Semester VII

MAJOR COURSE- MJ 16	Quantum Mechanics-II	(Theory Credit -03) (Total Marks=60+15)

Course Objective:

1. To deepen understanding of quantum mechanics through the formalism of linear vector spaces, Hilbert spaces, and Dirac notation.
2. To explore the theory of angular momentum in quantum systems and its connection to symmetry, invariance, and conservation laws.
3. To provide an in-depth study of scattering theory, including partial wave analysis, Born approximation, and the use of Green's function.
4. To introduce approximation methods in quantum mechanics, including perturbation theory, WKB approximation, and Fermi's Golden Rule.
5. To study the behavior of identical particles, including symmetrization postulates and the addition of angular momentum.
6. To analyze relativistic quantum mechanics using the Klein-Gordon and Dirac equations and understand their physical implications.
7. To understand the process of field quantization and apply it to scalar, electromagnetic, and Dirac fields.

Course Outcomes:

Upon completion of the course, students will be able to:

1. Apply the formalism of linear vector spaces and Dirac notation to quantum states, operators, and observables.
2. Analyze and solve problems involving angular momentum and understand its relationship to symmetry and conservation laws.
3. Calculate scattering cross-sections and apply partial wave analysis, Born approximation, and Green's function in scattering problems.
4. Utilize approximation methods like perturbation theory, WKB, and Fermi's Golden Rule for solving quantum mechanical systems.
5. Understand the behavior of identical particles, apply symmetrization, and use Clebsch-Gordon coefficients for angular momentum addition.
6. Solve the Klein-Gordon and Dirac equations and interpret their applications in relativistic quantum mechanics.
7. Quantize scalar, electromagnetic, and Dirac fields and understand the role of symmetries and conservation laws in field theory.

Course Contents:

Review of Linear Vector Spaces (03 HRS): Linear vector spaces, Hilbert space, basis and orthogonality, Dirac notation (bra-ket formalism), inner and outer products, completeness relation, and operator representation.

Theory of Angular Momentum (05 HRS): Symmetry, invariance, and conservation laws, relation between rotation and angular momentum, commutation relations, matrix representations.

Scattering Theory (10 HRS): Differential and total scattering cross-sections, partial wave analysis, simple applications (e.g., Rutherford scattering), Green's function and its use in scattering theory, Born approximation and its validity, and simple applications. Emphasis on partial wave expansion in scattering problems.

Approximation Methods (09 HRS): Time-independent perturbation theory (non-degenerate and degenerate), Zeeman effect (normal), Stark effect, variational method (applications to helium atom), WKB approximation; time-dependent perturbation theory, Fermi's Golden Rule.

Identical Particles (04 HRS): Permutation symmetry, symmetrisation postulates, Slater determinant, addition of angular momentum, Clebsch-Gordon coefficients.

Relativistic Quantum Mechanics (07 HRS): Klein-Gordon equation, Dirac equation, Dirac matrices, spinors, positive and negative energy solutions, non-relativistic limit of the Dirac equation.

Field Quantization (07 HRS): Lagrangian density and equation of motion for fields, symmetries and conservation laws, Noether's theorem, canonical quantization of scalar fields, complex scalar fields, electromagnetic field, and Dirac field; problems in quantizing the electromagnetic field.

Reference Books:

1. Relativistic Quantum Mechanics – J.D. Bjorken and S.D. Drell, 1964, McGraw-Hill.
2. Relativistic Quantum Fields – J.D. Bjorken and S.D. Drell, 1965, McGraw-Hill.
3. A First Book on Quantum Field Theory – Amitabha Lahiri and P.B. Pal, 2005, Narosa Publishing House.
4. Modern Quantum Mechanics – J.J. Sakurai and Jim Napolitano, 2nd Edition, 2017, Cambridge University Press.
5. Principles of Quantum Mechanics – R. Shankar, 2nd Edition, 1994, Springer.
6. Quantum Mechanics (Volume 1 & 2) – Claude Cohen-Tannoudji, Bernard Diu, and Frank Laloë, 1977, Wiley.
7. Quantum Field Theory in a Nutshell – A. Zee, 2nd Edition, 2010, Princeton University Press.
8. Advanced Quantum Mechanics – Franz Schwabl, 4th Edition, 2008, Springer.
9. Scattering Theory: The Quantum Theory of Nonrelativistic Collisions – John R. Taylor, 1972, Dover Publications.
10. Lectures on Quantum Mechanics – Ashok Das, 2nd Edition, 2012, World Scientific Publishing.

