# Semester-I (CORE)

## 1. (CORE) Mathematical Physics: (Credit: 1), Total: 15 hrs.

Linear vector spaces, matrix methods and eigenvalue problems, tensors.
Ordinary and partial linear differential equations, non-linear differential equation, Green's function method.
Theory of complex variables, analytic functions, contour integration.
Group theory and its applications.

Suggested Books:

1. Mathematical Methods for Physicists: A concise introduction, T L Chow
2. Methods of Mathematical Physics Vol. I & Vol. II, R Courant & D Hilbert
3. Complex variables & applications, J W Brown & R V Churchill
4. Mathematical methods in physical sciences, M L Boas
5. Group theory and quantum mechanics, M Tinkham
6. Group Theory in a Nutshell, A. Zee

**Course Outcome:** The student will have a basic understanding of mathematical methods such as linear vector spaces, matrix methods, differential equations, complex variables and group theory and will be ready to apply such tools in their research.

## 2. (CORE) Classical Mechanics: (Credit: 1), Total: 15. hrs.

Introduction to dynamical systems, Discrete dynamical systems (Maps), Continuous dynamical systems, Classifications of continuous system, Autonomous system, Phase space, Phase portraits, Fixed points, Nature of fixed points, Stability analysis of linear systems, 1$^{st}$ order system-phase line, 2$^{nd}$ order system-phase plane, Examples- Logistic growth, Simple harmonic oscillator.

Gradient system and Hamiltonian system, Hamilton's equations of motion, Liouville'stheorem, Symplectic nature of phase space. Poisson brackets and Canonical transformations, Canonical transformation through Generating functions.

Suggested Books:

1. Nonlinear dynamics and chaos, Steven Strogatz
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
5. Mathematical Methods of Classical Mechanics, V I Arnold
6. Classical Dynamics: A Modern Perspective, E. C. G. Sudarshan and N. Mukunda
7. Chaos : Introduction to dynamical systems, K. T. Alligood, T. D. Sauer and J. A. Yorke

**Course Outcome:** This course will provide a basic idea about classical dynamical systems, gradient systems and Hamiltonian systems, canonical transformations and generating functions

## 3. (CORE) Quantum Mechanics: (Credit: 1), Total: 15 hrs.

Postulates of Quantum Mechanics, Bloch sphere, Projective Measurement, Commutators, Expectation value and the uncertainty, Heisenberg uncertainty relations, Simple one dimensional systems in time independent scenario.

General properties of the Schrodinger Equation, Evolution operator, Schrodinger, Heisenberg, and Interaction pictures, Two state system, Rabi-Oscillation, Mixed states, Density Operator, Description of more than one particle, Partial Trace, Partial Transpose.

Quantum entanglement, Entanglement entropy.

Suggested Books :

1. Modern Quantum Mechanics, J. J. Sakurai
2. Non-Relativistic Quantum Mechanics, R. R. Puri

3. Principle of Quantum Mechanics, R. Shankar
4. Lectures On Quantum Mechanics, Steven L. Weinberg
5. Quantum Mechanics, Vol. 1, 2 & 3, Claude Cohen-Tannoudji, Bernard Diu,and Franck Lalo

**Course Outcomes**: After completion of the course, a student should be able to understand the postulates of quantum mechanics and its applications, along with the time-dependent scenario. This course also introduces the more modern aspects like entanglement and how to quantify it in physical systems.

### 4. (CORE) Statistical Mechanics: (Credit: 1), Total: 15 hrs.

Information entropy, Maximization of Information entropy to derive classical ensembles. Equivalence of different ensembles. Introduction to Density matrix. Quantum statistics, Bose Einstein condensation. Degenerate Fermi gas, White dwarf.
Phase transitions and critical phenomena: Lee-Yang theory for first order phase transition.
Non-equilibrium statistical mechanics: Liouville's theorem, BBGKY hierarchy, the Boltzmann equation, transport phenomena
Stochastic Processes, Fokker-Planck Equation and Brownian motion; Fluctuation-Dissipation theorem

