

# 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 nation

## PHD COURSEWORK FOR THEORY DIVISION

The following coursework is proposed for the candidates joining SINP from August. As per new HBNI rules, the minimum requirement for students to register for Ph.D. under HBNI needs 18 credits as follows:

18 Credit = 12 Credit (Coursework) + 6 Credit (Project)

**Definition of a Credit:** 1 Credit = 15 hour Classroom/30 hr Lab. For each credit, a total of 50 marks may be used.

Assuming a standard lecture to be 1.5h, 1 credit = 10 lectures.

Assuming two lectures a week, 1 credit = 5 weeks.

Following lengths are recommended for various types of courses:

Credit course	Classes	Weeks
<b>1</b>	<b>10</b>	<b>5</b>
<b>2</b>	<b>20</b>	<b>10 (2.5 month)</b>
<b>3</b>	<b>30</b>	<b>15 (4 month)</b>

Semester-I = 10 Credit (Classroom) + 2 (Project) = 12 credits

Semester-II = 2 Credit (Classroom) + 4 (Project) = 6 credits

**Total Credits = 12 + 6 = 18 Credits. OGCE expected in April**

The student is expected to join the PhD program during April, which is simultaneous with the formation of the OGCE council.

### Semester-I (Aug-December)

Sr. No	Code	Name of Course	No. of Lecture Hours	Credit	Marks
1	05-PHYS04-001-C	Advanced Quantum Mechanics	45	3	150
2	05-PHYS04-002-C	Advanced Statistical Physics	45	3	150
3	05-PHYS04-003-C	Research Methodology & Research Publication Ethics	45	3	150
4	05-PHYS04-004-C	Computational Physics	30	2	100
5	05-PHYS04-001-PR	Reading Project (1)	30	2	100
<b>Total</b>				<b>13</b>	<b>600</b>

[C]: Classroom course      [P]: Project course

### Semester-II (January-March)

Sr. No	Code	Name of Course	No. of Lecture Hours	Credit	Marks
1	05-PHYS04-005-C	Advanced Course	30	2	100
2	05-PHYS04-002-PR	Project (2)	60	4	200
<b>Total</b>				<b>6</b>	<b>300</b>

4-credit project is approximately  $30 \text{ hrs} \times 4 = 120 \text{ hrs}$  for the student.

Assuming the student devotes 3hrs/work day to the project:

Total hours/week =  $3 \times 5$  working days = 15 hrs

Total hours/month =  $15 \times 4$  weeks = 60 hrs

Approximate duration of Project ~ 2 months ~ 120 hours.

Anticipating 2.5-3 months for Semester-II should be optimal.

## COURSES CO-ORDINATOR FOR THEORY

Course	Coordinators	Email
Advanced Quantum Mechanics	Arti Garg	<a href="mailto:arti.garg@saha.ac.in">arti.garg@saha.ac.in</a>
Advanced Statistical Physics		
Research Methodology & Research Publication Ethics		
Computational Physics		
Reading Project (1)		
Advanced Course		
Project (2)		

## DETAILED SYLLABUS FOR THE PHD COURSES

### 05-PHYS04-001-C: Advanced Quantum Mechanics (45 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

#### *Course Details:*

- **Review of basic quantum mechanics, symmetries:**  
Parity, time reversal, continuous symmetries.
- **Approximation methods:**  
variational method, WKB approximation, quantum adiabatic theorem. Atoms, atoms in external fields. Time dependent Perturbation Theory, Scattering Theory, Approximation Methods, Open Quantum Systems, Quantum Entanglement, Quantum Measurements, Quantum Algorithms.

#### *Course Outcomes:*

- Upon completing the course, the student should be able to successfully apply the ideas of quantum mechanics to mathematically formulate a physical problem, perform the necessary computations, whether analytic or numerical, and derive and interpret appropriate results to reach a conclusion.

#### *References:*

1. Advanced Quantum Mechanics, *J. J. Sakurai*.
2. Principles of Quantum Mechanics, *R. Shankar*.
3. Quantum Mechanics: Relativistic Theory *Landau and Lifshitz*.
4. Quantum Computation and Quantum Information, *Nielsen and Chuang*.

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**05-PHYS04-002-C: Advanced Statistical Physics (45 Lecture Hrs):****Coordinators: Arti Garg**  
**arti.garg@saha.ac.in****Course Details:**

Ensemble theory (ergodicity, thermodynamic limit for various kinds of interactions: local, long-ranged), microcanonical, canonical, and grand canonical. Approach to equilibrium: H-theorem. Thermalization in Quantum systems, and its violations.

**▪ Quantum Gases. Bosons:**

Bose-Einstein condensation, weakly-interacting Bose gas, Fermions: degenerate Fermi gases, superfluidity. Photons and blackbody radiation.

**▪ Phase Transitions, Renormalization Group, and Critical Phenomena:**

Landau-Ginzburg theory. Transfer Matrices and connections to quantum field theory. Minimal Models: Ising, Potts, XY, O(3) models. Kramers-Wannier dualities. Series expansions for lattice models.

**▪ Linear response: fluctuation-dissipation theorem.**

Non-equilibrium statistical mechanics: Boltzmann equation, relaxation time approximation.

**Course Outcomes:**

- Upon completing the course, the student should be able to appreciate the statistical ideas to treat complex systems, and apply them as appropriate to various advanced topics in condensed matter physics, soft-matter physics, high-energy physics, astrophysics etc.

**References:**

1. Statistical Mechanics, *Kerson Huang*.
2. Statistical Physics, *Mehran Kardar*.
3. Statistical Physics, *Landau and Lifshitz*.
4. Theory of Phase Transitions and Critical Phenomena (Vol 1,3,6), *Domb & Green*.
5. Quantum and Statistical Field Theory, *M. LeBellac*.
6. Quantum Field Theory and Condensed Matter, *R. Shankar*.
7. Condensed Matter Field Theory, *A. Altland and B. Simons*.
8. Equilibrium Statistical Physics by *Plischke and Bergersen*.

## 05-PHYS04-003-C: Computational Physics (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

- **Programming and Technical Computing (C/python/julia):**  
Data types, flow control, functions, pointers, arrays, I/O, libraries, parallelization, elements of object-oriented programming.  
Basic Numerical Algorithms, Linear Algebra, Solution of nonlinear equations, interpolation and extrapolation, numerical differentiation and integration, differential and integral equations, variational methods.
- **Classification of errors, Error propagation**  
Data analysis: linear and non-linear fitting, parameter estimation, confidence intervals. Monte Carlo techniques, Basics of Learning techniques and their applications.

### Course Outcomes:

- This course aims to provide the student a comprehensive knowledge about the various computational techniques necessary for performing research in high-energy, astro, and condensed matter physics, including the familiarity with special-purpose scientific libraries.

