Tata Institute of Fundamental Research

Graduate School

Physics Subject Board

Course Syllabi

for

4xx Courses

Taught at TIFR-Mumbai

P-401.1 (P-4301): Astronomy and Astrophysics II

Syllabus:

Observational Techniques in Astronomy

1. Basics of Observational Astronomy: Coordinate Systems, Measures of distances & time, Formats for astronomical data, Precision & Accuracy, Statistical fluctuations and Systemic errors, Error distributions, propagation of errors
2. Telescopes: Basic parameters (Magnifying power, light gathering power, resolution, plate scale, speed), Types of telescopes (reflector, refractor, catadioptric), Optical Aberrations, Different Reflector Focii, Telescope Mounts, X-ray telescopes (focussing & non-focussing), Gamma Ray Cerenkov Telescopes, Radio Telescopes, Interferometers
3. Telescope beams, Atmospheric Effects, Active & Adaptive Optics, Speckle Interferometry
4. Astronomical Detectors : Coherent & incoherent detectors, Detector parameters, Use of semiconductors in detectors, Photomultiplier tubes, Charge Coupled Devices (CCDs): Optical & X-ray, Infrared Arrays, Bolometers, Cryogenics & Vacuum methods, Coherent Receivers, Long wavelength Spectrometers (Filter banks, Acousto Optic Spectrometers, Digital Autocorrelator, Fast Fourier Transform Spectrometers), Optical instruments: Photometers, Cameras (design with magnification), Spectrometers (Diffraction Grating, GRISM, Fourier Transform Spectrometers, Fabry Perot Etalons)
5. Basics of measurement of radiation: Intensity, Flux, Luminosity, Antenna temperature, Magnitude scale, Photometric Systems, Color indices, Basics of photometric measurements, Aperture and PSF photometry
6. Properties & Distances of Celestial Objects: Luminosity, Mass, Temperature, Distance Ladder (Primary & Secondary distance estimators), Standard Candles, Standard Sirens.
7. Spectra of electromagnetic radiation: Spectral Lines & Continuum Spectrum, Observational signatures of Thermal Bremsstrahlung, Synchrotron, Blackbody Radiation, Origin of spectral lines in astrophysical objects, equivalent width, broadening of spectral profiles, derivation of physical parameters from observed spectral lines

Radiative Processes in Astrophysics

1. Radiative transfer: Mainly recapitulation, with a few new topics, such as Radiative diffusion: Rosseland approximation
2. Preliminaries of radiative processes: Radiation spectrum, Dipole approximation of radiation.
3. Bremsstrahlung: Emission from electrons with the same speed, Thermal emission, Thermal Bremsstrahlung with absorption, typical spectrum, Relativistic Bremsstrahlung
4. Synchrotron radiation: Total emitted power, Spectrum (simple method to gain insight), Spectral index for the emission from charges with power-law energy distribution, Detailed spectrum and polarization, Observed frequency, Synchrotron self-absorption, typical spectrum
5. Compton Scattering: Scattering from electrons at rest, Inverse Compton power for single scattering, Inverse Compton spectra for single scattering, Spectrum for a power-law distribution of relativistic electrons, Repeated scatterings, the Kompaneets equation, typical spectrum

P-402.1 (P-4302): Fluid Mechanics

Syllabus:

1. Hydrodynamic limit - deriving fluid equations
2. Mass, momentum and energy conservation
3. Euler's and Bernoulli's equations for inviscid fluid equations
4. Streamfunctions for incompressible flows and exact solutions
5. Irrotational flow and velocity potential formulation
6. Vorticity dynamics
7. Boundary layers and viscosity
8. Introduction to multi-scale turbulence
9. Transport in turbulent flows

Recommended Textbooks:

1. Fluid Mechanics by Piyush Kundu

P-403.1 (P-4303): Physics and Chemistry of the Interstellar Medium

Syllabus:

1. Discovery of ISM, Cycle of Matter, Phases & Constituents of ISM
2. Continuum radiation processes
3. Hot Gas: Ionized Gas: Ionization & Recombination, HII Regions
4. Dust: Optical properties, emission, photoelectric effect, dust composition
5. Neutral Gas: Absorption lines, Curve of growth, Neutral atomic hydrogen, Diffuse ISM
6. Molecular Gas: Interstellar molecules & spectra, Molecular Clouds; Star Formation; Feedback
7. Heating & Cooling of the ISM; Two-phase equilibrium
8. Chemistry of the ISM: Gas- and grain-chemistry, Chemistry of Photodissociation regions

Recommended Textbooks:

1. The Physics & Chemistry of the Interstellar Medium: A. G. G. Tielens
2. Physics of the Interstellar & Intergalactic Medium: B. T. Draine
3. Physical Processes in the Interstellar Medium: Lyman Spitzer
4. Radiative Processes in Astrophysics: Rybicki & Lightman

P-404.1 (P-4501): Gravitation and Cosmology

Syllabus:

Gravitation

1. Gravity from Newton to Einstein
2. Why did Einstein develop the general theory of relativity?
3. Gravity is the same thing as curvature of spacetime
4. Distances, spacetime metric and the gravitational potential
5. Connection, the gravitational field, and geodesic equations
6. The Riemann curvature tensor
7. General Relativity: Einstein's field equations for the gravitational field
8. Newton's law of gravitation as a limiting case of Einstein's equations
9. The cosmological constant
10. Experimental tests of general relativity
11. Other possible theories of gravitation

Cosmology

1. The early 20th century view: Milky Way is the whole Universe
2. The discovery that there are galaxies outside the Milky Way
3. The discovery of the expansion of the Universe
4. Friedmann, Lemaitre, Robertson and Walker: Using general relativity to provide a mathematical description of the expanding universe
5. The steady state cosmology
6. 1965: Discovery of the cosmic microwave background radiation [CMB]
7. Big Bang Cosmology; Synthesis of Helium in the early universe as evidence for a hot Big Bang
8. The thermal history of the Universe
9. 1992: COBE and the discovery of temperature fluctuations in the CMB; Why are these fluctuations so significant?
10. The distribution of galaxies and the large scale structure of the universe
11. Origin and seeds of large scale structure; the connection between initial matter density perturbations and temperature fluctuations of the CMB
12. The idea of an inflationary epoch in the very early universe; inflation and the generation of seed density perturbations
13. Problems with the idea of inflation; Inflation, CMB, and WMAP
14. 1999: Discovery of faint supernovae, and the possible implication that the expansion of the universe is accelerating
15. The concept of Dark Energy; alternate possible explanations of the observations. Dark Matter and material constitution of the Universe.

