

J. Stöhr  
H. C. Siegmann

# Magnetism

From Fundamentals  
to Nanoscale  
Dynamics

磁性

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From Fundamentals  
to Nanoscale Dynamics

With 325 Figures and 39 Tables

 Springer

图书在版编目 (CIP) 数据

磁性 = Magnetism: 英文/ (美) 司徒著. —影印本.  
—北京: 世界图书出版公司北京公司, 2010. 7  
ISBN 978 - 7 - 5100 - 2403 - 0

I. ①磁… II. ①司… III. ①磁性—教材—英文  
IV. ①O441. 2

中国版本图书馆 CIP 数据核字 (2010) 第 135232 号

---

书 名: Magnetism: From Fundamentals to Nanoscale Dynamics

作 者: J. Stöhr, H. C. Siegmann

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中 译 名: 磁性

责任编辑: 高蓉 刘慧

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出 版 者: 世界图书出版公司北京公司

印 刷 者: 三河国英印务有限公司

发 行 者: 世界图书出版公司北京公司 (北京朝内大街 137 号 100010)

联系电话: 010 - 64021602, 010 - 64015659

电子信箱: kjb@wpcbj.com.cn

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开 本: 24 开

印 张: 35

版 次: 2010 年 08 月

版权登记: 图字: 01 - 2009 - 5392

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书 号: 978 - 7 - 5100 - 2403 - 0/O · 816

定 价: 99.00 元

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To my three favorite women,  
my mother Marga, my wife Linda and my daughter Megan,  
who have taught me much more than science  
and given me the most important gift of all, love.

*J. Stöhr*

To my collaborators and students  
who, through their inspiration and company,  
have made my life as a physicist a joyful adventure.

*H.C. Siegmann*

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## Preface

This book emerged from a close collaboration of the authors which started in the fall of 2000. Early that year one of us (J.S.) had joined the Stanford faculty after spending nearly 15 years at the IBM Almaden Research Center and the other (H.C.S.) had just retired from a chair at the ETH Zürich and come to Stanford as a visiting professor. Together we organized magnetism meetings of a small group of scientists which oscillated weekly between the Stanford Synchrotron Radiation Laboratory (SSRL) and the Advanced Light Source (ALS) in nearby Berkeley. We also organized annual winter workshops at Lake Tahoe where all participants reported on their research – of course we snuck in a few ski runs, as well. These meetings were great fun and some seemed to go on forever because there was so much interest and enthusiasm and so much to discuss. . . The participants varied over the years and consisted of students, postdocs, Stanford and Berkeley scientists, visiting scientists and participants from industry. In alphabetical order, some of the people involved were Yves Acremann, Scott Andrews, Andreas Bauer, Mark Burkhardt, Venkatesh Chembrolu, Kang Chen, Sug-Bong Choe, Bruce Clemens, Alexander Dobin, Thomas Eimüller, Stefan Eisebitt, Sara Gamble, Alexander Kashuba, Marcus Lörger, Jan Lüning, Gereon Meyer, Hendrik Ohldag, Howard Padmore, Ramon Rick, Andreas Scherz, Bill Schlotter, Andreas Scholl, Christian Stamm, John Paul Strachan, Jan Thiele, Ioan Tudosa, Ashwin Tulapurkar, Shan Wang and Xiaowei Yu. All this would have been impossible without support from the Office of Basic Energy Sciences of the US Department of Energy (DOE), and we gratefully acknowledge DOE's support of our research program.

We have also greatly benefitted from discussions with colleagues and from material they have provided, and we would especially like to thank Elke Arenholz, Sam Bader, Carl Bennemann, Matthias Bode, Patrick Bruno, John Clendenin, Markus Donath, Olle Eriksson, Jürgen Kirschner, Peter Oppeneer, Jürg Osterwalder, Stuart Parkin, Danilo Pescia, Dan Pierce, Theo Rasing, Andrei Rogalev, Kai Starke, Dieter Weller and Ruqian Wu.

