Syllabus for the Doctoral Course
Variable Energy Cyclotron Centre (VECC)
1/AF, Bidhan Nagar, Kolkata 700 064.

Total credits: 60. Duration: one year. The 42 credits basic courses tabulated serially in I to XIII are common to all. After completion of this 42 credits, a student may either choose: [2 advance courses from XIV to XX (2×4=8 credits)] or [one advance course (4 credits) + Self Study Course (equivalent to 4 credits)] and finally a project equivalent to 10 credits.

I. Mathematical Physics: (3 Credits)

Linear vector spaces, Linear operators and matrices, Systems of linear equations. Eigen values and Eigen vectors, Numerical methods to solve eigenvalue problems. Tensors.

Linear ordinary differential equations, Linear partial differential equations in physics, Separation of variables method of solution, Special functions and their applications in physics. Introduction to non-linear differential equation.

Complex variable theory; Analytic functions. Taylor and Laurent expansions, Classification of singularities, Analytic continuation, Contour integration, Integral equations and Green functions.

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.

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

II. Classical Mechanics: (3 Credits)

Introduction to dynamical systems, Discrete dynamical systems (Maps), Continuous dynamical systems, Phase portraits, Topological equivalence, Fixed points, Stability and linearization of non-linear systems, Lyapunov stability, Linear stability analysis, Bifurcations, Chaos in simple maps. Lyapunov exponents.

Hamiltonian systems, Hamilton’s equations of motion, Liouville’s theorem, Symplectic nature of phase space, Poisson brackets, Canonical transformations, Generating functions, Action-angle variables, Hamilton-Jacobi equation, Perturbation theory, Integrability, Kolmogorov-Arnold-Moser theorem, Introduction to general theory of relativity.

Suggested books:

1. Nonlinear dynamics and chaos, Steven Strogatz
2. Chaos: Introduction to dynamical systems, K. T. Alligood, T. D. Sauer and J. A. Yorke
3. Classical Mechanics, T. W. B. Kibble and F. H. Berkshire
4. Classical Mechanics, H. Goldstein
5. Classical Mechanics, L. D. Landau and L. M. Lifshitz
6. Mathematical Methods of Classical Mechanics, V. I. Arnold
7. Classical Dynamics: A Modern Perspective, E. C. G. Sudarshan and N. Mukunda
8. A First Course in General Relativity, 2nd Edition, by Bernard Schutz, Cambridge Univ. Press, 2009.
9. Gravity: An Introduction to General Relativity by James Hartle
10. Gravitation: Foundations and Frontiers, Cambridge University Press by T. Padmanabhan

III. Classical Electrodynamics: (3 Credits)

Maxwell equations, Conservation laws, Conservation of charge, Maxwell equations in vacuum, Vector and scalar potential, Gauge transformation, Lorentz gauge, Coulomb gauge, Green functions for the wave equations, Classical limits, Aharonov - Bohm effect, Magnetic monopole and Dirac quantization condition.

Electromagnetism & special theory of relativity, Lorentz transformation and kinematics of special relativity, Transformation of electromagnetic fields, Maxwell-Faraday tensor

Maxwell equations in matter, Electric & magnetic fields in matter, The Macroscopic Maxwell Equations, Poynting's theorem, Reflection, refraction and dispersion, Causality and Kramers-Kronig relation, Electromagnetic wave in conductor, Drude model, Electromagnetic plasma, charge screening and plasma oscillation

Electromagnetic Radiation, Retarded and advanced Greens functions, Lienard-Weirchert potential, Electric dipole, Magnetic dipole and electric quadrupole radiations, Larmor formula and its relativistic generalization, Applications to spinning neutron stars (Pulsars)

Suggested books

1. Classical Electrodynamics, J. D. Jackson (John Wiley & Sons Inc, 2007)
2. Modern Electrodynamics, A. Zangwill (Cambridge University Press, 2012)

IV. Quantum Mechanics: (3 Credits)

Introduction, Vector spaces, Inner product space, Matrix representations, Similarity transformation, Spectral decomposition, Schmidt decomposition (Singular value decomposition), Infinite dimensions and Hilbert spaces, Symmetric operator, Self-adjoint operator, Positive operator, Tensor product of vector spaces, Partial trace, Partial transpose.

