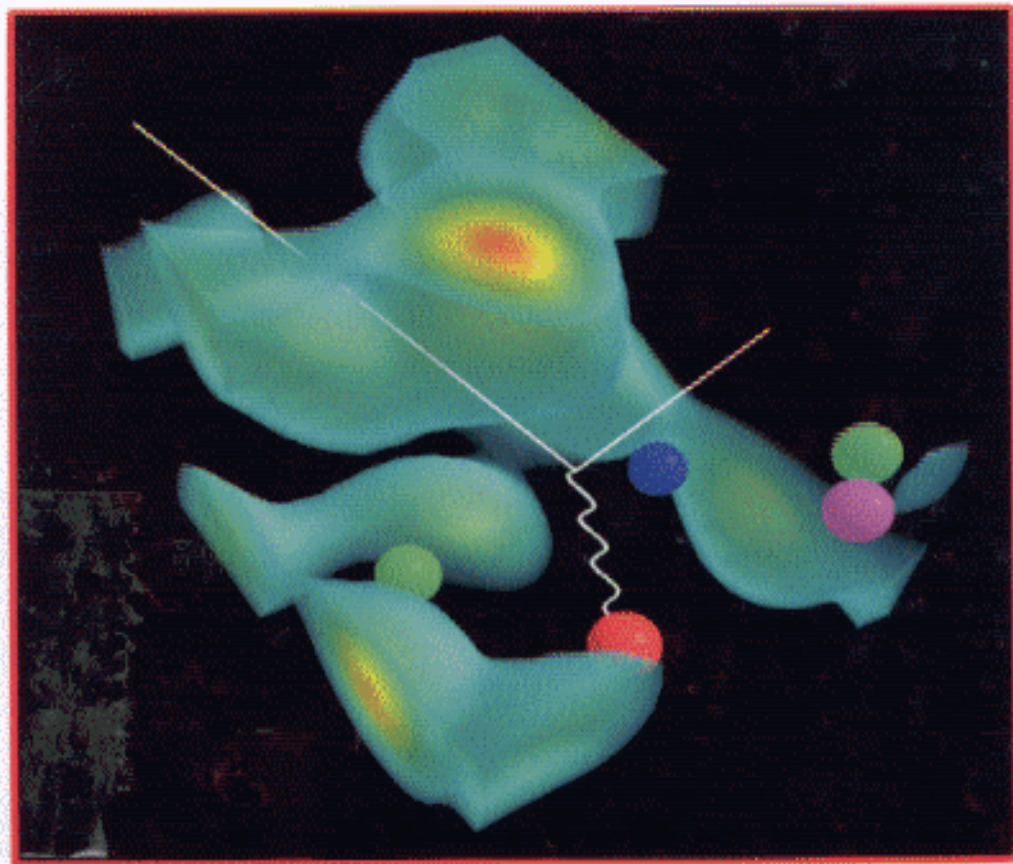


Anthony W. Thomas, Wolfram Weise

---

# The Structure of the Nucleon



 WILEY-VCH

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Prelude	1
1.2	Electroweak Interactions in the Standard Model	2
1.3	Electromagnetic Quark Currents	3
1.4	Weak Quark Currents	5
<b>2</b>	<b>Electromagnetic Structure of the Nucleon</b>	<b>7</b>
2.1	Elastic Electron Scattering	7
2.2	Electromagnetic Form Factors of the Nucleon	9
2.2.1	Low $Q^2$ Data	10
2.2.2	High $Q^2$ Data	15
2.2.3	Light-Front Distributions	18
2.2.4	Dispersion Relations	20
2.2.5	Vector Meson Dominance	21
2.2.6	Spectral Functions	24
2.2.7	Form Factors in the Timelike Region	26
2.3	Nucleon Resonances	27
2.3.1	Inelastic Electron Scattering	28
2.3.2	Pion Electroproduction	32
2.3.3	Watson's Theorem	33
2.3.4	Selected Examples	35
2.4	Compton Scattering	37
2.4.1	Scattering Amplitudes and Cross Sections	37
2.4.2	Dispersion Relations and Sum Rules	41
2.4.3	Electromagnetic Polarizabilities of the Nucleon	44
2.4.4	Virtual Compton Scattering	47
<b>3</b>	<b>Weak Probes of Nucleon Structure</b>	<b>53</b>
3.1	Matrix Elements of the Weak Currents	53
3.2	Axial Matrix Elements in Charged Current Neutrino Reactions	54
3.2.1	Charged Current Neutrino Scattering	56
3.2.2	Inelastic Charged Current Interactions	59
3.3	Beta-Decay	62
3.3.1	Experimental Determination of $g_A/g_V$	62
3.3.2	Determination of $V_{ud}$	63

