Contents

Foreword *xi*
Preface *xv*
Contributor *xvii*
Future Contributions *xix*

1. Introduction to Neutron and X-ray Optics **1**

1. Compound Refractive Lenses for Neutrons and X-rays: Background and Theory 2
2. Experiments with Neutron Compound Refractive Lenses, Magnetic Lenses, and Microscopes 44
3. Experiments with X-ray Compound Refractive Lenses and Microscopes 100
4. Thermal Neutron Radiography, Coded Aperture, and Phase-Contrast Imaging 199
5. Experiments in Fast Neutron Radiography 237
6. A Brief History of Neutron Optics Before Compound Refractive Neutron Lenses 272
7. Brief History and Overview of Diffractive and Reflective X-ray Optics and Microscopy 282

References 312

2. Compound Refractive Lenses and Prisms **335**

1. The Compound Refractive Lens 336
2. Numerical Aperture and Thin Lenses 338
3. Biconcave Parabolic Lens: Path Length, Focal Length, and Absorption Aperture Radius 339
4. Biconcave Spherical Lens: Path Length, Focal Length, and Absorption Aperture Radius 346
5. Parabolic Aperture Radius in Spherical Biconcave CRLs 349
6. Matrix Representation of X-ray and Neutron Optics with Paraxial Approximation 350
7. Thin Lens Matrix and Ray Angle Deviation in a Thin Lens 353
8. Average CRL Transmission for X-rays or Neutrons 358
9. CRL Intensity Gain Including Attenuation 361

10. CRL Transverse and Axial Magnification 368
11. CRL Depth of Field and Depth of Focus 371
12. Modulation Transfer Function for CRL Resolution Determination 373
13. Calculation of CRL Modulation Transfer Function by Line Profile Measurements of Knife-Edge Images 377
14. CRL Field of View 380
15. Thick Lens CRLs 382
16. CRL Surface Roughness and Lens Alignment 390
17. Compound Refractive Prisms: X-ray and Neutron Deflection by a Single Prism 398
18. Deflection of X-rays and Neutrons in a Compound Refractive Prism 402
19. Calculation of X-ray or Neutron Absorption Aperture Depth and Transmission in a Compound Refractive Prism 404
20. Use of a Compound Refractive Prism to Offset Neutron Gravity Droop in Small-Angle Scattering 406
21. Curvature and Radius of Curvature of Lens Surface and Wave Surface 409
22. Measurement of Spherical and Parabolic Lens Curvature 411
23. Wave Vergence and Wave Vergence Change by Lens Surface 413
24. Refractive Index, Snell's Law, Huygens' Principle, and Fermat's Principle of Least Time 414
25. The Paraxial Approximation and the Fundamental Paraxial Equation 417
26. The Gaussian Lens Equation for Thin Lenses 418
27. Thick Lens Power and Focal Length, and Wave Vergence Change in Thick Lenses 420
28. Wave Vergence Change and Power and Focal Length of a Separated Lens Doublet 424
References 426

3. Geometric Neutron and X-ray Optics – Aberrations 429

1. Chromatic Aberration in Spherical and Parabolic Biconcave Lenses 430
2. Spherical Aberration in Spherical Biconcave Lenses and Total Object Resolution 434
3. CRL Image and Object Resolution: Spherical and Chromatic Aberration 438
4. CRL Aberrations: Astigmatism, Curvature of Field, Coma, and Distortion 444
5. Parabolic and Spherical Waves Converge to Different Focal Points by CRL 450
6. Monochromatic and Chromatic Aberrations Occur in Parabolic and Spherical Lenses 453
7. Aberrations from an Imperfect Spherical Lens Surface 456
8. Derivation of the Five Seidel Monochromatic Aberrations of a Spherical Biconcave Lens 461

9. Relation of the Optical Path Length Difference to its Associated Aberration 470
10. Spherical Aberration 473
11. Coma 475
12. Coma: The Abbe Sine Condition and the Coddington Shape Factor 477
13. Curvature of Field and the Petzval Condition 479
14. Astigmatism 481
15. Combined Astigmatism and Curvature of Field 483
16. Astigmatism: Sturm's Interval and Remedy by Upstream Aperture Stop 485
17. Distortion 487
18. Images without and with Distortion 490
19. Prevention of Distortion and the Petzval Condition 492
20. Distortion in Compound Refractive Lens Imaging with Synchrotron X-ray Sources 494
References 495

