time ordering and normal ordering. Wick's theorem.

Dirac field. Lagrangian and Hamiltonian. Canonical quantization and anticommutators. Green's function.

Interacting scalar field, phi-4 and Yukawa interactions. Ising Model and scalar field theory. Interaction picture. Green's functions of interacting field and perturbation theory. Feynman rules and Feynman diagrams.

LSZ reduction formula. S-matrix. Tree level correlators.

Loops and divergences. UV and IR divergences. Connected and disconnected diagrams. Examples of divergences in two- and four-point correlators. Introduction to regularization and renormalization.

References:

1. **M. Maggiore,** *A Modern Introduction to Quantum Field Theory,* Cambridge University Press
2. **P. Ramond,** *Field theory, a Modern Primer,* Addison-Wesley
3. **L. Ryder,** *Quantum Field Theory,* Academic Press
4. **A. Altland and B. Simon,** *Condensed Matter Field Theory,* Cambridge University Press
5. **M.E. Peskin and D.V. Schroeder,** *An Introduction to Quantum Field Theory,* Levant
6. **A. Zee,** *Quantum Field Theory in a Nutshell,* Universities Press

PS 525 Biophysics (3 credits)

Introduction

Evolution of biosphere, aerobic and anaerobic concepts, models of evolution of living organisms.

Physics of Polymers

Nomenclature, definitions of molecular weights, polydispersity, degree of polymerization, possible geometrical shapes, chirality in biomolecules, structure of water and ice, hydrogen bond and hydrophobocity.

Static Properties

Random flight model, freely-rotating chain model, scaling relations, concept of various radii (i.e., radius of gyration, hydrodynamic radius, end-to-end length), end-to-end length distributions, concept of segments and Kuhn segment length, excluded volume interactions and chain swelling, Gaussian coil, concept of theta and good solvents with examples, importance of second virial coefficient.

Polyelectrolytes

Concepts and examples, Debye-Huckel theory, screening length in electrostatic interactions.

Transport Properties

Diffusion: Irreversible thermodynamics, Gibbs-Duhem equation, phenomenological forces and fluxes, osmotic pressure and second virial coefficient, generalized diffusion equation, Stokes-Einstein relation, diffusion in three-component systems, balance of thermodynamic and hydrodynamic forces, concentration dependence, Smoluchowski equation and reduction to Fokker-Planck equation, concept of impermeable and free-draining chains.

Viscosity and Sedimentation: Einstein relation, intrinsic viscosity of polymer chains, Huggins equation of viscosity, scaling relations, Kirkwood-Riseman theory, irreversible thermodynamics and sedimentation, sedimentation equation, concentration dependence.

Physics of Proteins

Nomenclature and structure of amino acids, conformations of polypeptide chains, primary, secondary and higher-order structures, Ramachandran map, peptide bond and its consequences, pH-pK balance, protein polymerization models, helix-coil transitions in thermodynamic and partition function approach, coil-globule transitions, protein folding, protein denaturation models, binding isotherms, binding equilibrium, Hill equation and Scatchard plot.

Physics of Enzymes

Chemical kinetics and catalysis, kinetics of simple enzymatic reactions, enzyme-substrate interactions, cooperative properties.

Physics of Nucleic Acids

Structure of nucleic acids, special features and properties, DNA and RNA, Watson-Crick picture and duplex stabilization model, thermodynamics of melting and kinetics of denaturation of duplex, loops and cyclization of DNA, ligand interactions, genetic code and protein biosynthesis, DNA replication.

Experimental Techniques

Measurement concepts and error analysis, light and neutron scattering, X-ray diffraction, UV spectroscopy, CD and ORD, electrophoresis, viscometry and rheology, DSC and dielectric relaxation studies.

Recent Topics in Bio-Nanophysics

References:

1. **H. Bohidar,** *Fundamentals of Polymer Physics and Molecular Biophysics,* Cambridge Univ Press
2. **M.V. Volkenstein**, *General Biophysics,* Academic Press
3. **C.R. Cantor and P.R. Schimmel**, *Biophysical Chemistry Part III: The Behavior of Biological Macromolecules,* W.H. Freeman
4. **C. Tanford**, *Physical Chemistry of Macromolecules,* John Wiley
5. **S.F. Sun**, *Physical Chemistry of Macromolecules: Basic Principles and Issues,* Wiley

PS 526 Laser Physics (3 credits)

Introduction

Masers versus lasers, components of a laser system, amplification by population inversion, oscillation condition, types of lasers: solid-state (ruby, Nd:YAG, semi-conductor), gas (He-Ne, CO_2, excimer), liquid (organic dye) lasers.

