

Index

A

- Abel summation, 214
- abelian group, 535
- abelian Higgs model, 82
- acceleration
 - constant in special relativity, 179
 - four vector, 46
 - Lorentz transformation of, 43–46
 - proper, 44–46
- action, 29, 79
 - Dirac, 579
 - Euclidean, 267, 269, 469
 - field, 79
 - graviton-scalar field, 563–565
 - Gupta-Bleuler, 348
 - Klein-Gordon, 513
 - Maxwell, 286, 348, 492–493
 - gauge fixing, 495
 - particle in electromagnetic field, 20
 - Polyakov, 549
 - QCD, 398
 - QED, 326
 - quark, 384
 - string of masses, 29
 - string sigma, 548–550
 - superstring, 552, 553
 - supersymmetric particle, 541
 - Yang-Mills, 384, 394
 - invariance under gauge transformation, 394
- action integral, 270, 272
- adjoint representation, 312, 384, 406, 578, 582
- advanced Green function, 138, 139
- Aharonov-Bohm effect, 513–516
- algebra, 445
 - semi-simple, 583
- Ambrose-Singer theorem, 306
- amplitude
 - bremsstrahlung, 210
 - Compton scattering, 227–229
 - electron-fermion scattering, 331
 - electron-muon scattering, 330
 - electron-proton scattering, 341
 - four fermion, 219, 242
 - gluon to meson decay, 395
 - inverse muon decay, 193
 - Møller scattering, 327, 347
 - muon decay, 243, 244, 247
 - neutrino mixing, 532
 - neutrino-electron interaction, 194
 - photon emission in scalar QED, 365, 366
 - pion decay, 239–240
 - pseudoscalar coupling, 234
 - pseudoscalar-scalar interaction, 258
 - quark-anti-quark scattering, 442

- quark-quark scattering, 449–450, 452–455
- scalar-fermion coupling, 232
- spin-2 particle emission, 557–559
- angular momentum
 - electromagnetic field, 352
- angular momentum addition theorem, 425
- annihilation and creation operators, *see* creation and annihilation operators
- anomalous magnetic moment, 358–364
- anti-quark, *see* quark
- anticommutation relations, 9, 100, 103, 118, 158, 213, 254
 - creation and annihilation operators, 104, 213
 - Dirac field, 100–104
 - Grassmann numbers, 502, 591
 - SU(3) generators, 445, 454
- anticommutator of γ -matrices, 165, 525
- antisymmetrization operation, 106
- asymptotic conditions, 127
- auxiliary field, 409
- auxiliary magnetic field, 55
- axial gauge, 501
- B**
- background metric, 564
- Baker-Campbell-Hausdorff formula, 118, 119
- Baryon current, 302
- Baryon number, 303
- Becchi-Rouet-Stora-Tyutin symmetry, 405, 409
- Berezin integral, 594
- Berezinian, 485
- Bessel function of the first kind, 547
- Bessel functions, 32
- β (inverse temperature), 469
- β^+ decay, 530–531
- Bethe-Heitler formula, 209
- Bianchi identity
 - for gauge covariant derivatives, 391
- bilinear trace form, 388–389
 - SU(2), 389
 - SU(N), 389
- bilinearity, 581
- bilinears of Dirac spinors, 242
- bispinor, 522
- Bogolyubov coefficients, 183
- Born-Infeld scalar field, 282
 - Lagrangian density, 282
- bosonic string, 548–552
- Breit-Wigner formula, 465
- bremsstrahlung radiation, 178, 204
- BRST charge, 410–412
- BRST current, 409, 410
- BRST symmetry, 405, 409
- BRST transformation, 405
- C**
- Cabibbo angle, 252
- canonical commutation relations of quantum mechanics, 17
- canonical momentum, 17
 - complex scalar field, 97
 - Dirac field, 100
 - electromagnetic field, 348–349
 - field theory, 78
 - Gupta-Bleuler, 349
 - Klein-Gordon field, 89, 91, 565
 - particle in electromagnetic field, 20, 281, 542
 - with gauge fixing term, 349, 351
- Cartan subalgebra, 439, 583
- Cartan-Killing form, 389
- Casimir effect, 374–382
- Casimir energy, 381
- Casimir operator or invariant, 311, 582
 - of the Poincaré algebra, 63–65, 68
 - su(2), 582
 - su(3), 448
- Casimir pressure, 381
- Cauchy's integral theorem or Cauchy-Goursat theorem, 135, 587
- Cauchy-Riemann equations, 587
- Cauchy-Schwarz inequality for timelike vectors, 262
- causality, 146
- center of mass, 30
- center of mass frame, 171

