**CONFIRMED**
**DEAN**
**/Prof. Dr. G. Rainovski/**

# E X A M   T O P I C S

for PhD applicants in study direction 4.1 (AMO Physics)

## I. Quantum Optics and Quantum Information Theory

1. Quantum linear harmonic oscillator
2. Potential well and potential barrier. Tunneling. Reflection and transmission coefficients.
3. Angular momentum in quantum mechanics. Addition of angular momenta. Spin.
4. Magnetic moment: orbital and spin. Stern-Gerlach effect.
5. Hydrogen atom. Spectrum and wavefunctions.
6. Two-body problem in quantum mechanics.
7. Time-independent perturbation theory. Zeeman effect.
8. Time-dependent perturbation theory. Two-level system. Rotating wave approximation. Rabi oscillations.
9. Identical particles. Pauli principle. Helium atom.
10. Adiabatic evolution. Avoided and unavoided crossings. Landau-Zener model.
11. Three-level systems. Dark states. Stimulated Raman adiabatic process (STIRAP).
12. Degenerate systems. Morris-Shore transformation.
13. Density matrix. Liouville - von Neumann equation. Bloch sphere and Bloch vector. Spontaneous emission in dephasing processes.
14. Electromagnetically induced transparency, 'slow' and 'fast' light. Lasing without inversion.
15. Relativistic quantum mechanics. Klein-Gordon equation. Klein paradox. Dirac equation.

**LITERATURE:**


1. A. Donkov and M. Mateev, Quantum Mechanics (Sofia University Press, 2010, Sofia).
2. B.W. Shore, The Theory of Coherent Atomic Excitation (Wiley, New York, 1990).
3. L. Allen and J.H. Eberly, Optical Resonance and Two-Level Atoms (Dover, New York, 1987).
4. N. V. Vitanov, Quantum Transitions (Sofia University Press, 2010, Sofia).

## II. AMO physics

1. Electron spin. Spin-orbit coupling. Fine structure in the spectra of alkali metals.
2. Electronic structure of the Helium atom.
3. Nuclear spin. Hyperfine structure. Example: Rb atom
4. Atomic spectra. Transition probability. Selection rules
5. Zeeman effect. Stark effect.
6. Interaction between two neutral atoms at large inter-nuclear distances. Dispersion coefficients C3, C5, C6.
7. Diatomic molecules. Born-Oppenheimer approximation. Potential energy curves.
8. Classification of electron states in diatomic molecules.
9. Homonuclear and heteronuclear molecules.
10. Vibrational and rotational structure in diatomic molecules.
11. Molecular spectra. Selection rules. Franck-Condon principle.
12. Electron spectra. Vibrational and rotations spectra.
13. Physical vacuum. Lifetime of atomic states. Lamb shift.
14. Elementary dispersion elements: prism, diffraction grating, interference filer. Spectrographs and monochomator gratings. Basic theory and applications.
15. Interferometers: Mach-Zehnder, Michelson, Fabry-Pérot. Comparison between planar and confocal Fabry-Pérot interferometers.
16. Detectors: photomultiplier, photodiode, avalanche photodiode. Basic theory and circuits.
17. Lasing. Active media with three and four energy levels. Modes of laser radiation.
18. Tuneable lasers. Selective resonators with prisms, diffraction gratings, etalons. Single mode generation – selection of single longitudinal mode.
19. Main characteristics of gas (He-Ne, Ar+), solid state (Nd:YAG, Ti:Al2 O3), dye and semiconductor lasers.
20. Width and profile of spectral lines. Homogenous broadening. Doppler broadening. Voight profile. Collisional and saturation broadening.
21. Absorption laser spectroscopy. Laser-induced fluorescence.
22. Optogalvanic spectroscopy.
23. Saturation laser spectroscopy. Polarization spectroscopy.

