
Appendix

In this appendix we collect a number of bibliographic references for the interested reader who either wants to learn more about Quantum Electrodynamics or is interested in the imbedding of QED in the more general framework of Quantum Field Theory.

1. Books which contain details on the formulation of QED and the calculation of various processes:

- A. Akhiezer and V.B. Berestetskii: *Quantum Electrodynamics*, Interscience, New York (1965)
- J.M. Jauch and F. Rohrlich: *The Theory of Photons and Electrons*, Springer-Verlag, New York, Heidelberg, Berlin (1976)
- G. Källén: *Quantum Electrodynamics*, Springer-Verlag, Berlin (1972)
- I. Bialynicki-Birula and Z. Bialynicka-Birula: *Quantum Electrodynamics*, Pergamon, Oxford (1975)
- V.B. Berestetskii, E.M. Lifshitz, and L.P. Pitaevskii: *Relativistic Quantum Theory*, Pergamon Press, Oxford (1971)
- P.W. Milonni: *The Quantum Vacuum – An Introduction to Quantum Electrodynamics*, Academic Press, San Diego (1994)

2. Two books covering topics related to QED with strong external fields:

- W. Greiner, B. Müller, J. Rafelski: *Quantum Electrodynamics of Strong Fields*, Springer-Verlag, Berlin (1985)
- V.L. Ginzburg (ed.): *Issues in Intense-Field Quantum Electrodynamics*, Nova Science Publ., Commack, N.Y. (1987)

3. The most recent information on the status of QED experiments contrasted with theory has to be extracted from original research papers and from review articles published in conference proceedings. In addition the following book provides a good overview:

- T. Kinoshita (ed.): *Quantum Electrodynamics*, World Scientific, Singapore (1990)

4. An old but still useful collection of reprints of many of the basic original papers related to QED:

- J. Schwinger (ed.): *Quantum Electrodynamics*, Dover, New York (1958)

5. An account of the history of QED:

- S.S. Schweber: *QED and the Men Who Made It*, Princeton University Press, Princeton (1994)

6. Classical textbooks on Quantum Field Theory, in chronological order:

- N.N. Bogoliubov and D.V. Shirkov: *Introduction to the Theory of Quantized Fields*, Interscience, New York (1959)
- S.S. Schweber: *An Introduction to Relativistic Quantum Field Theory*, Harper & Row, New York (1962)
- J.D. Bjorken and S.D. Drell: *Relativistic Quantum Mechanics*, and *Relativistic Quantum Fields*, Mc.Graw-Hill, New York (1964)
- D. Lurié: *Particles and Fields*, Interscience, New York (1968)
- C. Itzykson, J.-B. Zuber: *Quantum Field Theory*, McGraw-Hill, New York (1980)
- S. Weinberg: *Quantum Theory of Fields I–III*, Cambridge University Press, Cambridge (1995 ff.)

7. Some further references on quantum fields and gauge theories, which emphasize the path integral formulation:

- L.H. Ryder: *Quantum Field Theory*, Cambridge University Press, Cambridge (1985)
- D. Bailin and A. Love: *Introduction to Gauge Field Theory*, Adam Hilger, Bristol, Boston (1986)
- R.J. Rivers: *Path Integral Methods in Quantum Field Theory*, Cambridge University Press, Cambridge (1987)
- S. Pokorski: *Gauge Field Theories*, Cambridge University Press, Cambridge (1987)

