

Index

A

absorption, 188–90, 195, 226, 231–37, 253, 257, 298, 348, 412–14, 417, 519–22
 saturation, 349
 two-photon, 231
adjoint, 96, 480, 484
Airy functions, 42–43, 529–30
Ångstrom, 15
angular momentum, 242–55
 classical, 242
 operators, 250
 spin, 303
antibonding state, 176
anticommutation relation, 384, 389, 390, 392, 397
anticommutator, 389
antiderivative, 476
arcsin. *See* sine, inverse
Argand diagram, 463, 495
associated Laguerre polynomials, 269–70, 531
associated Legendre functions, 249, 252, 255, 530
associative, 102, 483

B

band gap energy, 215
band structure, 216
basis, 24, 25, 103, 140–41
 changing, 115–16, 149
 direct product, 303–6
 multiple particle, 323–28
 normalized to a delta function, 142–44
 subset, 160
beam splitter, 320–21
Bell state, 431, 432, 438, 439, 442
Bell's inequalities, 6
Bessel functions, 43, 529
 spherical. *See* spherical Bessel functions
bilinear expansion, 108–10
Bloch equations, 347
Bloch sphere, 303–4, 435
Bloch theorem, 212
Bohm's pilot wave, 451–52
Bohr magneton, 534
Bohr model, 523
Bohr radius, 264
Boltzmann constant, 291, 534

bonding state, 176
Bose–Einstein distribution, 328
boson, 315
bound state, 33
boundary condition, 19, 38
 Born–von Karman, 210
 differential equation, 469
 Dirichlet, 473
 finite step, 26–27
 matrix, 283
 Neumann, 473
 periodic, 146, 211, 419
bra, 96, 98
bra-ket notation. *See* Dirac notation
Bravais lattice, 208
Brillouin zone, 214, 233

C

Cartesian coordinates. *See* coordinates, Cartesian
center of mass. *See* coordinates, center of mass
central potential, 265
charm, 297
chemical potential, 329
classical mechanics, 491
 Hamiltonian, 491
 Lagrangian, 491, 520
 Newtonian, 10, 491
classical turning point, 45
closure, 140–41
coherence, 346
coherent state, 63–65, 66, 74, 370, 372
collapse of the wavefunction, 5, 74, 76, 424–25, 442, 448, 449, 453, *see also* measurement, quantum mechanical
color, 1–2
commutation
 of operators, 129–31
 remainder of, 130
commutation relation, 130
 angular momentum, 244
 boson operators, 377
 electromagnetic field operators, 378
 operators for different particles, 406–7
 photon creation-annihilation, 365
 position-momentum, 355
 spin, 302

- commutative, 99, 102, 106, 483
 commutator, 129
 completeness
 of eigenfunctions, 122
 of quantum mechanics, 5–6
 of sets, 23–24
 complex conjugate, 462
 complex number, 461–64
 complex plane, 463
 conduction band, 215
 configuration space, 258
 conjugate transpose, 480
 conservative field, 492, 507
 constant of integration, 476
 continuity equation, 502
 continuum of states, 37
 coordinates
 Cartesian, 457–59
 center of mass, 260–62
 cylindrical, 506–7
 spherical, 245, 263, 504–5
 Copenhagen interpretation of quantum mechanics, 450
 Coulomb's law, 259, 494
 crystal, 207–9
 cubic lattice, 208
 cuboid, 477
 curl, 502–4
 cylindrical coordinates, 507
 spherical coordinates, 505
 cylindrical coordinates. *See* coordinates, cylindrical
- D**
- Davisson–Germer experiment, 9, 523
 de Broglie's hypothesis, 8, 9, 10, 523
 degeneracy, 20
 del, 499
 delta function, 136–49
 density matrix, 335–51
 time evolution, 341–42
 density of states, 136, 142, 213–14, 219–25
 density operator. *See* density matrix
 dephasing, 346
 derivative
 first, 464–65
 matrix representation of, 125
 partial, 466–68
 second, 465
 total, 467
 determinant, 486–87
 Laplace formula, 486
 Leibniz formula, 322, 486
 Slater, 322, 330, 384, 390
 vector cross product, 459
 diamond lattice, 208
 difference frequency generation, 196, 201
 differential, 467
 differential calculus, 464–68
 chain rule, 527
 derivative of common functions, 527
 product rule, 527
 quotient rule, 527
 differential equation, 468–73
 first order, 468–69
 general solution, 469
 in one variable, 468–71
 linear, 470
 partial, 471–73
 second order, 469–71
 series solution, 268–70
 diffraction, 9, 498
 Huygens–Fresnel, 498
 single slit, 14
 two slit, 15
 two-slit, 12
 dipole moment, 192, 193, 343–48, 509
 Dirac delta function. *See* delta function
 Dirac equation, 308
 Dirac notation, 95–98, 480
 direct gap, 215
 direct product space, 303–6, 317, 323
 dispersion, 68, 217, 495, 498
 distinguishable particles, 331–32
 distributive, 483
 divergence, 500–502
 cylindrical coordinates, 507
 spherical coordinates, 505
 theorem, 501
 divergenceless field, 501
 dot product. *See* vector, dot product
 double barrier, 285
- E**
- effective mass, 38, 72, 87, 281
 effective mass theory, 216–19
 eigenenergy, 20
 eigenequation, 20
 matrix, 487–89
 eigenfunction, 20
 energy, 20
 momentum, 137, 149
 position, 147–48, 148
 eigenvalue, 20
 continuous, 146
 matrix, 487–89