### References:

1. Computational Physics, *J. M. Thijssen*.
2. An Introduction to Computer Simulation Methods, Gould, *Tobochnik, and Christian*.
3. Introduction to computational physics, *Tao Pang*.
4. A guide to Monte Carlo Simulations in Statistical Physics, *D. P. Landau and K. Binder*.
5. Data Reduction and Error Analysis, *P. R. Bevington and D. K. Robinson*.
6. Numerical Recipes in C: The Art of Scientific Computing, by *William H. Press, Saul A. Teukolsky, William T. Vetterling, Brian P. Flannery*.
7. Introduction to Bayesian Statistics, by *Karl-Rudolf Koch*.

## 05-PHYS04-005-C: Advanced Course Suggestions (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

*Various advanced courses can be given in the second semester, including, but not limited to:*

1. General Relativity and Cosmology
2. Astrophysics
3. Particle Physics
4. Advanced Computational Physics
5. Quantum Field Theory
6. Lattice Field Theory
7. Conformal Field Theory
8. Special Topics in String Theory
9. Quantum many-body physics: Analytical and numerical tools
10. Strongly correlated systems and exotic phenomena
11. Advanced Condensed Matter Physics
12. Quantum many-body systems out of equilibrium.
13. An introduction to some topological phases of matter.

**Note:**

Although the student has to credit at least ONE advanced course, they should be encouraged to attend other advanced courses as may be given in consultation with the project supervisors. If more advanced courses are credited, then they can be stated on the Marksheet.

## Syllabus for the advanced courses:

### General Relativity and Cosmology (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

#### Course Details:

Review of Special Relativity, Tensor Analysis, Equivalence Principle, General Covariance, Newtonian Limit, Covariant differential and Riemann tensor, Einstein-Hilbert action and Einstein equations, Schwarzschild solution, Classical tests of General Theory of Relativity, Interior solution and Kerr's solution, Collapse into black hole, Friedman-Robertson-Walker cosmology. Weak-field limits, Newtonian limits.

- **Gravitational radiation:**  
propagation, detection, and generation of gravitational waves, memory effect and associated phenomena, examples of astrophysical sources.
- **Theory of Manifolds, Basics of Differential Geometry and the associated mathematical formulation of General Relativity.**

#### Course Outcomes:

- Upon completion of this course a student is expected to learn and apply the basic conceptual and technical aspects of general relativity in relevant research problems.

#### References:

1. Spacetime and Geometry, *Sean Carroll*.
2. A First Course in General Relativity, *by Bernard Schutz*.
3. Gravity, *James Hartle*.
4. Gravitation, *Misner, Thorne, Wheeler*.

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## Astrophysics of Compact Stars (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

- **Birth and Death of stars:**
- **Introduction to stellar evolution:**  
Hydrogen burning, pp chain and CNO cycle, Helium burning and synthesis of heavier elements and end of fusion chain: formation of iron. group elements, Gravitational core collapse, Equation of state, Neutrinos, supernova explosions and birth of compact stars, SN1987, Type I Supernovae, standard candle.
- **White Dwarfs:**  
Degenerate pressure of electrons, polytropic equation of state, hydrostatic stability and Lane-Emden equation and structures of white dwarfs, Chandrasekhar mass.
- **Neutron Stars:**  
Discovery of neutrons and Landau's prediction of neutron stars in 1932, measurement of masses and radii of neutron stars, Pulsars and Magnetars, their astrophysical evolutions in isolated and binary systems.
- **Dense Matter in Neutron Star:**  
Composition of neutron stars, novel phases of dense matter and EoS, Non-relativistic and relativistic models of dense matter, Tolmann-Oppenheimer-Volkoff equation and masses and radii of neutron stars, Quark stars versus neutron stars. Observational constraints from gravitational waves, prospects from binary neutron star mergers and continuous gravitational waves.

### Course Outcomes:

- Upon completion of this course, the student should have a basic background of astrophysics of stellar evolutions and life-cycles of a star, stellar deaths and birth of degenerate compact stars, their structure, compositions and evolutions in astrophysical timescales. The course should introduce some of the recent developments, open questions and future prospects.

### References:

1. Compact Stars: Nuclear Physics, *Particle Physics and General Relativity*, by Norman K. Glendenning.
2. Multi-Messenger Astrophysics, a review article by Peter Meszaros, Derek B. Fox, Chad Hanna, Kohta Murase.

## Particle Physics (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Computation of cross-sections and decays of tree level and 1-loop processes of quantum electrodynamics, weak-interactions, and perturbative chromodynamics. Running couplings, beta-functions and renormalization. Phenomenology of weak interactions, spontaneous symmetry breaking and Higgs mechanism. Non-perturbative physics of confinement and chiral symmetry breaking. Theories of Neutrinos. Structure of the Standard Model and leading candidates for beyond the Standard Model theories.

### Course Outcomes:

- The student is expected to appreciate the historical development of the field leading to the construction of the Standard Model, and should be able to perform tree level calculations of simple processes in particle physics. Emphasis should be given to the future development of the field in terms of the open questions, relations to other fields such as astrophysics and machine learning.

### References:

1. Concepts of elementary particle physics, *Peskin*.
2. Particle Physics, *Martin*.
3. Gauge theory of elementary particle physics, *Cheng and Lee*.
4. QCD and collider physics, *Ellis, Stirling, Webber*.

## Advanced Computational Physics (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

- **Solution of ordinary and partial differential equations, finite element methods, time-series analysis, discrete and fast Fourier analysis.**
- **Advanced Monte Carlo algorithms for particle and condensed matter physics:**  
Metropolis, Heatbath, Cluster, Worm, Hybrid Monte Carlo, Molecular Dynamics. Using advanced linear algebra packages.
- **Numerics for quantum systems:**  
Exact diagonalization, Lanczos methods, Density Matrix Renormalization Group, Matrix Product States. Basic algorithms of Machine Learning and Artificial Intelligence.
- **Error analysis and propagation: Bayesian methods, Concepts of prior, likelihood, posterior and evidence; parameter estimation:**  
Bayes's box, sampling distribution and likelihood; Parameter Estimation, summarizing the posterior distribution, point estimates, introduction of decision theory, loss function; computing point estimates, credible intervals and confidence intervals; hypothesis testing and model selection.

### Course Outcomes:

- The student is introduced and exposed to modern computational methods used in different areas of computational intensive research ranging from quantum field theories, condensed matter physics, and astrophysics.

### References:

1. Computational Physics, *J. M. Thijssen*.
2. An Introduction to Computer Simulation Methods, *Gould, Tobochnik, and Christian*.
3. Introduction to computational physics, *Tao Pang*.
4. A guide to Monte Carlo Simulations in Statistical physics, *D. P. Landau and K. Binder*.
5. Introduction to Bayesian Statistics, *by Karl-Rudolf Koch*.

## Quantum Field Theory (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

- Elementary classical field theory Lorentz group and its representations. Canonical quantization, path integral methods. Transfer Matrix.
- Scalar and fermionic quantum field theories. Interactions. Symmetries and conservation laws. Correlation functions. Scattering and S-matrix.
- Perturbative methods of QFT: the weak-coupling expansion, structure of perturbation theory. Computation of correlation functions. Strong coupling expansion (hopping-parameter expansion in lattice models).
- Kramers-Wannier duality. Abelian and non-Abelian gauge theory, Fadeev-Popov procedure. Photons.
- Renormalization group: structure of QFTs, fixed points, phases, conformal field theories.

