

Contents

Part I Microscopic Classical Theory

1	Survey of the Classical Theory	3
1.1	Why is the Classical Theory Needed?	3
1.2	Classical Electrodynamics: Macroscopic vs. Microscopic Theory	4
1.3	Maxwell–Lorentz Electrodynamics	6
1.4	The Standard Green Functions (Not Propagators)	7
1.5	Evanescent Electromagnetic Fields	8
1.6	Multipole Electrodynamics: A Richly Faceted Subject	11
1.7	Local Electromagnetic Fields and Resonances	14
1.8	Radiation Reaction in a Classical Perspective	15
2	Maxwell–Lorentz Electrodynamics in Space-Time	17
2.1	The Maxwell–Lorentz Equations	17
2.2	Vector and Scalar Potentials: Gauge Invariance	17
2.3	The Implicit Solution of the Maxwell–Lorentz Equations	19
2.4	The Newton–Lorentz Equation	22
2.5	The Liénard–Wiechert Potentials and Fields	23
2.6	Some Important Global Conservation Laws	28
2.6.1	Global Energy Conservation	28
2.6.2	Global Momentum Conservation	30
2.6.3	Global Angular Momentum Conservation	32
2.7	Some Local Conservation Laws	33
2.7.1	Charge Conservation	33
2.7.2	Local Energy Conservation: Microscopic Poynting Vector	34
2.7.3	Local Momentum Conservation: Maxwell Stress Tensor	35
2.7.4	Local Angular Momentum Conservation: Angular Momentum Flow	37

3	Electromagnetic Green Functions in Spectral Representation	39
3.1	The Maxwell–Lorentz Equations in the Space–Frequency Domain	39
3.2	Dyadic Green Functions in the Space–Frequency Domain	40
3.2.1	Green Function for the Electric Field	40
3.2.2	Green Function for the Magnetic Field	42
3.3	Near-, Mid-, and Far-Field Parts of \mathbf{G} and \mathbf{G}_M	43
3.3.1	Green Functions in Spherical Coordinates	43
3.3.2	Far-Field Zone	44
3.3.3	Mid-Field Terms	45
3.3.4	Near-Field Zone	45
3.4	Green Functions and Wave Equations in the Space–Frequency Domain	46
3.5	Spectral Representation of the Electromagnetic Field from an Assembly of Moving Point Particles	48
4	Angular Spectrum Representation of the Green Functions and Fields	51
4.1	Maxwell–Lorentz Equations in Mixed Representation	51
4.2	Interlude: Monochromatic Plane-Wave Representation of the Maxwell–Lorentz Equations and Green Functions	53
4.3	Green Functions in Mixed Representation	56
4.3.1	Scalar Propagator, $g(\mathbf{Z}; \mathbf{q}_{\parallel}, \omega)$	56
4.3.2	Dyadic Green Function, $\mathbf{G}(\mathbf{Z}; \mathbf{q}_{\parallel}, \omega)$	58
4.3.3	Dyadic Green function, $\mathbf{G}_M(\mathbf{Z}; \mathbf{q}_{\parallel}, \omega)$	59
4.4	Evanescent Electromagnetic Fields	60
4.4.1	Electromagnetic Fields from a Sheet Source	60
4.4.2	Transfer Matrices	61
4.4.3	Mixed Current Density of a Moving Point Charge	62
4.4.4	Cycle-Averaged Field Momentum Density	63
4.5	Nonretarded ($c_0 \rightarrow \infty$) Electrodynamics in Vacuum	66
4.6	Weyl Representation of the Green Functions	68
4.6.1	Integrals Over Propagating and Evanescent Waves	68
4.6.2	Integrals Over Generalized Inhomogeneous Waves	71
5	Multipole Electrodynamics	75
5.1	Moment Expansion of Localized Current Density Distribution	75
5.2	Electric and Magnetic Dipole Fields	79
5.3	Electric Quadrupole Fields	81
5.4	Transverse Electromagnetic Multipole Waves	83
5.4.1	Spherical Scalar Waves	83
5.4.2	Interlude: Angular Field Momentum Operator \hat{J}	85
5.4.3	Electric and Magnetic Multipole Fields	87
5.5	Microscopic Sources of Multipole Fields	89
5.5.1	Microscopic Maxwell Equations with a New Electric-Field Variable	89