- center of momentum frame, 29, 31, 171
- change-of-basis matrix, 526
- charge
 - BRST, 410–412
 - conserved, 276
 - electric, 544
 - magnetic, 545
 - Noether, 276, 321
- charge conjugation, 271, 527
- charge conjugation operator, 287, 526
- charge density form factor, 212
- charge-isospin-hypercharge relation, 299, 303
- charged particle
 - in electric field, 173–174
 - in electromagnetic field, 542
 - in magnetic field, 173
- charm quark, 433
- chiral field transformations, 296
- chiral gauge theory, 118
- chiral quark meson model, 296
- chiral spinor, 6, 527
- color factor, 417, 419
- color multiplet, 415
- colorless particle, color neutral, color singlet, 394
- COM frame, *see* center of momentum frame or center of mass frame
- commutation relations, 8
 - anti, 9, 118, 158, 213, 254
 - canonical, 17
 - complex scalar field, 97, 98
 - creation and annihilation operators, 8, 92, 99, 129, 160, 238
 - harmonic oscillator, 25
 - involving number operator, 25–26
 - neutral scalar, 117
 - photon field, 352
 - position-momentum, 25
 - real scalar field, 89
 - SU(2) generators, 388
 - SU(3) generators, 445, 454
 - SU(N) generators, 307, 311
 - supercharge, 539
 - unequal times, 124
- compact group, 284, 573
- complex representation, 432
- complex scalar field, *see also* Klein-Gordon field, 96, 277
- Compton scattering, 153
 - in scalar QED, 224–231
 - differential cross-section, 169
- conjugate representation, 423
- connection, 279, 305, 306
 - curvature of, 306
- conservation of Baryon number, 298
- conservation of ghost number, 409
- conserved axial vector current, CAC, 292
- conserved charge, *see* charge
- conserved vector current, CVC, 292
- constant of the motion, 71
- contact term, 227
- convergence factor for integrals, 214
- coordinate components, 105
- coordinate transformation, 272
 - infinitesimal, 271
- correlation function
 - two-point, 121
- Coulomb gauge, 501
- Coulomb scattering, 211–217
- covariant derivative, 104
 - adjoint representation, 384, 390, 406
 - gauge, 83, 112, 281, 301, 305, *see also* gauge covariant derivative, 313
 - commutator of, 305–306
 - transformation under U(1) transformation, 282
 - integration by parts, 410–411
- creation and annihilation operators, 26, 94
 - alternate normalization, 8
 - anticommutation relations, 104, 213
 - commutation relations, 8, 92, 99, 129, 160, 238
 - in terms of field variables, 91–92
- cross-section, *see also* differential cross-section, 3
 - invariant, 345
 - quark scattering, 451, 453
 - Rutherford, 16

- scattering, 228
- current
 - Baryon, 302
 - BRST, 409, 410
 - conserved axial, 292
 - conserved string, 551, 552
 - conserved vector, 292
 - Dirac, 373
 - electric, 544
 - gauge, 276
 - magnetic, 545
 - neutrino, 218
 - Noether, 272
 - non-abelian fermion, 287
 - nucleon, 304, 305
 - partially conserved axial vector, 292, 296
 - pseudoscalar, 257
 - V-A (vector minus axial), 194, 258
- curvature, 307
- curvature of the connection, 306
- cyclotron frequency, 173
- D**
- d* symbols, 446
- d'Alembert operator or d'Alembertian, 50
- D-branes, 282
- de Broglie relation, 18
- decay, *see specific processes*
- defining representation, 577
- deuterium, 530
- differential cross-section, 193, 198, 222, 329, 331, 335, 451, 455
 - bremsstrahlung, 211
 - Compton scattering, 169, 170, 231
- dimension of a group, 573
- dimension of group representation, 308
- dimensional representation, 423
- Dirac
 - Hamiltonian density, 4
- Dirac current, 373
- Dirac delta function
 - properties, 184, 196, 566–571
 - zero argument, 535
- Dirac equation, 4, 101, 254, 347, 361, 421, 524
 - coupled to electromagnetic field, 152
 - Green function, 152–153, 487–488
 - in arbitrary coordinate system, 107
 - in cylindrical coordinate system, 109
 - in spherical coordinate system, 111
 - Majorana representation, 524–526
 - momentum space, 114, 165, 209, 259, 419
- Dirac field
 - action, 579
 - canonical momentum, 100
 - generating functional, 482
 - Hamiltonian, 102
 - Hamiltonian density, 100
 - Lagrangian density, 482
- Dirac form factor, 341
- Dirac mass, 522, 524
- Dirac matrices, *see gamma matrices*
- Dirac propagator, 482–488
- Dirac string, 543
- discrete symmetries, 271
- dispersion relationship of special relativity, 66, 85, 93, 184, 324, 377, 461, 536, 540
- divergence theorem in covariant form, 275
- Doppler effect, 56–57
- dubiosity, 536
- DuBois-Reymond lemma, 81
- E**
- eccentricity, 13
- Einstein equations, 291
- elastic scattering process, 185–188, 192–193
- electric charge, 544
 - quantization from magnetic monopole, 544
- electric current, 544
- electric displacement, 55
- electric field
 - due to beam aperture, 547–548
- electric scalar potential, 20

