

Contents

Preface	vii
Part 1 Basic Nuclear Structure	1
Chapter 1 Nuclear forces — a review	3
1.1 Attractive	3
1.2 Short-range	3
1.3 Spin dependent	4
1.4 Noncentral	5
1.5 Charge independent	5
1.6 Exchange character	6
1.7 Hard core	8
1.8 Spin-orbit force	10
1.9 Summary	10
1.10 Meson theory of nuclear forces	10
Chapter 2 Nuclear matter	13
2.1 Nuclear radii and charge distributions	13
2.2 The semiempirical mass formula	15
2.3 Nuclear matter	18
Chapter 3 The independent-particle Fermi-gas model	20
3.1 Isotopic spin	20
3.2 Second quantization	21
3.3 Variational estimate	21
3.4 Single-particle potential	24
Chapter 4 The independent-pair approximation	26
4.1 Bethe-Goldstone equation	26

4.2	Effective mass approximation	29
4.3	Solution for a nonsingular square well potential	30
4.4	Solution for a pure hard core potential	31
4.5	Justification of the independent-particle model	35
4.6	Justification of the independent-pair approximation	35
Chapter 5 The shell model		36
5.1	General canonical transformation to particles and holes	36
5.2	Single-particle shell model	40
5.3	Spin-orbit splitting	43
Chapter 6 The many-particle shell model		45
6.1	Two valence particles: general interaction and $\delta^{(3)}(\mathbf{r})$ force	45
6.2	Several particles: normal coupling	49
6.3	The pairing-force problem	50
Chapter 7 Electromagnetic interactions		53
7.1	Multipole analysis	53
7.2	Photon in an arbitrary direction	59
7.3	Transition probabilities and lifetimes	62
7.4	Reduction of the multipole operators	63
7.5	Static moments	66
7.6	Electron scattering to discrete levels	68
Chapter 8 Electromagnetism and the shell model		71
8.1	Extreme single-particle model	71
8.2	Nuclear current operator	76
8.3	Relativistic corrections to the current	77
Chapter 9 Excited states — equations of motion		81
9.1	Tamm-Dancoff approximation (TDA)	82
9.2	Random phase approximation (RPA)	84
9.3	Reduction of the basis	87
Chapter 10 Collective modes — a simple model with $-g\delta^{(3)}(\mathbf{r})$		91
10.1	The [15] supermultiplet in TDA	92
10.2	Random phase approximation (RPA)	95
10.3	The [1] supermultiplet with $S = T = 0$	98
10.4	Application to nuclei	99
Chapter 11 Application to a real nucleus — ^{16}O		101
Chapter 12 Problems: Part 1		106

Part 2	The Relativistic Nuclear Many-Body Problem	115
Chapter 13	Why field theory	117
Chapter 14	A simple model with (ϕ, V_μ) and relativistic mean field theory	119
14.1	A simple model	119
14.2	Lagrangian	120
14.3	Relativistic mean field theory (RMFT)	121
14.4	Nuclear matter	124
14.5	Neutron matter equation of state	127
14.6	Neutron star mass vs. central density	127
Chapter 15	Extensions of relativistic mean field theory	129
15.1	Relativistic Hartree theory of finite nuclei	129
15.2	Nucleon scattering	132
Chapter 16	Quantum hadrodynamics (QHD-I)	136
16.1	Motivation	136
16.2	Feynman rules	136
16.3	An application — relativistic Hartree approximation (RHA)	139
Chapter 17	Applications	143
17.1	RPA calculation of collective excitations of closed-shell nuclei	143
17.2	Electromagnetic interaction	145
Chapter 18	Some thermodynamics	152
18.1	Relativistic mean field theory (RMFT)	153
18.2	Numerical results	155
18.3	Finite temperature field theory in QHD-I	158
Chapter 19	QCD and a phase transition	160
19.1	Quarks and color	160
19.2	Quantum chromodynamics (QCD)	161
19.3	Properties of QCD	163
19.4	Phase diagram of nuclear matter	164
Chapter 20	Pions	169
20.1	Some general considerations	169
20.2	Pseudoscalar coupling and σ exchange	170
20.3	Feynman rules for baryon, scalar, and pion contributions to S_{fi}	171
20.4	Particle-exchange poles	172
20.5	Threshold behavior	174
20.6	Decay rate for $\phi \rightarrow \pi + \pi$	176

