

**Syllabus**  
**for**  
**Doctoral Course**  
**Variable Energy Cyclotron Centre**  
**Department of Atomic Energy**  
**1/AF Bidhan Nagar, Kolkata 700 064**

*Total credit: 60. Duration: one year. The 40 credit basic courses tabulated serially in I to XII are common to all. After completion of this 40m credit, a student may either choose: [2 advance courses from XIII to XIX ( 2×4=8 credit)] or [one advance course (4 credit) + one mini-project( equivalent to 4 credit)] and finally a project equivalent to 12 credit.*

**I. Mathematical Physics:**

**Credit: 3**

Linear vector spaces, Linear operators and matrices, Systems of linear equations. Eigen values and eigen vectors, infinite-dimensional vector spaces: Hilbert space & Hermitian operators. Linear ordinary differential equations, Special functions. Linear partial differential equations in physics, Separation of variables method of solution. Complex variable theory; Analytic functions. Taylor and Laurent expansions, Classification of singularities, Analytic continuation, Contour integration, Method of steepest descent. Integral equations and Green functions, Ideas about nonlinear equations, Approximation methods : WKB approximation, Fourier and Laplace transforms.

Introduction to finite and continuous groups. Group representations and operations, Permutation group and its representations, Lie group and Lie algebras. SU(2), SU(3) and SU(N) groups, Poincare groups. Introduction to manifolds, Tangent Vectors and tangent spaces, Vector fields, Differential geometry, Riemannian manifolds and Gauge theories.

**Suggested Books :**

1. A Course in modern Mathematical Physics : Groups, Hilbert Space and Differential Geometry, *Peter Szekeres*
2. Mathematical Methods for Physics and Engineering: A Comprehensive Guide, *K.F. Riley, M. P. Hobson, S. I. Bence*
3. Complex Variables: Introductions and Applications, *M. J. Ablowitz and A. S. Focas*
4. Geometrical Methods of Mathematical Physics, *Bernard Shutz*
5. Lectures on Advanced Mathematical Methods for Physicists, *S. Mukhi & N. Mukunda.*

## II. Quantum Mechanics:

**Credit: 3**

**Approximation methods in quantum mechanics :** W. K. B. and variational methods and applications. Time independent perturbation theory (for non degenerate and degenerate cases) and its application to helium atom, Stark and Zeeman effects, Time dependent perturbation theory and Fermi golden rule, its applications to beta decay theory and principle of detailed balance.

**Collision theory : Born series and interaction pictures :** Propagator in quantum mechanics. Measurements in Quantum Mechanics, EPR paradox, Hidden variables and Bell's inequality.

**Relativistic quantum mechanics :** Klein-Gordon and Dirac equations and their solutions, Gamma matrices Non relativistic limit of Dirac equation; Parity inversion and time reversal, Bilinear covariants, Charge conjugation.

**Lagrangian formulation :** Symmetries of Lagrangian density, Noether's theorem, Energy-momentum tensor  $T^{\mu\nu}$ -its origin & physical meaning of different components.

**Path integral formulation of quantum mechanics and its Applications.**

### **Suggested Books :**

1. Quantum Mechanics, *Leonard I. Schiff*
2. Quantum Mechanics, *Eugen Merzbacher*
3. Quantum Mechanics, *A. S. Davydov*
4. Principle of Quantum Mechanics, *R. Shankar*
5. Relativistic Quantum Mechanics, *James D. Bjorken and Sidney D. Drell*
6. (i) Quantum Mechanics : Non-Relativistic Theory & (ii) Classical Theory of Fields, *L.D. Landau and E.M. Lifshitz*
7. Quantum Mechanics and Path Integrals, *P. Feynman and A.R. Hibbs*

### **III. Classical Mechanics:**

**Credit: 2**

#### **Newton's Laws (Definition of inertial frames, Galilean group)**

Lagrangian formulation: Lagrangian and its properties, Minimum action principle, Euler-Lagrange's equations, Constrained motion, Cyclic coordinates, Noether's theorem. Application: Two body problem, Restricted three body problem.

Hamiltonian formulation: Legendre transformation, Generalized momentum, Phase Space, Hamilton's equations of motion, Liouville's theorem, Fixed points and Linear Stability analysis, Phase portraits, Symplectic nature of Phase Space, Poisson Brackets, Canonical Transformations, Generating functions, Action-Angle variables, Hamilton-Jacobi equation, Singular Lagrangian and examples like time crystal/ Gauge field theory.

