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J. Stöhr   H.C. Siegmann

Magnetism

From Fundamentals to Nanoscale Dynamics

With 325 Figures and 39 Tables

Springer

Professor Dr. Joachim Stöhr
Professor Dr. Hans Christoph Siegmann
Stanford Synchrotron Radiation Laboratory
P.O. Box 20450, Mail Stop 69, Stanford, CA 94309, USA
E-mail: Stohr@slac.stanford.edu, Siegmann@slac.stanford.edu

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Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany
* Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Strasse 38
01187 Dresden, Germany

Professor Dr. Roberto Merlin
Department of Physics, 5000 East University, University of Michigan
Ann Arbor, MI 48109-1120, USA

Professor Dr. Horst Störmer
Dept. Phys. and Dept. Appl. Physics, Columbia University, New York, NY 10027 and
Bell Labs., Lucent Technologies, Murray Hill, NJ 07974, USA

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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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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

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[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.

1.2 History of Magnetism

The most primitive electrical and magnetic phenomena were no doubt observed before recorded history began, and they are perhaps the oldest topics in physics. According to Pliny the Elder's (23–79 AD) *Historia Naturalis* the name "magnet" came from a shepherd called Magnes, who found his iron-nailed shoes or iron-tipped cane stuck to the ground.[2] It seems more likely that the name originates from Magnetes, the inhabitants of a town called Magnesia, located in Asia Minor (part of the Greek Empire), who knew about ore in the area nearby that was naturally magnetic. Since around 1500 AD, the name *lodestone* ("lode" being old English for "lead") has been used to describe such magnetic ore because of its use in navigation. Today we more specifically associate lodestone with the spinel magnetite, Fe_3O_4, which is magnetically aligned in nature, most likely by the earth's magnetic field during the cooling process of hot lava.

Local alignment may also occur by the strong magnetic field of a lightning bolt that leaves a characteristic circular pattern around the point of impact as shown in Fig. 1.1 [5–8]. A lightning bolt contains a current of the order of 100

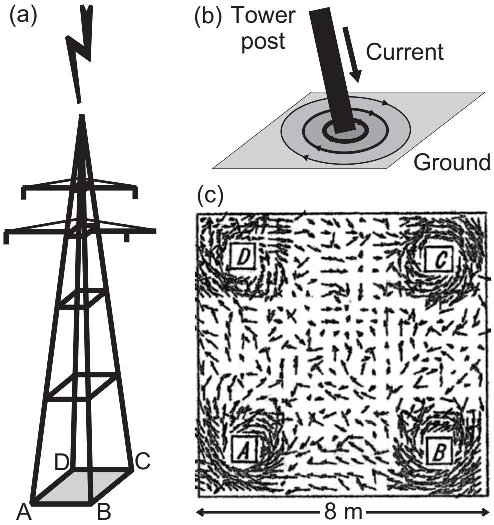

Fig. 1.1. Imprint of the magnetic field caused by a lightning current in the iron-oxide containing ground at the foot of a transmission-line tower. (**a**) shows the geometry of the transmission-line tower, (**b**) the direction of current (positive charge) flow and the associated magnetic field lines, and (**c**) the measured magnetization around the four feet of the transmission-line tower labelled A, B, C, and D [5]. The magnetization (arrows) in the iron-oxide rock is seen to follow the circular magnetic field around the four points

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[2] The smelting of iron was developed already around 1200 BC.

Fig. 1.2. Working model of the first instrument known to be a compass, called Si Nan (the south governor) by the Chinese. The spoon is of magnetic lodestone, and the plate is of bronze [10]

kA with a typical current density of 10^5 A/m^2 in a flash of a few microseconds duration. The current direction (flow of positive charge) is typically from the ground to the clouds, i.e., is in the opposite direction as that observed in the case shown in Fig. 1.1.

The first definite statement on magnetism is attributed to Thales of Miletus (about 634–546 BC) who said that lodestone attracts iron. Starting with the Chinese writer Guanzhong (died 645 BC) the Chinese literature in later centuries is also full of references to lodestone, called *ci shi*, the "loving stone" because of its ability to attract iron [9]. It is believed that the first direction pointers were made during the Qin dynasty (221–206 BC) by balancing a piece of lodestone. The lodestone was ground into the shape of a serving spoon that was placed on a bronze plate as shown in Fig. 1.2. Its handle miraculously pointed to the south.

