SATYENDRA NATH BOSE NATIONAL CENTRE FOR BASIC SCIENCES

INTEGRATED Ph.D. PROGRAMME IN PHYSICAL SCIENCES (IPhD-PH)

In Collaboration with the

UNIVERSITY OF CALCUTTA

COURSE DESCRIPTION IN OUTLINE

The Integrated PhD Programme in Physical Sciences (IPhD-Ph) at the S. N. Bose National Centre for Basic Sciences (SNBNCBS) in Collaboration with the University of Calcutta (CU) is monitored by a Board of Studies comprising representatives from both SNBNCBS and CU, and also eminent faculty members from other academic institutions as per CU rules. The duration of this course is 2+5 = 7 years. A student seeking admission to this course must have passed B.Sc with Physics & Mathematics securing at least 60% marks in the main subject. Final selection will be made on the basis of national level written tests e.g. JEST/ NGPE or other standard national level eligibility tests followed by personal interview/Counseling. The candidate must also possess other qualifications as may be prescribed by the Academic Council (AC) from time to time. After admission the candidates shall have to register with CU, and as per rules, students coming from Universities other than CU shall have to submit migration certificate.

Syllabus and Course Structure: The syllabus and course structure approved by the Students' Curriculum and Research Evaluation Committee (SCREC) of SNBNCBS is monitored by the Board of Studies and all strictly follow the UGC guidelines issued from time to time.

The course descriptions given below are simply an attempt to give a rough outline of the material to be covered. But of course the detailing out and the point of view is one to be decided upon by the teacher. The same is true regarding the suggested textbooks. Generally one expects that attempts will be made to suggest to the students even at the level of the basic courses (in the first two semesters) the linkages with more advanced courses to come later.
Also to indicate how the core material relates to more recent applications. Furthermore, efforts may be made to establish connectivity to other courses going on concurrently or to those that are to come subsequently, to impart the sense of organic unity of the physical sciences. Emphasis will be placed on tutorials and in having examples of the material covered in the lectures to concretize the underlying ideas and facilitate the application of basic principles to solving problems.

[Note: All Course Numbers have changed from this Academic Session.]

COURSE STRUCTURE

FIRST SEMESTER COURSES & SYLLABUS

L=Lectures T=Tutorials P=Practicals in hours per week & C=Credit points

PAPERS FOR 1ST SEMESTER (AUGUST – DECEMBER)

Course No.	Course Title	L	T	P	C
PHY 401	Mathematical Methods	3	1	-	4
PHY 403	Classical Dynamics	3	1	-	4
PHY 405	Quantum Mechanics I	3	1	-	4
PHY 407	Computational Methods in Physics	2	-	2	4
PHY 491	Basic Laboratory I	-	2	6	6

Examination: 2nd week of December
Semester Break: 4th week of December

PHY 401. MATHEMATICAL METHODS I: 3-1-0-4

• **Linear spaces and algebra of linear transformations**: Axiomatic definition of a linear space with examples, dual spaces, inner product spaces, definition of an associative algebra with examples, vector space homomorphisms with examples, Algebra of linear transformations, matrices, characteristic roots and associated properties, canonical form of matrices, general definition of hermitian and unitary operators with examples.

• **Group Theory**: Definition of a group (examples); subgroup (examples); normal subgroups and quotient groups (examples); homomorphisms (examples), permutation groups, orthogonal, unitary, pseudo-orthogonal groups; definition of a Lie algebra with examples; structure constants, adjoint representation; SU(2) and SO(3) groups as Lie groups, Lie algebra of their generators, homomorphism between SU(2) and SO(3); Poincare group and its algebra.

• **Functions of a complex variable**: Review of complex numbers; definition of a complex function; continuous functions; differentiability; definition of an analytic function; Cauchy-Riemann equations; the exponential function; the trigonometric functions; the hyperbolic functions; multivalued functions and principal branch; power series for log(1+z); zeros and poles of functions; classification of singularities; Cauchy's theorem; analytic continuation; Cauchy's integral formula; Laurent expansion, calculus of residues.

• **Metric spaces and Hilbert spaces**: definition and some examples of a metric space; open sets; closed sets; convergence; completeness; compactness; continuous mappings; spaces of continuous functions; Euclidean and unitary spaces; Hilbert space, the Schwarz inequality; orthogonal complements (basic theorems); orthonormal sets; Bessel's inequality, Riesz-Fischer theorem; the adjoint of an operator; Hermitian and self-adjoint operators; normal and unitary operators; projections.

Suggested Textbooks:

- *Brown and Churchill: Complex variables and applications*
- *Dennery and Krzywicki: Mathematics for Physicists*

PHY 403. CLASSICAL DYNAMICS: 3-1-0-4

- Generalized coordinates with examples, Principle of least action, Lagrange's equations of motion
- Small oscillations, normal modes, forced and damped oscillators
- Legendre transformation, Hamilton's equations of motion,
- Symmetries and conservation laws (Noether's theorem), central force problem
- Concept of a phase space, Poisson bracket and its properties, Hamilton's equations of motion, Constants of motion, Poisson bracket algebra of angular momentum, rigid body rotations and Eulerian angles, algebra of rotation group, Liouville's theorem
- Canonical Transformations, generating functions, generators of symmetries, Hamiltonian as generator of time translation, HamiltonJacobi equation, action angle variables.
- Continuous systems and fields, action, variational principle, Lagrangian and Hamiltonian for a free scalar field, general variation of the action, derivation of Euler-Lagrange equation, Noether's theorem and conservation equation, energy momentum tensor and conservation equation (analogy with the discrete case), Euler-Lagrange equations for pure electromagnetic theory and Maxwell's equations.

Suggested Textbooks:

- *H. Goldstein : Classical Mechanics, 2nd edition.*
- *John L. Synge and Byron A. Griffith : Principles of Mechanics, 3rd Edition.*
- *L.D.Landau and E. M. Lifshitz : Mechanics (Volume I of - A course of Theoretical Physics).*
- *E.C.G.Sudarshan and N. Mukunda : Classical Mechanics - a modern perspective.*

PHY 405. QUANTUM MECHANICS I: 3-1-0-4

- ***Mathematical preliminaries:***
  - Vector spaces: Definition, Dirac notation, inner product, Hilbert space, orthonormal basis, Gram-Schmidt construction, dual vectors, Cauchy-Schwarz inequality;
  - Linear operators: Definition, algebra, inverse, adjoint, Hermitian, unitary, projection operator, matrix representation, eigenvalue, eigenvector, complete set of commuting operators, functions and derivatives of operators;
  - Continuous basis: x-basis, delta function, -i d/dx, p-basis, Fourier transform;

- ***Quantum Mechanics:***
  - Formulation in terms of postulates, Schrödinger equation, stationary states, evolution operator, time independent systems, non-relativistic wave equation, 1-d oscillator in operator formulation, relation with wave functions;
  - Ehrenfest theorem, parity, 1-d potentials, square well, periodic potential, Dirac comb, 1-d scattering
- ***3-d systems:***
  - Central potential, angular momentum operator algebra, eigenvalues, eigenvectors, spherical harmonics, free particle, spherical oscillator, Hydrogen atom, operator methods;
- ***Identical particles:***
  - Multiparticle states and Hilbert space, bosons and fermions;
- ***Continuous Symmetry transformations:***
  - Translation, rotation, general structure, internal symmetries, conserved charge, gauge symmetry and coupling with electromagnetic field, Aharonov-Bohm effect;
- ***Spin:***
  - Stern-Gerlach experiment, operator algebra and representation, Zeeman effect;
  - Addition of angular momentum, **L** + **S.**

Suggested Textbooks:

- *R. Shankar: Principles of Quantum Mechanics*
- *A. Bohm: Quantum Mechanics: Foundations and Applications*

PHY 407. COMPUTATIONAL METHODS IN PHYSICS: 2-0-2-4

1. Computational Language (FORTRAN / C / Python)

1.01 Basic Linux commands and vi editor commands.
1.02 Constants and variables; variable types and declarations.
1.03 Assigment and arithmatic expressions.
1.04 Read and write statements, logical expression.
1.05 IF, Arithmatic IF, IF-THEN-ELSE statements.
1.06 GO TO, Computed GO TO statements.
1.07 DO loops, nested DO loops.
1.08 Functions and subroutines.
1.09 Arrays, 1-2-3 dimensionals.
1.10 Formatted input / output statements.
1.11 Precision – single, double, quartic.
1.12 xmgrace and gnuplot.