### Course Outcomes:

- The student is introduced to modern methods of quantum field theory and is able to identify relevant situations where such methods can be applied.

### References:

1. Lectures of Sidney Coleman in QFT.
2. Quantum Field Theory, E. Fradkin.
3. Quantum Field Theory and the Standard Model, M. Schwartz.
4. Quantum Field Theory, *M. Srednicki*.

## Lattice Field Theory (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Quantum fields defined on a space-time lattice: scalar, fermionic, and gauge fields. Subtleties with fermions: Nielsen-Ninomiya theorem, fermion doubling. Lattice Gauge Fields, proof of confinement, hopping parameter expansion. Non-perturbative renormalization and scale setting, continuum limit. Monte Carlo sampling and sign problem. Lattice Quantum Chromodynamics. Relation to condensed matter physics, quantum information and simulations.

### Course Outcomes:

- The student is able to appreciate the modern methods to non-perturbatively study quantum field theories using the lattice regularization and effectively use them in research problems.

### References:

1. Lattice Gauge Theories, *Rothe*.
2. Introduction to quantum fields on the lattice: *Smit*.
3. Lattice Methods for Quantum Chromodynamics, *DeTar and DeGrand*.
4. Quantum Fields on a lattice, *Montvay and Münster*.

## Conformal Field Theory (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Some basics in Statistical Physics, Ising model and scaling, Mean Field Theory, Real-Space Renormalization Group.

- **Introduction to Conformal Invariance, The Free Boson & Free Fermion Theory, Conformal Field Theory & Operator Product Expansion, Conformal Invariance, Energy-momentum Tensor and Ward Identities.**

Virasoro Algebra & the Hilbert Space of Conformal Field Theory, Introduction to Minimal Models, Null States & Correlation Functions. Monodromy, Affine-Lie Algebras or Current Algebras.

Partition Functions, A Route to Anti de-Sitter (AdS)/Conformal Field Theory (CFT) correspondence, Conformal Field Theory Techniques in condensed-matter problems.

### Course Outcomes:

- Upon completing this course, the student is expected to understand and apply the conceptual and technical aspects of conformal field theories in problems in both theoretical high energy physics and condensed-matter physics.

### References:

1. Conformal Field Theory by Di Francesco, *Mathieu, Senechal*.
2. Introduction to Conformal Field Theory by *Blumenhagen, Plauschinn*.
3. Scaling and Renormalization in Statistical Physics, *Cardy*.

## Special Topics in String Theory (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

- **Introduction to String theory:**  
Quantization, spectrum and different kinds of string theories and their low energy limits.
- **Introduction to Holography:**  
Emergence of Gravity, Weinberg-Witten no-go theorem, Black Holes and Black Hole Thermodynamics, The Holographic Principle.
- **A Specific Example of Holography:**  
The AdS/CFT Correspondence, The Conjecture with a Bit of String Theory, The Many Avatars of AdS, A Brief Introduction to Conformal Field Theory, Into the Duality Toolbox: Calculating Observables.
- **Insights into Many Body Systems:**  
Transport Properties & Hydrodynamics, Condensed Matter-Inspired Systems, Real-time Dynamics: Physics Out-of-equilibrium.
- **Towards Quantum Gravity:**  
Black Hole Information Paradox, Issues with Quantum Gravity.

### Course Outcomes:

- Upon completing this course, the student is expected to understand and apply the conceptual and technical aspects of string theoretic framework. This overlaps largely with other theoretical courses of QFT, CFT and gravity and complements them for advanced theoretical training of students.

### References:

1. String Theory by *Polchinski*.
2. String theory and M-theory by *Becker, Becker, Schwarz*.
3. A First Course in String Theory by *Zwiebach*.

## Quantum Many-Body Physics: Analytical and Numerical Tools (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Green's functions, Kubo formalism, Mean Field theory and dynamical mean field theory. Exact Diagonalization, Introduction to Monte Carlo Methods, Molecular Dynamics and Density functional theory like techniques. Application of these methods to study various models (like Hubbard model, Spin-fermion model, Heisenberg model etc) and their correlation with observed phenomena that arise in complex body systems.

### Course Outcomes:

- Provide an overview of basic theoretical/numerical approaches to many-body systems, both classical and quantum and prepare students for carrying out research in theoretical condensed matter physics.

### References:

1. Many-Particle Physics by *G. D. Mahan, Plenum Press (1981)*.
2. Computational Physics by *J. M. Thijssen, Cambridge University Press (2007)*.
3. Introduction to Many Body Physics by *Piers Coleman, Cambridge University Press (2015)*.
4. Green's functions for solid state physicists by *S. Doniach and E.H. Sondheimer*.

## Strongly Correlated Systems and Exotic Phenomena (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Hubbard model, Schrieffer-Wolf Transformation, physics of t-J model, Mott Insulators, metal to Mott insulator transition, unconventional superconductivity, pseudogap phase, strange metal phase and non-fermi liquid theory, Quantum Heisenberg model and its possible phases, spin-wave analysis, spontaneous breaking of continuous symmetry and Mermin-Wagner Theorem. Spectral functions, transport in strongly correlated systems, flat-band superconductors and ferromagnetism, physics of Moiré superlattices and van der Waals heterostructures of strongly correlated systems.

### Course Outcomes:

- Purpose of the course would be to make students familiar with the complex physics of strongly correlated systems, where many exotic phases of matter are realized.

### References:

1. Lecture notes on electron correlation and magnetism by *P. Fazekas*.
2. Introduction to Many Body Physics by *Piers Coleman*, Cambridge University Press (2015).
3. Interacting Electrons and Quantum Magnetism by *Assa Auerbach*, Springer.
4. Many-Particle Physics by *G. D. Mahan*, Plenum Press (1981).
5. Recent reviews on superconductivity, flat band systems and heterostructures.

## Advanced Condensed Matter Physics (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Conventional and unconventional superconductivity, Magnetism, Linear Response Theory and Transport, Spontaneous breaking of continuous symmetry, Long-range ordered and quasi-long range ordered phases, spin liquids, Kondo effect and heavy fermions, Anderson Localization and localization in interacting disordered systems.

### Course Outcomes:

- Purpose of the course is to introduce interesting phenomena in condensed matter physics and how to characterize these phenomena.

### References:

1. Introduction to Superconductivity by *Tinkham, McGraw Hill*.
2. Superconductivity by *Ketterson and Song*.
3. Recent Reviews on unconventional superconductivity, quantum spin liquids.
4. Interacting Electrons and Quantum Magnetism by *Assa Auerbach, Springer*.
5. Many-Particle Physics by *G. D. Mahan, Plenum Press (1981)*.
6. Introduction to Many Body Physics by *Piers Coleman, Cambridge University Press (2015)*.
7. The Kondo Problem to Heavy Fermions edited by *D. Edwards and D. Melville, Cambridge Studies in Magnetism*.
8. 50 years of Anderson Localization by *E. Abrahams*.
9. Review on Localization by *Z. Jaanen* and recent reviews on many-body localization.