Rather than navigation, these simple direction pointers were likely used for *feng shui* [3] or geomancy, the technique of achieving harmony with the forces of nature by properly aligning buildings and placing of objects. In particular, feng shui seeks to optimize the attractive and repulsive forces of magnetic fields that according to ancient Chinese philosophy surrounds all objects. In the context of magnetic energy it is interesting that much later, around 1780, Franz Anton Mesmer formulated a healing method on the belief that living bodies could be magnetized and healed – "mesmerized" – by magnetic fields [4]. His influence

---

[3] Feng shui (also fung shui), which translates literally as "wind water", is an ancient Chinese philosophy and practice based on the principle that all living things in the universe are subject to the control of the environment. It is still widely practiced today and tries to achieve harmony with the eight elements of nature – heaven, earth, hills, wind, fire, thunder, rain, and ocean. Also important are energies such as the air or "chi" and the magnetic energy, as are the spirits of yin (female-passive) and yang (male-active).

was so strong that his name has passed into the English language, an honor accorded to few.[4]

The development of civilization has been defined by mastering the production and use of materials. To our knowledge, magnetic direction pointers or compasses were first used for navigation in China in the late 11th or early 12th century and the compass became known in Europe sometime later in the 12th century. Without magnetic materials in the form of a compass, the great voyages of discovery may not have taken place and the history of the world might have evolved differently!

The first scholarly treatment of magnetism is attributed to the French crusader and scholar Peter Peregrinus (Pierre Pèlerin de Maricourt) who in 1269 wrote an extended letter, an *epistola*, that described facts known about loadstones and discussed how to make instruments with them [3]. Three centuries later William Gilbert (1540–1603), a medical doctor and gentleman scientist, built on this work and conducted a truly systematic study of magnetism, summarized in his famous treatise *De Magnete*, published in 1600. He proposed that the earth itself is a giant magnet, with a field similar to that of a bar magnet. He also suggested that the magnetic poles do not coincide with the geographic ones defined by the earth's axis of rotation. This explained earlier observations of navigators like Columbus, who noted discrepancies between the direction of a compass needle and directions indicated by the stars. The earth's field was modeled in detail later around 1835 by Carl Friedrich Gauss (1777–1855).[5]

Until 1819 only one kind of magnetism was known, the one produced by lodestones or by iron compasses that had been magnetized by lodestones.[6] Over the following years the world of magnetism was revolutionized by the work of four people.

In 1819 Hans Christian Ørsted (often spelled Oersted) (1777–1851) observed the magnetic force exerted on a magnetic needle by the electric current in a nearby wire. A year later the French scientists Jean-Baptiste Biot (1774–1862) and Felix Savart (1791–1841) derived the magnetic field around a current carrying wire and during 1820–1825 André Marie Ampère (1775–1836) considered the forces between current carrying wires. This led to the famous laws named after the discoverers.

---

[4] Mesmer's teachings were based on earlier claims by Paracelsus (1493–1541) that magnets could be used for healing. In addition, Mesmer claimed that *animal magnetism* was residing in humans, and that healing could proceed by exchange of a "universal fluid" between him and his patients, without the explicit use of magnets.

[5] The origin of the earth's magnetic field is not well understood but is attributed to turbulent motions within electrically conductive liquid Fe in the earth's core (see Fig. 3.2).

[6] It is interesting to note that compass needles were typically made of iron which has a larger saturation magnetization than lodestone. However, because Fe has a much smaller coercivity than lodestone the needle often had to be remagnetized by a lodestone that was carried on board of ships [4].

Classical electromagnetism peaked with the work of two of the greatest physicists of the 19th century, the experimentalist Michael Faraday (1791–1867) and the theorist James Clerk Maxwell (1831–1879) [1]. In 1831 Faraday discovered electromagnetic induction, and in 1845 he discovered a direct connection between magnetism and light: the magneto-optical or Faraday effect [11]. The magneto-optical Faraday effect is the change of light polarization in *transmission* through a magnetized material. The same effect in *reflection* was discovered in 1876 by the Scottish physicist John Kerr (1824–1907), and is called the magneto-optical Kerr effect in his honor. Faraday's ideas developed in his book *Experimental Researches in Electricity*, and in particular, his discoveries of electric motors, generators, and transformers, have become the foundation of the industrialized society. We shall come back to this point at the end of this section, in conjunction with the importance of strong permanent magnets.

