

Contents

Foreword *XIX*

Preface *XXI*

1	Historical Introduction	1
2	The Standard Model	9
2.1	Introduction	9
2.2	Standard Electroweak Model	9
2.2.1	Electroweak Gauge Bosons	10
2.2.2	Standard Model Matter Fields	10
2.3	Spontaneous Symmetry-Breaking: Mass Generation	13
2.4	Quantization in the Standard Model	17
2.5	Renormalization in the Standard Model	19
2.6	Anomalies	21
2.6.1	The Axial Anomaly	21
2.6.2	Gauge Anomalies	23
2.7	Quantum Chromodynamics	24
2.8	Higgs Boson and Unitarity in the Standard Model	25
2.9	Theory Considerations on the Higgs Boson Mass	27
2.10	Experimental Tests of the Standard Model	30
2.11	Open Issues in the Standard Model	32
2.11.1	The Hierarchy Problem	34
2.11.2	Coupling Constant Unification	36
2.12	Summary	38
2.13	Problems for Chapter 2	39
3	Neutrino Masses and Mixing	41
3.1	Two-Component Formalism	41
3.2	Quantization of Majorana and Dirac Fermions	43
3.3	The Lepton Mixing Matrix	45
3.3.1	Lepton Mixing Matrix for Dirac Neutrinos	45
3.3.2	Lepton Mixing Matrix for Majorana Neutrinos: Unitary Approximation	47

3.3.3	General Seesaw-Type Lepton Mixing Matrix	48
3.3.3.1	Symmetrical Parametrization of the General Lepton Mixing Matrix	48
3.4	The Neutrino Neutral Current in Seesaw-Type Schemes	50
3.5	CP Properties of Majorana Fermions	50
3.5.1	CP Properties and Neutrinoless Double-Beta Decay	51
3.5.2	Electromagnetic Properties of Majorana Neutrinos	52
3.5.3	Majorana–Dirac ‘Confusion Theorem’	53
3.6	Summary	54
3.7	Problems for Chapter 3	54
4	Neutrino Oscillations	57
4.1	Preliminaries	57
4.2	Neutrino Oscillations Formalism <i>In Vacuo</i>	57
4.3	Matter Effects in Neutrino Oscillations	62
4.4	Neutrino Oscillation Data	65
4.4.1	Solar Neutrino Data	65
4.4.2	Reactor Neutrino Data	67
4.4.3	Atmospheric Neutrino Data	69
4.4.4	Accelerator Neutrino Data	73
4.4.5	The Measurement of θ_{13}	74
4.5	Global Neutrino Oscillation Analysis	76
4.6	Global Fit Results for Neutrino Oscillation Parameters	77
4.7	Summary and Outlook	80
4.8	Problems for Chapter 4	83
5	Robustness of Oscillations: The Case of Solar Neutrinos	87
5.1	Theoretical Preliminaries: Beyond the Standard Model	88
5.2	Beyond the Standard Solar Model	91
5.3	Oscillations with Spin-Flavour Precession	94
5.4	Constraining Neutrino Magnetic Moments	97
5.5	Summary	100
5.6	Problems for Chapter 5	100
6	Absolute Neutrino Masses	103
6.1	Preliminaries	103
6.2	Beta-Decay and Direct Searches for Neutrino Mass	103
6.2.1	Relativistic Beta-Decay Kinematics	104
6.2.2	Beta Decay in the Three-Neutrino Case	106
6.3	Neutrinoless Double-Beta Decay	110
6.4	Light-Neutrino Exchange $0\nu\beta\beta$ Mechanism	112
6.5	Experimental Prospects in the Search for $0\nu\beta\beta$	115
6.6	Neutrinoless Double-Beta Decay in Flavour Models	115
6.7	Short-Range Contributions to $0\nu\beta\beta$ Decay and the Weak Interaction Scale	117

