Ph.D. PROGRAMME IN PHYSICAL SCIENCES

COURSE STRUCTURE & SYLLABUS

Fifth Semester

Course No.	Course Title	L	T	P	C
PHY 501	Research Methodology	4	-	-	4
PHY 502	Review of the topical Research	4	-	-	4
PHY 503	Condensed Matter Physics	4	-	-	4
PHY 504	Computational Methods in Physics	3	1	-	4
PHY 505	Classical Mechanics & Electromagnetism	4	-	-	4
PHY 506	Quantum Physics (Formal)	4	-	-	4
PHY 507	Mathematical Methods - I	3	1	-	4
PHY 508	Numerical Methods	3	1	-	4
PHY 509	Relativity & Cosmology	4	-	-	4
PHY 510	Astrophysics	4	-	-	4
PHY 511	High Energy Astrophysics around compact stars	4	-	-	4
PHY 591	Project Research – Part I	-	-	8	8
	Total hours of contact per week	*16*			
	Total credits	*16*			

Sixth Semester

Course No.	Course Title	L	T	P	C
PHY 601	Advanced Condensed Matter Physics – Magnetism & Superconductivity	4	-	-	4
PHY 602	Advanced Condensed Matter Physics – Electronic Structure & Physics of Materials	4	-	-	4
PHY 603	Statistical Physics	3	1	-	4
PHY 604	Quantum Physics (Application)	3	1	-	4
PHY 691	Project Research (Two semesters) – Part II	-	-	8	8
	Total hours of contact per week	*16*			
	Total credits	*16*			

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

COURSE DESCRIPTION IN OUTLINE

Fifth Semester Syllabus

PHY 501 RESEARCH METHODOLOGY: 4-0-0-4

1. Define Research and Methodology; Types of research methods available; Describe Experiments, Theory and Computation/ Simulation in general terms; Spell out explicitly (with a few examples) the connection among them.

2. Define Library Research, Field Research and Laboratory Research; Explain Sample Survey, Sample Collection and/or Preparation, Data Analyses, Hypothesis, Modeling, Interpretation, and Conclusion.

3. Error in Data Analyses and Ways to Report Error; Statistical Analyses of Collected Data; Importance of Error Analyses in Experimental/Numerical Study. Validity, Reliability and Reproducibility of Measured/Acquired Data.

4. Accuracy and Precision in Measurements/ Predictions. Selectivity and Specificity of a Method Developed; Generalization and External Validity; Internal Validity and Inter-relationship between measurements and the underlying theory/hypothesis.

5. Formulation of a Research Problem: Motivation, Induction, Hypothesis, Deduction, Observation and Conclusion

6. Scientific Reporting of Data/Observation/Prediction; Difference between Magazine or Newspaper Reporting, and Science Journal Reporting; Expression Skill Development and Nurturing.

7. Plagiarism – Self and External. Ethics, Attitude, Discipline and Holistic Approach to Research; Implication of Research Tenure on Personality Development. Importance of Focus, Challenge and Self-belief in Research.

8. Research and Society – Coupling and Necessary Aloofness. Relevance to “Old fashion” Indian Philosophy of High Thinking. Basic Scientific Research, Translational Research, Technology Development and Elements of Commerce.

9. Specific Experimental, Theoretical and Simulation Techniques for Decoding the Systems Around; Interconnection Between Theory and Experiments. Computer Languages Necessary for Machining a Scientific Problem, and Relevant Data Collection; Examples of a few commercially available software; Popular Numerical Techniques and Libraries (For example, MATLAB).

PHY 502 REVIEW OF THE TOPICAL RESEARCH: 4-0-0-4

Goal of the review – History of the subject – development of the subject: theoretical and experimental – alternative models and theories – pros and cons of various models and theories if any – the relevance of the topical research from the perspective of the subject – Possible ways to develop the research topic further.

PHY 503 CONDENSED MATTER PHYSICS: 4-0-0-4

- 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.
- Lattice vibrations, harmonic approximation, dispersion relations and normal modes, quantization of lattice vibrations and phonons. thermal expansion and need for anharmonicity.
- Transport properties of solids. Boltzmann transport equation. Wiedemann-Franz law. Hall effect.
- Superconductivity: Phenomenology, penetration depth, flux quantization etc. Josephson effect.
- Semiconductors: intrinsic and extrinsic, carrier mobility etc.
- Thermal properties of solids.
- Magnetism in solids.
- Optical and Dielectric Properties.

