

# Contents

<b>1</b>	<b>Introduction</b> .....	1
1.1	Elastic Nuclear Resonant Scattering .....	2
1.2	Inelastic Nuclear Resonant Scattering .....	3
1.3	Outline of this Book .....	4
	References .....	6
<b>2</b>	<b>General Aspects of Nuclear Resonant Scattering</b> .....	7
2.1	Classification of Scattering Processes .....	7
2.1.1	Coherent Elastic Nuclear Resonant Scattering .....	8
2.1.2	Coherent Inelastic Nuclear Resonant Scattering .....	9
2.1.3	Incoherent Elastic Nuclear Resonant Scattering .....	10
2.1.4	Incoherent Inelastic Nuclear Resonant Scattering .....	11
2.2	Features of Elastic Nuclear Resonant Scattering .....	12
2.2.1	X-ray Diffraction in Space and Time .....	13
2.2.2	The Nuclear Exciton .....	14
2.2.3	The Index of Refraction .....	15
2.2.4	Pulse Propagation .....	19
2.2.5	Speedup .....	20
2.2.6	Quantum Beats .....	22
2.2.7	Suitable Isotopes .....	24
2.3	Forward Scattering from a Single Target .....	25
2.3.1	Solution in the Time Domain .....	26
2.3.2	Solution in the Energy Domain .....	28
2.4	Forward Scattering from Separated Samples .....	29
2.5	Nuclear Bragg Scattering .....	30
2.5.1	Pure Nuclear Reflections .....	30
2.5.2	Electronically Allowed Reflections: Ta(110) .....	31
2.5.3	Applications in Materials Science .....	32
	References .....	33
<b>3</b>	<b>Methods and Instrumentation</b> .....	37
3.1	Synchrotron Radiation Sources .....	37
3.1.1	Historical Development .....	37
3.1.2	Properties of Synchrotron Radiation .....	40
3.1.3	Synchrotron Radiation for Mössbauer Experiments ...	45

3.2	Monochromatization .....	46
3.2.1	Heat-Load Monochromators .....	47
3.2.2	High-Resolution Monochromators .....	47
3.2.3	Polarization Filtering .....	52
3.3	Detection Schemes .....	56
3.3.1	Basic Requirements .....	56
3.3.2	Timing Electronics .....	57
3.3.3	Detectors .....	58
3.4	Beamlines .....	61
	References .....	62
<b>4</b>	<b>Coherent Elastic Nuclear Resonant Scattering .....</b>	<b>67</b>
4.1	The Dynamical Theory .....	68
4.1.1	The Scattering Amplitude .....	70
4.1.2	Forward Scattering .....	73
4.1.3	Total Reflection from Boundaries .....	74
4.1.4	Grazing-Incidence Reflection from Stratified Media ...	76
4.1.5	The Radiation Field in Layered Systems .....	81
4.1.6	Coherent Reflection from Ultrathin Layers .....	81
4.1.7	The Influence of Boundary Roughness .....	84
4.1.8	Calculation of Intensities .....	87
4.2	Nuclear Resonant Scattering .....	88
4.2.1	The Nuclear Scattering Amplitude .....	90
4.2.2	Polarization Dependence .....	91
4.2.3	Resonant Reflection from Surfaces .....	96
4.2.4	Resonant Reflection from Ultrathin Films .....	96
4.2.5	Determination of Magnetic Moment Orientations and Spin Structures .....	98
4.2.6	Comparison with Conventional Mössbauer Spectroscopy .....	104
4.3	Special Aspects .....	106
4.3.1	Kinematical vs. Dynamical Theory .....	106
4.3.2	Transverse Coherence: Influence of the Detector Aperture .....	107
4.3.3	Standing Waves in Thin Films .....	110
4.4	Magnetism of Multilayers, Thin Films, and Nanostructures ..	115
4.4.1	Depth Selectivity in Resonant X-Ray Reflection .....	115
4.4.2	Magnetic Superlattices .....	117
4.4.3	The Spin Structure of Exchange-Coupled Films .....	123
4.4.4	Magnetism of Fe Islands on W(110) .....	130
4.4.5	Perpendicular Magnetization in Fe Clusters on W(110)	139
4.4.6	Nuclear Resonant Small-Angle X-ray Scattering .....	144
4.5	Magnetism at High Pressures .....	150
4.6	Study of Dynamical Properties .....	155
4.6.1	Quasielastic Nuclear Resonant Scattering .....	155

