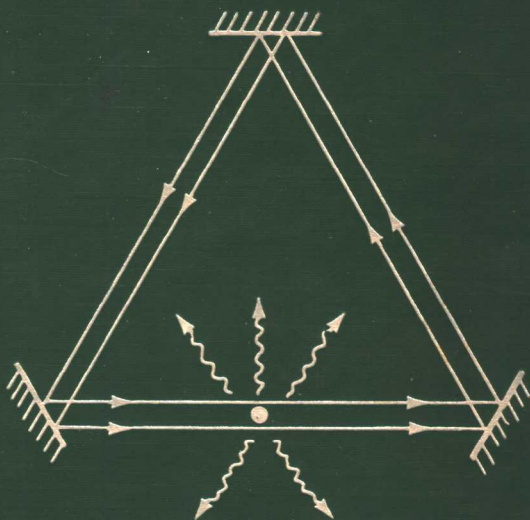


ATOM-PHOTON INTERACTIONS

Basic Processes
and Applications



Claude Cohen-Tannoudji
Jacques Dupont-Roc
Gilbert Grynberg

Atom-Photon Interactions

Basic Processes and Applications

Claude Cohen-Tannoudji
Jacques Dupont-Roc
Gilbert Grvnberg

A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS, INC.

New York Chichester Brisbane Toronto Singapore

In recognition of the importance of preserving what has been written, it is a policy of John Wiley & Sons, Inc., to have books of enduring value published in the United States printed on acid-free paper, and we exert our best efforts to that end.

Copyright © 1992 by John Wiley & Sons, Inc.

This is a translation of *Processus d'interaction entre photons et atomes*.

Copyright © 1988, InterEditions and Editions du CNRS.

Translation by Patricia Thickstun.

All rights reserved. Published simultaneously in Canada.

Reproduction or translation of any part of this work beyond that permitted by Section 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons, Inc.

Library of Congress Cataloging in Publication Data:

Cohen-Tannoudji, Claude, 1933–

[Processus d'interaction entre photons et atomes. English]

Atom-photon interactions: basic processes and applications/

Claude Cohen-Tannoudji, Jacques Dupont-Roc, Gilbert Grynberg.

p. cm.

Translation of: *Processus d'interaction entre photons et atomes*.

"A Wiley-Interscience publication."

Includes bibliographical references and index.

ISBN 0-471-62556-6 (cloth: acid-free paper)

1. Photonuclear reactions. 2. Quantum theory. 3. Statistical physics. I. Dupont-Roc, Jacques. II. Grynberg, Gilbert.

III. Title.

QC794.8.P4C6413 1992

91-40587

539.7'56-dc20

CIP

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Preface

The spectacular development of new sources of electromagnetic radiation, covering a range of frequencies from radio waves to far ultraviolet (lasers, masers, synchrotron radiation, microwave sources), has resulted in considerably renewed interest in photon-atom interactions. New methods have appeared for obtaining more precise information about the structure and dynamics of atoms and molecules, for controlling their internal and external degrees of freedom, and for generating new types of radiation. These developments have caused a growing number of physicists, chemists, researchers, and engineers to become interested in interactions occurring between matter and low-energy radiation. With these two books on photons and atoms, our aim is to provide the theoretical bases necessary for undertaking the study of these processes beginning at a level of quantum mechanics and classical electromagnetism corresponding to that of first-year graduate course.

Such a program is naturally composed of two parts. First, one must introduce a theoretical framework that can be used to describe the quantum dynamics of the global system "electromagnetic field + nonrelativistic charged particles" and discuss the physical content of the theory, as well as its different possible formulations. These problems have been studied in a previous volume entitled *Photons and Atoms—Introduction to Quantum Electrodynamics*. Second, one must show how such a theoretical framework can be used to analyze the interactions between photons and atoms as they appear in atomic and molecular physics, quantum optics, and laser physics. This is the goal of the present volume entitled *Atom-Photon Interactions: Basic Processes and Applications*. The goals of these two volumes are thus clearly distinct and, depending on the concerns and needs of the reader, one or the other or both volumes of this work may be used.

It is, of course, impossible to present in a single volume an exhaustive study of the interaction between matter and radiation and of all the related physical phenomena. We have thus emphasized the aspects that we consider to be essential. First we will analyze in detail the elementary processes in which photons are emitted, absorbed, scattered, emitted and reabsorbed, or exchanged between atoms. Extensive use of diagrammatic representations will allow us to visualize the processes being described. A knowledge of these elementary processes is, nevertheless, not always sufficient for analyzing in simple terms the extremely large variety of

phenomena which may result from the interplay of these processes. Thus we thought it important to bring together in this book different theoretical approaches, which are usually dispersed in more specialized works, and which are more particularly adapted to one aspect or another of the phenomena being discussed (perturbative methods, resolvent method, master equation, Langevin equation, optical Bloch equations, dressed atom method, etc.). Finally, we have decided to illustrate each of these methods in simple systems, so as to be able to show as clearly as possible their significance and their limitations. Our hope is to have integrated in this volume the basic elements allowing the physics of the matter-radiation interaction be mastered in all its different aspects.

ACKNOWLEDGMENTS

This work is based on teaching and research that has been carried out over several years at Collège de France and the Physics Department of the Ecole Normale Supérieure. We would like to express our thanks to our colleagues and friends, in particular Serge Reynaud and Jean Dalibard, who directly participated in this research and from whose comments we benefited.

We are also especially grateful to Martine Guillaume, Patricia Bouniol, and Catherine Emo who were in charge of preparing the manuscript, and to Christophe Salomon, who checked the translation.

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 A₁—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 Electron: Mass Correction. b. Case of an Atomic Electron: Natural 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 Photodetector. b. Narrow-Band Photodetector</i>	128
2. Excitation Probability and Correlation Functions— <i>a. Hamiltonian. 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 $\mathcal{U}_b(E)$. b. Graphical Determination of the Maxima of $\mathcal{U}_b(E)$. 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 $\mathcal{U}_b(E)$ 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{S} 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>	