With the present book we intend to give an account of the historical development, the physical foundations and the continuing research underlying

the field of magnetism, one of the oldest and still vital field of physics. Our book is written as a text book for students on the late undergraduate and the graduate levels. It should also be of interest to scientists in academia and research laboratories.

Throughout history, magnetism has played an important role in the development of civilization, starting with the loadstone compass. Our modern society would be unthinkable without the generation and utilization of electricity, wireless communication at the speed of light and the modern high-tech magnetic devices used in information technology. Despite the existence of many books on the topic, we felt the need for a text book that reviews the fundamental physical concepts and uses them in a coherent fashion to explain some of the forefront problems and applications today. Besides covering the classical concepts of magnetism we give a thorough review of the quantum aspects of magnetism, starting with the discovery of the spin in the 1920s. We discuss the exciting developments in magnetism research and technology spawned by the computer revolution in the late 1950s and the more recent paradigm shift starting around 1990 associated with spin-based electronics or “spintronics”. The field of spintronics was largely triggered by the discovery of the giant magnetoresistance or GMR effect around 1988. It utilizes the electron spin to sense, carry or manipulate information and has thus moved the quantum mechanical concept of the electron spin from its discovery in the 1920s to a cornerstone of modern technology.

These historical and modern developments in magnetism are discussed against the background of the development and utilization of spin-polarized electron techniques and polarized photon techniques, the specialties of the authors. It is believed that the technological application of magnetism will continue with a growth rate close to Moore’s law for years to come. Interestingly, the magnetic technology goals of “smaller and faster” are matched by “brighter and faster” X-ray sources, which are increasingly used in contemporary magnetism research. Novel ultra-bright X-ray sources with femtosecond pulse lengths will provide us with snapshots of the invisible ultrafast magnetic nanoworld. These exciting developments are another reason for the present book.

Last not least, this book is born out of our passion for the subjects discussed in it. In the process we had to get to the bottom of many things and understand them better or for the first time. This process took a deep commitment and much time, with “the book” often preoccupying our minds. The process was greatly aided by discussions with our colleagues and students and we would like to thank them at this place. In particular, we need to thank Ioan Tudosa for his critical comments and for helping us with numerous illustrations. In this book we give an account of the field of magnetism that is colored by personal taste and our way of looking at things. We hope that you will enjoy the result.

Stanford, CA  
January 2006

*Joachim Stöhr*  
*Hans Christoph Siegmann*

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# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Magnetism: Magical yet Practical	1
1.2	History of Magnetism	3
1.3	Magnetism, Neutrons, Polarized Electrons, and X-rays	12
1.3.1	Spin Polarized Electrons and Magnetism	15
1.3.2	Polarized X-rays and Magnetism	22
1.4	Developments in the Second Half of the 20th Century	25
1.5	Some Thoughts about the Future	30
1.6	About the Present Book	32

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## Part I Fields and Moments

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<b>2</b>	<b>Electric Fields, Currents, and Magnetic Fields</b>	<b>39</b>
2.1	Signs and Units in Magnetism	39
2.2	The Electric Field	39
2.3	The Electric Current and its Magnetic Field	40
2.4	High Current Densities	45
2.5	Magnetic and Electric Fields inside Materials	47
2.6	The Relation of the Three Magnetic Vectors in Magnetic Materials	49
2.6.1	Stray and Demagnetizing Fields of Thin Films	52
2.6.2	Applications of Stray and Demagnetizing Fields	54
2.7	Symmetry Properties of Electric and Magnetic Fields	57
2.7.1	Parity	57
2.7.2	Time Reversal	59
<b>3</b>	<b>Magnetic Moments and their Interactions with Magnetic Fields</b>	<b>61</b>
3.1	The Classical Definition of the Magnetic Moment	61
3.2	From Classical to Quantum Mechanical Magnetic Moments	64