- electromagnetic field, *see also* photon
 - angular momentum, 352
 - generating functional, 492
 - invariants of, 55–56
 - Lorentz transformation of, 50–55
 - propagation speed, 40
- electron capture, 318
- electron muon scattering, 329–335
- electron neutrino scattering, 193
- electron-positron annihilation, 175–176
 - Higgs production in, 456
- “energy” representation, 24
- energy-momentum tensor, 290
- equipartition of energy, 27
- Euclidean action, 267, 269, 469
- Euclidean time, 267
- Euclideanized integral, 598
- Euclideanized wave equation, 269
- Euler-Lagrange equations, 80
 - for fields, 81, 301
 - hydrodynamics
 - scalar, 301
 - vector, 301
 - Proca field, 285
 - scalar coupled to electromagnetic field, 282
- Euler-Maclauren formula, 381
- extremal action principle, 29
- F**
- Fabri–Picasso theorem, 325
- Faddeev-Popov determinant, 409, 488, 491, 496–499
 - electromagnetism, 499
 - gauge invariance of, 491, 496–497
- Faddeev-Popov ghost, *see* ghost fields
- Faddeev-Popov method, 496–500
- Fermi coupling constant, 193, 217, 258
- fermionic coordinates, 541
- Feynman Green function, *see also* propagator, 140–143
- Feynman parameters, 359
- Feynman rules
 - Compton scattering, 227
 - ghost fields, 422
 - quarks and gluons, 414
- field deformations, 272, 273
- field momentum
 - Klein-Gordon, 93
- field transformations, 272
- field-strength tensor, 83, 281, 306
 - as commutator of covariant derivatives, 306
 - behavior under gauge transformations, 392–394
 - for isoscalar vector, 300
 - non-abelian, 383, 392, 509
- fine structure constant, 170, 231, 335
- flux, 198, 222
- Fock states, 88
- Fock-Ivanenko coefficients, 104, 106
 - cylindrical coordinates, 109
 - spherical coordinates, 111
- force
 - four vector, 46
 - Minkowski, 47
 - Newtonian, 46
- form factor
 - F_2 , 359
 - axial, 457
 - charge density, 212
 - Dirac, 341
 - Pauli, 341
 - proton, 341
 - Sachs, 341
 - vector, 457
- four fermion interaction, 193
- four-acceleration, 46, 179
 - relation to proper acceleration, 46
- four-force, 46–48
- four-momentum, 2, 47, 172
 - differential operator, 2
- four-position, 47
- four-velocity, 46, 47
- Fraunhofer approximation, 546
- frequency of relativistic uniform circular motion, 173
- Fried-Yennie gauge, 501
- Fulling-Davies-Unruh effect, 183
- functional derivative, 467
- fundamental lemma of the calculus of variations, 81, 350, 468, 551

- Furry's theorem, 374
- G**
- g-factor, Landé, 363–364
- gamma matrices
- 2×2 , 541, 552
 - Clifford algebra of, 109, 525
 - conversion from Weyl to Dirac basis, 112–114
 - Dirac representation, 112
 - Majorana representation, 525
 - properties, 5
 - trace of products, 220
 - Weyl representation, 112
- gauge
- axial, 501
 - Coulomb, 501
 - current, 276
 - Fried-Yennie, 501
 - Landau, 501
 - Lorenz, 144, 495–496
 - quantum version, 349–351
 - radiation, 227
 - temporal, 501
 - 't Hooft-Feynman, 501
- gauge covariant derivative, 83, *see also*
- covariant derivative, 112, 281, 301, 313, 384
 - gauge transformation of, 308–309
- gauge current, 276
- gauge field, 305
- gauge fixing
- Lagrangian density, 405, 409
- gauge fixing term, 500
- electrodynamics, 348, 495, 500
 - non-abelian, 510
- gauge orbits, 488, 489
- gauge slice, 489
- gauge transformation
- abelian, 495, 496
 - as a phase, 21, 277, 542, 544
 - electromagnetic field, 21, 286, 372, 542
 - field-strength tensor, 392–394
 - global, 277
 - infinitesimal, 279
 - local, 279
 - non-abelian, 392, 507, 580
 - phase, 579
 - SU(N), 307, 308, 392
 - U(1), 495, 542
 - Yang-Mills action, 394
- gauge volume, 488, 498
- Gell-Mann - Levy model, 296
- Gell-Mann - Levy trick, 292, 293, 297, 302, 304
- Gell-Mann matrices, 385, 433, 446
- Gell-Mann-Nishijima formula, 441
- Gell-Mann-Zweig theory, 433
- generating functional, 472, 511
- Dirac, 482
 - electromagnetic, 493
 - electromagnetism, 492, 500
 - Klein-Gordon, 470–472, 511
 - ϕ^4 theory, 475–479
- generators, 311
- of function transformation, 387
 - Lorentz, 57–59, 61
 - commutator of, 58
 - of a gauge group, 383
 - of a group, 581
 - SU(2), 384–388
 - three dimensional, 426
 - SU(3), 385, 388, 433, 445, 446
 - normalization condition, 447
 - SU(5), 518
- geometric transformations (also space-time transformations), 272
- ghost fields, 398, 405, 409, 412–413, 499, 591
- conservation of, 409
 - covariant derivative, 406
 - Feynman rules, 422
 - Lagrangian density, 405, 409
- ghost propagator, 511
- global symmetry transformation, 291
- glueball, 394
- gluon
- Feynman rules, 414
 - octet, 416
 - vertex factor, 400–403, 405
- gluons, 518

