PROFILE-SPECIFIC QUESTIONS

Solid state physics profile

Block A: Semiconductors, metals and x-ray spectroscopy in solid state physics

1. Crystalline structure and chemical bonds in solids.
2. Band structure of solids – the tight binding model and the quasi-free electron model; Bloch theorem; electronic density of states.
3. Experimental methods for studying the band structure of solids (optical, photoemission, electric).
4. Dynamics of electrons in crystals; energy dispersion relation; effective mass.
5. Defects in crystals: hydrogen-like impurities in semiconductors.
6. Vibrations of the crystal lattice: phonons; specific heat of solids.
7. Electrical conductivity of metals and semiconductors: charge carriers, mobility, scattering mechanisms; Drude model, Boltzmann equation.
8. Electronic structure of solids in a magnetic field: Landau quantisation, magneto-conduction, quantum oscillations.
9. Absorption and reflection of electromagnetic radiation, and photoluminescence in solids.
10. P-n junctions; photodetectors; photovoltaic cells; semiconductor lasers.
11. Electronic structure of semiconductor nanostructures: quantum wells, nanowires and quantum dots.
12. Hall effects: normal, anomalous, quantum.
13. Processes associated with x-ray penetration into matter (elastic and inelastic scattering – diffraction and spectroscopy).
14. X-ray fluorescence and its practical applications.
15. Comparison of the interaction of electron, proton, neutron, and x-ray wavepackets with matter.

Block B: Magnetism and superconductivity

1. Mechanisms that lead to the formation of a magnetic moment, effective magnetic moment of ions (Hund rules, different groups of elements).
2. Influence of a non-magnetic environment on a magnetic ion (Kramers theorem, Jahn-Teller theorem, crystalline electric field, the phenomena of magnetic anisotropy and magnetostriction).
3. Exchange interactions – their nature and types (direct and indirect exchange interactions, in particular: super-exchange, double-exchange, RKKY and Dzyaloshinskii-Moriya interactions).
4. Different kinds of magnetic ordering (ferromagnetic, antiferromagnetic, ferrimagnetic, super-paramagnets and spin glasses).
5. Basic models used to describe magnetically ordered systems (molecular field model, Ising model, Heisenberg model).
6. Processes for magnetisation of various materials (paramagnetic, diamagnetic, ferrimagnetic, and ferromagnetic), magnetic susceptibility and its dependence on temperature.
7. Magnetostatic interactions between ionic magnetic moments, the concept of the demagnetisation field, domain structure in ferromagnets, magnetic hysteresis.
8. Itinerant magnetism (basis of the Pauli, Stoner, and Hubbard models).
9. Phase transitions (classification, critical phenomena, Landau theory).
10. Superconductivity – basic properties of the superconducting state, parameters that characterise a superconductor (penetration depth, coherence length), the two types of superconductors, the influence of magnetic field and temperature on a superconductor.
11. Materials that display superconductivity (BCS, HTC).
12. Ginzburg-Landau theory – mixed state in Type II superconductors, magnetic flux quantisation, and the Josephson effect.
13. The development of the theoretical description of superconductors: the London equation, Ginzburg-Landau theory, basis of the BCS theory.
14. Resonance methods in the study of magnetic materials – in particular: nuclear magnetic resonance and its medical applications.
15. Spintronics and nanomagnetism (giant, colossal, and tunnel magnetoresistance, super-paramagnetism of nanoscale objects).

Atomic and molecular physics profile

Block A: Atomic physics

1. Energy structure of the Hydrogen atom; fine and hyperfine structure; Lamb shift.
2. Structure of multi-electron atoms, energy shells and orbitals, spin-orbit coupling. Their relationship to the periodic table of elements.
3. Radiative transitions, transition matrix elements, Einstein coefficients, selection rules. Spontaneous and stimulated emission.
4. Atoms in electric and magnetic fields. Stark and Zeeman effects.
5. Atomic clocks.
6. Trapping and cooling of atoms.
7. Coherent phenomena, Rabi oscillations, resonance fluorescence.
8. Photons, states of the electromagnetic field, squeezed states.
9. Interaction of single photons with atoms, Jaynes-Cummings model.
10. Interaction of strong laser radiation with atoms, multi-photon phenomena.
11. Bell inequalities, tests of quantum mechanics, Hong-Ou-Mandel effect.
12. Entangled states and their properties.
13. Basic properties of condensates: coherence, interference, superfluidity, off-diagonal long-range order.
14. Mean field description of many weakly interacting particles (bosons, fermions).
15. Systems of ultracold atoms in periodic lattices.

