

Author Index

Aharonov, Y., 305, 337	Christensen, J. H., 142
Anderson, H. L., 134	Clauser, J. F., 344
Anderson, M. H., 125	Commins, E. D., 344
Andrade, E. N. da Costa, 6	Compton, Arthur H., 4
Aspect, Alain, 343	Condon, E. U., 132, 223
	Cornell, E. A., 125
Bacciagaluppi, G., 27	Creutz, M., 296
Bailey, V. A., 224	Cronin, J. W., 142
Bakshi, P. M., 266	
Bassi, A., 82	Dalibard, J., 343
Bayh, W., 307	Darwin, C. G., 98
Bell, John S., 342	Davisson, Clinton, 12
Berry, Michael V., 196, 197	DeGrand, T., 296
Beyer, R. T., 85	DeTar, C., 296
Bloch, F., 77	Deutsch, D., 90
Block, M. M., 252	DeWitt, B. S., 82, 90, 266
Boersch, H., 307	DeWitt, C., 90
Bohm, David, 82, 305, 337, 338	Dicks, D., 348
Bohr, Niels, 7, 12, 42, 81, 82, 144	Dirac, Paul A. M., xv, xvi, 18, 21, 52,
Born, Max, 16, 18, 21, 25, 59, 165,	57, 60, 67, 98, 153, 192, 285,
193, 214, 229	287, 315, 332
Bose, Satyendra Nath, 122, 125	Dyson, F. J., 264
Bousso, R., 88	
Boyanovsky, D., 266	Eckart, Carl, 119
Breit, G., 222	Ehrenfest, Paul, 23, 109
Brillouin, Leon, 77, 172	Einstein, Albert, 3, 10, 11, 21, 26,
Brogie, Louis de, 11, 12	125, 192, 336–338
Burgoyne, N., 122	Elsasser, Walter, 12
	Ensher, J. R., 125
Cassen, B., 132	Everett, Hugh, 83
Caves, C. M., 92	
Chadwick, James, 9, 27	Faddeev, L. D., 258
Chambers, R. G., 307	Farhi, E., 90, 91
Chinowsky, W., 140	Feenberg, E., 211

Author Index

351

- Fermi, Enrico, 122, 134
 Feynman, Richard P., 169, 290, 293–295
 Fierz, M., 122
 Fitch, V. L., 142
 Fock, V., 193
 Fowler, H. A., 307
 Friedman, J. I., 141
 Froissart, M., 252

 Gamow, George, 3, 223
 Garwin, R., 141
 Geiger, Hans, 5
 Gell-Mann, M., 93, 94, 134, 135
 Gerlach, Walter, 83, 86, 108, 115
 Germer, Lester, 12
 Ghirardi, G. C., 82
 Gibbs, J. Willard, 4
 Gisin, N., 340
 Goeppert-Mayer, M., 127
 Goldstone, J., 90, 91
 Goudsmit, Samuel, 97
 Graham, N., 90
 Grangier, P., 343
 Griffiths, R. B., 93
 Grohmann, K., 307
 Gurney, R. W., 223
 Gutmann, S., 90, 91

 Halzen, F., 252
 Hamisch, H., 307
 Hartle, J. B., 90, 91, 93, 94
 Hartree, D. R., 123
 Heisenberg, Werner, 14, 16, 21, 25, 46, 50, 98, 120, 285, 331
 Hellmann, F., 169
 Herglotz, A., 272
 Hibbs, A. R., 290, 294, 295
 Holt, R. A., 344
 Horne, M. A., 344

 Jeans, James, 2
 Jensen, J. H. D., 127
 Joos, E., 87
 Jordan, Pascual, 18, 21, 98

 Keldysh, L. V., 266
 Kent, A., 88
 Klibansky, R., 81
 Kocher, C. A., 344
 Kramers, Hendrik A., 172
 Kuhn, W., 16

