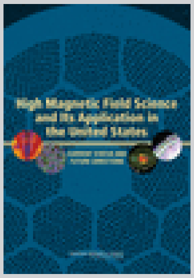

High Magnetic Field Science and Its Application in the United States: Current Status and Future Directions

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High Magnetic Field Science and Its Application in the United States

CURRENT STATUS AND FUTURE DIRECTIONS

Committee to Assess the Current Status and Future Direction of
High Magnetic Field Science in the United States

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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Cover: Background image: Round wire Bi-2212, a new high field superconductor technology, courtesy of the Applied Superconductivity Center, National Magnetic Field Laboratory. Images from left to right: (1) Electronic band structure engineering, from B. Hunt, J.D. Sanchez-Yamagishi, A.F. Young, et al., 2013, Massive Dirac fermions and Hofstadter butterfly in a van der Waals heterostructure, *Science* 340:1427-1430; reprinted with permission from the American Association for the Advancement of Science (AAAS). (2) Superconducting thick film (Ytrium-123), courtesy of the National High Magnetic Field Laboratory. (3) A bismuth atom, positioned in silicon crystal, whose nuclear spin potentially can host quantum information; artwork from the London Centre for Nanotechnology by Manuel Vögtli. (4) Close-up view of fiber tracts in the retina, courtesy of the National High Magnetic Field Laboratory.

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[1] Nai Phuan Ong resigned from the committee on May 18, 2012.
[2] Zlatko B. Tesanovic passed away on July 26, 2012.

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ZLATKO B. TESANOVIC
1956-2012

The Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States dedicates this report to a dear friend and valued colleague, Zlatko Tesanovic, who served as a member of this committee, and contributed strongly to it, until his untimely death on July 26, 2012. Zlatko was a condensed matter theorist, with particular research interests in the areas of superconductivity and strongly correlated electron materials. However, his broad knowledge of condensed matter physics, his deep understanding of the effects of strong magnetic fields, and his talent for exposition were influential throughout this report.

Preface

High-field magnets have become an important research tool in many scientific disciplines. Originally developed for studying the characteristics of materials under extreme conditions, they have increasingly been used by other disciplines, including biology, chemistry, and geology, and have found applications beyond basic science, serving many applied fields from medicine to the petroleum industry. In the United States, high-magnetic-field research principally takes place at the National High Magnetic Field Laboratory (NHMFL), operated under the auspices of the National Science Foundation (NSF). In the more than 20 years that it has been in existence, NHMFL has emerged as the leading facility in the world for providing researchers, and others, access to the highest magnetic fields available while working at the forefront of developing magnet technology for future users.

In line with this investment, the U.S. government has periodically commissioned a review of the current status and future prospects of the field. The most recent previous review was commissioned in 2003 and its conclusions were published in the National Research Council report *Opportunities in High Magnetic Field Science* (The National Academies Press, Washington, D.C., 2005). At the request of NSF, the National Research Council established the current committee in the spring of 2012 to provide an updated review. The Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States was asked to assess the needs of the U.S. research community for high magnetic fields and to determine the status and identify trends in the use of high magnetic fields throughout science and technology. Based on its assessment, the committee was asked to provide guidance for the future of magnetic-field research and technology development in the United States, taking into account worldwide capabilities and any potential for international collaborations or cooperative arrangements. A full statement of the charge to the committee may be found in Appendix A of this report. This report is the work of that committee in response to its charge.

In the course of its efforts, the committee heard from a number of people who either are responsible for providing the capabilities offered through the NHMFL or are among the scientists and agents of federally funded programs relying on those facilities to conduct their research or to meet their programmatic needs. The committee is grateful to those individuals for their information and insights—their presentations and the discussions that followed served as a valuable resource for the committee. The committee is also grateful to the NHMFL staff in Tallahassee and at Los Alamos National Laboratory for their hospitality when members of the committee visited. Finally, I thank the members of this committee and the NRC staff for their diligent efforts in producing this report.

Bertrand I. Halperin, *Chair*
Committee to Assess the Current Status and Future Direction of
High Magnetic Field Science in the United States

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Amy Andreotti, Iowa State University,
Helene Benveniste, Brookhaven National Laboratory,
Collin Broholm, Johns Hopkins University;
Laura Greene, University of Illinois at Urbana-Champaign,
Neil Kelleher, Northwestern University,
Robert Lindeman, Northrop Grumman (retired),
D. Bruce Montgomery, Magplane Technology,
Andrew Sessler, Lawrence Berkeley National Laboratory, and
Mansour Shayegan, Princeton University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John F. Ahearne, Sigma Xi, The Scientific Research Society. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

APPENDIXES

Executive Summary

The Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States was convened by the National Research Council in response to a request by the National Science Foundation. The committee was charged with answering three questions:

1. What is the current state of high-field magnet science, engineering, and technology in the United States, and are there any conspicuous needs to be addressed?
2. What are the current science drivers, and which scientific opportunities and challenges can be anticipated over the next 10 years?
3. What are the principal existing and planned high magnetic field facilities outside of the United States, what roles have U.S. high-field magnet development efforts played in developing those facilities, and what potentials exist for further international collaboration in this area?

A magnetic field is produced by an electrical current in a metal coil. This current exerts an expansive force on the coil, and a magnetic field is "high" if it challenges the strength and current-carrying capacity of the materials that create the field. Although lower magnetic fields can be achieved using commercially available magnets, research in the highest achievable fields has been, and will continue to be, most often performed in large research centers that possess the materials and systems know-how for forefront research. Only a few high field centers exist around the world; in the United States, the principal center is the National High Magnetic Field Laboratory (NHMFL).

Owing in large measure to the NHFML, high-field magnet science in the United States is currently very strong. The NHMFL operates a variety of magnets including dc superconducting/resistive hybrids, pulsed magnets, a high-field, low-temperature facility, and a 900 MHz (21.1 tesla [T]) nuclear magnetic resonance (NMR) facility. These magnets, along with their advanced measurement instrumentation, constitute a highly successful user program. The recent achievement of 100 T at NHMFL's Los Alamos venue represents the state of the art for high magnetic fields and has already produced new scientific results. In addition to NHMFL, other laboratories in the United States, including major laboratories supported by the Department of Energy, have made important contributions to high-magnetic field science through the design and deployment of state-of-the-art superconducting magnets for the purposes of high-energy physics and controlled nuclear fusion. However, despite the success of the NHMFL, U.S. leadership has eroded in at least one important area: high-field nuclear magnetic resonance (NMR) spectroscopy for chemical and biological applications. Here, European agencies have made large investments in new magnets and associated equipment that have not been matched in the United States.

The present report considers continued support for a centralized high-field facility such as NHFML to be the highest priority. At the same time, the report notes that if current efforts to develop a 32 T all-superconducting magnet are successful, it could be advantageous also to establish several smaller regional facilities utilizing this technology. The report also contains a recommendation for the funding and siting of several new high field NMR magnets at user facilities in different regions of the United States.

High magnetic fields have enabled major breakthroughs in science and have improved the capabilities of medical care. High field research can be divided into two broad areas. First, high fields, in competition with internal magnetic forces, can create exotic magnetic states in advanced electronic materials. The nature of these states challenges our basic understanding of matter. For example, in the fractional quantum Hall effect, accessed only in strong magnetic fields, electrons organize themselves into a peculiar state of matter in which new particles appear with electrical charges that have a fraction, such as one-third or one-fifth, of the charge of an electron. In other magnetic materials, the field can create analogues of the different forms of ice that exist only in magnetic matter. These exotic states also provide insight for future materials applications. Among these states are phases with spin-charge interactions needed in next-generation electronics. Here, the availability of the highest magnetic fields complements the development of novel materials. In the next 10 years, new materials possessing topological phases and useful functionalities will be advanced by their study in high fields. Future implementation of high fields collocated with advanced photon and neutron spectroscopies will accelerate such advancements.

