Ph.D. PHYSICAL SCIENCES

Programme Code: PHYS04

Programme Outcome:

- Manpower development with the ability to apply basic concepts and methods in physics to research problems.
- Training of manpower with the ability to work in interdisciplinary subjects, particularly those in the interface of different disciplines in physics.
- Developing an understanding of modern mathematical methods and using them in the research environment.
- Training of manpower which has the ability to work in diverse areas and adapt to change in professional and national requirements.

Syllabus structure for VECC Ph.D. Program

(following NEP2020 guidelines)

Trimester-I (CORE)

S. No.	Subject Code	Subjects	Lecture Hour / Lab	Credits
1	04-PHYS04-001-C	Mathematical Physics	15	1
2	04-PHYS04-003-C	Classical Mechanics	15	1
3	04-PHYS04-002-C	Quantum Mechanics	15	1
4	04-PHYS04-004-C	Statistical Mechanics	15	1
5	04-PHYS04-001-E	Introduction to Python for scientific computing	7+15 = 22 (Partial classroom + lab)	1

Trimester-II (BASIC)

Any 4 subjects out of first 5

S. No.	Subject Code	Subjects	Lecture Hour / Lab	Credits
1	04-PHYS04-004-B	Quantum Field Theory	15	1
2	04-PHYS04-002-B	Condensed Matter Physics	15	1
3	04-PHYS04-003-B	Nuclear Physics	15	1
4	04-PHYS04-001-B	Accelerator Physics	15	1

5	04-PHYS04-005-B	High Energy Collisions & QGP	15	1
6	04-PHYS04-002-E	Numerical techniques and application	7+15 = 22 (Partial classroom + lab)	1
7	04-PHYS04-003-R	Research Methodology & Research Publication Ethics	45	3

Trimester-III (ADVANCED)

S. No.	Subject Code	Subjects	Lecture Hour / Lab	Credits
1	04-PHYS04-001-A	Advanced Course (one/two from list) / Self Study	30	2
2	04-PHYS04-002-A	Advanced Laboratory Experiments	60	2
3	04-PHYS04-001-PR	Project Work	60	2

Advanced Topics

S. No.	Subjects
1	Advanced Accelerator Physics
2	Advanced Nuclear Theory
3	Advanced Experimental Nuclear Reaction Studies
4	Advanced Experimental Nuclear Structure and Decay Studies
5	Advanced Condensed Matter Physics
6	Advanced Materials Science
7	Advanced Relativistic Heavy-ion Collision Experiments & Quark-Gluon Plasma

Advanced Laboratory Experiments will be chosen from the list of experiments offered. Earning **2 credits** from Advanced Laboratory Experiments will be **mandatory**. Supervisor may suggest additional Advanced Laboratory Experiments.

TOTAL CREDITS: CORE (4 credits) + Basic (4 credits) + Research Methodology (3 credits) + Project (2 credits) + Advanced Course (2 credits) + Advanced Laboratory Experiments (2 credits) + Elective (1/2 credits) = 18/19 Credits

**Students may take additional credits from NPTEL.

CORE COURSE CO-ORDINATORS

Course	Coordinators	Email
Mathematical Physics	Pranika Das	parnika@vecc.gov.in
Classical Mechanics		
Quantum Mechanics		
Statistical Mechanics		
Introduction to Python for scientific computing (Elective)		

BASIC COURSE CO-ORDINATORS

Course	Coordinators	Email
Quantum Field Theory	Pranika Das	parnika@vecc.gov.in
Condensed Matter Physics		
Nuclear Physics		
Accelerator Physics		
High Energy Collisions & QGP		
Numerical techniques and application (Elective)	Pranika Das	parnika@vecc.gov.in
Research Methodology & Research Publication Ethics		

ADVANCED COURSE CO-ORDINATORS

Course	Coordinators	Email
Advanced Accelerator Physics	Dr. Animesh Goswami	animesh@vecc.gov.in
Advanced Nuclear Theory	Dr. Gargi Chaudhuri	gargi@vecc.gov.in
Advanced Experimental Nuclear Reaction Studies	Dr. Kaushik Banerjee	kaushik@vecc.gov.in

Advanced Experimental Nuclear Structure and Decay Studies	Dr. Pranika Das	parnika@vecc.gov.in
Advanced Condensed Matter Physics	Dr. Gayathri N.Banerjee	gayathri@vecc.gov.in
Advanced Materials Science	Dr. Pranika Das	parnika@vecc.gov.in
Advanced Relativistic Heavy-ion Collision Experiments & Quark-Gluon Plasma	Dr. Pranika Das	parnika@vecc.gov.in
Advanced Laboratory Experiments	Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay	gayathri@vecc.gov.in and supm@vecc.gov.in

Semester-I (CORE)

04-PHYS04-001-C : (CORE) Mathematical Physics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- 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.