Recommended Textbooks:

1. Gravitation and Cosmology by Weinberg;
2. Gravitation by Misner, Thorne and Wheeler;
3. A first course in general relativity by Schutz;
4. Gravitation by Padmanabhan; Cosmology by Dodelson;
5. The early universe by Kolb and Turner;
6. Cosmological Physics by Peacock.
7. Bibliography: http://www.astro.ucla.edu/~wright/cosmobib.html

P-405.1 (P-4818): Cosmology-I

Syllabus:

1. The expanding Universe
2. Thermal history of the Universe
3. Neutrinos Thermal dark matter
4. Big bang nucleosynthesis
5. Cosmic microwave background
6. Recombination
7. Gravitational collapse and structure formation
8. Dark energy
9. Initial conditions and inflation

P-406.1 (P-4828): Astroparticle Physics

Syllabus:

1. Basic Particle Physics: units, Lagrangians, cross sections, decays, effective theory, standard model particle content and interactions
2. Basic Cosmology: Hubble, FRW universe, distance, horizon, redshift, energy-momentum tensor, Friedmann equations, thermodynamics in expanding universe, rates of reactions, Boltzmann equations, newtonian treatment of structure formation
3. Basic Astrophysics: color-magnitude, gravitational dynamics, lensing, acceleration of charged particles
4. Dark Matter: evidence, bounds on basic properties such as mass, charge, etc. and relate physics such free-streaming length, why baryons/MOND/neutrinos are disfavored, models, productions and interactions of particle dark matter, e.g., axions, WIMPs, sterile neutrinos, searches in lab, sky, and cosmos.
5. Neutrinos: history, bounds, oscillations, role in stars and cosmology
6. Special topics if time permits (gravitational waves/high-energy astrophysics/cosmic rays)

Recommended Books:

1. Kolb and Turner (Early Universe)
2. Dodelson (Modern Cosmology)
3. Kuo and Pantaleone (Neutrinos in Physics and Astrophysics)
4. Binney and Tremaine (Galactic Dynamics)
5. Goobar and Bergstrom (Astroparticle Physics)
6. Raffelt (Stars as Labs for Fundamental Physics)
7. Bertone ed. (Particle Dark Matter)
8. Raichaudhuri (Astrophysics)

P-421.1 (P-4201): Superconductivity

Syllabus:

1. Phenomenology of Type I and Type II supercondutors (at a very phenomenological level: This is recap of the basics)

2. Basics of Quantum Field Theory: (Covering mainly techniques for second quantization, from "Pedestrian Approach to QFT" by Harris)

3. BCS theory - Formulation and applications (Including basic formulation, application to tunneling, low and high frequency electrodynamics, coherence factors)

4. Real space formulation of BCS theory- Bogoliubov de- Gennes equations (Formulation and application to Interface problems such as Andreev reflection)

5. Ginzburg-Landau theory (Formulation and Basic application.)

6. Application to G-L theory to fluctuation problems particularly in superconducting nanowires and nanoparticles

Recommended Textbooks:

1. Rose Innes and Rhoderick- Introduction to Superconductivity
2. M. Tinkham- Introduction to Superconductivity
3. J. B. Ketterson- Superconductivity
4. Harris - A Pedestrian approach to Quantum Field Theory

P-422.1 (P-4202): Transmission Electron Microscopy for nanoscale research

Syllabus:

1. Introduction of Transmission Electron Microscopy
2. Scattering: elastic scattering, inelastic scattering, beam damage
3. Instrument: electron sources, lenses and apertures, detectors, operational modes (TEM, STEM)
4. Specimen preparation
5. Diffraction: diffracted beams, diffraction from crystalline materials, indexing parallel beam diffraction, Kikuchi diffraction
6. Imaging: amplitude contrast, phase contrast, imaging of defect, high resolution TEM, image simulation and quantification
7. Spectroscopy: energy dispersive x-ray spectroscopy, electron energy loss spectroscopy, element specific imaging

P-423.1 (P-4203): Finite Size Effects in Condensed Matter Physics

Syllabus:

1. Introduction: history, basic phenomenology, scaling laws
2. Experimental techniques: synthesis and fabrication (top-down and bottom-up approaches, nanofabrication)
3. Experimental techniques: observation and characterization (electron microscopy, X-ray diffraction, light scattering, particle size analysis)
4. Atomic clusters ("bond to band" transition)
5. One dimensional nanostructures: nanorods and quantum wires
6. Two dimensional nanostructures: thin films
7. Size effects on crystal structure
8. Size effects on band structure
9. Semiconductor nanoparticles and heterostructures
10. Size effects on lattice vibrations and thermal properties
11. Surface excitations
12. Optical properties of nanostructured metals
13. Transport properties of nanostructured metals
14. Nanomechanical properties
15. Size effects in magnetism
16. Size effects in superconductivity
17. Size effects in ferroelectricity
18. Nanostructured liquids
19. Carbon-based nanostructures
20. Seminar series: nanoelectronic devices (quantum dots, single electron transistors, resonant tunneling diodes, supercapacitors…)
21. Seminar series: applications of nanomaterials in energy (solar cells, fuel cells, Hydrogen storage, batteries …)
22. Seminar series: applications of nanomaterials in environment (remediation of polluted soil and water, pollutant sensing and degradation…)
23. Seminar: applications of nanomaterials in healthcare (biosensors, targeted delivery, hyperthermia…)

Pre-Requisite*:* Basic knowledge of solid state concepts and phenomenology (crystal symmetry, reciprocal space, band structure, lattice vibrations, transport, magnetism, etc.)