MAJOR COURSE- MJ 16	Quantum Mechanics-II	(Practical Credit -01) (Total Marks=25)

1. To perform computational simulations of quantum states, operators, and inner products using matrix representations.
2. To verify the commutation relations for angular momentum operators and compute matrix representations for spin systems.
3. To simulate and compute partial wave expansions for a scattering potential, calculating differential and total cross-sections.
4. To apply the Born approximation to a scattering potential and compare the results with exact solutions.
5. To calculate the energy shifts of an atom due to external magnetic and electric fields using time-independent perturbation theory.
6. To use the variational method to approximate the ground state energy of the helium atom.
7. To compute the transmission and reflection coefficients for quantum mechanical tunneling using the WKB approximation.
8. To calculate and visualize Clebsch-Gordon coefficients and use them in adding angular momentum for composite systems.
9. To solve the Dirac equation for a free particle and explore the physical significance of negative energy solutions.
10. To simulate the quantization of the electromagnetic field and study the creation and annihilation of photon states.

Reference book

1. Experiments in Modern Physics – Adrian C. Melissinos, Jim Napolitano
2. Advanced Practical Physics for Students – B.L. Worsnop, H.T. Flint
3. Computational Quantum Mechanics – Joshua Izaac, Jingbo Wang
4. Quantum Mechanics Using Computer Algebra – Willi-Hans Steeb, Yorick Hardy
5. A Student's Guide to Python for Physical Modeling – Jesse M. Kinder, Philip Nelson

MAJOR COURSE- MJ 17	Statistical Mechanics	(Theory Credit -03) (Total Marks=60+15)

Course Objective:

1. To introduce the fundamental principles of classical and quantum statistics, including probability theory, phase space, and statistical equilibrium.
2. To explore the Maxwell-Boltzmann distribution and its applications to thermodynamic quantities of ideal gases, including the equi-partition theorem and Gibbs' paradox.
3. To understand quantum statistics and study Bose-Einstein and Fermi-Dirac statistics, ideal gases, and applications like black body radiation and Bose-Einstein condensates.
4. To provide insight into irreversible processes, random walks, Brownian motion, and Langevin equation.
5. To analyze fluctuations, the fluctuation-dissipation theorem, and applications of quantum statistics in the classical limit.
6. To investigate the concept of thermodynamic fluctuations and their impact on physical systems through Fourier analysis and Onsager relations.

Course Outcomes:

Upon completion of the course, students will be able to:

1. Understand and apply classical statistical mechanics principles, including phase space, ensembles, and statistical equilibrium.
2. Derive and apply the Maxwell-Boltzmann distribution to ideal gases and paramagnetism, and calculate thermodynamic quantities using the canonical distribution.
3. Analyze quantum ideal gases using Bose-Einstein and Fermi-Dirac statistics, and understand applications such as Bose-Einstein condensates and white dwarf stars.
4. Study irreversible processes and the role of fluctuations in thermodynamics, including random walk theory and Brownian motion.
5. Apply the fluctuation-dissipation theorem and Fourier analysis of random functions to analyze the impact of fluctuations in physical systems.
6. Solve problems related to quantum statistics in the classical limit and interpret the behavior of systems in this regime.

Course Contents:

Classical Statistics (10 HRS): Probability calculations, Phase space, Ensembles and its classifications, Basic postulates, Behavior of density of states, Statistical Equilibrium, Liouville theorem, Irreversibility and conditions of equilibrium, Reversible and irreversible processes.

Maxwell Boltzmann Statistics (12 HRS): Maxwell-Boltzmann Distribution, Simple applications of the canonical distribution–Paramagnetism, Molecule of an ideal gas in the presence of gravity, Partition function of ideal gas and their properties, Calculation of thermodynamic quantities of ideal Mono atomic gas, Gibbs' paradox, Equi-partition theorem.