Suggested Books:
1. Introduction to Statistical Physics, Slivio Salinas, Springer
2. Statistical Physics of Particles, Mehran Kardar, Cambridge University Press
3. An Introductory Course of Statistical Mechanics, Palash B. Pal, Narosa Publishing
4. Thermodynamics Kinetic Theory and Statistical Thermodynamics, F. W. Sears and G. L. Salinger
5. Statistical Mechanics. Huang, Kerson. 2nd ed. Wiley
6. Statistical Mechanics. Pathria, R. K. Pergamon Press
7. Statistical Physics, Part 1. Landau, L. D., and E. M. Lifshitz. Pergamon Press
8. Fundamentals of Statistical and Thermal Physics., Reif, Frederick, ed. McGraw-Hill.
9. Statistical Dynamics: matter out of equilibrium, R. Balescu, World Scientific
10. Non Equilibrium Ststistical Mechanics, D.N. Zubarev, Studies in Soviet Science

**Course Outcome:** On completion of the course the student is expected to know about the different statistical ensembles in both classical and quantum domain and their applications; dynamics of non equilibrium processes, transport theory and phase transition.

### 5. (CORE) Research Methodology (Introduction to Python for scientific computing): (Credit: 1), Total: 22 hrs.

**Introduction to Python for scientific computing**
Functions with variable number of arguments, Lambda function and List comprehension Classes, String Introduction, Datatypes, Tuples, Lists, Mutability, Dictionaries, Branching, Iteration, Functions, Modules, Manipulation, File handling, Exception handling, Numpy, Scipy, Matplotlib, Statistical analysis of data using Python.

Suggested Books:
1. Python for Scientists, 2$^{nd}$ ed., John M. Stewart, Cambridge University Press
2. Learning Scientific Programming with Python, 2$^{nd}$ ed., Christian Hill, Cambridge University Press
3. Practical Numerical Computing Using Python: Scientific and Engineering Applications, Mahendra Verma
4. Scientific Computing in Python, 2$^{nd}$ ed., Abhijit Kar Gupta

**Course Outcome:** After completing the course, students are expected to be able to design and write programming code to solve practical problems of a scientific or engineering nature using python. They will be able to read, test and debug python programs and will develop the ability to use key python libraries for data processing and visualization

## Semester-II (BASIC)

### 1. (BASIC) Quantum Field Theory:(Credit: 1), Total: 15 hrs.

Preview of fundamental particles and their interactions in the Standard Model.
Action functional, Euler-Lagrange equations, Hamiltonian formalism and Poisson brackets for classical fields and Noether's theorem.
Canonical quantization and propagators for scalar, spinor and gauge fields.
Interaction picture, Dyson formula for time evolution, S-matrix, Wick expansion and Feynman diagrams.
Evaluating cross-sections and decay widths.
Introduction to Quantum Electrodynamics and calculation of invariant amplitudes for elementary scattering processes.

Suggested Books:

1. Quantum Field Theory, F. Mandl and G. Shaw
2. Lectures on Quantum Field Theory, A. Das
3. Field Quantization, W. Greiner and J. Reinhardt
4. Quantum Field Theory, Lectures of Sydney Coleman
5. Introduction to Elementary Particles, D. Griffiths

**Course Outcome:** On completion of the course, a student is expected to get a general idea about the Standard Model of Particle Physics and given any interaction Lagrangian should be able to calculate the cross sections of elementary scattering processes and decay rates starting from first principles.

### 2. (BASIC) Condensed Matter Physics: (Credit: 1), Total: 15 hrs

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: Concept of classical, semi-classical and quantum electrons in solids, nearly free electron model and origin of band gap, Bloch's theorem, tight binding model, concept of many body problem, HartreeFock theory, introduction to Density Functional Theory.

Lattice vibrations: Phonons-Einstein and Debye model for specific heat of solids-lattice dynamics-phonon spectrum, Electrical & thermal transport in solids

Magnetism:Origin of magnetism, Quantum theory of diamagnetism and paramagnetism, Heisenberg's exchange interaction and ferromagnetism

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.

Suggested Books:

1. Solid State Physics : N. Ashcroft and N. D. Mermin
2. Introduction to Solid State Physics : Charles Kittel
3. Introduction to Superconductivity :A.C.Rose- Innes, E.H. Rhoderick
4. Solid State Physics : A.J. Dekker

**Course outcome**: On completion of the course, students are expected to get a general idea about the crystallography, electronic structure, and their importance in determining the electronic and phononic properties in materials. They will also have deep understanding on magnetism, superconductivity and superfluidity of materials.