P-424.1 (P-4204) Correlated Electrons

Syllabus

1. Phenomenology of Fermi liquids
   a. Quasiparticle concept
   b. Pomeranchuk stability conditions
   c. Collective excitations and zero sound
   d. Fermi liquid regime of the Kondo problem

2. Microscopic theory
   a. Response of an ideal Fermi gas
   b. Collective excitations
   c. Effect of disorder on interactions
   d. Bridging phenomenological and microscopic aspects (including Luttinger theorem, Hertz theory)

3. Beyond Fermi liquid theory
   a. Effect of Ampere forces in metals
   b. Overscreened Kondo Model and Nozières-Blandin Theory

4. Open questions
   1. Quasiparticle decay and many-body localization
   2. Marginal Fermi liquids

Recommended Textbook:

1. Statistical Physics II, Landau and Lifshitz

P-425.1 (P-4205): Condensed Matter Physics: Phenomena and Techniques

Syllabus:

1. Elements: Basic Properties
2. Elastic scattering- X-rays and neutron
   a. Atomic structure; magnetic structure
   b. Experimental technique of X-ray and neutron scattering
3. DC transport –T dependence;
   a. Metal vs insulator;
   b. Insulator- activated hopping;
   c. Metal—different T dependencies from Drude, phonon, electronelectron; SC
   d. D.C. transport measurements at low temperatures and high fields
4. Magnetic susceptibility
   a. Paramagnet,
   b. Ferromagnet,
   c. Antiferromagnet;
   d. SC; diamagnetism
   e. Basics of magnetometry
5. Transport and thermodynamic properties
6. Specific heat:
   a. Phase transition
   b. Strong correlation mass enhancement
   c. Specific heat measurements
   d. Separating various contributions from experimental specific heat data
7. Magnetotransport—longitudinal, Hall (in a metal)
   a. Electron density
   b. Quantum oscillations
   c. Hall effect measurements
   d. Determination of Fermi surface from quantum oscillations
8. Thermal transport
   a. Metal: Wiedeman Franz;
   b. Insulator; SC
   c. Measurement of thermal conductivity and thermopower
9. Spectroscopic measurements
10. Optical conductivity
    a. Drude weight;
    b. Gaps; SC; sum rules
    c. Measurement of optical conductivity at microwave and TeraHertz frequency range
11. Photoemission spectroscopy; angle resolved
    a. Electronic density of states; electronic structure
12. Inelastic scattering – Xrays and neutron (in an insulator)
    a. Phonons; Magnons,
13. Tunneling; SC; Josephson tunneling; scan probe
    a. Gaps, coherence peaks
    b. Scanning tunneling spectroscopy
14. Raman scattering for phonons - optical gaps - direct gap
15. Magnetic resonance (nuclear, electron) (in both metals and insulators)
    a. Knight shift: spin susceptibility
    b. SC singlet, triplet pairing

P-426.1 (P-4206): Photonics: Basic Concepts, Design, Fabrication and Applications

Syllabus:

1. Introduction
   a. Role of photonics in information processing covering both classical and quantum communication and computing.
   b. Present interest in all-optical devices and integrated optical circuits.

2. Photonic Crystals
   a. Concept of photonic crystals and theory of photonic crystals,
   b. Defect in photonic crystals, light manipulation using defects in photonic crystals – waveguiding, light localization in microcavities, enhancement of optical nonlinearities and all-optical devices.
   c. Numerical methods to simulate and design photonic crystals.

3. Plasmonics or Nanophotonics
   a. Concepts of surface and localized plasmon modes
   b. Ways to probe these modes;
   c. Applications of surface plasmon polaritons in waveguiding, surface enhanced raman scattering, imaging and sensing and applications of localized plasmons in lasing, sensing, enhancement in emission
   d. Nanophotonic or sub-wavelength optical components for integrated optics.

4. Metamaterials
   a. Introduction to metamaterials, theory of metamaterials,
   b. Interesting phenomena using metamaterials like negative index materials, slow light, inverse Doppler effect, cloaking.

5. Nanofabrication
   a. Fabrication techniques used for photonic crystals and metamaterials like bottom-up (based on optical techniques and self-assembly) and top-down (photo-, interference and e-beam lithography) techniques.
   b. Different techniques for deposition of thin films and etching.

6. Optical Characterization
   a. Laser spectroscopy for absorption and emission
   b. Nonlinear optical techniques
   c. Ultrafast techniques to measure various time scales governing carrier dynamics.
   d. Time resolved photoluminescence, four wave mixing, pump-probe, Hanbury Brown- Twiss, time correlated single photon counting among others.

Recommended Textbooks:

1. Photonic Crystals: Molding the flow of light by J. D. Joannopoulos, S. G. Johnson, J. N. Winn, R. D. Meade
2. Optical Properties of Photonic Crystals by K. Sakoda
3. Wave Propagation by P. Markoš, C. M. Soukoulis
4. Plasmonics by S. A. Maier

P-428.1 (P-4810): Statistical Physics II

Syllabus:

1. Phase transitions: Phenomenology, Models, Correlation functions, Mean field theory
2. Ordering: Absence in 1-d; Peierls argument, Mermin-Wagner theorem
3. Solution: 2-d Ising model:
4. Critical phenomena: Ornstein-Zernike theory, Ginzburg criterion, Scaling, Multicriticality
5. Renormalization group: Idea and phenomenology, Real-space RG, Epsilon expansion
6. Dynamics: Stochastic kinetics, Phase ordering kinetics, Lifshitz law, Dynamical critical phenomena
7. Nonequilibrium steady states: Exclusion processes, Zero-range process, Evolving interfaces, Aggregation-fragmentation processes

P-429.1 (P-4823): Topological Aspects of Quantum Matter

Syllabus:

1. Concept of quantum of conductance
2. Landauer-Buttiker approach
3. Integer quantum Hall effect
4. Tightbinding method to bandstructure calculations
5. Example of tightbinding – graphene
6. Berry curvature, Berry phase and Chern number
7. Symmetry properties of Berry curvature
8. Semiclassical implication of Berry curvature for anomalous velocity in bands
9. Dirac equation and bound states at interface
10. Su-Schiefer-Heeger model
11. Haldane model, its analysis in continuum and confined geometry
12. Kane and Mele model, its analysis in continuum and confined geometry
13. Chern number of generalized Dirac Hamiltonian
14. Topological superconductivity
15. Majorana fermions and their experimental realizations
16. Weyl fermions

P-430.1 (P-4803): Ideas and Methods in Condensed Matter Theory

Syllabus:

This course will introduce some key ideas and methods in modern condensed matter theory, with focus on trying to understand some specific examples chosen to illustrate these ideas and methods.

