

Index

• Numerics •

3D harmonic oscillators, 184–187, 203
3D Schrödinger equation, 170–172

• A •

adjoints, 36–37
algorithm, Numerov, 115
allowable bound states, energy of, 59
alpha particle, 246, 292
amplitude, 9, 303
angular frequency of motion, 263
angular momentum
 in classical mechanics, 128
 commutators, 130–131
 defined, 303
 deriving eigenstate equations, 134–137
 eigenfunctions, 159–160
 eigenstates, 132–134
 eigenvalues, 134–139
 equations, 148
 lowering operator, 132–134
 matrices, 140–147
 momentum operators, 130
 orbital, 161–162
 overview, 128
 position operators, 130
 quantum number, 160, 222
 raising operator, 132–134
 rotating disk, 129–130
 rotational energy of diatomic molecule,
 137–139
 spherical coordinates, 147–156
 spin operators, 161–162
annihilation operator, 94–95, 303
anti-Hermitian operators, 38–39, 41, 303
anti-particle, 18
antisymmetric wave functions, 237–239,
 244, 246–247, 250
atoms. *See also* hydrogen atom
 as composite particles, 246
 discrete spectra, 301

 with multiple electrons 233–239
 Pauli exclusion principle, 250–251
 periodic table, 251–252
 in quantum mechanics, 128
 in rotating diatomic molecule, 137

• B •

barriers. *See* potential barriers
basis-less vectors, 31
Bessel function, 196–197, 200–201
black-body radiation, 10–13, 303
Bohr, Niels, 217
Bohr radius, 62–64, 217, 229, 272, 303
Born approximation, 288–292. *See also*
 scattering
bosons, 161, 245–246, 303
bound states, 59–60, 68, 303. *See also* free
 particles
box potentials, 177, 180–184. *See also*
 rectangular coordinates
bra-ket notation, 26–29, 303
bras, 29–31
bull's eye analogy, 277

• C •

Cat, Schrodinger's, 302
center-of-mass frame
 cross sections, 281–282
 lab frame and, 277–283
 defined, 303
 overview, 277–278
 scattering angle, 278–280, 292
central potential
 angular part of $\psi(r, \theta, \phi)$, 193–194
 defined, 303
 radial part of $\psi(r, \theta, \phi)$, 194–195
 Schrödinger equation, 192–193
charged oscillator
 energy of, 265–267
 wave functions, 267–268
classical physics, 9

cloud chambers, 18
 coefficients of λ , 258–259
 College of St. Benedict's tutorial, 297
 column vector, 34
 commutator
 of angular momentum vector, 130–131
 defined, 303
 finding, 37–38
 of operators, 37–39
 unitary transformations, 51
 complex conjugate
 as bra, 29
 defined, 303
 in Hermitian adjoints, 36
 unitary operators, 50
 complex number, 36
 composite particles, 246
 Compton, Arthur, 16
 Compton effect, 16–17, 304
 Compton wavelength, 17
 conjugate, Hermitian, 36–37
 conservation of energy, 304
 continuous representations, 51–54
 cosmic rays, 18
 creation operator, 94–95, 304
 cubic potential
 degeneracies in energies, 183–184
 energy of 3D isotropic harmonic oscillator and, 187
 energy of ground state, 183
 wave function, 184
 current density, 276, 304

• **D** •

d state, 226, 251
 De Broglie, Louis, 18–20
 degeneracy
 of 3D isotropic harmonic oscillator, 187
 defined, 304
 exchange, 244–245
 ground state, 183–184
 of hydrogen atom, 222–228
 Stark effect, 273
 degenerate Hamiltonians, 269–271
 diatomic molecule, rotational energy of,
 137–139
 dice, 24–26

differential cross section
 Born approximation, 291
 center-of-mass frame, 281–282
 defined, 276, 304
 lab frame, 281–282
 particle scattering and, 276–277
 spinless particles, 285–286
 differential operators, 158–159
 Dirac, Paul, 17, 26–27
 Dirac notation
 abbreviating state vectors as kets, 27–28
 defined, 303
 overview, 26–27
 writing complex conjugate as bra, 29
 Dirac's constant, 304
 discrete spectra of atoms, 301
 dual-slit apparatus, 19