2. Simple Problems to Practice the Language

2.01 Finding the largest number in a set of numbers.
2.02 Sum of some numbers except one of them.
2.03 Arranging numbers in increasing / decreasing order.
2.04 To test if the given number is prime;
generating all prime numbers up to a given number.

2.05 Mean, variance standard deviation of a given set of numbers.
2.06 Factorial of a given number.
2.07 Generating the Fibbonaci series.
2.08 N atoms, each has two spin states. Enumerate all possible microstates, estimation of the energy of each of these states, distribution of magnetisation and energy.
2.09 Converting a decimal number into a binary.
2.10 Matrix operations.

3. Numerical Techniques

3.01 Error in computation – definition and source of errors, propagating and control of errors.
3.02 Root finding for polynomial equations, Bisection method and Newton-Raphson method, or use any other two methods.
3.03 Interpolation, extrapolation – Polynomial interpolation or any other method.
3.04 Numerical integration – Mid-point rule and Trapezoidal rule or any two other methods.
3.05 Solving linear equations – Gauss elimination methods and Iterative solution methods.

4. Simulation Techniques

4.01 Random number generation.
4.02 Monte Carlo (MC) method, Importance Sampling.
4.03 Estimate of (i) the value of π, (ii) area of an annular ring and (iii) Integration of simple functions using MC.
4.04 Biased and un-biased Random walks in one and two dimension, probability distribution, dispersion, mean-square-distance, exponents.
4.05 Simple example of simulations using Monte Carlo method.

Suggested Textbooks:

- *Numerical Recipes in C/Fortran:The Art of Scientific Computing By William H. Press et al.*
- *Monte Carlo Simulation in Statistical Physics: An Introduction by Kurt Binder, Dieter Heermann.*
- *Computer Programming In Fortran 90 and 95 By V. Rajaraman*

PHY 491. BASIC LABORATORY I: 0-2-6-6

The aim of this course is to help develop a temperament among the students so that they may feel some confidence in setting up experimental arrangements for investigating physical problems, and go beyond the black box push-button mentality. Instead of specifying a set of pre-existing equipment and already set-up experiments, this curriculum gives emphasis to the universal principles and underpinnings of experimental techniques through a laboratory based hands-on course and design of experiments.

As a first step towards this goal it is necessary to introduce the working principles of basic measuring instruments and sensors and how they can be used to measure and to control different physical variables. For this purpose it is essential that the students become familiar with the principles and practice of electronics. Accordingly one of the components of this course is Electronics which will be superposed on the part devoted to the investigation of physical phenomena in order to avoid compartmentalisation. For convenience this component is spelt out first:

1. Measurement of Thevenin parameters (V[TH] and R[TH]) of a DC power supply (Battery).
    - Plot V[load] versus R[load] curve and mark slope and stiff regions.
    - In the slope region measure V[load] for at least two different R[load] and characterize V[TH] and R[TH].
    - In the stiff region measure I[Load] for at least two different R[Load] and characterize V[TH] and R[TH].
    - Measure V[TH] by using a multimeter and compare with the estimated value of V[TH] and comment.
2. Characterization of semiconductor diodes and designing of transformer based full wave rectifier.
    - Draw three characterization curves of two rectifier diodes (Germanium, Silicon) and one Zener diode.
    - Estimate turn ratio of a transformer by measuring voltage ratio (primary and secondary).
    - Construct a Full wave rectifier and measure input and output waveforms of the rectifier.
3. Characterization of a Zener Regulated DC power supply.
    - Measure V[C], V[rms], g and PIV of a full wave rectifier and compare them with their calculated values.
    - Design a R-C filter and measure p-p ripple voltage and compare with calculated value.
    - Design a Zener regulator after the above filter and measure load dependency and load regulation (voltage).
4. Characterization of an n-p-n transistor and designing of fixed biased CE transistor amplifier.
    - Draw base and collector characteristic curves of an n-p-n transistor in the CE configuration.
    - Mark saturation, cutoff and active regions and determine Q point for best transistor operation.
    - Design a simple fixed biased CE amplifier with the estimated Q point. Determine current gain and compare with the specified value.
5. Use of a transistor as electronic switch and designing a memory unit (R-S flip flop).
    - Use a transistor as a switch to operate a LED in the output with low frequency input.
    - By using high frequency square wave input measure t[on] and t[off].
    - Design a R-S flip-flop and complete its truth table with S as input. Catch a bit from a low frequency pulse train.
6. Use of IC 741 as an adder, amplifier, integrator, differentiator etc.

Suggested References:

- Price, Analog Electronics (Prentice Hall)
- Hickman, Analog Electronics (Newnes)
- Bogart, Electronic Devices and Circuits (Universal Book Stall)
- Streetman, Solid State Electronic Devices (P/H/I)
- Horowitz and Hall, The Art of Electronics (Cambridge)

The other important component of this course is Optics. The details of this course are spelt out below:

1. Experiments related to Laser beam characteristics such as:

- To study the intensity distribution of Laser Beam
- Determination of spot size and the angle of divergence of a given laser source.
- Measurement of absorption coefficient (Beer Lambert's Law) of a material (supplied) using laser light.

2. Experiments related to interference such as:

- To determine wavelength of He-Ne Laser by Michelson Interferometer

3. Experiments related to diffraction such as:

- To measure the number of lines in a transmission grating using Laser.
- To measure the wavelength of He-Ne Laser using a grating.

4. Experiments related to polarization such as:

- To study circularly polarized light by a quarter wave plate.
- To verify Malus law and to determine Verdet constant of a given crystal.
- To demonstrate Faraday effect
- To demonstrate Electro-optic effect

5. Experiments related to Spectroscopy:

- Construction of a simple spectrometer using a white light source and a grating as major components.
- Measurement of absorption spectra of a given liquid sample.
- Validation of Beer Lambert's Law of molecular absorption from the setup.

6. Experiments using Fibre optics such as:

- To measure the Numerical aperture of an optical fibre.
- To measure the attenuation in an optical fibre.
- To measure the bending loss in a fibre.

SECOND SEMESTER COURSES & SYLLABUS

L=Lectures T=Tutorials P=Practicals in hours per week & C=Credit points

PAPERS FOR 2ND SEMESTER (JANUARY – MAY)

Course No.	Course Title	L	T	P	C
PHY 402	Electromagnetic Theory	3	1	-	4
PHY 404	Statistical Mechanics	3	1	-	4
PHY 406	Quantum Mechanics II	3	1	-	4
PHY 408	Electronics & Instrumentation	2	-	2	4
PHY 492	Basic Laboratory II*	-	2	6	6
PHY 494	Summer Project Research I**	-	-	8	6

Semester Break: June & July (Project Research)

*For these laboratory based courses tutorials involve discussions on the underlying theory and methodology of the experiments. Each such course would occupy eight lab-hours distributed over two days in each week. In the Summer following the Second Semester students will start taking up projects to enable him or her to develop an integrated research attitude towards physics.

**In the case of Project-based Courses "P" indicates the number of interaction hours per week.

PHY 402. ELECTROMAGNETIC THEORY: 3-1-0-4

- Review of Electrostatics & Magnetostatics
- Maxwell's equations
- Lorentz Invariance of Maxwell's equations; Review of Special Relativity; Maxwell's equations in covariant form; four-vector potential and the electromagentic field tensor.
- Propagation of plane electromagnetic waves, reflection and refraction.
- Propagation through anisotropic and chiral media.
- Radiation from an accelerated charge, retarded and advanced potentials.
- Radiation multipoles
- Wave guides, Resonant Cavities.