## Quantum Many-Body Systems Out of Equilibrium (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Introduction to quantum non-equilibrium, dynamics of isolated quantum systems and eigenstate thermalization hypothesis, quantum quench, quantum dynamics in short to intermediate time scales- prethermalization, periodically driven isolated quantum systems, discrete time crystals, Floquet approach, Non-equilibrium Green's functions, quantum systems out of equilibrium using quantum Langevin equations.

### Course Outcomes:

- The goal is to make students familiar with complex physics of quantum-many body systems out of equilibrium and teach them analytical and numerical tools to explore these systems. They will also learn about novel phases and phase transitions in driven quantum many-body systems.

### References:

1. Open Quantum Systems far from equilibrium by *G. Schaller*.
2. Non-equilibrium Green's function method by *S. Dutta et al.*, *arXiv: 2008.01275*.
3. Lecture notes: Dynamics of Quantum Many-body systems far from thermal equilibrium by *M. Schiro*.
4. An introduction to non-equilibrium Green's functions by *R. Van Leeuwen and N. E. Dahlen (online lecture notes)*.

## An Introduction to Some Topological Phases of Matter (30 Lecture Hrs):

Coordinators: Arti Garg  
arti.garg@saha.ac.in

### Course Details:

Topological insulators, quantum (spin) Hall effect, bulk-edge correspondence, chiral and helical edge modes (Dirac fermions), topological superconductors, Majorana fermions and vortex zero-modes, universality classes (tenfold way), topological invariants (Chern number), Weyl semimetals and surface Fermi arcs, Topology in classical systems, Topology in interacting systems:

Gauge and topological field theories.

### Course Outcomes:

- The purpose of the course is to become familiar with some of the research trends in Condensed Matter encapsulating the fascinating world of topological phases of matter. The first objective is to become proficient in analysing a physical theory and the second is to learn how to distil the essentials from a set of advanced review and current research articles.

### References:

1. A short course on topological insulators by *J. K. Asbóth, L. Oroszlány, and A. Pályi*.
2. An introduction to topological insulators by *M. Fruchart and D. Carpentier*.
3. Maxwell Lattices and Topological Mechanics by Xiaoming Mao and Tom Lubensky.
4. Topological Phases of Matter by *R. Moessner and J. E. Moore* (Cambridge University Press, 2021).

## PHD COURSEWORK FOR EXPERIMENTAL PHYSICS

The following coursework is proposed for the candidates joining SINP from August 2024. As per new HBNI rules, the minimum requirement for students to register for Ph.D. under HBNI requires 18 credits as follows:

18 Credit = 12 Credit (Coursework) + 6 Credit (Project)

**Definition of a Credit:** 1 Credit = 15 Hrs Classroom/30 Hrs Lab.

For each credit, a total of 50 marks may be used.

Assuming the standard lecture to be 1.5 Hrs, 1 credit = 10 lectures.

Assuming two lectures a week, 1 credit = 5 weeks.

Assuming 3 Hrs of laboratory work per day, 1 credit = 2 week

The following lengths are recommended for various types of courses:

credit course	classes	weeks
1	10	5
2	20	10 (2.5 months)
3	30	15 (4 months)
6 credit project	180 Hrs lab. work	12 (3 Months)

In the experimental Physics stream, we plan to have two semesters, where Semester I will have 4 theory courses and 1 experimental lab course with a total of 12 credits, while Semester II will have 6 credits for 1 experimental project. The details are listed in the table below.

### Semester-I (August-December) – 5 Months

Sr. No	Code	Name of Course	No. of Lecture Hours	Credit	Marks
1	05-PHYS04-101-C	Theory course - I	45	3	150
2	05-PHYS04-102-C	Theory course - II	45	3	150
3	05-PHYS04-003-C	Research Methodology & Research Publication Ethics	45	3	150
4	05-PHYS04-104-C	Computational Physics	45	2	100
5	05-PHYS04-105-C	Experimental Techniques and Analytical Methods	30	2	100
<b>Total</b>				<b>13</b>	<b>600</b>

### Semester-II (January-March) – 3 Months

Sr. No	Code	Name of Course	No. of Lab Hours	Credit	Marks
1	05-PHYS04-101-L	Experimental Project	120	6	300
<b>Total</b>				<b>6</b>	<b>300</b>

## COURSES COORDINATOR FOR EXPERIMENTAL PHYSICS

Course	Coordinators	Email
Advanced Condensed Matter Physics	Prof. Pratik Majumder & Dr. Mrinmay Kumar Mukhopadhyay	<a href="mailto:pratik.majumdar@saha.ac.in">pratik.majumdar@saha.ac.in</a> <a href="mailto:mrinmay.mukhopadhyay@saha.ac.in">mrinmay.mukhopadhyay@saha.ac.in</a>
Surface and Interface Physics		
Astroparticle Physics		
Physics, Signatures and Astrophysics of Quark-Gluon Plasma (QGP)		
Modern Atomic Physics		
Introduction to Modern Particle Physics		
Nuclear Physics and Nuclear Astrophysics Course		
Computational Physics		
Experimental Techniques and Analytical Methods		
Experimental Project		

## DETAILED SYLLABUS FOR THE PHD COURSES

### Options for Theory Courses I & II:

*Students need to take at least two courses of their choice from the list below.*

1. Advanced Condensed Matter Physics
2. Surface and Interface Physics
3. Astroparticle Physics
4. Physics, Signatures and Astrophysics of Quark-Gluon Plasma (QGP)
5. Modern Atomic Physics
6. Nuclear Physics and Nuclear Astrophysics Course
7. Introduction to Modern Particle Physics

### Advanced Condensed Matter Physics (45 Lecture Hrs):

**Coordinators: Prof. Pratik Majumdar**  
[pratik.majumdar@saha.ac.in](mailto:pratik.majumdar@saha.ac.in)  
& **Dr. Mrinmay Kumar Mukhopadhyay**  
[mrinmay.mukhopadhyay@saha.ac.in](mailto:mrinmay.mukhopadhyay@saha.ac.in)

*Students have to complete all four modules to complete this course.*

### Module 1: Quantum Transport Phenomena in solid state physics

Electrons as quantum gas, density of states, properties of electron gas, Metal-Semiconductor contacts, Ohmic contacts, Two-dimensional electron gas, scattering mechanism, Transport at low dimension, Coulomb blockade, conductance quantisation, Quantum Hall effect, edge state transport, quantum electron optics, fractional quantum Hall effect.

#### **Course Outcomes:**

- Upon completing this course module, the student should know the fundamental physics of electron transport and scattering phenomena, Coulomb blockade effect, integer and fractional quantum Hall effect.