Subject Index

- Adiabatic approximation 415
Adiabatic switching 13, 242
Ampère's law 267
Annihilation amplitude 150
Annihilation processes 43, 203 ff.
– differential cross section of 206, 215
– total cross section of 208 ff., 215
Anomalous magnetic moment 124
Anomaly of the electron 326 ff.
Anti-unitary operator 23
Asymptotic freedom 297
Auger transition 306
- Backward propagation 30, 45
Barred operator 89
Bessel function 77, 241, 389, 430
– asymptotic behaviour of 81, 431
– spherical 390
Bessel's differential equation 388
Bethe logarithm 339
Bethe–Heitler formula 174, 188
– for pair creation 222 ff.
Bethe–Salpeter equation 347 ff.
– for positronium 358 ff.
– in momentum space 353
– in the ladder approximation 352, 362
– nonretarded approximation of 368
Bhabha scattering 149 ff., 154
– cross section of 152, 158
Birefringence of the vacuum 442 ff.
Bohr radius 306, 392
Born approximation 188, 223
Bose statistics 203, 460
Boson 449 ff.
– spin-0 453
Boson line 460
Boundary condition 27, 47, 56
– for particle scattering 454
Box normalization 14, 85, 441
Breit frame 129
Breit interaction 370, 374, 377
Breit–Wheeler formula 219, 231, 246
Breit–Wigner resonance 401, 408
Bremsstrahlung 168 ff.
– static limit of 181 ff.
- Causality 12
Chain approximation 275, 310
Charge cloud 410
Charge conjugation 363
Charge radius of the nucleus 385
Charge renormalization 283, 311, 318, 432
Charged vacuum 382, 410
Chemical potential 65
Classical radius of the electron 199, 210
Collinear collisions 112
Completeness 19
– relation of the polarization vectors 178, 213, 335
Compton scattering 189 ff., 203, 461 ff.
– cross section for 200, 463
– nonlinear 248
Compton tensor 191, 205, 461
Compton wavelength 193, 301, 306, 384, 436, 445
Compton's formula 193
Connected graphs 273
Continuum 381

- Continuum normalization 14, 450
 Continuum wave function 396
 Correlation diagram 416
 Coulomb barrier 415, 420
 Coulomb gauge 35, 227 ff., 266, 369
 Coulomb potential 83, 286, 297, 333, 369, 386, 415
 – Fourier-transformed 84, 171, 458
 Coulomb scattering 83 ff., 161 ff.
 – of pions 458
 – of positrons 100 ff.
 Coulomb waves 102, 188, 223
 Coupled-channel equations 419
 Coupling constant 301, 436
 – running 294
 Critical charge 391
 Critical distance 416
 Critical field strength 249, 384, 433
 Critical potential 382
 Critical wave function 389
 Cross section 87, 109, 259
 Crossing symmetry 151, 191, 204, 217, 220, 248
 Current 32, 87
 – transition 106
 Cutoff momentum 282
- Decay law 405, 409
 Degeneracy factor 260
 Delbrück scattering 425
 Dielectric function of the vacuum 293
 Diffusion equation 21, 32
 Dipole fit 128
 Dirac
 – plane waves 51, 53
 Dirac equation 46, 55, 386
 – continuum of 381, 391, 393
 – discrete solutions of 393
 – exact solution 250
 – in a homogenous magnetic field 440
 – mass gap 383, 436
 – radial 388 ff.
 – square of 86
 – stationary two-center 415
 – time-dependent two-center 418
 Dirac plane waves 51, 60
 Dirac sea 60, 381, 410, 417, 436
 Dirac's delta function 14, 26
 – Fourier representation of 36
 – square of 85
 Dirac's hole picture 45, 59, 436, 454
 Direct pair production 417
 Disconnected graphs 273
 Dispersion relation 190, 355, 356
 – subtracted 290, 293
 Displacement field 442
 Divergence 273, 282
 – infrared 312, 329 ff.
 Diving point 388
 Dressed state 240
 Dual field tensor 426
- Effective charge 294
 Effective interaction 369, 374
 Effective Lagrangian 425 ff., 437
 Effective mass 240, 255
 Eigenfunction
 – expansion 18, 29
 Electron–electron scattering 141, 154
 Electron–positron annihilation 203 ff., 212 ff., 463
 Electron–positron bound state 359
 Electron–positron pair creation 204, 217 ff., 237 ff., 293, 436
 Electron–positron scattering 149 ff., 154
 – in fourth order 271
 Electron–proton scattering 103 ff., 121 ff.
 – higher-orders of 130 ff.
 Electro-production of pions 463 ff.
 Electron scattering 57, 83 ff.
 Electrostatic potential well 382
 Ellipticity 446
 Energy shift 307, 332 ff., 339
 – in hydrogen-like ions 342
 Energy splitting 341
 Equivalent photons 225 ff.