 Landau, Lev, 302
 Lederman, L., 141
 Lee, Tsung-Dao, 141
 Leggett, A. J., 87
 Levinson, Norman, 226
 Lewis, G. N., 5
 Lippmann, B., 205
 Lord, J. J., 134
 Lorentz, Hendrik A., 4, 156
 Low, Francis, 267
 Lüders, G., 122, 142

 Magnus, W., 228
 Mahanthappa, K. T., 266
 Marsden, Ernest, 5
 Martin, R., 134, 307
 Maskawa, T., 287
 Matsuda, R., 307
 Matthews, M. R., 125
 Mermin, N. D., 346
 Messiah, Albert, 193
 Millikan, Robert A., 4
 Möllenstedt, G., 307
 Moseley, H. G. J., 9

 Nagle, D. E., 134
 Nakajima, H., 287
 Nakamura, K., xix
 Nakano, T., 134
 Ne'eman, Y., 135
 Neumann, J. von, 85
 Newell, D. B., 2
 Newton, R. G., 211
 Nishijima, K., 134, 287
 Noether, Emmy, 278
 Nye, M. J., 27

 Oberhettinger, F., 228
 Olson, P. T., 2

- Omnès, R., 93
 Oppenheimer, J. Robert, 165
 Orear, J., 134
- Pauli, Wolfgang, 18, 97, 98, 122, 125, 142
 Perlmutter, S., 324
 Planck, Max, 2
 Podolsky, Boris, 336–338
 Polchinski, J., 340
 Preskill, J., 346
- Ramsauer, C., 224
 Rayleigh, Lord, 1, 211
 Riess, A. G., 324
 Rimini, A., 82
 Ritz, Walther, 7
 Roger, G., 343
 Rosen, Nathan, 336–338
 Rutherford, Ernest, 5–7, 203, 215, 233
- Schack, R., 92
 Schiff, Leonard I., xv
 Schmidt, B., 324
 Schrödinger, Erwin, 12, 13, 18, 21, 26, 27, 84, 86
 Schwartz, Laurent, 61
 Schwinger, J., 205, 266
 Shapere, A., 201
 Shimony, A., 344
 Shohat, J. A., 272
 Shor, P. W., 347
 Simpson, J. A., 307
 Slater, J. C., 124
 Sommerfeld, Arnold, 9, 12, 18, 177
 Stark, J., 157
 Steinberger, J., 140
 Steiner, R. L., 2
 Stern, Otto, 83, 86, 108, 115
 Streater, R. F., 122
 Strutt, John William, *see* Rayleigh, Lord
 Suddeth, J. A., 307
 Susskind, L., 88
 Suzuki, R., 307
- Tamarkin, J. D., 272
 Telegdi, V. L., 141
 Thomas, W., 16
 Thomson, Joseph John, 3, 5
 Tomomura, A., 307
 Townsend, J. S., 224
 Tsao, C. H., 134
 Turlay, R., 142
 Tuve, M. A., 132
- Uhlenbeck, George, 97
- Valentini, A., 27
 Vega, H. J. de, 266
- Waerden, B. L. van der, 27
 Watson, G. N., 174
 Weaver, A. B., 134
 Webber, J., 228
 Weber, T., 82
 Weinberg, Steven, i, xvi, 71, 100, 142, 181, 229, 258, 267, 271, 287, 324
 Weinrich, M., 141
 Weisskopf, Victor, 99
 Wentzel, Gregor, 172
 Wheeler, John A., 81, 85, 90, 342
 Wieman, C. E., 125
 Wightman, A. S., 122
 Wigner, Eugene P., 71, 119, 222, 225
 Wilczek, F., 196, 201
 Williams, E. R., 2
 Wohlleben, D., 307
 Wolf, E., 229
 Wooters, W. R., 348
 Wu, C. S., 141
- Yang, Chen-Ning, 141
 Yukawa, Hideki, 215
- Zee, A., 196
 Zeeman, Pieter, 152, 155
 Zeit, H. D. Zeh, 87
 Zumino, B., 122
 Zurek, W. H., 81, 86, 342, 348

