

# Chiral Nuclear Dynamics II

From Quarks to Nuclei  
to Compact Stars

Mannque Rho



World Scientific

# Contents

<i>Preface</i>	vii
1. Introduction	1
2. Multi-Facets Of QCD In Matter	9
3. Cheshire Cat Phenomenon	17
3.1 Motivation . . . . .	17
3.2 Chiral Bag Picture . . . . .	18
3.2.1 Cheshire Cat as a gauge artifact . . . . .	21
3.2.2 Baryon charge and the exact Cheshire Cat phenomenon . . . . .	24
3.3 Cheshire Cat Principle in Nature . . . . .	28
3.3.1 Flavor singlet axial charge $a^0 \equiv g_A^0$ . . . . .	28
3.3.2 “Charge-spin separation” for Cheshire Cat phenomena . . . . .	34
3.4 CCP and Multi-Facets of CBM . . . . .	35
3.4.1 Chiral quark-soliton model . . . . .	36
3.4.2 Cloudy bag model . . . . .	36
3.4.3 Skyrmion model . . . . .	37
3.4.4 Heavy baryon chiral perturbation approach . . . . .	37
4. Effective Field Theory For Nuclei	39
4.1 Role of Effective Field Theory in Nuclear Physics . . . . .	39
4.2 Standard Nuclear Physics Approach and EFT . . . . .	40
4.2.1 The power of SNPA . . . . .	40
4.2.2 The power of EFT . . . . .	41
4.3 Chiral Lagrangians . . . . .	42
4.3.1 Relevant scales and degrees of freedom . . . . .	42
4.3.2 Vector mesons and baryons . . . . .	43
4.3.3 Baryon fields . . . . .	44

4.4	Pionless EFT ( $\not\! EFT$ ) . . . . .	46
4.5	More Effective EFT . . . . .	48
4.5.1	Weinberg's counting rule . . . . .	48
4.5.2	Strategy of MEEFT . . . . .	50
4.5.3	The chiral filter . . . . .	51
4.5.4	Working of MEEFT . . . . .	52
4.5.4.1	What does the chiral filter say? . . . . .	53
4.5.4.2	Sketch of the calculational procedure . . . . .	55
4.5.4.3	How the cutoff $\Lambda$ enters . . . . .	58
4.5.4.4	Physical meaning of $\Lambda$ . . . . .	59
4.5.5	Predictions of MEEFT . . . . .	60
4.5.5.1	Thermal $np$ capture . . . . .	60
4.5.5.2	Polarization observables in $np$ capture . . . . .	62
4.5.5.3	Deuteron form factors . . . . .	65
4.5.5.4	Predicting the solar neutrino processes . . . . .	70
4.5.5.5	Magnetic moments of the trinucleons . . . . .	74
4.5.5.6	Further implications of the $\hat{d}^R$ term . . . . .	75
4.6	EFT “Completion” of SNPA . . . . .	78
4.7	EFT for Heavy Nuclei and Nuclear Matter . . . . .	78
5.	Hidden Local Symmetry For Hadrons	81
5.1	Emergence of Local Flavor Symmetry . . . . .	82
5.2	Tower of Hidden Gauge Fields . . . . .	84
5.2.1	Simplest open moose diagram . . . . .	84
5.2.2	General open moose . . . . .	86
5.2.3	Spectrum of the open moose . . . . .	87
5.2.4	Dimensional deconstruction . . . . .	88
5.3	AdS/QCD and hQCD . . . . .	89
5.3.1	Objectives . . . . .	89
5.3.2	Bottom-up approach . . . . .	90
5.3.3	Top-down approach . . . . .	93
5.3.4	Vector dominance . . . . .	95
5.3.5	Instanton baryons . . . . .	96
5.4	HLS $_{K=1}$ from Holographic Dual QCD . . . . .	96
5.4.1	Going from 5D to 4D . . . . .	97
5.4.2	Doing quantum corrections . . . . .	98
5.5	Hidden Local Symmetry and the “Vector Manifestation” . . . . .	99
5.5.1	HLS $_{K=1}$ : Hidden local symmetry à la Bando <i>et al.</i> . . . . .	99
5.5.2	HLS $_{K=1}$ with loop corrections . . . . .	100
5.5.2.1	Wilsonian matching . . . . .	101
5.5.2.2	Vector manifestation (VM) . . . . .	105