Suggested Textbooks:

- *J.D. Jackson, Classical Electrodynamics*
- *J.R. Reitz, F.J. Milford & R.W. Christy, Foundations of Electromagnetic Theory.*

PHY 404. STATISTICAL MECHANICS: 3-1-0-4

- Review of the laws of thermodynamics. Need for statistical mechanics.
- Probability and statistics: Random walks, Gaussian and Poisson

- Distributions, Central Limit Theorem, Saddle point integration
- Distribution functions and phase space. Liouville equation, mixing and ergodicity, Markov process and Master equation
- Ensembles: Micro canonical, Canonical, Grand canonical. Partition function and connection with thermodynamic potentials, equivalence of different ensembles
- Quantum Ideal Gases: Bose and Fermi Statistics, density of states, equation of state
- Ideal Fermi gas: Analysis of equation of state and properties of $f_{3/2}(z)$ function, high temperature low density limit and Maxwell-Boltzmann form, low temperature high density limit and Fermi level. Landau diamagnetism, Pauli paramagnetism.
- Bose gas: Black body radiation, Phonons in solids, Bose-Einstein condensation
- Ising Model: Definition, spontaneous magnetization, Bragg-William approximation, Bethe-Peierls approximation, exact solution of 1-d Ising model.
- Basic ideas of phase transitions.

Suggested Textbooks:

- M. Kardar, Statistical Physics of Particles
- L.E. Reichl, A Modern Course in Statistical Physics
- Kerson Huang, Statistical Mechanics

PHY 406. QUANTUM MECHANICS II: 3-1-0-4

- Scattering theory - Born approximation and partial wave analysis.
- Time independent perturbation theory.
- Variational method
- The WKB approximation.
- Time independent perturbation theory (Fermi's Golden Rule).
- Adiabatic and Sudden Approximations
- Geometric Phases and the Bohm-Aharanov Effect.
- Rotation group, Tensor operators and the Wigner-Eckart theorem.
- Illustrations from atomic, molecular and nuclear physics.
- Pure and Mixed states. Density Matrix formalism

Suggested Textbooks:

- *Shankar : Quantum Mechanics*
- *Landau & Lifshitz: Quantum Mechanics*
- *Messiah, Quantum Mechanics I & II*
- *Davidov, Quantum Mechanics*
- *Sakurai : Modern Quantum Mechanics*
- *Cohen-Tannoudji, Diu & Lal¨oe, Quantum Mechanics II*
- *Ryder, Quantum Field Theory*
- *Flugge, Practical Quantum Mechanics*

PHY 408. ELECTRONICS & INSTRUMENTATION: 2-0-2-4

Analog electronics
[31 lecture hours]

1. Semiconductor devices part I: electron and hole concentrations in semiconductors; Band diagram of p-n junction; Current flow in a semiconductor: concept of drift current and diffusion current; Basic equations of semiconductor; current voltage characteristics of a p-n junction diode; Dynamic diffusion capacitances; Ebers-Moll equation. **[6 lecture hours]**

2. Semiconductor devices part II: Metal-semiconductor junctions: Schottky barriers; Rectifying and Ohmic contacts. Miscellaneous semiconductor devices such as Photodiode; Tunnel diode; Solar cell; LED and LDR.
[6 lecture hours]

3. Amplifiers: Revision of Op-amp circuits, OP-AMP architecture, Constant current sources, Input stage of an Op-Amp, characteristics and parameters of OP-AMP circuit. MOSFET Characteristics and applications, FET and MOSFET Amplifiers.
[7 lecture hours]

4. Network analysis: Network theorems and equivalent circuits, hybrid parameters, Topological descriptions of different networks, π to T and T to π conversion techniques, reduction of a complicated network to its equivalent T and π form. **[5 lecture hours]**

5. Filter Circuit: L and π filters, iterative and image impedance of a network, symmetrical network, characteristic impedance and propagation constant of a network. Development methods of different constant-K filters such as high pass, low pass, band pass and band stop filter circuits. **[5 lecture hours]**

6. Transducer & sensors: Photo-transducer, photo-electric transducer, thermistor, photoconductors, Photo diodes and photo-transistors.
[2 lecture hours]

Digital electronics
[11 lecture hours]

1. Combinational logic gates: Karnaugh mapping: Minimization or reduction techniques of Product of Sum (POS) and Sum of Products (SOP) expressions of 2, 3 and 4 variables Boolean expression, Logical implementations, Revision of Flip-Flop circuits, Conversion of Flip-Flops. **[4 lecture hours]**

2. Registers: Shift Register, Serial in Serial out, Parallel in Serial out, Parallel in parallel out registers, Bi-directional and Universal registers.
[2 lecture hours]

3. Counter: Synchronous and Asynchronous counter, other different counters like modulo-, decade, ring and twisted ring counter and Up/Down Counter.
[2 lecture hours]

4. Combinational circuits: MUX, De-MUX, Encoder, Decoder, comparator. Analog to Digital and Digital to Analog Conversion. **[3 lecture hours]**

Experimental methods and error analysis
[6 lecture hours]

1. Scintillation and Solid state detectors. Measurement of time and energy using electronic signals from the detectors and associated instrumentation, Signal processing; Multi channel analyzer; Time of fight and Lock-in detection technique; Propagation of errors, Distribution, Least square fit and Criteria for goodness of fit. **[4 lecture hours]**

2. Production and measurement of high vacuum: Rotary, Diffusion, Turbo-molecular and Ion pump; McLeod, Pirani and Penning gauge.
[2 lecture hours]

PHY 492 BASIC LABORATORY II: 0-2-6-6

As an essential component of this course is to introduce the student to the advanced techniques in electronics the syllabus of which is given below:

1. Perform following experiments with proper truth table:
   - Use NAND gate to realize the functions of NOT, AND, OR and EX-OR gates. Indicate corresponding Boolean operation.
   - Design a digital voting machine (using NAND gates only) for three voters by following Karnaugh Map optimization technique.

2. Perform following experiments with proper truth table:
   - Design digital circuits for half adder and subtractor by using NAND gates only.
   - Show a circuit diagram of a full adder by using NAND gates only. Explain the design and operation.

3. Perform following experiments with proper truth table:
   - Make a J-K flip-flop circuit by using NAND gates only. Show toggle and self oscillation (racing) in the output.
   - Design Master-Slave J-K flip-flop and show the output performance.

The other component of this course is to develop the innovativeness of the student to put to use the knowledge, attitudes and techniques acquired through the basic electronics and optics courses in the first semester, to conceive, design, build and implement projects for the measurement of say a physically interesting quantity or the experimental verification of some physical principle or the quantitative observation of some interesting phenomena etc.

Some of the experiments are listed below:

- Frank-Hertz experiments.
- Hall effect
- Study of magnetic properties of ferro and paramagnetic materials
- Determination of Band gap in a semiconductor
- Millikan's oil drop experiments
- Experiments on Photoelectric Effect
- Electron spin resonance experiments to determine Lande-g-factor
- Use of Geiger-Muller counter to determine half life of a radioactive source etc.
- Use of a telescope and CCD camera for astronomical experiments

PHY 494 COMPULSORY (Summer Research Project): 0-0-8-6
(May – June – July)

THIRD SEMESTER COURSES & SYLLABUS

L=Lectures T=Tutorials P=Practicals in hours per week & C=Credit points

PAPERS FOR 3RD SEMESTER (AUGUST – DECEMBER)

Course No.	Course Title	L	T	P	C
PHY 501	Atomic & Molecular Physics	3	1	-	4
PHY 503	Condensed Matter Physics	3	1	-	4
PHY 505	Advanced Quantum Mechanics & Applications	3	1	-	4
PHY 507	Nuclear & Particle Physics	-	-	8	6
PHY 509	Project Research II	3	1	-	4

PHY 501. ATOMIC & MOLECULAR PHYSICS: 3-1-0-4

1. Atoms: One electron system, significance of quantum numbers, space quantization, spin quantum number, orbital angular momentum, spin angular momentum, Parity operator, time dependent perturbation theory, atoms in external field, many electron systems, Pauli exclusion principle, spin-orbit interaction, hyperfine structure.