Core Topics:

1. Renormalization group framework
2. Effective Hamiltonians and actions
3. Spontaneously symmetry breaking and long range order
4. Topological order
5. Quenched disorder (impurity) effects.
6. Quantum phase transitions

Optional topics: (depending on time and interest)

1. Introduction to relevant theorems/bounds/arguments (Mermin-Wagner Thm Chayes-Chayes-Fisher-Spencer bound, Lieb-Schulz-Mattis Thm, Oshikawa's argument, Lieb-Robinson bound, Hastings Theorem)
2. Introduction to computational methods (Quantum Monte Carlo, Canonical Typicality, Tensor network ideas etc).

Recommended textbooks:

1. Anderson's `Basic Notions of Condensed Matter Physics'
2. Auerbach's `Interacting Electrons and Quantum Magnetism' 3.
3. Chaikin and Lubensky's `Principles of Condensed Matter Physics'
4. Goldenfeld's `Lectures on phase transitions and critical phenomena'.
5. Negele and Orland's `Quantum Many-particle Systems'
6. Sachdev's `Quantum Phase Transitions
7. Krauth's Statistical Mechanics: Agorithms and Computation

P-441.1 (P-4401): Experimental High Energy Physics

Syllabus:

1. Interaction of high energy particles with matter: heavy charged particles, electrons, photons, neutrons, hadrons, neutrinos.
2. Gaseous detectors, physical processes. Examples of types of gas detectors
   a. Ionization, drift chamber, proportional, MWPC, TPC, RPC, GEM, MicroMegas, MPGD.
3. Scintillator, photomultiplier, light guides, wavelength shifting fibres - Time of flight method, trigger.
4. Photo Diode, APD, HPD, SiPM.
5. Neutron detectors, moderator.
6. Semiconductor detectors, silicon and Si(Li), high purity germanium, Silicon vertex detector (strip/pixel)
7. Cerenkov emission, transition radiation -Threshold counter, Differential counter, PID
8. Electromagnetic Calorimeter, Hadron Calorimeter.
9. Design of High Energy Physics detectors for the following expt:
   a. Collider
   b. Fixed target
   c. Neutrino,
   d. Cosmic ray

Recommended Textbooks:

1. Introduction to experimental particle physics: Richard Fernow
2. Techniques for nuclear and particle physics experiments: W. R. Leo
3. Radiation Detection and Measurement: Glenn F. Knoll
4. Calorimeter, Energy Measurement in Particle Physics: Richard Wigmans
5. Gaseous Radiation detectors: Fabio Sauli
6. Experimental Techniques in High Energy Physics: edited by T. Ferbel

P- 442.1 (P-4402): Quantum Chromodynamics in Colliders

Syllabus:

1. Gauge Theory
2. Brief review of The Standard model including Higgs sector
3. e+q -> e+q scattering
4. Brief Review of Relativistic kinematics
5. QCD Lagrangian and various interactions
6. Deep Inelastic scattering(DIS)
7. Parton distribution function
8. e+e -> q q g scattering
9. Renormalization: Basic idea
10. QCD in DIS, scaling violation etc
11. Evolution of PDF with energy scales: DGLAP equation
12. Discussed: how to determine PDF
13. Few Physics processes at the LHC
14. Monte Carlo simulation
15. Event Generators
16. Theory of Jets

Recommended Textbooks:

1. Elementary Particle Physics: H. Halgen and A. Martin
2. QCD and Collider Physics: R.K. Ellis, W.J. Stirling and B.R. Webber
3. Collider Physics: V. Barger and R.J.N Phillips
4. Foundations of QCD: T.Muta
5. Few Review articles

P-444.1 (P-4404): Programming, Data Analysis and Simulation Techniques in High Energy Physics

Syllabus:

1. C++ Programming
   a. Basic data types, Arrays, Pointers, Loops, Conditionals, Inputs/Outputs, File handling
   b. Object oriented programming concepts and C++ classes
2. Data Analysis with ROOT
   a. Introduction, Installation, Writing of Macros, Graphs/Histograms, Fittings, Minuit
   b. ROOT Trees and handling large volumes of data
   c. ROOT Mathematical library
3. Statistical Interpretation of Data
   a. Statistical Distributions (Poisson, Gaussian, Landau), Characterizing Distributions (Mean, Median, Mode, Standard Deviation, Chi square, Confidence Intervals)
   b. Measurement Errors and Types, Error Propagation, Working with Real Data
4. Monte Carlo Simulation Method
   a. Introduction, Random Numbers, Probability Distributions, Example Applications,
   b. Writing of own simulation codes

P-445.1 (P-4405): Machine Learning in High Energy Physics

Syllabus:

Part I

1. What is Machine Learning?
2. Why Machine Leaning in High Energy Physics?
3. Linear Regression and Classification
4. Supervised and Unsupervised Learning
5. How does Supervised Learning work?
6. Overfitting of the Model
7. Bias-Variance Tradeoff
8. Regularization
9. Training and Cross Validation
10. Optimization of Cost Function

Part II

1. What is a Neural Network (NN)?
2. Feed Forward and Multilayer Perceptron NN
3. NN Optimization and Gradient Descent
4. Chain Rule and Backpropagation
5. Neural Networks in High Energy Physics
6. Decision Trees
7. Bagging, Boosting and Random Forest
8. Randomized Trees and Pruning
9. Multivariate Analysis Techniques
10. Boosted Decision Trees in High Energy Physics

Part III

1. Two Examples from High Energy Physics
2. CMS: t-channel Single Top Quark Production
3. Belle: Continuum Background Suppression

Recommended Books:

1. Pattern Recognition and Machine Learning, Christopher M. Bishop (Springer)
2. CERN Lectures on Machine Learning for High Energy Physics (online material)

P-447.1 (P-4806): Neutrino Physics

Syllabus:

1. Neutrinos in the Standard Model: discoveries, helicity, limits on masses through direct measurements
2. Atmospheric neutrino problem: solution through 2x2 neutrino mixing and oscillations
3. Solar neutrino problem and solution: modified neutrino mixing in the presence of matter, propagation through constant and variable matter density, concept of adiabaticity,Landau-Zener level crossing
4. Formulation of three-neutrino mixing, PMNS matrix, measurements of parameters, current and future experiments, possible signals of new physics through neutrino experiments
5. Neutrino interactions with matter: quasi-elastic and deep inelastic scattering, detection of neutrinos, measurements of neutrino energies and arrival directions
6. Neutrino mass generation: Dirac and Majorana masses, lepton number violation, seesaw mechanisms, radiative mass generation, exotic mass generartionmechanisms
7. Neutrinos in astrophysics and cosmology: Supernova neutrinos, relic neutrinos, neutrinos as dark matter candidates
8. The future of Neutrino Physics

Recommended textbooks:

1. "Massive Neutrinos in Physics and Astrophysics" (Mohapatra and Pal)
2. "Fundamentals of Neutrino Physics and Astrophysics" (Giunti and Kim)
3. Lecture notes available athttp://theory.tifr.res.in/~amol/nuphy/lecnotes.html

P-448.1 (P-4809): Flavour Physics

Syllabus:

1. Introduction:
   a. A brief review / history of particle physics
   b. How to read the Review of Particle Properties (Particle Data Group)
2. Charged lepton flavours:
   a. Muon energy loss, muon decay, Fermi theory
   b. Tau decays
3. The strange flavour:
   a. Decays of K mesons and branching fractions, decay constants, form factors
   b. Quark mixing, GIM mechanism, tau-theta puzzle
   c. K-Kbar mixing, CP violation, direct vs indirect CPV
4. CP violation in flavour decays:
   a. Standard Model Lagrangian, CKM matrix
   b. Neutral meson mixing and decay
   c. CPV through decay, mixing and interference
5. The flavours of beauty and charm:
   a. Decays of B mesons for CKM magnitudes, semileptonic decays, radiative decays
   b. Unitarity triangles, determination of CKM phases beta, gamma, alpha, beta_s
   c. Decays of D mesons, CP violation
   d. Effective field theories, heavy quark effective theory, soft collinear effective theory
6. Beyond Standard Model through flavors:
   a. Effect of new physics on flavour observables
   b. Observed anomalies and possible new physics explanations
   c. Model-dependent and model-independent new physics searches
7. Some added flavours:
   a. Top physics, Baryons, charmonia and bottomonia

Prerequisites:

At least one completed course in Particle Physics
Familiarity with calculating (at least) tree-level Feynman diagrams

Recommended Textbooks:

1. Review of Particle Properties (PDG)
2. "CP violation", Bigi and Sanda: available in Indian edition
3. "CP violation", Branco, Lavoura and Silva
4. The Belle-II Physics book
5. "Just a taste: lectures on flavor physics", Grossman and Tanedo
6. "Effective field theories", Petrov and Blechman

P-449.1 (P-4811): Physics of Standard Model

Syllabus:

1. Review of some of the techniques in QFT: quantum corrections, counter-terms, renormalization, renormalization group equations, etc.
2. Basics of effective field theories (EFT): examples from perturbative physics.
3. Standard Model as a renormalizable theory in the far UV.
4. EFT below the top mass; EFT below the Higgs scale — physics of precision electroweak observables; EFT below the electroweak scale -- the Fermi Theory; EFT of heavy flavour physics — NREFT and HQET; EFT below the scale of heavy flavour —the chiral perturbation theory
5. Standard Model as an EFT — linear and non-linear realisation of electroweak symmetry; SMEFT and HEFT.

Prerequisites:

Quantum Field Theory Course (P-4801)

P-461.1 (P-4601): Laser Physics

Syllabus:

PART: **Basic laser physics**

1. Simple considerations for obtaining laser action
2. Properties of laser light
3. Lasers - types, materials and designs
4. Resonators, amplification and different lasing regimes.
5. Practical aspects of lasers

PART: Ultrashort laser pulses

1. Principles of generation of short laser pulses
2. Methods of ultrashort pulse generation
3. Recent advances in femtosecond laser pulses
4. Propagation of Ultrashort laser pulses
5. Practical femtosecond lasers
6. Amplification schemes for short laser pulses
7. Nonlinear optical effects of ultrashort laser pulses
8. Measurement of ultrashort pulses

PART: Nonlinear Optics

1. Basics of optical nonlinearity (models, susceptibilities etc.)
2. NLO phenomena- 2^{nd} and 3^{rd} orders (harmonics, wave mixing, self-action effects, stimulated scattering etc.)
3. Nonlinear optical effects of /on ultrashort laser pulses.

Special Topics:

1. Amplification schemes for short laser pulses
2. Physics at short time scales (femtosecond, attosecond)

Recommended Textbooks:

1. A.E. Siegman, Lasers
2. O. Svelto, Lasers
3. A.M. Weiner, Ultrafast Optics
4. J.C. Diels and W. Rudolph, Ultrashort Laser Pulse Phenomena
5. R.W. Boyd, Nonlinear Optics
6. Born and Wolf - Principles of Optics, 7^{th} edn

P-463.1 (P-4615): Advanced Techniques in Nuclear Spectroscopy

Syllabus:

1. Overview of nuclear physics experiments
    a. Determination of basic properties of nuclei. Experimental observables and comparison with nuclear models. Examples of experiments to measure reaction cross-sections, nuclear mass, deformation and properties of excited states. Production and identification of radioactive ions and investigation of excited states of nuclei
2. Basic detectors and readout schemes
    a. Interaction of radiations with matter, detectors for gamma-rays, charged particles, neutrons and fragments. Generation of detector signals and signal processing processes. Analog and digital readout schemes. Overview of modern data acquisition systems.
3. Nuclear structure at high-spin using gamma ray spectroscopy
    a. Heavy ion fusion reactions to study high spin states of nuclei, angular distribution, angular correlation and polarization measurements to extract the spin and parity of excited states. Coincidence techniques to develop level structure. Use of large array of Compton suppressed high purity germanium detectors and associated readout scheme.
    b. Lifetime measurements for the excited states of nuclei, slow-fast coincidence, recoil distance method, Doppler shift attenuation method.
    c. Fission fragment spectroscopy for neutron rich nuclei using large gamma array and e.m. spectrometer
4. In-flight spectroscopy of rare isotopes
    a. Relativistic projectile coulomb excitation, inelastic proton scattering in inverse kinematics, nucleon removal reactions
    b. Coulomb excitation of reaccelerated exotic ion beams below barrier
5. Decay spectroscopy, Isomers and e.m. moments
    a. Proton and alpha decay of rare isotopes and heavy nuclei
    b. Beta-decay processes
    c. Identification of nuclear isomers. measure the e.m. moments.
6. Invariant mass spectroscopy
    a. Structure and resonances of exotic nuclei using invariant mass spectroscopy