6.8	Black Box and the Significance of $0\nu\beta\beta$	120
6.9	Summary	121
6.10	Problems for Chapter 6	121
7	Neutrino Masses in $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Theories	123
7.1	Preliminaries: The Origin of Neutrino Mass	123
7.2	Effective Seesaw Mechanism: Explicit Lepton Number Violation	125
7.3	Seesaw Dynamics in $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ and the Majoron	127
7.3.1	Basic Considerations	127
7.3.2	The Majoron in the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Seesaw	128
7.3.3	The Structure of Majoron Couplings: Type I Seesaw Example	130
7.3.4	Inverse $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ Seesaw Mechanism	132
7.4	Summary	134
7.5	Problems for Chapter 7	134
8	Higgs Boson Physics and Neutrinos	135
8.1	Higgs Production in the Standard Model	135
8.1.1	Higgs Production at Electron–Positron Colliders	136
8.1.1.1	Higgs-Strahlung Processes	136
8.1.1.2	Vector Boson Fusion	136
8.1.2	Higgs Production at Hadron Colliders	139
8.1.2.1	Associated Production with the W/Z Bosons	140
8.1.2.2	The Vector Boson Fusion Mechanism	141
8.1.2.3	The Gluon–Gluon Fusion Process	141
8.1.2.4	Associated Production with Heavy Quarks	142
8.2	Higgs Decays in the Standard Model	142
8.2.1	Decays into Fermions: Quarks and Leptons	143
8.2.2	Decays into W/Z Gauge Bosons	143
8.2.2.1	Two-Body Final States	144
8.2.2.2	Three-Body Final States	144
8.2.2.3	Four-Body Final States	145
8.2.3	Loop-Induced Higgs Boson Decays: $\gamma\gamma$, γZ and gg	145
8.2.3.1	$H \rightarrow \gamma\gamma$	145
8.2.3.2	$H \rightarrow Z\gamma$	146
8.2.3.3	$H \rightarrow gg$	147
8.2.3.4	Standard Model Higgs Boson Branching Ratio Summary	147
8.3	Higgs Physics in Models with Low-Scale Lepton Number Violation	147
8.3.1	Invisible Higgs Boson Decays	148
8.4	Summary	150
8.5	Problems for Chapter 8	151
9	Supersymmetry	153
9.1	Introduction and Motivation	153
9.2	Supersymmetry Algebra and Representations	155

9.2.1	Supersymmetry Algebra	155
9.2.2	Implications of the Supersymmetry Algebra	156
9.2.3	Supersymmetry Representations	157
9.2.3.1	Massive Case	157
9.2.3.2	Massless Case	158
9.3	How to Build a Supersymmetric Model	158
9.3.1	Kinetic Terms	159
9.3.2	Interactions	159
9.3.2.1	Self- Interactions of the Gauge Multiplet	159
9.3.2.2	Interactions of the Gauge and Matter Multiplets	159
9.3.2.3	Self- Interactions of the Matter Multiplet	160
9.3.3	Supersymmetry-Breaking Lagrangian	160
9.3.4	R-Parity	161
9.4	The Minimal Supersymmetric Standard Model	162
9.4.1	The Gauge Group and Particle Content	162
9.4.2	The Superpotential and Supersymmetry-Breaking Lagrangian	164
9.4.3	Spontaneous Symmetry-Breaking	164
9.4.4	MSSM Scalar Potential: UFB Directions and CCB Minima	165
9.4.5	The Constrained Minimal Supersymmetric Standard Model	167
9.5	Mass Matrices in the MSSM	168
9.5.1	Gaugino Mass Matrices	168
9.5.1.1	The Chargino Mass Matrix	168
9.5.1.2	The Neutralino Mass Matrix	169
9.5.2	Higgs Boson Mass Matrices	170
9.5.2.1	Neutral Higgs Mass Matrix	170
9.5.2.2	Charged Higgs Mass Matrix	172
9.5.3	Fermion Mass Matrices	172
9.5.3.1	Charged Lepton Mass Matrix	172
9.5.3.2	Quark Mass Matrices	173
9.5.4	Sfermion Mass Matrices	174
9.5.4.1	Slepton Mass Matrices	174
9.5.4.2	Sneutrino Mass Matrices	175
9.5.4.3	Squark Mass Matrices	175
9.6	Couplings in the MSSM	176
9.6.1	Charged Current Couplings as an Example	176
9.6.2	Other Couplings	179
9.7	Coupling Constant Unification	179
9.8	Experimental Constraints on the MSSM	180
9.9	Summary	180
9.10	Problems for Chapter 9	182
10	Spontaneous R-Parity Violation	183
10.1	Introduction	183
10.2	A Viable Spontaneous R-Parity-Breaking Model	184
10.3	Symmetry-Breaking	186