#### **References:**

1. Solid State Physics by Ashcroft and Mermin. Publisher: Cengage Learning.

### Module 2: Nanomagnetism and Spintronics

#### **Course Details:**

Brief overview of various types of magnetic order in solids, Spin dynamics of nanomagnetic systems and Landau–Lifshitz–Gilbert equation, Spin Transfer Torque, Spin-orbit torques, Magneto-resistive phenomena: Anisotropic Magnetoresistance, Spin-Hall magnetoresistance, Giant Magnetoresistance and Tunnel Magnetoresistance, Real and inverse space topology in magnetic materials, 2D magnetism and its prospects.

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**Course Outcomes:**

- Upon completing this course module, the student should know the fundamental physics behind the stabilisation of magnetic order in solids and the effect of quantum and relativistic interactions in nanomagnetic heterostructure systems.

**References:**

1. Magnetism in Condensed Matter by Stephen Blundell. Publisher: Oxford Master series in Condensed Matter Physics.
2. Topology in Magnetism by Jiadong Zang, Vincent Cross and Axel Hoffmann. Publisher: Springer series in solid state physics.

**Module 3: Memory devices and introduction to neuromorphic computing****Course Details:**

Understanding the concept of Memristor (4th circuit element); different kinds of memory devices such as resistive random access memory, Phase change memory, Ferroelectric memory, magnetic memory and their mechanism; the difference between the concept of traditional computers based on von Neuman architectures and neuromorphic computers; materials and interfaces for neuromorphic computing; spike time-dependent plasticity and different learning rules related to neuromorphic computing.

**Course Outcomes:**

- Upon completing this course module, the student should have a basic understanding of different kinds of memory devices and an overview of neuromorphic computing for condensed matter physics.

**References:**

1. Resistive Switching: From Fundamentals of Nanoionic Redox Processes to Memristive Device Applications by Daniele Ielmini, Rainer Waser; Publisher: Wiley.
2. Memristor For Neuromorphic Circuits And Artificial Intelligence Applications, by Jordi Suñé, Publisher – MDPI.

**Module 4: Soft Matter Physics**

- **The course will provide a brief overview of different classes of soft matter:** colloids, liquid crystals, surfactants, micelles, microemulsions etc. Various interactions that control the phase behaviour of these materials, the phase transitions in these soft matters, and their thermodynamics and kinetics will be discussed in this course.

**Course Outcomes:**

- Upon completion of this course module, the student should know the different classes of soft matter and the underlying interactions that govern the phase behaviour, phase transition, thermodynamics, and kinetics of these classes of materials.

**References:**

1. Soft Condensed Matter by Richard A. L. Jones. Publisher – Oxford University Press.
2. Scaling Concepts in Polymer Physics by P. G. de Gennes. Publisher – Cornell University Press.

## Surface and Interface Physics (45 Lecture Hrs):

*Students have to complete all five modules to complete this course.*

**Coordinators: Prof. Pratik Majumdar**  
[pratik.majumdar@saha.ac.in](mailto:pratik.majumdar@saha.ac.in)  
& **Dr. Mrinmay Kumar Mukhopadhyay**  
[mrinmay.mukhopadhyay@saha.ac.in](mailto:mrinmay.mukhopadhyay@saha.ac.in)

### Module 1: Electron and spin transport at the atomic scale

#### **Course Details:**

Conductance of a single atom from the Landauer approach, Heuristic derivation of Landauer formula, Different methods to fabricate atomic-scale junctions and measuring current through a single atom, different statistical methods to analyse the experimental data. A brief overview of scanning tunnelling microscopy and spectroscopy and its importance to understanding the local density of states of materials; introduction to spintronics and different kinds of magnetoresistances, spin valves and spin transport at the atomic scale.

#### **Course Outcomes:**

- Upon completing this course module, the student should know the underlying mechanism and methods to study electron and spin propagation through materials down to the scale of a single atom.

#### **References:**

1. Molecular electronics: Cuevas & Scheer.

### Module 2: Course on Soft matter and its characterisation

#### **Course Details:**

The first part of the course will provide a brief overview of different classes of soft matter: colloids, liquid crystals, surfactants, micelles, microemulsions etc. The second part of the course will focus on the techniques to understand the structure and physical properties of these complex systems. X-ray scattering techniques is one of the most useful techniques to understand the structure of these materials. The basic theory of the scattering technique will be discussed in this course. Some other techniques to measure optical properties, viscoelastic properties etc. will be discussed here.

#### **Course Outcomes:**

- Upon completing this course module, the student should know the different classes of soft matter underlying physics governing surface and interfacial properties in soft matter and the techniques for investigating the surface and interface structure in these materials.

#### **References:**

1. Soft Condensed Matter by Richard A. L. Jones. Publisher – Oxford University Press.
2. Elements of Modern X-ray Physics, J. Als-Nielsen and D. McMorrow. Publisher – John Wiley and Sons, New York.

### Module 3: Surface and Interface Magnetism

#### **Course Details:**

Interfacial effects on magnetic order at reduced dimensions, Effects of interfacial spin-orbit coupling in

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magnetism: Rashba–Edelstein effect, proximity effect, Dzyaloshinskii–Moriya interaction, etc. Skyrmions, antiskyrmion and other spin-textures in magnetic systems, Micromagnetic modelling of interfacial interactions and its effect of spin dynamics in nanomagnetic systems.

**Course Outcomes:**

- Upon completing this course module, the student should know the fundamental physics behind interfacial magnetic order in solids and the effect of interfacial interactions in nanomagnetic systems.

**References:**

1. Magnetism in Condensed Matter by Stephen Blundell. Publisher – Oxford Master series in Condensed Matter Physics.
2. Topology in Magnetism by Jiadong Zang, Vincent Cross and Axel Hoffmann. Publisher – Springer series in solid state physics.

## Module 4: Electronic Structure at surface and interfaces

**Course Details:**

This module will cover the fundamentals of surface science. The requirement of ultra-high vacuum for the surface studies will be discussed along with different practical ways to achieve it. Surface structure studies using low-energy electron diffraction, surface analysis with the help of electron spectroscopy, and electronic structure studies at surfaces will also be covered here.

**Course Outcomes:**

- Upon completing this course module, the student will be exposed to the various aspects of surface physics, such as surface structure, surface analysis methods and photoemission experiments for surface electronic structure studies.

**References:**

1. Photoelectron Spectroscopy – Principles and Applications by Stefan Hüfner. Published by Springer-Verlag Berlin Heidelberg GmbH (2003).
2. Low-Energy Electron Diffraction – Experiment, Theory and Surface Structure Determination by M. A. Van Hove, W. H. Weinberg and C.-M. Chan. Published by Springer-Verlag Berlin Heidelberg GmbH (1986).

## Module 5: Semiconductor optoelectronics

**Course Details:**

Semiconductor Physics and Materials – Band structures, carrier distribution in thermal equilibrium and under excitation, temperature dependence and other experimental techniques.

Optoelectronic materials and devices – Absorption and emission of EM radiation, Photoluminescence Lineshape Analysis, Low-temperature exciton dynamics, Characteristics of photodetectors, Photoconductive photodetectors, Photodiodes, P-i-n photodetectors, Solar cells.