References:

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*

04-PHYS04-003-C: (CORE) Classical Mechanics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- 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.
- 1st order system-phase line, 2nd order system-phase plane, Examples- Logistic growth, Simple harmonic oscillator.
- Gradient system and Hamiltonian system, Hamilton's equations of motion, Liouville's theorem. Symplectic nature of phase space. Poisson brackets and Canonical transformations, Canonical transformation through Generating functions.

Course Outcomes:

- This course will provide a basic idea about classical dynamical systems, gradient systems and Hamiltonian systems, canonical transformations and generating functions.

References:

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. Lifshit*
5. Mathematical Methods of Classical Mechanics, *V. I. Arnol*
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*

04-PHYS04-002-C: (CORE) Quantum Mechanics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- 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 Schrödinger Equation. Evolution operator, Schrödinger, 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.

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.

References:

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*

04-PHYS04-004-C: (CORE) Statistical Mechanics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- 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.

References:

1. Introduction to Statistical Physics, *Silvio 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. Salinge*
5. Statistical Mechanics, *Huang, Kerson, 2nd ed., Wiley*
6. Statistical Mechanics, *Pathria, R. K., Pergamon Press*
7. Statistical Physics Part-I, *Landau L. D. and Lifshitz E. M., Pergamon Press*
8. Fundamentals of Statistical and Thermal Physics, *Frederick Reif, McGraw-Hill*
9. Statistical Dynamics: Matter out of equilibrium, *R. Balescu, World Scientific*
10. Non-Equilibrium Statistical Mechanics, *D. N. Zubarev*

04-PHYS04-001-E: Introduction to Python for scientific computing (22 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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.

Course Outcomes:

- 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.

References:

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

Semester-II (BASIC)

04-PHYS04-004-B: (BASIC) Quantum Field Theory: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- 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.

References:

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

04-PHYS04-002-B: (BASIC) Condensed Matter Physics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- 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 – 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.

Course Outcomes:

- 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.

References:

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. Rhoderic*
4. Solid State Physics, *A. J. Dekker*

04-PHYS04-003-B: (BASIC) Nuclear Physics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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:**
  α-decay, β-decay, γ-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.

Course Outcomes:

- After completing this course, students will have basic understanding of nuclear structure and reactions.

References:

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 and Bhaduri*
6. Nuclear Physics in a nutshell, *C. A. Bertulani*
7. The Nuclear Many-Body Problem, *P. Ring and P. Schuck*

04-PHYS04-001-B: (BASIC) Accelerator Physics: (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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.
- **Charged 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 Alvarez 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-I and Indus-II at RRCAT.

Course Outcomes:

- 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.

References:

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

04-PHYS04-005-B: (BASIC) Introduction to high energy nuclear collisions and quark-gluon plasma (QGP): (15 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- Introduction to high energy nuclear collisions and quark-gluon plasma (QGP).
- Comparison of 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, quarks 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 bgeneral 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.

Course Outcomes:

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

References:

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 Verla*
5. Data Reduction and Error Analysis for the Physical Sciences, *Philip R. Bevington and D. Keith Robinson, McGraw-Hill*

04-PHYS04-002-E: (BASIC) Numerical techniques and application: (22 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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 π by Monte-Carlo method, Monte-Carlo technique of numerical integration, Metropolis algorithm.

- **Machine Learning:**
  Introduction to machine learning, Application.

Course Outcomes:

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

References:

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++, *William H. Press, Saul A. Teukolsky, William T. Vetterling and Brian P. Flannery, Cambridge University Press, 2nd edition, 2002*
4. Scientific Computing in Python, *Abhijit Kar Gupta*

Semester-III (Advanced)

04-PHYS04-001-A : 1. (ADVANCED) Accelerator Physics (30 Lecture Hrs)

Coordinators: Animesh Goswami
animesh@vecc.gov.in

Course Details:

- **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 superconductors and their properties. Superconducting 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.

Course Outcomes:

- 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.

References:

1. Vacuum Technology, 3rd edition, *A. Roth, North Holland*
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 University Accelerator School, 2003*
5. CERN Accelerator School Proceedings: Magnets, *2009, Editor D. Brandt*
6. Superconducting Magnets, *M. N. Wilson, Oxford University Press*
7. Case Studies in Superconducting Magnets, *Yukikazu Iwasa, Springer*

04-PHYS04-001-A : 2. (ADVANCED) Nuclear Theory (30 Lecture Hrs)

Coordinators: Gargi Chaudhuri
gargi@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- After completing this course, students will have adequate understanding and skill to initiate nuclear theory research.

