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Magnetism

From Fundamentals to Nanoscale Dynamics

磁性

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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

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 Lörgen, 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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Part V Topics in Contemporary Magnetism

1

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.[1]

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, Fe_3O_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

[1] 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.