3.2.1	The Bohr Magneton .....	65
3.2.2	Spin and Orbital Magnetic Moments .....	66
3.3	Magnetic Dipole Moments in an External Magnetic Field ....	68
3.4	The Energy of a Magnetic Dipole in a Magnetic Field .....	69
3.5	The Force on a Magnetic Dipole in an Inhomogeneous Field ..	72
3.5.1	The Stern–Gerlach Experiment .....	74
3.5.2	The Mott Detector .....	79
3.5.3	Magnetic Force Microscopy .....	83
3.6	The Torque on a Magnetic Moment in a Magnetic Field .....	84
3.6.1	Precession of Moments .....	85
3.6.2	Damping of the Precession .....	87
3.6.3	Magnetic Resonance .....	91
3.7	Time–Energy Correlation .....	97
3.7.1	The Heisenberg Uncertainty Principle .....	97
3.7.2	Classical Spin Precession .....	98
3.7.3	Quantum Mechanical Spin Precession .....	99
<b>4</b>	<b>Time Dependent Fields .....</b>	<b>105</b>
4.1	Overview .....	105
4.2	Basic Concepts of Relativistic Motion .....	106
4.2.1	Length and Time Transformations Between Inertial Systems .....	106
4.2.2	Electric and Magnetic Field Transformations between Inertial Systems .....	107
4.3	Fields of a Charge in Uniform Motion: Velocity Fields .....	109
4.3.1	Characteristics of Velocity Fields .....	109
4.3.2	Creation of Large Currents and Magnetic Fields .....	112
4.3.3	Creation of Ultrashort Electron Pulses and Fields ....	115
4.3.4	The Temporal Nature of Velocity Fields .....	118
4.4	Acceleration Fields: Creation of EM Radiation .....	121
4.4.1	Polarized X-rays: Synchrotron Radiation .....	125
4.4.2	Brighter and Shorter X-ray Pulses: From Undulators to Free Electron Lasers .....	133
<b>5</b>	<b>Polarized Electromagnetic Waves .....</b>	<b>141</b>
5.1	Maxwell's Equations and their Symmetries .....	142
5.2	The Electromagnetic Wave Equation .....	143
5.3	Intensity, Flux, Energy, and Momentum of EM Waves .....	145
5.4	The Basis States of Polarized EM Waves .....	147
5.4.1	Photon Angular Momentum .....	147
5.4.2	Linearly Polarized Basis States .....	148
5.4.3	Circularly Polarized Basis States .....	149
5.4.4	Chirality and Angular Momentum of Circular EM Waves .....	153



5.4.5	Summary of Unit Polarization Vectors .....	154
5.5	Natural and Elliptical Polarization .....	155
5.5.1	Natural Polarization .....	155
5.5.2	Elliptical Polarization .....	156
5.5.3	The Degree of Photon Polarization .....	157
5.6	Transmission of EM Waves through Chiral and Magnetic Media .....	159

---

## Part II History and Concepts of Magnetic Interactions

---

6	Exchange, Spin-Orbit, and Zeeman Interactions .....	167
6.1	Overview .....	167
6.2	The Spin Dependent Atomic Hamiltonian or Pauli Equation ..	169
6.2.1	Independent Electrons in a Central Field .....	170
6.2.2	Interactions between two Particles – Symmetrization Postulate and Exclusion Principle .....	172
6.3	The Exchange Interaction .....	175
6.3.1	Electron Exchange in Atoms .....	175
6.3.2	Electron Exchange in Molecules .....	180
6.3.3	Magnetism and the Chemical Bond .....	186
6.3.4	From Molecules to Solids .....	188
6.3.5	The Heisenberg Hamiltonian .....	190
6.3.6	The Hubbard Hamiltonian .....	193
6.3.7	Heisenberg and Hubbard Models for H <sub>2</sub> .....	195
6.3.8	Summary and Some General Rules for Electron Exchange .....	202
6.4	The Spin-Orbit Interaction .....	203
6.4.1	Fine Structure in Atomic Spectra .....	203
6.4.2	Semiclassical Model for the Spin-Orbit Interaction ..	204
6.4.3	The Spin-Orbit Hamiltonian .....	206
6.4.4	Importance of the Spin-Orbit Interaction .....	209
6.5	Hund's Rules .....	209
6.6	The Zeeman Interaction .....	212
6.6.1	History and Theory of the Zeeman Effect .....	212
6.6.2	Zeeman Versus Exchange Splitting of Electronic States ..	218
6.6.3	Importance of the Zeeman Interaction .....	220
7	Electronic and Magnetic Interactions in Solids .....	221
7.1	Chapter Overview .....	221
7.2	Localized versus Itinerant Magnetism: The Role of the Centrifugal Potential .....	223
7.3	The Relative Size of Interactions in Solids .....	230
7.4	The Band Model of Ferromagnetism .....	234
7.4.1	The Puzzle of the Broken Bohr Magneton Numbers ..	234