Second, in biological and chemical systems, high-field NMR performed on complex molecules has become indispensable for analyzing molecular structure and motion. Since resolution and sensitivity of NMR measurements increases with magnetic field, high magnetic field research translates into leadership in the investigation of the structural and functional properties of biological systems as well as the properties of technologically important materials. New frontiers in biological and medical imaging of human physiology and metabolism are being opened up by access to higher fields than available currently. The impact of high-field studies of biological and chemical systems is amplified by an expanding variety of techniques, including multidimensional NMR, dynamic nuclear polarization, functional magnetic resonance imaging, in vivo magnetic resonance spectroscopy, and Fourier transform ion cyclotron resonance. Applications of these and other techniques depend on increasing magnetic field strengths at the associated facilities.

Future prospects for instruments with higher magnetic fields are bright. Pulsed field magnets, such as that which produced 100 T, can be advanced with higher strength materials to produce even higher fields. Self-destructive magnets now produce fields much higher than 100 T, but at drastically reduced measurement times. Improvements in instrumentation and measurement techniques will make fields of this magnitude more widely available and useful to researchers. Opportunities for superconducting magnets lie in replacing low-T_c materials such as Nb_3Sn, which presently produce 24 T dc, with high-T_c materials such as $YBa_2Cu_3O_7$, which promise to reach 30 T dc in the next 5 years. New superconducting materials that would raise the attainable field even higher are presently being pursued. Superconducting magnets with the highest possible fields are also essential in high-energy physics and fusion physics. In medical devices, better imaging resolution afforded by higher fields will improve the physician's ability to treat disease.

Continued advancement in high-magnetic-field science requires substantial investments in magnets with enhanced capabilities. The report contains recommendations for the further development of all-superconducting, hybrid, and higher field pulsed magnets that meet ambitious but achievable goals. It also contains recommendations for the development and deployment of high-field magnets at facilities for X-ray and neutron scattering and for the development of a 20 T, wide-bore magnet suitable for research using MRI on large animals and humans. Opportunities for the combination of high magnetic fields with a powerful source of terahertz radiation are also underscored.

High-field magnet facilities require infrastructure for the production of large electrical currents and for handling large amounts of cryogenic liquid; they also need the metal-forming capability to build new magnets. Such facilities have been built in Germany, France, the Netherlands, Japan, and China, but the NHMFL in the United States is presently considered to be the world leader in both advancing magnet technology and high-field science. The global high-field community has a very good record of scientific collaboration, while retaining the competition between laboratories important for advancing magnet technology and producing scientific results. The report recognizes that future opportunity for U.S. high-field magnet technology lies in exploiting the expertise centered at NHMFL, while involving other laboratories and companies to enhance U.S. commercial competitiveness in such areas as the production of NMR magnets, and the report contains recommendations for pursuing those opportunities.

Finally, the NHMFL is a major multidisciplinary facility, and effective stewardship is critical to its vitality. In this regard, its continued effective management, its exploration of prospective partnerships for facilities development, and a predictable facilities recompetition plan are essential. Accordingly, the report contains a recommendation that NHMFL should have a recompetition cycle that is longer than that of the average major facility.

1

Overview

MAGNETS AND MAGNETIC FIELDS

It is not known when humans first noticed the attraction or repulsion between pieces of magnetic material. The first important device depending on these forces was the magnetic compass, which is believed to have been invented in China around 200 BCE. However, the concept of a magnetic field as a description of the forces felt by magnetic objects, and the laws that govern the interactions between magnetic fields and ordinary matter, were first understood in the nineteenth century. It was shown that an electric current, produced by the motion of electrical charges, will generate a magnetic field in the surrounding space, while an electric charge moving in a magnetic field will feel a physical force in a direction perpendicular to the magnetic field and to the direction of motion.

An electric charge that is completely stationary should generate no magnetic field, nor would it feel a force due a magnetic field generated by other sources. However, according to the laws of quantum mechanics, discovered in the early twentieth century, electrons and nuclei are always in motion, even at zero temperature, and electrons and most nuclei also have an internal rotation (spin), which can generate magnetic fields on the atomic scale. In most materials, the electron spins and other

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NOTE: Portions of this and other sections in this chapter have been extracted from National Research Council, 2005, *Opportunities in High Magnetic Field Science*, The National Academies Press, Washington, D.C.

local currents are oriented in random directions, so they do not produce a magnetic field on the macroscopic scale. However, in certain ferromagnetic materials, such as iron, cobalt, and nickel, the local moments can be aligned by application of a modest magnetic field. In many cases this alignment persists when the applied field is removed, and the result is a permanent magnet, which can then act as a source of magnetic fields by itself.

Although permanent magnets made using ferromagnetic materials have many important applications, they are not useful for producing the strongest magnetic fields. The highest magnetic fields currently obtainable from permanent magnets are on the order of 2 tesla. (One tesla, abbreviated T, is equal to 10,000 gauss and is approximately 50,000 times the magnetic field of Earth at a latitude of 50 degrees.) Much higher fields can be produced by electromagnets.

Electromagnets can be made of any material that conducts electricity, regardless of the magnetic properties of its atoms, and they produce magnetic fields whenever an electric current flows through the conductor. Electromagnets are commonly made from multiple coils of a conductor. Since the field contributed by each turn in a coil adds to that of its neighbors, and the field per turn increases with electric current, the more turns in the coil and the greater the current put through it, the stronger the magnetic field that results. All high-field magnets—that is, magnets that generate fields substantially greater than 2 T—are electromagnets.

IMPORTANCE OF STRONG MAGNETIC FIELDS

Magnetic fields are central to the operation of many devices crucial for the functioning of a modern society. For example, electric motors and generators of electrical power take advantage, respectively, of the force exerted by a magnetic field on a wire that carries an electric current and of the complementary process whereby electrons in a wire moving across a magnetic field will feel a force that can drive a current along the wire. Other devices, such as read-out heads in magnetic disk memories, depend on magnetic-field-induced changes in the electrical resistance of certain materials, which are used to sense the orientations of the microscopic magnetic domains that encode digital information on the disk.

Magnetic resonance imaging (MRI) devices, which are now extensively used for medical applications, take advantage of a different aspect of the interactions between fields and matter. Here, the combined effects of ac and dc magnetic fields on the magnetic moments of the spinning nuclei (particularly protons) in the human body are used to obtain detailed information about the environment of the nuclei, which can distinguish between tissues of different types and can reveal changes due to pathological conditions.

For motors and generators and many other electromechanical devices, increases in strength of the magnetic fields employed could lead to important improvements in performance—for example, by achieving more power output in a smaller volume. However, the fields used in these devices are generally limited by practical considerations of cost and weight and do not approach the strengths employed in specialized research applications. By contrast, MRI devices require the highest available fields to achieve satisfactory resolution and sensitivity, and the magnets used in these devices are constantly pushing the limits of magnetic field technology.

Very high fields are necessary for many crucial research applications in materials science, chemistry, and biology. The success of these experiments may have major impacts on health care and technology. High magnetic fields in very large volumes are also required for accelerators in high-energy physics and in plasma research aimed at the realization of controlled nuclear fusion.