### 3. (BASIC) Nuclear Physics: (Credit: 1), Total: 15 hrs

**Nuclear Structure :**

Basic properties: Charge, mass, binding energy, nucleon-nucleon interactions, and moments.
Nuclear models: Liquid drop model and collective motion, shell model, Fermi gas model, modern perspectives.
Nuclear decay: $\alpha$-decay, $\beta$-decay, $\gamma$-decay, selection rules.

**Nuclear Reaction :**
Basic concepts: Elementary kinematics, conservation laws, reaction cross-section.
Types of reaction: direct reactions, compound and non-compound reactions (fusion-fission), nuclear multifragmentation.
Nuclear astrophysics: Breit-Wigner theory, Astrophysical s-factor, nucleosynthesis reactions.

**Suggested Books :**


1. Nuclear models, by W Greiner and J A Maruhn
2. Nuclear structure Vol I, by A Bohr and B Mottelson
3. Introductory Nuclear Physics by Kenneth S Krane
4. Theoretical Nuclear Physics, by Blatt and Weisskopf
5. Physics of the nucleus, by Preston and Bhaduri
6. Nuclear Physics in a nutshell, by C. A. Bertulani
7. The Nuclear Many-Body Problem, by P. Ring and P. Schuck


**Course Outcome:** After completing this course, students will have basic understanding of nuclear structure and reactions.

## 3. (BASIC) Accelerator Physics: (Credit: 1), Total: 15 hrs

Introduction to Accelerators: History of accelerators. Basic principle of DC and RF accelerators. Accelerators in India. Application of accelerators

Ion Sources for Particle Accelerator: Principle of ionization, PIG, ECR and Multicusp ion sources, Low energy beam transport line. Ion sources for K130, K500 and Medical cyclotron at VECC.

Charge particle beam Dynamics: Accelerator coordinate systems, Charged particle motion in electric and magnetic field, Quadrupole and Solenoid focusing, Hill's equation, Transfer matrices, Stability criterion, Beta function, Beam emittance. Longitudinal Equation of Motion, Off-momentum orbits in synchrotrons, Transition energy and Momentum compaction, Phase stability

Linear Accelerator: Principle of LINAC, Wideroe and Alveraz linac, Transit time factor, Shunt impedance, Quality factor, Ion and electron Linac, Principle of RFQ. Linac in RIB at VECC.

Cyclotron and synchrotron: Basic principle of cyclotron, AVF cyclotron, Shape of cyclotron magnet, Injection, Extraction, Beam quality, Cyclotrons at VECC. Basic principle of Synchrotron, Synchrotron radiation, Indus 1 and Indus 2 at RRCAT.

**Suggested Books:**


1. An Introduction to Particle Accelerators (Oxford University Press 2001) Edmund Wilson
2. Principles of Charged Particle Acceleration (Wiley 1986) Stanley Humphries, Jr.
3. Principles of Cyclic Particle Accelerators (Van Nostrand, NJ 1961) John Jacob Livingood.


**Course Outcome:** The purpose of this course is to familiarize the students to the physics and technology of particle accelerators and its applications. On completion of this course, students will be able to design simple beam transport systems for charged particles and explain the operation of the most common particle accelerator.

## 4. (BASIC) Introduction to high energy nuclear collisions and quark-gluon plasma (QGP) (Credit: 1), Total: 15 hrs

Introduction to high energy nuclear collisions and quark-gluon plasma (QGP),
Comparison and big bang and little bang, critical conditions for QGP formation in laboratory, QCD phase diagram

Four vector notations and Lorentz transformation, frequently used reference frames, rapidity and pseudo-rapidity variables, light cone variables, collision and decay kinematics, relativistic invariants

Thermodynamics of Relativistic gas (hadrons, quark and gluons) and its statistical and thermodynamic properties, introduction to MIT Bag model and Hadron Resonance Gas (HRG) model

Different stages of space-time evolution, criteria for freeze-out conditions, Bjorken and Landau models for estimation of initial energy density

A general overview of past, present and future experimental facilities dedicated to the search for QGP and related basic observables (centrality, multiplicity, spectra)

Signals of QGP: Collective flow, Strangeness enhancement, Quarkonia suppression, Electromagnetic probes and Jet quenching.