Subject Index

- absorption of light, 10, 15, 191–192
- action principle, 276
- adiabatic approximation, 193–201
- adjoints of operators, 62–63
- Aharonov–Bohm effect, 305–307
- alkali metals, 42, 97, 126, 152
- alpha decay, 5, 223–224, 253
- angular momentum, 30–33, 100–104, 279
 - addition, 109–118
 - multiplets 104–108
 - also see* commutators, spin, Wigner–Eckart theorem
- annihilation operators, 319–322
- antilinear operators, 71, 79
- associated Legendre polynomials, 37, 39
- atomic nucleus
 - discovery, 5–7, 210–211, 233–234
 - also see* atomic number, beta decay, charge symmetry, isospin invariance, magic numbers
- atomic number, 6, 9
- atomic spectra, 5–11, 97
 - also see* fine structure, hydrogen atom, hyperfine splitting, Lamb shift, radiative transitions, Paschen–Back effect, Stark effect, Zeeman effect
- atomic weight, 9
- band structure, 77, 130
- barrier penetration, 179–181, 220–224, 252–253, 262
- basis vectors, 55
- Bell inequalities, 341–345
- Berry phase, 197–201, 307
- Bessel functions, 174–175
 - also see* spherical Bessel functions
- beta decay, 141, 260–262
- black-body radiation, 1–4
 - also see* Planck distribution
- Bloch waves, 77, 130
- Bohm paradox, 337–338
- Bohr atomic theory, 7–10, 42, 177
- Bohr radius a , 42
- Boltzmann constant k_B , 2–3
- boost generator, 80–81
- Born approximation, 214–215, 257
 - also see* distorted wave Born approximation
- Born–Oppenheimer approximation, 165–170
- Born rule, 26, 82, 88, 90–92
- Bose–Einstein condensation, 125
- Bose–Einstein statistics, 129–130
- bosons and fermions, 123–125
 - also see* Bose–Einstein condensation, Bose–Einstein statistics, Fermi–Dirac statistics, magic numbers, Pauli exclusion principle, periodic table
- bound states
 - limits on binding energy, 259–260
 - related to phase shifts, 226–227
 - shallow states, 267–272
 - also see* atomic spectra, Schrödinger equation

- bra-ket notation, 57–58, 62, 67
- branching ratios, 255–256
- Breit–Wigner formula, 220, 256
- Brillouin zones, 77
- broken symmetry, 179–181
- canonical commutators, xv, 281–285
- charge and current densities, 311
- charge conjugation invariance, 80, 141–142
- charge symmetry, 131
- chemical potential, 129
- chirality, 181
- classical limit of path integral, 293
- Clebsch–Gordan coefficients, 111–115, 119, 134, 246, 248
- closure approximation, 162
- coherent states, 326–327
- collapse of the state vector, 82
- commutators, 25, 285
 - of angular momentum operators, 31, 101–104, 283–284
 - of creation and annihilation operators, 321
 - of electromagnetic field components, 313–316
 - of general symmetry generators, 73
 - of momentum and position operators, 17–18, 20, 74
- compact groups, 144
- completely continuous operators, 257
- completeness, 55, 64
- Compton scattering, 4–5
- Compton wavelength, 5
- conservation laws, *see* Noether’s theorem, symmetry principles
- consistent histories approach, *see* decoherent histories approach
- constrained Hamiltonian systems, 285–289
- continuum normalization, 58–59
- cooling of hot gases, 42
- Copenhagen interpretation, 81–84, 86
- correlation function, 190
- correspondence principle, 8
- Coulomb gauge, 313–315
- Coulomb potential, 8, 39, 317
- Coulomb scattering, 215, 227–229, 233, 261–262
- CPT symmetry, 81, 142
- creation operators, 319–322
- cross-section
 - classical, 233–234, 251
 - differential cross section defined, 210
 - for Coulomb scattering
 - for diffraction scattering, 214, 251–252
 - general formula, 247–248
 - low energy, 220
 - partial wave expressions, 249–251
 - resonant, 222, 256
- crystals, 76–77, 130
- cyclotron frequency, 303
- D lines of sodium, 97, 152, 155–156
- Davisson–Germer experiment, 12
- De Broglie wavelength, 11
- De Haas–van Alphen effect, 305
- decay rates, 242–243
 - also see* radiative transitions
- decoherence, 87–88, 95, 180
- decoherent histories approach, 93–95
- degeneracy
 - in adiabatic approximation, 196
 - in harmonic oscillator, 48, 137–138
 - in hydrogen atom, 43, 144–146
 - in perturbation theory, 149–152
 - of Landau energy levels, 304
- delta functions, 60–61, 75, 185–186, 240–241
- Δ particles, 133–134
- density matrix, 68–69
- deuteron, 45, 131, 140, 272
- diagonalization, 64
- diffraction peak, 214
- Dirac brackets, 287–289, 315–316
- Dirac equation, xv, 98, 153
- distorted wave Born approximation, 260–261
- dyads, 67