**Course Outcomes:**

- Upon completing this course module, the student should know advanced topics on optoelectronic materials and devices and research tools on optoelectronic material growth and characterisation.

**References:**

1. S. M. Sze, *Physics of Semiconductor Devices* (Wiley, 2015).
2. Handbook of Optoelectronics Ed. John P. Dakin, Robert G. W. Brown, (Taylor and Francis, New York, London, 2006).

## Astroparticle Physics (45 Lecture Hrs):

**Coordinators: Prof. Pratik Majumdar**  
[pratik.majumdar@saha.ac.in](mailto:pratik.majumdar@saha.ac.in)  
& **Dr. Mrinmay Kumar Mukhopadhyay**  
[mrinmay.mukhopadhyay@saha.ac.in](mailto:mrinmay.mukhopadhyay@saha.ac.in)

### **Course Details:**

Rare event detection, Challenges, Dark Matter, Radiation Backgrounds, Different dark matter experiments, Radiation detectors, Detectors for Astroparticle Physics, Electronics, Radiation interaction with matter, Neutrino detection, Cosmic rays and acceleration mechanisms, Radiation Processes in Astrophysical Objects (Ionisation losses, Bremsstrahlung, Synchrotron radiation, Inverse Compton Scattering, Cherenkov Radiation etc.), High Energy Gamma ray astrophysics, sources of cosmic rays, gamma rays and high energy neutrinos.

### **Course Outcomes:**

- The above course will give detailed knowledge on the rare event detection techniques and how to overcome the challenges of running such an experiment. The course will provide the understanding of the basic interaction mechanism of the particles and radiation with matter, astrophysical objects and the detection techniques.

### **References:**

1. Radiation detection and measurement (book), *G. F. Knoll*.
2. Nuclear Radiation Detectors (book), *S. S. Kapoor and V. S. Ramamurthy*.
3. An Introduction to Dark Matter Direct Detection Searches & Techniques, *I. Saab*, *arXiv: 1203.2566v1 [physics.ins-det]* 12 Mar (2012).
4. Dark Matter 2013, Marc Schumann, *arXiv: 1310.5217v1 [astro-ph.CO]* 19 Oct (2013).
5. Direct Detection of Dark Matter: A Critical Review, *Marcin Misiaszek and Nicola Rossi*, *Symmetry* 16, 207 (2024).
6. High Energy Astrophysics: *M. S. Longair Vol 1 and Vol 2*.
7. Cosmic Rays and Particle Physics: *T. K. Gaisser*.
8. Radiation Processes in Astrophysics: *Rybicki and Lightman*.

## Physics, Signature and Astrophysics of Quark-Gluon Plasma (QGP) (45 Lecture Hrs):

Coordinators: Prof. Pratik Majumdar  
 pratik.majumdar@saha.ac.in  
 & Dr. Mrinmay Kumar Mukhopadhyay  
 mrinmay.mukhopadhyay@saha.ac.in

### Course Details:

- **Introduction:**  
The physics aspects of high energy heavy ion collisions and Quark-Gluon-Plasma (QGP).
- **Relativistic Kinematics:**  
Four vectors notations, rapidity and pseudo rapidity variables, relativistic invariants, cross-sections.
- **Thermodynamic aspects:**  
Relativistic gas (hadrons, quarks and gluons) along with the statistical and thermodynamical properties, MIT Bag model, phase diagram.
- **Collision Dynamics:**  
Initial state of nuclear collisions, relativistic hydrodynamics, particle production.
- **Experiments:**  
Exploring experimental facilities related to the search for QGP and relevant observables.
- **Signatures of QGP:**  
Collective flow,  $J/\psi$  suppression, strangeness enhancement, jet quenching, electromagnetic probes, Hanbury–Brown–Twiss measurement.
- **Astrophysics aspects:**  
QGP in the early universe, Big Bang and Little Bang (comparisons).
- **Recent progress and understanding.**

### Course Outcomes:

- Upon the completion of this advanced course, the student will learn the basics of relativistic kinematics, thermodynamics and experimental aspects, hence providing the necessary background required to understand the relativistic nuclear scattering processes and physics of Quark-Gluon Plasma.

### References:

1. Hadrons and QGP by *Letessier and Rafelski*.
2. Introduction to High Energy Heavy Ion Collisions by *C. Y. Wong*.
3. Ultra relativistic heavy ion collisions by *R. Vogt*.
4. Introduction to relativistic heavy ion collisions, by *L. P. Csernai*.
5. A Short Course On Relativistic Heavy Ion Collisions by *A. K. Chaudhuri*.
6. The Early Universe by *Kolb and Turner*.
7. Research Reports in Physics, Quark Gluon Plasma, Invited lectures of Winter School, Published by Springer Verlag, Editors – *B. Sinha, S. Pal and S. Raha*.
8. Quark Gluon Plasma – From big bang to little bang, *K. Yagi, T. Hatsuda, Y. Miake, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology*.
9. Review paper: “Exploring sQGP and Small Systems” (*Debasish Das*) *UMPA 36 (2021) 24, 2130014*.

## Modern Atomic Physics (45 Lecture Hrs):

**Coordinators: Prof. Pratik Majumdar**  
**pratik.majumdar@saha.ac.in**  
**& Dr. Mrinmay Kumar Mukhopadhyay**  
**mrinmay.mukhopadhyay@saha.ac.in**

### **Course Details:**

Atomic Physics of multi-electron systems, Coherent interactions of a radiation field and an atomic system, Resonance, Semi-classical theory and density matrix formalism, Electromagnetically induced phenomena, Laser spectroscopy of alkali atoms and Line-shapes, Cooling and Trapping of Neutral atoms.

#### ▪ **Special Topics:**

Bose-Einstein condensation, Atomic magnetometry, Rydberg atoms, Photon-photon coincidence, Applications in quantum sensing and quantum communication.

### **Course Outcomes:**

- Upon completing the course, the student should be well-versed in the quantum mechanical knowledge of multi-electron atoms. They should understand the basics of light-atom interaction and apply their knowledge in the theoretical formulation of special topics (as mentioned below) before performing advanced experimental study.

### **References:**

1. Modern Atomic Physics – *Vasant Natarajan*.
2. Structure of Multielectron Atoms – *Anders Kastberg*.
3. Quantum Optics: an introduction – *Fox, Mark*.
4. Quantum Optics – *Scully, Marlan O. and Zubairy, M. Suhail*.
5. Laser Cooling and Trapping – *Metcalf, Harold J. and Van Der Straten, Peter*.
6. Physics of Atoms and Molecules – *B. H. Bransden and C. J. Joachain*.

