

Contents

	Preamble	xi
I	A new phase of matter?	1
1	Micro-bang and big-bang	1
1.1	Energy and time scales	1
1.2	Quarks and gluons	6
1.3	The hadronic phase transition in the early Universe	8
1.4	Entropy-conserving (isentropic) expansion	10
1.5	The dynamic Universe	11
1.6	Looking for quark–gluon plasma: strangeness	14
1.7	Other probes of quark–gluon plasma	20
2	Hadrons	24
2.1	Baryons and mesons	24
2.2	Strange hadrons	27
2.3	Charm and bottom in hadrons	36
3	The vacuum as a physical medium	37
3.1	Confining vacuum in strong interactions	37
3.2	Ferromagnetic vacuum	40
3.3	Chiral symmetry	43
3.4	Phases of strongly interacting matter	46
3.5	The expanding fireball and phase transformation	50
3.6	QGP and confined hadronic-gas phases	52
4	Statistical properties of hadronic matter	54
4.1	Equidistribution of energy	54
4.2	The grand-canonical ensemble	57
4.3	Independent quantum (quasi)particles	58
4.4	The Fermi and Bose quantum gases	61
4.5	Hadron gas	64
4.6	A first look at quark–gluon plasma	68

II	Experiments and analysis tools	72
5	Nuclei in collision	72
5.1	Heavy-ion research programs	72
5.2	Reaction energy and collision geometry	78
5.3	Rapidity	81
5.4	Pseudorapidity and quasirapidity	85
5.5	Stages of evolution of dense matter	90
5.6	Approach to local kinetic equilibrium	95
5.7	The approach to chemical equilibrium	97
6	Understanding collision dynamics	100
6.1	Cascades of particles	100
6.2	Relativistic hydrodynamics	104
6.3	The evolution of matter and temperature	107
6.4	Longitudinal flow of matter	108
7	Entropy and its relevance in heavy-ion collisions	112
7.1	Entropy and the approach to chemical equilibrium	112
7.2	Entropy in a glue-ball	116
7.3	Measurement of entropy in heavy-ion collisions	120
7.4	The entropy content in 200A-GeV S–Pb interactions	122
7.5	Supersaturated pion gas	124
7.6	Entropy in a longitudinally scaling solution	128
III	Particle production	130
8	Particle spectra	130
8.1	A thermal particle source: a fireball at rest	130
8.2	A dynamic fireball	137
8.3	Incomplete stopping	144
8.4	Transverse-mass fireball spectra	148
8.5	Centrality dependence of $m_{\perp}$ -spectra	155
9	Highlights of hadron production	159
9.1	The production of strangeness	159
9.2	Hadron abundances	165
9.3	Measurement of the size of a dense-matter fireball	171
9.4	Production of transverse energy	176
9.5	RHIC results	178
IV	Hot hadronic matter	187
10	Relativistic gas	187
10.1	Relation of statistical and thermodynamic quantities	187
10.2	Statistical ensembles and fireballs of hadronic matter	191
10.3	The ideal gas revisited	193
10.4	The relativistic phase-space integral	195
10.5	Quark and gluon quantum gases	199

	<i>Contents</i>	ix
	10.6 Entropy of classical and quantum gases	204
11	Hadronic gas	207
	11.1 Pressure and energy density in a hadronic resonance gas	207
	11.2 Counting hadronic particles	211
	11.3 Distortion by the Coulomb force	215
	11.4 Strangeness in hadronic gas	217
	11.5 The grand-canonical conservation of strangeness	219
	11.6 Exact conservation of flavor quantum numbers	223
	11.7 Canonical suppression of strangeness and charm	228
12	Hagedorn gas	235
	12.1 The experimental hadronic mass spectrum	235
	12.2 The hadronic bootstrap	241
	12.3 Hadrons of finite size	247
	12.4 Bootstrap with hadrons of finite size and baryon number	251
	12.5 The phase boundary in the SBM model	254
V	QCD, hadronic structure and high temperature	258
13	Hadronic structure and quantum chromodynamics	258
	13.1 Confined quarks in a cavity	258
	13.2 Confined quark quantum states	262
	13.3 Nonabelian gauge invariance	267
	13.4 Gluons	271
	13.5 The Lagrangian of quarks and gluons	273
14	Perturbative QCD	274
	14.1 Feynman rules	274
	14.2 The running coupling constant	277
	14.3 The renormalization group	280
	14.4 Running parameters of QCD	281
15	Lattice quantum chromodynamics	287
	15.1 The numerical approach	287
	15.2 Gluon fields on the lattice	289
	15.3 Quarks on the lattice	290
	15.4 From action to results	293
	15.5 A survey of selected lattice results	298
16	Perturbative quark–gluon plasma	303
	16.1 An interacting quark–gluon gas	303
	16.2 The quark–gluon liquid	306
	16.3 Finite baryon density	309
	16.4 Properties of a quark–gluon liquid	311

x	<i>Contents</i>	
VI	Strangeness	316
17	Thermal production of flavor in a deconfined phase	316
17.1	The kinetic theory of chemical equilibration	316
17.2	Evolution toward chemical equilibrium in QGP	322
17.3	Production cross sections for strangeness and charm	326
17.4	Thermal production of flavor	330
17.5	Equilibration of strangeness at the RHIC and SPS	337
18	The strangeness background	340
18.1	The suppression of strange hadrons	340
18.2	Thermal hadronic strangeness production	343
18.3	The evolution of strangeness in hadronic phase	349
19	Hadron-freeze-out analysis	352
19.1	Chemical nonequilibrium in hadronization	352
19.2	Phase space and parameters	355
19.3	SPS hadron yields	357
19.4	Strangeness as a signature of deconfinement	361
	<i>References</i>	371
	<i>Index</i>	389