Research using high magnetic fields has proven to be a critical tool in solving problems of technological relevance. High field research has led to an increased understanding of matter, to the discovery of entirely new phenomena, and, subsequently, to the development of new devices and products of significant technological and societal importance. Many of the most highly demanded products in today's marketplace involve technology whose development was enabled, in part, by research using high magnetic fields. And magnetic fields continue to be used to attack many problems of scientific and technological interest. One of the current problems being addressed with high field research is in energy generation and storage. Nuclear magnetic resonance (NMR) has been used as an effective tool to probe the transport of Li ions during charge/discharge cycling of Li batteries, where gaining a fundamental understanding of how Li dendrites grow is necessary to optimize battery design. As another example, ion cyclotron resonance (ICR) has proven to be an essential analytical tool for understanding oil-pipeline-clogging deposits and oil-spill pollution. These are just a couple of examples, and more will be presented in the body of this report. Given the important role that high fields have played in past technological advances, it is a good bet that research involving high magnetic fields will continue to yield technological advances in the future.

One indication of the broad range of research dependent on the availability of high magnetic fields may be seen in Figure 1.1, which shows the growth in research reports resulting from use of magnets at the National High Magnetic Field Laboratory (NHFML), during the period 1995-2010, classified by field of research. The categories listed are condensed matter physics and materials, engineering (materials, instrumentation, and magnet technology), biology and biochemistry, chemistry, and geochemistry. Figure 1.1 does not tell us about such key areas of high magnetic field research and applications as high-energy physics accelerators, controlled fusion, and human magnetic resonance imaging, which are not represented at NHMFL. These topics are discussed in Chapters 4, 5, and 7.

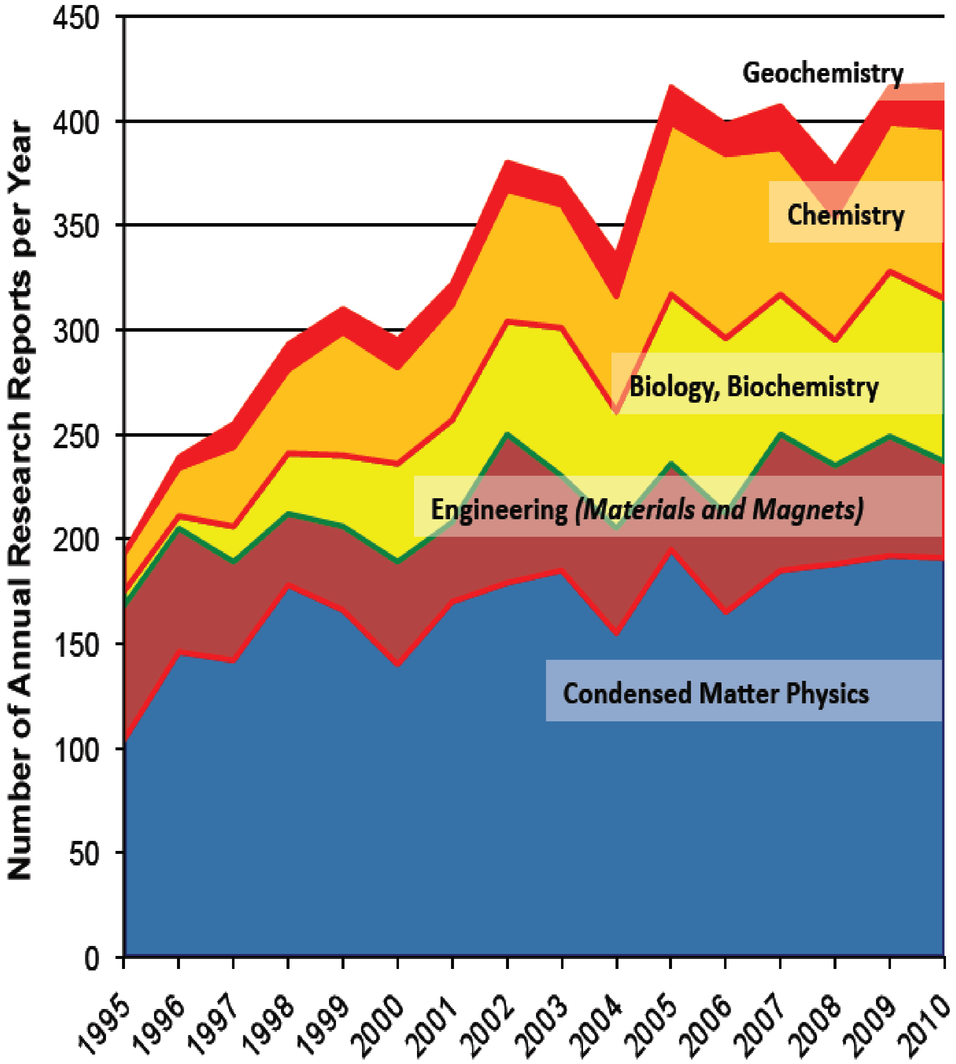

FIGURE 1.1 Research reports resulting from projects using high-field magnets at the NHFML during the period from 1995 to 2010, classified by field of research. SOURCE: National High Magnetic Field Laboratory.

MAGNETS FOR HIGH MAGNETIC FIELDS

Scientists have been building electromagnets that deliver fields of ever-increasing strength since the nineteenth century. Two issues have had to be confronted at every step of the way. First, the field of an energized electromagnet exerts forces on its own structure that increase as the square of the field strength and that will destroy it if not contained. Second, if the electrical conductor of which the magnet is made is a normal metal, resistive heating produced by the electric currents can cause the magnet to fail. Beginning in the 1960s, scientists learned how to build magnets using superconducting wires, which can carry a current without resistance at sufficiently low temperatures; however, superconductors have their own limitations, as will be discussed later in this report. In particular, all superconducting materials have a critical magnetic field above which they can no longer support resistance-less current flow and cannot be used in magnet construction. A major goal of research in high magnetic fields is to learn how to create superconductors with higher critical fields and to learn how to make magnets out of these materials. However, the highest magnetic fields attained to date have been produced by resistive magnets that are operated in a pulsed mode to minimize destructive heating effects.

The construction of magnets that operate at high fields is, and has always been, an engineering challenge. In this report, in line with previous studies, *the committee defines* "high magnetic field magnet" *as one whose construction tests the limits of our current technological capabilities*. The quantities that determine whether a magnet meets this definition are not just the magnitude of the field itself but include the total energy stored in the field, which is proportional to the integral of the square of the field over the volume affected. Thus an MRI magnet having a maximum field strength of 8 T and a bore large enough to accommodate a human being is as much a high-field magnet as a smaller-bore magnet for an NMR spectrometer operating above 20 T. The highest field attained so far in a dc magnet is 45 T, while pulsed field magnets can operate at 60 T and above. In pulsed-field experiments, there is generally an inverse relationship between the field strength attained and the duration of the pulse. The current record for a nondestructive pulsed magnet is 100 T for a duration of about 10 ms. If partial or total destruction of the magnet coil and/or the sample can be tolerated, fields well above 300 T can be generated for several microseconds. (See Figure 1.2 for a graph of field strengths and available measurement times in various types of high-field magnets, and see Box 1.1 for a list of some other magnetic field strengths.)

The technological challenges involved in construction and operation of the various kinds of high-field magnets are discussed in Chapter 7 of this report, along with recommendations of goals for new magnet construction in the coming decade.