- Goldstone bosons, 319
 Goldstone's theorem, 319
 Gordon decomposition of the Dirac current, 114–116, 361
 Grassmann coordinate, 541
 Grassmann numbers, 499, 502, 591–596
 anticommutation relations, 502, 591
 degree, 592
 derivatives with respect to non-Grassmann, 592
 determinant in terms of, 502–506, 596
 differentiation, 592–593
 integration, 593–595
 Grassmann, H.G., 591
 graviton potential, 563
 graviton-scalar field action, 563–565
 Green function
 advanced, 138, 139
 as kernel of integral operation, 145
 Dirac equation, 152–153, 487–488
 Feynman, 140–143
 four-point
 Klein-Gordon field, 474–475
 Klein-Gordon equation, 132–144, 474
 n -point, 472
 of d'Alembertian, 145
 retarded, 135, 136, 138, 146
 three-point
 Klein-Gordon field, 475
 two-point, 472
 Klein-Gordon field, 470
 ϕ^4 theory, 479–482
 Green's theorem, 586
 Gribov ambiguity, 511
 group
 abelian, 535, 572
 axioms, 39, 572
 closure, 572
 compact, 284, 573
 composition rule, 572
 connected, 573
 definition, 572–573
 dimension, 383, 573
 dimension of representation, 308
 $E(2)$, 367, 369
 elements, 572
 generators, 311, 581
 identity, 572
 isomorphic, 573
 Lie, 573
 Lie transformation, 272
 little, 364, 367–371
 metric, 389
 order, 573
 Poincaré, 63
 rank of Lie group, 583
 representation, 383
 adjoint, 578, 582
 defining, 577
 irreducible, 577
 reducible, 577
 semi-simple, 389
 $SL(2, \mathbb{C})$, 522, 575
 $SO(2)$, 283, 574
 $SO(3)$, 311
 $SO(3,1)$, 575
 special orthogonal, 283, 284, 574
 special unitary, 574
 $SU(2)$, 304, 384–385, 426
 $SU(3)$, 445
 $SU(N)$, 307
 subgroup, 573
 topological transformation, 272
 $U(1)$, 277, 283
 group metric, 389
 group theory, 572–575
 representation, 575–581
 Gupta-Bleuler action, 348
 Gupta-Bleuler condition, 351
- H**
 Haag's theorem, 536
 Haar measure, 574
 hadrodynamics, *see* quantum hadrodynamics - QHD
 Hamiltonian
 Dirac, 102
 harmonic oscillator, 24
 Klein-Gordon field, 89

- particle in an electromagnetic field, 20, 542
 - relation to Hamiltonian density, 78
 - renormalized, 95–96
 - Hamiltonian density, 100, 290
 - coupling of current with vector potential, 155
 - Dirac, 4, 100
 - Klein-Gordon field, 92, 536
 - neutrino electron interaction, 193
 - π^- decay, 252
 - pseudoscalar decay, 252
 - real scalar field, 124
 - relation to Hamiltonian, 78
 - harmonic oscillator
 - Hamiltonian, 24
 - in quantum mechanics, 24–27
 - Schrödinger equation, 24
 - Heine-Borel theorem, 573
 - Heisenberg picture, 72
 - helicity
 - photon, 357
 - helicity operator, 67
 - Heun triconfluent functions, 266
 - Higgs
 - discovery of, 458
 - field, 313
 - with abelian gauge theory, 82
 - Higgs production, 456, 458
 - Higgs-bremsstrahlung, 456
 - highest weight, 438
 - Hilbert space
 - two-particle, 425
 - Hodge dual, 544
 - of field-strength tensor, 56, 545
 - hollow matrix, 525
 - Huygens' principle, 153
 - hypercharge, 303
 - hypercharge-charge-isospin relation, 299, 303
- I**
- $i\epsilon$ (i -epsilon) prescription, 590
 - ideal
 - abelian, 583
 - impact parameter, 12, 33
 - infinitesimal coordinate transformation, 271
 - infrared divergence, 209
 - interaction picture, 72–73
 - internal symmetry transformation, 271
 - internal symmetry transformations, 272
 - interval, spacetime, 37
 - invariant cross-section, 345
 - invariant flux, 198, 222
 - invariant function λ , 3, 171, 172, 185, 451
 - inverse muon decay, 193
 - involutory matrix, 114
 - irreducible representation, 577
 - isochronous vectors, 262
 - isomorphic groups, 284, 573
 - isoscalar vector field, 300
 - isospin
 - quantum number, 303
 - isospin-hypercharge-charge relation, 299, 303
 - isotopic spin, *see also* isospin, 303
 - isovector, 118
- J**
- Jacobi identity, 311, 581
 - Jacobi sn elliptic function, 268
 - Jordan's lemma, 584–586
 - Jordan-Pauli function, 124
- K**
- kaon to pions decay, 231–232
 - Killing form, 389
 - Kirchhoff diffraction integral, 545
 - Klein-Gordon equation, 82, 89, 133
 - with external source, 133, 140, 471, 512
 - Klein-Gordon field, 89, *see also* scalar field, 277
 - action, 513
 - complex, 283
 - generating functional, 470–472, 511
 - Green function, 132–144, 474
 - Hamiltonian density, 92, 536
 - Lagrangian density, 89, 133, 277, 278, 283

