Ph d course structure

Preamble: The Ph d course structure consists of advanced courses to train a student interested in a particular area of research. The structure offers enough flexibility to choose courses as per their interests. The Ph d coursework spills over to two semesters; in each semester a student will take two courses. The only compulsory course in the structure will be 'Computational Physics' which will run in Monsoon semester. Apart from lecture based advanced/specialised courses (three in each semester) there will be a course called 'Mini project' which will give opportunity to the students to get exposed to real research during the period of the coursework. The course structure is quite open-ended which is desirable for a Ph d student.

Course structure: The course curriculum spills over 2 semesters. A student will take 2 courses in each semester

A) **Monsoon semester**:

Course Number	Course Name	Credits (L-T-P-C)
PH701	Advanced Condensed Matter Physics	3-0-0-6
PH703	Quantum Electronics	3-0-0-6
PH705	Quantum Field Theory and the Standard Model	3-0-0-6
PH707	Computational Physics	3-0-2-8

B) **Winter semester**:

Course Number	Course Name	Credits (L-T-P-C)
PH702	Statistical Methods in Condensed Matter Physics	3-0-0-6
PH704	Fourier and Guided-wave optics	3-0-0-6
PH706	Gravitation and Cosmology	3-0-0-6
PH708	Mini Project	0-0-6-6

Total credits: 26

- In Monsoon semester, a student has to take the mandatory PH707 course. He/she can choose any one of the other three in that semester.
- In winter semester, a student can choose any two courses out of the available four.
- The student can choose any research field for 'Mini Project' provided a supervisor is available and is ready to guide the student for this. The evaluation for the project will be done by DPPC constituted committee(s) before end-semester examination.

PH701: Advanced Condensed Matter Physics 3 0 0 6

Preamble: This course is intended to equip the graduate students with current state of the art concepts in Condensed Matter Physics research apart from the standard basic theory that are generally taught in at the undergraduate level. The course is divided into two parts. The first part, which is generally planned to have time-span between beginning of the semester and until the mid-semester break, revolves around setting up an adequate base to deal with the non-interacting systems. This part gives an overview of the free-electron model and its associated predictions to obtain the electronic structure. It is followed by the discussion on Quantum Hall effect, Landau levels, transport in semiconductors. Finally, the electronic structure of Graphene and an introduction to topological insulators is planned. The second part of the course, scheduled post mid sem, generally puts emphasis over introducing the theoretical tools concepts used to deal with interacting systems. This part begins with Hatree-Fock theory, then discusses magnetism and the associated models. Finally, superconductivity is taken up for discussion which deals with electrodynamics and thermodynamics of superconductors, BCS theory. As practical examples, Superconducting quantum interference devices (SQUIDs) are introduced and their applications as magnetometers are discussed. The course intends to give a thorough overview of the modern day Condensed Matter Physics to both experimentalists and theorists.

Course content

Non-interacting system

Free electron gas, Fermi surface determination, De Haas- Van Alphen effect (2L).

Quantum Hall effect, Landau Levels.

Excess Carriers in Semiconductors. Electron phonon interaction, Electron- photon interactions, carrier transport in low dimensional structures, Band structure and carrier transport in multilayer and superlattice structures .

Electronic structure of Graphene, Dirac points, Haldane model, Berry curvature, Chern number, Chern and Z_2 topological insulators.

Interacting systems

Hartee-Fock approximation and exchange energy

Magnetic properties of solids: Exchange interaction, Ferromagnetism and its ground state, Antiferromanetism, Hubbard Model, Spin Waves.

Electrodynamics of superconductors, Flux quantization, London equations, Cooper pairing and variational aspects of BCS theory, Thermodynamics of superconductors, AC and DC Josephson effects, Josephson junctions, SQUIDS, RF and DC SQUIDs, Applications of SQUID as magnetometer.

References:

1. N. W. Ashcroft and N. Mermin, *Solid State Physics*. Saunders College Press, Philadelphia, 1976.
2. C. Kittel, *Introduction to Solid State Physics*, John Wiley and Sons Eds. 8th edition 2005.
3. P. Philips, *Advanced solid State Physics,* Cambridge University Press, 2nd edition, 2012.
4. M. Tinkham, *Introduction to Superconductivity*, Dover Publications, Inc, 2nd edition 1996.
5. D. Feng and G. Jin, *Introduction to Condensed Matter Physics I*. World Scientific, Singapore, 2005.
6. C. Kittel, *Quantum Theory of Solids*. John Wiley and Sons, 2nd edition 1987.