eigenvector
 matrix, 487–89
 electric constant, 510, 534
 electric dipole approximation, 185, 232, 407
 electric displacement, 510, 511
 electric field, 511
 electromagnetic field
 mode, 361–63, 366–67, 373–74
 operators, 367–69, 377–78
 quantization of, 361–78
 electron g factor, 534
 electron rest mass, 10, 534
 electron-photon interaction, 407–9
 electron-volt, 22
 electrostatics, 494
 elementary charge, 534
 emission
 spontaneous, 188, 415, 417, 418–20
 stimulated, 188, 415–17
 energy density of electric and magnetic fields,
 363, 514
 energy eigenfunction. *See* eigenfunction, energy
 ensemble average, 339–40, 351
 entanglement, 6, 7, 431–33
 envelope function, 218, 222
 EPR pair, 431, 438, 442, 443, 447
 EPR paradox, 6, 439, 442
 Euler's formula, 463
 even function. *See* parity, even
 exchange, 315, 384, 394, 395, 402
 exchange energy, 316–19, 403
 expansion
 coefficient, 25, 99
 in eigenfunctions, 23
 in energy eigenstates, 61
 expectation value, 73–74, 78
 exponential, 460

F

factorial function, 490
 Fermi energy, 291
 Fermi–Dirac distribution, 291
 fermion, 315
 Fermi's Golden Rule, 186–90, 231–37
 field emission, 279, 290
 fine structure constant, 534
 finite basis subset method, 157–60, 173, 179, 227
 finite matrix method. *See* finite basis subset
 method
 Fock state. *See* number state
 force, 492
 Fourier analysis, 23, 24, 84
 Fourier series, 23–24, 97, 306

Fourier transform, 93, 104, 106, 145
 of a Gaussian, 83
 four-wave mixing, 195, 196, 199
 free current density, 511
 free electric charge density, 511
 frequency, 495
 angular, 495
 function, 94
 fundamental theorem of calculus, 476

G

Gamma function, 531–32
 Gamow penetrability factor, 289
 gauge, 521–22
 Gauss's theorem, 501, 512
 Gaussian, 70, 71, 72, 83, 85, 139
 Gaussian elimination, 486
 Goos–Hänchen shift, 29
 gradient, 473, 494, 499
 cylindrical coordinates, 506
 spherical coordinates, 505
 Gram–Schmidt orthogonalization, 26, 177
 group velocity, 69
 group-velocity dispersion, 71

H

Hamiltonian, 77–81, 125, 134, 186
 boson, 356, 365, 376
 classical, 492
 classical electromagnetic, 363, 519
 electric dipole, 408
 electromagnetic mode, 365
 fermion, 395–403
 harmonic oscillator, 356
 hydrogen atom, 259, 262
 multimode, 376
 perturbing, 162, 166, 182, 185, 198, 232, 299,
 408, 410, 411
 spin, 307
 Hamilton's equations, 360–61
 harmonic generation, 196, 199, 202
 harmonic oscillator, 18, 39–41, 354–59, 470
 time evolution, 62–66
 Heaviside function, 140
 Heisenberg's uncertainty principle. *See* uncertainty
 principle
 Helmholtz free energy, 329
 Helmholtz wave equation. *See* wave equation,
 Helmholtz
 Hermite polynomials, 40, 531
 Hermitian adjoint, 96, 114, 119, 480
 Hermitian conjugate, 96