## **Nuclear Physics and Nuclear Astrophysics (45 Lecture Hrs):**

**Coordinators: Prof. Pratik Majumdar**  
[pratik.majumdar@saha.ac.in](mailto:pratik.majumdar@saha.ac.in)  
& **Dr. Mrinmay Kumar Mukhopadhyay**  
[mrinmay.mukhopadhyay@saha.ac.in](mailto:mrinmay.mukhopadhyay@saha.ac.in)

### **Course Details:**

- **A) Nuclear Physics:**
  - The nuclear landscape – Elementary knowledge on the modes of radioactive decay
  - Binding energy and production of nuclei beyond iron
  - Overview of the liquid drop model and the shell model
  - Kinematics of Nuclear Reactions
  - Nuclear potential & Optical model of nuclear reactions
  - Direct reactions (elastic, inelastic, transfer, breakup)
  - Deformation parameters and spectroscopic factors
  - Compound reactions (Fusion-Fission)
  - Resonant and non-resonant reactions
  - Thermonuclear radiative capture reactions
  - Cross sections
  
- **B) Nuclear Astrophysics:**
  - Low energy reaction theory, physics of nuclei and reactions, relevant to nuclear astrophysics, nuclear reaction rates in stellar environments, Big Bang nucleosynthesis, Gamow window and stellar burning processes, r-process, p-process and rp-process, s-, the i- as well as the vp-processes of nucleosynthesis (heavy-element production), astrophysical S-factor and its implications.

### **Course Outcomes:**

- A comprehensive understanding of the core principles of nuclear structure and
- reactions essential for carrying out research in the domain, with a broad view of some
- of the active areas of research comprising nuclear physics and nuclear astrophysics
- today.

### **References:**

1. Introductory Nuclear Physics - Samuel S. M. Wong
2. Introductory Nuclear Physics - Kenneth S. Krane
3. Direct Nuclear Reactions - G. R. Satchler
4. Nuclear Physics in a Nutshell - Carlos A. Bertulani
5. Nuclear physics of stars by Christian Iliadis
6. An Introduction to Nuclear Astrophysics by Richard N. Boyd
7. Cauldrons in the Cosmos by Claus E. Rolfs and W.S. Rodney

## Introduction to Modern Particle Physics (45 Lecture Hrs):

Coordinators: Prof. Pratik Majumdar  
 pratik.majumdar@saha.ac.in  
 & Dr. Mrinmay Kumar Mukhopadhyay  
 mrinmay.mukhopadhyay@saha.ac.in

### Course Details:

- **Introduction:**  
The Standard Model; Interactions of particles with matter; Particle physics experiments; Basics of relativistic kinematics; Concept of natural units
- **Decay rates and cross-sections:**  
Fermi's golden rule; Feynman diagram; Particle decays; Interaction and differential cross-sections; The Dirac equation; Spin and helicity states; Antiparticles
- **Particle Collider Experiment:**  
Particle acceleration mechanism; Particle collision; Detector coordinates; Detector components - tracking system, calorimetry, muon system and unobservable neutrinos; Triggering and data acquisition system; Particle reconstruction; Statistical analysis of data; Role of simulation
- **Quantum Electrodynamics (QED):**  
Feynman rules for QED; Virtual particles; Cross-section calculation for the electron-positron annihilation; Chirality; Inclusive hadronic cross-sections Deep inelastic scattering  
Electron-proton elastic scattering; Deep inelastic scattering; Electron-quark scattering; Electron-proton scattering at the HERA collider; Parton distribution function measurements
- **Quantum Chromodynamics (QCD):**  
Symmetries; Quark model of hadrons; Colour and Colour confinement; Running coupling constant and asymptotic freedom; Gluons; Hadron-hadron collisions
- **Weak Interactions:**  
The weak charged-current interactions; Parity and parity violation (Wu's experiment); V-A structure; Experimental evidence of V-A; Lepton universality; CKM matrix; CP violation in Kaon; Electroweak unification; The Higgs mechanism
- **Discovery of Standard Model particles:**  
J/Psi; gluon;  $W^\pm$ , Z bosons; top quark; Higgs boson
- **Neutrinos:**  
Neutrino flavours; Mass and weak eigenstates; Neutrino oscillations of two and three flavours; Neutrino oscillation experiments; Neutrino reactor experiments.
- **Beyond Standard Model:**  
Open questions in particle physics; Dark matter: Dark matter in direct and collider searches

### Course Outcomes:

- This course aims to provide the student with comprehensive knowledge about the various computational techniques necessary for performing research in high-energy, astro, and condensed matter physics, including familiarity with special-purpose scientific libraries.

### References:

1. Modern Particle Physics. Mark Thomson. Cambridge University Press
2. Particle Physics in the LHC Era. G Barr, R. Devenish, R. Walczak, & T. Weidberg. Oxford University Press
3. Elementary Particle Physics: An Intuitive Introduction. Andrew J. Larkoski. Cambridge University Press
4. An Introductory Course on Particle Physics. Palash B Pal. CRC Press
5. Introduction to Experimental Particle Physics, R.C. Fernow, Cambridge University Press
6. Introduction to Elementary Particles, D.J. Griffiths, John Wiley & Sons
7. Introduction to High Energy Physics, D. H. Perkins, Cambridge University Press
8. Relativistic Kinematics: A Guide to the Kinematic Problems of High Energy Physics, R Hagedorn & J. David, Jackson, Literary Licensing, LLC
9. Data Analysis Techniques for High-Energy Physics, R. Frühwirth, M. Regler, R. K. Bock, H. Grote, D. Notz, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology
10. Data Reduction and Error Analysis for the Physical Sciences, P. Bevington & D. K. Robinson, McGraw-Hill

## 05-PHYS04-104-C: Computational Physics (30 Lecture Hrs):

**Coordinators: Prof. Pratik Majumdar**  
[pratik.majumdar@saha.ac.in](mailto:pratik.majumdar@saha.ac.in)  
& **Dr. Mrinmay Kumar Mukhopadhyay**  
[mrinmay.mukhopadhyay@saha.ac.in](mailto:mrinmay.mukhopadhyay@saha.ac.in)

### **Course Details:**

Classification of errors, Error propagation, Basics of Monte Carlo techniques, Basics of Learning techniques and their applications, Programming and Technical Computing, Data Analysis, Basic Numerical Algorithms, Linear Algebra, Solution of non-linear equations, differential and integral equations, variational method.

### **Course Outcomes:**

- This course aims to provide the student with comprehensive knowledge about the various computational techniques necessary for performing research in high-energy, astro, and condensed matter physics, including familiarity with special-purpose scientific libraries.

### **References:**

1. Data Reduction and Error Analysis – *P. R. Bevington and D. K. Robinson.*
2. A Student's Guide to Data and Error Analysis – *H. J. C. Berendsen.*
3. Computational Physics – *J. M. Thijssen.*
4. A First Course in Machine Learning – *S. Rogers and M. Girolami.*
5. Introduction to Computer Simulation Methods – *H. Gould et al.*
6. An Introduction to Computational Physics – *T. Pang.*
7. Computational Physics – *R. H. Landau and M. J. Paez.*
8. *B. Stroustrup*, C++ Programming Language.

