

# Contents

<i>Preface</i>	v
1. Introduction	1
1.1 Why neutron scattering? . . . . .	1
1.2 Basic properties of the neutron . . . . .	2
2. Basic Principles of Neutron Scattering	7
2.1 Aim of a neutron scattering experiment . . . . .	7
2.2 Neutron scattering cross-section . . . . .	8
2.3 Correlation functions . . . . .	10
2.4 Coherent and incoherent scattering . . . . .	12
2.5 Principle of detailed balance . . . . .	14
2.6 Magnetic scattering . . . . .	15
2.7 Polarized neutrons . . . . .	19
2.8 Dynamical neutron scattering . . . . .	21
2.9 Further reading . . . . .	23
3. Instrumentation	25
3.1 Neutron sources . . . . .	25
3.1.1 Historical evolution of neutron sources . . . . .	25
3.1.2 Practical requirements for neutron sources . . . . .	26
3.1.3 Fission sources . . . . .	26
3.1.4 Spallation sources . . . . .	27
3.1.5 Moderation of neutrons . . . . .	29
3.2 Instrument components . . . . .	30
3.2.1 Beam tubes and static collimators . . . . .	30

3.2.2	Neutron guides . . . . .	31	5.2	Phonon dispersion relations and phonon polarization vectors	89
3.2.3	Time-of-flight monochromators . . . . .	33	5.2.1	Linear chain with identical atoms . . . . .	89
3.2.4	Monochromator (and analyzer) crystals . . . . .	34	5.2.2	Linear chain with two different atoms . . . . .	91
3.2.5	Neutron beam filters . . . . .	37	5.2.3	Experimental . . . . .	93
3.2.6	Spin polarizers (and spin analyzers) . . . . .	38	5.3	Incoherent scattering: phonon density of states . . . . .	95
3.2.7	Guide fields and spin flippers . . . . .	39	5.4	Multi-phonon processes: coherent scattering . . . . .	98
3.2.8	Detectors . . . . .	40	5.5	Further reading . . . . .	98
3.3	Neutron instruments . . . . .	41	5.6	Exercises . . . . .	98
3.3.1	Introductory remarks . . . . .	41	5.7	Solutions . . . . .	101
3.3.2	Powder diffractometers . . . . .	42	6.	Liquids and Amorphous Materials	105
3.3.3	Single-crystal diffractometers . . . . .	43	6.1	Introduction . . . . .	105
3.3.4	Small-angle scattering instruments . . . . .	45	6.2	Static structure factor . . . . .	107
3.3.5	Reflectometers . . . . .	46	6.3	Diffusion . . . . .	112
3.3.6	Time-of-flight spectrometers . . . . .	48	6.4	Further reading . . . . .	118
3.3.7	Triple-axis spectrometers . . . . .	50	6.5	Exercises . . . . .	119
3.3.8	Backscattering spectrometers . . . . .	51	6.6	Solutions . . . . .	120
3.3.9	Spin-echo spectrometers . . . . .	52	7.	Magnetic Structures	123
3.4	Sample environment . . . . .	54	7.1	General cross section . . . . .	123
3.4.1	Temperature . . . . .	54	7.2	Paramagnets . . . . .	123
3.4.2	Magnetic field . . . . .	56	7.3	Ferromagnets . . . . .	124
3.4.3	Pressure . . . . .	57	7.4	Antiferromagnets . . . . .	125
3.5	Further reading . . . . .	61	7.5	Helical spin structures (magnetic spiral structures) . . . . .	127
4.	Structure Determination	63	7.6	Magnetic ordering wavevector . . . . .	130
4.1	Cross section . . . . .	63	7.7	Zero-field magnetization . . . . .	130
4.2	Examples of structure factors . . . . .	65	7.8	Spin densities . . . . .	131
4.3	Polycrystalline materials . . . . .	66	7.9	Further reading . . . . .	132
4.4	Single crystals . . . . .	69	7.10	Exercises . . . . .	133
4.4.1	Rotating crystal method . . . . .	70	7.11	Solutions . . . . .	134
4.4.2	Laue method . . . . .	70	8.	Magnetic Excitations	137
4.5	Extinction and absorption . . . . .	71	8.1	Magnetic cluster excitations . . . . .	137
4.6	Characterization of residual stress . . . . .	73	8.1.1	Dimers . . . . .	137
4.7	Further reading . . . . .	74	8.1.2	Trimers . . . . .	139
4.8	Exercises . . . . .	76	8.1.3	Tetramers . . . . .	142
4.9	Solutions . . . . .	79	8.1.4	N-mers . . . . .	143
5.	Lattice Dynamics	85	8.2	Spin waves . . . . .	145
5.1	Cross section for one-phonon scattering . . . . .	85			