Stern-Gerlach experiment, Postulates of quantum mechanics, Bloch sphere, Projective measurement, Positive Operator Valued Measure (POVM), Discriminating the states, Commutators, The expectation value and the uncertainty, Heisenberg uncertainty relations, Self-adjoint extension, von-Neumann's prescription.

General properties of the Schrodinger equation, Complete Set of Commuting Operators (CSCO), Evolution operator, Schrodinger, Heisenberg and interaction pictures, Quantum recurrences, Two state system, Rabi-oscillation, Conservative systems, Density operator, Quantum entanglement, Entanglement entropy.

Infinite potential well, Particle moving on a ring, Particle moving on a ring enclosing a magnetic flux, Aharonov- Bohm effect, Charged particle in a magnetic field, Landau levels, Quantum Hall effect, Periodic potential, Bloch's Condition, Kronig-Penney model.

Lipmann-Schwinger equation, Born approximation, Partial waves, Optical theorem, Determination of phase-shifts, Hard sphere scattering, Low energy scattering, Resonances.

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 Laloë

V. Statistical Mechanics: (3 Credits)

A review of thermodynamics:

Laws of thermodynamics, extensive and intensive parameters,
thermodynamic potentials, Maxwell relations

Basics of probability theory, Coin-toss problem, Binomial distribution, Central limit theorem, Information entropy,

Statistical description of a physical system: Microstates and macrostates; States in classical systems. States in quantum systems, Maximization of information entropy to derive classical

Gibsian ensembles. Equivalence of different ensembles. Introduction to Density matrix.

Quantum statistics: Bose-Einstein statistics, Fermi-Dirac statistics; Application to different physical systems and passage to the classical limit. Bose-Einstein condensation. White dwarf.

Phase transitions and critical phenomena: Classical theories; The Ising model-critical exponents and the universality, Lee-Yang theory.

Introduction to linear response theory: response functions, Kubo Formula.

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

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

VI. Computational Methods and Programming: (4 Credits)

Introduction to scientific programming, Fundamentals of computer and computer programming, Programming languages with input and output statements, Control and loop statements, Arrays, Functions and subroutines, Algorithms and flow chart.

Numerical techniques, Finding roots of equations, Matrix diagonalisation and matrix inversions, Solution of linear simultaneous equations, Curve fitting, Least square methods, Interpolation techniques.

Generation and use of random numbers, Sorting and searching, Differentiation and integration (including Monte Carlo techniques), Solution of ordinary differential equations and partial differential equations

Statistics and treatment of statistical analysis of data, Statistical random distributions, parameters.

Error analysis (statistical and systematic) in measurements and numerical calculations, Estimation and propagation of error, Confidence limit and ANNOVA analysis.

Introduction of PYTHON and C++.

Suggested books:

1. Numerical Mathematical Analysis, James B. Scarborough
2. Computer Oriented Numerical Methods, V. Rajaraman
3. Numerical Recipes in C, The art of scientific computing, Q. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery
4. Scientific Computing in Python by Abhijit Kar Gupta.

VII. Experimental Techniques and Methods: (5 Credits)

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.

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).

Detectors and Techniques for Nuclear and High Energy Physics:
Interaction of radiations with matter: Interaction of charged particles, electrons, photons, neutrons, muons and neutrinos with matter. Radiation exposure and dose.

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.

Basics of Nuclear Electronics: Pre-amplifier, amplifier, discriminators, gate and delay generators, Analog to Digital Converter (ADC), Time to Amplitude Converter (TAC) and the basics of data acquisition systems.

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.