Chapter 21	Chiral invariance	178
21.1	Isospin invariance — a review	179
21.2	The chiral transformation	181
21.3	Conserved axial current	184
21.4	Generators of the chiral transformation	186
Chapter 22	The σ-model	187
22.1	Spontaneous symmetry breaking	188
Chapter 23	Dynamic resonances	195
23.1	A low-mass scalar	196
23.2	The $\Delta(1232)$	201
Chapter 24	Effective field theory	207
24.1	Model hadronic field theories – revisited	207
24.2	Spontaneously broken chiral symmetry – revisited	209
24.3	Effective field theory	212
24.4	Effective lagrangian for QCD	215
24.5	Effective lagrangian and currents	218
24.6	RMFT and density functional theory	219
24.7	Parameters and naturalness	220
24.8	An application	222
24.9	Pions – revisited	224
Chapter 25	Density functional theory — an overview	226
Chapter 26	Problems: Part 2	231
Part 3	Strong-Coupling QCD	245
Chapter 27	QCD — a review	247
27.1	Yang-Mills theory — a review	247
27.2	Quarks and color	252
27.3	Confinement	256
27.4	Asymptotic freedom	257
Chapter 28	Path integrals	259
28.1	Propagator and the path integral	259
28.2	Partition function and the path integral	261
28.3	Many degrees of freedom and continuum mechanics	266
28.4	Field theory	267
28.5	Relativistic quantum field theory	268

Chapter 29	Lattice gauge theory	271
29.1	Some preliminaries	271
29.2	QED in one space and one time dimension	273
29.3	Lattice gauge theory	274
29.4	Summary	281
Chapter 30	Mean field theory	283
30.1	Counting	283
30.2	Ising model — review	284
30.3	Mean field theory (MFT)	285
30.4	Lattice gauge theory for QED in MFT	288
30.5	An extension	292
30.6	Some observations	295
Chapter 31	Nonabelian theory — SU(2)	296
31.1	Internal space	296
31.2	Gauge invariance	298
31.3	Continuum limit	300
31.4	Gauge-invariant measure	303
31.5	Summary	306
Chapter 32	Mean field theory — SU(n)	308
32.1	Mean-field approach	309
32.2	Evaluation of required integrals for SU(2)	313
Chapter 33	Observables in LGT	316
33.1	The $(\bar{l}l)$ interaction in QED	316
33.2	Interpretation as a $V_{\bar{l}l}(R)$ potential	319
33.3	Nonabelian theory	320
33.4	Confinement	321
33.5	Continuum limit	322
33.6	Results for $V_{\bar{q}q}$	325
33.7	Determination of the glueball mass	326
Chapter 34	Strong-coupling limit	329
34.1	Nonabelian theory	332
34.2	Basic observation	333
34.3	Strong-coupling limit ($\sigma \rightarrow 0$)	334
34.4	Strong-coupling SU(2)	337
34.5	Strong-coupling SU(3)	337
34.6	Strong-coupling U(1)	338
Chapter 35	Monte Carlo calculations	339
35.1	Mean values	339

35.2	Monte Carlo evaluation of an integral	342
35.3	Importance sampling	344
35.4	Markov chains	346
35.5	The Metropolis algorithm	348
Chapter 36 Include fermions		351
36.1	Fermions in U(1) lattice gauge theory	352
36.2	Gauge invariance	354
36.3	Continuum limit	354
36.4	Path integrals	355
36.5	Problem — fermion doubling	356
36.6	Possible solution to the problem of fermion doubling	358
36.7	Chiral symmetry on the lattice	359
Chapter 37 QCD-inspired models		361
37.1	Bag model	361
37.2	Quark model state vectors	369
37.3	Matrix elements	373
37.4	Transition magnetic moment	375
37.5	Axial-vector current	377
37.6	Large N_C limit of QCD	378
Chapter 38 Deep-inelastic scattering		382
38.1	General analysis	382
38.2	Bjorken scaling	387
38.3	Quark-parton model	388
38.4	Momentum sum rule	395
38.5	EMC effect	395
Chapter 39 Evolution equations		398
39.1	Evolution equations in QED	399
39.2	Splitting functions	403
39.3	Weizsäcker-Williams approximation	404
39.4	QCD — Altarelli-Parisi equations	406
Chapter 40 Heavy-ion reactions and the quark-gluon plasma		409
40.1	The quark gluon plasma	409
40.2	Relativistic heavy ions	411
40.3	Transport theory	413
40.4	Summary	419
Chapter 41 Problems: Part 3		421

