

Contents

1	Historical Survey	1
1.1	The Dirac Field	2
1.1.1	The Fermion in the Electromagnetic Field	4
1.2	The Idea of the Neutrino	6
1.3	The β Decay	9
1.4	Neutrino Observations	12
1.5	The Pursuit of Neutrino Properties	16
2	Global Symmetries	19
2.1	Elements of Group Theory	21
2.2	Classical Physics: Parity and Time Reversal	25
2.3	Magnetic and Electric Dipole Moments	28
2.4	Lorentz Transformations	29
2.4.1	The Proper Lorentz Group	32
2.5	Poincaré Transformations	34
2.6	Flavour Quantum Numbers	36
2.7	Charge Conjugation	38
2.7.1	G -Parity	39
2.8	Parity Eigenstates	39
2.8.1	Observations of Parity Violation	44
2.9	Charge Conjugation Eigenstates	46
2.9.1	Charge Symmetry and G -Parity	48
2.10	CP Invariance	51
2.11	Time Reversal	54
2.11.1	Observations of Time Reversal Violation	55
2.12	Lorentz Transformations for Spin 1/2 Fields	59
2.13	Field Transformations Under C , P and T	61
2.14	Helicity and Chirality	69
2.15	The CPT Theorem	75

3	Gauge Theories	79
3.1	Electromagnetism	81
3.2	Gauge Theories and the Covariant Derivative	83
3.3	Spontaneous Symmetry Breaking	87
3.3.1	Internal Discrete Symmetry	90
3.3.2	Continuous Global Symmetry	93
3.3.3	Linear Sigma Model	96
3.3.4	The Higgs Mechanism	98
4	The Standard Model	101
4.1	The Electroweak Gauge Symmetry	102
4.2	The EW Lagrangian for Massless Fermions	107
4.2.1	Isospin and CVC Hypothesis	111
4.3	Charged and Neutral Currents	112
4.4	The Higgs Mechanism in the SM	114
4.4.1	Massive Gauge Fields and Higgs Interactions	116
4.5	The Yukawa Lagrangian	120
4.6	Fermion Mass Eigenstates	122
4.7	The CKM Matrix	126
4.7.1	Two Fermion Generations	127
4.7.2	Three Generations	129
4.8	C , P and CP Symmetries in the EW Lagrangian	133
4.8.1	Matrix Elements of Hadronic Currents	134
4.9	Accidental Symmetries	135
4.10	Lepton Universality	138
5	The Mass of Neutrinos	143
5.1	The Neutrino in the Standard Model	144
5.2	Dirac Mass Terms	146
5.3	Majorana Neutrinos	149
5.4	Majorana Mass Terms	152
5.5	Mass Terms and Gauge Symmetry	157
5.6	Dirac-Majorana Mass Term	159
5.6.1	One-Generation Case	160
5.6.1.1	Real Dirac-Majorana Mass Matrix	162
5.6.2	More Generations	164
5.7	The Seesaw Mechanism	164
5.7.1	More Generations	166
5.8	The Effective Lagrangian	169
5.9	Opening Up the Weinberg Operator at Tree Level	172
5.10	Type II See-Saw Mechanism	175
5.11	Type III See-Saw Mechanism	179
6	The Mixing of Neutrinos	183
6.1	The Lepton Mixing Matrix	184
6.1.1	Parameter Counting	186
6.2	Neutrino Oscillations	188

6.3	Two-Generations Mixing	194
6.4	CP Violation	197
6.5	Hierarchy and Simplified Mixing.....	202
6.5.1	Two-Neutrino Formalism	204
6.5.2	Electron Neutrino Disappearance.....	206
6.6	Neutrino Oscillations in Matter.....	207
6.6.1	Uniform Density	212
6.6.2	Variable Density	214
7	Natural Neutrino Sources.....	219
7.1	The Standard Solar Model	219
7.2	Solar Neutrino Experiments	225
7.2.1	The Homestake Experiment.....	227
7.2.2	The Cherenkov Detector	228
7.2.3	The Kamiokande Experiment	231
7.2.4	The GALLEX and SAGE Experiments	232
7.2.5	The SNO Experiment.....	233
7.2.6	The KamLAND Experiment	234
7.2.7	The Borexino Experiment.....	235
7.3	Supernova Neutrinos	236
7.3.1	Formation of a Supernova.....	238
7.3.2	Core-Collapse Supernovae	240
7.3.3	Detection	244
7.4	Atmospheric Neutrinos	246
7.4.1	Production	247
7.4.2	Detection	250
7.5	Cosmic Neutrinos	252
7.5.1	Cosmic Neutrino Background	252
7.6	Neutrinos at High Energy	256
7.7	Cubic-Kilometer Detectors	260
7.7.1	The IceCube Experiment.....	261
7.8	Geoneutrinos	263
8	Oscillations at Reactors and Accelerators	267
8.1	Neutrinos at Reactors	268
8.1.1	The First Direct Neutrino Detection	271
8.1.2	Early Oscillation Experiments	273
8.1.3	Oscillation Experiments Since the Turn of the Century.....	275
8.2	Accelerator Experiments	277
8.2.1	Non Conventional Neutrino Beams.....	281
8.2.2	First Generation LBL Experiments	283
8.2.2.1	K2K.....	283
8.2.2.2	MINOS	284
8.2.2.3	ICARUS and OPERA	286
8.2.3	Off-Axis Technique.....	288

8.2.4	New Generation LBL Experiments	292
8.2.4.1	T2K	293
8.2.4.2	NO ν A	294
8.2.4.3	HK, T2HK and DUNE	295
8.2.5	SBL Accelerator Experiments	297
8.3	Oscillation Parameters Determination	299
9	Neutrino Cross Sections	303
9.1	Neutrino-Electron Scattering	305
9.1.1	Elastic and QE Amplitudes	306
9.1.2	QE Scattering Cross Sections	310
9.2	Neutrino-Nucleon Interactions	315
9.2.1	Charged Current QE Scattering	317
9.2.2	Single Pion Production	321
9.2.3	Deep Inelastic Scattering	323
9.2.4	The Bjorken Scaling and the Parton Model	327
9.3	The Gargamelle Neutrino Experiment	332
9.4	Neutrino Interactions with Nuclei	334
9.4.1	Coherent Nuclear Scattering	336
9.4.2	Nuclear Effects	340
9.4.3	The Fermi Gas Model	342
10	Theoretical and Experimental Prospects	345
10.1	Absolute Values of Neutrino Masses	345
10.1.1	Direct Neutrino Mass Measurements	348
10.2	Double β Decay	352
10.3	Neutrinoless Double β Decay	354
10.3.1	Total Decay Rate and Effective Majorana Mass	356
10.3.2	Experimental Searches	359
10.3.3	Direct Detection Experiments	362
10.3.4	Majorons	366
10.4	Neutrino Magnetic Moments	370
10.5	Sterile Neutrinos	374
10.5.1	Mixing in the Dirac-Majorana Case	378
10.5.2	In Search of eV-Scale Sterile Neutrino Oscillations	381
10.5.2.1	LSND	382
10.5.2.2	KARMEN	382
10.5.2.3	MiniBooNE	383
10.5.2.4	Short-Baseline Neutrino Program at Fermilab	384
10.5.2.5	JSNS ²	386
10.5.2.6	Gallium and Reactor Anti-neutrino Anomalies	386
10.5.2.7	Unstable Sterile Neutrinos	387
	References	389
	Index	413