Maxwell placed Faraday's notion of a connection between electricity and magnetism on a firm mathematical footing, developed in his book *Treatise on Electricity and Magnetism.* This constituted the birth of electromagnetism and the electromagnetic field. Today the concept of a "field" is a cornerstone of physics. In 1855 Wilhelm Eduard Weber (1804–1891) had derived a value $1/\sqrt{\mu_0\epsilon_0} = 3.1074 \times 10^8$ m/s in laboratory based experiments but could not understand why this was close to the speed of light. This connection was made by Maxwell who through studies of the equations describing electric and magnetic fields was led to the value $c = 1/\sqrt{\epsilon_0\mu_0}$. Maxwell concluded that light is a form of electromagnetic wave. The connection between magnetism and light had been established. Even today we still marvel at the power of Maxwell's equations and our continued struggle to comprehend their full content makes it even more remarkable that they were derived as early as 1864 – they are one of the truly great achievements in physics![7]

Maxwell's theories and their experimental verification by Heinrich Hertz (1857–1894) in Germany, who discovered radio waves in 1888, today are the basis for global communications at the speed of light. It is fair to say that Maxwell's theory became accessible mostly through Hertz and the theoretical teachings of Henri Poincaré (1854–1912) in France. The 19th century development of magnetism concluded with Pieter Zeeman's (1865–1943) discovery in 1896 of the effect named after him. The century was crowned by the discovery of the electron by Joseph John Thomson (1856–1940) in 1897, and independently around the same time by Emil Wiechert (1861–1928) [13].

The understanding of magnetic phenomena in the 20th century largely concentrated on the development of an atom-based picture [2]. While correspondence between Augustin Jean Fresnel (1788–1827) and Ampère already mentioned the idea of microscopic currents as the origin of magnetism, a for-

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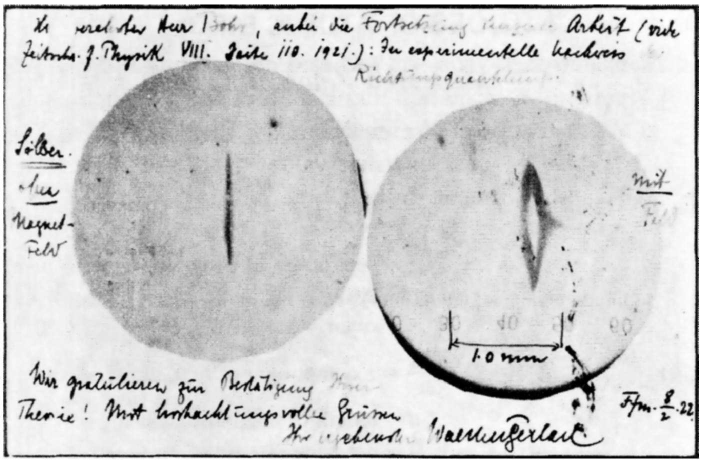
[7] Maxwell's work was already deeply appreciated during his lifetime. For example, Ludwig Boltzmann wrote full of admiration "Was it a God who wrote these symbols …?" [12]



Hochverehrter Herr Bohr, anbei die Fortsetzung unserer Arbeit (vide Zeitschr. f. Physik VIII. Seite 110. 1921.): Der experimentelle Nachweis der Richtungsquantelung.

Wir gratulieren zur Bestätigung Ihrer Theorie! Mit hochachtungsvollen Grüssen Ihr ergebenster Walther Gerlach

Ffm. $\frac{8}{2}$.22

Fig. 1.3. Postcard sent by Walther Gerlach to Niels Bohr on February 8, 1922. In translation it says "Honorable Mr. Bohr, here [is] the continuation of longer work (see Z. Phys. **8**, 110 (1921)). The experimental proof of directional quantization. We congratulate [you] on the confirmation of your theory! With respectful greetings, yours truly, Walther Gerlach." From [15]

mal treatment was not developed until 1907 when Pierre Weiss (1865–1940) introduced a theory of ferromagnetism based on a molecular field concept [14]. His theory, combined with that of Paul Langevin (1872–1946), explained the ferromagnetic–paramagnetic transition observed by Pierre Curie (1859–1906) at the so-called Curie temperature.

