

Contents

Chapter 1. An Overview of Synchrotron Radiation Research

Herman Winick and S. Doniach

1. Introduction	1
2. An Interdisciplinary Tool	3
3. Some Recent History	3
4. Earlier History	4
5. Photon Physics	6
6. The Future	7
References	9

Chapter 2. Properties of Synchrotron Radiation

Herman Winick

1. Introduction	11
2. Radiated Power	12
3. Spectral and Angular Distribution	13
4. Polarization	19
5. Pulsed Time Structure	20
6. Brightness and Emittance	21
Appendix	23
References	24

Chapter 3. Synchrotron Radiation Sources, Research Facilities, and Instrumentation

Herman Winick

1. Introduction	27
2. Sources of Synchrotron Radiation	27
2.1. General	27
2.2. Storage Rings	30
2.3. Synchrotrons	32
3. Synchrotron Radiation Research Facilities	33
3.1. General	33
3.2. Beam Channels	33
3.2.1. Vacuum Considerations	34

3.2.2. Thermal Problems	39
3.2.3. Beryllium Windows	39
3.3. Radiation Shielding and Personnel Protection Interlock Systems	45
3.3.1. General	45
3.3.2. Low-Energy Storage Rings	45
3.3.3. High-Energy Storage Rings	46
3.4. Synchrotron Radiation Beam Position Monitoring and Control	48
3.5. Experimental Support Facilities	49
4. Instrumentation for Synchrotron Radiation Research	51
4.1. General	51
4.2. Mirrors	51
4.3. Monochromators	53
4.4. Detectors	56
References	58

Chapter 4. Inner-Shell Threshold Spectra

Frederick C. Brown

1. Introduction	61
1.1. Kossel-Kronig Structure	61
1.2. Lifetime Effects	61
1.3. Early Work on Excitons	63
1.4. Atomic Effects	64
2. Experimental Techniques	65
2.1. Use of Synchrotron Radiation	65
2.2. Synchrotron Radiation Monochromators	65
2.3. Various Spectroscopic Techniques	66
2.4. Absorption Measurements on Solids and Gases	67
3. Hydrogenlike Photoabsorption Spectra	70
3.1. The Hydrogen Model for X-Ray Absorption; K Edge of Argon	70
3.2. K Edge of Chlorine in Cl ₂ Gas	70
4. Oscillator Strength for Rydberg and Continuum Transitions	71
4.1. Atomic Absorption in the Dipole Approximation	71
4.2. Oscillator Strength and Spectral Density	73
4.3. Comparison of Hydrogen and Lithium Valence Transitions	75
4.4. K Edge of Neon Gas	75
5. Core Excitons in Insulators	76
5.1. Valence Excitons in Solid Neon	76
5.2. L Edge of Solid Argon; Altarelli-Bassani Theory	77
5.3. N _{2, 3} Edge of Rubidium in RbCl; Satoko-Sugano Theory	78
5.4. Deeper Core Structure in RbCl	79
5.5. Recent Reflectivity Data on the Potassium Halides	81
5.6. K Edge of Lithium in the Lithium Halides; Zunger-Freeman Theory	82
6. Threshold Resonances in Solids	83
6.1. White Lines, the K Edge of Germanium, and the L Edge of Tantalum	83
6.2. K Edge of Arsenic; Recent Theory	85
6.3. L Edge of Silicon and the Elliot Exciton	86
6.4. K Edge of Titanium in Some Transition-Metal Compounds, TiSe ₂ and MnO ₂	88
7. Simple Polyatomic Gases	89
7.1. Inner-Outer Well Potential	89
7.2. K Edge of Nitrogen in N ₂ Gas	91
7.3. K Edge of Carbon in Methane and the Fluoromethanes	92
7.4. Second-Row Hydrides and Fluorides; Effect of Condensation on the SiH ₄ and SiF ₄ Spectra	93