**Suggested books:**


1. Introduction to High-Energy Heavy-Ion Collisions, C. Y. Wong, World Scientific
2. The Physics of the Quark-Gluon Plasma: Introductory Lectures, Sourav Sarkar, Helmut Satz, Bikash SInha (Eds.), Springer
3. A Short Course on Relativistic Heavy Ion Collisions, Asis Kumar Chaudhuri, IOP Publishing
4. Quark-Gluon Plasma Lectures, Bikash Sinha, Santanu Pal, Sibaji Raha (Eds.), Springer Verlag
5. Data Reduction and Error Analysis for the Physical Sciences, Philip R. Bevington and D. Keith Robinson, McGraw-Hill


**Course Outcome:** This course provides basic background knowledge of relativistic nuclear collisions and physics of quark-gluon plasma.

## 5. (BASIC) Research Methodology (Numerical techniques and application): (Credit: 1), Total: 22 hrs

Numerical Root Finding: Solution of polynomial equations: Bisection method, False position method, Newton-Raphson method and Secant method, Multidimensional Newton's method.

Interpolation and Least Square Fitting: Linear Interpolation, Newton and Lagrange Interpolation, Linear and non-linear curve fitting.

Matrix and Solution of system of simultaneous equations: Matrix diagonalization and matrix inversions, Eigen value problems, Gauss elimination, Gauss Jordan elimination method, Pivoting.

Numerical Differentiation and Integration: Numerical formulae for ordinary derivative and partial derivative, Trapezoidal formula and Simpson's formula for numerical integration, Numerical multiple integral.

Numerical techniques for solving Differential Equation: Ordinary differential equation, Initial value problems and boundary value problems, Taylor series method, Euler's method, Runge-Kutta fourth order method, Shooting method, Finite difference method, Partial differential equation, Application of numerical techniques to solve Poisson's equation, Wave equation, Heat equation, Schrödinger equation.

Random numbers and Monte-Carlo Simulation: Introduction to random numbers, Monte-Carlo simulations, Evaluation of $\pi$ by Monte-Carlo method, Monte-Carlo technique of numerical integration, Metropolis algorithm.
Machine Learning: Introduction to machine learning. Application.

**Suggested Books:**


1. Introductory Methods of Numerical Analysis, S. S. Sastry, PHI Learning; 5th edition, 2012
2. Computer Oriented Numerical Methods:V. Rajaraman, PHI Learning; 4th edition, 2019
3. Numerical Recipes in C++ : The Art of Scientific Computing; William H. Press, Saul A. Teukolsky, William T. Vetterling and Brian P. Flannery, Cambridge University Press; 2nd edition, 2002
4. Scientific Computing in Python by Abhijit Kar Gupta


**Course Outcome:** On completion of the course, a student is expected to get a general idea on numerical techniques and its application in scientific research.

Semester-III (Advanced)

## 1. (ADVANCED) Accelerator Physics (Credit: 2), Total: 30 hrs

Vacuum: Equations governing vacuum systems, Creation of vacuum – Different types of pumps (Rotary, Roots, Dry, Diffusion, Cryo pumps), Measurement of vacuum – Different types of gauges, working principles, range of operation, Leak testing, Different materials and their physical properties for vacuum systems, Sealing techniques. Vacuum systems in VECC cyclotrons.

Beam Diagnostics and electrostatic lens: Measurement of beam current (Faraday cup, Wall current monitors, CT, DCCT), Measurement of beam profile (Scanners, scintillators etc.), Measurement of time structure (Fast Faraday cup, Harp monitor), Measurement of beam phase, Measurement of beam energy (Spectrometer, TOF, Nuclear techniques), Electrostatic deflector, Quadrupole, Einzel lens, Aperture lens.