• **E** •

eigenfunctions
 for angular momentum, 159–160
 of angular momentum operators L_z and
 L^2 , 147–149
 antisymmetric, 237–239
 of L^2 in spherical coordinates, 151–156
 of L_z in spherical coordinates, 150–151
 symmetric, 237–239
 in total energy of free particles, 175
 eigenstates
 angular momentum, 132–134
 β_{\max} , 34–36
 β_{\min} , 132–134
 energy of $a | n \rangle$, 97
 energy of $a^\dagger | n \rangle$, 97–98
 first excited state, 103–104
 hermite polynomials, 105–106
 lowering operator, 132–134
 position space, 99–101
 raising operator, 132–134
 second excited state, 104–105
 using a and a^\dagger , 97–98
 wave function of ground state, 102–103
 eigenvalues
 defined, 304
 eigenvectors and, 43–45
 exact energy, 264

- finding, 47–49
 - lowering operator, 139–140
 - raising operator, 139–140
 - eigenvectors
 - defined, 304
 - degenerate Hamiltonians, 271
 - eigenvalues and, 43–45
 - finding, 47–50
 - of operators, 46–47
 - Einstein, Albert, 15
 - elastic collision, 304
 - electric field
 - defined, 304
 - harmonic oscillators in, 262–269
 - hydrogen in, 271–273
 - weak, 263
 - electron. *See also* spin
 - anti-particle, 18
 - Bohr radius, 229
 - collisions, 242–243
 - Compton wavelength, 17–18
 - defined, 304
 - emitted, 14–15
 - kinetic energy, 206
 - location in hydrogen, 228–230
 - orbitals, 226–228, 251–252
 - periodic table, 251
 - photoelectric effect, 14–16
 - shell structure, 251–252
 - subshells, 251–252
 - wave-like properties, 19–20
 - electron beam, 19
 - electron volts, 304
 - electrostatic potential energy, 207
 - emissivity, 304
 - emitted electrons, 14–15
 - energy, 9, 17, 265–267, 304
 - energy degeneracy
 - of 3D isotropic harmonic oscillator, 187
 - defined, 304
 - ground state, 183–184
 - of hydrogen atom, 222–228
 - Stark effect, 273
 - energy levels. *See also* Hamiltonian operator
 - degeneracy of, 223
 - determining, 62–64
 - floating cars analogy, 241
 - harmonic oscillators in electric fields, 264
 - particle in box potential, 180–181
 - perturbations, 258
 - spherical coordinates, 190
 - energy state equations, 94–96
 - energy wells
 - binding particles in potential wells, 60
 - box potentials, 180–181
 - energy levels, 62–64
 - escaping from potential wells, 60–61
 - free particles, 85–87
 - Gaussian wave packet, 88–89
 - infinite square potential wells, 61–68
 - nonzero solution, 76–78
 - normalizing wave function, 64–65
 - particle without enough energy, 74–78
 - particle with plenty of energy, 69–81
 - physical particle with wave packet, 87–89
 - potential barriers, 78–85
 - reflection coefficient, 71–72, 76
 - Schrödinger equation, 57
 - square well, 57–59
 - symmetric square wells, shifting to, 67–68
 - time dependence in wave functions, 65–67
 - transmission coefficient, 71–74, 76
 - trapping particles in potential wells, 59–68
 - wave-function equation, 61–62
 - exchange operator, 235–237, 244–245
 - expectation value
 - of anti-Hermitian operator, 39
 - defined, 304
 - of Hermitian operator, 37
 - of operators, 34–36
 - of radius r , 228–230
- F •**
- f state, 226, 251
 - fermions, 160, 162–165, 245–246, 305
 - first excited state, 103–104, 217
 - first-order corrections, 257, 259–260, 265
 - floating cars analogy, 239–241
 - force
 - due to electric field, 263
 - equation, harmonic oscillation, 92
 - MKS unit, 306
 - potential energy and, 307
 - restoring, 184–185, 201

free particles. *See also* bound states
 Schrödinger equation, 85–89, 172–173
 spherical coordinates, 195–196
 in three dimensions, 172–177
 time dependence, 175–177
 total energy equation, 174–175
 wave packet, 87–89
 x , y , and z equations, 173–174
 frequency, 305

• G •

g state, 251
 gamma rays, 18
 Gaussian wave packet, 88–89, 176–177
 Gerlach, Walther, 157
 Goudsmit, Samuel, 158
 gradient operator, 33
Grains of Mystique: Quantum Physics for the Layman, 296
 gravitons, 161
 Green's functions, 287
 ground state energy, 115, 183–184, 241