Quantum Statistics (08 HRS): Quantum ideal gas, Identical particles and symmetry requirements, Quantum distribution functions, Bose - Einstein statistics, Ideal Bose gas, black body radiation, Bose - Einstein condensate ion, specific heat of Ideal Bose gas.

Fermi-Dirac statistics (08 HRS): Fermi-Dirac distribution, Ideal Fermi gas, properties of simple metals, Pauli paramagnetism, electronic specific heat, White-Dwarf Star, Chandrasekhar Mass Limit, Quantum statistics in the classical limit.

Irreversible processes and fluctuations (07 HRS): Random walk in one dimension, Brownian motion, Langevin equation, Fluctuation dissipation theorem, Einstein relation, Fourier analysis of random functions, Wiener- Khintchine relations Nyquist's theorem, Fluctuations and Onsager relations.

Reference Books:

1. Fundamentals of Statistical and Thermal Physics, F Reif, First Indian Edition, Levant Books, 2010.
2. Statistical Mechanics, K Huang, Wiley Eastern Limited, New Delhi, 1963.
3. Statistical Mechanics, RK Pathria and PD Beale,3 rd Edition, Academic Press (Oxford), 2011.
4. Introduction to Statistical Physics, Silvio R A Salinas, Springer, 2001.
5. Fundamentals of Statistical Mechanics, BB Laud, 5 th Edition, New Age International Publication, 2015.
6. An introduction to statistical thermodynamics, Terrel Hill, Courier corporation, 1986.
7. Principles of statistical Mechanics, Richard Tollman Claredon Press, 1979.
8. An introduction to Thermodynamics and Statistical Mechanics, 2nd Edition, Cambridge Uni Press, 2013.
9. Statistical mechanics, McQuarrie, Donald A, New York: Harper & Row, 2nd edition, 2000.

MAJOR COURSE- MJ 17	Statistical Mechanics	(Practical Credit -01) (Total Marks=25)

Use C/C++/Scilab/Python/other numerical simulations for solving the problems based on Statistical Mechanics like:

1. Computational analysis of the behavior of a collection of particles in a box that satisfy Newtonian mechanics and interact via the Lennard-Jones potential, varying the total number of particles N and the initial conditions:
   a) Study of local number density in the equilibrium state (i) average; (ii) fluctuations
   b) Study of transient behavior of the system (approach to equilibrium)
   c) Relationship of large N and the arrow of time
   d) Computation of the velocity distribution of particles for the system and comparison with the Maxwell velocity distribution.

2. Plot the probability of various macrostates in coin-tossing experiment (two level system) versus number of heads with 4, 8, 16 coins etc.
3. Computation of the partition function Z(b) for the systems with a finite number of single particle levels (e.g., 2 level, 3 level etc.) and finite number of non-interacting particles N under Maxwell-Boltzmann/ Fermi-Dirac/Bose Einstein statistics:
   a) Study the behavior of Z(b), average energy, Cv, and entropy and its dependence upon the temperature, total number of particles N and the spectrum of single particle energy states.
   b) Plot the probability of occupancy of all the states w.r.t. temperature.

4. Plot the Maxwell speed distribution function at different temperatures in a 3-dimension system. Calculate the average speed, root mean square and most probable speed
5. Plot Specific Heat of Solids w.r.t temperature
   a) Dulong-Petit law,
   b) Einstein distribution function
   c) Debye distribution function

6. Plot the following functions with energy at different temperatures
   a) Maxwell-Boltzmann distribution
   b) Fermi-Dirac distribution
   c) Bose-Einstein distribution

7. Plot the distribution of particles w.r.t. energy (dN/de versus e) in 3 Dimensions for
   a) Relativistic and non-relativistic bosons both at high and low temperature.
   b) Relativistic and non-relativistic fermions both at high and low temperature.

8. Plot Planck's law of Black body radiation w.r.t. wavelength/frequency at different temperatures. Compare it with Rayleigh-Jeans Law and Wien's distribution law for a given temperature.