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:

1. Materials Characterization: Introduction to Microscopic and Spectroscopic Methods, Yang Leng
2. Characterization of Materials, Elton Kaufmann
3. Radiation Detection and Measurement, Glenn F. Knoll
4. Nuclear Radiation Detectors, S.S. Kapoor and V. S. Ramamurthy.
5. Techniques for Nuclear and Particle Physics Experiments: A How-to Approach, William R. Leo
6. Experimental Techniques in High-energy Nuclear and Particle Physics edited by Thomas Ferbel
7. Introduction to Experimental Particle Physics, Richard Clinton Fernow
8. Data Reduction and Error Analysis for the Physical Sciences, Philip Raymond Bevington, D. Keith Robinson
9. Data Analysis Techniques for High-Energy Physics, edited by R. Frühwirth, M. Regler.

VIII. Basic Field Theory: (3 Credits)

Basis ideas of Lorentz invariance and Relativistic kinematics. A preview of fundamental particles and their interactions. Review of classical field theory: Principle of least action, Lagrangian formulation for continuous system and fields, symmetries and conservations laws, Noether's theorem.

Introduction to field quantization: Canonical quantization of scalar, spin one-half and gauge fields. Principle of gauge invariance: Global and local gauge transformations, Abelian gauge fields. Interacting fields: Perturbation expansion of correlation functions, Wick's theorem, Feynman diagrams, S-matrix and cross section, Calculations of cross section and decay rates for elementary processes in quantum electrodynamics.

Suggested books:

1. Quantum Field Theory, F Mandl and G Shaw
2. Lectures on Quantum Field Theory, Ashok Das
3. An introduction to Quantum Field Theory, M. E. Peskin and D. V. Schroeder
4. Quantum Field Theory, L. H. Ryder
5. Quantum field theory lectures, Sidney Coleman

IX. Basic Condensed Matter Physics (3 Credits)

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, Hartree Fock theory, 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 para-magnetism, Heisenberg's exchange interaction and ferromagnetism, Introduction to super exchange, Direct exchange and double exchange

Superconductivity and 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.

Strength of materials: Cohesion in solids, Elasticity and Plasticity, Defects in solids, point defect, line defect, planar defects, 3D defects. Concept of dislocations, role of dislocations in material behaviour, interaction of dislocations with other defects.

Irradiation effects in solids: Material behaviour under irradiation, Concept of DPA, Introduction to nuclear reactor materials**.**

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
5. Irradiation Effects in Crystalline Solids: J.H. Gittus

X. Basic Nuclear Physics (3 Credits)

Chart of nuclei, nuclear ground state properties (mass, binding energy, moments, and symmetries), basics of nuclear interactions.

Introduction to nuclear models: liquid drop model, concept of mean field and single-particle shell model, nuclear deformation and deformed shell model. nuclear level density and temperature. Concept of nuclear pairing.

Nuclear excitations: single particle excitations, collective rotations and vibrations, giant dipole resonances.

Nuclear decay: alpha decay, beta decay, gamma decay, spontaneous fission, selection rules for decay.

Elementary kinematics and conservation laws, reaction cross section. Types of nuclear reactions: coulomb scattering, nuclear scattering, compound nuclear reactions, fusion-evaporation, fusion-fission, quasi-fission, nuclear multi-fragmentation.

The optical model, resonances, Breit-Wigner formula, astrophysical s-factor and reactions of astrophysical interests.

Introduction to experimental probes for nuclear structure study, Experimental probes in nuclear reactions to study different reaction observables and their detections. Production of rare isotope beams and their applications in nuclear physics.

Suggested books:

1. Nuclear Models, W. Greiner and J. A. Maruhn
2. Nuclear Structure Vol I, A. Bohr and B. Mottelson
3. Introductory Nuclear Physics, Kenneth S. Krane
4. Theoretical Nuclear Physics, Blatt and Weisskopf
5. Physics of the Nucleus, Preston & Bhaduri
6. Nuclear Physics in a Nutshell, C. A. Bertulani

XI. Basic Accelerator Physics: (3 Credits)

Introduction to accelerators : History of accelerators. Basic principle of DC and RF accelerators. Accelerator in India. Application of accelerators in basic research, medicine and industry.