• H •

h state, 251
 Hamiltonian operator
 3D Schrödinger equation, 170–172
 defined, 33, 305
 eigenvalues, 51
 harmonic oscillators, 93–94, 263
 multi-particle system, 233
 perturbations, 256, 258, 272–273
 zeroth-order approximation, 269
 harmonic oscillators
 3D, 184–187
 a and a^\dagger , using, 97–98
 annihilation operator, 94–95
 classical, 92
 creation operator, 94–95
 defined, 91
 eigenstates, 99–106
 in electric fields, 262–269
 energy of $a | n \rangle$, 97
 energy of $a^\dagger | n \rangle$, 97–98
 energy state equations, 94–96

exact ground state energy, 115
 first excited state, 103–104
 Hamiltonians, 91–94
 hermite polynomials, 105, 186
 isotropic, 187, 201–203
 Java code, 114–124
 as matrices, 108–113
 position space, 99–102
 proton, 106–107
 quantized energy of, 301
 quantum, 93–94
 second excited state, 104–105
 wave function of ground state, 102–103
 Web sites, 301–302
 harmonics, normalized spherical, 155
 Heisenberg uncertainty principle, 20–21, 39–43, 300–301, 305, 307
 hermite polynomials, 105–106, 186
 Hermitian adjoints, 36–37, 305
 Hermitian conjugate, 36–37
 Hermitian operators
 anti-Hermitian operators, 38–39
 commutator, 47
 defined, 305
 eigenvalues, 43
 finding, 38–39
 replacing operators with, 37
 unitary transformations, 51
 Hilbert space
 creating vectors in, 24–26
 position vectors, 31
 state vectors, 28
 Hogben, Giles (tutorial creator), 295
 Hooke's law, 91
 hydrogen atom
 allowed energies of, 216–217
 center of mass, 208–209
 in electric fields, 271–273
 electron in, 205–206
 energy degeneracy, 222–223
 orbitals, 226–228
 proton in, 205–206
 quantum states, 224–226
 radial Schrödinger equation, 211–220
 Schrödinger equation, 205–210
 spin, 224–226
 hydrogen wave functions, 28, 220–222

• I •

identical noninteracting particles, 247–250
 identity matrix, 52
 identity operator, 33
 incident current density, 71–72
 incident flux, 276, 305
 incident light, 16–17
 incident wave function, 282–288
 incoming particle, kinetic energy of, 292
 inelastic collision, 305
 inertia, rotational moment of, 138
 infinite square wells
 adding time dependence to wave functions, 65–67
 determining energy levels, 62–64
 finding wave-function equation, 61–62
 normalizing wave function, 64–65
 shifting to symmetric square wells, 67–68
 trapping particles in, 61–68
 instantaneous acceleration, 92
 intensity (wave), 305
 interchange symmetry
 antisymmetric wave functions, 237–239
 exchange operator, 235–237
 symmetric wave functions, 237–239
 interference of waves, 20
 An Introduction to Quantum Mechanics (tutorial), 295
 isotropic harmonic oscillator, 187, 201–203

• J •

Java code
 approximating $\psi(\infty)$, 116–118
 approximations, 114–116
 creating, 116–124
 one-dimensional Schrödinger equation, 114
 running, 123–124
 writing, 118–122
 Joule, 305

• K •

kets
 as basis-less state vectors, 31
 multiplying bras and, 30
 normalized, 30
 orthogonal, 32

orthonormal, 32
 Schwarz inequality, 31–32
 state vectors as, 27–28
 kinetic energy
 defined, 305
 of electron, 206
 incoming particle, 292
 multi-electron atom, 234
 of proton, 206
 radial, 193
 rotational, 193

• L •

L^2 operator, 161–162
 lab frame
 center-of-mass frame and, 277–283
 cross sections, 281–282
 defined, 305
 overview, 277–278
 particles of equal mass, 282–283
 scattering angles, 278–280
 Laguerre polynomial, 220, 272
 Laplacian operator, 33, 54, 170, 192, 305
 light
 black-body radiation and, 10
 frequency, 12
 incident, 16–17
 as particles, 13–18, 300
 photoelectric effect, 14–16, 299–300
 photons, 15, 19, 306
 scattering, 16–18
 spectrum, 12
 speed of, 17
 wavelength shift, 17
 light waves, 9, 12
 limited potential
 nonzero solution, 76–78
 particle without enough energy, 74–78
 particle with plenty of energy, 69–73
 reflection coefficient, 71–72, 76
 transmission coefficient, 71–72, 76
 linear momentum operator, 33
 linear operator, 36
 lowering operator
 angular momentum eigenstates, 132–134
 finding eigenvalues, 139–140
 harmonic oscillators, 97–98, 101, 110–111
 spin, 162