MAJOR COURSE- MJ 18	Nuclear and Particle Physics	(Theory Credit -03) (Total Marks=60+15)

Course Objective:

1. To introduce the general properties of nuclei, including their intrinsic properties such as mass, radius, binding energy, and nuclear excitations.
2. To study various nuclear models, including the liquid drop model, semi-empirical mass formula, and the shell model, and understand nuclear stability and the concept of nuclear forces.
3. To understand the processes of radioactive decay, including alpha, beta, and gamma decays, and apply theories such as the Gamow factor and Geiger-Nuttall law.
4. To explore nuclear reactions, their kinematics, conservation laws, and reaction types, including compound and direct reactions, resonance, and Coulomb scattering.
5. To analyze the interaction of nuclear radiation with matter, including ionization energy loss, Cerenkov radiation, and gamma ray interaction mechanisms.
6. To introduce various nuclear radiation detectors, their principles, and applications, including gas detectors, scintillation detectors, and semiconductor detectors.
7. To study particle accelerators and their use in nuclear and particle physics experiments, with emphasis on accelerators available in India.
8. To explore particle physics, including particle interactions, symmetries, and conservation laws, and introduce the concept of quark models and color quantum numbers.

Course Outcomes:

Upon completion of the course, students will be able to:

1. Understand and explain the general properties of nuclei, including binding energy, angular momentum, parity, and nuclear magnetic moments.
2. Apply nuclear models such as the liquid drop model and shell model to explain nuclear stability and behavior, and interpret nuclear magic numbers and forces.
3. Analyze radioactive decay processes (alpha, beta, gamma) and their corresponding kinematics, and apply decay laws in practical scenarios.
4. Understand and compute the kinematics of nuclear reactions, Q-values, reaction rates, and cross-sections, and differentiate between various types of reactions.
5. Explain the interaction of nuclear radiation with matter and apply the Bethe-Bloch formula, Compton scattering, and pair production to various physical situations.
6. Identify and compare different types of nuclear radiation detectors and their applications in detecting charge particles, photons, and neutrons.
7. Describe the working principles of particle accelerators and their role in nuclear and particle physics research, with an understanding of accelerator facilities in India.
8. Understand the symmetries and conservation laws in particle physics, including concepts such as quark model, baryon and lepton numbers, iso spin, and gluons, and apply them to analyze particle interactions.

Course Contents:

General Properties of Nuclei (07 HRS): Constituents of nucleus and their Intrinsic properties, quantitative facts about mass, radii, charge density (matter density), binding energy, average binding energy and its variation with mass number, main features of binding energy versus mass number curve, N/A plot, angular momentum, parity, magnetic moment, electric moments, nuclear excites states.

Nuclear Models (06 HRS): Liquid drop model approach, semi empirical mass formula and significance of its various terms, condition of nuclear stability, two nucleon separation energies, evidence for nuclear shell structure, nuclear magic numbers, basic assumption of shell model, concept of mean field, residual interaction, concept of nuclear force.

Radioactive Decay (06 HRS): (a) Alpha decay: basics of α-decay processes, theory of α-emission, Gamow factor, Geiger Nuttall law, α-decay spectroscopy. (b) β-decay: energy kinematics for β-decay, positron emission, electron capture, neutrino hypothesis. (c) Gamma decay: Gamma rays emission & kinematics, internal conversion.

Nuclear Reactions (05 HRS): Types of Reactions, Conservation Laws, kinematics of reactions, Q-value, reaction rate, reaction cross section, Concept of compound and direct Reaction, resonance reaction, Coulomb scattering (Rutherford scattering).

Interaction of Nuclear Radiation with matter (05 HRS): Energy loss due to ionization (Bethe-Bloch formula), energy loss of electrons, Cerenkov radiation. Gamma ray interaction through matter, photoelectric effect, Compton scattering, pair production, neutron interaction with matter.

Nuclear Radiation Detectors (07 HRS): Behavior of ion pairs in electric field, Gas detectors: estimation of electric field, mobility of particle, for ionization chamber and GM Counter. Basic principle of Scintillation Detectors and construction of photo-multiplier tube (PMT). Semiconductor Detectors (Si and Ge) for charge particle and photon detection (concept of charge carrier and mobility), neutron detector.

Particle Accelerators (03 HRS): Accelerator facility available in India: Van-de Graaff Generator (Tandem accelerator), Linear accelerator, Cyclotron, Synchrotrons.

