Contents

Abbreviations xv		
Preface <i>xvii</i>		
Author <i>xxi</i>		
1. Metrology 1		
 A. Measurement systems 3 □ MKS units □ SI units (and why Gaussian units are better) B. Universal units and fundamental constants 7 C. Atomic units 8 □ Fine structure constant 		
 D. Problems 10 □ Atomic units for E and B fields □ Unit of charge □ Universal units (Planck units) 		
2. Preliminaries 13		
 A. Classical harmonic oscillator 14 □ Not driven: (i) Strong damping (ii) Critical damping (iii) Weak damping □ Driven with weak damping: (i) Amplitude (ii) Phase (iii) Power □ Harmonically bound electron □ Coupled oscillators 		
□ Energy eigenstates □ Time dependence □ Quantum uncertainties		
C. Coherent states 28 □ Definition and properties □ Time evolution □ Coherent states have minimum uncertainty □ Phase space behavior		
 D. Squeezed states 32 □ Hyperbolic transform of the HO Hamiltonian □ Squeezed vacuum □ Classical squeezing by FM at 2ω₀ □ Generating squeezed light: (i) Parametric down conversion (ii) Four-wave mixing □ Balanced homodyne detector F. Badiation 41 		
$\square \text{ Field modes are classical oscillators } \square \text{ Quantization} \\ \square \text{ Zero-point energy and fields } \square \text{ Casimir effect}$		

□ An electron on a spring □ Quantum harmonic oscillator □ Damping in a driven harmonic oscillator □ Squeezing operators □ Squeezed states □ Size of zero-point energy

60

- 3. Atoms
 - A. Spectroscopic notation

59

49

- B. Energy levels of one-electron atoms 62
 □ Bohr atom □ Radial Schrödinger equation for central potentials
 □ Radial equation for hydrogen □ One-electron atoms with cores
 Quantum defect: (i) Phenomenology (ii) Explanation
- C. Interaction with magnetic fields 71 \Box Magnetic moment of circulating charge \Box Intrinsic electron spin and moment \Box Spin-orbit interaction \Box The Landé vector model of g_j — Weak field
- D. Atoms in static electric fields Stark effect 76
 □ Restrictions due to parity □ Stationary perturbation theory:
 (i) First order (ii) Second order (iii) Third order □ DC
 polarizability and dipole moment □ Beyond the quadratic Stark effect □ Field ionization
- E. Permanent atomic electric dipole moment (EDM) 87 □ EDM implies P and T violation □ Experimental method
- F. Atoms in oscillating electric fields 90
 □ AC polarizability □ Oscillator strength expression for polarizabilities □ Susceptibility and index of refraction:
 (i) Causality and the Kramers-Kronig relations □ Level shifts The AC Stark effect
- G. Strong oscillating fields Dressed atoms 98
 □ The problem □ The solution □ Time dependence
 □ Eigenenergies versus field strength at fixed detuning
 □ Eigenenergies versus detuning at fixed strength □ Atom plus field basis states □ Spectrum of fluorescence from dressed atoms
- H. Problems 108 □ Quantum defect □ Classical electron bound by a harmonic potential □ Oscillator strength □ Dressed atoms
- 4. NUCLEUS **117**
 - A. Isotope effects 119 \Box Mass effect \Box Volume effect
 - B. Hyperfine structure 122

 $\Box Magnetic dipole \quad \Box Electric quadrupole \quad \Box Order-of-magnitude of hyperfine structure \quad \Box Zeeman shift in weak magnetic field$

- C. **Problems** 133
- 5. RESONANCE 141
 - A. Introduction 142 □ Resonance measurements and QED □ Experimental precision
 - B. Magnetic resonance 145
 □ Classical motion of magnetic moment in a static B field
 □ Rotating coordinate transformation □ Larmor's theorem
 □ Motion in a rotating B field: (i) On-resonance behavior
 (ii) Off-resonance behavior □ Adiabatic rapid passage and the Landau–Zener crossing: (i) Quantum treatment
 - C. Magnetic resonance of quantized spin 1/2 156
 □ Pauli spin matrices □ Expectation value of quantized moment
 □ The Rabi transition probability □ Wavefunctions for quantized spin 1/2 □ Separated oscillatory fields SOF
 - D. Resonance in a two-state system 166
 □ Rotating wave approximation □ Isomorphism with spin 1/2 in a magnetic field
 - E. Density matrix 168
 □ General results □ Density matrix for a two-state system
 □ Phenomenological treatment of relaxation Bloch equations
 - F. Resonance of a realistic two-state system 174
 □ Steady-state solution □ Free induction decay □ Damping of Rabi probability
 - G. Problems 179 □ RF-induced magnetic transitions □ Rabi transition probability □ Steady-state solution for two-level system
- 6. INTERACTION **187**
 - A. Interaction of EM radiation with atoms 188 □ Hamiltonian □ Electric dipole approximation — E1 □ Higher approximations
 - B. Selection rules and angular distribution 192 □ General □ Electric dipole radiation □ Higher-order processes
 - C. Transition rates 196 □ Saturated and unsaturated rates □ Rates for monochromatic excitation □ Cross-section for absorption □ Rates for broadband excitation