• M •

magnetic field, 305
 magnitude, 305
 mass, 17, 92, 263, 305
 matrices
 angular momentum, 140–147
 harmonic oscillator, 108–113
 Pauli, 165–166
 spin $1/2$, 163–165
 matrix mechanics, 51
 matrix representations, 51–54
 MKS system, 305
Modern Physics Tutorials, 295
 momentum, 305
 momentum operator, 53, 93, 130
 momentum vector, 9, 31, 129
 multi-electron atom, 233–239
 multi-particle system
 antisymmetric wave functions,
 244, 246–247
 antisymmetry, 244
 atom with multiple electrons, 233–235
 exchange degeneracy, 244–245
 exchange operator, 235–237
 floating cars analogy, 239–242
 ground state energy, 241
 Hamiltonians, 232–233
 identical noninteracting particles,
 247–250
 interchange symmetry, 235–239
 losing identity, 242–243
 overview, 232
 Pauli exclusion principle, 250–251
 periodic table, 251–252
 steady Hamiltonian, 244–245
 symmetric wave functions, 244, 246–247
 symmetrization postulate, 245–246
 symmetry, 244
 total energy equation, 233, 241
 two-particle systems, 248–249
 wave functions, 232–233, 247–250

• N •

Neumann function, 196–197, 200–201
 neutrons, 246
 Newton (unit), 306

Newton's laws, 300
 nondegenerate Hamiltonians, 256–257
 normalized function, 64–65, 306
 normalized ket, 30
 normalized spherical harmonics, 155
 nucleons, 246
 number operator, 95
 Numerov algorithm, 115

• O •

operators, 32–33. *See also specific operators by name*
 orbital angular momentum, 161–162, 192
 orbitals, 226–227, 251, 306
 orthogonal kets, 32, 306
 orthonormal kets, 32, 306
 oscillation, 306

• P •

p state, 226, 251
 pair annihilation, 18, 306
 pair production, 17–18, 306
 particles, 9, 18–20, 59–60, 92–93, 263, 306
 Pauli exclusion principle, 231, 250–251, 306
 Pauli matrices, 165–166
 period, 306
 periodic table, 251–252
 permutation operator, 249
 perturbation theory, 255–256, 264–269
 perturbations
 coefficients of λ , 258–259
 defined, 306
 degenerate Hamiltonians, 269–271
 energy levels, 258
 energy of unperturbed system, 256–257
 equations, 257–258
 first-order corrections, 257, 259–260
 Hamiltonian, 256, 258, 272–273
 harmonic oscillators in electric fields,
 262–269
 hydrogen in electric fields, 271–273
 nondegenerate Hamiltonians, 256–262
 second-order corrections, 257, 261–262
 time-independent, 255–256
 wave function, 258
 photoelectric effect, 14, 299–300, 306

photons, 15, 19, 306
Physics 24/7's Tutorial, 296
 pi meson, 246, 306
 Planck, Max, 12–13
 Planck's constant, 13, 17, 306
 Planck's equation, 13
 Planck's quantization rule, 13
 position operators, 93
 position vectors, 31, 52–53
 positron, 306
 potential barriers
 defined, 306
 overview, 78–79
 reflection coefficient, 83–84
 Schrödinger equation, 79–81
 tunneling, 84–85
 Wentzel-Kramers-Brillouin
 approximation, 85
 when $E < V_0$, 81–83
 when $E > V_0$, 79–81
 potential energy, 193, 207, 234, 239, 307
 potential step, 74, 307
 potential wells, 59–61, 83–84, 307
 power, 307
 principal quantum number, 216, 222, 251
 probability, 21–22
 probability amplitudes, 25, 307
 probability density, 21, 307
 proton, 106–107, 115, 205–206, 246
 proton/electron system, center of
 mass, 208

• **Q** •

quantization-condition equation, 216–217
Quantum Atom Tutorial, 297
 quantum mechanics, 128
Quantum Mechanics Tutorial, 295
 quantum number
 angular momentum, 128, 131–133, 136,
 160, 222
 of i th particle, 240, 249
 orbitals, 226
 Pauli exclusion principle and, 250–251
 periodic table and, 251–252
 principal, 216–217, 222
 of quantized states, 63
 quantum state of hydrogen atom, 222–223

radial, 215–216
 radial part of $\psi(r, \theta, \phi)$, 194
 spin, 160
 total energy of particle, 181
 quantum oscillation, 93–94
Quantum Physics for the Layman
 (tutorial), 296
Quantum Physics Online Version 2.0, 296
 quantum tunneling, 201, 301
 quark, 246, 307