7. S. Blundell, *Magnetism in Condensed Matter*. Oxford University, 2001.
8. J.B. Ketterson and S.N. Song, *Superconductivity*, Cambridge University Press, 1999.

PH 703: Quantum Electronics 3 0 0 6

Lasers: Semi-classical theory of interaction of radiation with matter; laser rate equations; Laser resonators and Gaussian beams; Q-switching; Mode locking; Ultrashort light pulses; Different types of lasers, laser amplifier; Detectors and Modulators

Nonlinear Optics: Anisotropic medium, susceptibility tensor, Nonlinear optical susceptibility; wave-equation for nonlinear optical media; second-harmonic generation; sum and difference frequency generation; Pump probe spectroscopy, four-wave mixing; Kerr effect;, Stimulated Raman scattering; Multi-photon absorption; Nonlinear optics in the two-level approximation, Density matrix formalism.

Quantum Optics: Quantum theory of nonlinear optical susceptibility, Coherent population trapping; electromagnetically induced transparency; Quantization of electromagnetic waves; Non-classical states of light; Photon statistics; Hanbury-Brown-Twiss experiment, Photon antibunching.

References:

1. Milonni and Eberly, *Laser Physics*, Wiley (2010).

2. W.T. Silfvast, *Laser Fundamentals* (2nd Edition), CUP (2004).

2. R. W. Boyd, *Nonlinear Optics* (3rd Edition), Academic Press (2010).

3. M. Fox, *Quantum Optics*, Oxford University Press (2007)

4. G. Grynberg, A. Aspect and C. Fabre, *Introduction to Quantum Optics*, Cambridge University Press (2010)

5. Marlan O. Scully, and M. Suhail Zubairy, *Quantum Optics*, Cambridge University Press (2012)

PH705: Quantum Field Theory and the Standard Model 3 0 0 6

Preamble: The course is aimed to provide a pedagogical development of quantum field theory in Canonical quantization technique to elucidate fundamental particles and their interactions. Thereafter the formalism of Standard model of particle physics is discussed in the light of local gauge field theory and calculates observables related to the model.

Course content

Canonical Quantization: Real and Complex Scalar fields: The Klein-Gordon (KG) Equation, Lagrangian and Hamiltonian field theory, Noether's theorem: symmetries and currents; Quantization: KG field as Harmonic Oscillator, KG field in space-time; Concept of Fock Space; KG propagator. Fermion fields: Dirac Equation and solution, Covariance of Dirac equation, Bilinear covariants, Quantization of the Dirac field, Dirac propagators, Weyl and Majorana Spinors.

Interacting Fields and Feynman Diagrams: Types of Interaction, Interaction Picture, Dyson's Formula, Wick's Theorem, Connected Diagrams and Vacuum Bubbles, Feynman diagrams and rules, Cross sections and S matrix; Scattering: phi-4 theory; Green's Functions and propagators, Decays and Cross Sections: examples through decay of a scalar into fermion anti-fermion pair, muon decay with four fermion interaction.

Elementary Processes of Quantum ElectroDynamics: Vector fields and quantization, gauge fixing, propagator and Feynman Rules; QED Processes and scattering amplitude calculation: e.g. electron-muon scattering, Compton scattering, Bhabha scattering etc.; Mandelstam variables, crossing symmetry.

Renormalization: Degree of divergence of a diagram: examples from QED, Ward-Takahasi identity, vacuum polarization, Regularization, counter terms, vertex function, running coupling constant, Renormalization group.

Gauge theories: Local symmetries in field theory: abelian and non-abelian gauge theories; spontaneous symmetry breaking and the Higgs mechanism.

Standard Electroweak Theory: Basic Structure: Weak interactions and the choice of gauge symmetry: SU(2)_L X U(1)_Y; mass generation through Higgs mechanism: masses of fermions and W, Z bosons; unbroken QED and massless photon; Standard Model Lagrangian; Feynman diagrams; discovery of the Higgs boson at LHC and its interaction with gauge fields.