P-464.1 (P-4604): Atomic Collisions: Theory and Technique

Syllabus:

1. Atomic Collisions: Basic concepts, channels, threshold; Basic collision kinematics, potential functions
2. Elastic scattering-partial wave method, Phase shift, resonances: First Born approximation, Screened Coulomb potential scattering,
3. Ionization: Models perturbed stationary state, binary-encounter and semi classical methods, features in ion and electron impact ionization, Bethe-Born approximation, semi-empirical models, Scaling rules for ionization
4. Electron-transfer: loosely bound and strongly bound electron transfer, OBKN approximation, JS (or B1) approximation, B2 approximation, scaling laws for total capture, Thomas scattering radiative electron capture, Two and Three component models in charge-changing collisions, Equilibrium charge state distribution in gases and solid-foils
5. Energy loss of ions in matter and related models
6. Thomas-Fermi model for multi electron system
7. Photoionization, Radiative recombination
8. Distorted wave model and close coupling (comparison with experiments).
9. Experimental techniques in collision physics.

Recommended Books:

2. McDaniel
3. McDowell and Coleman
4. Brandsden and Joachain

P-465.1 (P-4605): Quantum Optics

Syllabus:

1. A short review on classical optics and quantum mechanics, includes Maxwell's equations, Diffraction, Interference, Coherence, Quantized states in atoms, harmonic oscillator etc
2. Radiative transitions in atoms, Einstein coefficients, spectral linewidths and lineshapes, laser lines.
3. Quantization of light fields, coherent states, phasor diagrams, number-phase uncertainty, squeezed states, their generation and detection, photon number states
4. Photon statistics, Poissonian, sub-poissonian, super-poissonian light.
5. Photon bunching, antibunching, Hanbury Brown -Twiss experiment, single photon sources
6. Resonant light-atom interaction, weak field and strong field limit, Rabi oscillations, Bloch sphere
7. Atom cavity coupling, weak coupling, Purcell enhancement, strong coupling, cavity QED.
8. Laser cooling of atoms

Recommended Textbooks:

1. Introduction to Quantum Optics - Mark Fox
2. Introductory Quantum Optics - Gerry and Knight,
3. The Quantum Theory of Light - Rodney Loudon,
4. Quantum Optics - Marlan Scully,

P-466.1 (P-4606): Plasma Physics

Syllabus:

1. Single charged particle in E and B fields, influence of E and B fields on collection of charges, motion of a single plasma particle in E and B fields
2. Plasmas- basic concepts, Debye shielding,
3. The Vlasov, two-fluid, and MHD models of plasma dynamics
4. Different types of plasmas,
5. Streaming instabilities and the Landau problem
6. Collisionless and collisional behaviour, absorption
7. Transport phenomena,
8. Elementary description of waves in hot plasmas, and cold plasmas
9. EM wave propagation,
10. Basic magnetohydrodynamics,
11. Wave-wave and wave-particle nonlinearities
12. Laser interaction with plasmas
13. Laser interaction with inhomogenous plasmas- resonance absorption, vacuum heating and anharmonic resonance
14. Electron acceleration and relaxation
15. Kinetic theory of plasmas.

Special topics:

1. Laser interaction with plasmas,
2. Plasma instabilities.

Recommended Books:

1. Introduction to Plasma Physics and controlled fusion - Chen
2. Introduction to Plasma Physics- Goldston
3. Introduction to Plasma Theory- Nicholson
4. Principles of Plasma Physics- Krall and Trivelpiece
5. The Physics of Plasmas - Boyd and Sanderson
6. Physics of Laser-Plasma interactions- Kruer
7. The Physics of Fluids and Plasmas: An Introduction for Astrophysicists -Rai Choudhuri

P-470.1 (P-4610): Nuclear Structure and Fundamentals of Nuclear Models

Syllabus:

1. Elements of nuclear structure
    a. Nuclear deformations and its relation to different excitation modes. Pairing in nuclei, singly-closed shell, open-shell nuclei and nuclear deformation. Low-energy collective structure in doubly-even nuclei, low-energy collective structure in odd nuclei, shape coexistence, nuclear structure at high excitation energy, nuclear isomers for investigation of structure.
2. The Bohr Collective Model
    a. Coordinates and observables, harmonic spherical vibrator submodel, Wilets-Jean submodel, rigid rotor model, adiabatic Bohr model, E2 moments and transitions in the adiabatic limit, beta gamma vibrations of axial and triaxial rotors, comparison with experiments.
3. Shell Model
    a. Representation of antisymmetric states, one-body unitary transformations, isospin in nuclear physics, relationship with exchange symmetry, Coulomb energy and isobaric multiplet mass euqation, isospin symmetry and gamma-decay selection rule, nucleon-nucleon interaction, effective interactions and operators for shell model.
4. Projected Shell Model
    a. Nilsson model, BCS approximation, quasi-particle structures for odd-mass, even-even and odd-odd nuclei, Angular momentum projection techniques, Rotational matrices, Band diagram, configuration mixing calculations, comparison of computational results with experimental data for rotating nuclei.
5. Rotating nuclei and Cranking Model
    a. High spin phenomena using discrete spectroscopy, normal and exotic rotations in nuclei, tilted axis rotation, Magnetic rotational band, anti-magnetic bands, chiral rotation and wobbling modes in nuclei.
    b. Basics of cranking model for understanding the nuclear rotations.