7.5. K Edge of Germanium in GeCl_4 , GeBr_4 , and GeH_4	96
7.6. Summary Remarks	97
References	98

Chapter 5. Electron Spectrometry of Atoms and Molecules

Manfred O. Krause

1. Introduction	101
2. The Domain of Synchrotron Radiation	102
3. Basic Relations and Background	105
3.1. Energies	106
3.2. Photoionization Cross Sections	107
3.3. Angular Distribution of Photoelectrons	108
3.4. Two-Electron Processes	111
3.5. Level Widths	113
4. Experimental Apparatus and Procedures	113
4.1. The Monochromator	115
4.2. The Electron Spectrometer	116
4.2.1. Energy Calibration	117
4.2.2. Spectrometer Function	119
4.2.3. Transmission Function and Intensity Measurements	119
4.3. Source for Circularly Polarized Light	124
4.4. Comparison with Discrete Sources	124
5. Restricted Photoelectron Spectrometry—Energies	125
6. Level Widths and Line Widths	127
7. Partial Photoionization Cross Sections	128
7.1. Atoms	129
7.1.1. Spin–Orbit Photoelectron Intensity Ratios	134
7.1.2. Two-Electron Transitions	135
7.2. Threshold Laws	135
7.3. Quasi-Atomic Systems	136
7.4. Molecules	136
8. Angular Distributions of Photoelectrons	139
8.1. Closed-Shell Atoms	139
8.2. Open-Shell Atoms	141
8.3. Molecules	142
9. Resonances and Autoionization	142
9.1. Atoms	143
9.2. Molecules	144
10. Post-Collision Interactions	145
11. Photoexcited Auger Spectra	147
12. Coincidence Experiments	148
13. Outlook	149
References	151

Chapter 6. Photoemission as a Tool to Study Solids and Surfaces

I. Lindau and W. E. Spicer

1. General Considerations	159
1.1. The Physics of the Photoemission Process	159
1.2. The Characteristics of Synchrotron Radiation Important for Photoemission Studies	161
1.3. The Probing Depth in Photoemission	162
1.4. The Energy Dependence of Partial Photoionization Cross Sections	164
1.5. Different Photoemission Techniques	167

2.	Experimental Details	168
2.1.	Synchrotron Radiation Beam Lines	169
2.2.	Monochromators	170
2.3.	Sample Chambers, Energy Analyzers, and Detector Systems	171
2.4.	Concluding Remarks	174
3.	Research Applications	174
3.1.	Introduction	174
3.2.	Bulk Electronic Structure	174
3.2.1.	The Bulk Electronic Structure of the Ge Valence Band	175
3.2.2.	The Density of States of Some IV, III-V, II-VI, and I-VII Compounds: A Comparison between Theory and Experiment	176
3.2.3.	The Electronic Structure of the Gold Valence Band	178
3.3.	Surface Electronic Structure	183
3.3.1.	Surface States and Resonances on Single Crystals of Metals	183
3.3.2.	The Surface Electron Structure of GaAs (110)	185
3.4.	Chemisorption and Oxidation Studies	188
3.4.1.	Oxygen Chemisorption and the Initial Oxidation Stages on the GaAs (110) Surface	189
3.4.2.	Chemisorption of CO on Transition Metal Surfaces—Molecular Levels	192
3.4.3.	The Effect of Chemisorption on the Substrate Core Levels	196
3.4.4.	The Chemisorption and Oxidation Properties of Al Surfaces	197
3.5.	The Electronic Structure of Interfaces	199
3.5.1.	Oxygen Chemisorption onto Si (111) and the Si-SiO ₂ Interface	199
3.5.2.	Metal Overlays on III-V Semiconductor Surfaces	202
3.5.3.	Cesium–Oxygen Overlays on GaAs (110)	205
3.6.	The Electronic Structure of Cu–Ni Alloy Surfaces	207
3.7.	Concluding Remarks	210
4.	Future Prospects and Developments	211
	References	212