- plane wave expansion, 7, 8, 97, 123
- Klein-Gordon propagator, 472–474
- Klein-Nishina formula, 154, 170
- L**
- Lagrangian
 - field, 79
 - particle in a magnetic field, 514
 - particle in an electromagnetic field, 20
 - string of masses, 28
- Lagrangian density, 28
 - Born-Infeld scalar field, 282
 - complex Klein-Gordon field, 277, 283
 - complex scalar field, 97, 278
 - coupling of current with vector potential, 155
 - current-current interaction, 242
 - Dirac, 300, 482
 - four fermion, 242
 - gauge fixing, 405, 409
 - Gell-Mann - Levy model, 296
 - ghost, 405, 409
 - glueball-vector coupling, 395
 - graviton-scalar field interaction, 565
 - hadrodynamics, 299
 - Higgs coupled to gauge bosons, 313
 - Higgs- Z^0 coupling, 457
 - Klein-Gordon, 133
 - lepton-photon coupling, 329
 - linear sigma model, 291
 - massive abelian (Proca) vector field, 284
 - Maxwell, 348
 - non-abelian Yang-Mills, 405, 409
 - nucleon, 302, 303
 - ϕ^4 theory, 475
 - pion decay, 236
 - pion field, 119
 - pseudoscalar coupling, 232
 - real Klein-Gordon field, 89
 - real scalar field, 124
 - scalar field electrodynamics, 281
 - scalar-fermion coupling, 232
 - string of masses, 28
 - vector minus axial (V-A), 242
 - WW coupling, 314
 - Yang-Mills, 407
- Landé g-factor, 363–364
- Landau gauge, 501
- Laurent expandable function, 587
- Lebesgue integration, 567
- left and right circular polarization, 357
- Legendre polynomials, 32
- Legendre transformation, 78
- Lehmann-Symanzik-Zimmermann (LSZ)
 - formula, 124, 126, 132
- leptoquark bosons, 519
- Levi-Civita tensor, 56, 196, 220
- Liénard-Wiechert scalar potential, 151
- Liénard-Wiechert vector potential, 152
- Lie algebra, 445, 581
- Lie algebra product (commutator), 307
- Lie bracket, 581
- Lie group, 573
- Lie group transformation, 272
- light-cone coordinates, 180
- linear sigma model, *see* sigma model
- little group, 364, 367–371, 560
- local transformations, 272, 273
- Lorentz factor, 35
- Lorentz force, 53, 173
 - with magnetic monopoles, 545
- Lorentz generators, 57–59, 61
 - commutator of, 58
- Lorentz transformation, 35
 - boost in arbitrary direction, 36
 - boost in the x -direction, 36, 37, 57
 - classification of, 39–40
 - composition of boosts, 38–39
 - electromagnetic field, 50–55
 - matrix representation, 37
 - of acceleration, 43–46
 - of an analytic function, 61–63
 - of derivatives and second derivatives, 48–49
 - of wave equation, 49–50
 - on spinors, 523, 575
 - on Weyl spinors, 59
 - parity inversion, 40
 - proper orthochronous, 40

- rotation about the z -axis, 58
- $SL(2, \mathbb{C})$, 523, 575
- time reversal, 40
- Lorenz gauge, 144, 495–496
 - quantum version, 349–351
- lowering operator, *see also* raising and lowering operator
 - $su(2)$, 425–426
- LSZ formula, 124, 126, 132
- luxons, 67
- M**
- magnetic charge, 545
- magnetic current, 545
- magnetic dipole transition, 395
- magnetic field
 - auxiliary, 55
- magnetic moment
 - anomalous, 358–364
- magnetic monopole, 542–544
 - gauge transformation, 543
 - magnetic field, 542
 - vector potential, 543
- magnetic vector potential, 20
 - magnetic monopole, 543
- Majorana mass, 522, 526, 528–530
- Majorana representation, 524–526
- Majorana spinor, 528, 552
- Mandelstam variables, 171–172
 - s variable, 171
 - t variable, 172
 - u variable, 172
- mass
 - Dirac, 522, 524
 - Majorana, 522, 526, 528–530
 - reduced, 30
 - renormalized, 482
- mass matrix, 316, 320
- Maxwell action, 348, 492–493
- Maxwell tensor, 83, 281
- Maxwell's equations, 152, 392, 544
 - symmetry under rotation mixing \vec{E} and \vec{B} , 544–545
 - with magnetic monopoles, 545
- mean field theory, 300
- meson, 427
- decay, 250
 - π , 251, 432
 - ρ , 285, 432
- metric, 2
 - background, 564
 - coordinate form in cylindrical coordinates, 105
 - coordinate form in spherical coordinates, 110
 - group, 389
 - orthonormal vs coordinate form, 105
 - world sheet, 549, 550
- Mexican hat potential, 265
 - vacuum to vacuum transition, 267–270
- minimal substitution, 281
- Minkowski force, 47
- Møller operators, 125
- Møller scattering, 327, 346
- momentarily comoving reference frame, 45, 179
- momentum
 - canonical, 17
 - kinetic, 20
- momentum operator, 17
 - eigenfunction, 18–19
 - eigenvalue, 18–19
 - gauge invariance of, 23–24
- Mott scattering, 211–217
- Mott scattering formula, 211, 217
- Moyal bracket, 18
- Moyal product, 18
- muon decay, 241–250
- N**
- n -representation, 24
- Nakanishi-Lautrup field, 409
- Nambu-Goldstone phase, 119
- negative energy, 103
- neutral currents, 217, 218
- neutrino
 - current, 218
 - first observation of, 530
 - solar, 530, 532
- neutrino electron scattering, 193, 217–224