P-471.1 (P-4611): Ultrashort Pulses and Nonlinear Optics

Syllabus:

1. General principles of lasers
2. Modulation of light waves
3. Pulse Compression
4. Mode-locking- the why and how
5. Mode-locking methods
6. Recent advances in femtosecond laser pulses
7. Measurement of ultrashort pulses
8. Nonlinear optical effects of ultrashort laser pulses
9. Propagation of ultrashort laser pulses
10. Practical femtosecond lasers
11. Amplification schemes for short laser pulses
12. Physics at short time scales (femtosecond, attosecond)

Recommended Textbooks:

2. A.E. Siegman, Lasers
3. A.M. Weiner, Ultrafast Optics
4. J.C. Diels and W. Rudolph, Ultrashort Laser Pulse Phenomena
5. P.E. Powers- Fundamentals of Nonlinear Optics
6. R.W. Boyd- Nonlinear Optics
7. Born and Wolf - Principles of Optics, 7^{th} edn

P-472.1 (P-4612): Physics of Extreme States

Syllabus:

1. Extreme states- what, where and how?
2. Properties of dense, hot plasmas
3. Laser energy absorption by matter
4. Hydrodynamic motion
5. Shocks
6. Equation of state
7. Ionization
8. Energy transport

Recommended Textbooks:

1. Extreme Physics- Colvin and Larsen
2. Extreme states- Fortov

P-473.1 (P-4613): Plasma Physics and Laser-Plasma Interactions

Syllabus:

1. Plasmas- basic concepts
2. The Vlasov, two-fluid, and MHD models of plasma dynamics
3. Motion of a single plasma particle in E and B fields
4. Elementary description of waves in plasmas
5. Streaming instabilities and the Landau problem.
6. Waves in cold plasmas
7. Waves in hot plasmas
8. Magnetohydrodynamics
9. Wave-wave and wave-particle nonlinearities
10. Laser interaction with plasmas
11. Collisional and collisionless absorption.
12. Laser interaction with inhomogenous plasmas- resonance absorption, vacuum heating and anharmonic resonance.
13. Electron acceleration and relaxation.

Prerequisites:

Basic courses in electrodynamics and statistical physics

(Knowledge of fluid dynamics would be helpful, but not necessary).

Recommended Textbooks:

1. The Physics of Fluids and Plasmas: An Introduction for Astrophysicists -Rai Choudhuri
2. Introduction to Plasma Physics and controlled fusion - Chen
3. Introduction to Plasma Physics- Goldston
4. The Physics of Plasmas - Boyd and Sanderson
5. Physics of Laser-Plasma interactions- Kruer

P-474.1 (P-4614): Selected Topics in Atomic Collisions and Technique

Syllabus:

The course will include several topics in atomic molecular collisions studied using ion sources, accelerators and e- beams. Besides the physical processes, we will also include relevant experimental techniques and demonstrations. The detection and analysis technique along with a brief introduction to the application of atomic physics in ion sources and accelerator will be included.

P-481.1 (P-4801): Quantum Field Theory I

Syllabus:

1. A Brief description of Quantum Mechanics, and symmetry transformations
2. Utilitarian Group Theory with a focus on the Lie algebra
3. Relativity, homogeneous and inhomogeneous LorentzTransformation and the Poincare algebra (with a discussion of SL(2C))
4. Classification of quantum mechanical one particle states based on transformations under Poincare group (alternatively, under SL(2C))
5. Building a theory for relativistic and Quantum mechanical system (QFT) — start with a quantum mechanical system and add ingredients for relativity bit by bit
6. Simplest QFTs with non-interacting particles: continuous and discrete symmetries
7. Understanding and calculating observables in QFT for a system with interacting particles
    a. A made-up theory of pion-nucleon interactions assisted by a turn-on/turn-off function:
        i. Scattering: Derive S-matrix; perturbation theory and Feynman rules for evaluating S-matrix; Evaluate 1->2, 2->2, 2->3 processes for examples
        ii. Using unitarity and analyticity of S-matrix to derive features in the plane of kinetic variables
        iii. Disconnect between observables and parameters in the Lagrangian: Counter-terms, Renormalization, Schemes of Renormalization — with a particular emphasis on physical renormalization scheme.
        iv. Infinities: Regularization and various schemes of regularizations — with a particular emphasis on dimensional regularization
    b. Remove the evil of turn-on/turn-off function: S-matrix in a realistic theory, Green's functions, generating functionals, and LSZ
8. The scale of renormalization and renormalization group equations
9. QFT with Fermions:
        i. Fermions without interactions: symmetries, from Weyl fermions to Dirac fermions
        ii. Fermions with interactions: calculating in a toy model of interactions with scalars: counter-terms, Feynman rules, renormalization, and renormalization group equations.

Prerequisite:

Quantum Mechanics (Vector Space formulation and Perturbation Theory), Classical Mechanics, Special Relativity

Recommended Textbooks:

1. QFT: Steven Weinberg
2. Lie groups and Lie algebra: Howard Georgi
3. QFT: Peskin and Schroeder
4. QFT: Matthew Schwartz
5. QFT: Notes from Sidney Coleman's Physics 253a

P-482.1 (P-4802): Quantum Field Theory II

Syllabus:

b. Non Abelian gauge theories
c. Quantization and renormalization, beta function
d. Symmetries and symmetry breaking
e. Anomalies
f. Wilsonian renormalization group
g. Phase transitions and critical exponents from anomalous dimensions
h. Wilson Fisher fixed point
i. Non-perturbative aspects.

P-483.1 (P-4804): String Theory I

Syllabus:

2. A discussion of 2 d conformal field theory
3. Quantization of the free string
4. BRST quantization and ghosts
5. Vertex operators
6. Development of the formula for string scattering amplituteds
7. The relationship between worldsheet RG flows and spacetime effective actions
8. D branes
9. T-duality
10. Unitarity and infrared divergences in superstring amplitudes
11. High tempertature behaviour of string theory
12. The generalization of all of the above to the 5 10-d superstrings (including a discussion of picture changing) spacetime effective actions for the superstring and string - string duality.

P-484.1 (P-4805): How to do back of the envelope calculations

Syllabus:

1. Dimensional Analysis
   a. A couple of examples of non-trivial systems treated in dimensional analysis;
   b. Conversion of units and the meaning of dimensionful "constants of nature"
   c. Use of dimensional analysis in converting equations to dimensionless form
   d. The use of dimensional analysis in comparing the importance of different physical effects on a system.