Connection of classical mechanics with quantum mechanics

Generic Scattering crosssection, crosssection with  $1/r$  potential. Secular perturbation theory

Integrability, Kolmogorov-Arnold-Moser theorem, Elements of Chaos theory.

#### **Suggested Books:**

1. Mathematical Methods of Classical Mechanics, V I Arnold
2. Classical Mechanics, T W B Kibble and F H Berkshire
3. Classical Mechanics, H Goldstein
4. Classical Mechanics, L D Landau and L M Lifshitz

### **IV. Statistical Mechanics**

**Credit: 3**

Distribution functions: Mean Values and standard deviations; Gaussian limit of the binomial distribution, distribution of several random variables. Gibbsian statistical ensembles: Micro-canonical, Canonical and Grand Canonical ensembles. Gibb's theorem: Information entropy: Fluctuations: Quantum statistics: Bose-Einstein statistics, Fermi-Dirac statistic and passage to the classical limit. Ising Model: Theory of phase transitions and critical phenomena-Critical exponents and universality, Phase transformation kinetics: Homogeneous and Heterogeneous nucleation, Spinodal decomposition

Non-equilibrium statistical mechanic: Liouville's equation, BBGKY hierarchy, Boltzmann equation, Fokker-Planck Equation and Brownian motion.

### **V. Classical Electrodynamics:**

**Credit: 3**

**Maxwell equations, Macroscopic electromagnetism, conservation laws:** Maxwell's displacement current, Vector and scalar potential, Gauge transformations, Lorentz gauge and Coulomb gauge, Green's theorem of the wave equation, Poynting's theorem and conservation of energy and momentum, Boundary value problems and numerical techniques.

**Plane electromagnetic wave and wave propagation, Wave guides and resonant cavities:** Plane wave in a non-conducting medium, Linear and circular polarization, Fields at the surface and within conductor, Cylindrical cavities and Wave-guides, Modes in a rectangular Wave-guide, Energy flow and attenuation in a Wave-guide.

**Radiating systems, Multiple fields and radiation:** Fields and radiation of a localized oscillating source, Electric dipole field and radiation, Multipole expansion and electromagnetic fields, Properties of multipole fields, energy and angular momentum of multipole radiation, Sources of multipole radiation : Multipole moments.

**Relativistic electrodynamics:** The special theory of relativity, The Lorentz transformation and basic kinematic results of special relativistic, Invariance of electric charge, Covariance of electrodynamics, Transformation of electromagnetic fields, Relativistic charged particles in an electromagnetic field.

**Radiation by moving charges:** The Lienard-Wiechert potentials and field for a point charge, Total power radiated by an accelerated.

**Suggested Books:**

1. Classical electrodynamics, *I. D. Jackson*.
2. Modern Electrodynamics, A Zangwill, Cambridge University Press, 2016

**VI a. Research Methodology:**

**Credit: 1**

1. Research – meaning, characteristics and types, steps of research, research ethics and plagiarism.
2. Introduction to patent laws – patent laws, process of patenting a research finding, copy right, cyber laws.
3. Scientific presentation procedure
4. Scientific seminars by faculties’.

Suggested books:

- a. Research Methodology: Methods and Techniques, C.R. Kothari

**Vib. Computational Methods and Programming:**

**Credit: 2**

1. Scientific programming- Procedural programming and Object oriented programming (examples in Fortran and C++)

- 2a. Simulation techniques - Random variables, discrete and continuous, Montecarlo techniques and application of Montecarlo techniques, Techniques of dynamical simulations.
- 2b. Statistics and treatment of Statistical analysis of data: - estimation and propagation of error, curve fitting, least square methods, Confidence limit.
3. Numerical techniques – Integration, differentiation, diagonalization of matrices, root finding (bisection and Newton-Raphson method); Interpolation techniques; ODE, PDE, Runge-Kutta method, Solution of numerical problem using different numerical technique.

**Suggested books:**

1. Numerical Mathematical Analysis by James Blaine Scarborough, Oxford and IBH Publishing
2. Computer oriented numerical methods , V. Rajaraman
3. Data reduction and error analysis for the physical sciences, By Philip R. Bevington and D. Keith Robinson
4. An Introduction to Error Analysis (University Science Books, Mill Valley, California, 1982) by J.R. Taylor.

