

Contents

<i>Preface</i>	xxi
<i>Introduction</i>	1

I

TRANSITION AMPLITUDES IN ELECTRODYNAMICS

<i>Introduction</i>	5
A. Probability Amplitude Associated with a Physical Process	7
B. Time Dependence of Transition Amplitudes	9
1. Coupling between Discrete Isolated States	9
2. Resonant Coupling between a Discrete Level and a Continuum	10
3. Couplings inside a Continuum or between Continua	12
C. Application to Electrodynamics	15
1. Coulomb Gauge Hamiltonian	15
2. Expansion in Powers of the Charges q_α	16
3. Expansion in Powers of the Interaction with the Transverse Field	17
4. Advantages of Including the Coulomb Interaction in the Particle Hamiltonian	18
5. Diagrammatic Representation of Transition Amplitudes ...	19

COMPLEMENT A_I—PERTURBATIVE CALCULATION OF TRANSITION AMPLITUDES—SOME USEFUL RELATIONS

<i>Introduction</i>	23
1. Interaction Representation	23

2.	Perturbative Expansion of Transition Amplitudes— <i>a. Perturbative Expansion of the Evolution Operator. b. First-Order Transition Amplitude. c. Second-Order Transition Amplitude . . .</i>	25
3.	Transition Probability— <i>a. Calculation of the Transition Probability to a Final State Different from the Initial State. b. Transition Probability between Two Discrete States. Lowest-Order Calculation. c. Case Where the Final State Belongs to an Energy Continuum. Density of States. d. Transition Rate toward a Continuum of Final States. e. Case Where both the Initial and Final States Belong to a Continuum</i>	31

COMPLEMENT B₁—DESCRIPTION OF THE EFFECT OF A PERTURBATION BY AN EFFECTIVE HAMILTONIAN

1.	Introduction—Motivation	38
2.	Principle of the Method	41
3.	Determination of the Effective Hamiltonian— <i>a. Iterative Calculation of S. b. Expression of the Second-Order Effective Hamiltonian. c. Higher-Order Terms</i>	43
4.	Case of Two Interacting Systems	46

COMPLEMENT C₁—DISCRETE LEVEL COUPLED TO A BROAD CONTINUUM: A SIMPLE MODEL

<i>Introduction</i>	49
1. Description of the Model— <i>a. The Discrete State and the Continuum. b. Discretization of the Continuum. c. Simplifying Assumptions</i>	50
2. Stationary States of the System. Traces of the Discrete State in the New Continuum— <i>a. The Eigenvalue Equation. b. Graphic Determination of the New Eigenvalues. c. Probability Density of the Discrete State in the New Continuum</i>	51
3. A Few Applications of This Simple Model— <i>a. Decay of the Discrete Level. b. Excitation of the System in the Discrete Level from Another State. c. Resonant Scattering through a Discrete Level. d. Fano Profiles</i>	56
4. Generalization to More Realistic Continua. Diagonalization of the Hamiltonian without Discretization	64

II

A SURVEY OF SOME INTERACTION PROCESSES BETWEEN PHOTONS AND ATOMS

<i>Introduction</i>	67
A. Emission Process: A New Photon Appears	69
1. Spontaneous Emission between Two Discrete Atomic Levels. Radiative Decay of an Excited Atomic State— <i>a. Diagrammatic Representation. b. Spontaneous Emission Rate. c. Nonperturbative Results</i>	69
2. Spontaneous Emission between a Continuum State and a Discrete State— <i>a. First Example: Radiative Capture. b. Second Example: Radiative Dissociation of a Molecule</i> ...	73
3. Spontaneous Emission between Two States of the Ionization Continuum—Bremsstrahlung	76
B. Absorption Process: A Photon Disappears	78
1. Absorption between Two Discrete States	78
2. Absorption between a Discrete State and a Continuum State— <i>a. First Example: Photoionization. b. Second Example: Photodissociation</i>	79
3. Absorption between Two States of the Ionization Continuum: Inverse Bremsstrahlung	82
4. Influence of the Initial State of the Field on the Dynamics of the Absorption Process	83
C. Scattering Process: A Photon Disappears and Another Photon Appears	86
1. Scattering Amplitude—Diagrammatic Representation	86
2. Different Types of Photon Scattering by an Atomic or Molecular System— <i>a. Low-Energy Elastic Scattering: Rayleigh Scattering. b. Low-Energy Inelastic Scattering: Raman Scattering. c. High-Energy Elastic Scattering: Thomson Scattering. d. High-Energy Inelastic Scattering with the Final Atomic State in the Ionization Continuum: Compton Scattering</i>	88
3. Resonant Scattering	93
D. Multiphoton Processes: Several Photons Appear or Disappear	98
1. Spontaneous Emission of Two Photons	98
2. Multiphoton Absorption (and Stimulated Emission) between Two Discrete Atomic States	100