7.4.2	The Stoner Model .....	235
7.4.3	Origin of Band Structure .....	240
7.4.4	Density Functional Theory .....	243
7.5	Ligand Field Theory .....	245
7.5.1	Independent-Electron Ligand Field Theory .....	247
7.5.2	Multiplet Ligand Field Theory .....	256
7.6	The Importance of Electron Correlation and Excited States ..	261
7.6.1	Why are Oxides often Insulators? .....	262
7.6.2	Correlation Effects in Rare Earths and Transition Metal Oxides .....	264
7.6.3	From Delocalized to Localized Behavior: Hubbard and LDA+U Models .....	271
7.7	Magnetism in Transition Metal Oxides .....	274
7.7.1	Superexchange .....	274
7.7.2	Double Exchange .....	279
7.7.3	Colossal Magnetoresistance .....	282
7.7.4	Magnetism of Magnetite .....	283
7.8	RKKY Exchange .....	290
7.8.1	Point-like Spins in a Conduction Electron Sea .....	291
7.8.2	Metallic Multilayers .....	292
7.9	Spin-Orbit Interaction: Origin of the Magnetocrystalline Anisotropy .....	294
7.9.1	The Bruno Model .....	295
7.9.2	Description of Anisotropic Bonding .....	297
7.9.3	Bonding, Orbital Moment, and Magnetocrystalline Anisotropy .....	299

---

## Part III Polarized Electron and X-Ray Techniques

---

8	Polarized Electrons and Magnetism .....	313
8.1	Introduction .....	313
8.2	Generation of Spin-Polarized Electron Beams .....	314
8.2.1	Separation of the Two Spin States .....	314
8.2.2	The GaAs Spin-Polarized Electron Source .....	315
8.3	Spin-Polarized Electrons and Magnetic Materials: Overview of Experiments .....	318
8.4	Formal Description of Spin-Polarized Electrons .....	319
8.4.1	Quantum Behavior of the Spin .....	319
8.4.2	Single Electron Polarization in the Pauli Spinor Formalism .....	320
8.4.3	Description of a Spin-Polarized Electron Beam .....	324
8.5	Description of Spin Analyzers and Filters .....	327
8.5.1	Incident Beam Polarization: Spin Analyzer .....	327
8.5.2	Transmitted Beam Polarization: Spin Filter .....	328