**VII. Experimental techniques and methods:**

**Credit: 5**

1. Philosophy of experimental science - laboratory safety, measurement of various physical properties with appropriate transducers, Vacuum - production methods and measurement techniques, Cryogenics - production and measurement, Workshop practice and basics of engineering drawing.

2. Material Characterization techniques – Electrical, Magnetic, and Optical property measurements, X-ray diffraction, neutron scattering and electron scattering techniques, Surface structure and topography (Scanning Electron Microscopy) and surface property measurements (Scanning Probe Microscopy), Phase changes.

(Differential Scanning Calorimeter), Mechanical property measurement: Tension and compression testing, Micro and Nano-indentation techniques, Characterization of defects and their detection (Positron Annihilation Spectroscopy, Transmission Electron Microscopy)

**Suggested books:**

- a. Materials Characterization: Introduction to Microscopic and Spectroscopic Methods, Yang Leng
- b. Characterization of materials, Elton Kaufmann

**Detectors and Techniques for Nuclear and High Energy Physics**

- (a) Interaction of Radiations with matter: Interaction of charged particles, Electrons, photons, Neutrons, Muons and neutrinos with matter.

Radiation exposure and Dose

(b) Basics of detectors: General properties of radiation detectors, Simplified detector model, Modes of detector Operation, Pulse height spectra, Energy resolution, Detector efficiency, Working principle and properties of different types of detectors - Gas detectors, Scintillation Detectors, Semiconductor Detectors

(c) Basics of nuclear electronics: Pre-amplifier, amplifier, discriminators, gate and delay generators, Analog to Digital Converter, Time to Amplitude Converter and the basics of data acquisition systems.

(d) Experimental Nuclear physics techniques and detectors: Charged particle spectroscopy and particle identifications, Gamma ray spectroscopy, Fast neutron spectroscopy and detectors related to the different techniques

(e) Experimental High Energy Physics techniques and detectors: General concept of building a HEP experiment, coverage and options, tracking detectors, calorimeters, vertex detectors, muon chambers, neutrino detectors, particle identification detectors in HEP. Data analysis in HEP: General approach of data cleanup, calibration, track reconstruction, reconstruction of events, challenges in each stage.

Suggested books:

- a. Radiation Detection and Measurement, Glenn F. Knoll
- b. Nuclear Radiation Detectors, S.S. Kapoor and V. Ramamurthy
- c. Techniques for Nuclear and Particle Physics Experiments: A How-To Approach, William R. Leo
- d. Experimental Techniques in High-energy Nuclear and Particle Physics, edited by Thomas Ferbel
- e. Introduction to Experimental Particle Physics, Richard Clinton Fernow
  
- f. Data Reduction and Error Analysis for the Physical Sciences, Philip Raymond Bevington, D. Keith Robinson
- g. Data Analysis Techniques for High-Energy Physics, edited by R. Frühwirth, M. Regler

## **VIII. Basic Field Theory:**

**Credit: 3**

**Lorentz invariance and Relativistic kinematics. A preview of fundamental particles and their interactions. Review of classical field theory :** Principle of least action, Lagrangian formulations for continuous system and fields.

**Symmetries and conservations laws, Noether's theorem, Introduction to field quantization:**

Canonical quantizations of scalar, Spinor and gauge fields.

**Principle of gauge invariance:** Global and local gauge transformations, Abelian gauge fields.

**Interaction fields :** Perturbation expansion of correlation functions, Wick theorems, Feynman diagrams, S-matrix and cross section, Calculations of cross section and decay rates for elementary processes.

**Suggested Books :**

1. An introduction to Quantum Field Theory, *M. E. Peskin and D. V. Schroeder*
2. Quantum Field Theory, *L. H. Ryder*
3. Field Theory, *P. Ramond*
4. Gauge Field theory, *S. Pokoroski*
5. Quantum field theory, *L. S. Brown*

**IX. Basic Accelerator physics:**

**Credit: 3**

**Introduction to accelerators:** History of accelerators. Types of particle accelerators. Basic principle of Cockcroft-Walton, Van-de-graaff, Tandem, Linear accelerator, Cyclotron, Synchrotron, Storage rings and Betatron. Accelerators in India.