Room Temperature Magnets: Maxwell equations, Magnetic materials and their properties, Basic equations governing magnet design, Design of different types of magnets for accelerators, Permanent magnets, Magnet design codes, characterization of magnets (Hall probe, NMR probe, magnetic coils, magnet test bench and harmonic coils), Examples of special magnets (RTC, MCP etc.).

Super-conductivity in accelerators: Super-conductivity, Different types of super-conductors and their properties, Super-conducting coils and their selection in magnet design, Quench and quench protection, Practical design examples of superconducting magnets. Superconducting cavities, different types of superconducting cavities, Practical design examples of SC cavities.

**Suggested Books:**


1. Vacuum Technology, 3rd edition - (North Holland, 1990) A. Roth.
2. CERN Accelerator School on Vacuum for Particle Accelerators, 2017, Paolo Chiggiato.
3. CERN Accelerator School on Beam Diagnostics, 2008, Editor D. Brandt.
4. Lecture Notes on Beam Instrumentation and Diagnostics, Peter Forck, Joint Iniversity Accelerator School, 2003.
5. CERN Accelerator School Proceedings: Magnets, 2009, Editor: D. Brandt
6. M. N. Wilson, Superconducting Magnets, New York: Oxford University Press (1983).
7. Yukikazu Iwasa, Case Studies in Superconducting Magnets: Design and Operational Issues, Springer Science.


**Course Outcome:** The course is proposed for students planning to do research in the field of charged particle accelerators. After completion of the course, the student will get a complete knowledge of the design of particle accelerator and its associated ion source, vacuum system and beam transport system.

## 2. (ADVANCED) Nuclear Theory (Credit: 2), Total: 30 hrs

Theoretical models for heavy-ion induced reactions, nuclear scattering theory, concept of nuclear dissipation. Nuclear thermodynamics, calculation of density of states, different phase transitions in nuclei, statistical model theory for nuclear multi-fragmentation.

Stochastic dynamics for heavy-ion reactions. Theory for direct reactions. Dynamical theories at intermediate energies: QMD and BUU.

Small amplitude collective dynamics and Bohr’s theory. Electromagnetic transitions. Theory for large angular momentum.

Quantum many-body theory for nucleus: Hartree-Fock theory. Introduction to nuclear energy density functional. Nuclear pairing, BCS and Hartree-Fock-Bogoliubov theory. Introduction to time-dependent models.

**Suggested Books :**

1. Shell-Model applications in nuclear spectroscopy, by P J Brussaard and P W M Glaudemans.
2. Nuclear shell theory, by A de-Shalit and I Talmi
3. The nuclear many-body problem, by P Ring and P Schuck
4. Nuclear models, by W Greiner and J AMaruhn
5. Nuclear structure from a simple perspective by R F Casten
6. Theory of nuclear structure by M K Pal
7. Direct nuclear reactions, by N K Glendenning
8. Theory of nuclear fission, by H Krappe and K Pomorski
9. Nuclear structure Vol I and Vol II, by A Bohr and B Mottelson
10. Introduction to Nuclear Reaction G. R. Satchler

**Course Outcome:** After completing this course, students will have adequate understanding and skill to initiate nuclear theory research.

### 3. (ADVANCED) Experimental Nuclear Reaction Studies (Credit: 2), Total: 30. Hrs

Heavy-ion induced reactions and their classifications, Fusion fission, quasi-fission, deep inelastic reactions - experimental probes and measurements. Major challenges in the search of super heavy elements. Fusion evaporation and Hauser Feshback model. Nuclear level density and its experimental determination. Heavy-Ion Induced Transfer reactions, their implication to fusion fission dynamics, Giant dipole resonances and GDR as a probe to study shape of nuclei, nuclear dissipation.

Direct reaction study, Different types of light ion induced transfer reactions, transfer reactions as a spectroscopic information tool, Complex fragment emission mechanisms and their experimental characterisations, Structure and decay of particle unbound state using multi-particle correlation, Nuclear reaction in intermediate & Fermi energy domains, experiments with large arrays, Nuclear thermometry, isoscaling. Data analysis techniques for multi detector array.

Experimental setup to study different nuclear reactions and data analysis techniques.