Subject Index

355

- dynamical phase, 194–196
 Dyson series, 264
- effective range, 220, 271–272
 Ehrenfest's theorem, 23–24, 109
 eigenstates, eigenvectors, eigenvalues, 63–64
 eikonal approximation, 230–234, 305–306
 Einstein *A* and *B* coefficients, 10, 15, 192
 Einstein–Podolsky–Rosen paradox, 336–337
 electromagnetic potentials, 298, 305, 311
 electron
 discovery, 5
 spin, 97–98
 also see atomic spectra, Bloch waves, Compton wavelength, Davisson–Germer experiment, hydrogen atoms, gyromagnetic ratio, photoelectric effect
 energy, *see* atomic spectra, bound states, Hamiltonian, perturbation theory
 entanglement
 entropy, 340–341
 experimental tests, 341–343
 faster-than-light communication?, 92, 338–340
 in quantum computing, 349
 paradoxes, 336–338
 ϵ_{ijk} tensor, 102
 equipartition, 2, 4
 Euler–Lagrange equations, 309–310
 expectation values, 23, 64–65
- factorizable solutions, 35
 factorization of *S*-matrix elements, 262, 265
 Fermi surface, 130, 304
 Fermi–Dirac statistics, 130
 fermions, *see* bosons and fermions
 Fermi's golden rule, 186
- field theory, *see* Euler–Lagrange equations, quantum electrodynamics
 fine structure, 116, 153
 fine structure constant, xix, 253
 first and second class constraints, 287
 Fock space, 324–5
 Froissart bound, 252
- Galilean invariance, 80–81
 Gamma function, 228
 gauge invariance, 300–302
 Gaussian integrals, 294–296
 generators of symmetries, 72
 also see angular momentum, boost generator, Hamiltonian, momentum
 grand canonical ensemble, 129
 Green's function, 208, 239, 259
 group velocity, 11–12
 gyromagnetic ratio, 152–153, 334
- halogens, 127
 Hamiltonian, 9, 13, 18, 79–81, 275
 derived from Lagrangian, 279–281
 effective Hamiltonians, 171
 for central potential, 29
 for charged particle in electromagnetic field, 299–300
 for electromagnetic field, 316–317
 for harmonic oscillator, 47, 49
 for photons, 323
 harmonic oscillator, 15–16, 21, 45–50, 137–138
 Hartree approximation, 123–124
 Heisenberg picture, 78, 203, 281
 Heisenberg uncertainty principle, 25, 65–66
 Hellmann–Feynman theorem, 169–170
 Herglotz theorem, 272
 Hermite polynomials, 47
 Hermitian operators, 17, 24, 32, 63–64, 72
 hidden variables, 82, 341–344

