PHYS 685: Quantum Optics (Winter 2007)

Instructor: Daniel A. Steck  
Office: 277 Willamette  
Phone: 346-5313  
email: dsteck@uoregon.edu  
Office hours: Tth 10-11, and by appointment (best to email first)  
Course home page: http://atomoptics.uoregon.edu/~dsteck/teaching/07/winter/phys685

Schedule: TTh 8:30-9:50 (am), 318 Willamette  
Course reference number: 26006  
Credits: 4  
Prerequisites: PHYS 684  
Links: news, course notes, homework sets and keys.

Course overview

This is a continuation of quantum optics from last term. This course will provide a broad overview of quantum-mechanical interactions between light and matter. We will focus mainly on light-atom interactions and thus we will also do some atomic structure.

Recommended Texts:

- Loudon, The Quantum Theory of Light (QC446.2 .L68 2000)
- Meystre and Sargent, Elements of Quantum Optics (QC446.2 .M48 1999)

Note that the above books are no: required, and we will not follow any particular text. The above texts are useful references, however. There are many other excellent standard texts that you may find useful for this course, some of the classics and good modern works are listed here. Titles with call numbers are on reserve in the science library. You should consider obtaining the Dover titles, since they are cheap.

General Quantum Optics

- Allen and Eberly, Optical Resonance and Two-Level Atoms (QC476.5 .A44) (Dover)
- Mandel and Wolf, Optical Coherence and Quantum Optics (QC403 .M34 1994)
- Scully and Zubairy, Quantum Optics (QC446.2 .S4 1997)
- Schleich, Quantum Optics in Phase Space
- Vogel and Welsch, Quantum Optics: An Introduction (QC446.2 .V64 2006)
- Fain and Khanin, Quantum Electronics
- Louisell, Radiation and Noise In Quantum Electronics (QC174.45 .L6)
- Louisell, Quantum Statistical Properties of Radiation (QC680 .L65)
- Nussenzveig, Introduction to Quantum Optics

Atom Optics

- Metcalf and van der Straten, Laser Cooling and Trapping (QC689.5 .L35 M47 1999)
- Meystre, Atom Optics (QC446.2 .M46 2001)

Atomic Physics and Atomic Structure

- Corney, Atomic and Laser Spectroscopy (QC688 .C67)
- Bethe and Salpeter, Quantum Mechanics of One and Two Electron Atoms (QC714.17 .P78A7 1977)
- Fano and Fano, Physics of Atoms and Molecules (QC173.F315)
- Bergmann and Schaefer, Constituents of Matter: Atoms, Molecules, Nuclei, and Particles
- Davydov, Quantum Mechanics (QC174.1 .D3713 1976)
- Born, Atomic Physics (QC173.B634) (Dover)
- Shank and Satchler, Angular Momentum (QC793.3 .A5 B75 1993) (Dover)

Quantum Electrodynamics

- Power, Introductory Quantum Electrodynamics
- Berestetski, Lifshitz, and Pitaevski, Quantum Electrodynamics (QC174.45 .B3813)

Laser Physics

- Sargent, Scully, and Lamb, Laser Physics (QC476.2 .S27 1977)
- Yariv, Quantum Electronics (QC688.Y37 1989)
- Siegman, Lasers (TK7871 .S552)
Grades

Grades for the course will be based on homework and a take-home final exam. The relative weights will be as follows:

- Homework: 50%
- Final exam: 50%

Homework: about 4-6 problem sets will be assigned during the term.

Final exam: the final exam will be in-class, during the regularly scheduled slot on Tuesday, 20 March 2007, 8-10 am.

Pass/fail grading option: a passing grade requires the equivalent of a C- grade on all the course work (homework and final).

Syllabus

This is a tentative outline of topics we will cover in this (and the following) course in the sequence. Note that this is very ambitious for the probable duration of this course.