In 1913 Niels Bohr (1885–1962) first postulated that the angular momentum of electrons is quantized and that orbital magnetic moments are associated with orbiting electron currents. An elegant experiment by Otto Stern (1888–1969) and Walther Gerlach (1889–1979) in 1921 showed the splitting of a beam of Ag atoms upon traversing a nonuniform magnetic field due to quantized spin orientation. The important experiment is discussed in detail in Sect. 3.5.1. A postcard sent by Walther Gerlach to Niels Bohr on February 8, 1922, showing the refined results of the original experiment is shown in Fig. 1.3. The postcard shows photographs of the recorded pattern of Ag atoms without (left) and in the presence of (right) a magnetic field. It is interesting that the observed splitting into a doublet was incorrectly interpreted as arising from an orbital magnetic moment with $l = 1$ and $m = \pm 1$, as evident from Gerlach's note on the postcard in Fig. 1.3. He believed his experiment to confirm Bohr's theory of orbital angular momentum. At the time, the concept of spin was still unknown. The proper explanation of the splitting is due to the fact that Ag atoms have a single electron in their outer shell with $s = 1/2$, and so the splitting is actually due to the states $m_s = \pm 1/2$.

In order to account for the observed splitting of the emission lines of alkali atoms in magnetic fields, called the "anomalous Zeeman effect" (see

Sect. 6.6.1), Wolfgang Pauli (1900–1958) asserted in January 1925 that no two electrons may occupy the same states and cannot be described by the same set of quantum numbers, the famous principle later named by Dirac the *Pauli exclusion principle.* It is remarkable that at the time of Pauli's paper [16] the electron spin had not yet been discovered. Instead of today's quantum numbers n, l, m_l, m_s, Pauli's paper used a different, not easy to understand, set of quantum numbers. He realized that a satisfactory explanation of the anomalous Zeeman effect required more than the three quantum numbers n, l, m_l and called this a "Zweideutigkeit" (two-valuedness) of the quantum properties of the electron without specifying its origin [17]. The important step of identifying the "Zweideutigkeit" with the electron spin was taken by Uhlenbeck and Goudsmit later that year, in October 1925 [18–20] (see later).

The three year period 1925–1928 constituted a quantum jump in physics. It saw the development of quantum mechanics by Werner Heisenberg (1901–1976) and Erwin Schrödinger (1887–1961) and the introduction of the electron spin. The idea of a "spinning electron" was mentioned for the first time by Arthur Holly Compton (1892–1962) in 1921 for reasons that were wrong and unconvincing [20]. Unaware of Compton's suggestion, George E. Uhlenbeck (1900–1988) and Sam A. Goudsmit (1902–1978) in 1925 used the fine structure (spin–orbit splitting) in atomic spectra to hypothesize the existence of the electron spin [18–20]. The revolutionary idea was the fact that the electronic spin had only half, $\hbar/2$, of the natural integer unit of angular momentum. The spin had independently been proposed in early 1925 by Ralph de Laer Kronig (1904–1995) [2] who told Pauli about it. Pauli objected to Kronig's suggestion of a half integer spin because it led to a discrepancy of a factor of 2 in the calculation of the fine structure splitting. Kronig did not publish his idea owing to Pauli's objection, as evidenced by the letter in Fig. 1.4.

In contrast, when Uhlenbeck and Goudsmit showed their idea to their mentor Paul Ehrenfest (1880–1933), he encouraged them to proceed with publication. For Uhlenbeck and Goudsmit, ignorance was bliss since they were unaware of the factor-of-2 problem. They worried more about the fact that it did not make sense to associate the spin with a classically rotating charged electron. The factor of 2 pointed out by Pauli was explained by a celebrated calculation of Llewellyn Hilleth Thomas (1903–1992) [20, 21] who in 1926 showed it to be due to a reference frame effect. Uhlenbeck and Goudsmit had been right after all![8]