5.5.2	Interlude: Spherical Wave Expansion of the Huygens Propagator	91
5.5.3	Multipole Coefficients	92
5.6	Mesoscopic Particle in a Prescribed External Electromagnetic Field	94
5.6.1	Rate of Energy Transfer	94
5.6.2	Rate of Momentum Transfer	95
5.6.3	Angular Momentum Transfer	96
6	Electrodynamic Interaction Between Point Dipoles: Local Fields	99
6.1	Multiple ED-Scattering to Infinite Order	99
6.2	ED-Scattering in a Born Series Approach	102
6.3	Local-Field Resonances	105
6.4	Two-Particle Interaction	106
6.5	Multiple MD- and EQ-Scattering	108
7	Radiation Reaction	111
7.1	The Nonrelativistic Abraham–Lorentz Equation of Motion	111
7.2	Damping Force on Electric and Magnetic Dipoles	116
7.2.1	Bare and Dressed Electric-Dipole Polarizability	116
7.2.2	Near-Zone Electric Green Function: Radiation Damping	118
7.2.3	Magnetic Radiation Damping	119
7.3	The Relativistic Lorentz–Dirac Equation of Motion	120
7.3.1	Manifestly Covariant Expression for the Energy–Momentum Radiation Rate	120
7.3.2	Rest-Mass Preserving Interactions	122
7.3.3	Abraham Four-Vector of Radiation Reaction	124
7.3.4	Lorentz–Dirac Equation on Integro-Differential Form	125
7.4	Self-Field Distortions	126
Part II Quantum Theory with Classical Fields		
8	About Local-Field Theory Based on Electron–Photon Wave Mechanics	131
8.1	Dynamical Variables and Redundancy: Rim Zone	132
8.2	Linear Response Theory in a Microscopic Perspective	133
8.3	On the Quantum Mechanical Calculation of Microscopic Conductivity Tensors	136
8.4	Coupled-Antenna Theory	137
8.5	Electromagnetic Propagators and Nonretarded Transverse Response	138

8.6	Photon Wave Mechanics: A Reinterpretation of Maxwells Theory	139
8.7	Near-Field and Gauge Photons: Photon Embryo	141
8.8	Photon Spin and Helicity	142
8.9	Superlocalization: One-Particle Position Operators	143
8.10	Transverse Photon Mass: Eikonal Theory for Photons	143
9	Transverse and Longitudinal Electrodynamics	145
9.1	Solenoidal and Irrotational Vector Fields	145
9.1.1	Helmholtz Theorem	145
9.1.2	Decomposition in Reciprocal Space	146
9.1.3	Transverse and Longitudinal Delta-Function Dyadics	147
9.2	Transverse and Longitudinal Parts of the Maxwell–Lorentz Equations	149
9.2.1	Field Equations in Direct Space	149
9.2.2	Rim Zone of Matter	151
9.2.3	Field Equations in Reciprocal Space	152
9.2.4	Potential Description	152
9.3	Role of the Longitudinal Electric Field	154
9.3.1	Instantaneous Coulomb Field	154
9.3.2	Coulomb Interaction and Self-Energy	155
9.3.3	Particle Momentum Associated with the Longitudinal Electric Field	157
9.3.4	Particle Angular Momentum Associated with the Longitudinal Electric Field	160
9.4	Dynamical State of the Coupled Field–Particle System	162
10	Linear Nonlocal Response Theory	163
10.1	Response Theory for Transverse External Excitations	163
10.1.1	Many-Body Constitutive Relation	163
10.1.2	Integral Equation for the Transverse Electric Field	165
10.1.3	Causal Response Tensors: Microscopic Conductivity	166
10.2	Causality and Dispersion Relations	167
10.2.1	Einstein Causality and Microcausality	167
10.2.2	Causality and Analyticity: Translational Invariance in Time	168
10.2.3	Frequency Dispersion and Hilbert Transforms	170
10.3	Local and Near-Local Microscopic Response Tensors	172
10.3.1	Spatial Correlation Range in Constitutive Equations	172
10.3.2	Local Dynamics with Hidden Nonlocality	174
10.4	Microscopic “Polarization” and “Magnetization” Dynamics	175
10.4.1	Generalized Polarization and Magnetization Concepts	175
10.4.2	Generalized Electric Displacement and Magnetic Vector Fields	177
10.4.3	Central Field Equations	178