Suggested Books:

1. Nuclear structure from a simple perspective by R F Casten
2. Introduction to Nuclear Physics by K. S. Krane.
3. Direct nuclear reactions, by N K Glendenning
4. Nuclear structure Vol I and Vol II, by A Bohr and B Mottelson
5. Introduction to Nuclear Reaction G. R. Satchler
6. Nuclear Fission R. Vandenbosch and J. R. Huizenga
7. Giant Resonances, Fundamental Highfrequency Modes of Nuclear Excitation, By M.N. Harakeh, A. van der Woude, Clarendon Press, Oxford, 2001.
8. Treatise on Heavy Ion Science, Volume 2, Fusion and Quasi-Fusion Phenomena, Edited by D. Allan Bromley
9. Treatise on heavy-ion science. Vol. 3: compound system phenomena, Edited by D. Allan Bromley
10. Heavy Ion Collisions at Intermediate Energy: Theoretical Models", by S. Das Gupta, S. Mallik and G. Chaudhuri,World Scientific Publishers, Singapore (2019)
11. Nuclear Dynamics in the Nucleonic Regime by D Durand, E Suraud, B Tamain
12. Treatise on heavy-ion science. Vol. 8: Nuclei far from Stability, Edited by D. Allan Bromley

**Course Outcome**: On completion of the course, the students are expected to have an in-depth knowledge of different types of nuclear reaction mechanisms. They will also get exposure to experimental techniques to study various reactions.

### 4. (ADVANCED) Experimental Nuclear Structure and decay studies (Credit 2) Total 30 hrs

High Resolution Gamma Spectroscopy**:** Introduction to high resolution gamma spectroscopy and gamma detector arrays: relevant parameters; Methods for production of excited states; Experimental observables and properties of discrete excited levels; Techniques for construction of level scheme: measurement of gamma-gamma coincidence, angular distribution & correlation, linear polarization; Ancillary detectors and tagging.

Nuclear level lifetimes and transition moments: nuclear level lifetime, transition probability and moments; different methods of nuclear lifetime measurements: Doppler shift techniques, Electronic techniques and Fast timing techniques, techniques of nuclear moment measurements: perturbed angular correlation methods.

Nuclear decay Spectroscopy: Theory of beta and isomer decay; decay rate and change in decay rate; beta-delayed particle emission; double beta decay; beta-gamma spectroscopy and total absorption gamma spectroscopy; beta-decay end point energy and its measurement technique; application of beta- and isomer decay.

Suggested Books:

1. In-beam gamma ray spectroscopy by H. Morinaga and T. Yamazaki
2. Alpha Beta and Gamma Ray spectroscopy, Edited by K. Siegbahn
3. Handbook of Nuclear Spectroscopy by J. Kantele
4. In-beam gamma ray spectroscopy by H. Moringa and T. Yamazaki
5. Gamma Ray and Electron spectroscopy in nuclear physics by H. Ejiri and M. J. A de Voigt
6. Suggested journal publications, review articles and theses

**Course Outcome:** On completion of the course the students are expected to get the idea on structure of nuclear excited levels and their relation with nuclear level lifetimes and moments. They will come to know how one can experimentally measure nuclear level lifetimes and transition moments. They will also get some idea on the application of gamma and beta decay spectroscopy in understanding nuclear structure.

## 5. (ADVANCED) Condensed Matter Physics (Credit: 2), Total: 30 hrs

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. Development of irradiation induced nanostructure and its characterization by AFM.

Advanced oxide materials :Crystal field splitting, John Teller distortion, Zener double exchange model, Mott Insulator, High temperature superconductor, Manganites, Density functional theory, Magnetic property of a solid, $d^0$ ferromagnetism, Defect in materials.Characterization of defect by Positron annihilation spectroscopy.Mossbauer spectroscopy.

Tight binding model, Graphene band structure, Su–Schrieffer–Heeger Model, Anderson Localization, Integer Quantum Hall Effect, Anomalous Integer Quantum Hall Sequence in Graphene

Suggested Books:

1. Solid State Physics, A. J. Dekker.
2. Physics of Nanostructures, Dresselhaus and Dresselhaus.
3. Transition Metal Oxides: An Introduction to Their Electronic Structure and Properties, P. A. Cox.
4. Modern Condensed Matter Physics, Steven M. Girvin, Kun Yang, Cambridge University Press, 2019
5. Solid State Properties: From Bulk to Nano, Mildred Dresselhaus, Gene Dresselhaus, Stephen B. Cronin, and Antonio Gomes Souza Filho, Springer, 2018.
6. Condensed Matter in a Nutshell, Gerald D. Mahan, Princeton University Press, 2010
7. Fundamentals of Condensed Matter Physics, Marvin L. Cohen, Steven G. Louie, Cambridge University Press, 2016.

