

Contents

Preface to the second edition	xiii
Preface to the first edition	xv
Notation	xvii
1 Important historical experiments	1
1.1 The birth of the neutrino	1
1.2 Nuclear recoil experiment by Rodeback and Allen	3
1.3 Discovery of the neutrino by Cowan and Reines	4
1.4 Difference between ν_e and $\bar{\nu}_e$ and solar neutrino detection	5
1.5 Discovery of parity violation in weak interactions	7
1.6 Direct measurement of the helicity of the neutrino	10
1.7 Experimental proof that ν_μ is different from ν_e	11
1.8 Discovery of weak neutral currents	12
1.9 Discovery of the weak gauge bosons W and Z	14
1.10 Observation of neutrinos from SN 1987A	15
1.11 Number of neutrino flavors from the width of the Z^0	15
2 Properties of neutrinos	19
2.1 Helicity and chirality	19
2.2 Charge conjugation	22
2.3 Parity transformation	23
2.4 Dirac and Majorana mass terms	24
2.4.1 Generalization to n flavors	28
2.5 Lepton number	29
2.5.1 Experimental status of lepton number violation	30
3 The standard model of particle physics	33
3.1 The V–A theory of the weak interaction	33
3.2 Gauge theories	35
3.2.1 The gauge principle	36
3.2.2 Global symmetries	38
3.2.3 Local (= gauge) symmetries	39
3.2.4 Non-Abelian gauge theories (= Yang–Mills theories)	40
3.3 The Glashow–Weinberg–Salam model	41

3.3.1	Spontaneous symmetry breaking and the Higgs mechanism	44
3.3.2	The CKM mass matrix	47
3.3.3	CP violation	50
3.4	Experimental determination of fundamental parameters	51
3.4.1	Measurement of the Fermi constant G_F	52
3.4.2	Neutrino–electron scattering and the coupling constants g_V and g_A	53
3.4.2.1	Theoretical considerations	53
3.4.2.2	$\nu_\mu e$ scattering	55
3.4.2.3	$\nu_e e$ and $\bar{\nu}_e e$ scattering	55
3.4.2.4	Neutrino tridents	58
3.4.3	Measurement of the Weinberg angle	58
3.4.4	Measurement of the gauge boson masses m_W and m_Z	60
3.4.5	Search for the Higgs boson	62
4	Neutrinos as a probe of nuclear structure	65
4.1	Neutrino beams	65
4.1.1	Conventional beams	65
4.1.1.1	Narrow-band beams (NBB)	67
4.1.1.2	Wide-band beams (WBB)	69
4.1.2	ν_τ beams	70
4.1.3	Neutrino beams from muon decay	70
4.2	Neutrino detectors	71
4.2.1	CDHS	71
4.2.2	NOMAD	72
4.2.3	CHORUS	72
4.3	Total cross section for neutrino–nucleon scattering	74
4.4	Kinematics of deep inelastic scattering	76
4.5	Quasi-elastic neutrino–nucleon scattering	78
4.5.1	Quasi-elastic CC reactions	79
4.5.2	Quasi-elastic NC reactions	80
4.6	Coherent, resonant and diffractive production	82
4.7	Structure function of nucleons	84
4.8	The quark–parton model, parton distribution functions	85
4.8.1	Deep inelastic neutrino proton scattering	87
4.8.1.1	QCD effects	90
4.9	y distributions and quark content from total cross sections	91
4.9.1	Sum rules	93
4.10	Charm physics	96
4.11	Neutral current reactions	99
4.12	Neutrino cross section on nuclei	101

5	Neutrino masses and physics beyond the standard model	105
5.1	Running coupling constants	106
5.2	The minimal SU(5) model	107
5.2.1	Proton decay	110
5.3	The SO(10) model	111
5.3.1	Left–right symmetric models	111
5.4	Supersymmetry	114
5.4.1	The minimal supersymmetric standard model (MSSM)	115
5.4.2	<i>R</i> -parity	116
5.4.3	Experimental search for supersymmetry	117
5.4.3.1	SUSY signatures at high energy colliders	119
5.4.3.2	SUSY GUTs and proton decay	119
5.5	Neutrino masses	120
5.5.1	Neutrino masses in the electroweak theory	121
5.5.2	Neutrino masses in the minimal SU(5) model	122
5.5.3	Neutrino masses in the SO(10) model and the seesaw mechanism	122
5.5.3.1	Almost degenerated neutrino masses	123
5.5.4	Neutrino masses in SUSY and beyond	123
5.6	Neutrino mixing	123
6	Direct neutrino mass searches	127
6.1	Fundamentals of β -decay	127
6.1.1	Matrix elements	129
6.1.2	Phase space calculation	132
6.1.3	Kurie plot and ft values	133
6.2	Searches for $m_{\bar{\nu}_e}$	136
6.2.1	General considerations	136
6.2.2	Searches using spectrometers	137
6.2.2.1	Future spectrometers—KATRIN	139
6.2.3	Cryogenic searches	140
6.2.4	Kinks in β -decay	142
6.3	Searches for m_{ν_e}	145
6.4	m_{ν_μ} determination from pion decay	146
6.5	Mass of the ν_τ from tau decay	146
6.6	Electromagnetic properties of neutrinos	147
6.6.1	Electric dipole moments	149
6.6.2	Magnetic dipole moments	149
6.7	Neutrino decay	152
6.7.1	Radiative decay $\nu_H \rightarrow \nu_L + \gamma$	153
6.7.2	The decay $\nu_H \rightarrow \nu_L + e^+ + e^-$	154
6.7.3	The decay $\nu_H \rightarrow \nu_L + \chi$	155