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 504 COMPUTATIONAL METHODS IN PHYSICS: 3-1-0-4

Introduction to Fortran programming and basic numerical methods will be imparted to the students through lectures and projects based on the numerical analysis of elementary physical problems illustrating such techniques.
This course will involve lectures on advanced numerical techniques and projects based on the numerical analysis of advanced physical problems illustrating such techniques.

PHY 505 CLASSICAL MECHANICS & ELECTROMAGNETISM: 4-0-0-4

Lagrangian treatment, Variational principle, Hamiltonian structure, Canonical transformations, Hamilton Jacobi theory, Spatial relativity, Electromagnetism from a least action principle, potential theory, retarded and advanced potentials, waves.

H. Goldstein, Classical Mechanics
J. D Jackson, Electrodynamics

PHY 506 QUANTUM PHYSICS (FORMAL): 4-0-0-4

The formal structure of quantum mechanics, Schroedinger equation, matrix formulations, application to simple systems, angular momentum, perturbation theory, variational techniques, and WKB approximations.

R. Shankar, Quantum Mechanics
L.D Landau and E. M Lifshitz, Course of Theoretical Physics

PHY 507 MATHEMATICAL METHODS – I: 3-1-0-4

- Vector analysis, Green, Gauss and Stokes theorems.
- Linear vector spaces and linear operators. Matrices & eigenvalue problem.
- Theory of complex variables, Cauchy-Riemann conditions, Cauchy integral theorem, Taylor- Laurent expansion, classification of singularities, analytic continuation, theorem of residues and evaluation of definite integrals and series.
- Ordinary differential equations and series solution. Sturm-Liouville problem and orthogonal functions, special functions.
- Green's functions for self-adjoint differential operators and eigenfunction expansion. (Laplace, Poisson, Diffusion, Wave equation etc to be discussed).

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

G. Arfken, Mathematical Methods for Physicists
I.N. Sneddon, Special Functions of Mathematical Physics & Chemistry
P.K. Chattopadhyay, Mathematical Physics
E. Kreyszig, Advanced Engineering Mathematics
Mathews and Walker, Mathematical Physics
P. Dennery & A. Kryzwicki, Mathematics for Physicists

C.M. Bender & S.A. Orszag, Advanced Mathematical Methods for Scientists & Engineers
E. Butkov, Mathematical Physics
R.W. Churchill & J.W. Brown, Com

PHY 508 NUMERICAL METHODS: 3-1-0-4

Basic programming in Fortran, Numerical methods of finding roots of an equation (Bisection method, Newton's method), Numerical methods of solving set of linear equations(Gauss elimination method, Thomas method), Numerical method of integration (Gregory-Newton expansion, Trapezoidal rule, Simpson's rule),Numerical method of differentiation, Numerical method of solving differential equation (Euler's method, Runge-Kutta method).

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

1. Programming in FORTRAN by Rajaraman.
2. Numerical Recipe by Press, Shapiro and Teukolski
3. Numerical methods for Scientists and Engineers by HM Antia

PHY 509 RELATIVITY & COSMOLOGY: 4-0-0-4

<u>The Equivalence Principle</u>: Non-Inertial frames and non-Euclidean Geometry, General Coordinate transformations and the general covariance of physical laws.
<u>Geometrical Basis</u>: 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.
<u>Einstein's Equations:</u> 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
<u>Simple Solutions and Singularities:</u> 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.
<u>Cosmology:</u> 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.
<u>Dark Matter and Dark energy:</u> need for them and possible models.

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

PHY 510 ASTROPHYSICS: 4-0-0-4

Basic Background and Instrumentations: Elecmentary radiative transfer equations, absorption and emission, atomic processes, continuum and line emission, Optical and radio telescopes, Fourier Transform methods, detectors and image processing, Distance measurements in astronomy, Hubble's law, modern observational techniques.

Spectral Classifications of Stars: Saha's equation, Harvard system, Luminosity effect, Absolute and apparent luminosity relation, spectroscopic parallax

Evolution of Stars: Observational basis, protostars, disks, bipolar outflows, hydrostatic equilibrium, Sources of stellar energy, Gravitational Collapse, Fusion reactions (p-p) chain, CNO Cycle, triple alpha reactions, formation of heavy elements, Hertzsprung-Russell diagram, evolution of lowmass and high mass stars, Chandrasekhar limit, Pulsars, neutron stars and black holes

The Sun: Different layers of the Sun and their properties, Solar cycles, sunspots, solar corona and solar winds, expected and observed solar neutrino spectra, Possible resolution of the solar neutrino problem.