- Hilbert space, 52–56
 hydrogen atom, 7–8, 13, 18, 39–43, 142–146, 157–160
 hypercharge, 136
 hyperfine splitting, 116, 153
- identical particles, *see* bosons and fermions
 impact parameter, 233
 induced emission, *see* stimulated emission
 “in” states, 204–208, 235–239
 independent state vectors, 54–55
 “in-in” formalism, 266–267
 interaction picture, 263, 266, 319–322
 internal symmetries, *see* charge symmetry, isospin invariance, strangeness, $SU(3)$
 isospin invariance, 131–134
- Jacobi identity, 284, 288
- K mesons, 134–135, 141, 334
 Kuhn–Thomas sum rule, 16
 Kummer function, 228
- Lagrangians 276–277
 and symmetry principles, 278
 density, 310
 for electromagnetic field, 311–313
 for charged particle in electromagnetic field, 298
 for particle in general potential, 277
 in path integral formalism, 293
 Laguerre polynomials, 42
 Lamb shift, 116, 161
 Landau energy levels, 302–305
 Landé g -factor 153–154
 lattice calculations, 296
 Legendre polynomials, 216
 Levinson’s theorem, 226–227
 Lippmann–Schwinger equation, 204–205, 256, 267
 Lorentz invariance, 81, 262, 264, 293, 310
- Low equation, 267–268
 Lyman α line, 43, 332
- magic numbers, 127–128
 magnetic moment, 108–109, 302–303, 334
 also see gyromagnetic ratio
 many worlds interpretation, 83–84, 86
 matrix algebra, 17
 matrix mechanics, 14–22
 Maxwell equations, 311, 317–318
 molecules, *see* Born–Oppenheimer approximation, broken symmetry
 momentum, 45, 73–77, 282
- neutron, 131–133
 no copying theorem, 348–349
 noble gases, 126, 224
 Noether’s theorem, 278–279
 norms, *see* scalar products
 nucleus, *see* atomic nucleus
- operators, 61–68
 optical theorem, 213–214, 244–245, 249
 orthogonal state vectors, 55
 orthonormal state vectors, 57
 “out” states, 235–240
- parity, *see* space inversion
 partial waves, 245–252
 also see phase shifts
 Paschen–Back effect, 156–157
 path-integral formalism, 290–296
 Pauli exclusion principle, 125
 Pauli matrices, 107, 342
 periodic boundary conditions, 186
 periodic table, 125–127
 perturbation theory
 convergence, 259–260
 for energy levels, 148–162
 for transition rates, 183–193
 old fashioned, 256–264
 time-dependent, 262–267
 also see Born approximation

Subject Index

357

- phase shifts, 216–223, 226–227, 250, 271
 photoelectric effect, 4
 photoionization, 187–189
 photons, 3–5, 322–326
 pions, 133–134, 140–141
 Planck distribution (of black-body radiation), 2–3, 129–130
 Planck's constant h , 2–4, 8
 plane waves, 11, 75
 pointer states, 86
 Poisson brackets, 18, 284–285, 287
 polar coordinates, 32, 277, 281
 polarization vectors, 321, 326, 344
 primary and secondary constraints, 285–287
 prime factors, 347–348
 principal quantum number, 41–42, 125
 probabilities, 57, 88–91
 probability density, 21–23, 59
 projection operators, 67–68, 94
 proton, 9, 45, 131–133
 magnetic moment, 116

 qbits, 346
 quantization, 4, 7, 9
 quantum computers
 advantage over classical computers, 346–347
 gates, 347–348
 limitations, 348–349
 quantum electrodynamics, 21, 309–334