2. Statistical inference
   a. Random sampling, bias and estimation;
   b. Bayes' theorem and inference from observations;
   c. The central limit theorem and exceptions;
   d. Covariance,
   e. Regression and reduction of variables;
   f. Fitting;
   g. Classification.

3. Approximation methods
   a. Solutions of equations, exploiting approximate symmetries, perturbation;
   b. Quick estimates of integrals, approximate solutions of ODEs;
   c. Exploiting linearity, using integral transforms, inverse transformations;
   d. Highly oscillatory integrals, asymptotic expansions, steepest descent

4. Searching data bases for information
   a. Hands-on introduction to major databases, using them for literature surveys, finding most important papers

5. Example problems
   a. Several problems where estimates of effects are used to extract dimensional quantities, unnecessary scales are removed, and simple models are written, the model is solved, and perturbations in the remaining small effects are set up.

Recommended Books:

1. Dimensional Analysis - Barenblatt,
2. How to Solve It - Polya,
3. Qualitative Methods in Quantum Theory - Migdal,
4. Surprises in Theoretical Physics - Peierls,
5. Scaling Concepts in Polymer Physics - de Gennes,

P-486.1 (P-4808): The Stochastic Thermodynamics of Computation

Syllabus:

1. Historical: Szilard heat engine, Negentropy, Landauer's principle, reversible computation, ballistic computation, Smoluchowski-Feynman ratchet and pawl, flashing ratchets.
2. Stochastic thermodynamics (from Seifert's book on the arXiv): Langevin equation, Fokker-Planck equation, stochastic energetics, stochastic entropy.
3. Geometric stochastic thermodynamics: Brownian motion on a manifold, covariant formulations of the Langevin equation and Fokker-Planck equation.
4. Recent work: Axiomatic descriptions of the Fokker-Planck equations, physics of the bit, finite-time versions of Landauer's principle by Aurell et al., batteries, catalysis, cost of computing.

P-487.1 (P-4812): General Theory of Relativity

Syllabus:

1. Equivalence principle
   a. Accelerated frames and gravity, free particle eqns in Cartesian coordinates become - geodesic eqns in general coordinates, introduction to Riemann normal coordinates
2. Mathematical framework
   a. Differentiable manifolds (coordinate charts), curves on manifolds, vectors (generalizing velocity vectors), tensors, differential forms. Integration on manifolds
   b. Metric tensor. Infinitesimal isometries: Killing form. Connection coefficients (non-tensor); geodesic eqns. Metric compatible connection; Curvature tensor; expression in terms of connection coefficients. Calculation of connection and curvature. Vierbeins, spin connection
3. Motion of particles in a fixed geometry:
   a. Solving geodesic eqns. (a) direct, (b) action principle (square root/quadratic). Isometry - conserved quantities. Motion of fields in a fixed geometry: scalar fields, electromagnetic fields [advanced: Dirac fields, using vierbeins and spin connection]
4. Coupled dynamics of particle/fields and geometry:
   a. Einstein eqn.: geometry determined by stress tensor; stress tensor determined by metric Einstein-Hilbert action principle: variational principle; Gibbons-Hawking boundary term.
5. Spherical solution of Einstein equation: (in empty space)
   a. Schwarzschild metric (Birkhoff's theorem). Physical situation: exterior geometry of spherical stars. (in presence of perfect fluid stress tensor): Form of spherical stress tensor of a fluid; eqn. of state [EOS] (pressure in terms of density); re-solve Einstein eqns in terms of parameters of EOS.
   b. Spherical soln. (of Einstein-Maxwell eqn.): Reissner-Nordstrom. Physical situation, axially symmetric soln. of Einstein eqn.: Kerr soln. Physical situation: exterior of a rotating star. Charged, rotating geometry: Kerr-Newman soln.
6. Black holes:
   a. Schwarzchild soln, null lines and causal structure. Maximal analytic extension: Eddington-Finkelstein coord., Kruskal coord., Penrose dgm; the eternal black hole, Einstein-Rosen wormhole.
   b. Causal structure of black holes with RN and Kerr black holes. Oppenheimer Snyder solution for gravitational collapse into a black hole.
7. Cosmology:
   a. Perfect cosmological principle, isotropy and homogeneity --> maximal symmetry of space. Maximal symmetry of space-time: flat space time, de Sitter, anti de Sitter. Causal structure and Penrose diagram of de Sitter.
   b. Maximal symmetry of space: Coordinate system, ansatz for metric and for perfect fluid stress tensor: Friedmann soln., Eqn. of state. Various types: matter, radiation, vacuum energy (cosmological const.). For a given type of matter: full time-dependent soln. Time-dependent soln. for mixed initial composition - age of the universe in this case. Cosmological history of Big bang universe. Problems with the Big bang universe: horizon problem, flatness problem. Inflation as a soln. Simple model of inflation; inflaton potential; slow roll. Initial perturbations, growth, structure formations (in brief).

Recommended Textbooks:

1. Carroll.
2. Weinberg
3. Landau-Lifshitz
4. Misner-Thorne-Wheeler (MTW)
5. Wald

P-488.1 (P-4826): Group Theory and Topology

Syllabus:

Group Theory:

1. Examples of Lie algebras:
2. SO(3), SU(2): Angular momentum, hydrogen atom, Pauli spinor, Wigner-Eckart;
3. SU(3): Quarks and hadrons; SO(3,1): Dirac equations
4. Structure of Lie algebras: Simple roots and Cartan Matrix. Dynkin diagrams
5. Classical Lie algebras (SU(n), SO(n), Sp(n)); exceptional Lie algebras.
6. Elements of representation theory:
7. Casimir Operators and Freudenthal's Formula; Weyl Group; Weyl's Dimension Formula
8. Reducing product representations; Young Tableaux; subalgebras and branching rules
9. Elements of finite groups and their representations. Applications to molecules and crystals etc.

Topology in Physics:

1. Kink soliton, vortices, strings, spin models, monopoles (Dirac, BPST), instantons, anomalies.

Recommended Textbooks:

Group theory

1. Cahn: Semi-simple Lie algebras and their representations
2. Georgi: Lie Algebras in Particle Physics

Topology

1. Polyakov: Particles, gauge fields and strings
2. Weinberg: Quantum field theory
3. Parisi: Statistical Field theory
4. Eguchi, Gilkey and Hanson: Physics reports