Part 4	Electroweak Interactions with Nuclei	429
Chapter 42	Weak interaction phenomenology	431
42.1	Lepton fields	431
42.2	$V - A$ theory	431
42.3	β -decay interaction	433
42.4	Leptons	433
42.5	Current-current theory	433
42.6	μ -decay	435
42.7	Conserved vector current theory (CVC)	436
42.8	Intermediate vector bosons	437
42.9	Neutral currents	439
42.10	Single-nucleon matrix elements of the currents	440
42.11	Pion decay	442
42.12	Pion-pole dominance of the induced pseudoscalar coupling	443
42.13	Goldberger-Treiman relation	444
Chapter 43	Introduction to the standard model	446
43.1	Spinor fields	446
43.2	Leptons	446
43.3	Point nucleons	448
43.4	Weak hypercharge	448
43.5	Local gauge symmetry	449
43.6	Vector meson masses	450
43.7	Spontaneous symmetry breaking	451
43.8	Particle content	455
43.9	Lagrangian	455
43.10	Effective low-energy lagrangian	456
43.11	Fermion mass	457
Chapter 44	Quarks in the standard model	460
44.1	Weak multiplets	460
44.2	GIM identity	461
44.3	Covariant derivative	461
44.4	Electroweak quark currents	462
44.5	QCD	463
44.6	Symmetry group	463
44.7	Nuclear currents	464
44.8	Nuclear domain	464
Chapter 45	Weak interactions with nuclei	466
45.1	Multipole analysis	466
45.2	Nuclear current operator	471

45.3	Long-wavelength reduction	474
45.4	Example – “allowed” processes	475
45.5	The relativistic nuclear many-body problem	476
45.6	Summary	478
Chapter 46 Semileptonic weak processes		479
46.1	Neutrino reactions	479
46.2	Charged lepton (muon) capture	484
46.3	β -decay	489
46.4	Final-state Coulomb interaction	492
46.5	Slow nucleons	492
Chapter 47 Some applications		494
47.1	One-body operators	494
47.2	Unified analysis of electroweak interactions with nuclei	495
47.3	Applications	495
47.4	Some predictions for new processes	504
47.5	Variation with weak coupling constants	506
47.6	The relativistic nuclear many-body problem	508
47.7	Effective field theory	510
Chapter 48 Full quark sector of the standard model		513
48.1	Quark mixing in the electroweak interactions: two-families — a review	513
48.2	Extension to three families of quarks	515
48.3	Feynman rules in the quark sector	516
Chapter 49 Neutrinos		518
49.1	Some background	518
49.2	Solar neutrinos	520
49.3	Neutrino mixing	521
49.4	Some experimental results	524
Chapter 50 Electron scattering		527
50.1	Cross section	527
50.2	General analysis	528
50.3	Parity violation in (\vec{e}, e')	531
50.4	Cross sections	533
50.5	An example — (\vec{e}, e) from a 0^+ target	536
Chapter 51 Problems: Part 4		539

Part 5	Appendices	547
Appendix A	Part 1	549
A.1	Meson exchange potentials	549
A.2	b_α^\dagger is a rank- j irreducible tensor operator	551
Appendix B	Part 2	553
B.1	Pressure in MFT	553
B.2	Thermodynamic potential and equation of state	554
B.3	π - N scattering	556
B.4	The symmetry $SU(2)_L \otimes SU(2)_R$	558
B.5	π - π scattering	560
B.6	Chiral transformation properties	562
Appendix C	Part 3	565
C.1	Peierls' inequality	565
C.2	Symmetric $(T, S) = (\frac{1}{2}, \frac{1}{2})$ state	566
C.3	Sum rules	568
Appendix D	Part 4	569
D.1	Standard model currents	569
D.2	Metric and convention conversion tables	573
D.3	Units and conventions	573
	Bibliography	578
	Index	593