Chapter 7. Microlithography with Soft X Rays

Andrew R. Neureuther

1.	Introduction	223
2.	X-Ray Replication and Results	225
3.	Fundamentals	240
3.1.	X-Ray Sources	240
3.1.1.	Synchrotron Radiation	240
3.1.2.	Electron Bombardment X-Ray Sources	241
3.2.	Optics	243
3.3.	Absorption	245
3.4.	Photoelectrons	245
3.5.	Energy Deposition	247
3.6.	Energy Deposition Effects	248
4.	X-Ray Lithography Technology	252
4.1.	X-Ray Sources	252
4.1.1.	Novel X-Ray Sources	252
4.1.2.	Electron Bombardment Sources	253
4.1.3.	Synchrotron Radiation Sources	254
4.2.	Windows and Masks	257
4.3.	Resists	260
4.4.	Alignment and Distortion	263
4.5.	Radiation Damage to Devices	265
5.	System Approaches	265
	References	271

Chapter 8. Soft X-Ray Microscopy of Biological Specimens

J. Kirz and D. Sayre

1. Introduction	277
2. Contrast Mechanisms	278
2.1. Removal of Photons; Transmission X-Ray Microscopy	280
2.2. Reaction Products; Fluorescence X-Ray Microscopy and Electron-Emission X-Ray Microscopy	282
2.3. Damage to the Absorbing Material	283
2.4. Quantitative Relationships	285
2.5. Summary	287
3. Image Formation	288
3.1. Magnification by Electron Optics	288
3.1.1. Contact Microradiography: General	288
3.1.2. Contact Microradiography: Resolution and Sensitivity of Resists	291
3.1.3. Contact Microradiography: Resolution of the Technique	293
3.1.4. Contact Microradiography: Details of the Technique	294
3.1.5. Contact Microradiography with Direct Photon-Electron Conversion	294
3.1.6. Image Formation Using Electrons Emitted from the Specimen	295
3.2. Magnification by X-Ray Optics	295
3.2.1. Grazing-Incidence Mirrors	295
3.2.2. Point Projection Microscopy	296
3.2.3. Microscopy with Zone Plate Objectives	296
3.2.4. Holographic Microscopy	299
3.3. Scanning Microscopy	300
3.3.1. The Microscope of Horowitz and Howell	300
3.3.2. Future Prospects for Scanning Microscopy	302
3.4. Summary	303
4. Sources of Soft X Rays for Microscopy	304
4.1. Requirements	304
4.2. Soft X-Ray Sources	305
4.2.1. Synchrotron Radiation	305
4.2.2. Conventional X-Ray Generators	306
4.2.3. Plasma Sources	306
5. Mapping the Concentration of a Particular Atomic Species	308
5.1. Absorption Microanalysis	309
5.2. Fluorescence Microanalysis	312
5.3. Summary	313
6. Additional Technical Aspects	314
6.1. Wet Specimens	314
6.2. Readout of Resist Images by Transmission Electron Microscopy	315
6.3. 3-D Imaging	315
7. Summary and Conclusions	318
References	318

Chapter 9. Synchrotron Radiation as a Modulated Source for Fluorescence Lifetime Measurements and for Time-Resolved Spectroscopy

Ian H. Munro and Andrew P. Sabersky

1. Introduction: Source Properties	323
2. Time Modulation of Synchrotron Radiation Sources	324
2.1. Storage Rings	324
2.2. Synchrotrons	325

2.3. Electron Bunches and Their Behavior in a Storage Ring	326
2.4. Optical Properties of the Pulsed Source	328
2.5. Source Parameters	329
2.6. Comparison with Other Sources	330
3. Experimental Techniques for Time-Resolved Measurements	332
3.1. Direct Time Measurements	332
3.2. Single-Photon Counting Method	333
3.3. Phase-Shift Measurements	336
3.4. Time-Resolved Spectroscopy	339
4. Research Applications	342
4.1. Fluorescence Lifetime Measurements of Organic Molecules	342
4.2. Time-Resolved Spectroscopy of Rare Gases	344
4.2.1. Pure Rare-Gas Solids	344
4.2.2. Solid Rare-Gas Mixtures	344
4.2.3. Rare-Gas Measurements	345
4.3. Time-Resolved Fluorescence Spectroscopy of Large Molecules	346
References	350