The concept of the spin with half-integer angular momentum is indeed quite amazing and even today its origin is not easily understandable. It naturally fell out of the celebrated relativistic theory of Paul Dirac (1902–1984), who in 1928 treated an electron in an external electromagnetic field, with-

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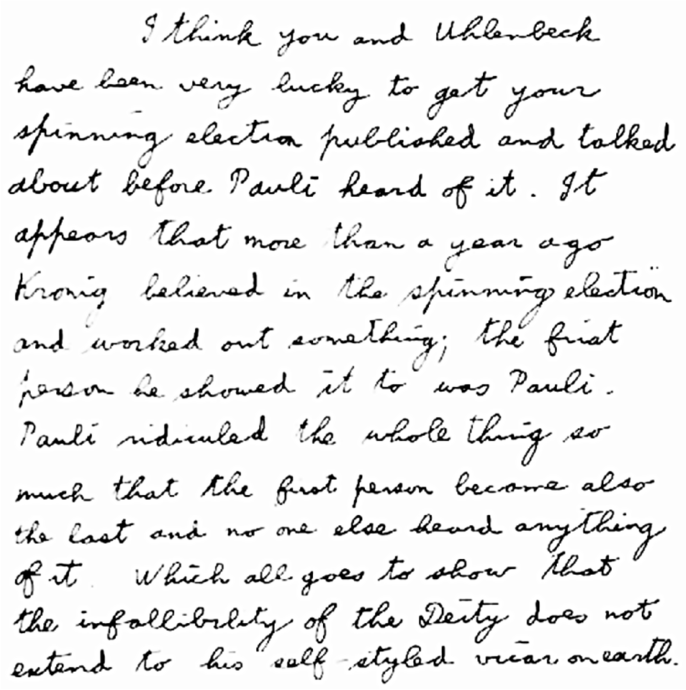
[8] Much has been written about the discovery of the spin and the fact that Uhlenbeck and Goudsmit (or Kronig) did not receive the Nobel Prize. For a more detailed account and more references the reader is referred to the Pauli biography by Charles P. Enz [22], especially Chap. 5.



I think you and Uhlenbeck
have been very lucky to get your
spinning electron published and talked
about before Pauli heard of it. It
appears that more than a year ago
Kronig believed in the spinning electron
and worked out something; the first
person he showed it to was Pauli.
Pauli ridiculed the whole thing so
much that the first person became also
the last and no one else heard anything
of it. Which all goes to show that
the infallibility of the Deity does not
extend to his self-styled vicar on earth.

Fig. 1.4. Part of a letter sent by Thomas to Goudsmit on March 26, 1926 [20]. It chronicles some of the events associated with the discovery of the spin. It reads as follows. "I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig believed in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth."

out explicitly introducing the electron spin [23, 24]. Dirac's quantum electrodynamics (QED) theory correctly described the magnetic properties of the electron and its antiparticle, the positron, but it proved difficult to calculate specific physical quantities such as the mass and charge of the particles. This was overcome in the late 1940s when Sin-Itiro Tomonaga (1906–1979), Julian Schwinger (1918–1994), and Richard P. Feynman (1918–1988) independently refined and fully developed QED[9]. An important feature of QED is that charged particles interact by emitting and absorbing photons, so that photons are the carriers of the electromagnetic force.

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[9] The theories by Tomonaga, Schwinger, and Feynman were later shown to be equivalent by Freeman J. Dyson (b. 1923).

In 1928, the year of Dirac's QED theory, there was another important breakthrough in the history of magnetism with Heisenberg's formulation of a spin-dependent model for the exchange interaction [25]. The molecular field postulated by Weiss could now be interpreted as having its origin in the exchange interaction. The introduction of the strong, short-range exchange interaction constituted the birth of modern magnetism theory, which has its roots in, both, quantum theory and relativity. In a series of papers starting in 1932, Louis Néel (1904–2000) developed the concept of antiferromagnetism [26]. Néel's ideas of antiferromagnetic and ferrimagnetic spin alignments were later verified by neutron diffraction, pioneered by Clifford G. Shull (1915–2001). In the mid 1930s, band theory was first applied to magnetic systems by Neville F. Mott (1905–1996) [27], John C. Slater (1900–1976) [28, 29] and Edmund C. Stoner (1899–1968) [30, 31]. Today further developments of this theory are a cornerstone of modern magnetism, explaining the noninteger values of magnetic moments.