Atom-Field Interactions

Lorenz theory, Einstein's rate equations, applications to laser transitions with pumping, two, three and four-level schemes, threshold pumping and inversion.

Optical Resonators

Closed versus open cavities, modes of a symmetric confocal optical resonator, stability, quality factor.

Semi-classical Laser Theory

Density matrix for a two-level atom, Lamb equation for the classical field, threshold condition, disorder-order phase transition analogy.

Coherence

Concepts of coherence and correlation functions, coherent states of the electromagnetic field, minimum uncertainty states, unit degree of coherence, Poisson photon statistics.

Pulsed Operation of Lasers

Q-switching, electro-optic and acousto-optic modulation, saturable absorbers, mode-locking.

Applications of Lasers

Introduction to atom optics, Doppler cooling of atoms, introduction to nonlinear optics: self-(de) focusing, second-harmonic generation (phase-matching conditions). Industrial and medical applications.

References:

1. **K. Thyagarajan and A.K. Ghatak,** *Lasers: Theory and Applications,* Springer
2. **A.K. Ghatak and K. Thyagarajan,** *Optical Electronics,* Cambridge University Press
3. **W. Demtroeder,** *Laser Spectroscopy,* Springer
4. **B.B. Laud,** *Lasers and Nonlinear Optics,* Wiley-Blackwell
5. **M. Sargent, M.O. Scully and W.E. Lamb, Jr.,** *Laser Physics,* Perseus Books
6. **M.O. Scully and M.S. Zubairy,** *Quantum Optics,* Cambridge University Press
7. **P. Meystre and M. Sargent,** *Elements of Quantum Optics,* Springer
8. **L. Mandel and E. Wolf,** *Optical Coherence and Quantum Optics,* Cambridge University Press

PS 527 Advanced Condensed Matter Physics (3 credits)

Dielectric Properties of Solids

Dielectric constant of metal and insulator using phenomenological theory (Maxwell's equations), polarization and ferroelectrics, inter-band transitions, Kramers-Kronig relations, polarons, excitons, optical properties of metals and insulators.

Transport Properties of Solids

Boltzmann transport equation, resistivity of metals and semiconductors, thermoelectric phenomena, Onsager coefficients. Quantum Hall Effect.

Many-electron Systems

Sommerfeld expansion, Hartree-Fock approximation, exchange interactions. Density functional theory. Concept of quasi-particles, introduction to Fermi liquid theory. Screening, plasmons. Fractional quantum hall effect.

Introduction to Strongly Correlated Systems

Narrow band solids, Wannier orbitals and tight-binding method, Mott insulator, electronic and magnetic properties of oxides, introduction to Hubbard model.

Magnetism

Magnetic interactions, Heitler-London method, exchange and superexchange, magnetic moments and crystal-field effects, ferromagnetism, spin-wave excitations and thermodynamics, antiferromagnetism.

Superconductivity

Basic phenomena, London equations, Cooper pairs, coherence, Ginzburg-Landau theory, BCS theory, Josephson effect, SQUID, excitations and energy gap, magnetic properties of type-I and type-II superconductors, flux lattice, introduction to high-temperature superconductors.

References:

1. **N.W. Ashcroft and N.D. Mermin,** *Solid State Physics,* Brooks/Cole
2. **D. Pines,** *Elementary Excitations in Solids,* Addison-Wesley
3. **S. Raimes,** *The Wave Mechanics of Electrons in Metals,* Elsevier
4. **P. Fazekas,** *Lecture Notes on Electron Correlation & Magnetism,* World Scientific
5. **M. Tinkham,** *Introduction to Superconductivity,* CBS
6. **M. Marder,** *Condensed Matter Physics,* Wiley
7. **P.M. Chaikin and T.C. Lubensky,** *Principles of Condensed Matter Physics,* Cambridge University Press

PS 528 Nonlinear Dynamics (3 credits)

Introduction to Dynamical Systems

Physics of nonlinear systems, dynamical equations and constants of motion, phase space, fixed points, stability analysis, bifurcations and their classification, Poincaré section and iterative maps.

Dissipative Systems

One-dimensional noninvertible maps, simple and strange attractors, iterative maps, period-doubling and universality, intermittency, invariant measure, Lyapunov exponents, higher-dimensional systems, Hénon map, Lorenz equations, fractal geometry, generalized dimensions, examples of fractals.