10.3.1	Tree-Level Breaking	187
10.3.2	Radiative Symmetry-Breaking	188
10.4	Main Features of the Model	189
10.4.1	Chargino Mass Matrix	190
10.4.2	Neutralino Mass Matrix	190
10.4.3	Charged-Current Couplings	191
10.4.4	Neutral Current Couplings	191
10.5	Implications for the Electroweak Breaking Sector	192
10.5.1	Higgs Spectrum	192
10.5.2	Higgs Boson Production	193
10.5.3	CP-Even Higgs Boson Decays	195
10.5.4	CP-Odd Higgs Boson Decays	196
10.6	Summary	197
10.7	Problems for Chapter 10	198
11	Bilinear R-Parity Violation	199
11.1	The Model	199
11.2	The Scalar Potential	200
11.3	Mass Matrices in the BRpV Model	201
11.3.1	Chargino Mass Matrix	202
11.3.2	Neutralino Mass Matrix	203
11.4	Couplings in the BRpV Model	203
11.4.1	Charged Current Couplings	204
11.5	Neutrino Masses and Mixings in the BRpV Model	205
11.5.1	Tree-Level Structure	205
11.5.2	One-Loop Neutrino Masses and Mixings	206
11.5.2.1	Definition	206
11.5.2.2	Relevant Diagrams	206
11.5.2.3	Gauge Invariance	207
11.5.3	The One-Loop Mass Matrix	208
11.6	Neutrino Properties and BRpV Parameters	208
11.6.1	The Atmospheric Neutrino Sector	208
11.6.2	The Solar Neutrino Sector	210
11.6.3	Constraining the BRpV Parameters	211
11.7	Approximate Formulae for the Neutrino Masses and Mixings	211
11.7.1	Approximate Rotation Matrices	212
11.7.2	Approximate Coupling Expressions	214
11.7.3	Relevant Topologies	214
11.7.4	The Solar Mass Scale	216
11.7.5	The Solar Mixing Angle	217
11.8	Summary	219
11.9	Problems for Chapter 11	219

12	Phenomenology of Bilinear R-Parity Violation	221
12.1	LSP Production	221
12.2	LSP Decays	223
12.2.1	LSP Decay Length and Displaced Vertices	223
12.2.2	LSP Decay Modes	223
12.3	Probing Neutrino Mixing via Neutralino Decays	226
12.4	Other LSP Scenarios	230
12.4.1	Stau as Lightest Supersymmetric Particle	230
12.4.2	Stop as Lightest Supersymmetric Particle	233
12.5	Summary	234
12.6	Problems for Chapter 12	234
13	Neutrino Masses and Left–Right Symmetry	237
13.1	Preliminaries: $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)$ Symmetry	237
13.2	‘Standard’ $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)$ Symmetric Seesaw	239
13.3	Low-Scale $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)$ Seesaw Mechanisms	241
13.4	Experimental Constraints	242
13.5	Direct Searches for the Messengers of Neutrino Mass	243
13.6	Summary	246
13.7	Problems for Chapter 13	247
14	Neutrino Masses and Unification	249
14.1	Preliminaries: Unification in $SU(5)$	249
14.2	Neutrinos in $SU(5)$	252
14.3	Neutrinos in $SO(10)$	254
14.4	Low-Scales in $SO(10)$ Models: Intermediate Gauge Symmetries	256
14.4.1	Model Class-I: One Intermediate Left–Right Scale	257
14.4.2	Model Class-II: Additional Intermediate Pati–Salam Scale	258
14.4.3	Models with an Intermediate $U(1)_R \times U(1)_{B-L}$ Scale	259
14.5	Neutrino Seesaw in Low-Scale $SO(10)$ model	259
14.6	Non Supersymmetric Low-Scale Models	263
14.7	Summary	263
14.8	Problems for Chapter 14	264
15	Lepton Flavour Violation	265
15.1	Charged Lepton Flavour Violation	265
15.1.1	Lepton-Flavour-Violating Muon Decays	265
15.1.2	$\mu - e$ Conversion in Nuclei	268
15.2	Models for Charged Lepton Flavour Violation	269
15.2.1	Low-Scale Seesaw Models	269
15.2.2	High-Scale Seesaw Models	271
15.2.2.1	Supersymmetric Type I Seesaw	272
15.2.2.2	Supersymmetric Type II Seesaw	274
15.2.3	Lepton Flavour Violation at the High-Energy Frontier	275
15.2.3.1	Lepton Flavour Violation in Slepton Decays	276

