

Contents

1	The basics of μSR	1
1.1	The key idea	1
1.2	The principles of the experiment	2
1.3	Muon beams and spectrometers	4
1.4	Experimental geometries	6
1.5	What can we do with μ SR?	6
I	Elements of muon spectroscopy	9
2	Introduction	10
2.1	Discovery of the muon	10
2.2	The first muon application	11
2.3	Muon perspectives	12
2.4	The μ SR experiment	17
	Exercises	20
3	Muon charge and spin states	21
3.1	State formation	22
3.2	Hydrogen analogues	24
3.3	Measuring the states	26
3.4	Influencing the states	27
	Exercises	28
4	The quantum muon	29
4.1	Larmor precession	29
4.2	Density matrices	33
4.3	Mixed states	34
4.4	Two spins: muonium	36
4.5	Multiple spins	44
	Exercises	52
5	Polarization functions	54
5.1	Static fields	55
5.2	Dynamical fields	60
5.3	Disordered systems	64
5.4	The stretched exponential	65
	Exercises	67

II	Science with μSR	69
6	Magnetism	70
6.1	The basics	70
6.2	Static magnetic order	72
6.3	The local magnetic field	76
6.4	Static field distributions	81
	Exercises	86
7	Dynamic effects in magnetism	87
7.1	Correlation functions	87
7.2	Dynamics in magnets	90
7.3	Dynamics with muons	92
7.4	Relaxation as resonance	95
7.5	Dynamic magnetism	96
7.6	Coupling tensors	101
7.7	Dilute spins	103
	Exercises	108
8	Measuring dynamic processes	110
8.1	Critical dynamics	110
8.2	Magnetism in metals	113
8.3	BPP relaxation	115
8.4	Mobile excitations	117
8.5	Muon diffusion	125
	Exercises	129
9	Superconductors	130
9.1	The discovery	130
9.2	London penetration depth	131
9.3	Ginzburg-Landau model	134
9.4	Type-II superconductors	136
9.5	Measuring the penetration depth	140
9.6	The microscopic model	144
9.7	Example materials	146
9.8	Clean versus dirty	150
9.9	The Uemura plot	151
9.10	Spontaneous fields	154
	Exercises	155
10	Semiconductors and dielectrics	157
10.1	Ubiquitous hydrogen impurities	159
10.2	Muonium	160
10.3	Silicon: the foundations	161
10.4	Shallow donor states	165
10.5	Related techniques	166
	Exercises	169
11	Ionic motion	170

11.1	Why use muons?	170
11.2	Science examples	173
11.3	Limitations	175
	Exercises	176
12	Chemistry	177
12.1	Chemical environments	177
12.2	Muonium spectroscopy	180
12.3	Reactions of muonium	183
12.4	Muoniated radicals	186
12.5	Structure and dynamics	191
	Exercises	198
III	Practicalities of muon spectroscopy	199
13	Making muons	200
13.1	Muon production	200
13.2	Surface and decay muons	202
13.3	Beamline components	204
	Exercises	209
14	Instrumentation	210
14.1	Spectrometer elements	210
14.2	Pulsed sources	213
14.3	Continuous sources	214
14.4	Small samples	215
15	Doing the experiment	217
15.1	Experimental setup	217
15.2	Calibrations	220
15.3	Data characteristics	221
15.4	Time domain analysis	224
15.5	Frequency domain	230
	Exercises	238
IV	Further topics in muon spectroscopy	239
16	Calculating muon sites	240
16.1	The site problem	241
16.2	What is DFT?	243
16.3	Methods	246
16.4	Basis sets	248
16.5	Functionals	250
16.6	Mixed methods	251
16.7	Obtaining sites	252
16.8	Quantum effects	257
16.9	Sites via experiment	258

Exercises	261
17 Numerical modelling	263
17.1 Beamline optimization	263
17.2 Muon range profile	265
17.3 Muon spin response	267
18 Low energy μSR	274
18.1 Generating slow muons	274
18.2 LEM facilities	277
18.3 Science examples	280
19 Stimulation methods	283
19.1 Types of stimulation	283
19.2 Case studies	285
19.3 Photoexcitation	288
19.4 Muon-spin resonance	293
Exercises	303
20 High magnetic fields	305
20.1 Why high fields?	305
20.2 Muons and high magnetic fields	307
20.3 Science at high field	310
Exercises	312
21 Muons under pressure	313
21.1 Requirements	313
21.2 The PSI setup	314
21.3 A gas-pressure setup	318
21.4 Science examples	320
21.5 Outlook	321
22 Negative muon techniques	323
22.1 μ^- SR spectroscopy	323
22.2 Elemental analysis	328
Exercises	334
V Complementary techniques	335
23 μSR versus other resonance and bulk techniques	336
23.1 Magnetic resonance	336
23.2 When the muon is a plus	340
23.3 Mössbauer spectroscopy	342
23.4 Bulk techniques	344
Exercises	349
24 X-rays, neutrons, and μSR	350
24.1 X-rays	350

24.2 Neutrons	352
24.3 Where do muons fit in?	353
Exercises	355
A Fundamental constants	357
B Nuclear moments	358
C Negative muon lifetimes	360
D Answers to selected problems	361
E Muon particle physics	366
E.1 Parity violation	366
E.2 Standard Model and weak interactions	367
E.3 Muon production	368
E.4 Muon decay	369
F Quantum-mechanical polarization functions	373
F.1 Time-dependent perturbations	373
F.2 Evaluating terms	376
G The second moment of a spin distribution	379
G.1 The dipolar interaction	379
G.2 High transverse field	380
G.3 Zero field	384
G.4 Quadrupolar coupling	385
H A short history of μSR	387
Index	406

$$n(t) = n(0)e^{-t/\tau} \quad (1.1)$$

$$\lambda(t) = -\frac{dn(t)}{dt} = \frac{n(0)}{\tau} e^{-t/\tau} = N(0)e^{-t/\tau} \quad (1.2)$$