3. Multiphoton Ionization	102
4. Harmonic Generation	104
5. Multiphoton Processes and Quasi-Resonant Scattering ...	106
E. Radiative Corrections: Photons Are Emitted and Reabsorbed (or Absorbed and Reemitted)	109
1. Spontaneous Radiative Corrections— <i>a. Case of a Free Elec- tron: Mass Correction. b. Case of an Atomic Electron: Natu- ral Width and Radiative Shift</i>	109
2. Stimulated Radiative Corrections	114
F. Interaction by Photon Exchange	118
1. Exchange of Transverse Photons between Two Charged Particles: First Correction to the Coulomb Interaction	118
2. Van der Waals Interaction between Two Neutral Atoms— <i>a. Small Distance: $D \ll \lambda_{ab}$. b. Large Distance $\lambda_{ab} \ll D$</i> ...	121

COMPLEMENT A_{II}—PHOTODETECTION SIGNALS AND CORRELATION FUNCTIONS

<i>Introduction</i>	127
1. Simple Models of Atomic Photodetectors— <i>a. Broadband Pho- todetector. b. Narrow-Band Photodetector</i>	128
2. Excitation Probability and Correlation Functions— <i>a. Hamilto- nian. Evolution Operator. b. Calculation of the Probability That the Atom Has Left the Ground State after a Time Δt. c. Atomic Dipole Correlation Function. d. Field Correlation Function</i>	129
3. Broadband Photodetection— <i>a. Condition on the Correlation Functions. b. Photoionization Rate</i>	137
4. Narrow-Band Photodetection— <i>a. Conditions on the Incident Radiation and on the Detector. b. Excitation by a Broadband Spectrum. c. Influence of the Natural Width of the Excited Atomic Level</i>	139
5. Double Photodetection Signals— <i>a. Correlation between Two Photodetector Signals. b. Sketch of the Calculation of w_{II}</i>	143

COMPLEMENT B_{II}—RADIATIVE CORRECTIONS IN THE PAULI–FIERZ REPRESENTATION

<i>Introduction</i>	147
1. The Pauli–Fierz Transformation— <i>a. Simplifying Assumptions.</i> <i>b. Transverse Field Tied to a Classical Particle. c. Determination</i> <i>of the Pauli–Fierz Transformation</i>	148
2. The Observables in the New Picture— <i>a. Transformation of the</i> <i>Transverse Fields. b. Transformation of the Particle Dynamical</i> <i>Variables. c. Expression for the New Hamiltonian</i>	152
3. Physical Discussion— <i>a. Mass Correction. b. New Interaction</i> <i>Hamiltonian between the Particle and the Transverse Field.</i> <i>c. Advantages of the New Representation. d. Inadequacy of the</i> <i>Concept of a Field Tied to a Particle</i>	157