## **Experimental Technique and Analytical Methods (30 Lab Hrs):**

**Coordinators: Prof. Pratik Majumdar**  
[pratik.majumdar@saha.ac.in](mailto:pratik.majumdar@saha.ac.in)  
& **Dr. Mrinmay Kumar Mukhopadhyay**  
[mrinmay.mukhopadhyay@saha.ac.in](mailto:mrinmay.mukhopadhyay@saha.ac.in)

*This course consists of several modules and each student complete two modules as per their research interest. Each course module contains theory lectures and laboratory work and requires – 30 Hrs for completion.*

### **Module Name: Basic Course on Experimental Nuclear, Particle and Astroparticle Physics.**

**Duration:30 hrs.**

#### **Course Details:**

Radiation interactions (interaction of charged particles, interactions of photons with matter, Cherenkov radiation), General properties of detectors, basic operational principle of Geiger Muller counters, Scintillator detectors, Semiconductor detectors, Cherenkov detectors. Simple statistical analysis process of data.

#### ▪ **Example of a typical particle physics detector:**

Subdetector elements, Trigger system, Particle reconstruction, identification, and physics analysis of data. Lab activity includes a small scintillator-based cosmic muon counter development, GEANT4 simulation for the passage of particles through a block of material and hands-on experience working with a fast-timing scintillation detector using digital and analog data acquisition system.

#### **Course Outcomes:**

- Upon completion of the course, the student should know various detection mechanisms used in Astro-Particle physics and Nuclear physics experiments and their interaction mechanism, as well as gain working knowledge of various data acquisition systems widely used.

#### **References:**

1. Radiation detection and Measurements: *Glenn F. Knoll*.
2. Techniques in Nuclear and Particle Physics experiments: *W. R. Leo*.

### **Module Name: Saturation Absorption Spectroscopy of Rb atoms**

**Duration:30 hrs.**

#### **Course Details:**

Diode laser spectroscopy, Hyperfine structure of Rubidium atoms, Doppler-free measurements, Frequency locking of laser cavity, calibration of SAS spectra with Etalon.

#### **Course Outcomes:**

- Learning the basics of multi-electron atoms and light atom interaction, gaining hands-on skill in setting up optics, alignment and handling lasers, identification, and calibration of spectra.

#### **References:**

1. Modern Atomic Physics – *Vasant Natarajan*.
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2. Physics of Atoms and Molecules – *B. H. Bransden and C. J. Joachain*.
3. Using diode lasers for atomic physics, *Carl E. Wieman and Leo Holberg, Rev. Sci. Instrum. 62, 1 (1991)*.
4. Doppler-free saturated absorption: Laser spectroscopy, *Daryl W. Preston, Amer. J. of Phys. 64, 1432 (1996)*.
5. A narrow band tunable diode laser system with grating feedback, and a saturated absorption spectrometer for Cs and Rb, *K. B. MacAdam, A. Steinbach, and C. Wieman, Amer. J. of Phys. 60, 1098 (1992)*.

## **Module Name: Background studies for the surface run of superheated liquid detector (SLD) for dark matter search**

**Duration:30 hrs.**

### **Course Details:**

Understanding of SLD detection technique, SLD Detector fabrication, electronic circuit fabrication, testing, measurement at the surface laboratory with the fabricated detector set-up, analysis, results, dark matter physics discussion.

### **Course Outcomes:**

- Hands-on experience in fabricating the SLD detector and related electronic boards; Experience in how to run the Dark matter experiment.

### **References:**

1. *Roy et al.*, Use of superheated liquid in neutron detection, *Current Science*, 84 No.4 (2003).
2. *S. Archambault et al.*, New insights into particle detection with superheated liquids, *New Journal of Physics* 13, 043006 (2011).
3. *Radiation detection and Measurements: Glenn F. Knoll*.
4. *S. Seth et al.*, Probing low-mass WIMP candidates of dark matter with tetrafluoroethane superheated liquid detectors, *Phys. Rev. D* 101, 103005 (2020).

## **Module Name: Basic growth techniques, device fabrication, and microscopy techniques for characterisation of materials**

**Duration: 30 hrs.**

### **Course Details:**

Thin Film deposition – physical vapour deposition, Dry Transfer Technique, Lithography (Photolithography), Physical and Chemical Etching techniques, Basic understanding of Transmission Electron Microscopy, Scanning Electron Microscopy techniques.

### **Course Outcomes:**

- On completion of this course, students will know various deposition techniques for thin film growth and lithography techniques for device fabrication and characterise the thin films or the device structures using microscopy techniques like Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM) etc.

**References:**

1. Fabrication Engineering at the Micro and Nanoscale by *Stephen A. Campbell*. Publisher – Oxford University Press.
2. Micro and Nano Fabrication: Tools and Processes by *H. H. Gatzert, V. Saile and J. Leuthold*. Publisher – Springer.
3. Transmission Electron Microscopy: A Textbook for Materials Science by *David B. Williams and C. Barry Carter*. Publisher – Springer.
4. Electron Microscopy: Principles and Fundamentals Edited by *S. Amelinckx, D. van Dyck, J. van Landuyt, G. van Tendeloo*. Publisher – VCH Verlagsgesellschaft mbH, Weinheim.

**Module Name: X-ray scattering and spectroscopic techniques for material characterization****Duration: 30 hrs.****Course Details:**

X-ray scattering methods – diffraction from crystalline materials, reflectivity from thin films and multilayers. Basic experiments to perform x-ray experiments. Basic concepts of various spectroscopic techniques like Fourier transformed Infrared spectroscopy (FTIR), Photoluminescence Spectroscopy, and Photo-electron spectroscopy (PES). Basics of Synchrotron radiation and its use in materials characterisation, optoelectronic materials – growth, characterisation and devices.

**Course Outcomes:**

- Upon completing this course, students will know the basic principles of X-ray scattering techniques and the spectroscopic methods for structural characterisation.

**References:**

1. M. Tolan, X-ray Scattering from Soft-Matter Thin Films, *Springer Tracts in Modern Physics, 148*, (Springer, Berlin, 1999).
2. J. Als-Nielsen and D. McMorrow, Elements of Modern X-ray Physics, (John Wiley and Sons, New York, 2000).
3. B. E. Warren, X-ray Diffraction, (Dover Publ., New York, 1990).
4. Frederick Wooten, Optical Properties of Solids, (Academic Press, New York, 1978).
5. Handbook of Optoelectronics Ed. John P. Dakin, Robert G. W. Brown, (Taylor and Francis, New York, London, 2006).

**Module Name: Advanced Monte Carlo Methods****Duration: 30 hrs.****Course Details:**

Principles of Monte Carlo simulations, Basics of relativistic kinematics, Particle interaction studies using Monte Carlo Event Generators like e.g. Pythia.

**Course Outcomes:**

- The student learns how Monte Carlo methods are used, how to perform a Monte Carlo simulation, and how
-

to interpret the obtained data in the context of studying many particle systems and their interactions.

**References:**

1. Advanced Monte Carlo methods – *Michael P. Allen, Dominic J. Tildesley (Oxford)*.
2. Statistical Methods for Data Analysis in Particle Physics – *Luca Lista (Springer)*.
3. The Pythia event generator: Past, present and future – *Torbjörn Sjöstrand, Computer Physics Communications, Volume 246, January 2020, 106910*.