FACILITIES AND STEWARDSHIP ISSUES

Magnets at the high-field frontier are necessarily complex and expensive, both to construct and to operate. High-field magnets require a highly skilled staff to keep them running and to maintain the instruments that make them useful. Serious

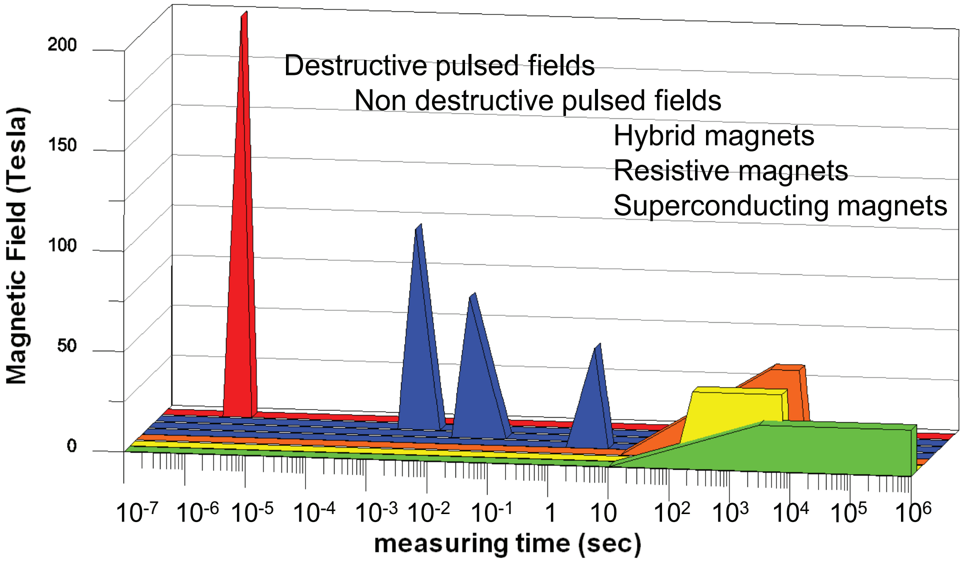

FIGURE 1.2 An overview of magnetic fields available with different technologies, showing the corresponding rise times for the fields and the times during which experiments in these fields can be performed. SOURCE: Graph courtesy of Jan Cornelis Maan, Radboud University Nijmegen, The Netherlands.

safety issues must be addressed in the operation of a high-field facility. In addition, resistive magnets require a large infrastructure to supply needed electric energy and cooling power. For these reasons, it is natural that the highest field magnets should be concentrated at a very small number of national facilities.

In the United States, the most advanced facilities are run by the NHFML, which provides user access to dc magnetic fields in Florida and to pulsed fields at Los Alamos National Laboratory in New Mexico (see Figure 1.3). Although there are important high-magnetic-field facilities in many other countries, NHFML is unquestionably the world's leader in this area. It also plays a crucial role in the training of high-magnetic field scientists and in the development of next-generation magnets and magnetic materials. The leading status of the United States in high-magnetic-field science is due in very large measure to the many contributions of NHFML.

There are, however, certain areas where it may be more advantageous to create distributed facilities, able to accommodate large numbers of users. An important example of this is in the field of chemical and biological NMR spectroscopy, where the committee envisions the establishment of several state-of-the-art user facilities

BOX 1.1
SOME MAGNETIC FIELD STRENGTHS

- In outer space the magnetic flux density is between 10^{-10} T and 10^{-8} T.
- Earth's magnetic field at latitude 50 degrees is 5.8×10^{-5} T and at the equator (latitude of 0 degrees), 3.1×10^{-5} T.
- The magnetic field of a horseshoe magnet is ~0.1 T.
- In a sunspot, the field is 0.15 T.
- The magnets in clinical medical MRI spectrometers operate around 4 T; high-resolution MRI operates at 9.4T, and the highest field used for study of a living animal is 21.1 T.
- Strongest NMR magnetic field in use: 23.5 T, or 1 GHz (Lyon, France; 2009)
- Strongest continuous magnetic field yet produced in a laboratory:
  —About 26.8 T with a single superconducting magnet (2007),
  —35.4 T for any superconducting magnet (2011),
  —36.2 T with a resistive magnet (2010), and
  —45.2 T with a hybrid magnet (2003).
- Strongest (pulsed) magnetic field yet obtained nondestructively in the laboratory: 100.75 T (2012) for ~10 ms.
- Strongest (pulsed) magnetic field ever achieved (with explosives) in the laboratory: 2,800 T (Sarov, Russia; 1998).
- The field on a neutron star is 10^6 T to 10^8 T.
- Maximum theoretical field strength for a neutron star, and therefore for any known phenomenon, is 10^{13} T.

around the country. Also, some important applications of high magnetic fields require the combination of high magnetic field with other expensive facilities, which may be best achieved by the deployment of a specialized magnet at an existing facility such as a synchrotron light source or a neutron source.

As mentioned above, the very highest magnetic fields for research are necessarily restricted to purpose-built facilities, which require significant infrastructure investments. In the United States, these research capabilities are available at the NHMFL, with operational support from the National Science Foundation (NSF). Because high magnetic field science is inherently multidisciplinary, effective stewardship of a major user facility like the NHMFL is critical to the vitality of the scientific enterprise. These facilities must be managed and operated in the most robust manner to provide the strongest possible scientific impact to the research community. This means that attention must be paid to (1) how the facilities are managed, (2) the roles and responsibilities of the federal agencies that steward them, and (3) the partners that join with the steward to leverage them for maximum impact. In addition to making available the highest fields, it is also desirable to translate proven magnet technology to decentralized facilities where appropriate