- neutrino mixing, 531–534
- neutrino oscillations, *see* neutrino mixing
- neutrinoless double-beta decay, 261–263, 529–530
- neutron stars, 299
- Newton’s second law, 268
- Newtonian force, 46
- Noether charges, 276, 321
- Noether currents, 272, 275
- Noether’s theorem, 272
- non-abelian fields, *see* Yang-Mills
- normal ordering
 - bosons, 96
 - fermions, 103
- nuclear physics, 299
- nuclear spaces, 18
- nucleon, 29
- nucleon current, 304, 305
- nucleon doublet, 302
- nucleon state, 302
- null coordinates, 180
- null vector
 - orthogonality, 42–43
- number operator, 86, 94
 - commutation relations, 25–26
 - eigenket and eigenvalue, 26
- O**
- one particle irreducible (1PI) vertices, 511
- orthonormal coordinates, 105
- orthonormal tetrad, 105
 - cylindrical coordinates, 108
 - spherical coordinates, 110
- orthonormality
 - Dirac, 18
- P**
- parity inversion, 40, 271
- partial wave expansion of plane wave, 32
- partially conserved axial vector current, PCAC, 292, 296
- partition function, 468, 470
- path integral
 - Euclidean, 470
 - quantum mechanics, 469
- Pauli exclusion principle, 100, 104
- Pauli form factor, 341
- Pauli matrices, 385, 524
- Pauli vector, 296, 303
- Pauli-Jordan function, 124
- Pauli-Lubanski pseudo-vector, 63
- phase space, 171
 - n particle, 183, 331
 - three particle, 247
 - two particle, 169, 203, 233, 256, 260
- phase transformation, 21, 277
- ϕ^4 theory, 475
- photon, 519
 - angular momentum, 352
 - commutation relations, 352
 - helicity, 357
 - propagator, 346, 492–502
 - spin, 352–358
- photon emission process, 176
- photon-muon scattering, 188–189
- π meson, 251, 432
- pion decay, 236, 257, 261
 - lifetime, 236
 - S -matrix, 239
 - width, 236–241, 260, 261
- Planck energy, 563
- Planck volume, 563
- PMNS matrix, 531
- Poincaré algebra, 63
 - Casimir invariant of, 63–65, 68
- Poincaré group, 63
- Poincaré transformation
 - on string spacetime coordinates, 549
- Poincaré’s Lemma, 543
- polarization
 - and ghost fields, 413–423
 - and little group, 369–371, 560
 - and the Casimir effect, 374–382
 - and the Ward identity, 370–371, 413
 - completeness relation, 327
 - left and right circular, 357
 - as eigenstates of L_z , 357–358