10.5	Response Theory Based on Generalized Permittivity and Permeability Tensors for Transverse Dynamics	179
10.5.1	Flexibility	179
10.5.2	Response Theory Based on the Choice $\mu_T(\mathbf{r}, \mathbf{r}', t, t') = U \delta(\mathbf{r} - \mathbf{r}') \delta(t - t')$	180
10.5.3	Response Theory Based on the Choice $D_T(\mathbf{r}, t) = \epsilon_0 E_T^{\text{ext}}(\mathbf{r}, t)$	181
10.6	Response to External Longitudinal Fields	182
10.7	The General Constitutive Relation	183
10.8	Response Tensors for Media with Finite and Infinitesimal Translational Invariance in Space	184
10.8.1	Lattice Periodicity	184
10.8.2	Slowly Varying External Fields	185
11	Density Matrix Formalism: Hamilton and Current Density Operators – Gauge Invariance	187
11.1	Density Matrix Operator	187
11.1.1	Pure State	187
11.1.2	Statistical Mixture of States	190
11.2	The Liouville Equation	193
11.3	The Configuration Space Representation	195
11.4	Hamilton Operator in Minimal Coupling Form	197
11.4.1	The Relativistic Standard Hamiltonian	197
11.4.2	Pauli and Nonrelativistic Hamiltonians	199
11.4.3	Canonical Quantization	200
11.5	Orbital Probability Current Density	204
11.5.1	Probability Current Density in Wave Function Space	204
11.5.2	Para- and Diamagnetic Current Densities	205
11.5.3	Transition Current Density	206
11.5.4	Orbital Current Density Operator	207
11.6	Gauge Invariance in Quantum Mechanics	209
11.6.1	Transformation of the Mechanical Momentum Operator	209
11.6.2	Unitary Transformation of the State Vector	210
11.6.3	Form Invariance of the Schrödinger Equation	212
11.6.4	Electromagnetic Forces and Local Phase Invariance	214
12	Quantum Theory of the Generalized Nonlocal Linear Response	217
12.1	Mean Value of the Orbital Current Density Operator in a Weak External Electromagnetic Field	217
12.1.1	Gauge Choices for the External and Induced Potentials: Interaction Hamiltonian	217
12.1.2	Iterative Solution of the Liouville Equation	220
12.1.3	Linearized Orbital Current Density	221