Hamiltonian Systems

Integrability, Liouville's theorem, action-angle variables, introduction to perturbation techniques, KAM theorem, area-preserving maps, concepts of chaos and stochasticity.

Advanced Topics

Selections from quantum chaos, cellular automata and coupled map lattices, pattern formation, solitons and completely integrable systems, turbulence.

References:

1. **E. Ott,** *Chaos in Dynamical Systems,* Cambridge University Press
2. **E.A. Jackson,** *Perspectives of Nonlinear Dynamics (Vol. I and II),* Cambridge University Press
3. **A.J. Lichtenberg and M.A. Lieberman,** *Regular and Stochastic Motion,* Springer
4. **A.M. Ozorio de Almeida,** *Hamiltonian Systems: Chaos and Quantization,* Cambridge University Press
5. **M. Tabor,** *Chaos and Integrability in Nonlinear Dynamics,* Wiley-Blackwell
6. **M. Lakshmanan and S. Rajasekar,** *Nonlinear Dynamics: Integrability, Chaos and Patterns,* CRC Press
7. **H.J. Stockmann,** *Quantum Chaos: An Introduction,* Cambridge University Press
8. **V. Arnold,** *Mathematical Methods of Classical Mechanics,* Springer

PS 529 Theory of Soft Condensed Matter (3 credits)

Review of statistical mechanics

Partition function, free energy, entropy. Entropy and information. Ideal systems. Interacting systems: Ising model and phase transition. Approximate methods for interacting systems: mean field and generalizations.

Complex molecues

The cell, small molecules, proteins and nucleic acids. Stretching a single DNA molecule, the freely jointed chain, the one-dimensional cooperative chain, the worm-like chain, zipper model, The helix-coil transition.

Biological matter

Polymer collapse: Flory's theory. Collapse of semiflexible polymers: lattice models and the tube model. The self-avoiding walk and the O(n) model. An introduction to protein folding and design. RNA folding and secondary structure. Protein and RNA mechanical unfolding. Molecular motors.

Physics of active matter

Active matter and self-propelled dynamics. Dry active matter, model of flocking. Hydrodynamic equations of active gels, entropy production, conservation laws, Thermodynamics of polar systems. Fluxes, forces, and time reversal. Constitutive equations, Microscopic interpretation of the transport coefficients. Applications of hydrodynamic theory to phenomena in living cell: Derivation of Hydrodynamics from microscopic models of active matter, microscopic models of self-propelled particles: motors and filaments.

Theoretical models of stochastic dynamics

Stochastic processes as an universal toolbox. Brownian Motion. Langevin Equation. Fokker-Planck description. Fluctuation-dissipation relations. From stochastic dynamics to macroscopic equations Smoluchowski dynamics. From Smoluchowski to hydrodynamics.

Numerical methods

Complex fluids, soft matter, colloids. Lattice gas cellular automata models. Lattice Boltzman equation.

References

1. **K. Huang**, *Statistical Physics*, Wiley
2. **R.K. Pathria and P.D. Beale**, *Statistical Mechanics,* Academic Press
3. **K. Sneppen and G. Zocchi**, *Physics in Molecular Biology,* Cambridge
4. **P. Nelson**, *Biological Physics*, Freeman
5. **B. Alberts et al**, *Molecular Biology of the Cell,* Garland

PS 530 Modern Experiments of Physics (3 credits)

Note: This course will familiarize students with some landmark experiments in physics through the original papers which reported these experiments. A representative list is as follows:

1. Mössbauer effect
2. Pound-Rebka experiment to measure gravitational red shift
3. Parity violation experiment of Wu et al
4. Superfluidity of ^{3}He
5. Cosmic microwave background radiation
6. Helicity of the neutrino
7. Quantum Hall effect - integral and fractional
8. Laser cooling of atoms
9. Ion traps
10. Bose-Einstein condensation
11. Josephson tunneling
12. Atomic clocks
13. Interferometry for gravitational waves
14. Quantum entanglement experiments: Teleportation experiment, Aspect's experiment on Bell's inequality
15. Inelastic neutron scattering
16. CP violation
17. J/Psi resonance
18. Verification of predictions of general theory of relativity by binary-pulsar and other experiments
19. Precision measurements of magnetic moment of electron
20. Libchaber experiment on period-doubling route to chaos
21. Anfinson's experiment on protein folding
22. Scanning tunnelling microscope
23. Discovery of the Higgs particle
24. Discovery of Neutrino oscillation

References

The original papers, review articles and Nobel Lectures constitute the resource material for this course.