 radiative transitions, 327–334
 electric dipole transitions, 14–15, 120–121, 192, 253, 331
 electric quadrupole and magnetic dipole transitions, 333–334
 selection rules, 43, 120–121, 139, 333
 raising and lowering operators, 46–47, 104
 Ramsauer–Townsend effect, 226
 ray paths, 230

 rays, 57, 71
 Rayleigh–Jeans formula, 1–2
 reduced mass, 29, 45, 243
 reduced matrix element, 119
 resolvent operator, 259, 268
 resonances, 220–225, 252–256
 Ritz combination principle, 7
 rotational symmetry, 99–102
 also see angular momentum, $SU(2)$ formalism
 Runge–Lenz vector, 143–144

 scalar products, 54, 56–57
 scattering, 21–22
 general scattering theory, 235–273
 potential scattering theory, 203–234
 scattering amplitude, 208–210, 212, 214–215, 218, 244
 scattering length, 220, 271–272
 Schrödinger equation, 12–14
 for central potential, 29–36
 for Coulomb potential, 39–42
 for harmonic oscillator, 45–50
 in path-integral formalism, 296
 time-dependent equation, 78, 183
 Schrödinger picture, 78
 Schrödinger's cat, 84
 Schwarz inequality, 65
 second class constraints, *see* first and second class constraints
 Shubnikow–de Haas effect, 305
 Slater determinant, 124
 S-matrix, 235–240
 Solvay conferences, 26
 $SO(3)$, *see* rotational symmetry
 $SO(3) \times SO(3)$ (or $SO(4)$) symmetry, 143
 Sommerfeld quantization condition, 9, 179
 space inversion, 39, 43, 100, 138–141, 250
 space translation, 73–77, 282
 spherical Bessel and Neumann functions, 216–220
 spherical components of vectors, 179

- spherical harmonics, 36–39, 119, 246, 248
 spin, 97–99, 103–104, 285
 spin–orbit coupling, 128, 151, 153, 155
 also see fine structure
 spontaneous emission, 10, 15, 192–193
 spontaneous symmetry breaking, *see* symmetry breaking
 Stark effect, 157–160, 162
 state vectors, 53–58
 statistical matrix, *see* density matrix
 statistics, *see* Bose and Fermi statistics
 Stern–Gerlach experiment, 83, 108–109, 115
 stimulated emission, 10, 15, 191–192
 strangeness, 134–135
 strong interactions, 131, 133–134
 $SU(2)$ formalism, 116–118
 $SU(3)$ symmetry
 for harmonic oscillator, 137–138
 in particle physics, 136
 symmetries, 69–73
 also see charge symmetry, CPT symmetry, Galilean invariance, isospin invariance, rotational symmetry, $SO(3) \times SO(3)$ (or $SO(4)$) symmetry, space inversion, space translation, strangeness, $SU(3)$, time translation, time reversal, $U(1)$ symmetries
 time delay, 224–226
 time ordered products, 265, 267
 time reversal, 73, 79
 time translation, 79–81
 traces of operators, 66–67
 transformation theory, 21, 52
 two-slit experiment, 296
 ultraviolet catastrophe, 2
 uncertainty principle, *see* Heisenberg uncertainty principle
 unitarity, 70–71
 $U(1)$ symmetries, 135
 vacuum state, 323
 valence, 126
 variational method, 162–165
 vector spaces, 52–54
 virial theorem, 165
 virtual particles, 161, 215
 von Neumann entropy, 69
 wave function, *see* probability density, Schrödinger equation, state vector, wave mechanics, wave packets
 wave mechanics, 11–14, 18–20
 wave packets, 11, 22, 66, 204–207
 weak interactions, 133–134, 141, 260
 Wigner–Eckart theorem, 118–121, 159
 Wigner’s symmetry representation theorem, 71
 WKB approximation, 171–179, 221
 work function, 4
 X rays, 4, 9
 Yukawa potential, 215, 252
 Zeeman effect, 152–157
 zero-point energy, 21, 47, 323–324