Ion Sources for Particle Accelerator : Principle of ionisation, Ion sources for positive ions – Duo-plasmatron, PIG, ECR, Ion sources for negative ions-surface, volume and charge exchange, ECR ion source and beam transport line. Ion sources for K130, K500 and Medical cyclotron at VECC.

Transverse beam dynamics: Accelerator coordinate systems, Magnetic field expansion, Particle equations of motion, Quadrupole and solenoid focusing, Hill's equation, 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. Familiar with TRANSPORT code notations.

Longitudinal Beam Dynamics: Longitudinal equation of motion, Off-momentum orbits in synchrotrons, Transition energy and Momentum compaction, Phase stability, Synchrotron oscillation, Longitudinal emittance.

Linear Accelerator: Principle of Linear accelerator, Wideroe and Alverazlinac, Transit time factor, Shunt impedance, Quality factor, Ion and electron Linac, Empty cavity and Loaded cavity, Travelling wave and standing wave structures, principle of RFQ. Linac in RIB at VECC.

Cyclotron: Basic principle of cyclotron, AVF cyclotron, Synchrocyclotron, Betatron tunes, Shape of the cyclotron magnet, Injection, Extraction, Beam quality, Time structure, Energy resolution and emittance. K130, K500 and medical cyclotron at VECC.

Synchrotron and Radiation Source : Basic principle of Synchrotron, Electron and ion Synchrotron, Synchrotron radiation source, Total radiated power, Properties of Synchrotron radiation, Insertion devices. Indus 1 and Indus 2 at RRCAT.

Suggested books:

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

XII. Research Methodology (Compulsory, Credit: 0)

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

XIII. Laboratory Experiments: (6 Credits)

(Each student will carry out minimum of 6 experiments)

The experiments performed by the students will make them 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, BaF2, etc.)
4. Thickness uniformity test of different detectors
5. Characterization of a neutron detector
6. Characterization of a gaseous detector (e.g; Gas electron multiplier, Avalanche counter etc)
7. Efficiency measurement of different types of γ 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. Characteristion of samples using Scanning Electron Microscope and Energy Dispersive X-ray Analysis.
12. Nano-structuring 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.

XIV. Advanced Accelerator Physics-I: (4 Credits)

Introduction: Sources of charged particle, Hamiltonian of a charged particle, Equations of motion, Planer diode without and with space charge. 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 Transport: Accelerator coordinate system, Paraxial ray equation and solutions, Electrostatic lenses, Solenoidal magnetic lens, Larmor frame, Aberrations, transfer matrix of transport elements, Stability condition, Beam envelope, Beam matrix, Basic focusing modules and different kinds of imaging, Coupled systems, Skew quadrupoles. Quadrupole doublet and Triplet.

Beam Dynamics: Beam envelope equation, Courant-Snyder invariant and emittance, Twiss parameters, Liouville's Theorem, Periodic system, FODO Cell, Dipole field and Quadrupole gradient errors, Resonances. 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, Bucket, Separatrix.

Intense Beam Dynamics: Space charge effects, Uniform beam model, 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, Linear beam model with charge neutralization, Space charge compensation. Vlasov model, K-V and Waterbag distribution, Concept of equivalent beams, RMS envelope equations, emittance growth.

RIB Accelerator Science: Introduction and overview of RIB facilities, Different types of RIB facilities, Ion sources & charge breeder, Ion guides and gas-jet systems, RFQ cooler, Mass Separators, RFQ linac, Heavy Ion LINAC, Applications of RIB in different fields (Nuclear physics, Material science, Medicine, Industrial applications), RIB facilities worldwide.

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, Beam lifetime.

Advance accelerators: Free electron laser, Plasma accelerators, Spallation neutron sources, Accelerators driven subcritical systems (ADSS),

Suggested books/References:

1. Accelerator Physics - (World Scientific 2019) S.Y. Lee.
2. RF Linear Accelerators - (Wiley 2008) Thomas P. Wangler
3. Theory and Design of Charged Particle Beams (Wiley 2008) Martin Reiser.