**Course Outcome:** After completing the course, students are expected to gain an understanding of the physics of nano-materials and advanced oxide materials. They will also acquire knowledge of density functional theory, topological insulators, superconductivity, and low-dimensional systems.

6. **(ADVANCED) Material Science (Credit: 2),** Total: 30 hrs

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.

Suggested Books :

1. GARY S. WAS Fundamentals of Radiation Materials Science : Metals and Alloys (2017)
2. Comprehensive Nuclear Materials, Elsevier, Editor-in-Chief Rudy J.M. Konings (2020)
3. J.H. Gittus, "Irradiation Effects in Crystalline Solids", Applied Science Ltd., (1978)

**Course Outcome:** On completion of the course the student would have the idea about the ion-material interaction, the types of defect created and its effect on the material property. The student will have the detailed understanding on the radiation damage created in specifically nuclear structural materials.

7. **(ADVANCED) Relativistic Heavy-Ion Collision Experiments & Quark-Gluon Plasma (Credit: 2),** Total: 30 hrs

Recapitulation of Relativistic Kinematics:
Fixed target and collider experiments, rapidity and pseudo-rapidity variables, collision and decay kinematics, relativistic invariants
Introduction to Monte-Carlo (MC) technique:
Uniformly distributed random numbers, transformation method, acceptance rejection method, application of MC method; different MC event generators: Pythia, Hijing, AMPT, EPOS (can be part of mini-projects)
Basic Experimental Dictionary:
Different experimental facilities dedicated to search for QGP, luminosity, interaction rate, control variables (centrality, root(s), system size), data analysis techniques, trigger, acceptance correction, extraction of four momentum, estimation of statistical and systematic errors; confidence interval and limits, statistical test and parameter estimation
Experimental Signals of QGP:
Global Observable: Multiplicity, ET, EF, (pseudo)Rapidity, pT distributions: explanations of various regions and connections with particle production mechanism; Correlations and fluctuations; Collective flow: radial, directed, elliptic and higher order flow harmonics extraction and interpretations; Heavy quark and quarkonia suppression, strangeness enhancement, jet quenching and electromagnetic signals (photon and di-lepton), recent progress

Suggested books**:**

1. Introduction to High-Energy Heavy-Ion Collisions, C. Y. Wong, World Scientific
2. The Physics of the Quark-Gluon Plasma: Introductory Lectures, Sourav Sarkar, Helmut Satz, Bikash SInha (Eds.), Springer
3. A Short Course on Relativistic Heavy Ion Collisions, Asis Kumar Chaudhuri, IOP Publishing
4. Phenomenology of Ultra-Relativistic Heavy-Ion Collisions, Wojciech Florkowski, World Scientific
5. Data Reduction and Error Analysis for the Physical Sciences, Philip R. Bevington and D. Keith Robinson, McGraw-Hill

6. Introduction to Experimental Particle Physics, Richard Fernow, Cambridge University Press

**Course Outcome:** This course provides working knowledge to start research on the experimental aspects of relativistic heavy-ion collision

## (ADVANCED) LABORATORY EXPERIMENTS (Credit: 2), Total: 60 hrs

**1. Experiments using gamma-spectroscopy detector/ detectors**

The characterization of HPGe detectors with different configuration and scintillator detectors will be carried out. The detectors will be characterized with respect to their energy calibration, energy resolution and photopeak efficiency. For this purpose, coaxial HPGe detector, Low Energy Photon Spectrometer (LEPS) in planar configuration and CeBr3 scintillator detectors will be used. The energy calibration, resolution and efficiency will be determined using standard radioactive sources. The energy resolution and photopeak efficiency of different detectors will be compared.

