

Contents

<i>Preface</i>	vii
PART I: OVERVIEW	1
1. Introduction	3
1.1 High-energy nuclear collisions	3
1.2 Theoretical methods	6
1.3 Quantum chromodynamics	6
1.4 Quark-gluon plasma	8
1.5 Chiral symmetry	11
1.6 Hot and dense nuclear matter	14
1.7 Units and notation	14
<i>Bibliography to Chapter 1</i>	20
2. Basic Dictionary	25
2.1 Participants, spectators, and impact parameter	25
2.2 Kinematical variables	27
2.2.1 Transverse mass	27
2.2.2 Rapidity and pseudorapidity	27
2.2.3 Light-cone variable x	29
2.2.4 Experimental rapidity and transverse-momentum distributions	29
2.3 Centrality	33
2.3.1 Competition of archers...	35
2.3.2 ... and heavy-ion experiment	37
2.4 Reaction plane	38
2.4.1 Sphericity method	38
2.4.2 Transverse-momentum method	40
2.4.3 Fourier analysis method	40

2.5	Collective flows	41
2.5.1	Directed flow	42
2.5.2	Elliptic flow	43
2.6	Stopping and transparency	45
2.7	Boost-invariance	47
<i>Bibliography to Chapter 2</i>		50
3.	Glauber Model	53
3.1	Eikonal approximation	53
3.2	Nucleon-nucleon collisions	56
3.2.1	Energy dependence of particle production	56
3.2.2	Thickness function	56
3.3	Nucleon-nucleus collisions	57
3.3.1	Nuclear density profiles	57
3.3.2	Independent collisions	59
3.4	Nucleus-nucleus collisions	60
3.4.1	Total inelastic cross section	60
3.4.2	Exclusion of elastic processes	62
3.5	Wounded nucleons	62
3.6	Soft and hard processes	64
3.7	Wounded-nucleon model	66
3.8	Nuclear modification factor	69
<i>Bibliography to Chapter 3</i>		71
4.	Spacetime Picture of Ultra-Relativistic Heavy-Ion Collisions	73
4.1	Particle production processes	74
4.1.1	String decays	75
4.1.2	Parton cascade model	76
4.1.3	Color glass condensate	76
4.2	Thermalization	78
4.3	Hydrodynamic expansion	80
4.4	Thermal freeze-out	81
4.5	Chemical freeze-out	82
4.5.1	Little Bang	84
4.6	Hanbury Brown – Twiss interferometry	84
<i>Bibliography to Chapter 4</i>		89
5.	More about Quarks and Gluons	95
5.1	Color	96
5.2	Gauge symmetry	96

5.3	Equation of state of weakly-interacting quark-gluon plasma	98
5.4	Lattice QCD	101
5.4.1	Order of phase transition at $\mu_B = 0$	102
5.4.2	Critical point	104
5.5	Color isotopic charge and color hypercharge	104
5.5.1	Quarks	105
5.5.2	Gluons	106
	<i>Bibliography to Chapter 5</i>	108
6.	More about Hadrons	111
6.1	Resonances	112
6.2	Statistical bootstrap model	113
6.3	Hagedorn temperatures for mesons and baryons	114
6.4	Dashen-Ma-Bernstein formalism	116
6.5	Virial expansion — non-relativistic treatment	117
6.6	EOS of strongly interacting matter	121
	<i>Bibliography to Chapter 6</i>	125
7.	Exercises to PART I	127
	PART II: RELATIVISTIC KINETIC THEORY	131
8.	Definitions	133
8.1	Distribution function	133
8.2	Particle current	134
8.3	Energy-momentum tensor	135
8.4	Entropy current	136
8.4.1	Fermions	136
8.4.2	Bosons	137
8.5	Internal degrees of freedom	138
8.6	Fluid velocity	140
8.7	Relativistic equilibrium distributions	140
8.7.1	Classical massive particles	141
8.7.2	Relativistic massless bosons	142
8.7.3	Relativistic massless fermions	143
8.7.4	Ideal relativistic gases — summary	145
	<i>Bibliography to Chapter 8</i>	147
9.	Relativistic Kinetic Equations	149