• **R** •

radial equation, 194–195
 radial kinetic energy, 193
 radial quantum number, 215–216
 radial Schrödinger equation
 allowed energies of hydrogen atom,
 216–217
 principal quantum number, 216
 radial quantum number, 215–216
 solutions, 212–215, 218–220
 solving for large r , 212
 solving for small r , 211–212
 radial wave function, 221–222
 radian, 307
 radiation, 10–13, 303, 307
 radius vector, 191
 raising operator, 98, 132–134, 139–140,
 162, 166
 Raleigh-Jeans Law, 12
 rectangular coordinates
 3D harmonic oscillators, 184–187
 3D Schrödinger equation, 169–172
 box potential, 177–184
 cubic potential, 183–184
 energy levels, 180–181
 free particles in 3D, 172–177
 Schrödinger equation, 177
 versus spherical coordinates, 190–191
 time dependence, 175–177
 total energy equation, 174–175
 wave function, 181–182
 x , y , and z equations, 173–174
 reduced mass, 209
 reflection coefficient, 71–72, 76, 83–84
 relative probability, 24
 relativity, theory of, 18

restoring force, 184–185, 201
 Roll operator, 34–36
 rotational energy, 128, 137–139
 rotational kinetic energy, 192
 row operator, 34
 Rydberg constant, 272–273

• S •

s state, 226, 251
 S^2 operator, 162
 scattered wave function, 285
 scattering. *See also* scattering angle
 Born approximation, 288–292
 center-of-mass frame, 277–278
 cross section, 275–277
 differential cross section, 276–277
 incident flux, 276
 lab frame, 277–278, 282–283
 overview, 275
 particles of equal mass, 282–283
 spinless particles, 283–288
 total cross section, 277
 translating cross sections, 281–282
 scattering angle
 center-of-mass frame, 292
 Compton effect, 304
 cross section, 292
 between frames, 278–282
 of light, 17
 as solid angle, 276
 translating cross sections, 281–282
 Schrödinger, Erwin, 52
 Schrödinger equation
 3D, 169–172
 3D harmonic oscillators, 186
 approximating $\psi(\infty)$, 116–118
 approximations, 114–116
 central potential, 192–193
 defined, 57, 307
 floating cars analogy, 241
 free particles, 85–89, 172–173
 for hydrogen atom, 205–210
 Java code, 116–123
 Numerov algorithm, 115
 one-dimensional, 114
 particle energy, 69

potential barriers, 82
 in potential step, 74
 radial equation, 212–215
 radial quantum number, 215–216
 radial solution of, 218–220
 simplifying, for hydrogen, 208–210
 solving for large r , 212
 solving for small r , 211–212
 solving for $\psi(R)$, 210–211
 solving for $\psi(r)$, 211–222
 splitting, for hydrogen, 208–210
 time-dependent, 66, 170, 207, 209
 wave mechanics, 54
 Schrödinger's Cat, 302
 Schwarz inequality, 31–32
 second excited state, 104–105, 217
 second-order corrections,
 257, 261–262, 265
 simple harmonic solution, 307
 speed of light, 17
 spherical Bessel function, 196–197, 200–201
 spherical coordinates
 angular part of $\psi(r, \theta, \phi)$, 193–194
 central potential, 192–195
 conversion equations, 148
 defined, 189, 191, 307
 eigenfunctions of L^2 , 151–156
 eigenfunctions of L_z , 150–151
 energy levels, 190
 free particles in 3D, 195–196
 isotropic harmonic oscillator, 201–203
 limits for large ρ , 197
 limits for small ρ , 197
 normalized spherical harmonics, 193
 overview, 147–148, 189
 radial part of $\psi(r, \theta, \phi)$, 194–195
 radius vector, 191
 versus rectangular coordinates, 190–191
 Schrödinger equation, 192–193
 spherical Bessel function, 196–197
 spherical Neumann function, 196–197
 spherical square well potential, 198–201
 wave function, 195
 spherical Laplacian operator, 192
 spherical Neumann function,
 196–197, 200–201
 spherical square well, 198–201