Chapter 10. The Principles of X-Ray Absorption Spectroscopy

George S. Brown and S. Doniach

1. Introduction—Overview of X-Ray Absorption Spectroscopy and EXAFS Applications	353
2. Physics of Photoabsorption in Atoms	356
2.1. Fully Relaxed Transitions	356
2.2. Shake Up and Shake Off	357
2.3. Form of the One-Electron Cross Section	357
2.4. Effect of Core-Hole Lifetime	358
3. Photoabsorption in Molecular and Condensed Systems	358
3.1. General Features of the Spectrum	358
3.2. Photoabsorption in the EXAFS Region	359
3.3. The Thermal Average of the EXAFS Cross Section	361
3.4. Determination of Electron-Atom Scattering Phase Shifts and Amplitudes in the EXAFS Region	362
3.5. Many-Electron Effects in the EXAFS Spectrum	364
3.5.1. Inelastic Events	365
3.5.2. Effect of Screening in Metals	366
3.5.3. Exchange and Correlation Effects on the One-Electron Potential	367
3.6. The Near-Edge Region of the X-Ray Absorption Spectrum—Multiple Scattering Effects	367
4. Instrumentation for X-Ray Absorption Spectroscopy	369
4.1. Introduction	369
4.2. X-Ray Monochromators	372
4.3. X-Ray Detectors	373
4.3.1. Ionization Chambers	374
4.3.2. Proportional Counters	375
4.3.3. Scintillation Counters	375
4.3.4. Semiconductor Devices	376
4.3.5. Analyzing Detectors	378
5. Numerical Analysis of X-Ray Absorption Data—Extraction of Physical Parameters	378
5.1. General Considerations in the Analysis of EXAFS Data	379
5.2. Subtracting the Background—Setting the k Scale	380
5.3. Fourier Filtering	381
5.4. Nonlinear Curve Fitting of EXAFS Data—Application to Model Compounds and Multishell Parameter Determination	382
5.5. Numerical Analysis of X-Ray Absorption Edge Data	383
References	383

Chapter 11. Extended X-Ray Absorption Fine Structure in Condensed Materials

George S. Brown

1. Introduction	387
2. Periodic and Quasi-Periodic Solids	389
3. Surface EXAFS	390
4. Disordered Solids	391
5. Liquids	397
6. X-Ray Sources	398
7. Future Directions	398
References	399

Chapter 12. X-Ray Absorption Spectroscopy: Catalyst Applications

F. W. Lytle, G. H. Via, and J. H. Sinfelt

1. Introduction	401
2. Nature of Catalysts	402
3. Analysis of EXAFS Data	403
4. Experimental Procedures	409
5. Structure of Catalysts	412
5.1. Dispersed Metal Catalysts	412
5.2. Metal Oxide Catalysts	417
5.3. Homogeneous Catalysts	418
6. Near-Edge Structure	418
7. Status and Outlook	422
References	423

Chapter 13. X-Ray Absorption Spectroscopy of Biological Molecules

S. Doniach, P. Eisenberger, and Keith O. Hodgson

1. Introduction	425
2. Discussion of Experimental Techniques Appropriate to Biological Molecules	427
2.1. Transmission versus Fluorescence	427
2.2. Fluorescence Detectors with Energy Discrimination	430
3. EXAFS Data Analysis for Biological Molecules	432
3.1. Scatterer Identification	433
3.2. Amplitudes and Numbers of Scatterers	434
3.3. An Example of Structure Determination	436
4. Selected EXAFS Applications to Problems of Biological Significance	437
4.1. Rubredoxin	439
4.2. Hemoglobin	440
4.3. Nitrogenase	442
4.4. Cytochrome P-450 and Chloroperoxidase	445
4.5. The "Blue" Copper Proteins	445
4.6. Xanthine Oxidase and Sulfite Oxidase	446
4.7. Hemocyanin	449
4.8. Ferritin	450
4.9. Cytochrome Oxidase	450
4.10. Calcium Binding Proteins	451