9.1	Systems without collisions	149
9.1.1	Boltzmann-Vlasov equations for QED plasma	151
9.2	Systems with collisions	152
9.2.1	Loss and gain terms	152
9.2.2	Boltzmann equation	154
9.2.3	Boltzmann-Uehling-Uhlenbeck equation	155
9.2.4	Vlasov-Uehling-Uhlenbeck equation	156
9.2.5	Transition rate W	156
9.3	Mixtures	157
9.4	Conservation laws	158
9.4.1	Quantities conserved in elementary collisions	158
9.4.2	Basic conservation laws	159
9.5	Boltzmann H-theorem	160
9.6	Local and global equilibrium distributions	162
9.7	Relaxation-time approximation	163

Bibliography to Chapter 9 164

10. Exercises to PART II 165

PART III: KINETIC DESCRIPTION OF PLASMA PRODUCTION **169**

11.	Color-Flux-Tube Model	171
11.1	Schwinger mechanism	172
11.2	Abelian dominance approximation	175
11.3	Kinetics of the plasma formation	177
11.4	Energy-momentum conservation laws	179
11.5	Implementation of boost-invariance	179
11.5.1	Boost-invariant variables	180
11.5.2	Boost-invariant transport equations	181
11.5.3	Conductive current	181
11.5.4	Displacement current	182
11.5.5	Oscillations of the quark-gluon plasma	183
11.6	Apparent thermalization	187

Bibliography to Chapter 11 189

12. Exercises to PART III 191

PART IV: RELATIVISTIC HYDRODYNAMICS	193
13. Perfect Fluid	195
13.1 Thermodynamics of fluid element	195
13.2 Euler equation and conservation laws	197
13.2.1 Systems with non-zero baryon density	197
13.2.2 Systems with vanishing baryon density	199
13.3 Euler equation in Cartesian coordinates	199
13.3.1 Non-zero baryon density	199
13.3.2 Vanishing baryon density	200
13.4 Euler equation with cylindrical symmetry	201
13.5 Euler equation with boost-invariance	203
13.5.1 Combining boost-invariance with cylindrical symmetry	205
13.6 Entropy conservation	205
13.6.1 Non-zero baryon density	206
13.6.2 Vanishing baryon density	206
13.7 One-dimensional expansion	208
13.7.1 Simple Riemann solution	208
13.8 Boost-invariant cylindrically asymmetric case	210
13.8.1 Introduction of cylindrical coordinates	210
13.8.2 Global entropy conservation	211
13.8.3 Characteristic form	211
13.8.4 Boundary conditions	213
<i>Bibliography to Chapter 13</i>	215
14. General Aspects of Perfect-Fluid Dynamics	217
14.1 Non-relativistic limit	217
14.2 Bernoulli equation	218
14.3 Relativistic circulation	218
14.3.1 Vortices in relativistic fluids	220
14.4 Relativistic shock waves	221
14.5 Mach cones	223
14.6 Convective stability	224
<i>Bibliography to Chapter 14</i>	225
15. Initial Conditions and Freeze-Out	227
15.1 Initial conditions	227
15.1.1 Boost-invariant systems	227
15.1.2 Non-boost-invariant systems	229
15.2 Freeze-out	231
15.3 Cooper-Frye formula	232

15.3.1	Space-like emission	236
15.4	Emission function	237
	<i>Bibliography to Chapter 15</i>	238
16.	Exercises to PART IV	239
PART V: PARTICLE INTERFEROMETRY		243
17.	Pion Correlation Functions	245
17.1	General definitions	246
17.1.1	Connection to inclusive distributions	246
17.1.2	Connection to density matrix	246
17.1.3	Very simple model	247
17.1.4	Connection to emission function	248
17.2	Gaussian parametrization	249
17.2.1	Mass-shell projection	252
17.2.2	Out-side-long coordinate system	253
17.3	Monte-Carlo approach	256
17.4	HBT data vs. theoretical expectations	256
	<i>Bibliography to Chapter 17</i>	257
18.	Exercises to PART V	261
PART VI: HYDRODYNAMIC DESCRIPTION OF NUCLEAR COLLISIONS		265
19.	Historical Perspective: Fermi Statistical Model	267
19.1	Pion production in low-energy nucleon collisions	268
19.2	Multiple pion production	270
19.3	From statistical to thermodynamical production	272
19.4	Fermi's legacy	272
	<i>Bibliography to Chapter 19</i>	273
20.	Landau Model	275
20.1	Initial one-dimensional expansion	276
20.1.1	Khalatnikov equation	278
20.2	Approximate formulas for one-dimensional expansion	282
20.3	Transition to three-dimensional expansion	283
20.4	Rapidity distributions	284