While research in magnetism today is largely driven by the fast moving pace of information technology, especially data storage and memory applications, one cannot forget that from a world-wide economic and societal point of view another more mundane application of magnetic materials may be more important. It is the use of *high energy product permanent magnets* that underlie the generation and use of electricity. Under the term "high energy product magnets" one understands magnets which exhibit a magnetization loop that is both wide (maximum coercive field) and high (maximum magnetization) [32]. Such magnets facilitate the reduction of the size and the weight of a device made from them, for example, electric motors and audio speakers. The historical increase of the energy product, formally defined as the product of the applied field and the magnetic induction $(H\,B)_{\mathrm{max}}$, is illustrated in Fig. 1.5.

Today the strongest commercial magnet is $\mathrm{Nd_2Fe_{14}B}$, developed in 1984 by Croat et al. [34] and Sagawa et al. [35]. Permanent magnets are key components of electrical generators.[10] On a global scale, it is well established that the economic output of nations today is strongly correlated with their use of electricity since electrification makes an economy more efficient [36]. For example, today about half of the US energy is consumed as electricity and the US electricity retail sales amount to about 250 billion dollars per year, or about 2.5% of the US gross domestic product (GDP). It is therefore important to keep in mind the future development of improved permanent magnets. Such work was given new impetus by the suggestion of spring magnets by Kneller and Hawig in 1991 [37] and Stromski and Coey in 1993 [38]. Recent research on spring magnets has been reviewed by Bader [39]. More information on the properties of magnetic materials can be found in O'Handley's book [40].

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[10] They have also revolutionized accelerator technology, allowing the construction of permanent magnet wigglers and undulators at third generation synchrotron radiation sources.

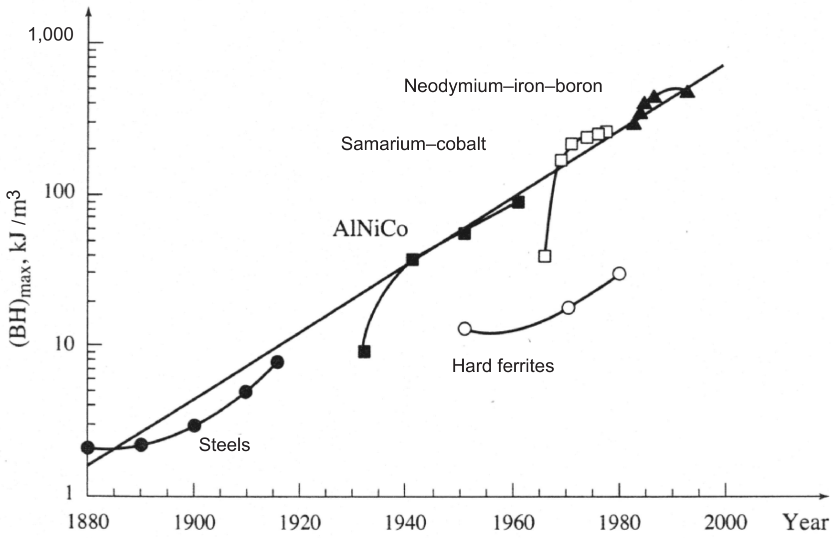

Fig. 1.5. Historical evolution of the performance of permanent magnets, defined by their energy product $(H\,B)_{\mathrm{max}}$. Shown are five principal industrial magnet families. Note that the ordinate has a logarithmic scale. Figure taken from [33] after [32]

The most advanced applications of magnetism today are closely related to the technology underlying magnetic storage and memory [41,42]. As early as 1888 magnetic recording was proposed by Oberlin Smith and the first successful magnetic recording device, the telegraphone, was patented by Valdemar Poulsen in 1894 [41,43]. In 1949, physicist An Wang at Harvard created a device based on small ferrite rings, so-called "cores", that could be switched by current flow through wires that penetrated the rings, as illustrated in Fig. 1.6. In the 1950s this led to the development of nonvolatile *magnetic core memories* which became the dominant computer memories in the early 1960s but were replaced by semiconductor memories in the 1970s.[11]

For the last 40 years magnetism has been used to store information in computers. This 50 billion dollars per year industry is based and dependent on fast developing concepts. It has fuelled a renaissance in magnetism research based on artificially engineered thin film structures [44,45]. Nonvolatile magnetic memory is also making a comeback as so-called MRAM for magnetic random access memory [46]. From a science point of view the last 15 years have been particularly exciting and these developments and envisioned future concepts and technologies will be extensively discussed in this book.