References

1. Michael E. Peskin and Daniel V. Shroeder, *An Introduction to Quantum Field Theory*, Sarat Book House; 1st edition (2005)
2. Amitabha Lahiri and Palash B. Pal, *A first book of Quantum Field Theory,* CRC Press; 2nd edition (2005)
3. Palash B. Pal, *An Introductory Course of Particle Physics,* CRC Press; 1st edition (2014)
4. Francis Halzen and Alan D. Martin, *Quarks and Leptons,* Wiley India (2008)
5. M. Thomson, *Modern Particle Physics,* Cambridge University Press India (2016)
6. T. P. Cheng and L. F. Li, *Gauge Theory of Elementary Particle Physics,* Oxford University Press (1984)
7. Matthew D. Schwartz, *Quantum Field Theory and The Standard Model*, Cambridge University Press (2014)
8. Franz Mandl and Graham Shaw, *Quantum Field Theory,* Wiley, 2nd Edition (2016).
9. Tom Lancaster and Stephen J. Blundell, *Quantum Field Theory for the Gifted Amateur*, Oxford (2015).

PH707: Computational Physics 3 0 2 8

Preamble: The course is aimed to provide exposure to the computational methods which are useful for both theoretical and experimental physicists. This course exposes students to ways to analyse experimental data, perform statistical averages of physical quantities, solve partial and ordinary differential equations using computers.

Course content

Overview of Programming in standard language: Standard libraries, language syntax, Functions, Arrays, pointers, strings, developing skill to write a skeleton of an optimized program.

Errors and fitting of data: Propagation of measurement errors; fitting experimental data with parametrized models, the method of maximum likelihood, least square method, linear chi2 solution, non-linear least square fit, convergence criteria, least square fit with constraints, fit quality tests.

Linear equations: Gauss and Gauss-Jordan elimination, Gauss-Seidel, LU decomposition; numerical integration, interpolation, splines and Fourier transformation, differential equation, random numbers and multidimensional integration.

Numerical Solutions of different types of linear and nonlinear ODEs and PDEs: Initial value problem, Boundary value problem: Finite difference solutions to hyperbolic, parabolic and elliptic partial differential equations, application to physics problems.

Monte Carlo simulation technique: Introduction to Monte Carlo simulation, generation of non-uniform distribution by inversion method, inversion method for discrete distribution, approximate inversion method using tabulation, Hit-or-Miss method, composition method; Monte Carlo generation from common continuous distributions, uniform distribution, Gaussian distribution, multidimensional Gaussian distribution, exponential distribution, chi2 distribution, Cauchy-Breit-Wigner distribution, Landau distribution, Monte Carlo integration:basics of the MC integration, convergence and precision of the MC integration, methods to accelerate the convergence and precision, limits of integration in the MC method, comparison of convergence with other methods**.**

References

1. K. E. Atkinson, *Numerical Analysis,* John Wiley (Asia) (2004).
2. S. C. Chapra and R. P. Canale, *Numerical Methods for Engineers,* Tata McGraw Hill (2002).
3. Glen Cowan, Statistical Data Analysis, Oxford Science Publication (1998)
4. D. P. Kroese, Thomas Taimre, Zdravko I. Botev, Handbook of Monte Carlo Methods, Wiley (2011).
5. A. Kelley and I. Pohl, A Book on C Programming in C, Pearson Education (2005).
6. K. R. Venugopal and S. R. Prasad, Mastering C Programs, Tata McGraw-Hill 2010.
7. Roger Barlow, Statistics: A Guide to the use of Statistical Methods in the Physical Sciences, Wiley (1993)
8. J. D. Hoffman, *Numerical Methods for Engineers and Scientists*, 2ed. CRC Press, Special Indian reprint (2010).
9. J. H. Mathews, *Numerical Methods for Mathematics, Science, and Engineering,* Prentice Hall of India (1998)

PH 702: Statistical methods in condensed matter physics 3 0 0 6

Preamble: This course intends to expose our graduate students to the recent experimental developments and further instil an attitude among them to analyze the experimental observations using some basic theoretical and phenomenological tools used while dealing the condensed matter physics at large lengths and time scales. The course is divided into two parts. The first part, which is generally planned to have time-span between beginning of the semester and until the mid-semester break, deals with the equilibrium state of the matter. This part gives an overview of the basic thermodynamics relations to deal with homogeneous fluid and magnetic systems. It is followed by the discussions on different phenomenological models to deal with the Phase transitions and critical phenomena. Various mean-field theories and methodology to compute the critical exponents for various models have also been included. The second part of the course, scheduled post mid semester, generally puts emphasis over introducing the theoretical tools concepts used to deal with the non-equilibrium phenomena encountered in the condensed matter Physics. This part begins with linear response theory, then fluctuation-dissipation theorem and associated applications in different scattering phenomena. This is followed by the discussions on the Goldstones theorem with possible examples of spin waves in ferromagnetic and anti-ferromagnetic systems. A brief introduction on the Nucleation and Spinodal decomposition will be helpful in dealing with the different situations related to the phase separation in the experiments. Finally, the discussions on the effect of topological defects on the destruction of the long range range order are taken up. To this end different sort of topological defects like vortices in xy-models, dislocations mediated crystal growth and melting are introduced. The course intends to give a thorough overview of the modern day Condensed Matter Physics to both experimentalists and theorists.