5.5.2.3	“Dropping mass” and local gauge symmetry . . . . .	107
5.5.2.4	Scaling near the VM fixed point . . . . .	107
5.6	Phenomenology with $\text{HLS}_{K=1}$ . . . . .	108
5.6.1	Doing chiral perturbation theory . . . . .	108
5.6.1.1	Chiral counting for the vector mesons in $\chi\text{PT}$ . . . . .	108
5.6.1.2	Loop calculations . . . . .	110
5.6.1.3	Comparison with experiments . . . . .	111
5.6.2	Weinberg sum rules . . . . .	111
5.6.3	Pion mass difference . . . . .	113
5.6.4	Perturbing from the VM point . . . . .	115
5.6.4.1	Heavy quark symmetry . . . . .	115
5.6.4.2	Constructing effective Lagrangians . . . . .	116
5.6.4.3	The fixed point Lagrangian . . . . .	117
5.6.4.4	Effects of spontaneous chiral symmetry breaking . . . . .	118
5.6.4.5	Lagrangian in parity eigenfields . . . . .	119
5.6.4.6	Calculation at the matching point . . . . .	120
5.6.4.7	Quantum correction . . . . .	121
5.6.4.8	Mass splitting . . . . .	123
5.7	$\text{HLS}$ with $\rho$ and $a_1$ : $\text{HLS}_{K=2}$ . . . . .	124
5.7.1	$\text{HLS}_{K=2}$ Lagrangian . . . . .	124
5.7.2	Fixed points . . . . .	126
5.7.3	Phase structures for different fixed points . . . . .	129
5.7.4	Multiplet structure and vector dominance . . . . .	130
5.7.5	Vector dominance and the fixed points . . . . .	131
5.7.6	Infinite tower and the VD . . . . .	132
6.	Skyrmions . . . . .	133
6.1	Preliminary Remarks . . . . .	133
6.2	Skyrmions in QCD . . . . .	134
6.2.1	A little history in nuclear physics . . . . .	134
6.2.2	Little bag and skyrmion . . . . .	135
6.3	Skyrmions and Vector Mesons . . . . .	136
6.3.1	Multiple scales . . . . .	136
6.3.2	$\text{HLS}$ Lagrangian “light” ( $\text{HLS}_{K=1}$ ) . . . . .	136
6.3.3	$SU(2)$ skyrmion . . . . .	138
6.3.3.1	Stabilizing the soliton . . . . .	139
6.3.3.2	Gauged skyrmion with the $\rho$ meson . . . . .	140
6.3.3.3	Defects of the Skyrme soliton . . . . .	142
6.3.4	Nuclei as skyrmions . . . . .	146
6.3.5	$SU(3)$ Skyrmions: $S > 0$ baryons . . . . .	146
6.3.5.1	Kaon-soliton bound skyrmions . . . . .	147
6.3.5.2	Deeply bound $K^-$ in nuclei . . . . .	152