- Euler–MacLaurin summation formula 429
 Even operators 375
 Exchange diagram 133, 141, 149, 272
 Excitation of an electron 417

 Fano’s formalism 395 ff.
 Fermi distribution 304
 Fermi gas 60
 Fermi momentum 65
 Fermi–Dirac statistics 65
 Feynman contour 48 ff.
 Feynman gauge 266, 369
 Feynman integral 180
 Feynman propagator
 – for Dirac particles 45 ff.
 – for Fermi Gas 60 ff.
 – for scalar particles 452 ff.
 – in coordinate space 73 ff.
 – in momentum space 46
 – integral representation of 277
 – nonrelativistic limit of 68
 – of the Klein–Gordon field 74
 – plane-wave decomposition of 53 ff.
 Feynman rules 83
 – for QED 259 ff.
 – for spinless QED 460
 Field tensor 426
 Fine-structure constant 269
 Flux factor 111, 116
 Foldy–Wouthuysen transformation 375
 Form factors 121
 – dipole fit 128
 – infrared-corrected 331
 – of the electron 154, 320 ff., 333
 – Sachs 127
 Frequency-dependent interaction 371
 Furry’s theorem 262 ff., 308

 g factor 326, 328
 Gamma function 433
 γ Matrices 96

 Gamow factor 384, 437
 Gauge invariance 169, 176, 192, 275
 – of the polarization tensor 280
 – of the scattering amplitude 461
 Gaussian integral formula 19, 34, 278, 308
 Gaussian units 170, 267
 Gordon decomposition 123, 317, 323
 Green’s function 3 ff.
 – advanced 4, 20
 – diffusion 32
 – free 7, 18 ff.
 – in momentum representation 25
 – interacting 31
 – retarded 4, 20, 37
 Green’s propagator 3
 Ground state 381

 Hadron tensor 115, 125, 226, 235
 Hadronic corrections 296, 328
 Hankel function 77
 Hartree approximation 413
 Heaviside–Lorentz units 267
 Heavy ion collisions 415 ff.
 Heavy photon 275
 Heisenberg’s scattering matrix 14
 Heisenberg’s uncertainty relation 423
 Helicity 162
 Hermitian conjugate 89
 Hilbert space 22
 Hole theory 58, 436, 454
 Huygens’ principle 3, 35, 82
 Hydrogenlike uranium 343
 Hyperfine splitting 339

 i factors
 – rule for 134 ff.
 Index of refraction 445
 Indistinguishability 132
 Induced positron production 417
 Inelastic scattering 329
 Infrared catastrophe 176, 329
 Infrared divergence 312, 329
 Initial-value problem 356