7	Double β-decay	157
7.1	Introduction	157
7.2	Decay rates	162
7.2.1	The $2\nu\beta\beta$ decay rates	162
7.2.2	The $0\nu\beta\beta$ decay rates	165
7.2.3	Majoron accompanied double β -decay	167
7.3	Nuclear structure effects on matrix elements	168
7.4	Experiments	170
7.4.1	Practical considerations in low-level counting	173
7.4.2	Direct counting experiments	175
7.4.2.1	Semiconductor experiments	175
7.4.2.2	Scintillator experiments	177
7.4.2.3	Cryogenic detectors	178
7.4.2.4	Ionization experiments	178
7.4.3	Geochemical experiments	179
7.4.4	Radiochemical experiments	181
7.5	Interpretation of the obtained results	181
7.5.1	Effects of MeV neutrinos	183
7.5.2	Transitions to excited states	184
7.5.3	Majoron accompanied decays	184
7.5.4	Decay rates for SUSY-induced $0\nu\beta\beta$ decay	184
7.6	Future plans and activities	186
7.7	$\beta^+\beta^+$ decay	186
7.8	CP phases and double β decay	187
7.9	Generalization to three flavors	188
7.9.1	General considerations	188
7.9.1.1	Muon–positron conversion on nuclei	189
7.9.1.2	Processes investigating $\langle m_{\mu\mu} \rangle$	189
7.9.1.3	Limits on $\langle m_{\tau\tau} \rangle$ from CC events at HERA	191
8	Neutrino oscillations	193
8.1	General formalism	193
8.2	CP and T violation in neutrino oscillations	196
8.3	Oscillations with two neutrino flavors	197
8.4	The case for three flavors	199
8.5	Experimental considerations	200
8.6	Nuclear reactor experiments	201
8.6.1	Experimental status	203
8.6.1.1	CHOOZ	203
8.6.1.2	Palo Verde	204
8.6.1.3	KamLAND	207
8.6.2	Geoneutrinos	209
8.6.3	Future	210
8.6.3.1	Borexino	210
8.6.3.2	SNO+	211

8.6.3.3	Measuring θ_{13} at reactors	211
8.7	Accelerator-based oscillation experiments	212
8.7.1	LSND	212
8.7.2	KARMEN	213
8.7.3	MiniBooNE	215
8.8	Searches at higher neutrino energy	216
8.8.1	CHORUS and NOMAD	217
8.9	Neutrino oscillations in matter	220
8.10	Future activities—Determination of the PMNS matrix elements	223
8.11	Possible future beams	224
8.11.1	Off-axis superbeams	224
8.11.2	Beta beams	226
8.11.3	Muon storage rings—neutrino factories	226
9	Atmospheric neutrinos	229
9.1	Cosmic rays	229
9.2	Interactions within the atmosphere	231
9.3	Experimental status	236
9.3.1	Super-Kamiokande	236
9.3.1.1	The ν_μ/ν_e ratio	238
9.3.1.2	Zenith-angle distributions	241
9.3.1.3	Oscillation analysis	242
9.3.2	Soudan-2	246
9.3.3	MACRO	246
9.4	Accelerator-based searches—long-baseline experiments	248
9.4.1	K2K	249
9.4.2	MINOS	250
9.4.3	CERN–Gran Sasso	251
9.4.4	INO-ICAL	254
9.4.5	Very large water Cerenkov detectors	255
9.4.6	AQUA-RICH	255
10	Solar neutrinos	257
10.1	The standard solar model	257
10.1.1	Energy production processes in the Sun	257
10.1.2	Reaction rates	260
10.1.3	The solar neutrino spectrum	262
10.1.3.1	Standard solar models	263
10.1.3.2	Diffusion	264
10.1.3.3	Initial composition	265
10.1.3.4	Opacity and equation of state	265
10.1.3.5	Predicted neutrino fluxes	266
10.2	Solar neutrino experiments	268
10.2.1	The chlorine experiment	270
10.2.2	Super-Kamiokande	270
10.2.3	The gallium experiments	272