Course content

Equilibrium statistical Mechanics

Thermodynamics of fluids and magnetic systems: Thermodynamic potentials, response functions and their relations, stability, convex and concave nature of thermodynamic potentials.

Phenomenology of Phase transitions and Critical Phenomena: Different phases of matter, phase diagrams of fluids and magnet, first and second order transitions, order parameter, spontaneous symmetry breaking, examples of phase transitions, critical point, Morphology, fluctuations and correlations.

Critical exponents and scaling: Critical exponents associated with order parameters, thermal and mechanical response functions, correlation length and correlation function, determination of critical exponents

Models and ground states: Spin-1/2 Ising model, application of spin-1/2 Ising model in order-disorder transition and lattice gas model, spin-1 Ising model, q-state Potts model, X-Y model, Heisenberg model, universality in different models.

Mean field theory: Weiss mean field theory, Bragg-William mean field theory, mean field exponents of correlation length and correlation function, scaling relations and upper critical dimension.

Landau theory of phase transition: Landau potential, continuous transition, determination of critical exponents, discontinuous transition and tri-critical points, asymmetry and first order transition. [**3L**]

Non-equilibrium phenomena

Correlation functions, The response functions with examples of damped and undamped harmonic oscillators, dissipation, elastic waves and phonons, diffusion: Fick’s law, the green function and dynamics response, Brownian motion, cooperative Vs self diffusion, Master equation for diffusion on a lattice, random forces and thermal equilibrium, correlation function for diffusion, fluctuation dissipation theorem for the harmonic oscillator, formal properties of the response function with example of response of magnetic system in presence of an external field. Inelastic scattering: Onsager relations, Neutron scattering, scattering of charged particles and photons.

Conserved and broken symmetry variables, the Goldstone theorem, Kubo Formulae, Spin Systems: Spin dynamics, The planar magnet, the Isotropic antiferromagnet, Isotropic ferromagnet, Nucleation and Spinodal decomposition.

Vortices in xy-model, Crystal growth, Grain boundaries, Dislocation mediated melting: effect of a substrate with examples from experiments and numerics, The twist grain boundary phase.

References

1. R. K. Pathria and P. D. Beale, *Statistical Mechanics*, 3rd edition, Butterworth-Heinemenn, Oxford, 2011.
2. P. V. Panat, *Thermodynamics and statistical mechanics*, Narosa Publishing House, New Delhi, 2008.
3. V. Balakrishnan, *Elements of Non-equilibrium Statistical Mechanics*, Ane Books Pvt.Ltd., New Delhi, 2008.
4. L. E. Reichl, *A modern course in Statistical Physics*. Wiley-Interscience, New York 1998.
5. P. M. Chaikin and T. C. Lubensky, *Principles of Condensed Matter Physics*. Cambridge University Press, 1995.
6. H. E. Stanley, *Introduction to phase transitions and critical phenomena*, Oxford University Press, 1971.
7. J. M. Yeomans, *Statistical Mechanics of Phase transitions,* Oxford University Press, 1992.
8. J. J. Binney, N. J. Dowrick, A. J. Fisher and M. E. J. Newman, *The theory of critical phenomena*, Clarendon Press, Oxford, 1992.
9. R. Kubo, M. Toda, and N. Hashitsume, *Statistical physics II. Nonequilibrium statistical mechanics*. Springer-Verlag, New York 1985.
10. Gerd Röpke, *Nonequilibrium Statistical Physics*. Wiley-VCH, 2013.

PH704: Fourier and Guided-wave optics 3 0 0 6

Fourier Optics: Maxwell's equations, Helmholtz Equation, Huygens-Fresnel Principle, Fresnel approximation, Fraunhofer approximation, examples of the diffraction pattern: rectangular aperture, circular aperture, and sinusoidal grating, lens as a Fourier transforming tool, image formation using monochromatic coherent and incoherent illumination, diffraction limit of resolution; Polarization of light, introduction to vectorial diffraction theory.