20.4.1	Original formulation	284
20.4.2	Freeze-out at constant temperature	285
	<i>Bibliography to Chapter 20</i>	286
21.	Bjorken Model	289
21.1	Pure longitudinal expansion	290
21.2	Simple estimates	291
21.3	First-order phase transition	293
21.4	Bjorken vs. Landau	294
	<i>Bibliography to Chapter 21</i>	295
22.	Modeling RHIC Data	297
22.1	2+1 hydrodynamic models	298
22.1.1	Cracow 2+1 hydrodynamic model	299
22.2	3+1 hydrodynamic models	304
22.2.1	Cracow 3+1 hydrodynamic model	304
22.3	RHIC HBT puzzle	309
22.3.1	Cracow 2+1 model with Gaussian initial conditions	311
22.4	Outlook at LHC	314
22.4.1	Saturation of elliptic flow?	316
	<i>Bibliography to Chapter 22</i>	316
23.	Exercises to PART VI	321
	PART VII: FREEZE-OUT MODELS	325
24.	Thermal Models	327
24.1	Thermal versus hydro-inspired models	327
24.2	Static fireball	329
24.3	Thermal analysis of ratios of hadron multiplicities	330
24.4	Inclusion of expansion	331
24.5	Examples of data analysis	332
24.6	Gaździcki's horn	336
24.7	Chemical non-equilibrium	337
24.8	Strangeness enhancement	338
	<i>Bibliography to Chapter 24</i>	339
25.	Hydro-Inspired Models	341
25.1	Blast-wave model of Siemens and Rasmussen	341

25.2	Blast-wave model of Schnedermann, Sollfrank, and Heinz	344
25.2.1	Constant transverse flow	346
25.2.2	Hubble-like expansion	350
25.3	Buda-Lund model	353
25.4	Seattle model	354
<i>Bibliography to Chapter 25</i>		355
26.	Decays of Resonances	357
26.1	Two-body decays	357
26.2	Three-body decays	360
26.3	Sequential decays: spectra	361
26.3.1	Boost-invariant, cylindrically symmetric case	363
26.3.2	Boost-invariant, cylindrically asymmetric case	365
26.4	Sequential decays: correlations	366
26.5	Single-freeze-out model	367
26.6	Open source computer codes for thermal and hydro-inspired models	369
<i>Bibliography to Chapter 26</i>		371
27.	Exercises to PART VII	373
PART VIII: ELECTROMAGNETIC SIGNALS FROM HOT AND DENSE MATTER		375
28.	In-Medium Modifications of Hadron Properties	377
28.1	Low-mass dilepton enhancement	378
28.2	Dileptons from pion annihilation	380
28.2.1	Vector dominance model	381
28.2.2	Effective decay width	383
28.2.3	Connection to field theory	386
28.3	Dropping masses and broadening widths	387
<i>Bibliography to Chapter 28</i>		388
29.	Exercises to PART VIII	391
PART IX: SUPPLEMENTS		395
30.	Cross Sections, Transition Rates, and Inclusive Distributions	397
30.1	Geometric interpretation of cross section	397

30.2	Scattering matrix	400
30.3	Differential transition rate	402
30.4	Differential decay rate and cross section	403
30.5	Inclusive processes	404
30.5.1	One-particle inclusive cross section	404
30.5.2	Two-particle inclusive cross section	406
30.5.3	Inclusive distributions	407
	<i>Bibliography to Chapter 30</i>	407
31.	Useful Mathematical Formulae	409
31.1	Heaviside and Dirac functions	409
31.2	Modified Bessel functions $K_n(x)$	409
31.3	Modified Bessel functions $I_n(x)$	410
31.4	Cylindrical and light-cone coordinates	411
	<i>Bibliography to Chapter 31</i>	411
	<i>Index</i>	413