2. Molecule: Electronic structure of diatomic molecules: MO theory (Quantum mechanical approach to explain molecular bonds, B.O. approximation, foundation of the MO theory, approximation methods for the calculation of electronic wave function, LCAO and VB approach, hydrogen molecule ion, hydrogen molecule etc., their charge distribution and the concept of covalent and ionic bonds), shape of molecular orbitals, spectroscopic term symbols, MO diagrams of some diatomic molecules.

2. Molecular Spectra: Electromagnetic spectra, interaction of radiation with matter, general features of stimulated absorption, spontaneous emission and stimulated emission, selection rule.

3. Rotational Spectroscopy: Moment of inertia of molecules, rotational spectra of rigid molecules, diatomic molecules as non-rigid rotors, prolate and oblate rotors, intensity of spectral lines.

4. Vibrational spectroscopy: Harmonic and an-harmonic oscillators, ro-vibrational spectra, vibrations of polyatomic molecules, Transition matrix elements, IR spectroscopy: basic theory and design (techniques), normal coordinates and normal modes, application of group theory to molecular vibration, FTIR spectroscopy.

5. Electronic spectroscopy: Electronic spectra of diatomic molecules, BO approximation, FC principle, dissociation energy, fine structures, Fortrat diagram.

6. Laser spectroscopy: Basic principle of lasers, population inversion, the Einstein coefficients, line-shape functions, two level, three level and four level laser systems, optical gain, optical resonators, pulsed operation of laser: Q-switching and Mode locking; experimental techniques of Q-switching and mode locking, different laser systems: Ruby, CO_2 , dye and Semiconductor diode lasers.

Suggested Textbooks:
- *'Physics of Atoms and Molecules' by B.H. Bransden and C.J. Joachain*
- *'Molecular Spectroscopy' by I. N. Levine*
- *'Laser Fundamentals' by W. T. Silfvast*

PHY 503. CONDENSED MATTER PHYSICS: 3-1-0-4

- Binding and cohesion in solids. Bonds and bands.
- Crystal Structure, X-ray Diffraction, Reciprocal Lattice.
- Periodic potentials, Bloch's Theorem, Kroning Penney Model, Free electrons and nearly free electrons; tight binding approximation.
- Elementary ideas of band structure of crystalline solids.
- Concept of holes and effective mass; density of states; Fermi surface; explanation of electronic behaviour of metals, semi-conductors and insulators.
- Transport properties of solids. Boltzmann transport equation.
- Introduction to Superconductivity
- Introduction to Semiconductors
- Magnetism in solids. Lattice vibrations, harmonic approximation, dispersion relations and normal modes, quantization of lattice vibrations and phonons. Magnetism in solids. Add, diamagnetism, paramagnetism, ferromagnetism, anti ferromagnetism. Curie-Weiss and Pauli Paramagnetism. Simple models for ferromagnetism - Ising model.

Suggested Books:
- *Dekker, Solid State Physics*
- *Kittel, Introduction to Solid State Physics*
- *Ashcroft and Mermin, Introduction to Solid State Physics.*
- *Ziman, Principles of the Theory of Solids.*

PHY 505. ADVANCED QUANTUM MECHANICS AND APPLICATIONS: 3-1-0-4

1. Relativistic Quantum Mechanics

(a) Klein-Gordon equation and failure of the probability interpretation. The presence of negative energy states and stability problem.

(b) Dirac equation. Its Lorentz covariance, Poincar_e group/algebra, Pauli-Lubanski vector, Casimir operators of Poincar_e algebra. Spin (½) particles. Physical content, plane wave solutions and pro-jectors, wave packets; Problems in localization below Compton wavelength. Necessity for multi-particle theory.

Electro-magnetic coupling, non-relativistic limit, gyromagnetic ratio, Foldy-Wouthysen transformation and appearance of spin-orbit interaction term and Darwin term.

Hydrogen-like atom, hyperfine structure, Lamb shift. Nuclear effects.
Hole theory, anti-particles and charge conjugation. Free Dirac ropagator, propagation in an arbitrary external electro-magnetic field. Relativistic corrections to Rutherford scattering.

2. Path Integrals

Hamiltonian path integral. Stationary phase approximations, Application in harmonic oscillator, Relation to Hilbert space formulation, Equation of motion satisfied by time-ordered product, Green's function. Interpretation of poles and residues. Feynman-Kac formula. Functional derivatives and commutation relations. Euclidean path integrals and statistical mechanics.

3. Multi-particle systems

Indistinguishability. Permutation symmetry, (Anti) Symmetrization postulate; Bosons and Fermions, Slater determinant, Helium atom, statement of spin-statistics theorem. Brief introduction to second quantization, Bose-Einstein and Fermi-Dirac statistics.

Suggested Books:

- Advanced Quantum Mechanics by F. Schwabl (Springer, 2000)
- Quantum Mechanics: Fundamentals by K. Gottfried and T-M. Yan (2nd Ed. Springer,2003)
- Techniques and Applications of Path Integrations by L.S. Schulman (John Wiley and Sons,1981)
- Fundamentals in Nuclear Physics by Jean-Louis Basdevan, J. Rich and M. Spiro (Springer, 2004)
- Introduction to Elementary Particles by D. Griffiths (John Wiley and Sons, 1987)

PHY 507. NUCLEAR & PARTICLE PHYSICS: 3-1-0-4

General properties of nuclei: nuclear size, Rutherford scattering, nuclear radius and charge distribution, nuclear form factor, mass and binding energy, Angular momentum, parity and symmetry, Magnetic dipole moment and electric quadrupole moment, experimental determination, Rabi's method. [4 lecture hours]

Particle accelerators: Pelletron, tandem principle, Synchrotron and synchrosyclotron, colliding beams, threshold energy for particle production. [4 lectures]

Two-body bound state: Properties of deuteron, Schrödinger equation and its solution for ground state of deuteron, rms radius, spin dependence of nuclear forces, electromagnetic moment and magnetic dipole moment of deuteron and the necessity of tensor forces.
[4 lecture hours]

Two-body scattering: Experimental n-p scattering data, Partial wave analysis and phase shifts, scattering length, magnitude of scattering length and strength of scattering, Signficance of the sign of scattering length; Scattering from molecular hydrogen and determination of singlet and triplet scattering lengths, effective range theory, low energy p-p scattering, Nature of nuclear forces: charge independence, charge symmetry and isospin invariance of nuclear forces. [6 lecture hours]

Nuclear structure: Liquid drop model, Bethe-Weizs ¨acker binding energy/mass formula, Fermi model, Shell model and Collective model. [6 lecture hours]

Nuclear reactions and fission: Different types of reactions, Quantum mechanical theory, Resonance scattering and reactions— Breit-Wigner dispersion relation; Compound nucleus formation and break-up, Statistical theory of nuclear reactions and evaporation probability, Optical model; Principle of detailed balance, Transfer reactions, Nuclear fission: Experimental features, spontaneous fission. [6 lecture hours]

Radio Active Decays: Alpha decay, Beta decay –Energy release in beta decay–Fermi theory of beta decay–Shape of the beta spectrum –decay rate Fermi-Curie plot–Fermi & G.T Selection rules – Comparatives half-lives and forbidden decays – Gama decay-Multi pole radation – Angular momentum and parity selection rules – Internal conversion – Nuclear isomerism. [8 lecture hours]

Elementryparticle Physics: Types and characteristics of interaction between elementary particles–Hadrons and laptons–Symmetry and conservation laws – CPT theorem– Gell-Mann-Nishijima formula-classification of hadrons –Quark model - symmetry classification of elementary particles- Parity non-conservation in weak interaction. Relativistic kinematics. [10 lecture hours]

Suggested Books:

1. B.B.Cohen: ConceptsofNuclearPhysics
2. J.S. Lilley: Nuclear Physics
3. M.K. Pal: Theory of Nuclear Structure
4. R.R. Roy and B.P. Nigam: Nuclear Physics
5. S.N. Ghoshal: Atomic and Nuclear Physics (Vol. 2)
6. D.H. Perkins: Introduction to High Energy Physics
7. D.J. Griffiths: Introduction to Elementary Particles
6. D.C. Tayal: Nuclear Physics

PHY 509 PROJECT RESEARCH I: 0-0-8-6

Projects shall be taken up by students under the supervision of a Project Guide.