6.4	Dense Skyrmion Matter and Chiral Transition . . . . .	152
6.4.1	Single skyrmion . . . . .	155
6.4.2	Skyrmion crystal . . . . .	156
6.4.3	Fluctuations on top of the skyrmion background and Brown-Rho scaling . . . . .	163
6.4.4	Pseudogap phase . . . . .	167
6.4.4.1	Skyrmion mass at high density . . . . .	169
6.5	Holographic Skyrmion . . . . .	169
6.5.1	Baryon as an instanton . . . . .	169
6.5.2	Chiral dynamics . . . . .	173
6.5.3	Deriving vector dominance . . . . .	174
6.5.3.1	“Old” vector dominance . . . . .	174
6.5.3.2	“New” vector dominance . . . . .	176
6.5.3.3	Generalized universality . . . . .	178
6.5.3.4	Nucleon EM form factors . . . . .	178
6.6	Neutron Stars As Giant Skyrmions . . . . .	184
6.6.1	Skyrmion EOS . . . . .	185
6.6.2	Einstein-skyrmion star . . . . .	186
7.	Hidden Local Symmetry In Hot/Dense Medium	187
7.1	HLS in Heat Bath . . . . .	187
7.1.1	Vector manifestation at $T_c$ . . . . .	187
7.1.2	Lorentz-invariant formulas . . . . .	188
7.1.2.1	Approaching the VM fixed point . . . . .	189
7.1.2.2	Pion decay constant . . . . .	189
7.1.2.3	“Dropping mass” . . . . .	190
7.1.2.4	Width . . . . .	191
7.1.2.5	Corrections from Lorentz non-invariance . . . . .	192
7.2	HLS in Dense Matter . . . . .	194
7.2.1	Dense HLS Lagrangian . . . . .	195
7.2.2	Hadrons near $\mu = \mu_c$ . . . . .	198
7.3	Hadronic Freedom . . . . .	201
7.3.1	Melting of “soft” glue and chiral restoration . . . . .	201
7.4	Applications . . . . .	203
7.4.1	Pion velocity near critical temperature $T_c$ . . . . .	204
7.4.1.1	Standard sigma model scenario . . . . .	205
7.4.1.2	HLS/VM scenario . . . . .	207
7.4.1.3	Measuring the pion velocity near $T_c$ . . . . .	210
7.4.2	Vector and axial vector susceptibilities near critical temperature $T_c$ . . . . .	211
7.4.3	Spectral function of the $\rho$ meson . . . . .	213

7.4.3.1	$\rho\pi\pi$ and $\gamma\pi\pi$ couplings in hot medium and violation of vector dominance . . . . .	214
7.4.3.2	EM form factor of the pion and the $\rho$ spectral function . . . . .	217
7.4.3.3	Confronting nature . . . . .	222
7.4.4	$\rho^0/\pi^-$ ratio in peripheral collisions . . . . .	222
8.	Hadrons In The Sliding Vacua Of Nuclear Matter	225
8.1	Brown-Rho Scaling . . . . .	225
8.1.1	Intrinsic density dependence via dilaton . . . . .	226
8.1.2	Scaling of baryon masses . . . . .	227
8.1.3	Parity-doubled sigma model . . . . .	228
8.1.4	Constraints from anomaly matching? . . . . .	230
8.1.5	Modernizing BR scaling . . . . .	231
8.2	Chiral Fermi Liquid . . . . .	231
8.2.1	Double-decimation approach . . . . .	231
8.2.2	Scaling masses and Landau-Migdal parameters . . . . .	232
8.2.3	Thermodynamic consistency . . . . .	237
8.2.4	Meaning of $C_{\omega_s}^*$ . . . . .	240
8.2.5	Many-body forces . . . . .	241
8.3	Observables in Finite Nuclei . . . . .	241
8.3.1	Nuclear magnetic moment . . . . .	242
8.3.2	Deducing $\Phi(n_0)$ from experiment . . . . .	245
8.3.3	Relation between the Landau mass $m_L^*$ and the axial coupling constant $g_A$ . . . . .	245
8.3.4	Pion decay constant in medium . . . . .	246
8.3.5	Effect on tensor forces . . . . .	246
8.3.6	Warburton ratio . . . . .	249
8.3.7	“Observing” the dropping vector meson masses . . . . .	251
8.4	Dropping Masses and Nuclear Matter . . . . .	253
8.4.1	Nuclear matter in chiral Fermi liquid approach . . . . .	254
8.4.2	Microscopic approach to Landau Fermi liquid with Brown-Rho scaling . . . . .	255
9.	Strangeness In Dense Medium	259
9.1	Kaon Condensation from Matter-Free Vacuum . . . . .	260
9.1.1	Kaon condensation as “restoration” of explicit chiral symmetry breaking . . . . .	260
9.1.2	Doing heavy baryon $\chi$ PT . . . . .	262
9.1.3	Kaon condensation driven by electrons . . . . .	264
9.1.4	Constraints from kaon-nuclear scattering . . . . .	266
	9.1.4.1 $\Lambda(1405)$ . . . . .	266