5. X-Ray Absorption Edge Structure for Biological Molecules	452
5.1. The Effect of Oxidation State on Edge Position	454
5.2. Continuum Spectral Features	454
5.3. Applications to Specific Biological Molecules	455
6. Prospects	456
References	457

Chapter 14. X-Ray Fluorescence Microprobe for Chemical Analysis

C. J. Sparks, Jr.

1. Introduction	459
2. Quantitative Analysis and Fluorescence Cross Sections	460
2.1. Equations for Quantitative X-Ray Fluorescence Analysis	461
2.2. Minimum Detectable Limit	464
2.3. Comparison of X-Ray and Charged-Particle Fluorescence Cross Sections	466
2.4. Backgrounds Beneath the Fluorescence Signals	468
2.5. Energy Deposited Versus Fluorescence Production	471
2.6. Summary of the Properties of X Rays and Charged Particles for Fluorescence Excitation ..	473
2.7. Microprobe Spatial Resolutions; Charged-Particle Intensities	474
3. Results of X-Ray Fluorescence Measurements with Synchrotron Radiation	475
3.1. Fluorescence Excitation with the Continuum Radiation	476
3.2. Fluorescence Excitation with Monochromatic Radiation	485
3.2.1. Experimental Arrangement	486
3.2.2. Fluorescence Spectra and Detectable Limits	488
3.2.3. Minimum Detection Limits for 37-keV Radiation	495
3.2.4. Intrinsic Background for X-Ray-Excited Fluorescence: Summary of Signal-to-Background Ratios	495
4. Optics for an X-Ray Microprobe	497
4.1. Mirrors for Focusing the Continuum Spectrum	498
4.2. Mirrors and Crystals for Focusing Monoenergetic X Rays	501
5. Final Comparative Analysis and Conclusions	506
References	509

Chapter 15. Small-Angle X-Ray Scattering of Macromolecules in Solution

H. B. Stuhrmann

1. Introduction	513
2. The Small-Angle Scattering Intensity	514
2.1. The Probability of Small-Angle Scattering from a Dilute Solution	515
2.2. The Energy Spectrum of the Source	518
2.3. The Efficiency of Gas-Filled Chambers	520
3. Small Angle Scattering Instruments	521
3.1. Instruments with One Monochromator Crystal	522
3.2. The Mirror-Monochromator System	523
3.3. The Double-Monochromator System	524
3.4. The Energy Dispersive Method	526
4. Experimental Results	527
5. Conclusions	529
References	531

Chapter 16. Small-Angle Diffraction of X Rays and the Study of Biological Structures

G. Rosenbaum and K. C. Holmes

1. Design Criteria for Small-Angle Diffraction	533
1.1. Conditions Imposed by the Specimen and Experiment	533
1.1.1. Specimens	533
1.1.2. Experimental Requirements	534
1.2. X-Ray Optics and Optimization	535
1.2.1. Definitions	535
1.2.2. Optical Principles of Curved Mirrors and Curved Crystal Monochromators	535
1.2.3. Optical Phase Space	539
1.2.4. The Optimum Condition	541
1.2.5. Choice of Wavelength	545
1.3. Small-Angle Diffraction Cameras for Synchrotron Radiation	546
1.3.1. Remote Control	546
1.3.2. Vacuum Window	546
1.3.3. Curved Mirrors	546
1.3.4. Curved Crystal Monochromators	547
1.3.5. Mirror-Monochromator Camera at DESY	549
1.3.6. Mirror-Monochromator Camera at NINA	551
1.3.7. Mirror-Monochromator Camera at SPEAR	551
1.3.8. Monochromator-Mirror Camera at VEPP-3	551
1.3.9. Mirror-Monochromator Cameras at DORIS	552
1.3.10. The Separated Function Focusing Monochromator at SPEAR	553
1.4. Conditions Imposed by Detector Technology	554
1.5. A Comparison of the Theoretical and Actual Performance of Mirror-Monochromator Systems	555
2. Applications	556
2.1. Muscle Fibers; Real Time Experiments on Muscle	556
2.1.1. Frog Muscle	556
2.1.2. Insect Flight Muscle	557
2.2. Collagen	559
2.3. DNA Fibers	559
3. Extensions of the Methodology	561
3.1. Wide-Band Monochromators—A Technological Challenge	561
3.2. Towards an Optimum Design	562
References	562