- Interaction kernel 349
 Interference term 145, 148, 152
 Invariant amplitude 108, 260, 461
 Ionization of an electron 417 ff.
 Irreducible interaction kernel 350
- K-hole production 420
 Kirchhoff representation 39
 Kirchhoff's integral 35 ff.
 Klein–Gordon equation 450 ff.
 – Feynman propagator of 74
 – propagator 452 ff.
 Klein–Nishina formula 198, 201, 463
- Ladder approximation 351
 Lagrangian
 – effective 425, 437
 – of strong electric field 435
 Lamb shift 287, 339 ff.
 Landau gauge 266
 Landau levels 441
 Laser field 238
 Left-handed electron 162
 Lepton tensor 115, 125, 126, 225
 Levi–Civita tensor 426
 Light-cone singularities 81 ff.
 Light-cone variables 251
 Lippmann–Schwinger equation 11, 55
 Loop diagram 45, 262, 458
 Lorentz force 268
 Lorentz gauge 104, 169, 266
 Low-density limit 65
 Low-energy theorem 175
- MacDonald function 78, 389, 430
 Magnetic dipole energy 325
 Magnetic field strength 442
 Magnetic moment
 – anomalous 124, 326 ff.
 Mandelstam variables 154
 Mass renormalization 316, 336
 Mass shell 122, 153, 202, 220, 284, 311, 314, 317, 320, 325
 Mass-shell condition 47, 465
- Maxwell's equations 103, 169, 425
 – in vacuum 268
 – inhomogeneous 35
 Mesons 306, 354, 446, 449
 Minimal coupling 451
 MKSA system 267
 Møller potential 106
 Møller scattering 148, 154
 – cross section 158
 Momentum cutoff 282
 Mott's scattering cross section 118, 168
 Mott's scattering formula 92
 Muon
 – anomalous magnetic moment 328
 Muon pair creation 152, 233 ff.
 Muonic atoms 306 ff.
- Negative-energy solutions 52
 Neumann function 77
 Nonperturbative pair creation 246, 436
 Normalization 14, 83, 171, 450, 459
 Nuclear charge distribution 304, 385
 Nuclear polarization 307
 Nuclear radius 306, 385
- Occupation probability function 65
 Odd operators 375
 One-photon vertex 457
 Operator
 – barred 89
 – even 375
 – odd 375
 Optical diffraction 40
 Orthogonality condition 70
 Orthonormality relations 53, 396, 418, 451
- Pair annihilation 43, 59, 203, 204, 208, 212
 Pair creation 43, 58, 204, 232, 293
 – bound-free 424
 – in a strong field 435
 – in intense laser fields 237
 – in the field of a nucleus 220 ff.

- nonperturbative 436
- of muons 152, 234
- of pions 463 ff.
- Particle–antiparticle gap 420, 436
- Pauli–Villars regularization 276, 313
- Permeability of the vacuum 443
- Permittivity of the vacuum 443
- Perturbation expansion 32, 57, 455
- Perturbation theory 83
- Phase shift 394, 402
- Photon 168
 - absorption 172
 - emission 172
 - longitudinal 178
 - loop 271, 458, 460
 - propagator 79, 104, 227, 265 ff., 274
 - scalar 178
 - splitting 425
 - vertex 108, 456
 - virtual 108, 150, 176, 220, 224, 225
- Photon–electron scattering 189 ff.
- Photon–photon interaction 220, 224, 231, 425
- Pion
 - pair production 463
 - scattering 453
- Plane waves 2, 14, 52, 94
- Polarization 442
 - averaging 89
 - charge density 302
 - current 275
 - degree of 165
 - function 276, 290 ff.
 - in Coulomb scattering 163
 - photon 169, 262, 444
 - spin 161
 - tensor 274 ff.
- Polarized particle
 - scattering 161
- Positive-energy solutions 52
- Positron 45, 49
 - scattering 59, 100, 409
- Positron production 382 ff.
 - induced 417
 - spontaneous 421
- Positronium 347, 374 ff., 377
- Principal-value singularities 403
- Principle of causality 12
- Projection operator 365, 420
 - energy 50, 365
 - mixed 368
 - spin 161
- Propagator 46
 - Feynman 53, 68, 73, 74
 - in coordinate space 73 ff.
 - nonrelativistic limit 68
 - of photon 79, 104, 265 ff., 274
 - two-particle 349
- Proton radius 129
- Quasi-molecule 415
- Radiation cloud 314, 331
- Radiation gauge 170, 178, 195, 199
- Reciprocity theorem 25
- Recoil 103, 120
- Reducible interaction kernel 349
- Regularization 276, 313, 322, 428
- Renormalization
 - constant 283, 311, 316, 318
 - of charge 283, 311, 318, 432
 - of field strength 432
 - of mass 316
 - of photon lines 285
 - of wave function 312
- Renormalized mass 311
- Residue theorem 26, 48, 367
- Resonance
 - energy 400
 - in Bhabha scattering 153
 - in positron continuum 383, 393 ff., 420
 - width 394, 401
- Retardation 365, 372
- Right-handed electron 162
- Rosenbluth’s formula 121 ff.
- Running coupling constant 294, 302
- Rutherford hyperbola 417
- Rutherford scattering cross section 88
- Rutherford’s scattering formula 92