9.1.4.2	Influence on kaon condensation . . . . .	270
9.1.4.3	“Dangerously irrelevant terms” . . . . .	272
9.1.5	Role of kaon-nuclear potential in kaon condensation . . . . .	274
9.1.5.1	Chiral perturbation approach . . . . .	274
9.1.5.2	Kaonic atom and deeply bound kaonic nuclei . . . . .	275
9.1.6	Kaon condensation with Brown-Rho scaling . . . . .	275
9.2	From the Vector Manifestation Fixed Point to Kaon Condensation . . . . .	280
9.2.1	Simplification at the VM . . . . .	280
9.2.2	Toward kaon condensation . . . . .	282
9.3	Dense Kaonic Nuclei as Strange Nuggets: “ <i>KaoN</i> ” . . . . .	283
9.3.1	With standard potentials . . . . .	284
9.3.2	With non-standard potentials . . . . .	285
9.3.3	<i>KaoN</i> as an “Ice-9” nugget . . . . .	286
10.	Dense Matter For Compact Stars	289
10.1	Dense Hadronic Phase With and Without Exotica . . . . .	290
10.1.1	Compact stars as dense neutron matter . . . . .	291
10.1.2	Working of the vector manifestation . . . . .	292
10.1.3	Demise of the VM scenario by massive compact stars? . . . . .	294
10.1.4	Kaon condensation as a doorway to quark matter . . . . .	295
10.2	Skyrmion-Half-Skyrmion Transition . . . . .	298
10.2.1	Half-skyrmions and emergence of “vector symmetry” . . . . .	299
10.2.2	Transition from the CFL phase to the normal nuclear phase . . . . .	301
10.3	QCD at High Density: Color Superconductivity (CSC) . . . . .	303
10.3.1	Color-flavor locking (CFL) . . . . .	304
10.3.2	Chiral Lagrangian for CFL . . . . .	305
10.3.3	“Un-hidden” local symmetry . . . . .	307
10.3.4	Superquarkons as baryons . . . . .	309
10.3.5	Kaon condensation in the CFL sector . . . . .	311
10.4	CSC at Non-Asymptotic Density . . . . .	312
10.4.1	Induced CFL . . . . .	313
10.4.2	Landscape of non-CFL phases . . . . .	315
11.	Compact Stars	317
11.1	Objective . . . . .	317
11.2	Star Observables . . . . .	318
11.3	Chiral Dynamics in the Core of Compact Stars . . . . .	318
11.3.1	TOV equation . . . . .	319
11.3.2	Neutron stars with kaon condensation “light” . . . . .	319
11.4	Maximum Neutron Star Mass . . . . .	324

11.4.1 $M_{NS}^{max}$ à la Brown-Bethe . . . . .	324
11.4.2 Cosmological constraint on $M_{NS}^{max}$ ? . . . . .	325
11.5 Formation of Double Neutron Star Binaries . . . . .	326
11.6 Neutron Stars Heavier than $M_{NS}^{max}$ ? . . . . .	327
11.6.1 Vela X-1 . . . . .	328
11.6.2 Neutron star-white dwarf binaries . . . . .	329
11.6.3 Two-branch scenario . . . . .	330
11.6.4 New measurement of the neutron star mass in J0751+1807	331
11.7 Outlook . . . . .	331
<i>Bibliography</i>	335
<i>Index</i>	349