Chapter 17. Single-Crystal X-Ray Diffraction and Anomalous Scattering Using Synchrotron Radiation

James C. Phillips and Keith O. Hodgson

1. Introduction	565
1.1. Uses of Synchrotron Radiation in Macromolecular Crystallography	565
1.1.1. High Intensity	566
1.1.2. The Phase Problem	566
1.1.3. Large Unit Cells	567
1.2. Early Protein Crystallography Results at SPEAR	567
1.3. Crystallography at Other Synchrotron Radiation Laboratories	568
1.4. Scope of the Remainder of the Chapter	568
2. A Four-Circle Diffractometer Used with Synchrotron Radiation	569
2.1. Introduction	569

2.2. Description of the System	569
2.2.1. Focusing Mirror-Monochromator System	569
2.2.2. Diffractometer Modifications	570
2.2.3. Alignment Carriage	570
2.2.4. Transportable Radiation Hutch	572
2.2.5. Computer Control and Software	572
2.3. Performance of the System	574
2.3.1. Diffractometer Positioning Accuracy	574
2.3.2. Alignment	574
2.3.3. Parameters of the Focused, Monochromatized Beam	575
2.3.4. Accuracy of Measurement of Diffracted Intensities	577
2.3.5. Tests Using a Graphite Monochromator	577
2.4. Discussion of System Tests and Possible Improvements	578
2.5. Possible Uses of the Systems	579
2.5.1. Macromolecular Crystallography	579
2.5.2. Other Types of Experiments	581
3. Measurement of the Anomalous Scattering Terms for Cesium and Cobalt at Noncharacteristic Wavelengths	582
3.1. The Phenomenon of Anomalous Scattering	582
3.2. Previous Determinations of f' and f''	583
3.3. Principles of the Present Method of Determining the Anomalous Scattering Factors	584
3.4. Experimental Details	584
3.5. Discussion and Correlation of Results with Absorption Spectra	585
4. Use of Anomalous Scattering Effects to Phase Diffraction Patterns from Macromolecules	589
4.1. Previous Work on Phasing Macromolecular Structures	590
4.2. A Quantitative Assessment of Anomalous Scattering Phasing	591
4.2.1. The Effect of Anomalous Scattering on the Diffraction Pattern	591
4.2.2. Criteria Governing the Choice of Wavelengths	592
4.2.3. How Many Measurements Should be Made?	595
4.2.4. A Method for Assessing Various Data Collection Strategies	595
4.2.5. An Example of the Use of the Multiple-Wavelength Phasing Method	596
4.3. Other Data Reduction Considerations	598
4.4. Conclusions	598
5. Progress on the Structure Determination of Gramicidin A: A Case Study of the Use of Synchrotron Radiation in X-Ray Diffraction	598
5.1. The Crystallographic Problem and the Possibility of Its Solution Using Synchrotron Radiation	599
5.2. Preliminary Results of Structural Studies to 3.8 Å Resolution Using Synchrotron Radiation	599
5.2.1. The Experiment	599
5.2.2. Data Analysis	600
6. Summary and Discussion	603
References	604

Chapter 18. Application of Synchrotron Radiation to X-Ray Topography

M. Sauvage and J. F. Petroff

1. Introduction	607
1.1. Features of X-Ray Topography	608
1.2. Relevant Characteristics of Synchrotron Radiation Sources for X-Ray Topography	609
1.2.1. Wavelength Spread	609
1.2.2. Angular Spread	610
1.2.3. Lateral Extension	611
1.2.4. Intensity and Polarization Properties	611