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[11] Wang's patent was not granted until 1955, and by this time core memory was already in use. This started a long series of lawsuits, which eventually ended when IBM paid Wang several million dollars to buy the patent outright.

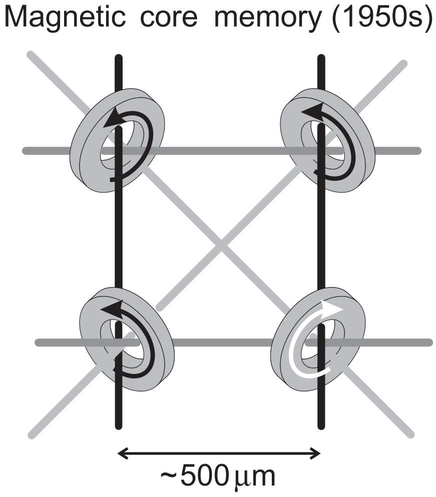

Fig. 1.6. Schematic of magnetic core memory used in computers in the 1960s. Currents through two wires were used for writing "bits", i.e., opposite magnetization states shown as white and black arrows, in small ferrite ceramic rings. The third wire was used for reading changes in magnetization through induction

1.3 Magnetism, Neutrons, Polarized Electrons, and X-rays

Early experiments to elucidate magnetic phenomena and materials were based on the measurement of forces and torques exerted on "samples" placed into magnetic fields produced by current flow through wires. Later experiments involved measurements of the magneto-optical Faraday (transmission) and Kerr (reflection) effects. Today the Kerr effect forms the basis of the magneto-optical recording technology by utilizing powerful yet small semiconductor lasers. The laser was proposed by Arthur L. Schawlow and Charles H. Townes in 1958 [47] and the first laser, made out of synthetic ruby, was built by Theodore H. Maiman in 1960. It is a powerful research tool for the study of modern magnetic materials, typically in the form of thin films, and scanning and imaging Kerr microscopy gives microscopic information with a resolution near the diffraction limit of light (about 200 nm). This diffraction limit is one of the Achilles' heals of visible light (and lasers) for the study of matter. The other one is the strong absorption of visible light by matter, making it difficult to look into or through many bulk materials. In principle, these limitations were overcome by Wilhelm Conrad Röntgen's (1845–1923) discovery of X-rays in 1895 [48] but the use of X-ray for the study of magnetic materials had to wait for nearly another century, as discussed later.

With the development of neutron diffraction and spectroscopy techniques in the 1940s and 1950s it was finally possible to determine the spin structure on an atomic level. The seminal contribution of neutron techniques to magnetism is reflected by the October 1994 press release by the Royal Swedish Academy of Sciences on the 1994 Nobel Prize in Physics, won by Bertram N. Brockhouse (1918–2003) and Clifford G. Shull (1915–2001), "Neutrons are small magnets, as are the atoms of a magnetic material. When a neutron beam strikes such material, the neutrons can therefore change direction through magnetic interaction with the atoms of the material. This gives rise to a new type of neutron diffraction which can be used to study the relative orientations of the small atomic magnets. Here, too, *the X-ray method has been powerless and in this field of application neutron diffraction has since assumed an entirely dominant position.* It is hard to imagine modern research into magnetism without this aid."