12.1.4	Calculation of the Mean Current Density in the \hat{H}_0 -Basis	222
12.2	The Nonlocal Linear Response Tensor	224
12.2.1	One-Electron Approximation	224
12.2.2	Many-Body Approach	227
12.3	Tensor Product Structure of the Orbital Response Tensor	229
12.4	Gauge Invariance of the Linearized Response	232
12.5	Remarks on the Low- and High-Frequency Responses	236
13	Microscopic Ewald–Oseen Extinction Theorem: Coupled-Antenna Theory	239
13.1	Extinction Theorem for Transverse Dynamics	239
13.1.1	Integral Relation Between Field and Current Density	239
13.1.2	Ewald–Oseen Extinction Theorem	242
13.2	Integral Equations	244
13.3	Coupled-Antenna Theory	245
13.3.1	Matrix Equation Problem for the Local Field	245
13.3.2	Local-Field Resonances	249
13.4	Two-Level System: Single Antenna Dynamics	251
14	Transverse and Covariant Electromagnetic Propagators: Principal Volume and Self-Field Dyadics	255
14.1	Transverse Propagator for the Electric Field	255
14.1.1	Spectral Representation	255
14.1.2	Genuine Transversality	257
14.1.3	Space–Time Form: Causality and Space-Like Near-Field Coupling	258
14.2	Eigenvector Expansion of Propagators	263
14.2.1	Distribution Theory	263
14.2.2	Transverse Eigenvector Expansion over a Finite Domain	264
14.2.3	Plane-Wave Eigenvector Expansion Over an Infinite Domain	266
14.3	Contraction Geometry and Transverse Self-Field Dynamics	267
14.3.1	Volume and Surface Integral Contributions to the Transverse Electric Field	268
14.3.2	The Connection Between the Volume Integral and the Exterior Solution for the Transverse Field	273
14.3.3	Self-Field Dyadic	274
14.4	Propagator Plus Self-Field Electrodynamics in the Rim Zone and Source Region	276
14.5	Near-Field Electrodynamics in Spherical Contraction Geometry	279
14.6	Relativistic Covariance of the Huygens Propagator	280

15	Photon Wave Mechanics: Complex Field Theory	283
15.1	Wave Mechanics and the Einstein–de Broglie Relations	283
15.2	Landau–Peierls Theory	285
15.3	Interlude: Complex Analytical Signals	287
15.4	Complex Field Theory in the Momentum–Time Domain	290
15.4.1	Photon Helicity Unit Vectors	290
15.4.2	Photon Helicity Eigenstates: Wave Function and Wave Equations	292
15.4.3	Photon Spinor Description	293
15.4.4	Quantum Mechanical Mean Values of the Photon Energy and Momentum	295
15.5	Complex Field Theory in the Space–Time Domain	297
15.5.1	Cartesian Photon Spin Operator: Helicity Operator	297
15.5.2	The Nonlocal Hamilton Operator of the Photon	300
15.6	Photon Probability Current Density and the Associated Operator ...	302
15.7	The Nonlocal Relation Between Field Vectors and Photon Wave Function	304
16	Photon Wave Mechanics: Energy Wave Function and Four-Potential Theories	307
16.1	Photon Energy Wave Function Formalism	307
16.1.1	Riemann–Silberstein Approach to Classical Electromagnetics in Free Space	307
16.1.2	Dynamical Equation for the Photon Energy Wave Function	309
16.1.3	Quantum Mechanical Mean Value of the Photon Energy–Momentum Operator in Reciprocal Space	312
16.1.4	Lorentz-Invariant Integration on the Light Cone	315
16.2	Relation Between the Energy Wave Function and Complex Field Formalisms in Direct Space	317
16.3	Wave Mechanics of Longitudinal and Scalar Photons: Standard Theory	319
16.3.1	Complex Field Theory in Terms of the Transverse Vector Potential	319
16.3.2	Longitudinal and Scalar Photon Wave Functions, and Their Related Wave Equations	320
16.3.3	Identity of the Longitudinal and Scalar Photons	322
16.3.4	Quantum Mechanical Mean Values of the Longitudinal and Scalar Photon Energies	323
16.4	Wave Mechanics of Gauge and Near-Field Photons	324
16.4.1	Transverse Photon Schrödinger-Like Equations in Direct and Reciprocal Space	325
16.4.2	Longitudinal and Scalar Photons Once More	326