Hermitian matrix. *See* matrix, Hermitian
 Hermitian operator. *See* operator, Hermitian
 Hermitian transpose, 96, 114, 480
 heterostructure, 218
 Hilbert space, 103, 305, 306
 hole, 216, 217, 235
 Huygens's principle, 13, 15, 498
 hydrogen atom, 18, 55, 257–71, 299
 hyperfine interaction, 257

I

identical particles, 5, 311–32
 identity matrix. *See* matrix, identity
 imaginary number, 462
 indirect gap, 215
 indistinguishable particles, 331–32
 infinitesimal, 475
 initial condition, 472
 inner product, 97, 101, 102, 459, 483
 integral
 definite, 476, 528
 equation, 93, 106
 indefinite, 476
 integral calculus, 475–78
 in one variable, 475–77
 integration by parts, 528
 surface integral, 478
 volume integral, 477–78, 505, 507
 integrand, 476
 intensity, 496, 515–16, 522
 interaction picture, 183
 interference, 71, 497
 constructive, 496
 destructive, 496
 inverse matrix. *See* matrix, inverse
 irrotational field, 492, 507

J

joint density of states, 189, 235

K

k.p method, 157, 231
 Kane model, 227
 Kelvin–Stokes theorem. *See* Stokes theorem
 Kerr effect, 196
 ket, 95, 96, 97
 kinetic energy, 11, 491
 Kramers degeneracy, 216
 Kramers–Kronig relations, 195
 Kronecker delta, 25
 k-space, 213

L

L^2 function, 17, 137
 Laguerre polynomials
 associated. *See* associated Laguerre polynomials
 Lamb shift, 257
 Laplace determinant formula. *See* determinant, Laplace formula
 Laplacian, 10, 247, 472–73, 499–500
 Cartesian coordinates, 472
 cylindrical coordinates, 507
 spherical coordinates, 505
 lattice vector, 207, 212, 239
 Lebesgue integration, 17, 137, 475
 Legendre functions
 associated. *See* associated Legendre functions
 Legendre polynomials, 26
 Leibniz notation, 464
 Levi–Civita symbol, 244
 Leibniz determinant formula. *See* determinant, Leibniz formula
 linear equation, 485
 linearity
 linear superposition, 59–60, 102
 multiplying by a constant, 16, 102
 of quantum mechanics, 59–60
 linearly varying potential, 18, 42–50
 Liouville equation, 342
 logarithm, 460
 logical positivism, 7
 longitudinal relaxation, 345
 Lorentz force, 519
 Lorentzian, 139, 349
 Luttinger–Kohn model, 227
 Luttinger–Kohn representation, 227

M

Maclaurin series, 525–26
 magnet, 298
 magnetic constant, 511, 534
 magnetic current density, 511
 magnetic dipole moment, 298–99
 magnetic field, 511
 magnetic flux density, 511
 magnetic induction, 511
 magnetic monopole, 511
 magnetic quantum number, 299
 magnetic vector potential. *See* vector potential
 magnetism, 3, 319
 magnetization, 511
 many-minds hypothesis, 453
 many-worlds hypothesis, 5, 453

matrix, 478–89
 addition, 481
 determinant. *See* determinant
 diagonal elements, 479
 element, 107–8, 479
 Hermitian, 480
 Hermitian adjoint, 480
 of a product, 484
 identity, 484
 inverse, 484–86
 invertibility, 486
 leading diagonal, 479
 mechanics, 523
 multiplication, 481–84
 off-diagonal elements, 479
 rectangular, 479
 square, 479
 subtraction, 481
 transfer, 279–86
 transpose, 114, 480
 Maxwell–Boltzmann distribution, 292
 Maxwell's equations, 4, 509
 measurement, quantum mechanical, 4, 5, 6, 7, 74,
 75, 76, 132, 133, 311, 371, 424–25, 446–54, *see*
 also collapse of the wavefunction
 mind/matter distinction, 453
 modes, 64, 188, 250, 316, 330–31, 359, 361–79,
 406–9, 418–20, 516–18
 modulus, 462
 molecular bonding, 175
 momentum
 classical, 491
 operator, 81, 124, 131, 137, 149, 364, 368, 399
 monochromatic waves, 496