8.2.1	Ferromagnets . . . . .	145	12.2	Liquid $^4\text{He}$ . . . . .	216
8.2.2	Antiferromagnets . . . . .	149	12.2.1	Phase diagram . . . . .	216
8.2.3	The random-phase approximation . . . . .	151	12.2.2	Elementary excitations . . . . .	216
8.3	Solitons . . . . .	154	12.2.3	The condensate fraction . . . . .	218
8.4	Further reading . . . . .	156	12.2.4	Static structure factor . . . . .	219
8.5	Exercises . . . . .	157	12.3	Liquid $^3\text{He}$ . . . . .	221
8.6	Solutions . . . . .	160	12.3.1	Phase diagram . . . . .	221
9.	Crystal-Field Transitions . . . . .	163	12.3.2	Elementary excitations . . . . .	222
9.1	Elementary concept of crystal fields . . . . .	163	12.4	Further reading . . . . .	223
9.2	Crystal-field interaction of $f$ -electron systems . . . . .	166	13.	Defects in Solids . . . . .	225
9.3	Neutron cross-section . . . . .	169	13.1	Introduction . . . . .	225
9.4	Interactions of the crystal-field split ions . . . . .	172	13.2	Short-range order of point defects . . . . .	226
9.5	Intermultiplet crystal-field transitions . . . . .	174	13.3	Macro-defects . . . . .	230
9.6	Calculation of thermodynamic magnetic properties . . . . .	174	13.4	The triangulation method . . . . .	232
9.7	Further reading . . . . .	176	13.5	Resonant and local modes . . . . .	233
9.8	Exercises . . . . .	176	13.6	Further reading . . . . .	236
9.9	Solutions . . . . .	177	14.	Surfaces and Interfaces . . . . .	237
10.	Phase Transitions . . . . .	181	14.1	Introduction . . . . .	237
10.1	Introduction . . . . .	181	14.2	Specular reflection . . . . .	240
10.2	Structural phase transitions . . . . .	182	14.3	Off-specular reflection . . . . .	244
10.3	Phase transitions in ice . . . . .	185	14.4	Grazing incidence scattering . . . . .	246
10.4	Magnetic phase transitions . . . . .	191	14.5	Further reading . . . . .	247
10.5	Quantum phase transitions . . . . .	193	15.	Hydrogen Dynamics . . . . .	249
10.6	Further reading . . . . .	197	15.1	Introduction . . . . .	249
11.	Superconductivity . . . . .	199	15.2	Dynamics of the hydrogen bond . . . . .	249
11.1	Introduction . . . . .	199	15.3	Hydrogen tunnelling . . . . .	255
11.2	The flux-line lattice . . . . .	202	15.4	Further reading . . . . .	259
11.3	Phonon density of states . . . . .	204	15.5	Exercises . . . . .	260
11.4	Phonon energies and linewidths . . . . .	206	15.6	Solutions . . . . .	261
11.5	Relaxation effects of crystal-field transitions . . . . .	208	Appendix A	Dirac $\delta$ -function and Lattice Sums . . . . .	263
11.6	Spin fluctuations in high-temperature superconductors . . . . .	210	Appendix B	Neutron Scattering Lengths and Cross Sections . . . . .	265
11.7	Further reading . . . . .	213	Appendix C	Pauli Spin Operators . . . . .	271
12.	Superfluidity . . . . .	215			
12.1	Introduction . . . . .	215			

Appendix D	Cross Section for Magnetic Neutron Scattering	273
Appendix E	Crystal Lattice and Reciprocal Lattice	277
Appendix F	The 3-j and 6-j Symbols	279
Appendix G	Impulse Approximation	281
	<i>List of Symbols</i>	285
	<i>Bibliography</i>	289
	<i>Index</i>	295