FOURTH SEMESTER COURSES & SYLLABUS

L=Lectures T=Tutorials P=Practicals in hours per week & C=Credit points

PAPERS FOR 4TH SEMESTER (JANUARY – MAY)

Course No.	Course Title	L	T	P	C
PHY 502	Project Research III	-	-	8	6
PHY 592	Methods of Experimental Physics	3	1	3	7
PHY 5xx	Elective 1*	3	1	-	4
PHY 5xx	Elective 2*	3	1	-	4
PHY 5xx	Elective 3*	3	1	-	4

* Reference to the list of optional courses given below. The student would be required to choose at least one course from Part A – 504, 506 & 508.

Part A

Course No.	Course Title	L	T	P	C
PHY 504	Astrophysics & Astronomy	3	1	-	4
PHY 506	Chemical Physics	3	1	-	4
PHY 508	Biological Physics	3	1	-	4

Part B

Course No.	Course Title	L	T	P	C
PHY 510	Advanced Mathematical Methods	3	1	-	4
PHY 512	Advanced Quantum Field Theory	3	1	-	4
PHY 514	Advanced Statistical Physics	3	1	-	4
PHY 516	Magnetism and Superconductivity	3	1	-	4
PHY 518	Non-Linear Dynamics	3	1	-	4
PHY 520	Optical Physics	3	1	-	4
PHY 522	Correlated Electrons & Disorder	3	1	-	4
PHY 524	Quantum Information Theory	3	1	-	4
PHY 526	Theory of Elementary Particles	3	1	-	4
PHY 528	Mesoscopic Physics	3	1	-	4
PHY 530	Soft Matter	3	1	-	4
PHY 532	General Relativity & Cosmology	3	1	-	4

* In the case of Project-based Courses "P" indicates the number of interaction hours per week.

Examination: 2nd week of May
Semester Break: June & July

PHY 502. PROJECT RESEARCH III: 0-0-8-6

Projects shall be taken up by students under the supervision of a Project Guide.

PHY 592. METHODS OF EXPERIMENTAL PHYSICS: 3-1-3-7

Students will use some advanced level experimental techniques which are extensively used in experimental research. Some of them are listed below:

1. X-Ray and crystallography
2. Gamma Ray Spectroscopy.
3. Experiments on Observational Astronomy.
4. Experiments on Chemical thermodynamics/kinetics
5. Experiments on spectroscopy
6. Experiments on Thermal properties of matter.
7. Error analysis: Errors in observation and treatment of experimental data, estimation of error, theory of errors and distribution laws, least squares method, curve fitting, statistical assessment of goodness of fit.

"Advanced Laboratory" involving routine experiments [such as NMR, Mossbauer, X-Ray Diffraction, Electron Microscopy, Accelerators etc in the research laboratories of the participating institutions], shall be integrated into this course.

PHY 504. ASTROPHYSICS AND ASTRONOMY: 3-1-0-4

Standard Theory of Cosmology: Simplifying assumptions of cosmology, the cosmological principle, Expansion of the Universe and redshift, Friedmann-Robertson-Walker models (closed, flat and open Universe), critical density, FRW solutions for simple equations of state of cosmic matter and radiation. Cosmological constant, de sitter Universe.

Early Universe: Big bang model, Thermodynamics and thermal history of early universe, baryogenesis, Nucleosynthesis, relic neutrinos and microwave background radiation, Recent observational results.

Dark Energy: Type IA supernova as standard candles. Luminosity-Redshift relation – dimming of the brightness of the supernovae: Resolution: a negative deceleration parameter q – an accelerated expansion : Agents driving acceleration – dark energy. The best candidate – Cosmological constant (ΛCDM model). Problems with Λ - discrepancy between the predicted and the observed values : Quintessence models: Qualitative description of the agreement of a presently accelerating universe with other observations – BAO, CMB, Hubble data etc. 05

Astronomy: Coordinate systems and Astronomical Time systems.

Basic Background: Elementary radiative transfer equations , absorption and emission, atomic processes, continuum and line emission Telescopes, Refracting and

Reflective telescopes, Ground-based and space-based observatories, Properties of telescope - Light gathering power and Angular resolution, Astronomical Instrumentation - Optical/IR filter-systems, Optical/IR detectors, X-ray detectors, Photometer/Imaging camera and spectrometer. distance measurements, Hubble's law.

Formation of stars: Formation of protostars and stars ; Star-formation - Jeans Instability, collapse of a spontaneous cloud and viral theorem.

Stellar structure: Equations for hydrostatic equilibrium, Virial theorem, basic Thermodynamics, polytropic stars, Lane Emden equations and its solutions.
Evolution of stars: Stellar energy sources, Gravitational lifetime for a star, Nucleosynthesis, Nuclear lifetime for a star, Evolution off the main sequence - Giant and super giants, Evolution of low and high mass stars, Thermonuclear reactions, Supernova, formation of heavy elements.

Compact objects: Degenerate electron gas, White dwarf, Chandrasekhar limit, Neutron stars, Maximum mass of neutron star, Black hole.

Properties of stars: Continuous radiation from stars: Brightness of starlight, The electromagnetic spectrum, Colors of stars, Quantifying color, Blackbody radiation, Planck's law, Stellar colors, Stellar distances, Stellar parameters (Apparent and Absolute magnitude, Luminosity, radius etc.) and their measurement techniques.

The Sun: A typical star, Basic structure, Elements of radiation transport theory, the photosphere, the chromosphere, the corona- Parts of the corona and Temperature of the corona, Solar activity - Sunspots, Solar flares, Coronal mass Ejection (CME).

Spectral Classifications of Stars: Spectral lines in stars, Spectral types, Origin of spectral lines, Line broadening due to Doppler, thermal and collisions, The Bohr atom model and hydrogen spectral lines. Formation of spectral lines - Excitation, Ionization and recombination, Boltzmann Equation, Stimulated and spontaneous emission, Absolute and apparent magnitudes, Mass luminosity relation, Mass luminosity relation, Hertsprung-Russell diagram. Saha Ionization Equation, Ionized hydrogen regions, Intensities of spectral lines.

Binary Stars: Different types of binary stars, Importance of binary systems, Accretion and gravitational radiation (basic ideas).

Interstellar medium (ISM): Interstellar extinction law; Theoretical extinction model and Mie scattering; Origin and evolution of chemical elements; Nucleogenesis; Interstellar dust and Abundances.

Galaxies: Formation and classification, Density wave theory of the formation of spiral arms, Rotation curves, Missing mass and dark matter, Quasars and active galactic nuclei, Our Galaxy, Oort's constants, magnetic field. Rotation Curve and Dark Matter; Classification of galaxies; Active galaxies ad Quasars.

Hands on (May be credited/ non credited):
Sdss Data Archieve (DR16):
http://skyserver.sdss.org/dr16/en/home.aspx

Tutorials in Sloan Digital Sky Survey (sdss.org)
http://skyserver.sdss.org/dr16/en/help/howto/search/searchhowtohome.aspx

Advanced projects:
http://skyserver.sdss.org/dr16/en/proj/advanced/advancedhome.aspx

Data Acess Tools:
http://skyserver.sdss.org/dr16/en/tools/toolshome.aspx

PHY 506. CHEMICAL PHYSICS: 3-1-0-4

- Quantum Chemistry and the Nature of the Chemical Bond.
- Chemical Kinetics and Thermodynamics. Order of the Reaction. Rate laws.
- Mechanism of Chemical Reactions: (a) Collision Theory (b) Transition State Theory (c) Potential Energy Surface (d) Kramers Escape Rate.
- Enzyme Reactions: Solution kinetics, characterization of enzymes, control mechanisms.
- Electron Transfer: (a) Dynamical Electrochemistry (b) Electron Transfer (c) Quantum Models (d) Electron Charge Transfer in Proteins.