**Transverse Beam Dynamics:** Two dimensional field expansion, Field calculations of magnetic focusing and bending optics, Particle equations of motion, Thin-lens and Quadrupole focusing, Edge focusing, Solenoid focusing, Hill's equation, Phase advance in periodic focusing lattices, Transfer matrix technique, Transfer matrices for drift space, dipole, quadrupole, Stability criterion, Beta function, Courant-Snyder invariant and Twiss parameters, Beam emittance.

**Longitudinal Beam Dynamics:** Longitudinal Equation of Motion, Off-momentum orbits in synchrotrons, Transition and Momentum compaction, Phase stability, Synchrotron oscillation, Longitudinal emittance.

**Cyclotron:** Basic principle of cyclotron, Resonance condition, AVF cyclotron, Synchrocyclotron, Betatron tunes, Shape of the cyclotron magnet, Injection, Extraction, Beam quality-time structure, energy resolution and emittance. Room temperature and Superconducting cyclotron.

**RF Linear Accelerator:** Principle of Linear accelerator, Wideroe and Alveraz linac, Transit time factor, Accelerating field and dispersion curve, Ion linac, Empty cavity and Loaded cavity, Travelling wave and standing wave structures.

**Ion Sources:** Principle of ionization, Ion sources for positive ions - Duoplasmatron, PIG, ECR, Ion sources for negative ions- surface, volume and charge exchange, Beam formation, ECR ion source and beam transport line.

**Synchrotron and storage rings:** Basic principle of Synchrotron, Electron and ion Synchrotron, Synchrotron radiation source, Total radiated power, Properties of Synchrotron radiation, Wiggler and undulator.

**Application of accelerators:** Research applications, Medicine, Industry etc.

## **X. Basic Condensed Matter Physics: Credit: 3**

**Crystal structure and crystallography :** Bravais lattice – Primitive vectors, Primitive unit cell, Conventional unit cell, Reciprocal lattice and Brillouin zone, X-ray diffraction, Comparison with electron and neutron diffraction.

**Electronic structure of solids :** Band structure of solids, Introduction to many body problem, Single particle approximation, Hartree-Fock methods, Bloch theorem, Tight binding method, Introduction to Density functional theory.

**Lattice vibrations :** Phonons-Debye model for specific heat of solids-lattice dynamics-phonon spectrum. Electrical & thermal transport in solids, Role of electron-phonon interaction-Boltzmann transport equation.

**Magnetism :** Origin of magnetism, Quantum theory of diamagnetism and paramagnetism, Heisenberg's exchange interaction and ferromagnetism, Introduction to superexchange, Direct exchange and double exchange,

**Superconductivity & Superfluidity :** Phenomenological description of superconductivity, Interaction between electron and phonon, Cooper pair, Meaning of energy gap, Meissner effect, London theory, Classification of superconductors, High temperature superconductors, Outline of the microscopic BCS theory, Ginzburg-Landau theory. Superfluidity in liquid He. Landau's critical velocity, Two-fluid model.

**Dielectric properties of solids :** Static dielectric constant, Electronic and ionic polarization of molecules, Ferroelectricity- dipole theory, Inter-band transitions, Kramers-Kronig relations, Polarons, Excitons, Optical properties of metals and insulators.

**Defects in solids:** Classification of defects, Role of dislocations in material behavior. Irradiation effects in solids, Concept of DPA, Introduction to nuclear reactor.

## **XI. Basic Nuclear physics: Credit 3**

1. **Nuclear structure:** Chart of Nuclide, Nuclear Ground State Properties (Mass, binding energy, moments, ...), Introduction to nuclear models, liquid drop model, mean field concept and basic shell model, Nuclear shapes and Deformed shell model, Introduction to Gamma-ray spectroscopy, Gamma ray selection rule, single particle states, collective states, Methods of production of excited states in nuclei, Present day challenges.
2. **Nuclear reactions:** Nuclear reaction kinematics, Nuclear radius and methods of determination of nuclear radius, Scattering theory (partial wave analysis etc.), Statistical model (compound nucleus), Fusion-evaporation, Fusion-Fission, Concept of Level density and Temperature and methods of its experimental estimation, Resonances, Breit-Wigner formula.



Introduction to different nuclear reactions: Coulomb excitation, Direct reactions, Multi-nucleon transfer, Deep inelastic collision, Multi-fragmentation and spallation.

Introduction to the present day interest in nuclear reaction studies.

3. **Radioactive Ion Beam (RIB):** What is RIB and why it is important, Basics of the methods of production of RIB, Challenges in doing experiments using RIB, RIB facilities in the world.