- longitudinal, 327–329
 - radiation gauge, 227, 228
 - real, 356
 - spin 2, 557–562
 - sum, 4, 210, 229, 239, 396, 459
 - Dirac field, 342
 - temporal, 327–329
 - transverse, 349–351
 - unphysical, amplitude independence
 - and conservation of charge, 364–368
 - Polyakov action, 549
 - Pontecorvo-Maki-Nakagawa-Sakata matrix, *see* PMNS matrix
 - position four-vector, 46
 - position operator, 17
 - eigenfunction, 19
 - eigenvalue, 19
 - positive root, 436
 - positive weight, 438
 - principle of extremal action, 29
 - Proca field, 284
 - Euler-Lagrange equations, 285
 - Lagrangian density, 284
 - projection operator, 303
 - SU(3), 446, 448
 - propagator
 - Breit-Wigner, 465
 - Dirac, 157–158, 482–488
 - ghost, 511
 - Klein-Gordon, 472–474
 - massive scalar field, 557
 - photon, 158, 346, 492–502
 - two-point, 474
 - W particle, 243
 - Yang-Mills, 506–511
 - proper acceleration, 44–46
 - proper time, 46
 - proton decay, 519, 521–522
 - proton form factors, 341
 - proton lifetime, 531
 - proton-proton collision, 178–179
 - pseudoreal representation, 432
 - pseudoscalar current, 257
- Q**
- QCD, 299
 - action, 398
 - quantum hadrodynamics - QHD, 299
 - model I, 300
 - model II, 300
 - quark
 - action, 384
 - charm, 433
 - chiral meson model, 296
 - dimensional representation, 423–424
 - Feynman rules, 414
 - vertices, *see* vertex factor
 - quark-anti-quark annihilation, 413–423
 - quark-anti-quark scattering, 442–445
 - quark-quark scattering, 448–456
- R**
- radiation gauge, 227
 - raising and lowering operators
 - su(3), 433–435
 - Ramond-Neveu-Schwarz (RNS) string, 553
 - rank of Lie algebra, 311, 448, 583
 - rapidity, 57
 - addition of velocities, 42
 - Rayleigh's formula for expansions of plane waves, 29, 31
 - reaction matrix, 253
 - real representation, 432
 - reduced mass, 30
 - reducible representation, 577
 - renormalized Hamiltonian, 95–96
 - renormalized mass, 482
 - representation
 - adjoint, 312, 578, 582
 - complex, 432
 - conjugate, 423
 - defining, 577
 - dimensional, 423
 - irreducible, 577
 - pseudoreal, 432
 - real, 432
 - reducible, 577
 - representation of a group, 383

- dimension of, 575
 - representation theory, 575–581
 - residue, 587
 - residue theorem, 587–590
 - retarded Green function, 135, 136, 138, 146
 - retarded time, 150
 - ρ meson, 285, 432
 - Ricci rotation coefficients, 104, 106
 - cylindrical coordinates, 108
 - spherical coordinates, 111
 - Riemann curvature tensor, 306
 - right-left acting derivative, 91, 297
 - root, 435–436
 - positive, 436
 - root vectors
 - $\text{su}(3)$, 435
 - Rosenbluth formula, 335, 346
 - Rutherford scattering, 11–17
 - Rutherford scattering formula, 16
- S**
- σ model, *see* sigma model
 - Sachs form factors, 341
 - saddle point approximation, 269
 - Sakata model, 441–442
 - scalar field, *see also* Klein-Gordon field, 7, 116
 - Born-Infeld, 282
 - complex, 8, 96, 277, 278
 - Hamiltonian density, 124
 - Lagrangian density, 89, 124, 277, 278
 - tachyonic, 282
 - scalar-pseudoscalar coupling, 257
 - scattering
 - Coulomb, 211–217
 - differential cross-section, 202
 - elastic process, 185–188, 192–193
 - electron-muon, 329
 - Møller, 327, 346
 - Mott, 211–217
 - neutrino electron, 193
 - nucleon, 29–33
 - photon-muon, 188–189
 - quark-anti-quark, 442–445
 - quark-quark, 448–456
 - Rutherford, 11–17
 - scattering angle, 12, 13
 - center of momentum, 189, 192, 193
 - elastic process, 188, 192, 193
 - Rutherford, 12, 13
 - Schrödinger picture, 71–72
 - Schrödinger equation, 32, 70
 - harmonic oscillator, 24
 - multi-particle, 30
 - particle in electromagnetic field, 21, 542
 - gauge transformed, 23
 - particle in Mexican hat potential, 266
 - Schur's lemma, 535, 581
 - seagull term, 225
 - semi-simple algebra, 583
 - semi-simple Lie group, 389
 - sigma action for strings, 548–550
 - sigma model, 120
 - axial current, 294
 - partially conserved, 296
 - axial transformation, 294
 - Lagrangian density, 291
 - linear, 291
 - $\text{SU}(2) \otimes \text{SU}(2)$, 119
 - symmetry breaking term, 291
 - vector current, 294, 295
 - sign function, 138
 - Skyrme model, 120
 - $\text{SL}(2, \mathbb{C})$, 522, 575
 - $\text{sl}(2, \mathbb{C}) \oplus \text{sl}(2, \mathbb{C})$, 583
 - S -matrix, 125
 - bremsstrahlung, 205, 206, 214
 - Coulomb scattering, 213
 - pion decay, 239
 - S -matrix operator, 154
 - $\text{SO}(2)$ group, 283, 574
 - $\text{SO}(3)$ group, 311
 - $\text{SO}(3,1)$, 575
 - $\text{so}(3,1)$, 583
 - soft limit, 366, 559
 - soft photon, 209, 364
 - solar neutrinos, 530
 - spacetime, 35