16.4.3	Gauge and Near-Field Photons	327
16.4.4	Gauge Transformations Within the Lorenz Gauge	328
16.4.5	Elimination of the Gauge Photon	329
17	Photon Angular Momentum	333
17.1	Bodily Rotation of Scalar and Vector Fields	334
17.2	Orbital and Spin Parts of the Photon Angular Momentum	337
17.2.1	Division of the Angular Momentum of the Transverse Electromagnetic Field	337
17.2.2	Quantum Mechanical Mean Values of the Orbital and Spin Angular Momenta in the Complex Field Theory	339
17.2.3	Quantum Mechanical Mean Values of the Orbital and Spin Angular Momenta in the Energy Wave Function Formalism	341
17.3	More on the Photon Spin and Helicity	342
17.3.1	Are $\hat{\mathbf{L}}$ and $\hat{\mathbf{S}}$ Separate Observables for a Photon?	342
17.3.2	Quantum Mechanical Mean Value of the Cartesian Photon Spin Operator	343
17.3.3	Projected Photon Spin Operator	345
17.3.4	Eigenvectors and Eigenvalues of the Photon Helicity Operator	346
18	Photon Emission from Micro- and Mesoscopic Sources: Near-Field Aspects	349
18.1	Microscopic Electrodynamics Based on \mathbf{D} - and \mathbf{H} -Fields	350
18.1.1	New Microscopic Field Equations	350
18.1.2	Duality Between Old and New Transverse Electrodynamics: New Wave Equations	351
18.2	The Photon Embryo Concept	352
18.2.1	Dynamical Photon Wave Function Variables	352
18.2.2	Dynamical Equations for the Photon Wave Function Variables	354
18.2.3	Photon Embryo in Momentum Space	355
18.3	One-Photon Sources	357
18.4	Propagator Description of Photon Embryo in Space–Time	359
18.4.1	Remarks on the Classical Source Term $\mathbf{W}(\mathbf{r}, t)$	359
18.4.2	Propagator Solutions of the Wave Equations for $\mathbf{D}(\mathbf{r}, t)$ and $\mathbf{H}(\mathbf{r}, t)$	359
18.4.3	Propagation of Embryo State	360

18.5	Gauge and Near-Field Photon Embryos.....	361
18.5.1	Dynamical Equations for G- and NF-Photon Variables.....	361
18.5.2	Time Reversal: Solution of the Dynamical Equations for the G- and NF-Variables	363
19	Eikonal Theory for Transverse Photons and Massive Particles of Zero Spin	365
19.1	Foundations of Geometrical Optics	366
19.1.1	Macroscopic Maxwell Equations	366
19.1.2	Eikonal Equation and Energy Transport.....	367
19.2	Massive Transverse Photon	370
19.2.1	Microscopic Transverse Electrodynamics at High Frequencies	370
19.2.2	Quantum Mechanical Photon Wave Equation in a Homogeneous Medium	372
19.2.3	Energy–Momentum Relation: Mass of Transverse Photon	373
19.2.4	Photon Mass in the Energy Wave Function Formalism.....	374
19.3	Photon Eikonal Gradient: Local Particle Momentum	376
19.3.1	Photon Eikonal Equation	376
19.3.2	Local Photon Momentum	378
19.4	Hamilton–Jacobi Formulation of Classical Mechanics.....	380
19.4.1	The Hamilton Equations and Their Derivation from a Variational Principle	381
19.4.2	A Particular Canonical Transformation	383
19.4.3	Hamilton–Jacobi Equation for Hamilton’s Principal Function	384
19.4.4	Hamilton–Jacobi Equation for Hamilton’s Characteristic Function	385
19.5	Eikonal Theory of Charged Particles in Quantum Mechanics	386
19.5.1	Nonrelativistic Hamilton–Jacobi Equation	386
19.5.2	Quantum Potential and Probability Fluid Flow	389
19.5.3	Relativistic Hamilton–Jacobi Equation: Particle of Zero Spin.....	390
20	Spin-1/2 Currents: Spatial Photon Localization in Emission from a Pure Spin Transition	395
20.1	Spin-1/2 Current Density	395
20.1.1	Dirac Equation in Minimal Coupling Form	396
20.1.2	Fully Relativistic Dirac Current Density	398
20.1.3	Weakly Relativistic Pauli Spin Current Density	399
20.2	Spin Source for Photons: Absence of the Rim Zone	403
20.3	Photon Emission from Spin-1/2 Transitions	406
20.3.1	Electromagnetic Far Field.....	406
20.3.2	Emission from an Isotropic Microscopic Source.....	407