## **XII. Laboratory experiments: Credit 6 (Each student will carry out minimum of 6 experiments)**

The experiments that will be carried out will make the students familiar with different types of detectors and nuclear electronics required for nuclear physics experiments and high energy physics experiments. The students will also carry out specific materials science experiments.

1. Operation of vacuum pumps and gauges
2. Thickness measurement of thin foils
3. Calibration and energy resolution of different types of radiation detectors (e.g. Si, CsI(Tl), HPGe, BaF<sub>2</sub>, etc.)
4. Thickness uniformity test of different detectors
5. Characterization of a neutron detector
6. Characterization of a gaseous detector (Gas electron multiplier/avalanche counter)
7. Efficiency measurement of different types of  $\gamma$  detectors
8. Characterisation of samples using XRD (X-ray diffractometer)
9. Measurement of stored energy in deformed samples using DSC (differential scanning calorimeter)
10. Measurement of mechanical strength of different materials using universal testing machine.
11. Characterisation of samples using Scanning Electron Microscope and Energy Dispersive X-ray Analysis.
12. Nanostructuring by ion beam.
13. Preparation and characterisation of Nanoparticles by sol-gel method.
14. Measurement of muon life time
15. Characteristic study of wavelength shifter fibres
16. Fabrication and characterization of a scintillator detector.

### **XIII. Advanced Nuclear Structure:**

**Credit: 4**

Nuclear Models (HF, HFB), Microscopic-macroscopic model and total energy calculations (Strutinsky method), Introduction to Density Functional Theory, Electromagnetic moments, Different modes of excitation in nuclei, Giant resonances, Gamma ray spectroscopy and nuclear structure, Construction of level scheme, Spin and parity assignment of nuclear levels, Lifetime measurement of nuclear levels, Observables and deduced quantities, Nuclear Isomerism, Introduction to total Absorption Spectroscopy and beta-delayed neutron emission.

### **XIV. Advanced nuclear reaction:**

**Credit: 4**

Damped nuclear collision: General features, Kinetic energy loss, Angular distribution, Angular momentum dissipation, Time scale, Phenomenological and theoretical models for heavy ion collision, Dissipative forces: one-body, two-body dissipation. Fission dynamics: Dynamical models of fission, Quasi fission, Synthesis of super heavy elements (SHE), Heavy-ion physics at low and intermediate energies: Intermediate mass fragments emission, Reaction near Fermi energy domain, Hot nucleus, Multi-fragmentation, Liquid-gas phase transition, Theoretical models of multi-fragmentations, simulations and QMD model. Nuclear astrophysics: Nuclear resonances, Deep-sub-barrier fusion, Astrophysical S-factor, Gamow peak, Calculation of nuclear reaction rates and its use in calculating primordial and Stellar abundances; Equation of State for dense nuclear matter,  $\beta$ -equilibrium, Compact stars.

## **XV. Advanced Accelerator physics:**

**Credit: 4**

**Introduction:** Sources of charged particle, Lorentz force and equation of motion, Hamiltonian of a charged particle, Charge particle motion in electromagnetic fields, Planer diode without and with space charge.

**Basic beam parameters:** Definition of beam parameters, Beam energy, Beam current, Time structure, Peak and average beam current, Beam size, Transverse beam dimensions, Bunch length, Energy spread, Beam emittances, Beam formation, Buncher, Beam chopper.

**Beam optics and transport elements:** Accelerator coordinate system, Paraxial ray equation for axially symmetric systems, Series representation of electric and magnetic fields, Paraxial ray equation, Solutions of the paraxial ray equations, Electrostatic lenses, Solenoidal magnetic lens, Larmor frame, Aberrations, Transfer matrix of transport elements, Stability condition, Beam envelope, Beam matrix, Transport notations, Basic focusing modules and different kinds of imaging, Telescopic system, Coupled systems, Transfer matrices of solenoid and Skew quadrupoles. Quadrupole doublet and Triplet.

**Transverse and longitudinal beam dynamics:** Beam envelope equation, Courant-Snyder invariant and emittance, Normalized emittance, Twiss parameters, Liouville's Theorem, Periodic system, FODO and FOFO Cell. Magnet imperfections, Dipole field and Quadrupole gradient errors, Resonances in circular accelerators. Off momentum orbit, Dispersion function, Momentum compaction, Transition energy, Negative mass, Dispersion matching, Chromaticity and its corrections. Longitudinal equation of motion, Phase stability and synchrotron oscillations, Fixed points, Bucket, Separatrix.