Suggested books:
- *Nitzan, Chemical Dynamics in Condensed Phases, OUP, 2006.*
- *H. Eyring, S H Lin, S M Lin, Basic Chemical Kinetics, John Wiley and Sons, 1980*

PHY 508. BIOLOGICAL PHYSICS: 3-1-0-4

1. Molecular structure of biological systems: this includes a brief introduction to molecular orbital theory, formation of various kinds of bonds, molecular excitation and energy transfer, thermal molecular movement, order and probability, molecular and ionic interactions: biological structures, interfacial phenomena and membranes.

2. Energetics and dynamics: Fundamental concept of thermodynamics, aqueous and ionic equilibrium in living cell, Fluxes, transport in biological systems, electric fields in cells, mechanical properties of biological materials, biomechanics and fluid behaviour.

3. Physical factors of the environment: temperature, pressure, sound, mechanical oscillation, static and EM fields, ionizing radiation.

4. Kinetics of biological systems: systems theory, systems of metabolism and transport, model approaches to some complex biological processes.

Some more topics could be included:

1. Biomolecular structures with emphasis on Proteins and Nucleic acids: Dihedral angles and base pair parameters along with different levels of structural organizations (descriptive only); water; carbohydrate and lipids; ATP.

2. Biophysical experimental techniques: Principles of Fluorescence, CD, NMR, X-Ray, crystallography, AFM, Single molecular spectroscopy etc.

3. Molecular Dynamics simulation: Verlet algorithm; PBC; Constraint systems; statistical analysis of data.

4. Biological modeling: Reaction-diffusion (or any other equivalent) systems for illustration.

5. Introduction to Bio-informatics: Data mining; sequence comparison and alignment.

Text book:
Biophysics by Roland Glaser

Reference books:
- *Biological Physics: Energy, Information, Life by Philip Nelson*
- *Biophysics: An Introduction by Rodney Cotterill*
- *Introduction to Molecular Biophysics by J.A. Tuszynski, M. Kurzynski*

PHY 510. ADVANCED MATHEMATICAL METHODS: 3-1-0-4

1. Group Theory
Basic definition of groups and subgroups. Homomorphism and isomorphism between groups, finite and infinite groups, conjugate classes, invariant subgroups and coset spaces. Representation of groups. unitary representation, character of a representation.Permutation group and Young' Tableaux. Elements of Lie Groups. unitary groups, orthogonal groups, homogeneous and inhomogeneous Lorentz groups, Wigner's little group and concept of helicity etc., conformal groups, symplectic groups. Local properties of Lie groups, infinitesimal group generators, Lie algebra, Adjoint representations, simple and semisimple Lie algebras, Casimir operators. Elementary ideas of root vectors, Cartan subalgebra, graph- ical representations, weight vectors. Dynkin diagrams and Cartan matrices.

2. Differential Geometry
Concept of differentiable manifolds, tangent and cotangent spaces(one forms), tensors and tensor product spaces. Calculus of forms, exterior differentiation, Lie differentiation, co-variant derivatives and connections, parallel displacements and geodesics. Torsion and curvature. cartan's equations of structure and metric tensor. Symmetries of Riemann curvature tensor. Elementary theories of fibre bundles and connection between gravity and gauge theories.

Reference books:
- *S. Mukhi & N. Mukunda, Introduction to topology, and differential geometry and group theory for physicists*
- *B. C. Hall, Lie Groups and representations*
- *Y. Choquet-Bruhat et al, Analysis, Manifolds & Physics*

PHY 512. ADVANCED QUANTUM FIELD THEORY: 3-1-0-4

- Relativistic notations.
- SU(2) and the rotation group.
- Lorentz Group and SL(2,C).
- Homogeneous and Inhomogeneous Lorentz Group and their Algebras.
- Spinors.
- Relativistic Covariant Equations- Klein Gordon, Dirac and Maxwell equations.
- Quantization of free fields: Canonical and Path Integral Approach.
- Covariant quantisation of the Maxwell field.
- Interacting Fields and the Gauge Principle.
- Feynman-Dyson Perturbation Expansion and Feynman Diagrams.
- Quantum Electro-Dynamics. Tree Level Calculations of Compton Scattering Cross-section etc.
- Loops, Divergences, Regularization and Renormalization.
- Anomalous magnetic moment of the electron and the Lamb-Shift.

Reference books:

- *Q. F. Theory by Hatfield*
- *Q. F. Theory by L. Ryder*
- *Q. F. Theory by s. Weinberg*
- *Q. F. Theory by Peskin & Schroder*

PHY 514. ADVANCED STATISTICAL PHYSICS: 3-1-0-4

Critical Phenomena: Mean Field Theory, Landau Ginzburg Theory, Renormalization Group, Ising Model in one and two dimensions.

Superconductivity and Superfluidity.

Approach to equilibrium: Boltzmann transport equation, Langevin equation, master equation approach, Fokker Planck equation.

Reference books:

- *K. Huang, Statistical Mechanics*
- *S.K Ma, Statistical Mechanics*

PHY 516. MAGNETISM AND SUPERCONDUCTIVITY: 3-1-0-4

Generalized Hamiltonian of Condensed Matter Physics and origin of various "effective theories"; Introduction to phenomenon of Superconductivity; Experimental features; Various phenomenological theories; Cooper's one pair problem; Gateway to microscopic theories - BCS Fermion pairing theory and BSB Bose Condensation theory; BCS ground state; Mean field treatment of BCS Hamiltonian; Gap equation and its solution; Equation for critical temperature; Brief applications of BCS theory to various experiments; Brief introduction to exotic phenomena like interplay of superconductivity and magnetism, high temperature superconductivity etc.

In addition to the above, some lectures at a more advanced level will be offered.

Reference books:

- *"Theory of Superconductivity" by J.R. Schrieffer.*
- *"Solid State Physics" by N. Ashcroft and N.D. Mermin.*
- *"Introduction to Solid State Physics" by C. Kittel.*
- *"Quantum Theory of Solids" by C. Kittel.*
- *"Quantum Theory of Many Particle Systems" by G.D. Mahan.*
- *"Elementary Excitations" by D. Pines*

PHY 518. NON-LINEAR DYNAMICS: 3-1-0-4

Discrete and continuous time dynamical systems. Flows and maps; phase space, orbits; fixed points, eventually periodic points and their stability attractors and repellors: hyperbolicity; logistic map, tent map, Baker's map; graphical analysis of orbits in one dimensional maps; maps of the circle: rotation number.

General solution of the continuous time linear systems, bifurcations in one dimensional systems, phase space trajectories in two dimensional: stable and unstable nodes and foci: saddle points, centres, Hartman's theorem.

Poinc are Bendixon Theorem, periodic orbits, anharmonic oscillators, Hopf bifurcations, limit cycles; sensitive dependence of initial conditions, Chaos.

Reference books:

- *S. H Strogatz, Nonlinear Dynamics and Chaos, 1994*
- *K. T Alligood, T. D Sauer and J A Yorke, Chaos: An Introduction to Dynamical Systems, 1997*

PHY 520. OPTICAL PHYSICS: 3-1-0-4

NONLINEAR and QUANTUM OPTICS:

- Classical linear and nonlinear optics:
- Anharmonic oscillator model, nonlinear susceptibilities, absorption, dispersion, nonlinear wave mixing, coupled mode equations, phase matching condition, phase conjugation, optical bistability.
- Few-level atom models: semiclassical theory
- Two-level atom, optical Bloch equations, steady state response, probe amplification and resonance fluorescence, semiclassical dressed states. Population trapping. Coherent transient phenomena such as optical nutation, photon echoes, self-induced transparency.
- Interaction between atoms and quantized fields:
- Quantization of the electromagnetic field, Jaynes-Cummings model, dressed states, vacuum field Rabi oscillations, collapses and revivals, spontaneous emission in free space, density of states, Fermi Golden Rule and Wigner-Weiskopf theory. Inhibition of spontaneous emission.
- Some remarks on unconventional cavities such as dielectric microspheres and photonic bandgap structures.