21	One-Particle Position Operators and Spatial Localization	411
21.1	Nonrelativistic Particle	411
21.2	Massive Relativistic Particle of Zero Spin	412
21.2.1	Position Operator	412
21.2.2	Eigenstates of the Position Operator: Localization in Configuration Space	413
21.3	Massless Spin-One Particle (Photon)	417
21.3.1	Transverse Eigenstates in Momentum Space	417
21.3.2	Dyadic Photon Position Operator	418
21.3.3	The Photon Position Operator Problem in Configuration Space	419
 Part III Quantum Electrodynamic Theory		
22	Near Fields and QED	423
22.1	The Zoo of Photons	423
22.1.1	One-Photon Wave Packets	425
22.2	Near-Field Commutators	425
22.3	Maxwell–Lorentz Operator Equations: Coulomb and Poincaré Gauges	426
22.4	Covariant Field Propagators	428
22.5	Photon Emission from Atoms and Mesoscopic Objects	429
22.6	Virtual Transverse Photon Exchange in Near-Field Electrodynamics	432
22.7	Exchange of Scalar Photons	433
22.8	Coherent States of Evanescent Fields	433
 23	 The Route to the Maxwell–Lorentz Operator Equations in the Coulomb Gauge	 435
23.1	Plane-Wave Quantization of the Transverse Electromagnetic Field	435
23.1.1	The Classical Field Vectors	435
23.1.2	The Classical Field Energy and Momentum in Free Space	438
23.1.3	The Classical Spin of the Free Field	440
23.1.4	Quantization Scheme for the Radiation Field: Transverse Field Observables	442
23.1.5	Hamilton, Momentum and Spin Operators for the Transverse Electromagnetic Field	444
23.1.6	Monochromatic Plane-Wave Photons: A Brief Review	445
23.2	Temporal Evolution of the Global Field–Matter System	448
23.2.1	State Space	448
23.2.2	Total Nonrelativistic Hamiltonian in the Coulomb Gauge	448
23.2.3	The Schrödinger Picture	449

23.2.4	The Heisenberg Picture	450
23.2.5	The Interaction Picture	451
23.3	The Quantized Newton–Lorentz Equation	452
23.4	The Quantized Maxwell–Lorentz Equations in the Coulomb Gauge	455
23.4.1	Equation of Motion for the Annihilation Operator, \hat{a}_{qs}	455
23.4.2	Equations of Motions for the Transverse Electric ($\hat{\mathbf{E}}_T$) and Magnetic ($\hat{\mathbf{B}}$) Field Operators	458
23.4.3	Longitudinal Electric Field Operator	460
24	Field Commutators and Integral Representation of Various Covariant Propagators	461
24.1	The Jordan–Pauli and Feynman Scalar Propagators	462
24.2	Free-Field Commutators for Fields Taken at Different Space–Time Points	463
24.3	Field Commutators in the Presence of Field–Matter Interaction	468
24.3.1	Equal-Time Commutators	468
24.3.2	Weighted Average Values of Fields and Commutators	469
24.3.3	Quantum Mechanical Mean Value and Variance of the Mean Field	470
24.4	Contour Integral Representations of Covariant Scalar Propagators	472
24.4.1	The Jordan–Pauli Propagator	472
24.4.2	The Feynman Propagator	473
25	Electrodynamics in the Poincaré Gauge	477
25.1	The Poincaré Gauge	478
25.2	A Specific Choice for the Generalized Polarization and Magnetization	480
25.2.1	Polarization Field	480
25.2.2	Magnetization Field	482
25.3	Lagrangians in the Coulomb and Poincaré Gauges	484
25.3.1	Nonrelativistic Standard Lagrangian and Its Gauge Transformation	484
25.3.2	The Power–Zienau–Woolley Transformation	485
25.3.3	On the Elimination of the Redundancy from the Standard Lagrangian	486
25.3.4	Coulomb Lagrangian: Regrouping of Parts	487
25.3.5	Poincaré Interaction Lagrangian	488
25.3.6	Multipole Interaction Lagrangian	489
25.4	Conjugate Momenta: Coulomb and Poincaré Hamiltonians	490
25.4.1	Conjugate Particle Momentum	490
25.4.2	Conjugate Field Momentum	490
25.4.3	Hamiltonians	491