**Beam with space charge:** Space charge effects, Uniform beam model with elliptical symmetry, Applied and self fields, Beam envelope equation with space charge, Pervience, Beam transport in a uniform and periodic focusing channel, Tune shift and current limits, Envelope oscillations, modes and instabilities, Linear beam model with charge neutralization, Space charge compensation. Vlasov model, K-V and Waterbag distribution, Stationary distributions in a uniform focusing channel, RMS emittance, Concept of equivalent beams, RMS envelope equations, Sources of emittance growth, Filamentation of phase space, Wake fields and image charge effects.

**Linear accelerators:** Particle Acceleration in an RF Field, Energy Gain in an RF Gap, Transit-Time-Factor, Shunt impedance, Quality factor, Phase and group velocities, Periodic Structures, Floquet Theorem and Space Harmonics, Traveling-Wave Linac Structures, Constant-Impedance and Constant-Gradient Structure, Independent-Cavity Linacs, Wideroe Linac, H-Mode Structures, Alvarez Drift-Tube Linac, Coupled-Cavity Linacs, Accelerating Structures for Superconducting Linacs, Transverse dynamics in a Linac, Transverse RF Focusing and Defocusing, Quadrupole Focusing in a Linac, Longitudinal dynamics in Linac, Longitudinal Focusing, Stability analysis, Separatrix, RF Bunching, Beam dynamics in RFQ accelerator.

**Storage rings and synchrotron radiation:** Radiation from moving charges, Coulomb regime, Radiation regime, Radiation sources, Bending magnet radiation, Wavelength shifter, Wiggler magnet radiation, Undulator radiation, Radiation power and angular distribution, Quantum fluctuation, Beam lifetime.

**Advance accelerators:** Free electron laser, Plasma accelerators, Spallation neutron sources, Rare ion beam (RIB) facilities. Accelerators driven subcritical systems (ADSS).

## **XVI. Advanced High Energy Physics                      Credit: 4**

**Renormalization in quantum field theory:** One loop radiative corrections in quantum electrodynamics (QED), Power counting and the index of Divergence, dimensional regularizations and renormalizations. Calculations of one loop diagrams in QED.

**Quantum Chromodynamics (QCD):** Non-abelian gauge theory, one loop diagrams and running coupling, Perturbative QCD.

**Structure of hadrons:** Proton form factor, Deep inelastic scattering of electron off proton, Parton evolutions.

**Heavy Ion collisions at Ultra Relativistic Energies :** Quark Gluon Plasma, Hadrons in thermal bath, Thermodynamics of strongly interacting matter, QCD phase transition in the laboratory, Space time evolution and signals of quark gluon plasma.

Space time evolution of Quark Gluon Plasma and relativistic hydrodynamics.

### **Suggested Books :**

6. An introduction to Quantum Field Theory, *M. E. Peskin and D. V. Schroeder*
7. Quantum Field Theory, *L. H. Ryder*
8. Field Theory, *P. Ramond*
9. Gauge Field theory, *S. Pokoroski*
10. Quantum field theory, *L. S. Brown*
11. Introduction to High Energy Heavy Ion Collisions, *C. Y. Wong*
12. Quark Gluon Plasma from Big Bang to Little Bang, *K. Yagi, T. Hatsuda ,and Y. Miake.*

## **XVII. Advanced Materials Science – I (Effects of radiation in metals and alloys): Credit: 4**

**Interaction of radiation with matter:** Interaction of electromagnetic radiation, neutrons and charged particles with matter, Concept of nuclear and electronic energy loss, Differential cross section in projectile target collision

**Radiation Damage Event:** Neutron-nucleus interactions, Interaction between ions and atoms, Ionization collisions.

**The displacement of atoms:** Elementary displacement theory, Modification to Kinchin-Pease displacement model, Displacement cross-section

**Damage cascade:** Displacement mean free path, Primary recoil spectrum, Cascade damage energy and cascade volume, stages of cascade development, behaviour of defects within the cascade

**Radiation induced defect formation:** Point defect formation, Thermodynamics of point defect formation, Diffusion of point defects, Dislocations.

**Radiation enhanced diffusion and reaction rate theory:** Point defect balance equation, Radiation enhanced diffusion, Defect reactions, Reaction-rate controlled processes.