1.3. Available and Future Facilities	612
2. Description of Experimental Techniques	612
2.1. White Beam Topography	612
2.2. Monochromatic Topography and Specialized Monochromators	616
2.2.1. Two-Axis Spectrometers	616
2.2.2. Specialized Monochromators	616
2.2.3. Monochromatic Topography	620
2.3. Interferometry	623
2.4. New Developments in Direct Viewing Detectors	623
3. Selected Examples of Applications of Synchrotron Radiation Topography	624
3.1. Recrystallization Experiments	625
3.2. Domain Wall Motion in Magnetic Materials	626
3.2.1. Antiferromagnetic Perovskites KNiF ₃ and KCoF ₃	627
3.2.2. Ferromagnetic Alloy Fe-3%Si	628
3.3. Plastic Deformation	629
3.4. Tunable Wavelength Topography in Absorbing Materials	632
3.5. Miscellaneous Applications	635
4. Future Developments	635
References	636

Chapter 19. Inelastic Scattering*P. Eisenberger*

1. Introduction	639
2. Theory	640
3. Experimental Techniques	641
4. Previous Experiments	644
5. Future Prospects	645
References	646

Chapter 20. Nuclear Resonance Experiments Using Synchrotron Radiation Sources*R. L. Cohen*

1. Introduction	647
2. Single Nucleus Excitations	649
2.1. Mössbauer Effect	649
2.2. Nuclear Excitation without the Mössbauer Effect	653
2.3. Experimental Results	654
3. Nuclear Bragg Scattering	656
3.1. Proposed Experiments	656
3.2. Experimental Problems	660
4. Conclusions	661
References	662

Chapter 21. Wiggler Systems as Sources of Electromagnetic Radiation*James E. Spencer and Herman Winick*

1. Introduction	663
2. General Characteristics of Wiggler Radiation	669
2.1. Directionality	670

2.2. Time and Frequency Structure	672
2.3. Monochromaticity	672
2.4. Tunability and Energy Range	674
2.5. Polarization	674
3. Theoretical Considerations	675
3.1. Macroscopic Approach—Classical Field Equations	675
3.2. Microscopic Approach—Quantization of the Field	677
4. Fundamentals of Operation	679
4.1. The Infinite Transverse Wiggler	679
4.1.1. The Flat or Planar Wiggler	680
4.1.2. The Helical or Axial Wiggler	681
4.1.3. The Rotatable Planar Wiggler	682
4.1.4. The Free-Electron Laser (FEL)	682
4.2. Wiggler Optics and Influence on Stored Beams	682
4.2.1. Optics	683
4.2.2. Effects on Stored Beams	684
4.3. Practical Design Considerations	688
5. Applications with Examples	692
5.1. The SPEAR Wiggler—A Detailed Example	694
5.1.1. Description of the SPEAR Lattice	695
5.1.2. Description of the Wiggler and Its Operation	696
5.1.3. Description of the Wiggler Transport Line	700
5.1.4. Effects of Wiggler on SPEAR Operation	700
5.2. Characteristics of Other Planned Wiggler Installations	705
5.2.1. Photon Factory at KEK, Japan	705
5.2.2. NSLS at Brookhaven, USA	707
5.2.3. PULS-Adone at Frascati, Italy	707
5.2.4. Pakhra at Moscow, USSR	707
5.2.5. LURE-ACO at Orsay, France	708
5.2.6. SSRL-SPEAR Undulator	708
5.2.7. Sirius at Tomsk, USSR	709
6. Future Directions, Possibilities, and Conclusions	712
References	713

Chapter 22. The Free-Electron Laser and Its Possible Developments

C. Pellegrini

1. Introduction	717
2. Spontaneous Radiation of Relativistic Electrons in Wiggler Magnets	718
3. Elementary Theory of the Free-Electron Laser	721
3.1. Stimulated Radiation by Relativistic Electrons	721
3.2. Classical Theory of Stimulated Radiation in Wiggler Magnets	723
3.3. Principles of Operation of a Free-Electron Laser	728
4. Free-Electron Laser Experiments	730
5. The Free-Electron Laser Operation in an Electron Storage Ring	732
5.1. Principal Characteristics of an Electron Storage Ring	732
5.2. Electron Beam-Free-Electron Laser Interaction	733
5.3. The Free-Electron Laser Operation in a Storage Ring	735
6. Conclusions	738
References	740