XV. Advanced Accelerator Physics-II: (4 Credits)

Vacuum: Equations governing vacuum systems, Creation of vacuum – Different types of pumps (Rotary, Roots, Dry, Diffusion, Cryo and ion 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, Design of simple vacuum systems. Vacuum systems in VECC cyclotrons.

Beam Diagnostics: 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 lenses: Dipole, Quadrupole, Einzel lens, Wien filter etc.

Room Temperature Magnets: Maxwell equations, Magnetic materials and their properties, Basic equations governing magnet design, Design of different types of magnets for accelerators (Dipole, Quadrupole, Sextuple, solenoid, steering magnets), Permanent magnets, Magnet design codes, characterisation 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, AC loss & magnetization, Stress analysis, Quench and quench protection, Current lead design, Practical design examples of superconducting magnets, High-Tc superconductors and their application in accelerators

Superconducting cavities – why it is required, Design considerations, 4K and 2K cavities, different types of superconducting cavities (QWR, HWR, elliptical cavities), Practical design examples of SC cavities (VECC QWR, proton accelerator for IIFC, VECC SC e-LINAC).

Suggested books/References:

1. Vacuum Technology, A. Roth, 3rd edition - (North Holland, 1990)
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.

XVI. Advance Course in Nuclear Physics: (4 Credits / 8 Credits)

A student can choose 4/8 credits from the following modules:

General Nuclear Theory (Credit 2):
Introduction to G-matrix theory, effective interactions and symmetries. Theoretical models for heavy-ion induced reactions (statistical and dynamical models), nuclear potential energy surface: explanation of fusion-fission, quasi-fission and thermal shape fluctuations in GDR. Strutinsky shell correction, concept of nuclear dissipation. Small amplitude collective dynamics and Bohr's theory. Electromagnetic transitions. Theory for large angular momentum: Cranking model. Nuclear thermodynamics, calculation of density of states, different phase transitions in nuclei, statistical model theory for nuclear multi-fragmentation.

Advance Nuclear Structure Theory (Credit 2):
Quantum many-body theory for nucleus: Hartree-Fock theory, Hartree-Fock-Bogoliubov theory and concept of quasiparticles, Introduction to nuclear energy density functional. Advanced theory on shell models. Theory beyond mean field: Residual interactions, Introduction to linear response theory and random phase approximation. Interacting Boson model. Angular momentum algebra: m-scheme and j-scheme for multi-nucleon systems.

Advance Nuclear Reaction Theory (Credit 2):
Stochastic Langevin dynamical model for heavy-ion induced reactions. Relevant input parameters and calculation procedures. Nuclear scattering theory, partial wave analysis. Theory for direct reactions: Distorted wave Born approximation. Dynamical theories at intermediate energies: QMD and BUU. Relevant numerical techniques. Signatures of phase transition. Introduction to time-dependent HFB theory.

Experimental Nuclear Reaction Studies I (Credit 2):
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.

Experimental Nuclear Reaction Studies II (Credit 2):

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.

Nuclear Structure Studies-I (Level Structure) (Credit 2):
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 Structure Studies-II (Lifetime and Moments) (Credit 2):
Nuclear Isomerism, transition probability, lifetime and moments; Nuclear structure and its interpretation from lifetime and moments; Direct & Indirect lifetime measurement techniques: Doppler shift techniques, Electronic techniques and Fast timing techniques; Perturbed angular correlation methods for moment measurements: TDPAC and IPAC.

Nuclear Structure Studies-III (Beta decay spectroscopy) (Credit 2):
Theory of beta decay; Physics of decay rate changes, Beta-delayed particle emissions & double beta decay; Experimental probes: Decay-half-life, endpoint energy, and transition probability; Measurement techniques: Beta-gamma spectroscopy, Total Absorption Gamma Spectroscopy (TAGS), Decay spectroscopy for reaction cross section measurement; Application in nuclear physics and nuclear astrophysics

Nuclear interactions and mass measurement techniques (Credit 2):
Introduction to mass models, techniques of mass measurements, Introduction to Ion trapping, Penning Ion Trap (PIT), Ion Manipulation in PIT, Loading and cooling of ions, Frequency measurement techniques, Mass measurement using PIT, Other applications of PIT.