N

nabla, 499
 Newton's Laws, 4, 492
 no-cloning theorem, 425–27
 nodal line, 497
 nonlinear optical coefficients, 195–202, 351
 nonlinear refraction, 195, 199
 nonlocality, 6, 7, 444
 normalization, 17–18
 to a delta function, 67, 141–42
 n th root of unity, 463
 number state, 367, 371

O

odd function. *See* parity, odd
 one-electron approximation, 209
 ontology, 330

operator, 77, 103–25
 angular momentum. *See* angular momentum,
 operators
 annihilation, 354–79, 383–403
 boson, 354–79
 creation, 354–79, 383–403
 electromagnetic field. *See* electromagnetic
 field, operators
 fermion, 383–403
 Hermitian, 110, 119–22
 identity, 110, 113
 inverse, 110, 113
 linear, 104–6
 lowering, 354–59
 momentum. *See* momentum operator
 position. *See* position operator
 projection, 113
 raising, 354–59
 spin. *See* spin operator
 time-evolution. *See* time-evolution operator
 unitary, 110, 114–18
 wavefunction. *See* wavefunction operator
 orthogonality, 24
 of eigenfunctions, 24–25
 orthohelium, 319
 orthonormality, 25
 outer product, 483

P

parabolic band, 217, 291
 parahelium, 319
 paraxial approximation, 16
 parity, 20, 40, 202
 even, 20
 odd, 20
 Parseval's theorem, 143, 145
 particle current, 85–87, 278
 particle in a box, 3, 18–22, 221
 finite depth, 18, 32–37
 particles, identical. *See* identical particles
 Pauli equation, 307
 Pauli exclusion principle, 297, 311, 315–16, 322,
 383, 385, 400
 Pauli spin matrices, 119, 131, 302, 303, 307
 penetration factor, 288–89
 permeability, 511
 of free space. *See* magnetic constant
 relative, 511
 permittivity, 510
 of free space. *See* electric constant
 relative, 510
 perturbation theory
 Brillouin–Wigner, 169

degenerate, 157, 299
 density matrix, 350
 first order, 164–65, 168, 183, 186, 192, 198
 Löwdin, 227
 nondegenerate, 164
 oscillating perturbations, 185–90
 Rayleigh–Schrödinger, 169
 second order, 166, 168, 196, 198
 stationary. *See* perturbation theory, time-independent
 third order, 168, 196, 198
 time-dependent, 182–90, 409–11
 time-independent, 161–72
 phase, 463
 front, 495
 velocity, 67, 69
 phonon, 209, 379
 photoelectric effect, 523
 photon, 1, 18, 39, 55, 330, 354–79, 523
 Pikus–Bir model, 227
 Planck's constant, 9, 523, 534
 plane wave, 495
 electromagnetic, 513
 Pockels effect, 196
 Poisson distribution, 64, 372
 polarizability, 180
 polarization
 circular, 514
 elliptical, 514
 linear, 232, 514
 of a material, 170, 192, 196, 509–10
 of a wave, 160, 232, 361, 419, 425, 514
 selection rules, 231, 253, 298
 position operator, 82, 149, 243, 356, 399
 potential
 energy, 492
 scalar, 507
 vector. *See* vector potential
 potential well
 coupled, 172
 finite. *See* particle in a box, finite depth
 infinite. *See* particle in a box
 rectangular, 19
 skewed infinite, 47, 155–60, 155–60, 179
 square, 19
 time evolution, 61
 triangular, 46–47
 with field, 47–50
 Poynting vector, 514–18
 principal quantum number, 271
 probability amplitude, 12
 probability density, 11–12, 478
 product notation, 489
 proton rest mass, 534

proton-electron mass ratio, 534
 pure state, 335–38

Q

quadratic equation, 525
 quantum box, 222, 273
 quantum computing, 6, 433–37, 454
 quantum cryptography, 6, 425–31
 quantum encryption. *See* quantum cryptography
 quantum mechanical amplitude, 12, 497
 quantum mechanical measurement. *See*
 measurement, quantum mechanical
 quantum mechanics, completeness. *See*
 completeness, of quantum mechanics
 quantum well, 3, 18, 38, 219, 210–11, 286
 quantum wire, 222, 225, 274
 quasi-bound states, 286