8.5.3	Determination of Analyzer Parameters .....	329
8.6	Interactions of Polarized Electrons with Materials .....	329
8.6.1	Beam Transmission through a Spin Filter .....	329
8.6.2	The Fundamental Interactions of a Spin-Polarized Beam with Matter .....	331
8.6.3	Interaction of Polarized Electrons with Magnetic Materials: Poincaré's Sphere .....	337
8.7	Link Between Electron Polarization and Photon Polarization ..	342
8.7.1	Photon Polarization in the Vector Field Representation ..	343
8.7.2	Photon Polarization in the Spinor Representation ....	344
8.7.3	Transmission of Polarized Photons through Magnetic Materials: Poincaré Formalism .....	345
8.7.4	X-ray Faraday Effect and Poincaré Formalism .....	348
8.7.5	Poincaré and Stokes Formalism .....	350
9	Interactions of Polarized Photons with Matter .....	351
9.1	Overview .....	351
9.2	Terminology of Polarization Dependent Effects .....	352
9.3	SemiClassical Treatment of X-ray Scattering by Charges and Spins .....	355
9.3.1	Scattering by a Single Electron .....	355
9.3.2	Scattering by an Atom .....	360
9.4	SemiClassical Treatment of Resonant Interactions .....	361
9.4.1	X-ray Absorption .....	361
9.4.2	Resonant Scattering .....	364
9.4.3	Correspondence between Resonant Scattering and Absorption .....	368
9.4.4	The Kramers-Kronig Relations .....	368
9.5	Quantum-Theoretical Concepts .....	370
9.5.1	One-Electron and Configuration Pictures of X-ray Absorption .....	370
9.5.2	Fermi's Golden Rule and Kramers-Heisenberg Relation ..	372
9.5.3	Resonant Processes in the Electric Dipole Approximation .....	374
9.5.4	The Polarization Dependent Dipole Operator .....	376
9.5.5	The Atomic Transition Matrix Element .....	378
9.5.6	Transition Matrix Element for Atoms in Solids .....	381
9.6	The Orientation-Averaged Intensity: Charge and Magnetic Moment Sum Rules .....	385
9.6.1	The Orientation-Averaged Resonance Intensity .....	385
9.6.2	Derivation of the Intensity Sum Rule for the Charge ..	386
9.6.3	Origin of the XMCD Effect .....	389
9.6.4	Two-Step Model for the XMCD Intensity .....	393
9.6.5	The Orientation Averaged Sum Rules .....	397

9.7	The Orientation-Dependent Intensity: Charge and Magnetic Moment Anisotropies .....	401
9.7.1	Concepts of Linear Dichroism .....	401
9.7.2	X-ray Natural Linear Dichroism .....	401
9.7.3	Theory of X-ray Natural Linear Dichroism .....	403
9.7.4	XNLD and Quadrupole Moment of the Charge .....	406
9.7.5	X-ray Magnetic Linear Dichroism .....	407
9.7.6	Simple Theory of X-ray Magnetic Linear Dichroism ...	408
9.7.7	XMLD of the First and Second Kind .....	411
9.7.8	Enhanced XMLD through Multiplet Effects .....	415
9.7.9	The Orientation-Dependent Sum Rules .....	421
9.8	Magnetic Dichroism in X-ray Absorption and Scattering ....	424
9.8.1	The Resonant Magnetic Scattering Intensity .....	425
9.8.2	Link of Magnetic Resonant Scattering and Absorption	427
10	<b>X-rays and Magnetism: Spectroscopy and Microscopy</b> ....	431
10.1	Introduction .....	431
10.2	Overview of Different Types of X-ray Dichroism .....	432
10.3	Experimental Concepts of X-ray Absorption Spectroscopy ....	437
10.3.1	General Concepts .....	437
10.3.2	Experimental Arrangements .....	441
10.3.3	Quantitative Analysis of Experimental Absorption Spectra .....	445
10.3.4	Some Important Experimental Absorption Spectra ....	449
10.3.5	XMCD Spectra of Magnetic Atoms: From Thin Films to Isolated Atoms .....	451
10.3.6	Sum Rule Analysis of XMCD Spectra: Enhanced Orbital Moments in Small Clusters .....	454
10.3.7	Measurement of Small Spin and Orbital Moments: Pauli Paramagnetism .....	457
10.4	Magnetic Imaging with X-rays .....	458
10.4.1	X-ray Microscopy Methods .....	459
10.4.2	Lensless Imaging by Coherent Scattering .....	463
10.4.3	Overview of Magnetic Imaging Results .....	468