Particle Physics (06 HRS): Particle interactions; basic features, types of particles and its families. Symmetries and Conservation Laws: energy and momentum, angular momentum, Parity, Baryon number, Lepton number, Isospin, Strangeness and Charm, Concept of quark model, Color quantum number and gluons.

Reference Books:

1. Nuclear Physics-An introduction, W. E. Burcham, 2/e, Longman Group Limited 1973
2. Introductory nuclear Physics by Kenneth S. Krane (Wiley India Pvt. Ltd., 2008).
3. Concepts of nuclear Physics by Bernard L. Cohen. (Tata McGraw Hill, 1998).
4. Introduction to the Physics of nuclei & particles, R.A. Dunlap. (Thomson Asia, 2004).
5. Introduction to High Energy Physics, D.H. Perkins, Cambridge Univ. Press
6. Introduction to Elementary Particles, D. Griffith, John Wiley & Sons
7. Quarks and Leptons, F. Halzen and A.D. Martin, Wiley India, New Delhi
8. Basic ideas and concepts in Nuclear Physics - An Introductory Approach by K. Heyde (IOP-Institute of Physics Publishing, 2004).

MAJOR COURSE- MJ 18	Nuclear and Particle Physics	(Practical Credit-01) (Total Marks=25)

1. Demonstration of presence of Static Electricity.
2. Demonstration of phenomenon of Corona Discharge.
3. To determine the plateau and optimal operating voltage of a Geiger-Müller.
4. To determining the resolving (dead) time τ of a Geiger – Muller counter.
5. determining the efficiency of a geiger-muller counter.
6. determining the half life of a radio isotope using geiger – muller counter.
7. Experiment with Alpha Scintillation Counter.

MAJOR COURSE- MJ 19	Solid State Physics – II	(Theory Credit -03) (Total Marks=60+15)

Course Objective:

1. To introduce the basic concepts of semiconductors, including intrinsic and extrinsic semiconductors, energy bands, and carrier concentration.
2. To study the advanced phenomena in semiconductors, such as Schottky barriers, quantum Hall effect, optical properties, and photovoltaic effects, and their technological significance.
3. To explore the magnetic properties of materials, including diamagnetism, paramagnetism, ferromagnetism, antiferromagnetism, and ferrimagnetism, along with their underlying mechanisms and applications.
4. To understand the phenomenology of superconductivity, including critical temperature, Meissner effect, and the classification of Type I and Type II superconductors.
5. To discuss the microscopic theory of superconductivity (BCS theory) and its implications for understanding the behavior of superconducting materials.
6. To examine the thermodynamic and magnetic properties of superconductors, and explore applications of superconductivity in technology, including SQUIDs, Josephson effects, superconducting magnets, and cryogenic techniques.
7. To investigate the future prospects and challenges of superconductivity, particularly in relation to power transmission and technological advancements.

Course Outcomes:

Upon completion of the course, students will be able to:

1. Understand the fundamental properties of semiconductors, including the behavior of carrier concentration, mobility, Fermi levels, and temperature dependence in both intrinsic and extrinsic semiconductors.
2. Analyze and explain advanced semiconductor phenomena, such as Schottky barriers, quantum Hall effect, excitons, and the photovoltaic effect, and their practical applications in devices like solar cells.
3. Demonstrate a comprehensive understanding of magnetism in materials, including the concepts of diamagnetism, paramagnetism, ferromagnetism, and ferrimagnetism, and apply these to real-world magnetic materials.
4. Understand the phenomenology of superconductivity and explain the significance of the Meissner effect, critical temperature, and the differences between Type I and Type II superconductors.
5. Apply BCS theory to explain superconductivity and understand its implications for the behavior and properties of superconducting materials.
6. Analyze the thermodynamic and magnetic properties of superconductors, and apply this knowledge to understand the functioning of superconducting devices such as SQUIDs and Josephson junctions.
7. Evaluate the technological applications of superconductivity, including its use in magnetic resonance imaging (MRI), power transmission, and the challenges associated with the development of practical superconducting materials.
8. Investigate the future prospects of superconductivity in advanced technologies, and critically assess the challenges that need to be overcome for widespread practical application.