III NONPERTURBATIVE CALCULATION OF TRANSITION AMPLITUDES

<i>Introduction</i>	165
A. Evolution Operator and Resolvent	167
1. Integral Equation Satisfied by the Evolution Operator	167
2. Green's Functions—Propagators	167
3. Resolvent of the Hamiltonian	170
B. Formal Resummation of the Perturbation Series	172
1. Diagrammatic Method Explained on a Simple Model	172
2. Algebraic Method Using Projection Operators— <i>a. Projector</i> <i>onto a Subspace \mathcal{E}_0 of the Space of States. b. Calculation of</i> <i>the Projection of the Resolvent in the Subspace \mathcal{E}_0. c. Calcula-</i> <i>tion of Other Projections of $G(z)$. d. Interpretation of the</i> <i>Level-Shift Operator</i>	174
3. Introduction of Some Approximations— <i>a. Perturbative Cal-</i> <i>culation of the Level-Shift Operator. Partial Resummation of</i> <i>the Perturbation Series. b. Approximation Consisting of Ne-</i> <i>glecting the Energy Dependence of the Level-Shift Operator. . .</i>	179
C. Study of a Few Examples	183
1. Evolution of an Excited Atomic State— <i>a. Nonperturbative</i> <i>Calculation of the Probability Amplitude That the Atom Re-</i>	

<i>mains Excited. b. Radiative Lifetime and Radiative Level Shift. c. Conditions of Validity for the Treatment of the Two Preceding Subsections</i>	183
2. Spectral Distribution of Photons Spontaneously Emitted by an Excited Atom— <i>a. Relevant Matrix Element of the Resolvent Operator. b. Generalization to a Radiative Cascade. c. Natural Width and Shift of the Emitted Lines</i>	189
3. Indirect Coupling between a Discrete Level and a Continuum. Example of the Lamb Transition— <i>a. Introducing the Problem. b. Nonperturbative Calculation of the Transition Amplitude. c. Weak Coupling Limit. Bethe Formula. d. Strong Coupling Limit. Rabi Oscillation</i>	197
4. Indirect Coupling between Two Discrete States. Multiphoton Transitions— <i>a. Physical Process and Subspace \mathcal{E}_0 of Relevant States. b. Nonperturbative Calculation of the Transition Amplitude. c. Weak Coupling Case. Two-Photon Excitation Rate. d. Strong Coupling Limit. Two-Photon Rabi Oscillation. e. Higher-Order Multiphoton Transitions. f. Limitations of the Foregoing Treatment</i>	205

COMPLEMENT A_{III}—ANALYTIC PROPERTIES OF THE RESOLVENT

<i>Introduction</i>	213
1. Analyticity of the Resolvent outside the Real Axis	213
2. Singularities on the Real Axis	215
3. Unstable States and Poles of the Analytic Continuation of the Resolvent	217
4. Contour Integral and Corrections to the Exponential Decay	220

COMPLEMENT B_{III}—NONPERTURBATIVE EXPRESSIONS FOR THE SCATTERING AMPLITUDES OF A PHOTON BY AN ATOM

<i>Introduction</i>	222
1. Transition Amplitudes between Unperturbed States— <i>a. Using the Resolvent. b. Transition Matrix. c. Application to Resonant Scattering. d. Inadequacy of Such an Approach</i>	222

2. Introducing Exact Asymptotic States— <i>a. The Atom in the Absence of Free Photons. b. The Atom in the Presence of a Free Photon</i>	229
3. Transition Amplitude between Exact Asymptotic States— <i>a. New Definition of the S-Matrix. b. New Expression for the Transition Matrix. Physical Discussion</i>	233

**COMPLEMENT C_{III}—DISCRETE STATE COUPLED TO A
FINITE-WIDTH CONTINUUM: FROM THE WEISSKOPF–WIGNER
EXPONENTIAL DECAY TO THE RABI OSCILLATION**

1. Introduction—Overview	239
2. Description of the Model— <i>a. Unperturbed States. b. Assumptions concerning the Coupling. c. Calculation of the Resolvent and of the Propagators. d. Fourier Transform of the Amplitude $U_b(\tau)$</i>	240
3. The Important Physical Parameters— <i>a. The Function $\Gamma_b(E)$. b. The Parameter Ω_1 Characterizing the Coupling of the Discrete State with the Whole Continuum. c. The Function $\Delta_b(E)$</i>	244
4. Graphical Discussion— <i>a. Construction of the Curve $\mathcal{W}_b(E)$. b. Graphical Determination of the Maxima of $\mathcal{W}_b(E)$. Classification of the Various Regimes</i>	246
5. Weak Coupling Limit— <i>a. Weisskopf–Wigner Exponential Decay. b. Corrections to the Exponential Decay</i>	249
6. Intermediate Coupling. Critical Coupling— <i>a. Power Expansion of $\mathcal{W}_b(E)$ near a Maximum. b. Physical Meaning of the Critical Coupling</i>	251
7. Strong Coupling	253