---

## Part IV Properties of and Phenomena in the Ferromagnetic Metals

---

11	<b>The Spontaneous Magnetization, Anisotropy, Domains</b> ....	479
11.1	The Spontaneous Magnetization .....	480
11.1.1	Temperature Dependence of the Magnetization in the Molecular Field Approximation .....	481
11.1.2	Curie Temperature in the Weiss-Heisenberg Model ...	484
11.1.3	Curie Temperature in the Stoner Model .....	488

11.1.4	The Meaning of "Exchange" in the Weiss-Heisenberg and Stoner Models .....	491
11.1.5	Thermal Excitations: Spin Waves .....	494
11.1.6	Critical Fluctuations .....	499
11.2	The Magnetic Anisotropy .....	504
11.2.1	The Shape Anisotropy .....	507
11.2.2	The Magneto-Crystalline Anisotropy .....	508
11.2.3	The Discovery of the Surface Induced Magnetic Anisotropy .....	510
11.3	The Magnetic Microstructure: Magnetic Domains and Domain Walls .....	511
11.3.1	Ferromagnetic Domains .....	511
11.3.2	Antiferromagnetic Domains .....	515
11.4	Magnetization Curves and Hysteresis Loops .....	515
11.5	Magnetism in Small Particles .....	517
11.5.1	Néel and Stoner-Wohlfarth Models .....	517
11.5.2	Thermal Stability .....	520
<b>12</b>	<b>Magnetism of Metals .....</b>	<b>521</b>
12.1	Overview .....	521
12.2	Band Theoretical Results for the Transition Metals .....	523
12.2.1	Basic Results for the Density of States .....	523
12.2.2	Prediction of Magnetic Properties .....	525
12.3	The Rare Earth Metals: Band Theory versus Atomic Behavior .....	530
12.4	Spectroscopic Tests of the Band Model of Ferromagnetism ...	534
12.4.1	Spin Resolved Inverse Photoemission .....	535
12.4.2	Spin Resolved Photoemission .....	539
12.5	Resistivity of Transition Metals .....	548
12.5.1	Conduction in Nonmagnetic Metals .....	548
12.5.2	The Two Current Model .....	553
12.5.3	Anisotropic Magnetoresistance of Metals .....	556
12.6	Spin Conserving Electron Transitions in Metals .....	558
12.6.1	Spin Conserving Transitions and the Photoemission Mean Free Path .....	558
12.6.2	Determination of the Spin-Dependent Mean Free Path using the Magnetic Tunnel Transistor .....	562
12.6.3	Probability of Spin-Conserving relative to Spin-Non-Conserving Transitions .....	565
12.6.4	The Complete Spin-Polarized Transmission Experiment .....	569
12.7	Transitions Between Opposite Spin States in Metals .....	573
12.7.1	Classification of Transitions Between Opposite Spin States .....	573
12.7.2	The Detection of Transitions between Opposite Spin States .....	575
12.8	Remaining Challenges .....	582