References:

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

04-PHYS04-001-A : 3. (ADVANCED) Experimental Nuclear Reaction Studies (30 Lecture Hrs)

Coordinators: Kaushik Banerjee
kaushik@vecc.gov.in

Course Details:

- 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-Feshbach 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 characterizations. 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.

Course Outcomes:

- 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.

References:

1. Nuclear structure from a simple perspective, *R. F. Casten*
2. Introduction to Nuclear Physics, K. S. Krane
3. Direct nuclear reactions, *N. K. Glendenning*
4. Nuclear structure *Vol. I and Vol. II, A. Bohr and B. Mottelson*
5. Introduction to Nuclear Reactions, G. R. Satchler
6. Nuclear Fission, *R. Vandenbosch and J. R. Huizenga*
7. Giant Resonances, *M. N. Harakeh and A. van der Woude*
8. Treatise on Heavy Ion Science, *Vol. 2, Edited by D. Allan Bromley*
9. Treatise on Heavy Ion Science, *Vol. 3, Edited by D. Allan Bromley*
10. Heavy Ion Collisions at Intermediate Energy, *S. Das Gupta, S. Mallik and G. Chaudhuri*
11. Nuclear Dynamics in the Nucleonic Regime, *D. Durand, E. Suraud, B. Tamain*
12. Treatise on Heavy Ion Science, *Vol. 8, Edited by D. Allan Bromley*

04-PHYS04-001-A : 4. (ADVANCED) Experimental Nuclear Structure and Decay Studies (30 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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 and 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.

Course Outcomes:

- 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.

References:

1. In-beam gamma ray spectroscopy, *H. Morinaga and T. Yamazaki*
2. Alpha Beta and Gamma Ray spectroscopy, *K. Siegbah*
3. Handbook of Nuclear Spectroscopy, *J. Kantele*
4. Gamma Ray and Electron spectroscopy in nuclear physics, *H. Ejiri and M. J. A. de Voigt*
5. Suggested journal publication, review articles and thesis

04-PHYS04-001-A : 5. (ADVANCED) Condensed Matter Physics (30 Lecture Hrs)

Coordinators: Gayathri N. Banerjee
gayathri@vecc.gov.in

Course Details:

- **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, Jahn-Teller distortion, Zener double exchange model, Mott insulator, High temperature superconductor, Manganites. Density functional theory. Magnetic property of a solid, d0 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.

Course Outcomes:

- After completing the course, students are expected to gain an understanding of the physics of nano-materials and advanced oxide materials.

References:

1. Solid State Physics, *A. J. Dekker*
2. Physics of Nanostructures, *Dresselhaus and Dresselhaus*
3. Transition Metal Oxides, *P. A. Cox*
4. Modern Condensed Matter Physics, *Steven M. Girvin and Kun Yang*
5. Solid State Properties: From Bulk to Nano, *Mildred Dresselhaus, Gene Dresselhaus, Stephen B. Cronin. and Antonio Gomes Sorrza 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.*

04-PHYS04-001-A : 6. (ADVANCED) Material Science (30 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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. 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, behavior 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.

Course Outcomes:

- 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.

References:

1. L 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. Cittus, "lnadiation Effects in Crystalline Solids',, Applied Science Ltd., (1978)

04-PHYS04-001-A : 7. (ADVANCED) Relativistic Heavy-Ion Collision Experiments & Quark-Gluon Plasma (30 Lecture Hrs)

Coordinators: Pranika Das
parnika@vecc.gov.in

Course Details:

- **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, E_T, (pseudo)Rapidity, p_T 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.

Course Outcomes:

- This course provides working knowledge to start research on the experimental aspects of relativistic heavy-ion collision.

References:

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*

04-PHYS04-002-A : (ADVANCED) LABORATORY EXPERIMENTS (60 Lab Hrs)

1. Experiments using gamma-spectroscopy detector/ detectors (60 Lab Hrs)

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- 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 $CeBr_3$ 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.

Course Outcomes:

- 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

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- Experiment will be performed to calibrate the pulse height response of a liquid scintillator based neutron detector using ^{22}Na and ^{137}Cs gamma-ray sources. Neutron gamma discrimination using pulse shape discrimination technique will be performed using 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 pulse height thresholds.

Course Outcomes:

- 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

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- 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 mono flux

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- 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 scalers.

Course Outcomes:

- 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

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

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

Course Outcomes:

- 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

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- 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

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- 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.

Course Outcomes:

- 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

Coordinators: Dr. Gayathri N. Banerjee and Dr. Supriya Mukhopadhyay
gayathri@vecc.gov.in and supm@vecc.gov.in

Course Details:

- 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 by applying an electrostatic potential difference. A magnetic field is applied to select a specific ion (isotope) to pass through an aperture. The energetic ion 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.

Course Outcomes:

- 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.