3.4	Muon Capture . . . . .	64
3.4.1	Radiative Muon Capture . . . . .	66
3.5	Near Threshold Pion Electroproduction . . . . .	67
3.6	Neutral Current Interactions . . . . .	68
3.6.1	Elastic Neutrino Scattering . . . . .	70
3.6.2	Parity Violation in Elastic Electron Scattering . . . . .	72
<b>4</b>	<b>Deep-Inelastic Lepton Scattering</b> . . . . .	<b>75</b>
4.1	Parton Model . . . . .	77
4.2	Scaling Violations . . . . .	80
4.3	Neutrino Deep-Inelastic Scattering . . . . .	85
4.4	Sum Rules . . . . .	90
4.4.1	Gross-Llewellyn-Smith Sum Rule . . . . .	90
4.4.2	Adler Sum Rule . . . . .	91
4.4.3	Momentum Sum Rule . . . . .	92
4.4.4	Gottfried Sum Rule . . . . .	93
4.5	Experimental Results for Unpolarized Targets . . . . .	95
4.6	Spin Dependent Structure Functions . . . . .	98
4.6.1	Spin Structure Function $g_1$ . . . . .	100
4.6.2	Bjorken Sum Rule . . . . .	101
4.6.3	Ellis-Jaffe Sum Rule . . . . .	102
4.6.4	Transverse Spin Structure Function $g_2$ . . . . .	105
4.7	Qualitative Understanding of Parton Distributions . . . . .	107
4.7.1	Counting Rules . . . . .	107
4.7.2	Small- $x$ Behaviour . . . . .	108
4.7.3	Formal Parton Model . . . . .	109
4.8	Off-Forward Parton Distributions . . . . .	110
<b>5</b>	<b>Elements of QCD</b> . . . . .	<b>113</b>
5.1	Basic Lagrangian . . . . .	113
5.2	Feynman Rules . . . . .	116
5.2.1	Gauge Invariance . . . . .	117
5.2.2	Free Propagators and Interactions . . . . .	119
5.3	Renormalization . . . . .	123
5.3.1	Renormalization Scale . . . . .	124
5.3.2	Renormalization of the Gauge Coupling Constant . . . . .	124
5.4	Renormalization Group . . . . .	126
5.4.1	Running Coupling . . . . .	127
5.4.2	Asymptotic Freedom . . . . .	129
5.5	Deep Inelastic Scattering: Operator Product Expansion . . . . .	131
5.6	Deep Inelastic Scattering within QCD . . . . .	134
5.6.1	Connection to Moments of the Structure Functions . . . . .	136
5.6.2	Flavour Structure . . . . .	137
5.6.3	Non-singlet Case . . . . .	138
5.6.4	Singlet Case . . . . .	141