**LITERATURE:**

L.D.Landau and E.M.Lifshitz Quantum mechanics. Nonrelativistic theory, 1977 Elsevier

P.Bernath Spectra of atoms and molecules, Oxford 1995

G. K. Woodgate, Elementary atomic structure, Oxford 2002

C. Herzberg, Molecular spectra and molecular structureSpectra of diatomic molecules, Van Nostrand, New York 1995.

W. Demtroder, Laser Spectroscopy, Basic Concepts and Instrumentation, Springer-Verlag, Berlin 1996.

O. Zvelto, Principles of Lasers, Springer 2010

**III. AMO physics (interactions with biological systems)**

1. Basic notions of Quantum Mechanics. Uncertainty principle. Superposition principle. Operators.
2. Schrödinger equation. One-dimensional potential well. Harmonic oscillator.
3. Angular momentum. Matrix elements and eigendecomposition of the angular momentum operator.
4. Hydrogen atom. Schrödinger equation in a central potential. Classification of energy levels.
5. Time-independent perturbation theory.
6. Variational principle.
7. Electron spin. Spin-orbit interaction.
8. Atomic spectra. Transition probability. Selection rules.
9. Multi-electron system. Thomas-Fermi model.
10. Hartree-Fock method.
11. Density functional theory. Hohenberg-Kohn theorem.
12. Kohn-Sham equation
13. Local density approximation.
14. Diatomic molecule. Vibrational and rotations structure of the diatomic molecule.
15. Molecular spectra. Selection rules.
16. Born-Oppenheimer approximation. Basic notion in molecular dynamics.
17. Ergodicity theorem. Molecular dynamics in the microcanonical ensemble.
18. Molecular dynamics in other statistical ensembles.

**LITERATURE:**

A. Donkov and M. Mateev, Quantum Mechanics (Sofia University Press, 2010, Sofia).

Parr, RG; Yang, W (1989). Density-Functional Theory of Atoms and Molecules. New York: Oxford University Press.

Daan Frenkel, Berend Smit, Understanding Molecular Simulation: From Algorithms to Applications, Computational Science Series, Vol1, Academic Press 2001.

IV. **Quantum Many-Body Physics**

1. Quantum linear harmonic oscillator: spectrum, wavefunctions, creation and annihilation operators.
2. Hydrogen atom. Spectrum and wavefunctions.
3. Time-independent perturbation theory. Zeeman effect.
4. Time-dependent perturbation theory. Two-level system. Rotating wave approximation. Rabi oscillations.
5. Adiabatic evolution. Avoided and unavoided crossings. Landau-Zener model.
6. Density matrix. Liouville - von Neumann equation. Bloch sphere and Bloch vector.
7. Angular momentum in quantum mechanics. Addition of angular momenta. Spin.
8. Identical particles. Pauli principle. Bose-Einstein and Fermi-Dirac distributions.
9. Ideal Bose and Fermi gases: partition function, free energy, heat capacity.
10. Ensemble theory: microcanonical, canonical and grand canonical ensemble. Partition function, free energy and heat capacity of coupled harmonic oscillators in one dimension.
11. Bose-Einstein condensation: equation of state, critical temperature.
12. Weakly-interacting bosons: Gross-Pitaevski equation, Bogoliubov transformation, Bogoliubov spectrum and quasiparticles, superfluid phase.
13. BCS theory of superconductivity: (s-wave) pairing function, gap equation, critical temperature; superconducting phase.
14. Transverse-field Ising model: exact solution and Jordan-Wigner transformation, spectrum, quantum phase transitions, (anti-)ferromagnetic and paramagnetic phases.

**LITERATURE:**

1. J. J. Sakurai and E. D. Commins, *Modern Quantum Mechanics, Revised Edition*, (American Association of Physics Teachers, 1995).
2. R. K. Pathria and P. D. Beale, *Statistical Mechanics, (Taylor & Francis 2011).*
3. Bipin R. Desai, *Quantum Mechanics with Basic Field Theory*, (Cambridge University Press).
4. S. Sachdev, Quantum Phase Transitions (Cambridge University Press, Cambridge 2001).

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