R

Raman amplification, 196
 reciprocal lattice, 213, 214
 rectangular parallelepiped, 477
 rectangular prism, 477
 recurrence relation, 269
 reduced mass, 261
 reflection high-energy electron diffraction
 (RHEED), 15
 refraction, 498
 refractive index, 192–95, 199, 513
 relaxation time approximation, 350
 representation, 24, 98
 Richardson constant, 293
 Richardson–Dushman equation, 293
 Riemann integration, 475
 right-hand rule, 458–59
 right-handed axes, 458
 rotating wave approximation, 347
 Rydberg, 264, 267
 Rydberg constant, 534

S

scalar, 462
 Schottky barrier, 290
 Schrödinger's cat, 4
 Schrödinger's equation, 8, 523
 generalized, 257
 time-dependent, 54–60
 time-independent, 8–11
 second derivative. *See* derivative, second
 secular equation, 488
 self-adjoint, 119

separability, 18, 23
 separation of variables, 222, 248, 262, 263
 sinc function, 14, 138, 142, 187, 188, 189
 sine
 inverse, 461
 slowly varying envelope approximation, 217
 solenoidal field, 501
 soliton, 195
 span, 103
 speed of light in vacuum, 534
 spherical Bessel functions, 274, 530
 spherical coordinates. *See* coordinates, spherical
 spherical harmonics, 250–52, 263, 270, 530
 spin, 3, 99, 216, 220, 228, 231, 297–308, 523
 half-integer, 315
 integer, 315
 spin operator, 302–3
 spinor, 305
 spin-orbit interaction, 257
 standard deviation, 83
 standard interpretation of quantum mechanics, 449
 standing wave, 21, 30, 31, 45, 71, 368, 369, 373, 497
 state vector, 99–100, 117
 Stern–Gerlach experiment, 76, 299, 523
 Stokes theorem, 504, 512
 strangeness, 297
 subband, 223
 sum frequency generation, 201
 summation notation, 474
 superposition state, 54
 surface integral. *See* integral calculus, surface
 integral
 susceptibility, 192, 197, 199, 348, 510
 nonlinear, 197, 202

T

Taylor series, 525–26
 tensor product, 306
 thermionic emission, 289
 field-assisted, 290
 three-wave mixing, 196
 tight-binding model, 176
 time evolution, 54
 time-evolution
 operator, 78–81, 314
 total derivative. *See* derivative, total
 total internal reflection, 29
 trace, 112–13
 transfer matrix. *See* matrix, transfer
 transpose. *See* matrix, transpose
 transverse relaxation, 346

trigonometric addition and multiplication
 formulae, 526–27
 tunneling, 3, 4, 7, 29, 72
 probability, 277–79, 284
 two-level system, 343–49
 two-slit experiment. *See* diffraction, two-slit

U

ultraviolet catastrophe, 2, 523
 uncertainty principle, 4, 7, 82–85, 135, 523
 diffraction angle, 85
 electromagnetic field, 369
 energy-time, 134
 frequency-time, 84, 135
 position-momentum, 84, 133
 unit cell, 207, 214
 unitary operator. *See* operator, unitary
 unitary transformation, 114

V

valence band, 215
 variational method, 179
 vector
 calculus
 identities, 507, 508
 operators, 500
 column, 479
 dot product, 98, 101, 459
 field, 500
 generalized, 479
 length, 102
 multiplication, 483
 norm, 102
 potential, 186, 232, 519
 projection, 458
 row, 479
 space, 103, 100–103
 vertical transition, 235
 vibrational mode, 378–79
 volume integral. *See* integral calculus, volume
 integral

W

wave amplitude, 495
 wave equation
 electromagnetic, 512
 Helmholtz, 10, 470, 472
 one-dimensional, 472
 three-dimensional, 472–73
 wave front, 495
 wavefunction, 9

meaninglessness, 92
operator, 392–403
wavelength
 electron, 9
wavepacket, 64, 72, 217, 311
wave-particle duality, 9, 523
WKB method, 288

Y

Young's slits. *See* diffraction, two slit

Z

Zeeman effect, 299
zero point energy, 21, 40
zinc-blende structure, 208, 228