25.5	Quantum Description in the Poincaré Gauge	493
25.5.1	Quantum Representations Related by a Unitary Transformation: A Brief Review	493
25.5.2	The Unitary Transformation Relating the Quantum Descriptions in the Coulomb and Poincaré Gauges	495
25.5.3	Transformation of Various Physical Quantities	496
25.5.4	Canonical Quantization: Hamilton Operator	499
26	Photon-Field Operators: Wave-Packet Photons	501
26.1	Free Photon-Field Operators	502
26.2	Single-Photon States: Relation to Photon Wave Mechanics	504
26.3	Local and Global Bilinear Operators: Nonstationary One-Photon States	506
26.4	Wave-Packet Photon Operators and States	507
26.5	Maxwell–Lorentz Operator Equations in the Poincaré Gauge	510
26.6	Matter-Coupled Photon-Field Operators	511
26.7	Photon Embryo in Spontaneous Emission	512
27	Photon Emission From Atoms: Elements of the Nonrelativistic QED Description	515
27.1	Integral Relations Between Field and Particle Operators	516
27.1.1	On the Nonrelativistic Lamb Shift and Spontaneous Emission	516
27.1.2	Propagator Connection Between the Photon-Field and Source-Particle Operators	518
27.2	Field Radiation from Single-Particle Source	520
27.2.1	Second-Quantization of Source Current Density: Flip Operators	520
27.2.2	The Retarded Relation Between Field and Flip Operators	522
27.2.3	Single-Electron Spontaneous Emission: Neglect of Diamagnetism	523
27.3	The Electric Dipole Hamiltonian and the Associated Operator	525
27.3.1	Long-Wavelength Approximation of the Classical Poincaré Hamiltonian	525
27.3.2	Long-Wavelength Unitary Transformation of the Coulomb Hamilton Operator	527
27.4	Two-Level Atom	530
27.4.1	Raising and Lowering Operators	531
27.4.2	Pauli Operators	532
27.4.3	Electron-Field Operators	533
27.4.4	Electric-Dipole Hamiltonian	535