Binary Stars: Different types of binary stars, Importance of binary systems, Accretion, spectral properties of radiations from accretion flows and identification of black holes and neutron stars.

Galaxies: Formations and classification, Density Wave Theory of the formation of spiral arms, Rotation curves, missing mass and dark matter, Quasars and active galactic nuclei magnetic fields in the galaxy.

Cosmic Rays: Extensive air shower and Fermi's theory of high energy cosmic rays; Interaction of high energy cosmic rays with the CMBR background and the GZK cutoff, Cosmic ray experiments like HiRes, AGASA, Pierre Augur Observatory.

1. *M. Zeilik and S.A. Gregory, Introductory Astronomy and Astrophysics*
2. *B. Basu, An Introduction to Astrophysics*
3. *Radiative processes in Astrophysics: G. Rybicki and A. Lightman*
4. *Accretion Power in Astrophysics, J. Frank*
5. *Physics of Astrophysics – F. Shu*
6. *General relativity with Application to Astrophysics: N. Straumann*

PHY 511 HIGH ENERGY ASTROPHYSICS AROUND COMPACT STARS: 4-0-0-4

Astrophysics of compact stars: Black Holes, Neutron Stars and White Dwarfs;
Accretion processes on these objects: Transonic Flows, Outflows and origin, acceleration and collimation of jets; Radiative Properties of the accretion flows; Observational Evidence for compact stars.
Data Analysis: Observations of high energy radiation from compact objects; satellite data and their analysis

1. *Accretion Power in Astrophysics - J. Frank*
2. *Theory of Transonic Astrophysical Flows – S. K. Chakrabarti*
3. *Accretion Processes in Astrophysics – (Physics Reports) S.K. Chakrabarti*

4. *Black Holes, Neutron Stars and White Dwarfs: Physics of Compact Objects by Shapiro and Teukolsky*

PHY 591 PROJECT RESEARCH – PART I

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

Sixth Semester Syllabus

PHY 601 ADVANCED CONDENSED MATTER PHYSICS – MAGNETISM & SUPERCONDUCTIVITY: 4-0-0-4

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.

(i) "Theory of Superconductivity" by J.R. Schrieffer.
(ii) "Solid State Physics" by N. Ashcroft and N.D. Mermin.
(iii) "Introduction to Solid State Physics" by C. Kittel.
(iv) "Quantum Theory of Solids" by C. Kittel.
(v) "Quantum Theory of Many Particle Systems" by G.D. Mahan.
(vi) "Elementary Excitations" by D. Pines

PHY 602 ADVANCED CONDENSED MATTER PHYSICS – ELECTRONIC STRUCTURE & PHYSICS OF MATERIALS: 4-0-0-4

- **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: V2O3, RNiO3, NiS etc
- Filling control M-I transition systems: R_{1-x}A_{x}Ti(V)O3
- High Tc super-conducting cuprates
- Quasi one-dimensional systems: Cu-O chain & ladder compounds
- Double-exchange systems: R_{1-x}A_{x}MnO3

D. DISORDER INDUCED INSULATORS

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

References:

1. Patrik Fazekas -- Lecture notes on Electron Correlation & Magn.
2. Imada, Fujimori, Tokura -- Metal-Insulator Transitions, Review. Mod. Phys. vol 70, pg 1039 (1998)
3. P.A. Lee & T.V. Ramakrishnan -- Disordered electronic system, Review. Mod. Phys. vol 57, pg 287 (1985)
4. 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

1. Ashcroft & Mermin -- Solid State Physics
2. Grosso & Pastore-Parravicini -- Solid State Theory
3. Kaxiras -- Electronic Structure of Solids
4. Sutton -- Electronic Structure of Materials
5. Fulde -- Electron correlation in Molecules and Solids

PHY 603 STATISTICAL PHYSICS: 3-1-0-4

Foundations, micro-canonical, canonical and grand canonical ensembles, non-interacting systems, interacting systems, phase transitions, quantum statistics, BEC, Quantum Hall, magnetism, superconductivity.

PHY 604 QUANTUM PHYSICS (APPLICATION): 3-1-0-4

Applications of quantum mechanics to atomic physics, condensed matter physics and nuclear physics.

PHY 691 PROJECT RESEARCH – PART II

Continuation of the fifth semester project under the supervision of a Research Guide.

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