Course Contents:

Basics of Semiconductors (10 HRS): Introduction to semiconductors: intrinsic and extrinsic semiconductors, energy bands in semiconductors, carrier concentration and mobility, effective mass and its significance, impurity band conduction and doping effects, p-n junctions:

formation and behavior, electrical conductivity in semiconductors, Fermi level and its position in different semiconductors, temperature dependence of carrier concentration.

Advanced Semiconductor Phenomena (10 HRS): Schottky barrier and its applications, quantum Hall effect and its significance, optical properties of semiconductors, absorption and emission spectra, excitons and their role in semiconductors, photovoltaic effect and solar cells, dielectric properties of semiconductors, ferroelectric and displasive modes in semiconductors, magneto-optic effects in semiconductors.

Magnetism in Materials (10 HRS): Overview of magnetic properties in materials, dia- and para-magnetism: classical and quantum treatments, Curie-Weiss law and its extension to different materials, Van Vleck and Pauli paramagnetism, ferro- and anti-ferromagnetism: concepts and differences, ferrimagnetism: definition and materials, exchange interaction in magnetic materials, spin waves and their significance, magnetic resonance and its applications.

Superconductivity Phenomenology (08 HRS): Discovery and experimental results of superconductivity, critical temperature and its dependence on material, Meissner effect and its significance, Type I and Type II superconductors, London's equation and penetration depth, isotope effect in superconductors, high-temperature superconductivity: an overview, superconducting materials and their applications, microscopic theory of superconductivity (BCS theory).

Superconductivity and Applications (07 HRS): Thermodynamic properties of superconductors, magnetic properties in superconductors, superconducting devices: SQUIDs and applications, Josephson effect and its technological implications, superconducting magnets and their use in MRI, cryogenic cooling techniques for superconductors, application of superconductivity in power transmission, future prospects of superconductivity in technology, challenges in the development of practical superconductors.

Reference Books:

1. Introduction to Solid State Physics, Charles Kittel, 8th Edition, 2004, Wiley India Pvt. Ltd.
2. Introduction to Solid State Physics, Arun Kumar, PHI
3. Elements of Solid-State Physics, J.P. Srivastava, 4th Edition, 2015, Prentice-Hall of India
4. Introduction to Solids, Leonid V. Azaroff, 2004, Tata Mc-Graw Hill
5. Solid State Physics, M.A. Wahab, 2011, Narosa Publications
6. Solid-state Physics, H. Ibach and H. Luth, 2009, Springer
7. Solid State Physics, Rita John, 2014, McGraw Hill
8. Elementary Solid State Physics, 1/e M. Ali Omar, 1999, Pearson India.

MAJOR COURSE- MJ 19	Solid State Physics – II	(Practical Credit -01) (Total Marks=25)

1. Band Gap Determination – Measurement of the energy band gap of semiconductors using optical absorption.
2. Intrinsic and Extrinsic Semiconductor Conductivity – Study of temperature dependence of conductivity in intrinsic and extrinsic semiconductors.
3. Hall Effect in Semiconductors – Determination of carrier concentration, Hall coefficient, and mobility in doped semiconductors.
4. p-n Junction Characteristics – Study of I-V characteristics of a p-n junction diode in forward and reverse bias.
5. Schottky Barrier Characteristics – Measurement of the Schottky barrier height and its rectifying behavior.
6. Photoconductivity in Semiconductors – Study of photoconductivity and carrier recombination in a semiconductor.
7. Dielectric Constant Measurement – Determination of dielectric constant and loss tangent in ferroelectric materials.
8. Hysteresis in Ferroelectric Materials – Study of P-E loop and coercivity in ferroelectrics.
9. Magnetic Susceptibility of Paramagnetic Materials – Study of Curie-Weiss law using a paramagnetic salt.
10. Magnetization in Ferromagnetic Materials – Measurement of magnetization and saturation in ferromagnetic materials.
11. Resonance Absorption in Magnetic Materials – Study of electron spin resonance (ESR) or nuclear magnetic resonance (NMR).
12. Superconductivity – Critical Temperature Measurement – Determination of transition temperature in a superconducting material.
13. Meissner Effect Demonstration – Observation of the expulsion of magnetic field from a superconductor.

Reference books

1. Practical Physics – G.L. Squires
2. Advanced Practical Physics for Students – B.L. Worsnop & H.T. Flint
3. Experimental Solid State Physics – R. Srivastava