IV

**RADIATION CONSIDERED AS A RESERVOIR: MASTER
EQUATION FOR THE PARTICLES**

A. Introduction—Overview	257
B. Derivation of the Master Equation for a Small System \mathcal{A} Interacting with a Reservoir \mathcal{R}	262
1. Equation Describing the Evolution of the Small System in the Interaction Representation	262

2. Assumptions Concerning the Reservoir— <i>a. State of the Reservoir. b. One-Time and Two-Time Averages for the Reservoir Observables</i>	263
3. Perturbative Calculation of the Coarse-Grained Rate of Variation of the Small System	266
4. Master Equation in the Energy-State Basis	269
C. Physical Content of the Master Equation	272
1. Evolution of Populations	272
2. Evolution of Coherences	274
D. Discussion of the Approximations	278
1. Order of Magnitude of the Evolution Time for \mathcal{A}	278
2. Condition for Having Two Time Scales	278
3. Validity Condition for the Perturbative Expansion	279
4. Factorization of the Total Density Operator at Time t	280
5. Summary	281
E. Application to a Two-Level Atom Coupled to the Radiation Field	282
1. Evolution of Internal Degrees of Freedom— <i>a. Master Equation Describing Spontaneous Emission for a Two-Level Atom. b. Additional Terms Describing the Absorption and Induced Emission of a Weak Broadband Radiation</i>	282
2. Evolution of Atomic Velocities— <i>a. Taking into Account the Translational Degrees of Freedom in the Master Equation. b. Fokker-Planck Equation for the Atomic Velocity Distribution Function. c. Evolutions of the Momentum Mean Value and Variance. d. Steady-State Distribution. Thermodynamic Equilibrium</i>	289

COMPLEMENT A_{IV}—FLUCTUATIONS AND LINEAR RESPONSE APPLICATION TO RADIATIVE PROCESSES

<i>Introduction</i>	302
1. Statistical Functions and Physical Interpretation of the Master Equation— <i>a. Symmetric Correlation Function. b. Linear Sus-</i>	

ceptibility. c. Polarization Energy and Dissipation. d. Physical Interpretation of the Level Shifts. e. Physical Interpretation of the Energy Exchanges	302
2. Applications to Radiative Processes— <i>a. Calculation of the Statistical Functions. b. Physical Discussion. c. Level Shifts due to the Fluctuations of the Radiation Field. d. Level Shifts due to Radiation Reaction. e. Energy Exchanges between the Atom and the Radiation</i>	312

COMPLEMENT B_{IV}—MASTER EQUATION FOR A DAMPED HARMONIC OSCILLATOR

1. The Physical System	322
2. Operator Form of the Master Equation	323
3. Master Equation in the Basis of the Eigenstates of H_A — <i>a. Evolution of the Populations. b. Evolution of a Few Average Values</i>	326
4. Master Equation in a Coherent State Basis— <i>a. Brief Review of Coherent States and the Representation P_N of the Density Operator. b. Evolution Equation for $P_N(\beta, \beta^*, t)$. c. Physical Discussion</i>	329