xi

- D. Spontaneous emission 202
 □ Thermal equilibrium Einstein A (emission) and B (absorption) coefficients □ Quantum mechanical expression for spontaneous decay rate
- E. Order-of-magnitude of spontaneous emission 205
 □ Electric dipole radiation □ Electric quadrupole radiation
 □ Magnetic dipole radiation
- F. Saturation intensities 208
 □ Closed systems: (i) Broadband radiation (ii) Monochromatic radiation □ Open systems
- G. Problems 212 □ Classical scattering in 2D □ Rabi frequency from matrix element □ Transitions in Na and H
- 7. Multiphoton **219**
 - A. Two-photon absorption 220
 □ General considerations □ Final-state amplitude from perturbation theory □ Transition rate
 - B. Two-photon de-excitation processes 224
 □ Two-photon stimulated emission □ One stimulated and one spontaneous photon
 - C. Raman processes 226 □ General □ Stimulated Raman scattering □ Spontaneous Raman scattering □ Raman scattering cross-section
 - D. Dressed atom for multiphoton processes
 229

 □ Two-photon absorption
 □ Raman scattering
 - E. **Problems** 233 □ Magnitude of Raman scattering cross-section
- 8. COHERENCE *235*
 - A. Coherence in single atoms236 \Box Quantum beats \Box Level crossing \Box Double resonance
 - B. Coherence in localized ensembles 241
 □ Superradiance: (i) Qualitative discussion (ii) For 2 two-level systems (iii) For N two-level systems □ Spin echoes
 - C. Coherence in extended ensembles 247
 □ Phase matching □ Intensity for finite mismatch □ Examples:
 (i) Degenerate four-wave mixing (ii) Generation of UV radiation

252

D. Mixed examples

□ Echoes in extended media: (i) Spin echo in an extended sample (ii) Echoes in multilevel atoms □ Strong superradiance in extended samples

- E. Coherent control in multilevel atoms 255
 □ Coherent population trapping CPT □ Electromagnetically induced transparency EIT □ EIT in a Λ system □ Role of dressed state interference in EIT □ EIT vs. CPT □ EIT in a Ξ system □ EIT in a V system
 F. Other effects in scherent control 267
- F. Other effects in coherent control 267 □ Optical rotation □ Electromagnetically induced absorption — EIA
- G. Problems 271 □ Quantum beats □ Hanle effect □ Dicke superradiance □ Spin echoes in extended media
- 9. LINESHAPES 281
 - A. Low-intensity and simple collisions 282
 □ Homogeneous vs. inhomogeneous broadening: (i) Homogeneous
 (ii) Inhomogeneous □ Lorentzian line □ Spontaneous decay lineshape
 - B. Relativistic effects in emission and absorption
 287

 □ Photon recoil
 □ Doppler shift
 - C. Lineshape of atoms in a gas 290 □ Gaussian distribution □ Voigt profile
 - D. Confined particles 292
 □ Spectrum of oscillating emitter □ Tight confinement:
 (i) Recoilless emission (ii) Sideband cooling (iii) Dicke narrowing
 □ Weak confinement The classical regime
 - E. Gaussian beam optics 297
 - F. **Problems** 299 \Box Convolution of lineshapes
- 10. Spectroscopy *301*
 - A. Alkali atoms 303
 - B. Experimental tools 305 □ Diode laser □ Lock-in amplifier □ Polarizing beam splitter cube — PBS □ Acousto-optic modulator — AOM □ Faraday isolator
 - C. Doppler-free techniques 309 □ Saturated absorption spectroscopy — SAS □ Crossover resonances □ Eliminating crossover resonances using copropagating SAS □ Two-photon Doppler-free
 - D. Nonlinear magneto-optic rotation NMOR 317 □ Chopped NMOR

E. Problems	322	
\Box Diode laser	linewidth	\Box Vapor cells

11. COOLING AND TRAPPING 327

A. Spontaneous force

□ Doppler cooling □ Polarization gradient cooling □ Magneto-optic trap — MOT □ Zeeman slower: (i) Decreasing field slower (ii) Increasing field slower (iii) Spin-flip slower □ Atomic fountain

328

B. Stimulated force 341

 $\hfill\square$ Dipole trap

- C. Magnetic trapping and evaporative cooling 343
- D. Bose–Einstein condensation 345

E. Optical tweezers 351

□ Calibrating the trap: (i) Escape force method (ii) Drag force method (iii) Equipartition method (iv) Power spectrum method (v) Step response method

F. Ion trapping 357

 \Box Penning trap \Box Paul trap \Box Mode coupling in a Penning trap \Box Sideband cooling \Box Quantum computation in a linear Paul trap

G. Problems 368 \Box Number of atoms in a MOT

Appendixes

A. STANDARDS 371

□ Time standards □ Length standards □ Mass standards □ Electrical standards □ Summary □ Additional items: (i) A brief history of time-keeping (ii) Frequency measurements (iii) Fun with dimensions

- B. WHAT IS A PHOTON? 387
- C. EINSTEIN AS ARMCHAIR DETECTIVE: THE CASE OF STIMULATED RADIATION **397** Examples of gedanken experiments: (i) Need for curved spacetime for gravity (ii) Gravitational redshift
- D. FREQUENCY COMB 409
- INDEX **415**