- spin
- angular momentum, 158–159
 - bosons, 161
 - defined, 157, 307
 - down, 158
 - eigenstates, 159–160
 - fermions, 160, 162–165
 - Pauli matrices, 165–166
 - postulating, 300
 - quantum states, 224–226
 - up, 158
- spin $1/2$ matrices, 163–165
- spin magnitude, 163
- spinless particles, 283–288
- square well. *See also* infinite square wells
- energy of allowable bound states, 59
 - overview, 57–59
 - quantized energy and, 302
 - for the region $0 < r < a$, 199–200
 - for the region $r > a$, 200–201
 - spherical, 198–201
 - trapping particles in, 58
 - wave function, 58
 - Web sites, 302
- Stark effect, 271
- state vectors
- adjoints, 36–37
 - anti-Hermitian operators, 38–39
 - basis-less, 31
 - bras, 31
 - commutators, 37–39
 - complex conjugate as bra, 29
 - continuous representations, 51–54
 - defined, 307
 - Dirac notation, 26–32
 - eigenvalues, 43–50
 - eigenvectors, 43–50
 - expectation value, 34–36
 - Heisenberg uncertainty principle, 39–43
 - Hermitian operators, 36–37
 - in Hilbert space, 24–26
 - kets, 27–28, 31
 - linear operators, 36
 - matrix representations, 51–54
 - multiplying bras and kets, 30
 - operators, 32–34
 - Schwarz inequality, 31–32
 - unitary operators, 50–51
 - wave function, 53
- steady Hamiltonian, 244–245
- Stern, Otto, 157
- Stern-Gerlach experiment, 157–159, 300
- subshells, 251–252
- symmetric square wells, 67–68
- symmetric wave functions, 237–239, 244, 246–247, 250
- symmetrization postulate, 245–246
- synchrotron, 307
- S_z operator, 162
- T ●
- 3D harmonic oscillators, 184–187, 203
- 3D Schrödinger equation, 170–172
- three-or-more-particle systems, 249–250
- threshold frequency, 15, 308
- Timberlake, Todd (physics professor), 296
- time dependence, 175–177
- time-dependent Schrödinger equation, 66, 170, 206
- time-independent wave function, 176
- total cross section, 277, 308
- total energy, 3D Schrödinger equation, 171
- total energy equation, 174–175, 234, 240
- transmission coefficient, 71–72, 76, 83–84
- tunneling, 84–85, 308
- tutorials
- College of St. Benedict's, 297
 - Grains of Mystique: Quantum Physics for the Layman*, 296
 - An Introduction to Quantum Mechanics*, 295
 - Physics 24/7's*, 296
 - Quantum Atom Tutorial*, 297
 - Quantum Mechanics Tutorial*, 295
 - Quantum Physics Online Version 2.0*, 296
 - Stan Zochowski's PDF, 297
 - Todd K. Timberlake's, 296
 - Web-based quantum mechanics course, 297
- two-particle systems, 248–249

• U •

Uhlenbeck, George E., 158
 ultraviolet catastrophe, 12, 308
 uncertainty principle, 20–21, 39–43,
 300–301, 305, 308
 unitary operators, 50–51
 unity operator, 33
 unperturbed energy, 257, 268, 273
 unperturbed system, 256–258

• V •

vectors. *See also* state vectors
 basis-less, 31
 defined, 308
 in Hilbert space, 24–26
 as kets, 27–28
 position, 31, 52–53
 of probability states, 24
 Schwarz inequality, 31–32
 velocity, 277–278, 308
 volt, 308

• W •

wave, 18–20, 308
 wave function
 adding time dependence to, 65–67
 antisymmetric, 237–239, 244, 246–247
 Born approximation, 288–292
 of charged oscillator, 267–268
 cubic potential, 184
 electron spin, 225

ground state, 184
 intensity of, 21–22
 multi-particle system, 232–233, 247–250
 normalizing, 64–65, 181–183
 perturbations, 258
 proton in harmonic oscillation, 107
 radial, 221–222
 spherical coordinates, 195
 for state vector, 53
 symmetric, 237–239, 244, 246–247
 of three-or-more-particle systems,
 249–250
 time-independent, 176
 of two-particle systems, 248–249
 wave mechanics, 53–54
 wave packet, 87–89, 176–177, 308
 wave vector, 9, 19
 wavelength, 9, 16–17, 19, 304, 308
 wavelength shift, 17
 wave-particle duality, 18–20, 299, 308
 Web-based quantum mechanics
 course, 297
 Wells. *See* energy wells
 Wentzel-Kramers-Brillouin
 approximation, 85
 Wien, Wilhelm, 12
 Wien's formula, 12
 work, 308

• Z •

z projection, 163
 zeroth-order approximation, 269
 Zochowski, Stan (physics professor), 297