Light and Matter

Lecturers

- Dr. Mike Tarbutt. Blackett 207, m.tarbutt@imperial.ac.uk. Office hours: During the first part of the course: 11:00 on Thursdays and 12:00 on Fridays. Afterwards: by arrangement via email.

- Prof. Jenny Nelson. Huxley 1007, jenny.nelson@imperial.ac.uk. Office hours: During the second half of the course: 17:00 on Tuesdays and 13:00 on Fridays.

- Dr. Will Branford. Huxley 1004, w.branford@imperial.ac.uk. Office hours: During the last part of the course: 12:00 on Tuesdays and 12:00 on Thursdays

Part I: Atoms, molecules, and their interaction with light

Aims. This part of the course introduces the structure of atoms and molecules and their interactions with static and time-varying fields, and develops an understanding of how light is scattered, dispersed and absorbed. It covers the application of these topics to lasers, atomic clocks, measurements of fundamental constants, radio-astronomy, and spectroscopy. The course builds a familiarity with applying the methods of quantum mechanics.

Objectives: On completion of this part of the course students should be able to:

- Describe the energy level structure of one-electron and many-electron atoms. Explain what is meant by the central field approximation and how it leads to atomic configurations. Use appropriate notation to label the energy levels.

- Know the properties of angular momentum eigenstates and how to add angular momenta together.

- Use the ideas of angular momentum and screening to explain the ordering of atomic energy levels. Use the concept of a quantum defect to calculate the energy levels of an alkali atom.

- Explain the idea of exchange symmetry and describe the effect of the residual electrostatic interaction for many-electron atoms.

- Explain the origin of the spin-orbit interaction and how it leads to the fine-structure splitting of atomic energy levels. Use perturbation theory to calculate the fine-structure splitting.

- Explain the origin of hyperfine structure, and use perturbation theory to calculate hyperfine splittings. Appreciate the importance of hyperfine structure in radio-astronomy and atomic clocks.

- Explain how energy levels are split by a magnetic field, and be able to calculate the splittings.

- Use the time-dependent Schrodinger equation to show that a two-level atom interacting with an oscillating field undergoes Rabi oscillations. Appreciate the role of spontaneous emission in damping these oscillations.
• Show how the quantum mechanical description of an atom interacting with light leads to the picture of the atom as an oscillating electric dipole.

• Describe the classical electron oscillator model of atoms and molecules interacting with light and use it to explain dispersion, absorption and scattering of light. Use this model to calculate the refractive index of a gas and the cross-sections for Thompson and Rayleigh scattering. Describe how the frequency dependence of scattering and absorption brings colour to the world.

• Explain the Einstein A and B coefficients that describe absorption, stimulated and spontaneous emission. Calculate steady-state populations for an atom interacting with light.

• Explain how atomic spectra can be understood in terms of atomic energy levels and selection rules. Explain spectral line broadening and calculate the widths of spectral lines.

• Show that a population inversion leads to amplification of light by stimulated emission. Explain how this is used to make lasers.

• Describe qualitatively how atoms bind to form molecules. Interpret the potential energy curves of diatomic molecules.

• Describe the energy level structure of diatomic molecules, including the electronic, rotational and vibrational structure. Estimate the spacings between energy levels.

**Part II: Interaction of light with solids**

**Aims.** This part of the course concerns the interaction of light with solids. We will address the treatment of light absorption and emission by semiconductors, metals and dielectrics and show how the electronic structure of the material controls the optical response in each case. For semiconductors, we develop the concepts of second year solid state physics to present a microscopic description of light absorption and emission. We show how the optical properties of particular solids enable applications in light emitting and light detecting devices.

**Objectives:** On completion of this part of the course students should be able to:

• Explain the different types of optical processes in solids: band to band transition, vibrational / rotational transition, free carrier absorption, scattering,

• Describe the differences in the optical properties of semiconductors, dielectrics, glasses, metals, molecular materials, low dimensional semiconductors.

• Understand how the dipole approximation leads to expressions for the rate of photon absorption and emission in solids.

• Understand the derivation of the absorption coefficient for a direct gap crystalline semiconductor

• Understand how selection rules control the optical properties of solids and explain the differences in the optical properties of direct gap and indirect gap semiconductors
Explain what is meant by an exciton in a solid, and distinguish types of exciton.

Explain the concept of luminescence and show how luminescence and absorption are related.

Show how dimensionality influences the form of the joint density of states and hence the optical properties of low dimensional semiconductor structures.

Understand the main features of how light absorption and emission in molecular semiconductors and how they relate to the molecular nature of the materials

Use the classical dipole oscillator model to describe the optical response of metals and doped semiconductors.

Use the dipole oscillator model to describe the optical response of polar solids and understand the role of lattice vibrations

Understand the origin of plasmonic effects in solids

Explain how optical properties of solids influence the choice of materials for applications in light detection and light emission

Explain one example of how optical measurements can be used to probe electronic structure.

Part III: Interaction of magnetic fields with solids

Aims: The final part of the course deals with the interaction of magnetic and electric fields with solids and with the physics of the collective phases, of ferromagnetism, superconductivity and ferroelectricity in solids. We will show how these phases can be applied to memory devices.

Objectives: On completion of this part of the course students should be able to:

Understand the role of exchange in mediating magnetic interactions

Derive the classical and quantum models of local moment paramagnetism

Be able to calculate (spin only) magnetic moment \( \mu \) for a defined electronic configuration; and convert to saturation magnetization for a ferromagnet.

Be able to relate magnetic moment/magnetization to (Zeeman) energy in applied field.

Know and understand the properties of different magnetic states: para-, dia-, ferro-, ferri- and antiferromagnetism.

Understand the Weiss model of ferromagnetism and the concept of a disordering (Curie) temperature

Understand the Weiss model of antiferromagnetism

Know the difference between hard” and “soft” ferromagnets; sources of magnetic anisotropy and how to improve permanent magnets; applications of soft and hard ferromagnets

Describe the elementary properties of superconductors: Zero electrical resistance,
superconducting phase transition at a critical temperature and Meissner effect

- Understand the variation of critical temperature with isotopic mass and the role of the electron-phonon interaction

- Describe the supercurrent as a superfluid (condensate) of Cooper pairs interacting through the exchange of phonons.

- Be aware of the temperature range of standard and 'high-temperature' superconductors.

- Be aware that ferroelectricity is analogous to ferromagnetism, but involves cooperative displacement of charged ions in the solid to give electric dipoles, which align to give an overall electric polarization.

- Describe how these three collective states of matter (ferromagnetism, superconductivity and ferroelectricity) exhibit hysteresis and be able to sketch a typical hysteresis loop for each type.

- Describe how the property of hysteresis enables the fabrication of memory devices.