- spacetime interval, 37
 - invariance under Lorentz boost, 37
- special orthogonal group, 283, 284, 574
- special unitary groups, 574
- spectral theorem, 597
- spin
 - higher than 2, problems with massless interactions, 561
 - photon, 352–358
 - spin-2
 - massless particle, 557
 - polarization, 557–562
 - universal coupling, 557–563
- spin connection, 104, 105
 - cylindrical coordinates, 108
 - spherical coordinates, 110
- spin sums, 3–4
- spinor
 - bispinor, 522
 - chiral, 6, 527
 - Majorana, 528, 552
 - negative energy, 6
 - plane wave expansion, 5, 9
 - positive energy, 6
 - Weyl, 6, 59, 112
- strange stars, 299
- strangeness, 299, 303
- stress-energy tensor
 - conservation of, 389
 - Yang-Mills, 390
- string
 - bosonic, 548–552
 - classical string of masses, 28–29
 - relation to Klein-Gordon field, 29
 - conserved current, 551, 552
 - Ramond-Neveu-Schwarz (RNS), 553
 - sigma action, 548–550
 - superstring, 552–556
 - tension, 549
- string theory, 282, 548, 552
- strong asymptotic conditions, 127
- structure constants, 307, 383, 390, 582
 - su(2), 307
 - su(3), 445, 448
- SU(2)
 - generators, 518
- SU(2), 304
 - generators, 384–388
 - three dimensional, 426
 - rotation, 303
- su(2)
 - Casimir operator, 582
 - lowering operator, 425–426
 - rank, 448
 - structure constants, 307
- SU(2) \otimes SU(2) – σ model, *see* sigma model
- SU(3)
 - generators, 518
- SU(3)
 - generators, 385, 388, 433, 445, 446
 - normalization condition, 447
 - group element, 445
 - projection operator, 446, 448
- su(3)
 - Casimir operators, 448
 - d symbols, 446
 - raising and lowering operators, 433–435
 - rank, 448
 - root vectors, 435–436
 - structure constants, 445, 448
- SU(3)_c \times SU(2)_L \times U(1)_Y, 424
- SU(5), 519
- SU(5)
 - generators, 518
- SU(N), 307
 - gauge transformation, 307, 308, 392
- subgroup, 573
- super-Poincaré algebra, 539
- supercharge, 541
 - eigenstate, 540
- supercharge operator, 539
- supercurrent, 541
- superspace, 541
- superstring, 552–556
- superstring action, 552, 553
- supersymmetric particle, 539–541
 - action, 541
- supersymmetry, 539
- supersymmetry transformation, 541, 553

- symmetries, discrete, 271
- symmetry transformation
 - global, 291
 - internal, 271
- T**
- T -matrix, 160
- tachyonic scalar field, 282
- tachyons, 68
- tardyons, 66
- Taylor-Slavnov identities, 423
- temporal gauge, 501
- tetrad, *see* orthonormal tetrad
- Thomas precession, 57, 59
- 't Hooft-Feynman gauge, 501
- three-momentum integral measure written in terms of four-momentum measure, 76–77, 143, 184
- time dilation formula, 47
- time ordering operator, 75
- time reversal, 40, 271
- topological group coordinate transformation, 272
- torsion, 307
- total decay width, 260
- total width, 260
- translation, 289
- tunneling, 267
- two-point correlation function, 121
- two-point Green function
 - Klein-Gordon field, 470
 - ϕ^4 theory, 479–482
- U**
- U -matrix, 154
- $U(1)$ group, 277, 283
- $U(1)$ gauge transformation, 495
- unitary transformation, 504–505
- V**
- vacuum state, 26, 88, 94
- Van der Waerden notation, 6, 59
- vector minus axial ($V - A$) interaction, 194, 218, 242, 251, 258, 261
- velocity addition rule, 40–42
 - implies constancy of the speed of light, 41
- velocity four vector, 46
- velocity four-vector, 46
- vertex factor
 - Fermi theory, 241
 - fermion-fermion- Z , 457
 - from action, 565
 - ghost-ghost-gluon, 403
 - graviton-scalar field, 565
 - quadrivalent gluon, 405
 - quark-quark-gluon, 398–400
 - scalar-spin-2 coupling, 557, 563–565
 - trivalent gluon, 400–403
 - W -fermion coupling, 242
 - ZZH , 456
- W**
- W boson
 - mass, 314
- W^\pm bosons, 519
- Ward identity, 371, 372, 413
 - QCD, 413–423
- Ward-Takahashi identities, 236
- wave number, 18
 - four vector, 19
- weak mixing angle, 316
- weight, 437
 - highest, 438
 - positive, 438
- weight vector, 435
- Weinberg angle, 218, 316, 457
- Weyl spinors, 6, 59, 112
 - Lorentz transformation on, 59
- Wick rotation, 469
- Wick theorem, 156
- width
 - decay, 2–3, 260
 - glueball decay, 397
 - muon decay, 250
 - pion decay, 236–241, 260
 - pseudoscalar, 234
- Wigner phase, 119
- Wigner's classification, 63
- world sheet, 549
- world sheet metric, 549, 550
- WW -fusion, 465

Y

Yang-Mills

- action, 394
- equations of motion, 389, 391, 411
- field-strength tensor, 392, 509
- Lagrangian density, 407
- propagator, 506–511
- stress-energy tensor, 390

Z

- Z^0 boson, 457, 519
- zero vector, 26, 94
- zero-operator, 95