OUTCOME: On completion of this experiment, a student is expected to get to know about different kind of gamma detectors, learn to calibrate a detector and determine its efficiency

**2. Experiments using neutron detectors**

Experiment will be performed to calibrate the pulse height response of a liquid scintillator based neutron detector using 22Na and 137Cs gamma -ray sources. Neutron gamma discrimination using pulse shape discrimination technique will be performed using a fission neutron source. Pulse shape discrimination will be achieved using Zero Cross Over (ZCO) technique. ZCO and pulse height data will be acquired to determine the Figure Of Merit (FOM) of the neutron gamma discrimination. FOM will be determined for different pulseheights thresholds

OUTCOME: On completion of this experiment, a student is expected to get to know about neutron detectors. Learn different techniques like zero-cross-over, pulse shape discrimination and determination of FOM

**3. Experiments using charge particle detectors**

Energy resolution measurement of charge particle detector will be carried out. Energy calibrations and thin film thickness measurements will be carried out. Measurement of activity of radioactive source will be performed using the calibrated detector. Finally, depletion depth measurement in a semiconductor detector for 5.5 MeV alpha particle will be carried out.

OUTCOME: On completion of this experiment, a student is expected to get to know about charge particle detectors. Learn about application of these detectors like thickness measurement, activity measurement.

**4. Experiments for measuring cosmic muon flux**

Experiment will be performed to measure the cosmic flux using plastic scintillator detectors. Characteristic study of the plastic scintillators coupled to photomultiplier tubes (PMT) will be carried out. A coincidence setup based on NIM based electronic modules will be used to generate coincidence signal due to cosmic muons, which will counted using suitable scalar.

OUTCOME: On completion of this experiment, the student will gain knowledge about the functioning of a plastic scintillator detector, will learn concept and techniques involved in building a coincidence setup, along with familiarization to some basic NIM based electronic modules, besides the basic physics related to the origin and composition of cosmic rays.

**5. Penning Trap experiments**

Work with Penning trap setup at room temperature. Determine Q-value of detection circuit.Determine storage time of trapped charged particles will be measured.

OUTCOME: On completion of this experiment, a student is expected to know about the working principle of a Penning trap. Learn techniques of trapping, resonant detection and determination of trapping time.

**6. Experiments using X-ray diffractometer.**

X-ray diffraction analysis to understand the effect of deformation on the microstructure of materials will be carried out. Two types of deformed (rolled sheet and ball-milled powder) of copper samples used for the study. X-ray diffraction data will be collected using laboratory X-ray source. Instrumental broadening of the X-ray diffractometer will be determined using NIST standard. The diffraction peaks from the XRD data of the samples will be analysed to extract the coherent domain size and microstrain and compared.

OUTCOME: On completion of this experiment, a student is expected to get to know about X-ray diffraction analysis. Learn about various reasons for line broadening and determine domain size, microstrain etc. from the XRD data.

**7. Experiment using SEM and EDAX**

The working principle of Scanning Electron Microscope (SEM) and energy dispersive spectrometer (EDS) set up will be explained. Good quality images captured previously will be shown to explain the important characteristics. One sintered ceramic sample (if available) or any alloy sample(s) will be used to obtain images using SEM and the composition using EDS. The analysis of the SEM images and EDS data will be explained.

OUTCOME: On completion of this experiment, a student is expected to get to know about SEM and EDX. The working principle and the determination of good microstructural images and chemical composition of materials using EDX

**8. Experiment using ion implanter.**

Ions of the desired element are accelerated to keV/MeV energies and then directed onto the surface of the target material. The atoms are ionized in the ion source and extracted through a vacuum tube by applying an electrostatic potential difference. A magnetic field is applied to select a specific ion (isotope) to pass through an aperture. The energetic and pure beam of ions is then directed onto a solid target to incorporate dopants or organized defects. The incorporation of foreign atoms and defects modifies the electrical, optical, chemical, mechanical, and magnetic properties of the material.

OUTCOME: On completion of the experiment the student would have learnt how atoms are ionized in the Electron Cyclotron Resonance ion source and how charged particles are accelerated and bent by applying electric and magnetic fields. They would've obtained hands-on experience on how controlled introduction of dopant atoms allows for precise manipulation of the material's physicochemical properties.