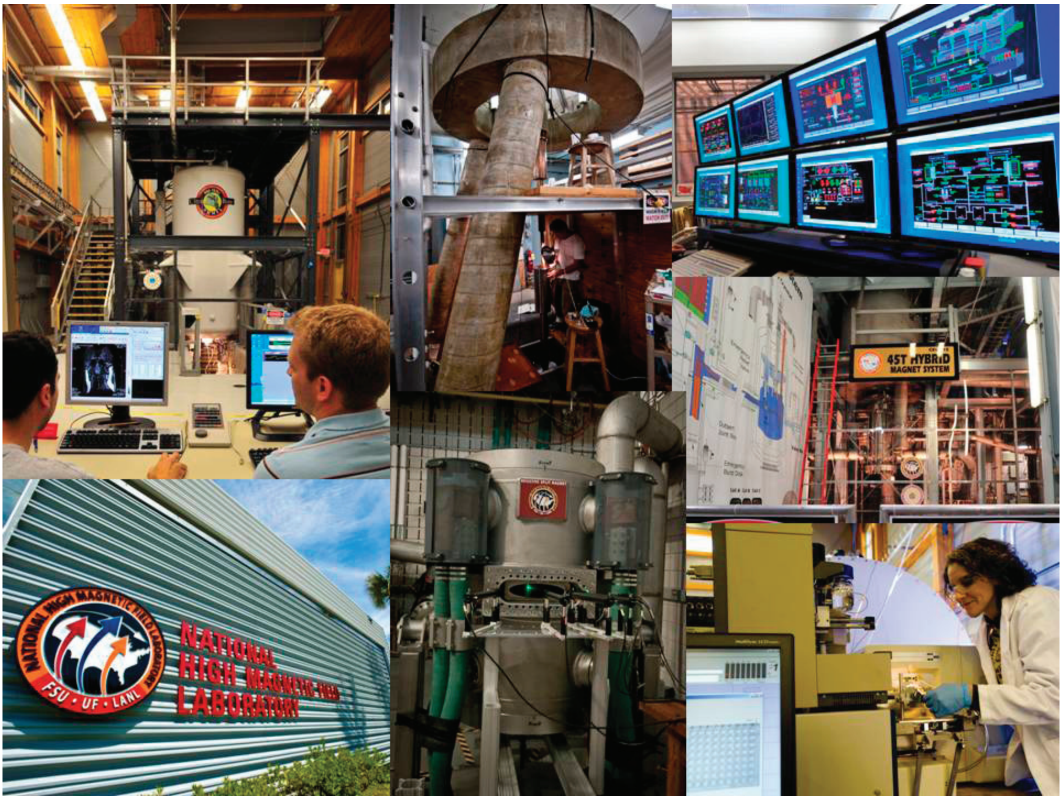

FIGURE 1.3 The NHMFL is the principal high magnetic field research laboratory in the United States. It is located on three campuses—Florida State University in Tallahassee, site of its general headquarters and much of its research facilities; the University of Florida in Gainesville, Florida, site of its low-temperature and advanced MRI programs; and Los Alamos National Laboratory in Los Alamos, New Mexico, where its pulsed magnetic field facility is located. (*Clockwise starting from the top left*) Users at the laboratory's 21.1 T 900 MHz ultra-wide-bore magnet. (*Top center*) A user prepares an experiment at the MagLab's High B/T facility in Gainesville, Florida. (*Top right*) A technician keeps close tabs on the magnets in the control room of the dc field facility. (*Middle right*) The MagLab's 45 T hybrid magnet, which holds the record for highest magnetic field for a continuous field magnet. (*Bottom right*) Amy McKenna, a staff chemist at the ICR facility, examining the flow of a sample in the ion cyclotron resonance magnet. (*Bottom center*) The 25 T split coil magnet at the MagLab's dc field facility. (*Bottom left*) The main sign of the MagLab. SOURCES: (*Top left*) Photo taken by Ray Stanyard, provided courtesy of NHMFL; (*top center*) photo taken by Dave Barfield, provided courtesy of NHMFL; (*top right*) photo courtesy of the NHMFL; (*middle right*) photo taken by Ray Stanyard, provided courtesy of NHMFL; (*bottom right*) photo courtesy of the NHMFL; (*bottom center*) photo taken by Dave Barfield, provided courtesy of NHMFL; (*bottom left*) photo courtesy of the NHMFL.

and technically and economically feasible. Furthermore, the long-term viability of this field of research is contingent upon the availability of a workforce capable of advancing the technological frontiers in magnet development. Education and training at the graduate and postgraduate levels are important to ensure this viability.

Issues of stewardship and of management of high-field facilities in the United States will be addressed, in some detail, in Chapter 9 of this report. Also, in Chapter 8, this report surveys high magnetic field facilities in foreign countries as well as in the United States and addresses some of the common issues involved in running such facilities. Chapter 8 also explores opportunities for cooperation between laboratories and between nations.

SCIENCE DRIVERS

Before discussing in detail the vital issues of organization, construction, and stewardship of high-magnetic-field facilities, the committee presents an overview of some of the science drivers that make high-magnetic-field science so important. Chapter 2 discusses the role of high magnetic fields in condensed matter and materials physics. Chapter 3 is devoted to the use of high magnetic fields for NMR, electron paramagnetic resonance (EPR), and ICR, in chemistry, biochemistry, and biology. Chapter 4 discusses the advantages that could be gained by using higher magnetic fields for MRI and magnetic resonance spectroscopy (MRS) for medical research on human subjects and proposes development of a 20 T magnet suitable for this purpose. Chapter 5 outlines the use of high magnetic fields in accelerator-based high-energy physics experiments and in confined-plasma controlled fusion projects. It also discusses the proposed development of compact superconducting cyclotrons for radiotherapy using charged particles and the possible use of higher magnetic fields in astrophysical particle detectors.

In several important research areas, it is necessary to combine magnetic fields with measurement tools that are themselves highly complex and expensive and that may be available only at specialized facilities. For example, experiments may require use of magnetic fields in conjunction with X-ray or neutron scattering facilities available at a synchrotron, nuclear reactor, or spallation source. Other experiments require that intense photon sources in the terahertz range be combined with high magnetic fields. As will be discussed in Chapter 6, improvements in the availability of high magnetic fields in combination with neutron and photon sources in the United States will be necessary if the nation is to maintain a leading role in these fields.

PRINCIPAL CONCLUSIONS AND RECOMMENDATIONS

The committee rounds out this overview chapter with a brief discussion of the principal conclusions and recommendations contained in this report. Numbers in parentheses refer to the chapters where the conclusions and recommendations appear. Supporting material for each of the conclusions and recommendations may be found in the discussions preceding them in those chapters.

Centralized and Distributed Facilities

First and foremost, the committee emphasizes that the status of high-magnetic-field science is very strong, and that this strength is due in large measure to the leadership role of the NHFML. A centralized national user facility that provides the highest magnetic fields in the world for the purposes of research offers numerous benefits to the scientific community; it is an essential part of our national prestige and, as a centralized entity, is a cost-effective resource (more so than an equivalent decentralized set of capabilities). The NHMFL provides high-magnetic-field measurement capabilities that are simply not available anywhere else in the United States. Indeed some of the NHMFL's measurement capabilities cannot be matched anywhere else in the world. By offering these capabilities to the U.S. scientific community, it enables cutting-edge research and enhances the nation's competitiveness. These magnets, and the associated scientific experiments requiring these fields, depend on a substantial infrastructure such as electricity and cooling. Locating these at a centralized facility, such as at the NHMFL, is a highly cost-effective approach. Moreover, developing high-field magnets requires a special and rare combination of expertise in and extensive knowledge of materials properties, physics, electrical engineering, mechanical engineering, and engineering design. Furthermore, locating these magnet developers at a centralized facility is cost-effective and ensures that they are well connected to the needs of a national user facility.

> **Conclusion:** There is a continuing need for a centralized facility like the NHMFL because (1) it is a cost-effective national resource supporting user experiments and thus advancing the scientific frontiers and (2) it is a natural central location with expert staff available to develop the next generation of high-field magnets. (9)
>
> **Recommendation: The National Science Foundation should continue to provide support for the operations of the NHMFL and the development of the next generation of high-field magnets. (9)**

On the other hand, there are several areas where decentralization may be advantageous. For example, assuming successful completion of the 32 T all-superconducting magnet under development at the NHMFL, one can envision a time shortly thereafter when this technology becomes available as a standard commercial product. At that time, it might be feasible to consider establishing satellite magnet user facilities at locations distributed around the country. The 32 T magnet technology would provide the basis for these satellite sites, since they will not require the extensive infrastructure required to power, cool, operate, and maintain the direct currect (dc) resistive magnets.

> **Conclusion:** There are benefits to decentralized facilities with convenient access to high magnetic fields for ongoing scientific research. Such facilities need not engage in expanding the frontiers of high magnetic field science nor lead the way in new magnet technology; instead, they should provide the broad user community with the up-to-date high-field magnets to relieve the shortage of user time at the NHMFL-style central facility. (9)

> **Recommendation: Taking into account, among other factors, the estimated costs and anticipated total and regional demand for such facilities, federal funding agencies should evaluate the feasibility of setting up some smaller regional facilities, ideally centered around 32 T superconducting magnets as the technology becomes available, and with optimized geographic locations for easy user access. These would be in addition to the premier centralized facility, which would remain, with its unique mission of expanding the frontiers of high magnetic field science. (9)**

Nuclear Magnetic Resonance Spectroscopy Facilities

NMR spectroscopy is another field where decentralized facilities are necessary. At the same time, substantial government support will be necessary if the United States is to retain leadership in the field.

> **Conclusion:** Nuclear magnetic resonance (NMR) spectroscopy is one of the most important and widely used techniques for structural, dynamical, and mechanistic studies in the chemical and biological sciences. However, in recent years, U.S. labs have failed to keep up with advances in commercial NMR magnet technology. If this trend continues, the United States will probably lose its leadership role, as scientific problems of greater complexity and impact are solved elsewhere. (3)

The report calls specifically for the funding of at least three magnets suitable for NMR spectroscopy at a proton NMR frequency of 1.2 GHz (28.2 T). As the cost of such a magnet is approximately $20 million, and there is currently no mechanism by which funds on this scale can be obtained through the conventional peer-review processes at NIH or NSF or DOE, new mechanisms are needed to fund and site high-field NMR systems in the United States.