At the time of this press release efforts were already underway to change the role of X-rays in magnetism. This relatively recent and important development will be discussed later. The last 30 years have seen another important development, the generation and manipulation of spin polarized electrons [45]. This development has culminated in phenomena like giant magnetoresistance and "spintronics". We shall see later that studies by means of polarized electrons and X-rays have provided important new information. Today one could rephrase the last sentence of the above quote by the Nobel Prize Committee: *It is hard to imagine modern research into magnetism without polarized electron and X-ray probes.*

Within this book we shall not discuss the technique and applications of neutron scattering for the study of magnetic materials. This has been done extensively by others such as Bacon [49], Squires [50], Balcar and Lovesey [51], or more recently by Fitzsimmons et al. [52] and in the book on magnetism techniques by Zhu [53]. Another reason is that in today's magnetism research, materials with nanoscale dimensions and phenomena associated with surfaces, thin films, and interfaces are of prime importance. This has led to an increased demand for techniques with high sensitivity to small amounts of magnetic material or a small number of magnetic atoms. The *atomic sensitivity* of different techniques based on neutrons, electrons or X-rays may be expressed by a *figure of merit per atom per second* (FOM), defined by the product of the respective atomic interaction cross-section, the available incident flux, and the square of the magnetic contrast, as done in Table 1.3.

In the Table we have assumed that we can use samples as large as $10\,\mathrm{mm} \times 10\,\mathrm{mm}$ so that we list the incident flux per cm^2. For smaller samples the neutron flux and FOM would be reduced proportional to the area while the electron and photon flux remains unchanged down to sample areas of mm^2 or less. The Table shows that the use of neutrons with a small FOM is unfavorable for nanoscale magnetism research where the quest is for tools that can image small magnetic structures in short observation times. Neutron techniques have been and remain important for studies of bulk materials where the small FOM per atom is overcome by the large number of contributing atoms. In contrast, electron, resonant X-ray, and optical techniques offer a

Table 1.1. Comparison of factors determining the interactions of neutrons, low energy ($< 10\,\mathrm{eV}$) electrons, X-rays, and optical photons with magnetic materials such as the ferromagnets Fe, Co, and Ni. For neutrons and X-rays, the listed elastic scattering cross-sections σ refer to the magnetic cross sections per atom, for all other cases we list the combined charge and magnetic cross sections and indicate the magnetic contribution through a fractional value for the magnetic contrast P. We also list the incident monochromatic flux per appropriate experimental bandwidth Φ, and the relative figure of merit per atom per second, defined as $\sigma\Phi P^2$. The true magnetic signal for a given sample will depend on the probed number of magnetic atoms in the beam. For a given lateral sample size the number of atoms can be increased by making the sample thicker but the maximum number of probed atoms is inversely proportional to the cross-section. Therefore neutron techniques can overcome the limited scattering signal per atom by use of large and thick samples

	technique	atomic cross-section σ [barn/atom][a]	magnetic contrast P	incident flux Φ[b] $[\mathrm{s^{-1}cm^{-2}BW^{-1}}]$	figure of merit $10^{-7}\sigma\Phi P^2$
neutrons	El. Scatt.[c]	1	1	1×10^7	1
electrons	El. Scatt	1×10^8	0.5	1×10^{10}	2.5×10^{10}
X-rays	El. Scatt.	5×10^{-2}	1	1×10^{12}	5×10^3
	Res. El. Scatt.[d]	5×10^3	0.5	1×10^{12}	1.25×10^8
	Res. Abs.[d]	5×10^6	0.3	1×10^{12}	4.5×10^{10}
light	Kerr Effect	5×10^6	0.01	1×10^{16}	5×10^{11}

[a] 1 barn = $10^{-24}\,\mathrm{cm}^2$

[b] We have used monochromatic fluxes with appropriate experimental bandwidths (BW). The BWs are 1% for neutrons and 0.1% for electrons and photons

[c] The nuclear and magnetic neutron cross sections are about the same

[d] Total resonant cross-section at $3d$ transition metal L-edge

large sensitivity per atom and are well suited for the studies of surfaces, thin films and nanostructures.

Of the various techniques the magneto-optical Kerr effect (MOKE) has a very high FOM and the technique is relatively simple in practice [54,55]. Consequently, it is the technique that enjoys the greatest popularity, particularly for the study of ultrafast magnetization dynamics where the availability of short and intense laser pulses is a great asset [56, 57]. The main drawback of the Kerr technique is its limited spatial resolution which arises from the relatively long wavelength of near-visible light. This makes MOKE unsuited for imaging the magnetic structure of nanoscale magnetic elements. It is therefore expected that in the future the use of X-ray techniques will increase, especially for the study of nanoscale dynamics as discussed in Chap. 15.

In the following we shall discuss the developments of electron and X-ray techniques.