- Quantum theory of four-wave mixing and parametric down-conversion.
- Coherent control of atom-field interactions - electromagnetically induced transparency, lasing without inversion.

LASER THEORY AND OPTICAL COHERENCE:

- Spontaneous and stimulated emission, modes of a cavity, population inversion, saturated gain and threshold, Doppler broadening, Lamb dip, hole burning, single mode laser master equation (Scully-Lamb theory), laser photon statistics and laser linewidth. Micromaser and microlaser.
- Classical and Quantum Coherence functions:

1. Young's double slit experiment, mutual coherence function, complex degree of coherence, van Cittert-Zernike theorem, Hanbury-Brown- Twiss experiment, higher-order coherence functions.
2. Polarization properties of quasi-monochromatic light - coherency matrix, degree of polarization, Stokes parameters, Poincare sphere.
3. Quantum Coherence functions a la Glauber - coherent states, sub-poissonian statistics, photon antibunching and squeezed states of light.

ATOMIC MOTION IN LASER LIGHT:
Atom cooling and trapping; atom interferometry; Bose-Einstein condensation of laser-cooled and trapped atoms, Atom lasers, Nonlinear atom optics, optical lattices.

Reference books:

- *"The Quantum Theory of Light" by R. Loudon*
- *"Nonlinear Optics" by R. W. Boyd*
- *"Laser Physics" by P. W. Milonni, J. H. Eberly*
- *"Elements of Quantum Optics" by P. Meystre & M. Sargent*
- *"Introductory Quantum Optics" by C. Gerry & P. Knight*
- *"Quantum Optics" by D. F. Walls & G. J. Milburn*
- *"Quantum Optics" by M. O. Scully & M. S. Zubairy*
- *"Quantum Optics" by G. S. Agarwal*
- *"Atom Optics" by P. Meystre*
- *"Laser Cooling and Trapping" by H. J. Metcalf & P. van der Straten*

Recommended reading:

- *"Optical Coherence and Quantum Optics" by L. Mandel, E. Wolf*

PHY 522. CORRELATED ELECTRONS & DISORDER: 3-1-0-4

- **Physics of Materials:**

Metals (M) and Insulators (I)

A. BAND INSULATORS vs CORRELATED INSULATORS

- Breakdown of independent electron description
- Mott transition
- Hubbard model
- Limiting cases of Hubbard models - band limit & atomic limit, Hubbard sub-bands
- Mott transitions in transition metal oxides
- Mott insulators & charge transfer insulator, Zaanen-Sawatzky-Allen classification

B. LARGE-U LIMIT

- Canonical transformation

- t-J model, Super-exchange
- Half-filled band : Heisenberg spin model
- Antiferromagnetic Heisenberg model : spin waves, strange world of D=1

C. SOME INTERESTING SYSTEMS

- Band-width-control M-I transition systems: V_2O_3, $RNiO_3$, NiS etc
- Filling control M-I transition systems: $R_{1-x}A_{x}Ti(V)O_3$
- High Tc super-conducting cuprates
- Quasi one-dimensional systems: Cu-O chain & ladder compounds
- Double-exchange systems: $R_{1-x}A_{x}MnO_3$

D. DISORDER INDUCED INSULATORS

- Anderson Localization
- Scaling theory
- Electron-electron interaction & disorder

References:

- Patrik Fazekas -- Lecture notes on Electron Correlation & Magn.
- Imada, Fujimori, Tokura -- Metal-Insulator Transitions, Review. Mod. Phys. vol 70, pg 1039 (1998)
- P.A. Lee & T.V. Ramakrishnan -- Disordered electronic system, Review. Mod. Phys. vol 57, pg 287 (1985)
- Fulde -- Electron correlation in Molecules and Solids

- **Electronic Structure of Materials**

A. BASICS

1. Electrons in periodic potentials
   - Bloch's theorem
   - Kronig-Penney model
   - concept of energy bands
2. Density of states
   - Green's function
   - Tridiagonal matrices & Continued fractions
   - Singularities in DOS
3. Reciprocal lattice & Brillouin zone
   - Special k-points in BZ sampling

B. EL-ION PROBLEM

4. Adiabatic approximation (Born-Oppenheimer).
5. Classical nuclei approximation (Ehrenfest Theorem).
6. Hellman-Feynman force on nuclei.

C. MANY-ELECTRON PROBLEM

7. Hartree approximation
   - LCAO method
8. Hartree-Fock approx.
   - Slater-determinantal wavefunction & its properties
   - Hartree-Fock equation
   - Fock operator
   - Energy of the groundstate
   - Koopman's theorem
9. Going beyond Hartree-Fock (introductory)
   - absence of correlation in H-F theory
   - Basics of MCI and Perturbative (Moller-Plesset) methods

10. Density Functional Theory
   - Energy as a functional of density : basic concepts
   - Thomas-Fermi theory
   - Hohenberg-Kohn Theorem
   - Kohn-Sham Eqn.
   - LDA for the exchange-correlation function

D. MOLECULAR DYNAMICS METHODS IN ELECTRONIC STRUCTURE

11. Introduction to MD methods
   - Deterministic vs. Stochastic methods
   - Connection to statistical mechanics & thermodynamics
   - Finite difference algorithms for solving eqns. of motion
   - running and controlling MD simulations
   - Limitations & errors in MD simulation
12. Tight-binding MD
   - Eqn of motion in TB-MD
13. Ab-initio (Car-Parrinello) MD
   - Basic concepts and effective Lagrangian
   - Eqn of motion
   - Iterative solution of Kohn-Sham eqn

E. EXPERIMENTAL MANIFESTATION OF ELECTRONIC STRUCTURE

   - Theory of photoemission
   - Core-levels and Final states
   - Satellites
   - Valance band
   - Band structure
   - Surface states and surface effects

Reference books:

- *Ashcroft & Mermin -- Solid State Physics*
- *Grosso & Pastore-Parravicini -- Solid State Theory*
- *Kaxiras -- Electronic Structure of Solids*
- *Sutton -- Electronic Structure of Materials*
- *Fulde -- Electron correlation in Molecules and Solids*

PHY 524. QUANTUM INFORMATION THEORY: 3-1-0-4

Foundations of quantum theory; states, observables, measurement, dynamics. Spin-half systems and photon polarizations, qubits versus classical bits. Pure and mixed states, density matrices. Orthogonal measurements, positive operator valued measures. Unitary evolution, extension to superoperators. Master equation and decoherence. Quantum measurement.

Quantum entanglement, Bell's theorems. Classical information theory, entropy. Quantum information theory, quantification of entanglement, communication complexity. Quantum cryptography and teleportation. Turing machines, reversible computation, universal logic gates and circuits. Quantum computers and circuits. Quantum algorithms: search, FFT, prime factorisation. Quantum simulations. Quantum error correction and codes. Faulttolerant quantum computation. Physical implementations: ion traps, quantum dots, cavity QED, NMR.