Recommendation: New mechanisms should be devised for funding and siting high-field NMR systems in the United States. To satisfy the likely demand for measurement time in a 1.2 GHz system, at least three such systems should be installed over a 2-year period. These instruments should be located at geographically separated sites, determined through careful consultation with the scientific community based on the estimated costs and the anticipated total and regional demand for such instruments, among other factors, and managed in a manner that maximizes their utility for the broad community. Moreover, planning for the next-generation instruments, likely a 1.5 or 1.6 GHz class system, should be under way now to allow for steady progress in instrument development. (3)

Combining Magnetic Fields with Scattering Facilities and Terahertz Radiation

Magnets for neutron or X-ray scattering experiments need to be built and operated at existing facilities that can provide neutrons or photons. High magnetic fields would provide an important complement to the recent advances in scattering capabilities in the United States. It is also important to construct a facility that combines a powerful source of terahertz radiation with high magnetic fields, since typical resonance frequencies of electrons fall in this range for fields above 20 T.

Recommendation: New types of magnets should be developed and implemented that will enable the broadest possible range of X-ray and neutron scattering measurements in fields in excess of 30 T. This requires, as a first step, the expeditious procurement of modern 10-16 T magnet/cryostat systems for U.S. facilities, together with the recruitment of low-temperature/high-field specialists. Second, a 40 T pulsed-field magnet should be developed with a repetition rate of 30 s or less. Third, building on the development of a high-temperature all-superconducting magnet, which was recommended earlier, a wider-bore 40 T superconducting dc magnet should be developed specifically for use in conjunction with neutron scattering facilities. New partnerships among federal agencies, including the Department of Energy, the National Institute of Standards and Technology, and the National Science Foundation, will likely be required to fund and build these magnets, as well

as to provide the funds and expertise that will be needed to operate these facilities for users once they are built. (6)

Recommendation: A full photon spectrum, covering at least all of the energies (from radio-frequency to far infrared) associated with accessible fields, should be available for use with high magnetic fields for diagnostics and control. At any point in the spectrum, transform-limited pulses of variable amplitude, allowing access to linear and nonlinear response regimes, should be provided. Consideration should be given to a number of different options, including (1) providing a low-cost spectrum of terahertz radiation sources at the NHMFL, (2) construction of an appropriate free electron laser (FEL) at NHFML, or (3) providing an all-superconducting, high-field magnet at a centralized FEL facility with access to the terahertz radiation band. (6)

Specific Magnet Goals

To maintain its leadership, it is essential that the United States support ambitious goals for the construction of new magnets that would extend the frontiers of high-field research in several directions.

Recommendation: A 40 T all-superconducting magnet should be designed and constructed, building on recent advances in high-temperature superconducting magnet technology. (7)

Recommendation: A 60 T dc hybrid magnet should be designed and built that will capitalize on the success of the current 45 T hybrid magnet at the NHMFL-Tallahassee. (7)

Recommendation: Higher-field pulsed magnets should be developed, together with the necessary instrumentation, in a series of steps, to provide facilities available to users that might eventually extend the current suite of thermal, transport, and optical measurements to fields of 150 T and beyond. (7)

Magnetic Resonance Imaging Magnet Development

Significantly increased field strengths available for MRI and NMR spectroscopy on humans and large animals could enable a number of important advances in medical science. The committee finds that current barriers in MRI medical science research motivate an initiative to develop a 20 T magnet that can image and perform spectroscopy on the human head, large animals, and plants. Although this development would not be for clinical applications, the research could lead to important clinical benefits.

Recommendation: A design and feasibility study should be conducted for the construction of a 20 T, wide-bore (65 cm diameter) magnet suitable for large animal and human subject research. The required homogeneity is 1 ppm or better over a 16 cm diameter sphere. The appropriate sponsorship might be multiple agencies (e.g., NIH, NSF, and DOE). In parallel, an engineering feasibility study should be undertaken to identify appropriate RF, gradient coils, and power supplies that will enable MRI and MRS and an extension of current health and safety research currently being conducted at lower fields. (4)

Stewardship

The report addresses a number of issues on stewardship needs for the NHMFL and the workforce that makes NHMFL's continued success possible. The basis for these conclusions and recommendations is discussed in detail in Chapter 9.

Conclusion: Recompetition on timescales as short as 5 years places at risk the substantial national investment in high-field research that is embodied in a national facility like NHMFL and could have disastrous effects on the research communities that rely on uninterrupted access to these facilities. Although this committee believes that recompetition of facilities is appropriate, it also believes a flexible approach should be taken in the implementation of recompetition of the NHMFL to fulfill the role as a steward and to avoid potential negative consequences of a short time interval between recompetitions. (9)

Conclusion: The committee strongly endorses the consideration given to this matter by the Subcommittee on Recompetition of Major Research Facilities.[1] It endorses the need for evaluating the long-term strategy and direction of national facilities, as well as for effective periodic reviews of their scientific programs. (9)

Recommendation: NSF, the NHMFL, and other interested entities that benefit from the use of high magnetic fields should adopt the steward-partner model as the basis for defining the roles in future partnerships in high-magnetic-field science. For magnets not sited at NHMFL, the host institution

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[1] Report of the Subcommittee on Recompetition of Major Research Facilities, NSF Business and Operations Advisory Committee, January 5, 2012.

is in most cases the natural steward, especially for the significant facility-specific infrastructure required for magnet operations. For magnets sited at the NHMFL, NSF should be the steward, although the partner organization could fund the construction and operation of these facilities. (9)

Recommendation: A high field-magnet science and technology school should be established in the United States. The school could use the U.S. Particle Accelerator School (USPAS) as a model for its organization. Oversight and support should be drawn from a consortium of government agencies, laboratories, and universities, and—possibly—industry. The NHMFL could be the initial host site, with the laboratory facilities providing an excellent resource for laboratory courses. (9)

International Cooperation

The small community of high-field facilities that exist worldwide has a good record of scientific collaboration and competition that is and will remain important in advancing magnet technology and producing scientific results. Success requires that these large facilities should have a threefold mission: (1) to generate the highest possible magnetic fields, by developing new magnets needed to produce those fields (magnet technology); (2) to make these fields, together with experimental support and expertise, available to qualified external users (act as a facility); and (3) to perform world-class research led by the facilities' staff.

Recommendation: High-field facilities worldwide should be encouraged to collaborate as much as possible to improve the quality of magnets and service for users. This can be accomplished through the establishment of a global forum for high magnetic fields that consists of representatives of large magnetic field facilities from all continents. Such a forum would further stimulate collaboration and the exchange of expertise and personnel, thereby providing better service to the scientific community and magnet technology development. The forum should establish a roadmap for future magnets and stimulate the realization of the defined targets on this roadmap. (8)

Recommendation: Large high-magnetic-field facilities should also have strong collaborations with smaller regional centers, providing them with support and expertise. Users of these regional centers may need the higher fields available in the large facilities, while users of the large facilities could be referred to the regional centers if their proposed experiments are better suited for those centers. (8)

2

Science Drivers—Condensed Matter and Materials Physics

OVERVIEW

Most applications of high magnetic fields to the study of condensed matter systems have been concerned with "hard" condensed matter systems—typically, rigid solids or structures fabricated from such solids. These would include the surfaces of solids and interfaces between solids, small particles of a solid, wires with nanometer-scale diameters, and two-dimensional materials such as graphene, which is regular and practically rigid even though it is just a single layer of carbon atoms.

The properties of hard condensed matter systems are determined by the Coulomb forces between electrons and the constituent ions and by the constant motion of the electrons, dictated by the microscopic laws of quantum mechanics. Scientific research seeks to understand how these fundamental laws lead to huge diversity in the macroscopic behavior of different materials, nanostructures, and devices. With increased understanding comes the ability to design and optimize materials to attain desired technological goals and, on occasion, to conceive of radically new technologies that can have a profound effect on our lives.

