Modern Physics - *Learning objectives*

The course is organized in five sections:

A	General introduction and Relativity Theory
B	Statistical physics and thermodynamics primer: the entropy concept, the first and second laws of thermodynamics, Boltzmann's probability distribution and statistical definition of entropy, and Maxwell's velocity distribution
C	The birth of the old quantum mechanics
D	De Broglie's wave-particle dualism, Heisenberg's uncertainty relation, Schrödinger's wave mechanical approach to atomic energies and Born's probability interpretation of his equation.
E	Working with the Schrödinger equation and the alternative bra-ket notation by Dirac. Particle in a box, expectation values, harmonic oscillator, angular momentum.

For each section I have defined the following primary learning objectives:

Section	After this section you will (among other things) be able to:
A	• *explain why we call relativity theory and quantum mechanics "Modern Physics";* • *define the principle of relativity, explain its name, and account for some key versions of it in the history of physics;* • *cite Einstein's postulates at the foundation of special relativity theory and define the concepts Lorentz contraction, time delation, space-time and four-vector;* • *explain the meanings of Galilean and Lorentz transformations and write the corresponding equations;* • *describe the Michelson-Morley experiment and discuss its consequences for the classical Newtonian mechanics world view and for the development of Einstein's relativity theory;* • *explain why simultaneity becomes a poorly defined concept at motion close to the speed of light by considering how fast information can travel;* • *calculate the relativistic Doppler shift of light for the cases that the source approaches and recedes from, respectively, the receiver;* • *write the equations for momentum, energy and mass for matter moving at speeds approaching that of light;* • *distinguish conserved quantities from invariants;* • *account for the essence of some classic apparent paradoxes of relativity theory and resolve them;* • *define the principle of equivalence of general relativity and apply it, for instance in applying the gravitational Doppler shift.*
B	• *define the concept entropy and account for its role in the free energy and in the condition of thermodynamic equilibrium;* • *formulate the first and second laws of thermodynamics;* • *write Boltzmann's statistical definition of entropy;* • *apply the Boltzmann distribution (the Canonical ensemble) to establish the probability of a certain state;* • *distinguish probability and probability density (=probability distribution function), and formulate the integral to calculate the former from the latter;* • *account for the essence of Maxwell's kinetic theory of gases, leading to his famous velocity distribution.*

Section	After this section you will (among other things) be able to:
C	• *account for the empirical data on Black Body radiation, the resemblance of the emission curves with those of the Maxwell velocity distribution and the reason for the failure of the Rayleigh-Jeans approach (leading to the ultraviolet catastrophe);* • *define the concept phenomenological theory;* • *account for Max Planck's phenomenological explanation of Black Body radiation based on the relation between temperature, energy and entropy and an interpolation between the Wien and Rayleigh-Jeans formulae for Black Body radiation;* • *demonstrate how a derivation of this phenomenological result using the Boltzmann probability distribution leads to the introduction of the quantum of action;* • *describe the photoelectric effect and its dependence on light wavelength and intensity as well as choice of material, and explain why it cannot be explained with classical physics;* • *account for Einstein's explanation of the photoelectric effect, using Wien's Black Body radiation formula, the relation between temperature, energy density and entropy density, and Boltzmann's statistical definition of entropy, leading to the introduction of light quanta;* • *describe how x-rays are generated in an x-ray tube generator, explaining the appearance of the emission spectra with the continuous Bremsstrahlung and the characteristic peaks;* • *account for the Compton effect and Compton scattering;* • *describe an x-ray diffraction experiment, interpret Bragg's law for x-ray diffraction, and demonstrate how it can be used to calculate lattice parameters from a diffraction pattern;* • *describe, qualitatively, the emission and absorption spectra of gases;* • *account for the scattering experiments leading to Rutherford's nuclear theory for atoms and how it differed fundamentally from Thomson's plum pudding model;* • *account for the historical development and the meaning of Bohr's basic orbital model of the atom, including the introduction of the concepts ground state and stationary states, and demonstrate how it explains the hydrogen line spectrum;* • *explain the meaning of the correspondence principle;* • *describe the Franck-Hertz experiment and explain the results using Bohr's atomic model;* • *discuss how additional quantum numbers are needed to explain the subtle details of line spectra, (like the classical Zeeman effect) and qualitatively describe Sommerfeld's explanations in terms of orbit shape and angular momentum;* • *account for the problems of Bohr-Sommerfeld's semi-classical physics (such as the Stern-Gerlach experiment) that led to the idea of an intrinsic atomic spin;* • *formulate the Pauli exclusion principle;*
D	• *explain the concept of a matter wave and write down the de Broglie equation relating momentum to wavenumber (or to wavelength or frequency);* • *account for the Davisson-Germer experiment and how it confirmed the wave nature of electrons;* • *reproduce de Broglie's explanation of Bohr's orbital angular momentum quantization postulate as a result of a standing electron wave;* • *explain what it means that operators do not commute in Heisenberg's matrix mechanics and discuss its consequences;* • *define Heisenberg's uncertainty relation on at least two forms and discuss its meaning in each case;* • *account, in qualitative terms, for Schrödinger's analysis of atomic energy states in terms of stationary waves;* • *discuss the meaning of each term in the time-independent Schrödinger equation;* • *account for the probability interpretation of the Schrödinger equation, as proposed by Born;* • *discuss the "Schrödinger's cat" thought experiment and its possible interpretations;* • *define the key elements of the Copenhagen interpretation of quantum mechanics.*

Section	After this section you will (among other things) be able to:
E	• *explain the fundamental elements of Dirac's Bra-Ket notation and give a simple example of how it can be used;* • *define the requirement on the potential in order to separate the full Schrödinger equation into a time-dependent and a time-independent equation, perform the separation, and write down wave functions for the full and the time-independent equations, respectively;* • *define the statistical concept expectation value and formulate its general calculation using wave functions that are solutions to the time-independent Schrödinger equation;* • *define the energy and momentum operators mathematically and show how how they can be used to reproduced the 1D time-independent Schrödinger equation;* • *formulate the requirements on the wave function, beyond the basic requirement that it must be a solution to the Schrödinger equation, and formulate a general procedure for applying the Schrödinger equation formulation of quantum mechanics to real problems;* • *explain the concept zero point energy;* • *derive quantization phenomena as a result of the boundary conditions imposed on wave functions by localized changes in potential;* • *explain the concept "particle in a box" and discuss how it can be used to describe properties of real systems such as the optics of conjugated aromatic molecules;* • *write the Schrödinger equation for the quantum harmonic oscillator as well as the general form of the corresponding wave functions;* • *formulate mathematically the general wave functions solving the Schrödinger in a regime with zero potential and in a regime with a non-zero but finite potential, and discuss the differences in the behavior in the two regimes;* • *calculate the reflection and transmission coefficients at a finite potential step in terms of wave vectors;* • *give a qualitative account of the phenomenon of tunneling and discuss how the quantum mechanical conclusion differs from the classical one, for different incoming particle energies and barrier heights;* • *explain why the most probable radius of the electron in the hydrogen atom is equal to the Bohr radius, despite the fact that the radial equation has its maximum for* $r = 0$*;* • *formulate the selection rules and use them to explain why only certain light absorption and emission lines, corresponding to changes in electronic state, are observed;* • *formulate the Aufbau principle and its three key components, and use this to explain the basic character of the periodic table of the elements, including the distinction in s-, p-, d- and f-blocks and the variations in ionization energy, radius and magnetic susceptibility with atomic number.*