4.6.2	Diffusion in Crystalline Systems	156
4.6.3	Slow Dynamics of Glasses	160
4.6.4	Relaxation Phenomena	162
4.7	Data Analysis	166
4.8	Comparison with Other Scattering Methods	167
4.8.1	Resonant Magnetic X-ray Scattering	168
4.8.2	Polarized Neutron Reflectometry	168
	References	171
<b>5</b>	<b>Inelastic Nuclear Resonant Scattering</b>	<b>181</b>
5.1	Inelastic Nuclear Resonant Absorption	182
5.2	Extraction of the Phonon Density of States	186
5.3	Experimental Aspects	189
5.3.1	Lamb-Mössbauer Factor and Multiphonon Excitations	189
5.3.2	Temperature Dependence and Anharmonicity	190
5.3.3	Thermodynamic Quantities	192
5.4	Vibrational Properties of Thin Films and Nanostructures	192
5.4.1	Phonon Damping in Thin Films of Fe	194
5.4.2	Vibrational Modes in Nanoparticles	198
5.4.3	Phonons in Fe Islands on W(110)	201
5.4.4	Vibrational Excitations in Amorphous FeTb Alloys	203
5.4.5	Phonon Softening in Fe-Invar Alloys	207
5.4.6	Local Vibrational Density of States: Interface Phonons and Impurity Modes	210
5.5	Further Applications	214
5.5.1	Lattice Dynamics at High Pressures: Geophysical Aspects	214
5.5.2	Dynamics of Biomolecules	219
5.6	Comparison with Other Scattering Methods	225
	References	226
<b>6</b>	<b>Advanced Scattering Techniques</b>	<b>233</b>
6.1	Resonant Scattering from Moving Matter	233
6.2	The Nuclear Lighthouse Effect	234
6.2.1	Basic Principles	234
6.2.2	Observation of the Nuclear Lighthouse Effect	236
6.2.3	Space-Time Description	238
6.2.4	Imaging the Temporal Evolution of Nuclear Resonant Scattering	240
6.2.5	Observation of the 22.5-keV Resonance of $^{149}\text{Sm}$	243
6.2.6	Practical Considerations	246
6.3	High-Resolution Filtering of Synchrotron Radiation	248
6.3.1	Energetic Bandwidth	249
6.3.2	Spectrometer Types	251
6.3.3	Considerations on Inelastic Spectroscopy	254

XIV Contents

6.4	Heterodyne and Stroboscopic Detection Schemes .....	255
6.5	Time-Domain Interferometry .....	259
6.5.1	General Considerations .....	259
6.5.2	Determination of the Intermediate Scattering Function .....	260
6.5.3	Application: Dynamics at the Glass Transition .....	262
6.6	SRPAC: Perturbed Angular Correlation with Synchrotron Radiation .....	263
	References .....	268
<b>7</b>	<b>Outlook and Perspectives .....</b>	<b>273</b>
7.1	Future Synchrotron Radiation Sources .....	273
7.2	Elastic Nuclear Resonant Scattering .....	278
7.2.1	Lighthouse Filtering .....	278
7.2.2	Picosecond Time-Resolution .....	278
7.2.3	Metrology .....	279
7.3	Inelastic Nuclear Resonant Scattering .....	280
7.3.1	Nuclear Inelastic Pump-Probe Experiments .....	280
	References .....	282
<b>8</b>	<b>Concluding Remarks .....</b>	<b>283</b>
<b>A</b>	<b>Appendix .....</b>	<b>285</b>
A.1	Hyperfine Interactions .....	285
A.2	Structure Function and Propagation Matrix .....	288
A.3	Calculation of the Matrix Exponential $e^{i\mathbf{F}z}$ .....	291
A.4	Transverse Coherence of X-rays .....	293
A.5	Derivation of the Roughness Matrix .....	296
A.6	The Projected and the Total Phonon Density of States .....	297
A.6.1	Single-Crystalline Systems .....	298
A.6.2	Polycrystalline Systems .....	299
A.7	Table of Resonant Isotopes .....	299
	References .....	312
	<b>Index .....</b>	<b>313</b>