Magnetic field studies have been a very important tool for exploring the electronic structure of condensed matter systems. Although applied magnetic fields in many cases have a relatively small effect on the overall electronic structure, they enable experimental techniques that can reveal properties of the underlying electronic structure that would be otherwise inaccessible. In other cases, magnetic field effects can be strong enough to drastically change the nature of the electronic state itself. In either situation, access to higher magnetic fields is important to allow the study of new materials and new phenomena.

Magnetic fields couple most strongly to the electrons in a material, either by acting on electrical currents generated by the electrons' quantum mechanical motion, or by coupling to the magnetic moments arising from the electrons' intrinsic spin. These coupling mechanisms are indeed the basis for the majority of experiments using high magnetic fields to study the electronic structure of materials. However, the much weaker coupling of magnetic fields to the magnetic moments of nuclear spins is also important, as it is the physical basis for nuclear magnetic resonance (NMR) techniques. Although NMR techniques are most widely used in studies of chemical and biological systems, which will be discussed in Chapters 3 and 4, NMR techniques can also be used to extract information about the electrons in condensed matter systems by measuring changes in the nuclear response that arise from magnetic interactions between the nuclei and the electrons. For example, NMR measurements have played a key role in elucidating the fundamental properties of electrons in superconductors, two-dimensional electron systems, and antiferromagnets.

The electronic structures of condensed matter systems can vary in many ways. Materials may be either electrical conductors or insulators, whose conductivities may differ by many orders of magnitude, even at room temperature. At low temperatures, some materials are *superconductors*, which can carry currents with no resistance at all. In many systems, both insulators and conductors, electrons on individual atoms can develop *magnetic moments*, which may order at low temperatures in a variety of ways. In other cases, instabilities in the electron system can lead to spatially periodic oscillations in the charge density and/or to displacements in atomic positions that change the symmetry of the crystal, and may lead to macroscopic electric dipole moments (*ferroelectricity*). In some cases, magnetic moments and atomic displacements are coupled, and magnetic fields can be used to influence electric polarizations. Of particular interest are systems that may change from one form of order to another as a function of temperature, pressure, or alloy composition; such materials may have very peculiar properties close to their phase transitions. Magnetic fields may provide a way for studying such phase transitions, and in some cases they may be strong enough to directly influence these transitions.

Crystalline materials are typically characterized by an electronic band structure, which specifies a discrete set of allowed electron energies for each possible electron momentum. Metals, which are good conductors of electricity, will typically have a surface in momentum space, known as the *Fermi surface*, separating occupied electron states, whose energies lie below a cutoff (the *Fermi energy*), from empty states, whose energies lie above the cutoff. Electrons close to the Fermi surface are of particular interest because they play a dominant role in electrical transport and many other properties of the material. Strong magnetic fields can lead to oscillations in transport and other electronic properties, whose periods depend on the precise size and shape of the Fermi surface. The ability to extract information about the Fermi surface through measurement of these oscillations is one reason magnetic fields are such an important tool for studying conducting materials.

Magnetic fields are particularly vital in the study of superconducting materials. Typically, superconductors will expel magnetic fields up to a certain field strength, denoted the *lower critical field*, H_{c1}. Above H_{c1}, magnetic fields will enter, but the material retains superconducting properties up to an *upper critical field*, H_{c2}. Measurement of the critical fields, as a function of temperature and orientation of the sample, gives important information about the underlying parameters of the superconductor. Superconductors with very large values of H_{c2} are of special interest, because it is precisely those superconductors that have potential for use in the construction of high-field superconducting magnets.

A relatively new direction of high magnetic field research is in the area of soft condensed matter, which encompasses a variety of physical systems that are soft in the sense that they can be easily deformed by mechanical or thermal stress or electric and magnetic fields. Such systems include polymers, gels, colloids, membranes, and biological cells or organisms. The binding between molecules in these mostly organic or biological materials (hydrogen bonding, van der Waals, or π-π bonding) is much weaker than in normal solids. High magnetic fields can be used to assemble and align functional, organic or inorganic, nano- and microstructures and to probe their structures, properties, and dynamics, with potential applications in drug delivery, optics, sensors, and nanoelectronics. Applications of high magnetic fields in these experiments make use of the torque exerted by a magnetic field on an object with an anisotropic diamagnetic susceptibility or the force exerted on any object by a strong gradient in field strength.

In the remainder of this chapter, a number of examples are discussed where high magnetic fields play a critical role in condensed matter research.

QUANTUM CRITICAL MATTER

All systems are disordered if the temperature is large enough, with no discernible correlations or patterns in time or space for the configurations of the particles that make up the system. In most solid materials, the particles of interest are the electrons, which carry both a charge and a magnetic moment. Interactions among these electrons can lead to instabilities in their overall energy that are resolved in most cases by the establishment of some type of order. Some compounds order magnetically, when the magnetic moments of individual atoms spontaneously take on long-lived and spatially periodic patterns that create internal magnetic fields as the temperature is reduced. In some cases, materials are transformed from metals, where electrons are free to move and carry current, to insulators, where they become spatially localized and thus incapable of carrying electrical current. Some metals can become superconducting, where a condensed state is formed that consists of electron pairs with opposite moments and opposite momenta, capable of carrying electrical current without dissipating energy. Order is overwhelmingly favored as the temperature is lowered toward absolute zero, where the system is said to enter its lowest energy, or *ground,* state. Most systems become ordered at nonzero transition temperatures, but in some cases this order can be suppressed to progressively lower temperatures by varying a parameter such as pressure or the electric or magnetic field, or simply by changing the composition of the material in question. An extremal ordered state occurs when the transition temperature is continuously suppressed to zero temperature, forming a quantum critical point (QCP). Here the system is poised just on the verge of becoming ordered, and in the absence of this order it fluctuates wildly and unpredictably among configurations where order is only present on short length scales and for short times (Hertz, 1976; Millis, 1993; Sachdev, 1999; Sachdev, 2008).

Much of the functionality that we demand of modern materials depends on the presence of these collective electronic instabilities, as they lead to different and competing ground states: superconductivity, and full or partial charge, orbital, and magnetic order. Controlling the relative stabilities of these ground states by means of external parameters such as electric or magnetic field, chemical variation, pressure, or temperature lends these materials their technological value as novel sensors, or as active elements in electrical or mechanical systems. Indeed, the greatest sensitivity to external variables, and the most complex interplay of energy scales, is generically found near QCPs. It is widely believed that materials with the most extremized functionality require the near balance of competing ground states, and examples of families hosting these QCPs have been documented in virtually every class of material where strong electronic correlations are possible. The most celebrated example is the emergence of superconductivity with the extinguishing of magnetic order in f-electron-based heavy fermion compounds (Mathur et al., 1998), as well as in the iron-pnictide and cuprate superconductors. One of the earliest QCPs studied involves the interplay of superconductivity and charge density wave instabilities in layered chalcogenides (Morosan et al., 2006), in conductors formed from organic molecules (Jaccard et al., 2001), and even in the A-15 family that hosts the most widely used conventional superconductors Nb_3Sn and NbTi (Bilbro and McMillan, 1976). Of particular interest for applications is the symbiosis of ferroelectricity and magnetic order present in multiferroic compounds (Rowley et al., 2010; Kim et al., 2009).