15.2.3.2	Slepton Mass Splittings	278
15.2.3.3	Lepton Flavour Violation in the Decays of Right-Handed Neutrinos	279
15.3	Summary and Prospects	281
15.4	Problems for Chapter 15	281
16	The Flavour Problem and the Quest for Family Symmetry	283
16.1	Preliminaries	283
16.2	Reference Neutrino Mixing Patterns	285
16.2.1	Tri-Bimaximal Pattern	285
16.2.2	Bi-Large Neutrino Mixing Pattern	287
16.3	Prototype Flavour Model with Tetrahedral Symmetry	289
16.4	Revamped A_4 Flavour Model: Generating θ_{13}	293
16.4.1	Minimal Flavon Extension with $\theta_{13} \neq 0$	293
16.4.2	Neutrino Oscillation Parameters	294
16.5	Fermion Masses in a Realistic A_4 -Based Standard Model	296
16.5.1	Quark-Lepton Mass Relation in a Realistic A_4 Extension of the Standard Model	297
16.5.2	The Charged Lepton–Quark Mass Relation	298
16.5.3	Quark Mixing: The CKM Matrix	299
16.5.4	Neutrino Masses and Mixing	300
16.6	Quarks, Non-Abelian Discrete Flavour Symmetries and Unification	302
16.7	Summary and Prospects	303
16.8	Problems for Chapter 16	304
17	Cosmological Implications of Neutrino Masses	307
17.1	The very Beginning: Inflation and Primordial Density Perturbations	307
17.2	The Cosmic Microwave Background	309
17.3	Neutrino Cosmology for Pedestrians	310
17.3.1	Neutrino Decoupling	311
17.3.2	The Cosmic Neutrino Background	313
17.3.3	Primordial Big Bang Nucleosynthesis	314
17.4	Dark Matter in the Universe	315
17.4.1	Evidence for Dark Matter in the Universe	316
17.4.2	Dark Matter and Large-Scale Structure in the Universe	319
17.5	Dark Matter Detection	320
17.6	Neutrino Mass Generation and Dark Matter Candidates	323
17.6.1	Massive Neutrinos as Dark Matter?	324
17.6.2	WIMP Dark Matter as Neutrino Mass Messenger	324
17.6.2.1	The Particle Content	325
17.6.2.2	Yukawa Interactions and Fermion Masses	326
17.6.2.3	Radiative Seesaw Neutrino Masses	328
17.6.2.4	Fermionic Dark Matter in Radiative Seesaw Scheme	328

17.6.3	WIMP Dark Matter Stabilized by Flavour Symmetry	332
17.6.4	Supersymmetric WIMP Dark Matter	334
17.6.5	Majoron as Decaying Dark Matter	336
17.6.6	Decaying Gravitino as Dark Matter	338
17.7	Summary	339
17.8	Problems for Chapter 17	340
A	Notation and Conventions	341
A.1	Special Relativity and Dirac Matrices	341
A.2	Two-Component Spinor Notation	342
A.3	Relating Two-Component and Four-Component Spinors	344
B	Feynman Rules for Majorana Fermions	347
B.1	Feynman Rules	347
B.1.1	External Fermions	348
B.1.2	Propagators	349
B.1.3	Couplings	350
B.2	A Simple Example	352
C	Feynman Rules for the Standard Model	355
C.1	Introduction	355
C.2	The Complete Standard Model Lagrangian	355
C.2.1	The Gauge Field Lagrangian	355
C.2.2	The Fermion Fields Lagrangian	355
C.2.3	The Higgs Boson Lagrangian	356
C.2.4	The Yukawa Lagrangian	356
C.2.5	The Gauge Fixing Term	356
C.2.6	The Ghost Lagrangian	357
C.3	The Feynman Rules for QCD	358
C.3.1	Propagators	358
C.3.2	Triple Gauge Interactions	358
C.3.3	Quartic Gauge Interactions	358
C.3.4	Fermion Gauge Interactions	359
C.3.5	Ghost Interactions	359
C.4	The Feynman Rules for the Electroweak Theory	359
C.4.1	Propagators	359
C.4.2	Triple Gauge Interactions	360
C.4.3	Quartic Gauge Interactions	360
C.4.4	Charged Current Interaction	361
C.4.5	Neutral Current Interaction	361
C.4.6	Fermion–Higgs and Fermion–Goldstone Interactions	362
C.4.7	Triple Higgs–Gauge and Goldstone–Gauge Interactions	362
C.4.8	Quartic Higgs–Gauge and Goldstone–Gauge Interactions	364
C.4.9	Triple Higgs and Goldstone Interactions	366
C.4.10	Quartic Higgs and Goldstone Interactions	367

C.4.11	Ghost Propagators	368
C.4.12	Ghost Gauge Interactions	368
C.4.13	Ghost Higgs and Ghost Goldstone Interactions	370
D	Minimal Supersymmetric Standard Model Couplings	373
D.1	Charged Current Couplings	373
D.2	Neutral Current Couplings	374
D.3	Scalar Couplings to Fermions	374
E	The Prototype Flavour Group: A_4	377
F	Mass Matrices and Couplings in the BRpV Model	381
F.1	Mass Matrices	381
F.1.1	Charged Scalars	381
F.1.2	CP-Even Neutral Scalars	383
F.1.3	CP-Odd Neutral Scalars	384
F.1.4	Squark Mass Matrices	385
F.1.5	Chargino and Neutralino Mass Matrices	386
F.1.6	Quark Mass Matrices	386
F.2	Couplings	386
F.2.1	Charged Current Couplings	386
F.2.2	Neutral Current Couplings	386
F.2.3	Charged Scalars Couplings to Fermions	387
F.2.4	Neutral Scalars Couplings to Fermions	387
G	Feynman Diagrams for Dark Matter Annihilation	391
	References	393
	Acknowledgments for the Figures	419
	Index	421