Block B: Molecular physics

1. Potential energy profiles in molecules: conformers, barriers, tunnelling.
2. Methods for determining the geometry of molecules.
3. Electric dipole moment of molecules in gas and liquid phases.
4. Ab initio and DFT computational methods for determining molecular properties.
5. Identification of molecules under astrophysical conditions: methods and objects.
6. Fundamentals and applications of rotational spectroscopy.
7. Intermolecular interactions.
8. Molecular vibrations: normal mode analysis, symmetry, and measurement methods.
9. Rotational structure in the vibrational spectra of diatomic and triatomic molecules.
10. The Frank-Condon rule; Breakdown of the adiabatic approximation: conditions and consequences.
11. Intramolecular transitions: general conditions for their occurrence, and selection rules.
12. Mechanisms of nonradiative electronic energy transfer (Förster and Dexter).
13. Methods of molecular spectroscopy that utilise the Fourier transform.
14. Lasers, including those based on molecular transitions.
15. Electronic states: Jabłoński diagram, fluorescence, and phosphorescence.

Biophysics profile

Block A: biomolecules and methods for molecular biophysics

1. NMR and EPR in the structural studies of biological macromolecules.
2. X-ray methods in the structural studies of biological macromolecules (diffraction, SAXS), protein crystallisation.
3. UV/VIS and IR spectroscopy in the study of biological macromolecules.
4. Jabłoński diagram, Frank-Condon rule, Stokes effect, mechanisms of non-radiative electronic energy transfer (Förster i Dexter).
5. Confocal microscopy methods and TIRF.
6. cryoEM in the study of biological macromolecules.
7. Single-molecule methods in biophysics.
8. Simulation methods for macromolecules: Monte Carlo and molecular dynamics.
9. Chemical and enzymatic kinetics, mass-action law, reversible and irreversible reactions, cooperativity, allostery, Hill coefficient.
10. Thermodynamic equilibrium in solutions: intermolecular interactions and conformational changes.
11. Non-covalent interactions: their nature, energies in vacuum and in water millieu.
12. The structure and conformation of biopolymers: proteins, nucleic acids, polysaccharides.
13. Disordered proteins.
14. Protein folding, denaturation and aggregation.
15. Phospholipid bilayers: structure and energetics, active and passive transport through the bilayer.

Block B: nanomaterials in biophysical applications

1. Types of non-organic nanomaterials (the role of dimensionality). The consequences of a change of scale (from macroscopic to nanoscale) on the physical and chemical properties of materials.
2. Examples of nanomaterial production methods (e.g. “bottom up” and “top down”). Manufacture and stabilisation of core/shell structures.
3. Types of nanomaterials produced from organic compounds (e.g. polymer nanoparticles, liposomes, dendrimers, fullerenes, carbon nanotubes).
4. Nanoparticle aggregation and techniques used to prevent it.
5. Experimental techniques for the study of nanoparticle structure, with particular focus on imaging methods.
6. Experimental techniques for the study of the chemical composition of nanoparticles.
7. Applications of nanomaterials for medical diagnostics (e.g. optical imaging methods, use of nanoparticles for magnetic contrast).
8. Applications of nanomaterials and nanoparticles in medical therapy (e.g. in gene therapy, targeted drug delivery).
9. Use of nanomaterials for a „lab on a chip”.
10. Hazards associated with the use of nanomaterials (especially in medicine).
11. Methods for the attachment of biologically active molecules to inorganic nanoparticles.
12. Methods for the transport of nanoparticles into the biological cell interior.