COMPLEMENT C_{IV}—QUANTUM LANGEVIN EQUATIONS FOR A SIMPLE PHYSICAL SYSTEM

<i>Introduction</i>	334
1. Review of the Classical Theory of Brownian Motion— <i>a. Langevin Equation. b. Interpretation of the Coefficient D. Connection between Fluctuations and Dissipation. c. A Few Correlation Functions</i>	334
2. Heisenberg–Langevin Equations for a Damped Harmonic Oscillator— <i>a. Coupled Heisenberg Equations. b. The Quantum Langevin Equation and Quantum Langevin Forces. c. Connection between Fluctuations and Dissipation. d. Mixed Two-Time Averages Involving Langevin Forces and Operators of \mathcal{A}. e. Rate of Variation of the Variances \mathcal{V}_N and \mathcal{V}_A. f. Generalization of Einstein's Relation. g. Calculation of Two-Time Averages for Operators of \mathcal{A}. Quantum Regression Theorem</i>	340

V OPTICAL BLOCH EQUATIONS

<i>Introduction</i>	353
A. Optical Bloch Equations for a Two-Level Atom	355
1. Description of the Incident Field	355
2. Approximation of Independent Rates of Variation	356
3. Rotating-Wave Approximation— <i>a. Elimination of Antiresonant Terms. b. Time-Independent Form of the Optical Bloch Equations. c. Other Forms of the Optical Bloch Equations</i> . . .	357
4. Geometric Representation in Terms of a Fictitious Spin $\frac{1}{2}$. . .	361
B. Physical Discussion—Differences with Other Evolution Equations	364
1. Differences with Relaxation Equations. Couplings between Populations and Coherences	364
2. Differences with Hamiltonian Evolution Equations	364
3. Differences with Heisenberg–Langevin Equations	365
C. First Application—Evolution of Atomic Average Values	367
1. Internal Degrees of Freedom— <i>a. Transient Regime. b. Steady-State Regime. c. Energy Balance. Mean Number of Incident Photons Absorbed per Unit Time</i>	367
2. External Degrees of Freedom. Mean Radiative Forces— <i>a. Equation of Motion of the Center of the Atomic Wave Packet. b. The Two Types of Forces for an Atom Initially at Rest. c. Dissipative Force. Radiation Pressure. d. Reactive Force. Dipole Force</i>	370
D. Properties of the Light Emitted by the Atom	379
1. Photodetection Signals. One- and Two-Time Averages of the Emitting Dipole Moment— <i>a. Connection between the Radiated Field and the Emitting Dipole Moment. b. Expression of Photodetection Signals</i>	379
2. Total Intensity of the Emitted Light— <i>a. Proportionality to the Population of the Atomic Excited State. b. Coherent Scattering and Incoherent Scattering. c. Respective Contributions of Coherent and Incoherent Scattering to the Total Intensity Emitted in Steady State</i>	382
3. Spectral Distribution of the Emitted Light in Steady	

State— <i>a. Respective Contributions of Coherent and Incoherent Scattering. Elastic and Inelastic Spectra. b. Outline of the Calculation of the Inelastic Spectrum. c. Inelastic Spectrum in a Few Limiting Cases</i>	384
--	-----

COMPLEMENT A_V—BLOCH–LANGEVIN EQUATIONS AND QUANTUM REGRESSION THEOREM

<i>Introduction</i>	388
1. Coupled Heisenberg Equations for the Atom and the Field— <i>a. Hamiltonian and Operator Basis for the System. b. Evolution Equations for the Atomic and Field Observables. c. Rotating-Wave Approximation. Change of Variables. d. Comparison with the Harmonic Oscillator Case</i>	388
2. Derivation of the Heisenberg–Langevin Equations— <i>a. Choice of the Normal Order. b. Contribution of the Source Field. c. Summary. Physical Discussion</i>	394
3. Properties of Langevin Forces— <i>a. Commutation Relations between the Atomic Dipole Moment and the Free Field. b. Calculation of the Correlation Functions of Langevin Forces. c. Quantum Regression Theorem. d. Generalized Einstein Relations</i>	398

VI THE DRESSED ATOM APPROACH

A. Introduction: The Dressed Atom	407
B. Energy Levels of the Dressed Atom	410
1. Model of the Laser Beam	410
2. Uncoupled States of the Atom + Laser Photons System . . .	412
3. Atom-Laser Photons Coupling— <i>a. Interaction Hamiltonian. b. Resonant and Nonresonant Couplings. c. Local Periodicity of the Energy Diagram. d. Introduction of the Rabi Frequency</i>	413