27.5	Dynamical Equations for a Coupled Two-Level Atom Plus Field System	537
27.5.1	Heisenberg Equation of Motion for the Atomic Flip Operator, \hat{b}	537
27.5.2	Heisenberg Equation of Motion for the Field Annihilation Operator, \hat{a}_{qs}	538
27.6	Spontaneous Emission and Lamb Shift: Heuristic Approach	539
27.6.1	Rotating-Wave Approximation	539
27.6.2	Markov Approximation	540
27.6.3	The Spontaneous Decay Rate	542
27.6.4	The Lamb-Shift Parameter	544
27.6.5	The Radiated Transverse Field	546
27.6.6	The $\{\hat{b}, \hat{b}^\dagger\}$ -Anticommutator Problem	549
27.6.7	Relation Between the Spontaneous Decay Rate and the Transverse Propagator	550
28	Particle–Particle Interaction by Transverse Photon Exchange	553
28.1	Multipole Expansion of the Coulomb Interaction Energy	554
28.2	Perturbation by an Effective Electronic Hamiltonian	556
28.3	Single-Photon Exchange Between Two Charged Particles	560
28.3.1	Qualitative Analysis of the Effective Hamiltonian to Second Order	561
28.3.2	Delay and Magnetic Corrections to the Coulomb Interaction	566
28.3.3	Momentum Exchange	569
28.4	Van der Waals Interaction Between Two Neutral Particles	571
28.4.1	Interaction from the Power–Zienau–Woolley Point of View	571
28.4.2	Exchange of Virtual Transverse Photons	574
28.5	Casimir Effect: Particle–Surface Interaction	578
28.6	Remarks on the Casimir–Polder Effect	581
29	Photons in a Manifestly Lorentz-Covariant Theory	583
29.1	Covariant Formulation of Classical Free-Field Dynamics	584
29.1.1	Covariant Notation	584
29.1.2	The Free Maxwell Equations in Covariant Form	585
29.1.3	Lagrange Equations for the Free Field: Standard Approach	586
29.1.4	Modified Field Lagrangian Density	587
29.2	Plane-Wave Expansion of the Four-Potential	589
29.2.1	Four-Component Polarization Vectors	589
29.2.2	Gauge, Near-Field, and Transverse Four-Component Potentials	590
29.2.3	Lorenz Condition: Gauge Arbitrariness	592
29.2.4	Electromagnetic Field Hamiltonian	593

29.3	Covariant Field Quantization	595
29.3.1	Hamilton Operator and Commutator Relations	595
29.3.2	Scalar Photons: The Problem of Negative Norms	597
29.3.3	Gupta–Bleuler–Lorenz Condition	598
29.3.4	Near-Field and Gauge Photon Quanta: Commutators and Hamilton Operator	600
29.4	Covariant Quantization with an Indefinite Metric	602
29.4.1	New Scalar Product and New Adjoining Operator, \tilde{O}	602
29.4.2	Choice of New Metric	603
29.4.3	Near-Field and Gauge Photons in the New Metric	605
29.5	$\hat{A}^\mu(x)$ -Commutators and the Feynman Photon Propagator	607
29.5.1	Covariant Commutation Relations	607
29.5.2	Equal-Time Commutation Relations	608
29.5.3	The Feynman Photon Propagator	609
30	Matter-Attached Quantized Fields	611
30.1	Analysis of the Covariant Photon Propagator	612
30.1.1	Combined Exchange of Longitudinal and Scalar Photons	612
30.1.2	Near-Field and Gauge Photon Exchange	615
30.2	Field–Particle Interaction in Covariant Notation	617
30.2.1	Interaction Lagrangian Density and Wave Equation	617
30.2.2	Retarded and Advanced Propagators: In- and Out-States	618
30.3	Interaction Between Two Fixed Charges: Exchange of Scalar Photons	621
30.3.1	Prescribed Particle Dynamics: Hamiltonian for Field Evolution	621
30.3.2	Energy Shift of the Ground State of the Field	622
30.3.3	Reinterpretation of Coulomb’s Law	625
30.4	Coulomb Interaction: The Near-Field and Gauge Photon Picture ..	627
30.5	Classical Potentials Generated by a Prescribed Sheet Source	629
30.5.1	Sheet Current Density	629
30.5.2	Longitudinal and Scalar Parts of the Classical Four-Potential	631
30.5.3	Quasi-Static Regime	635
30.5.4	Sheet Rim Zone	636
30.6	Quantum Field Radiated by a Classical Source	636
30.6.1	Current Density Without Quantum Fluctuations	636
30.6.2	Heisenberg Equations of Motion for the Annihilation Operators $\{a_r(q; t)\}$	637

30.6.3	Coherent Field State	638
30.6.4	Coherent Scalar and Longitudinal Photon Radiation from a Sheet Source	639
References	643
Index	653

Quantum Theory of Near-Field Electrodynamics

Keller, O.

2011, XXVI, 670 p., Hardcover

ISBN: 978-3-642-17409-4