<b>6</b>	<b>Aspects of Non-Perturbative QCD</b>	<b>143</b>
6.1	Symmetries, Currents and Anomalies . . . . .	143
6.1.1	Baryon and Flavour Currents . . . . .	144
6.1.2	Massless Quarks: Chiral Symmetry . . . . .	146
6.1.3	Spontaneous Breaking of Chiral Symmetry . . . . .	147
6.1.4	Dynamical Symmetry Breaking and Fermion Mass Generation . . . . .	151
6.1.5	A Schematic Model: Nambu and Jona-Lasinio . . . . .	152
6.1.6	The Axial Anomaly . . . . .	157
6.1.7	Scale Invariance and the Trace Anomaly . . . . .	158
6.2	Structure of the QCD Vacuum: brief survey . . . . .	160
6.3	QCD Sum Rules . . . . .	161
6.3.1	Correlation Functions . . . . .	161
6.3.2	Operator Product Expansion . . . . .	162
6.3.3	The Sum Rule Method . . . . .	163
6.3.4	Ioffe's Formula . . . . .	163
6.4	Lattice QCD and the Nucleon . . . . .	164
6.4.1	Field Theory on a Lattice . . . . .	165
6.4.2	Nucleon Mass . . . . .	171
6.4.3	Nucleon Form Factors . . . . .	173
6.4.4	Moments of Structure Functions . . . . .	176
6.4.5	Nucleon Spin Structure . . . . .	179
<b>7</b>	<b>Chiral Symmetry and Nucleon Structure</b>	<b>183</b>
7.1	Chiral Effective Field Theory . . . . .	183
7.1.1	Chiral Effective Lagrangian: Meson Sector . . . . .	184
7.1.2	Chiral Effective Lagrangian including Baryons . . . . .	187
7.2	Baryon Masses and Sigma Terms . . . . .	191
7.2.1	Pion-Nucleon Sigma Term . . . . .	191
7.2.2	Empirical Sigma Term and Scalar Form Factor of the Nucleon . . . . .	192
7.2.3	Strange Quarks in the Nucleon . . . . .	194
7.3	Chiral Low Energy Theorems . . . . .	194
7.3.1	Goldberger-Treiman Relation . . . . .	195
7.3.2	S-Wave Pion-Nucleon Scattering: Weinberg-Tomozawa Theorem . . . . .	195
7.3.3	Adler-Weisberger Sum Rule . . . . .	196
7.3.4	Charged Pion Photoproduction: Kroll-Ruderman Theorem . . . . .	197
7.3.5	Charged Pion Electroproduction and the Axial Radius of the Nucleon . . . . .	198
7.3.6	Neutral Pion Photoproduction . . . . .	199
7.3.7	Electromagnetic Polarizabilities of the Nucleon . . . . .	200
7.4	Summary: the Pion Cloud of the Nucleon . . . . .	201
<b>8</b>	<b>Models of the Nucleon</b>	<b>203</b>
8.1	Survey . . . . .	203
8.2	Non-Relativistic Quarks Models . . . . .	204
8.2.1	Constituent Quarks . . . . .	204
8.2.2	Magnetic Moments and Axial Currents . . . . .	206

8.2.3	Potential Model . . . . .	209
8.2.4	Baryon Spectroscopy . . . . .	210
8.2.5	The Model of deRujula, Georgi and Glashow . . . . .	211
8.2.6	The Isgur-Karl Model . . . . .	213
8.2.7	Transition Amplitudes . . . . .	216
8.3	Soliton Models . . . . .	219
8.3.1	The Friedberg-Lee Soliton Model . . . . .	221
8.3.2	The Color Dielectric Model . . . . .	222
8.4	Bag Models . . . . .	223
8.4.1	The Model of Bogoliubov . . . . .	223
8.4.2	The MIT Bag Model . . . . .	225
8.5	Chiral Quark Models . . . . .	232
8.5.1	The Cloudy Bag Model . . . . .	234
8.5.2	Corrections to Hadronic Masses . . . . .	237
8.5.3	Appearances can be deceptive . . . . .	239
8.6	Chiral Solitons . . . . .	242
8.6.1	Quarks Bound by Chiral Fields . . . . .	242
8.6.2	Nucleons as Chiral Solitons . . . . .	244
<b>9</b>	<b>Final Remarks</b> . . . . .	<b>247</b>
	<b>Appendices</b> . . . . .	<b>249</b>
<b>A</b>	<b>Notations and Conventions</b> . . . . .	<b>249</b>
A.1	Isospin . . . . .	249
A.2	Gell-Mann matrices . . . . .	249
A.3	Dirac matrices . . . . .	250
A.4	Dirac fields and spinors . . . . .	250
<b>B</b>	<b>Cross Sections for Lepton- and Photon-Nucleon Scattering</b> . . . . .	<b>253</b>
B.1	Electron and Muon Scattering . . . . .	253
B.2	Neutrino Scattering . . . . .	261
B.3	Compton Scattering . . . . .	262
<b>C</b>	<b>Grassmann Variables</b> . . . . .	<b>265</b>
<b>D</b>	<b>Dimensional Regularization</b> . . . . .	<b>267</b>
<b>E</b>	<b>Path Integrals</b> . . . . .	<b>271</b>
	<b>References</b> . . . . .	<b>275</b>
	<b>Index</b> . . . . .	<b>285</b>