4. Dressed States— <i>a. Energy Levels and Wave Functions.</i> <i>b. Energy Diagram versus $\hbar\omega_L$</i>	415
5. Physical Effects Associated with Absorption and Induced Emission	417
C. Resonance Fluorescence Interpreted as a Radiative Cascade of the Dressed Atom	419
1. The Relevant Time Scales	419
2. Radiative Cascade in the Uncoupled Basis— <i>a. Time Evolution of the System.</i> <i>b. Photon Antibunching.</i> <i>c. Time Intervals between Two Successive Spontaneous Emissions</i>	420
3. Radiative Cascade in the Dressed State Basis— <i>a. Allowed Transitions between Dressed States.</i> <i>b. Fluorescence Triplet.</i> <i>c. Time Correlations between Frequency Filtered Fluorescence Photons</i>	423
D. Master Equation for the Dressed Atom	427
1. General Form of the Master Equation— <i>a. Approximation of Independent Rates of Variation.</i> <i>b. Comparison with Optical Bloch Equations</i>	427
2. Master Equation in the Dressed State Basis in the Secular Limit— <i>a. Advantages of the Coupled Basis in the Secular Limit.</i> <i>b. Evolution of Populations.</i> <i>c. Evolution of Coherences—Transfer of Coherences.</i> <i>d. Reduced Populations and Reduced Coherences</i>	429
3. Quasi-Steady State for the Radiative Cascade— <i>a. Initial Density Matrix.</i> <i>b. Transient Regime and Quasi-Steady State</i>	435
E. Discussion of a Few Applications	437
1. Widths and Weights of the Various Components of the Fluorescence Triplet— <i>a. Evolution of the Mean Dipole Moment.</i> <i>b. Widths and Weights of the Sidebands.</i> <i>c. Structure of the Central Line</i>	437
2. Absorption Spectrum of a Weak Probe Beam— <i>a. Physical Problem.</i> <i>b. Case Where the Two Lasers Are Coupled to the Same Transition.</i> <i>c. Probing on a Transition to a Third Level. The Autler-Townes Effect</i>	442
3. Photon Correlations— <i>a. Calculation of the Photon-Correlation Signal.</i> <i>b. Physical Discussion.</i> <i>c. Generalization to a Three-Level System: Intermittent Fluorescence</i>	446
4. Dipole Forces— <i>a. Energy Levels of the Dressed Atom in a</i>	

<i>Spatially Inhomogeneous Laser Wave. b. Interpretation of the Mean Dipole Force. c. Fluctuations of the Dipole Force</i>	454
--	-----

COMPLEMENT A_{VI}—THE DRESSED ATOM IN THE RADIO-FREQUENCY DOMAIN

<i>Introduction</i>	460
1. Resonance Associated with a Level Crossing or Anticrossing— <i>a. Anticrossing for a Two-Level System. b. Higher-Order Anticrossing. c. Level Crossing. Coherence Resonance . . .</i>	461
2. Spin $\frac{1}{2}$ Dressed by Radio-Frequency Photons— <i>a. Description of the System. b. Interaction Hamiltonian between the Atom and the Radio-Frequency Field. c. Preparation and Detection</i>	468
3. The Simple Case of Circularly Polarized Photons— <i>a. Energy Diagram. b. Magnetic Resonance Interpreted as a Level-Anticrossing Resonance of the Dressed Atom. c. Dressed State Level-Crossing Resonances</i>	473
4. Linearly Polarized Radio-Frequency Photons— <i>a. Survey of the New Effects. b. Bloch–Siegert Shift. c. The Odd Spectrum of Level-Anticrossing Resonances. d. The Even Spectrum of Level-Crossing Resonances. e. A Nonperturbative Calculation: The Landé Factor of the Dressed Atom. f. Qualitative Evolution of the Energy Diagram at High Intensity</i>	479