**Radiation induced segregation (RIS):** RIS in concentrated binary alloys and ternary alloys, Effect of local composition changes on RIS.

**Phase stability under irradiation:** Radiation induced segregation, Radiation induced precipitation, Meta-stable phases, Amorphization.

**Unique effects of ion irradiation:** Ion irradiation techniques, Composition changes, Other effects of ion implantation like grain growth, Texture, Dislocation microstructure.

**Simulation of neutron damage with ions :** Aspects of radiation damage relevant to ion irradiation, Advantages and disadvantages of various particle types, Emulation of neutron irradiation damage with proton, Irradiation parameters for particle irradiation, Effects on mechanical properties due to irradiation hardening, Embrittlement, Irradiation creep and growth.

## **XVIII. Advanced Material Science II**

**Credit: 4**

**Multi-functional materials:** Ferroelectricity, Multiferroic materials, Ferroelasticity, Magnetoelectric coupling, Conducting polymer and nanocomposites.

**Nano-particle Physics:** Introduction to nanoscale physics, nano mechanics, nano electronics, nano photonics, spintronics, various nano structured materials and their synthesis processes, probing of nano materials by advanced tools, applications of nano materials.

**Advanced oxide materials:** Crystal field splitting, John Teller distortion, Zener double exchange model, Mott insulator, Theory of superconductivity, Manganites, Density functional theory, Magnetic properties of solids, d<sup>0</sup> ferromagnetism, Defect characterization in oxides by positron annihilation techniques, Mossbauer spectroscopy in oxides.

### **Suggested Books:**

1. Solid State Physics, A J Dekker
2. Physics of Nanostructures, Dresselhaus and Dresselhaus
3. Transition Metals Oxides: An introduction to their electronic structure and properties, P A Cox.

## **XIX. Advanced High Energy Physics (Experiment) :**

**Credit 4**

**Introduction to Relativistic Heavy-Ion Collisions-Experiments:** Flow-chart from beam to Physics.

**Relativistic Kinematics:** Lorentz transformation; frequently used reference frames, Rapidity, pseudo-rapidity, invariant cross-section Collision and decays;

**Distribution Functions:** particle production and measurement in high energy collisions. ;

**Detector Simulation in High Energy Physics:** Requirement of detector simulation, Introduction to Geant4, Illustration with an example. ;

**Physics of collisions:** Synchrotron and Storage ring, Energy, Cross-section, Luminosity, Event rate, beam parameters.

**Introduction to data analysis:** hits, primary vertex, tracks, secondary vertex, trigger and pile-up.

**Raw Data processing:** Concept of detector and electronic noise, Detector calibration, Acceptance and Efficiency estimation, event and physics trigger selection, analysis for physics objectives.

**Particle identification in high energy experiments:**  $dE/dx$ , Range, TOF technique, Transition radiation.

**Different techniques of Background and Error estimation.**

**Yield Calculations (Including Detector effects).**

**Global Observables:** Multiplicity, (pseudo)rapidity distributions, invariant yields. ;

**Centrality of events:** Glauber Model, experimental methods.

**Quarkonia suppression:** Quarkonium spectroscopy, dynamics of quarkonium production in elementary collisions, cold nuclear matter effects, Debye screening, experimental observables and interpretation,

**Correlations and Fluctuations:** Concepts, BE correlations, Two particle angular correlation, physics interpretation.

**Collective Flow:** Radial flow, anisotropic flow: different flow harmonics and methods of extraction.

**Physics of Jets:** Formation, Energy loss, Jet reconstruction in high energy collisions (methodology), Importance.

**Books:**

1. Introduction to high energy Heavy-Ion Collisions, C. Y. Wong
2. Quark Gluon plasma from Big Bang to Little Bang, K. Yagi, T. Hatsuda and Y. Miake
3. Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, Wojciech Florkowski
4. A Short Course on Relativistic Heavy Ion Collisions, Asis Kumar Chaudhuri
5. Ultrarelativistic Heavy-Ion Collisions, Ramona Vogt

**XX. Project work equivalent to 12 credit.**

**Total credit: 60**

*Contact:*

*Dean-Academic (Physical Sciences)  
Variable Energy Cyclotron Centre*

*Department of Atomic Energy  
1/AF Bidhan Nagar, Kolkata 700 064  
Email: [daps@vecc.gov.in](mailto:daps@vecc.gov.in)*