Reference books:

- *J. Preskill, http://www.theory.caltech.edu/people/preskill/ph229*
- *Peres, Quantum Theory: Concepts and Methods.*

PHY 526. THEORY OF ELEMENTARY PARTICLES: 3-1-0-4

1. Preliminaries
a)Relativity – notation, kinematics;
b)Particles as fields, Lagrangians and interactions;
c)Examples of scattering and decay processes;
d)Scattering cross-section and decay rate calculation;

2. Groups and Symmetries (briefly)
a)Definition of a group, matrix groups, direct product;
b)Lie group, generator, Lie algebra, representation;
c)SU(2) & SU(3), their representations, graphical representation;
d)Internal symmetries and particles as representation;
e)Symmetries and interactions;

3. PCT
a)P,C,T in QM;
b)P,C,T for Klein-Gordon, Dirac and Maxwell Equations (all as classical fields);
c)P,C,T for quantum fields and their interactions;
d)P,C,T violating terms in the Lagrangian;
4. SU(2)
a)Isospin and SU(2), nucleons, pions, composites;
b)Isospin in scattering and decay processes;
c)Isospin violations in electromagnetic and weak interactions;
d)Isospin of strange particles, charge and I3;

5. SU(3)
a)Isospin, Hypercharge and SU(3), quarks;
b)Eightfold way, octets and decuplet for mesons and baryons;
c)Existence of color;

6. Strangeness
a)Strangeness selection rules;
b)Weak interactions and strangeness;
c)K decays and mixing;
d)CP, long and short K;
e)Strangeness oscillations;

7. Weak Interactions
a)P violation, helicity and left-handed particles;
b)Weak interactions of quarks;
c)V-A interactions;
d)CP violation;

Reference books:

- *O. M. Boyarkin: Advanced particle physics*
- *P. B. Pal: An introductory course of particle physics*
- *A. Bettini: Introduction to elementary particle physics*
- *T. P. Cheng and L. F. Li: Gauge theory of elementary particle physics.*

PHY 528. MESOSCOPIC PHYSICS: 3-1-0-4

- History of the subject, fabrication techniques, basic differences between semi-conductors and metals.
- Quantum wave guides, effective mass approximation, Landauer-Buttiker approach to conductance, Comparison with Kubo formalism, violation of Onsager reciprocity relations, conductance quantization in point contacts, conductance quantization in superlattices, conductance quantization in modulated quantum wires.
- Breit-Wigner resonance and Fano resonance, delay time for resonances, Friedel sum rule, Levinson's theorem.
- Bound states in the continuum, weak and strong localization in disordered systems, Thouless energy scale, decoherence at 0 K.
- Persistent currents in closed and open systems, parity effect and its violation for persistent currents, temperature dependence of persistent currents, effect of disorder and electronelectron interactions on persistent currents.
- Integral and fractional Quantum Hall effect and conductance quantization.
- Quantum dots, electronic states in quantum dots, Hund's rule in a quantum dot, transport across quantum dots (capacitance approach), Kondo problem in a quantum dot, level statistics in a quantum dot and Random Matrix Theory.
- Luttiger liquid in 1D.
- Noises in mesoscopic systems, Nyquist-Johnson noise, shot noise, 1/f noise.
- Definition of mesoscopic superconductivity in terms of Ginzburg-Landau theory, Ginzburg-Landau limit and London limit, phase transitions- magnetization and heat capacity of mesoscopic superconductors, Giant vortex state and mixed vortex state, proximity effect and Andreev reflection.

Reference books:

- *Electronic Transport in Mesoscopic Systems by Supriyo Datta*
- *Introduction to Mesoscopic Physics by Yoseph Imry*

PHY 530. SOFT MATTER: 3-1-0-4

1. **Statistical Mechanics of an Interacting System:** Structural quantities of a liquid, Single point density, Pair correlation function. Structure factor; Thermodynamics of a liquid in terms of pair correlation function; Mean Field Theory in Variational approach; Grand partition function of a liquid as a function of external potential. Direct correlation function. Classical density functional theory and Application to phase transitions (examples can be taken from liquid crystals and colloids). (18 lectures)

2. Brownian motion: Onsager regression theorem; linear response theory; fluctuation-dissipation relations and spectra; Langevin equation, Master equation, Fokker-Planck and Smoluchowski approaches to dynamical processes and their solutions for simple problems. (10 lectures)

3. Computer simulations: Basic algorithm of Monte Carlo, Molecular Dynamics and Brownian Dynamics Simulation. Examples can be taken from simple Lennard-Jones systems. (4 lectures)

4. **Hydrodynamics:** Phenomenological formulation of equation of motion for conserved and nonconserved modes (model A and model B). Linearised hydrodynamics of simple fluids: diffusive and propagating modes. (6 lectures)
5. **Molecular spectroscopy:** Born-Oppenheimer approximation; variational calculations of many electron wave functions. Valence bond and molecular orbital theory. Potential energy surface; vibration and rotational motion on an electronic energy surface. (10 lectures)

PHY 532. GENERAL RELATIVITY & COSMOLOGY: 4-0-0-4

The Equivalence Principle: Non-Inertial frames and non-Euclidean Geometry, General Coordinate transformations and the general covariance of physical laws.
Geometrical Basis: Contravariant and covariant vectors; Tangent vectors and 1-forms; Tensors – product, contraction and quotient laws, Wedge product – closed forms, Levi-Civita Symbol, Tensor densities, the invariant volume element. The Parallel Transport and affine connection, Covariant derivatives, Metric tensors, rasing and lowering of indices, Christoffel connection on a Riemannian Space, Geodesics, Space-time curvature, curvature tensor Commutator and Lie derivatives, Equation for deviation, Symmetries of the survature tensor, Bianchi Identities, Isometries and Killing Vectors.
Einstein's Equations: Energy-Momentum Tensor and conservation laws, Einstein's equation, Hilvert's variational principle, Gravitational energy-momentum pseudo-tensors. Newtonian Approximation, Linearized field equations, Gravitaional Waves, Gravitaional radiation. Principles of gravitational wave detectors – LISA, LIGO, VIRGO
Simple Solutions and Singularities: Static, Spherically symmetric space-time, Schwarzschild's exterior solution, Motion of perihelion of Mercury, Bending of Light, Gravitational Red-Shift Radar Echo delay.
Black Holes; Kruskal –Szekeras diagram; Schwarzschild's interior solution; Tolman-Oppenheimer-Volkov equation, Collapse of Stars, Kerr Metric, Reissner-Nordstrom metric, Kerr-Newman metric. Weyl's postulate and the cosmological (Copernican) principle, Robertson Walker metric, Anisotropies, vorticity and shear, Raychoudhury equation, Singularity theorems of Hawking and Penrose.
Cosmology: Important models of the Universe; Red shift and expansion; Bigbang theory, Early Universe, and decoupling, neutrino temperature, nucleosynthesis, relative abundances of hydrogen, helium, deuterium, Radiation and matter dominated phases, Cosmic microwave background radiation, its isotropy and anisotropy properties, COBE and WMAP experiments; CMBR anisotropy as a hint to a large scale structure formation.
Dark Matter and Dark energy: need for them and possible models.

1. *Relativity: special, general, and cosmological, W. Rindler*
2. *General Theory of Relativity: Robert Wald*
3. *Gravitation and cosmology: principles and applications of the general theory of relativity, S. Weinberg*
4. *Relevant reviews from current journals as reading matter*

Reference books:

Text books: Chaikin and Lubensky

1. Hansen-McDonald
2. Allen and Tildesley
3. McQuerry

SUBSEQUENT SEMESTERS

Subsequent semesters will be essentially devoted to research activities in the chosen topics and from time to time courses on Special Topics at an advanced level will be offered to broaden and deepen the base of the research scholars.

The actual courses offered will vary from year to year depending on the choice of specialization made by the students in consultation with the Students' Curriculum and Research Evaluation Committee (SCREC), availability of teachers, and topicality of the subject etc.

This updated Course Structure has been approved by the Academic Council and the Board of Studies for the Integrated Ph.D Programme (IPhD) in a meeting held on 5th May 2011 at the S N Bose National Centre for Basic Sciences and submitted to the University of Calcutta for inclusion as regular curriculum for the M.Sc. in Physical Sciences being the first two years of the Integrated Ph.D Programme in Physical Sciences (IPhD-Ph).

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SENIOR PROFESSOR & DEAN (ACADEMIC PROGRAMME)
S N BOSE NATIONAL CENTRE FOR BASIC SCIENCES