I. Classical Atom-Field Interactions
   1. Lorentz Model of the Atom
   2. Polarizability, Cross Section
   3. Oscillator Strength
   4. Classical Radiation Damping
   5. Refractive Index
   6. Mechanical Effects of Light

II. Semiclassical Atom-Field Interactions: Rate Equations
   1. Einstein Rate Equations
   2. Density of States
   3. Relation Between A and B Coefficients
   4. Cross Section and Saturation Intensity
   5. Resonant Gain and Absorption

III. Two-Level Quantum-Mechanical Atom Interacting with a Classical Field
   1. Electric Dipole Interaction: Schrödinger Equation Treatment
   2. Density Operator, Schrödinger, Heisenberg, and Interaction Pictures
   3. Spontaneous Emission: Optical Bloch Equations
   4. Resonance Fluorescence
      1. Quantum Regression Theorem
      2. Elastic and Inelastic Scattering
      3. Hole and Triplet and Probe Absorption Spectra
      4. Lamb Dip Spectroscopy
   5. Dressed States, Bloch-Siegert Shift
   6. Adiabatic Passage: Landau-Zener Tunneling
   7. Mechanical Effects
      1. Radiation Pressure
      2. Laser Cooling and the Doppler Limit
      3. Dipole Force and the Adiabatic Approximation; Dipole Traps
      4. Stochastic Dipole Force
   8. Connection with the Classical Atom
   9. Atom in a Thermal Field
   10. Connection with Rate Equations
   11. Minimal-Coupling Hamiltonian and Gauge Invariance

IV. Quantum Theory of Open Systems
   1. Stochastic Calculus
      1. Wiener Process
      2. Itô Calculus
      3. Stratonovich Calculus
      4. Cauchy Process
   2. Lindblad Form of the Master Equation
   3. System-Reservoir Derivation of the Master Equation
   4. Heisenberg-Langevin Formalism (and the Ornstein-Uhlenbeck process)
   5. Master Equation for Spontaneous Emission
   6. Quantum Measurement
      1. Stochastic Master Equation: Quantum Jumps
      2. Stochastic Master Equation: Homodyne Detection
      3. Stochastic Schrödinger Equation
      4. Detector Inefficiency and Multiple Observers
      5. Positive Operator-Valued Measures

More Complicated Quantum-Mechanical Atoms Interacting with a Classical Field

- Stimulated and Spontaneous Raman Transitions
- Coherent Population Trapping and VSCPT Cooling
- Lamb Dip Spectroscopy Revisited: Crossover Resonances
- Lasing Without Inversion
- Autler-Townes Effect
- Hanle Effect
Quantum Jumps and the Quantum Zeno Effect

Structure of Simple Atoms
- Angular Momentum, Tensor Operators, and the Spherical Basis
- Fine Structure
- Zeeman and Stark Effects (Breit–Rabi Formula)
- Hyperfine Structure
- Anomalous Zeeman and Stark Effects
- Algebra of Dipole Matrix Elements, Wigner–Eckhart Theorem, and Selection Rules
- Optical Pumping of Hyperfine Levels
- Sub-Doppler Laser Cooling Mechanisms
- Magic Wavelengths

VII. Quantum-Mechanical Atom-Field Interactions
- Quantization of the Electromagnetic Field
- Jaynes-Cummings Model, Dressed States Revisited
- Quantum Vacuum Effects
  - Spontaneous Emission: Weizsäcker-Wigner Theory
  - Lamb Shift
  - Casimir–Polder Forces
  - Enhancement and Suppression of Spontaneous Emission
  - Vacuum Drag Forces
  - Unruh Effect
- Dissipation and Measurement in Cavity QED
- Cavity QED: Input-Output Formalism
- Quantization of a Traveling Wave
- Resonant Formalism
- Connection to the Classical Field

VIII. Coherence of the Quantum Electromagnetic Field
- Coherence Hierarchy, and the Wiener–Khinchin Theorem
- Experiment of Hanbury-Brown and Twiss
- Squeezed Light
- Bunching and Antibunching of Photons
- Parametric Downconversion
- Hong–Ou–Mandel Interference
- Interference of Independent Photons

IX. Quantum Theory of the Laser
- Master Equation and Fokker–Planck Equation
- Threshold Behavior
- Laser Oscillation and Gain Saturation
- Transient Behavior: Vacuum Seeding and Relaxation Oscillations
- Frequency Pulling
- Schwinger–Townes Limit
- Injection Locking
- Photon Statistics

X. Bose-Einstein Condensation in Dilute Gases
- Gross–Pitaevskii Equation
- Bogoliubov Linearization
- Hartree–Fock–Bogoliubov Approximation
- Production of BECs
- Coherence Properties
- Dispersion and Superfluid Behavior