---

**Part V Topics in Contemporary Magnetism**


---

<b>13 Surfaces and Interfaces of Ferromagnetic Metals</b>	587
13.1 Overview	587
13.2 Spin-Polarized Electron Emission from Ferromagnetic Metals	588
13.2.1 Electron Emission into Vacuum	588
13.2.2 Spin-Polarized Electron Tunneling between Solids	593
13.2.3 Spin-Polarized Electron Tunneling Microscopy	598
13.3 Reflection of Electrons from a Ferromagnetic Surface	601
13.3.1 Simple Reflection Experiments	603
13.3.2 The Complete Reflection Experiment	608
13.4 Static Magnetic Coupling at Interfaces	613
13.4.1 Magnetostatic Coupling	614
13.4.2 Direct Coupling between Magnetic Layers	615
13.4.3 Exchange Bias	617
13.4.4 Induced Magnetism in Paramagnets and Diamagnets	629
13.4.5 Coupling of Two Ferromagnets across a Nonmagnetic Spacer Layer	632
<b>14 Electron and Spin Transport</b>	637
14.1 Currents Across Interfaces Between a Ferromagnet and a Nonmagnet	637
14.1.1 The Spin Accumulation Voltage in a Transparent Metallic Contact	638
14.1.2 The Diffusion Equation for the Spins	642
14.1.3 Spin Equilibration Processes, Distances and Times	644
14.1.4 Giant Magneto-Resistance (GMR)	647
14.1.5 Measurement of Spin Diffusion Lengths in Nonmagnets	651
14.1.6 Typical Values for the Spin Accumulation Voltage, Boundary Resistance and GMR Effect	654
14.1.7 The Important Role of Interfaces in GMR	655
14.2 Spin-Injection into a Ferromagnet	656
14.2.1 Origin and Properties of Spin Injection Torques	657
14.2.2 Switching of the Magnetization with Spin Currents: Concepts	665
14.2.3 Excitation and Switching of the Magnetization with Spin Currents: Experiments	667
14.3 Spin Currents in Metals and Semiconductors	672
14.4 Spin-Based Transistors and Amplifiers	675
<b>15 Ultrafast Magnetization Dynamics</b>	679
15.1 Introduction	679
15.2 Energy and Angular Momentum Exchange between Physical Reservoirs	682

15.2.1	Thermodynamic Considerations .....	682
15.2.2	Quantum Mechanical Considerations: The Importance of Orbital Angular Momentum .....	684
15.3	Spin Relaxation and the Pauli Susceptibility .....	687
15.4	Probing the Magnetization after Laser Excitation .....	690
15.4.1	Probing with Spin-Polarized Photoelectron Yield .....	691
15.4.2	Probing with Energy Resolved Photoelectrons With or Without Spin Analysis .....	696
15.4.3	Probing with the Magneto-Optic Kerr Effect .....	702
15.5	Dynamics Following Excitation with Magnetic Field Pulses ..	705
15.5.1	Excitation with Weak Magnetic Field Pulses .....	712
15.5.2	Excitation of a Magnetic Vortex .....	715
15.6	Switching of the Magnetization .....	723
15.6.1	Precessional Switching of the In-Plane Magnetization ..	725
15.6.2	Precessional Switching of the Magnetization for Perpendicular Recording Media .....	733
15.6.3	Switching by Spin Injection and its Dynamics .....	744
15.6.4	On the Possibility of All-Optical Switching .....	751
15.6.5	The Hübner Model of All-Optical Switching .....	753
15.6.6	All-Optical Manipulation of the Magnetization .....	757
15.7	Dynamics of Antiferromagnetic Spins .....	759

---

## Part VI Appendices

---

Appendices .....	763
A.1 The International System of Units (SI) .....	763
A.2 The Cross Product .....	765
A.3 s, p, and d Orbitals .....	766
A.4 Spherical Tensors .....	767
A.5 Sum Rules for Spherical Tensor Matrix Elements .....	768
A.6 Polarization Dependent Dipole Operators .....	769
A.7 Spin-Orbit Basis Functions for <i>p</i> and <i>d</i> Orbitals .....	770
A.8 Quadrupole Moment and the X-ray Absorption Intensity .....	771
A.9 Lorentzian Line Shape and Integral .....	774
A.10 Gaussian Line Shape and Its Fourier Transform .....	774
A.11 Gaussian Pulses, Half-Cycle Pulses and Transforms .....	775
References .....	777
Index .....	805

## Introduction

*Magnetes Geheimnis, erklär mir das!  
Kein größer Geheimnis als Lieb' und Hass.  
The magnet's mystery, explain that to me!  
No greater mystery but love and hate.<sup>1</sup>*

Johann Wolfgang von Goethe (1749–1832)