Guided wave Optics: waveguide structures, formation of guided modes; Planar optical waveguides (slab and rectangular waveguides); Optical fibers, wave theory of step-index fibers; Coupled mode-theory; Co-directional couplers, Optical waveguide devices using directional coupler; optical fiber based sensors, Fiber Bragg gratings; Surface plasmon polaritons in multilayer systems, Plasmon waveguides.

References:

1. Joseph W Goodman, *Fourier Optics* (3rd Edition) Roberts & Company (2005)
2. E. Wolf, *Electromagnetic diffraction in optical systems. I & II*, Proc. R. Soc. London Ser. A 253 (1959).
3. K. Okamoto, *Fundamentals of Optical waveguides* (2nd Edition), Academic Press (2006).
4. A. Ghatak and K. Thyagarajan, *Optical Electronics*, CUP (2012).
5. S. A. Maier, *Plasmonics: Fundamentals and applications*, Springer (2007).

PH706: Gravitation and Cosmology 3 0 0 6

Preamble: In this course our basic goal is to introduce the theory of gravitation and its application to various physical problems. We will start with tensor analysis, which is the basic mathematical language of the theory. After the introduction of tensors and its various properties in curved space, we derive the Einstein's equation of gravity from Einstein-Hilbert action and find out different physically interesting solutions depending on the matter field distribution. We discuss in detail the properties of those solutions specifically focusing on two main areas of current research in the field of black hole and cosmology.

Course content

Mathematical Foundation: General coordinate transformation, contravariant and covariant tensors, parallel transport, covariant derivative, Lie derivative, Chistoffel symbol, curvature tensor, geodesic equation, energy momentum tensor for scalar and vector fields, conservation laws, Killing vectors and equation, Raychaudhuri equation: time-like, space-like, and null geodesics, geodesic congruence, energy conditions.

Solutions of Einstein's equation: Einstein's field equation, Linearized equation, Pseudo energy momentum tensor, gravitational waves, Black holes: Schwarzchild black hole, Birkhoff's theorem, bending of light, perihelion precession, gravitational redshift, electromagnetic field equation, Riessner-Nordstrom black hole, Kerr-Newman black hole, extremal limit, Penrose diagram

Black hole thermodynamics: Penrose process, zeroth law and area law, Noether current, first law of black hole mechanics.

Cosmology: Cosmological principles, Friedman-Lemaitre-Robertson-Walker cosmology: Radiation, matter, and cosmologcial constant dominated universe, Cosmological observables: luminosity distance, angular diameter distance, Early Universe Thermodynamics: Cosmic Neutrino Background Formation, Big Bang Nucleosynthesis (BBN), Photon Decoupling & Recombination, Cosmic Microwave Background Radiation (CMBR), Large scale structure, problems of Big-Bang cosmology, Inflation, Inflationary perturbation.

References

1. L D Landau, E.M. Lifshitz**,** *Classical Theory of Fields: Course of Theoretical Physics - Vol. 2*; Butterworth-Heinemann; 4th edition (1987)
2. E. Kolb and M. Turner**,** *The Early Universe***;** Westview Press (1994)
3. V. Mukhanov**,** *Physical Foundation of Cosmology*; Cambridge University Press (2005)
4. T. Padmanavan, *Gravitaion: Foundation and Frontier*; Cambridge University Press; 1st edition (2010).
5. Sean M. Carroll, *Spacetime and Geometry: An Introduction to General Relativity*; Pearson (2003)
6. Barbara Ryden, *Introduction to Cosmology*; Cambridge University Press; 2nd edition (2016)
7. C.W. Minser, K. S. Thorne, J. A. Wheeler, D. I. Kaiser; W. H. Freeman, *Gravitation***,** Princeton University Press; 1st edition (2017)
8. Steven Weinberg, *Gravitation And Cosmology: Principles And Applications Of The General Theory Of Relativity*; Wiley; 1st edition (2008)
9. P. K. Townsend**,** *Black Holes*; available in https://arxiv.org/abs/gr-qc/9707012

PH708 Mini Project 0 0 6 6

The courses in the new structure are of specialised nature which orient students to particular research fields. The mini project is a way to expose the student to the real research which supplement the things he/she learns in the courses. This way, the student can start the research early by getting to know the required background during the coursework itself so that he/she does not have to spend considerable time to prepare substantially for the state-of-the-art seminar.

However, the student is free to choose the field in which a supervisor is available and is willing to guide him/her for the Mini Project.