10.2.3.1	GALLEX	273
10.2.3.2	GNO	273
10.2.3.3	SAGE	274
10.2.4	The Sudbury Neutrino Observatory (SNO)	275
10.2.5	The Borexino experiment	278
10.3	Theoretical solutions—matter effects	279
10.3.1	Neutrino oscillations as a solution to the solar neutrino problem	279
10.3.2	Neutrino oscillations in matter and the MSW effect	279
10.3.2.1	Constant density of electrons	282
10.3.2.2	Variable electron density	284
10.3.3	Experimental signatures and results	285
10.3.4	The magnetic moment of the neutrino	290
10.4	Future potential experiments	292
10.4.1	Real-time measurement of pp neutrinos using coincidence techniques	294
11	Neutrinos from supernovae	297
11.1	Supernovae	297
11.1.1	The evolution of massive stars	298
11.1.2	The actual collapse phase	301
11.2	Neutrino emission in supernova explosions	306
11.3	Detection methods for supernova neutrinos	308
11.4	Supernova 1987A	309
11.4.1	Characteristics of supernova 1987A	309
11.4.1.1	Properties of the progenitor star and the event	309
11.4.1.2	γ -radiation	310
11.4.1.3	Distance	313
11.4.1.4	Summary	314
11.4.2	Neutrinos from SN 1987A	314
11.4.2.1	Possible anomalies	316
11.4.3	Neutrino properties from SN 1987A	316
11.4.3.1	Lifetime	316
11.4.3.2	Mass	318
11.4.3.3	Magnetic moment and electric charge	319
11.4.3.4	Conclusion	320
11.5	Supernova rates and future experiments	321
11.5.1	Cosmic supernova relic neutrino background	322
11.6	Neutrino oscillations and supernova signals	322
11.6.1	Effects on the prompt ν_e burst	323
11.6.2	Cooling phase neutrinos	324
11.6.3	Production of r-process isotopes	324
11.6.4	Neutrino mass hierarchies from supernova signals	326
11.6.5	Resonant spin flavor precession in supernovae	329

12 Ultra-high energetic cosmic neutrinos	331
12.1 Sources of high-energy cosmic neutrinos	331
12.1.1 Neutrinos produced in acceleration processes	332
12.1.2 Neutrinos produced in annihilation or decay of heavy particles	337
12.1.3 Event rates	337
12.1.4 Neutrinos from active galactic nuclei	338
12.1.5 Neutrinos from gamma ray bursters	340
12.1.6 Cross sections	343
12.2 Detection	347
12.2.1 Water Cerenkov detectors	353
12.2.1.1 Baikal NT-200	353
12.2.1.2 NESTOR	356
12.2.1.3 ANTARES	359
12.2.2 Ice Cerenkov detectors—AMANDA, ICECUBE	360
12.2.3 Alternative techniques—acoustic and radio detection	360
12.2.4 Horizontal air showers—the AUGER experiment	361
13 Neutrinos in cosmology	365
13.1 Cosmological models	366
13.1.1 The cosmological constant Λ	369
13.1.2 The inflationary phase	372
13.1.3 The density in the universe	372
13.2 The evolution of the universe	374
13.2.1 The standard model of cosmology	374
13.3 The cosmic microwave background (CMB)	380
13.3.1 Spectrum and temperature	380
13.3.2 Measurement of the spectral form and temperature of the CMB	381
13.3.3 Anisotropies in the 3 K radiation	381
13.3.3.1 Measurement of the anisotropy	382
13.3.3.2 Anisotropies on small scales	383
13.4 Neutrinos as dark matter	385
13.5 Candidates for dark matter	386
13.5.1 Non-baryonic dark matter	386
13.5.1.1 Hot dark matter, light neutrinos	387
13.5.1.2 Cold dark matter, heavy particles, WIMPs	388
13.5.2 Direct and indirect experiments	389
13.5.2.1 Annihilation inside the Sun or Earth	389
13.6 Neutrinos and large-scale structure	390
13.7 The cosmic neutrino background	393
13.8 Primordial nucleosynthesis	394
13.8.1 The process of nucleosynthesis	395
13.8.2 The relativistic degrees of freedom g_{eff} and the number of neutrino flavors	397

xii	<i>Contents</i>	
	13.9 Baryogenesis via leptogenesis	399
	13.9.1 Leptogenesis	400
	14 Summary and outlook	405
	References	411
	Index	443