- Scalar electrodynamics 449
 Scale transformation 279, 280, 313, 322
 Scattering 12, 259
 – Coulomb 83 ff.
 – electron–electron 141 ff., 154
 – electron–positron 141, 149 ff., 154
 – electron–proton 103 ff., 121 ff.
 – matrix 14
 – of antiparticles 455
 – of identical particles 141
 – of polarized particles 161 ff.
 – of spin-0 bosons 453 ff.
 – photon–photon 425
 – positron 59, 100, 409
 – semiclassical approximation 418
 Schrödinger's equation 3, 26, 27
 Screening 188, 413
 Seagull vertex 456
 Self-energy 265, 273, 309 ff., 318, 342
 – function 310, 313
 – regularized 314
 Semiclassical approximation 418
 Short-range attraction 286
 S matrix 14, 22 ff.
 – elements 56, 259
 – expansion of 32, 57, 456
 – unitarity 21
 Soft-photon emission 174, 329
 Soft-photon theorem 175
 Sommerfeld's fine-structure formula 386
 Specific heat capacity 32
 Spin polarization 161
 Spontaneous positron emission 382, 416, 421
 Static point charge 84, 297
 Statistical factor 260
 Step function 4, 25
 Strong electromagnetic field 381
 Stückelberg–Feynman definition 45
 Stückelberg–Feynman prescription 452
 Stückelberg–Feynman propagator 53
 Subcritical Hamiltonian 408
 Subcritical potential 393
 Substitution rule 151, 204
 Subtracted dispersion relation 290, 293
 Summation formula of Euler–MacLaurin 429
 Supercritical atom 408
 Supercritical heavy ion collision 417
 Supercritical point charge 411 ff.
 Supercritical potential 393
 Supercritical wave functions 408
 Superposition principle 4
 Symmetry transformation operator 23

 Tadpole graph 264
 Theorem of residues 26, 48, 367
 Thomson's scattering formula 199
 Time-reversal invariance 24
 Trace identities 96 ff.
 Trace technique 144, 162, 194
 Transition current 106
 Transition probability 85
 Transition rate 108
 Tunnel effect 384
 Tunnel process 436
 Two-centre Dirac equation 415 ff.
 Two-loop corrections 344
 Two-particle propagator 349
 Two-particle wave equation 347, 359
 Two-photon exchange 138
 Two-photon vertex 456, 462

 Uehling potential 286, 297
 – for an extended source 304 ff.
 – integral representation 300
 Unitarity 21

 Vacuum 381
 – charged 382, 410
 – decay 405
 – energy 427
 – fluctuations of 273
 – neutral 382

-
- Vacuum polarization 44, 273 ff., 343
– charge cloud 303, 410
– real 410
Vector dominance 466
Vertex 43, 108
– one-photon 457
– seagull 456
– two-photon 456, 462
Vertex correction 273, 316 ff., 318
Vertex function 317, 320, 322
Virtual photon 108, 150, 176, 220, 224, 225
Virtuality 227, 229
Volkov wave function 239, 250 ff.
Ward identity 319
Wave equation 36, 169
Wave-function renormalization 312
Weizsäcker–Williams approximation 230
Zitterbewegung 379