4. X-ray Optics 497

1. Damped Resonance for Driven Atomic Electron Oscillation and X-ray Emission 498
2. The Complex Atomic Scatter Factor for a Single Element 502
3. The Complex Atomic Scatter Factor for a Mixture or Compound 503
4. Maxwell's Equations Yield the Electromagnetic Vector Wave Equation in Material Media 505
5. The Electromagnetic Vector Wave Equation Contains the Refractive Index 506
6. The Complex Refractive Index and the Complex Atomic Scatter Factor 508
7. The Complex Refractive Index—Decrement, Absorption Index, and Linear Attenuation 510
8. X-ray Complex Index of Refraction—Kramers–Kronig Relation 513
9. X-ray Rayleigh Scatter Total Cross Section and the Complex Atomic Scatter Factor 514
10. Differential Cross Section for the Rayleigh Scatter and Complex Atomic Scatter Factor 517
11. Rayleigh and Thomson X-ray Scatters are Coherent, Elastic Scatter 519
12. Compton Scatter of X-rays is Incoherent and Inelastic 521
13. X-ray Attenuation by Photoelectric Absorption 525
14. X-ray Absorptive Attenuation by Pair Production 527
15. Collision Losses of Charged Particle Passage in Matter 528
16. Bremsstrahlung from Charged Particle Passage in Matter 536
17. Forward-Directed Bremsstrahlung from Relativistic Electrons Undergoing Acceleration 538

18. X-ray Wave Packets—Phase Velocity and Group Velocity, Spatial and Spectral Widths 541
19. X-ray Wave Packets—Dispersion and Group Velocity, and Relation to Real Part of Complex Atomic Scatter Factor 544
20. X-rays in Material Medium—Phase and Group Velocity and Pulse Broadening 548
21. Reflection and Transmission of X-rays at a Planar Interface of Two Media 550
22. Fraction of Transmitted and Reflected Polarized X-rays with an Electric Field Component Parallel to the Planar Surface Interface 554
23. Fraction of Transmitted and Reflected Polarized X-rays with a Magnetic Field Component Parallel to the Planar Surface Interface 556
24. X-ray Brewster Angle Occurs Only for Electric Field Parallel to Plane of Incidence 557
References 559

5. Neutron Optics 561

1. Neutron Phase and Group Velocity 561
2. Derivation of the Schrödinger Wave Equation for Neutron Wave 566
3. Derivation of the Schrödinger Wave Equation by the Electromagnetic Wave Equation Analogy 568
4. Derivation of the Schrödinger Wave Equation by Assumption of the Neutron Plane Wave Solution 572
5. Operator form of the Schrödinger Wave Equation for a Neutron Wave 574
6. Reflection and Transmission of Neutrons at Media Interfaces 576
7. Neutron Reflectometry 582
8. Measurement of the Complex Refractive Index via Refraction 588
9. X-ray and Neutron Interferometry 590
10. Interferometry and the Fizeau Effect 592
11. Pendellösung Oscillations and Anomalous Absorption in Perfect Crystals 596
12. Measurement of Refractive Index via Interferometry 601
13. The Maxwell–Boltzmann Distribution for the Reactor Source of Thermal Neutrons 603
References 606

6. X-ray and Neutron Optics 607

1. Derivation of the Index of Refraction for X-rays and Neutrons 607
2. Types of X-ray and Neutron Lenses and Significance of Delta/Mu Ratio 612
3. Coherent, Incoherent, Elastic, and Inelastic Scatter of X-rays and Neutrons 615
4. X-ray and Neutron Attenuation Comparison 619
5. Useful Formulas for X-rays and Neutrons 622
6. X-ray Multilayer Mirrors 624
7. Neutron Multilayer Mirrors 636

8. Capillary Optics and Kumakhov X-ray and Neutron Lenses 641
9. Bright-field, Dark-field, and Phase-Contrast Microscopy 646
References 653

Contents of Volumes 151–171 **655**

Index **663**