COMPLEMENT B_{VI}—COLLISIONAL PROCESSES IN THE PRESENCE OF LASER IRRADIATION

<i>Introduction</i>	490
1. Collisional Relaxation in the Absence of Laser Irradiation— <i>a. Simplifying Assumptions. b. Master Equation Describing the Effect of Collisions on the Emitting Atom</i>	491
2. Collisional Relaxation in the Presence of Laser Irradiation— <i>a. The Dressed Atom Approach. b. Evolution of Populations: Collisional Transfers between Dressed States. c. Evolution of Coherences. Collisional Damping and Collisional Shift. d. Explicit Form of the Master Equation in the Impact Limit</i>	494

3. Collision-Induced Modifications of the Emission and Absorption of Light by the Atom. Collisional Redistribution— <i>a. Taking into Account Spontaneous Emission. b. Reduced Steady-State Populations. c. Intensity of the Three Components of the Fluorescence Triplet. d. Physical Discussion in the Limit $\Omega_1 \ll \delta_L \ll \tau_{\text{coll}}^{-1}$</i>	501
4. Sketch of the Calculation of the Collisional Transfer Rate— <i>a. Expression of the Transfer Rate as a Function of the Collision S-Matrix. b. Case Where the Laser Frequency Becomes Resonant during the Collision. Limit of Large Detunings</i>	510

EXERCISES

1. Calculation of the Radiative Lifetime of an Excited Atomic Level. Comparison with the Damping Time of a Classical Dipole Moment	515
2. Spontaneous Emission of Photons by a Trapped Ion. Lamb-Dicke Effect	518
3. Rayleigh Scattering	524
4. Thomson Scattering	527
5. Resonant Scattering	530
6. Optical Detection of a Level Crossing between Two Excited Atomic States	533
7. Radiative Shift of an Atomic Level. Bethe Formula for the Lamb Shift	537
8. Bremsstrahlung. Radiative Corrections to Elastic Scattering by a Potential	548
9. Low-Frequency Bremsstrahlung. Nonperturbative Treatment of the Infrared Catastrophe	557
10. Modification of the Cyclotron Frequency of a Particle due to Its Interactions with the Radiation Field	564
11. Magnetic Interactions between Spins	571
12. Modification of an Atomic Magnetic Moment due to Its Coupling with Magnetic Field Vacuum Fluctuations	576
13. Excitation of an Atom by a Wave Packet: Broadband Excitation and Narrow-Band Excitation	580
14. Spontaneous Emission by a System of Two Neighboring Atoms. Superradiant and Subradiant States	585
15. Radiative Cascade of a Harmonic Oscillator	589
16. Principle of the Detailed Balance	596

17. Equivalence between a Quantum Field in a Coherent State and an External Field	597
18. Adiabatic Elimination of Coherences and Transformation of Optical Bloch Equations into Relaxation Equations	601
19. Nonlinear Susceptibility for an Ensemble of Two-Level Atoms. A Few Applications	604
20. Absorption of a Probe Beam by Atoms Interacting with an Intense Beam. Application to Saturated Absorption	608

APPENDIX

QUANTUM ELECTRODYNAMICS IN THE COULOMB GAUGE—SUMMARY OF THE ESSENTIAL RESULTS

1. Description of the Electromagnetic Field— <i>a. Electric Field \mathbf{E} and Magnetic Field \mathbf{B}. b. Vector Potential \mathbf{A} and Scalar Potential U. c. Coulomb Gauge. d. Normal Variables. e. Principle of Canonical Quantization in the Coulomb Gauge. f. Quantum Fields in the Coulomb Gauge</i>	621
2. Particles	628
3. Hamiltonian and Dynamics in the Coulomb Gauge— <i>a. Hamiltonian. b. Unperturbed Hamiltonian and Interaction Hamiltonian. c. Equations of Motion</i>	629
4. State Space	633
5. The Long-Wavelength Approximation and the Electric Dipole Representation— <i>a. The Unitary Transformation. b. The Physical Variables in the Electric Dipole Representation. c. The Displacement Field. d. Electric Dipole Hamiltonian</i>	635
<i>References</i>	641
<i>Index</i>	645