### 1.1 Magnetism: Magical yet Practical

What is magnetism? This question has fascinated people ever since Thales of Miletus (about 634–546 BC) first described the phenomenon as the attraction of iron by “lodestone”, the naturally occurring mineral magnetite,  $\text{Fe}_3\text{O}_4$ . Over the last 2,500 years we have not only extensively used the phenomenon for navigation, power production, and “high tech” applications but we have also come a long way in exploring its origin. Yet, even today, it is extremely difficult to answer the simple question why magnets attract. In fact, the term “magnetic” has acquired such a fundamental and familiar meaning that, following Thales of Miletus, “magnetic” and “attractive” (or repulsive) are used synonymously, and this association still serves to “explain” the phenomenon. Any deeper scientific explanation sooner or later runs into “mysteries”. An example is the very concept of spin which magically emerged from Dirac’s relativistic treatment of an electron in an external electromagnetic field. Today we simply accept this concept and base our understanding of magnetism on the elementary concepts of spin, giving rise to the spin magnetic moment, and the motion of electronic charges and the associated orbital magnetic moment.

Of the four forces of nature that form the pillars of contemporary physics, the electromagnetic force is arguably of greatest importance in our everyday lives because we can easily manipulate it and hence utilize it for our needs. We truly live in an electromagnetic world and electromagnetic phenomena form the basis of the modern industrialized society. This fact alone gives the old topic of magnetism a modern day vitality. The importance of magnetism

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<sup>1</sup>For Goethe the magnet constitutes a fundamental phenomenon (Urphänomen) that cannot be further explained. It incorporates the polarity (like love and hate) which became the essence of Goethe’s “Weltanschauung”. In this “natural philosophy” only pairwise opposites (e.g., love–hate, north–south) constitute a “whole”. It is interesting that this philosophy agrees with our modern knowledge of magnetism, i.e., that no magnetic monopoles have been found.



is enhanced by the fact that the field still undergoes dynamic developments. Ever new magnetic phenomena continue to be discovered in conjunction with our ability to atomically engineer new materials.

As throughout history, today's magnetism research remains closely tied to applications. It is therefore no surprise that some of the forefront research areas in magnetism today are driven by the "smaller and faster" mantra of advanced technology. The goal to develop, understand, and control the ultrafast magnetic nanoworld is furthermore accompanied by the development of new experimental techniques, that offer capabilities not afforded by conventional techniques. We shall see below that polarized electrons and X-rays provide us with unprecedented opportunities to get to the bottom of long standing and novel problems. At the brink of the 21st century we find ourselves in a situation where the old field of magnetism is full of vitality, life, and excitement and this fact constitutes the basis for our book.

Because magnetism is one of the oldest scientific topics there is of course (too) much to write about. It is therefore not easy to find the right emphasis on the many concepts, definitions, laws and the experimental and theoretical developments of this old and broad field. Our book aims at discussing fundamental concepts and modern applications of magnetism and we have selected topics based on three main principles. First, they were chosen to be the fundamental pillars of magnetism. Second, we emphasized those fundamentals with applications in modern magnetism research and technology. Third, we emphasized topics where new experimental approaches such as polarized electron beam and X-ray experiments, the specialties of the authors, have led to new insights and promise further breakthroughs in the future. In many cases we have chosen modern applications to illustrate the basic laws.

Rather than covering all aspects of magnetism, our book concentrates on magnetic phenomena that are the subject of modern conferences on magnetism and magnetic materials. Today's magnetism community is interested in the scientific understanding of magnetic phenomena and magnetic materials and, following the historical trend, is clearly motivated and influenced by the goal to utilize the acquired knowledge for technological advancement. Our treatment therefore does not cover other electron correlation phenomena which give rise to interesting charge and spin ordering effects, and may play an important role in high temperature superconductivity, for example. These phenomena deserve an extensive separate treatment since they are causing a paradigm shift in condensed matter physics.

It is only fitting that we start this book by taking a look at the historical development of the field. Some of the magnetism terminology used in this introduction is not explicitly defined but we shall come back to the important aspects later in this book. The following historical review is based on information from many sources. We found the books by Segrè [1,2], Verschuur [3] and Livingston [4] very valuable. In the age of the internet, much information was gathered and checked for consistency by means of searches and comparisons of sources on the world wide web.