Suggested books/References:

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. A. Maruhn
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 by G. R. Satchler
11. Theroetical Nuclear Physics by Blatt, Weisskopf
12. Nuclear Fission by R. Vandenbosch and J. R. Huizenga
13. Giant Resonances, Fundamental Highfrequency Modes of Nuclear Excitation, By M.N. Harakeh, A. van der Woude, Clarendon Press, Oxford, 2001.

14. Treatise on Heavy Ion Science, Volume 2, Fusion and Quasi-Fusion Phenomena, Edited by D. Allan Bromley
15. Treatise on heavy-ion science. Vol. 3: compound system phenomena, Edited by D. Allan Bromley
16. Heavy Ion Collisions at Intermediate Energy: Theoretical Models", by S. Das Gupta, S. Mallik and G. Chaudhuri, World Scientific Publishers, Singapore (2019)
17. Nuclear Dynamics in the Nucleonic Regime by D. Durand, E. Suraud, B. Tamain
18. Treatise on heavy-ion science. Vol. 8: Nuclei far from Stability, Edited by D. Allan Bromley
19. In-beam gamma ray spectroscopy by H. Morinaga and T. Yamazaki
20. Alpha Beta and Gamma Ray spectroscopy, Edited by K. Siegbahn
21. Handbook of Nuclear Spectroscopy by J. Kantele
22. Gamma Ray and Electron spectroscopy in nuclear physics by H. Ejiri and M. J. A de Voigt
23. Atomic Masses and Fundamental Constants edited by Jerry A. Nolen, Walter Benenson
24. Ion Traps by P. K. Ghosh

XVII. Advanced Materials Science: (4 Credits)

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.

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. Irradiation Effects in Crystalline Solids, J.H. Gittus, Applied Science Ltd., (1978)

XVIII. Advanced Condensed Matter Physics: (4 Credits)

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.

XIX. Advanced Course on Relativistic heavy-ion collision experiments & quark-gluon plasma: (4 Credits)

Introduction to relativistic heavy-ion collisions and quark-gluon plasma (QGP).

Relativistic kinematics: Lorentz transformation: frequently used reference frames, four vector notation, rapidity and pseudo-rapidity variables, light cone variables, collision and decay, relativistic invariants

Thermodynamics: Relativistic gas (hadrons, quarks and gluons) and its statistical and thermodyamical properties, MIT Bag model, Hagedron gas, phase diagram of QCD, criteria for formation of QGP in the laboratory

Collision dynamics: different stages of space-time evolution like pre-equilibrium, formation of QGP, chemical and thermal equilibria, freeze-out and particle production; Bjorken's model for energy density;

Basics of different Monte-Carlo event generators: Pythia, Hijing, AMPT, EPOS (can be part of mini-projects)

Experiments: a general overview of past, present and future experimental facilities dedicated to search for QGP, data analysis technique, extraction of 4 momentum, control variables (centrality, root(s), system size)

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).

Suggested books:

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

XX. Advanced Course on Quantum Chromodynamics (QCD) and Relativistic Heavy Ion Physics: (4 Credits)

Part - I (Quantum Field Theory and QCD)

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

Deep Inelastic Collisions: Proton form factor, Deep inelastic scattering of electron off proton, Parton evolutions.

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

Part – II (Relativistic Heavy Ion Physics)

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, Relativistic hydrodynamics and signals of quark gluon plasma.

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
6. Introduction to High Energy Heavy Ion Collisions, C. Y. Wong
7. Quark Gluon Plasma from Big Bang to Little Bang, K. Yagi, T. Hatsuda and Y. Miyake

XXI. Project work equivalent to 10 credits.

For any clarifications contact: Dean-Academic (Physical Sciences)
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