Quantum criticality, when ordering is prohibited at any nonzero temperature and occurs only at zero temperature, is increasingly believed to be a central feature of the phase behaviors of virtually every class of correlated electron system from the f-electron-based heavy fermions (Gegenwart, 2008; Von Lohneysen and

Wolfle, 2008), to complex oxides that include cuprates (Broun, 2008), as well as low-dimensional conductors (Jaccard, 2001), and three-dimensional-based metals with magnetism such as the Fe pnictides and chalcogenides (Dai et al., 2009). Very few compounds form with magnetic order possible only at zero temperature, and in most cases it is necessary to use pressures, compositions, or magnetic fields to tune the ordering temperature to zero degrees to form a QCP if magnetic order is continuous, or a quantum end point (QEP) if the magnetic transition becomes discontinuous or first order. Quantum critical (QC) compounds can be exquisitely sensitive to disorder, making compositional tuning problematic. Pressure tuning has an appealing simplicity, although the bulky equipment needed for high-pressure measurements may limit experimental access, particularly for thermodynamic measurements, which are of particular value for understanding how cooperative phases are stabilized at the lowest temperatures. For all these reasons, magnetic field B tuning is increasingly attractive, particularly if it is paired with low temperatures T to span an extended range of B/T. Since ordering temperatures are emergent scales, the fields required to suppress order may be very small, as in $YbRh_2Si_2$, where only 0.6 T is required to drive the 0.065 K Neel temperature to zero degrees (Custers et al., 2003), or very large, as in $SrCu_2(BO_3)_2$, where 20 T is required to induce magnetic order via the Bose-Einstein condensation of dimer triplets (Kageyama et al., 1999).

Systems where QCPs dominate have remarkable properties that challenge our understanding of such apparently simple concepts as metallic conduction. When magnetic fields suppress magnetic order in heavy fermions, or superconductivity in YBCO (Sebastian et al., 2010) to expose bare QCPs, the electrical resistivity ρ becomes linear in temperature, although the quadratic temperature dependence of a normal metal is regained when the system is tuned sufficiently far from the QCP (Custers et al., 2003). The violation of the Wiedemann-Franz law in $CeCoIn_5$ near the field-tuned QCP (Tanatar et al., 2007) implies that the entities that carry charge and heat are very different from the familiar conduction electrons found in normal metals. Indeed, the familiar idea that electrical current is carried by individual electrons, or *quasiparticles,* must itself fail when the strong QC fluctuations limit their lifetime to be less than $\hbar/E$, given by the Uncertainty Principle (Smith et al., 2008). It is not yet known how universal these observations are, and we have yet to even scratch the surface on how we might exploit these unusual metals to manipulate charge, spin, and heat to provide novel functionalities. These unconventional metals prove to have novel ground states, once the more familiar magnetic order is suppressed (Julian, 1996). Of most interest is the unconventional superconductivity that often is revealed when pressure or composition is used to suppress magnetic or charge order to a temperature of zero degrees. Indeed, this idea has become close to a prescription for finding new families of superconductors (Basov and Chubokov, 2011). Surely the discovery of field-induced superconductivity in ferromagnetic

UGe_2 and URhGe represents the most exotic realization of the expectation that unconventional superconductors are stabilized by the plethora of low-energy excitations that proximity to QCPs can afford (Lévy et al., 2005).

Superconductivity is not the only instability that is found when magnetic order becomes impossible beyond its QCP. One option, found in systems as diverse as $Sr_3Ru_2O_7$, Co-doped $BaFe_2As_2$, and possibly cuprates, is partial or nematic electronic order where there is a spontaneously broken rotation symmetry that does not involve the breaking of translational symmetry (Fradkin et al., 2010). High magnetic fields have been instrumental for delineating the full phase behaviors for these systems, most notably in URu_2Si_2 (Figure 2.1). Here, the nature of the "hidden" order parameter remains uncertain (Kim et al., 2003; Mydosh and Oppeneer, 2011), although it has recently been proposed to be an electronic nematic as well (Okazaki et al., 2011). It seems likely that new types of order will emerge as higher fields and more sophisticated measurement techniques become available.

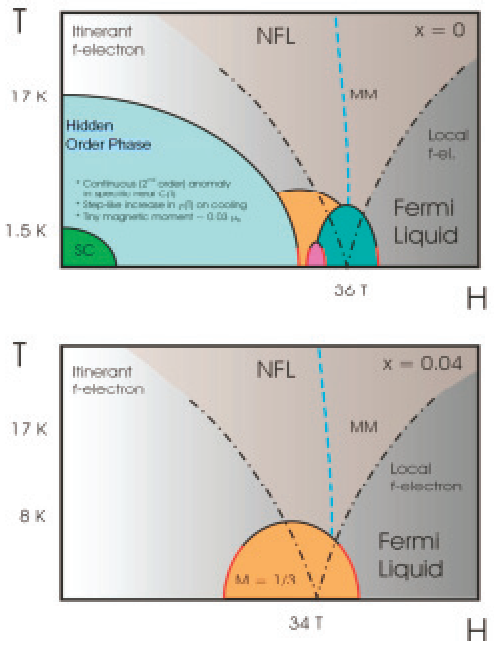


FIGURE 2.1 Sketch of the high magnetic field *T-H* phase diagrams for URu_2Si_2 and $U(Ru_{0.96}Rh_{0.04})_2Si_2$. MM, metamagnetic transitions; NFL, non-Fermi liquid; and phase II is colored in orange. SOURCE: Reprinted figure with permission from J.A. Mydosh and P.M. Oppeneer, 2011, Colloquium: Hidden order, superconductivity, and magnetism: The unsolved case of URu_2Si_2, *Reviews of Modern Physics* 83: 1301-1322, Figure 12. Copyright 2011 by the American Physical Society.

The electronic states of the system itself may also be in transition at the QCP, where the system may fluctuate between very different states such as a localized moment antiferromagnet and a nonmagnetic metal, where order persists only in the form of strong electronic correlations with limited range and lifetime (Figure 2.2). This dual role for the QCP as an electronic delocalization transition implies that there is an associated Fermi surface volume change. Indeed, Hall effect measurements on $YbRh_2Si_2$ (Paschen et al., 2004) and quantum oscillation studies of $CeIn_3$ (Harrison et al., 2007) and $CeRhIn_5$ (Shishido et al., 2005) have provided evidence for this quantum critical breakdown of the Fermi surface. It is clear that quantum oscillation measurements like the ones carried out on f-electron-based heavy fermions have been instrumental for establishing the link between QC and electronic delocalization, and the application of these ideas to other types of QC systems is an important area of future effort. High fields and low temperatures are particularly needed to resolve the heavy mass parts of the Fermi surface, which seem to be most strongly impacted by proximity to the QCP (McCollam et al., 2005).

Our understanding of quantum critical matter is driven forward by the continuous discovery of new materials with new and remarkable properties. The exploration of the phase behaviors of these new compounds is crucial, and there is an underlying expectation that there is an overarching phase diagram, with individual compounds representing various regimes of this master phase diagram. Magnetic fields, especially if they can be combined with other variables like pressure, are important not only for tuning the strength of order but also as a thermodynamically relevant scaling variable. There is every reason to believe that the availability of high fields will lead to the discovery of new types of QCPs and ordered phases, both in existing materials and in those that are yet to be discovered.

Innovations in high-field measurement techniques over the past decade have greatly accelerated progress. It is not enough to use high fields to access a novel ordered phase. Also needed is an experimental description of the thermodynamic and transport properties of this new phase. New techniques for carrying out measurements of the specific heat (Jaime et al., 2000), magnetocaloric effect (Kohama et al., 2010), and magnetostriction (Jaime et al., 2012) in pulsed fields have greatly increased the types of basic information available about these high-field phases, enabling a full thermodynamic analysis. Many of these innovations have been made possible by the availability of long-pulse magnets. In this vein, the availability of higher field magnets for neutron scattering experiments can similarly be expected to be transformative.

One of the most significant technical advances in pulsed field measurement techniques has been the application of focused ion beams (FIB) for shaping single crystals (Moll et al., 2010). Electrical resistivity measurements have been limited in the past by eddy current heating, while low signal-to-noise ratios made measurements on good conductors problematic. Both of these problems can be largely

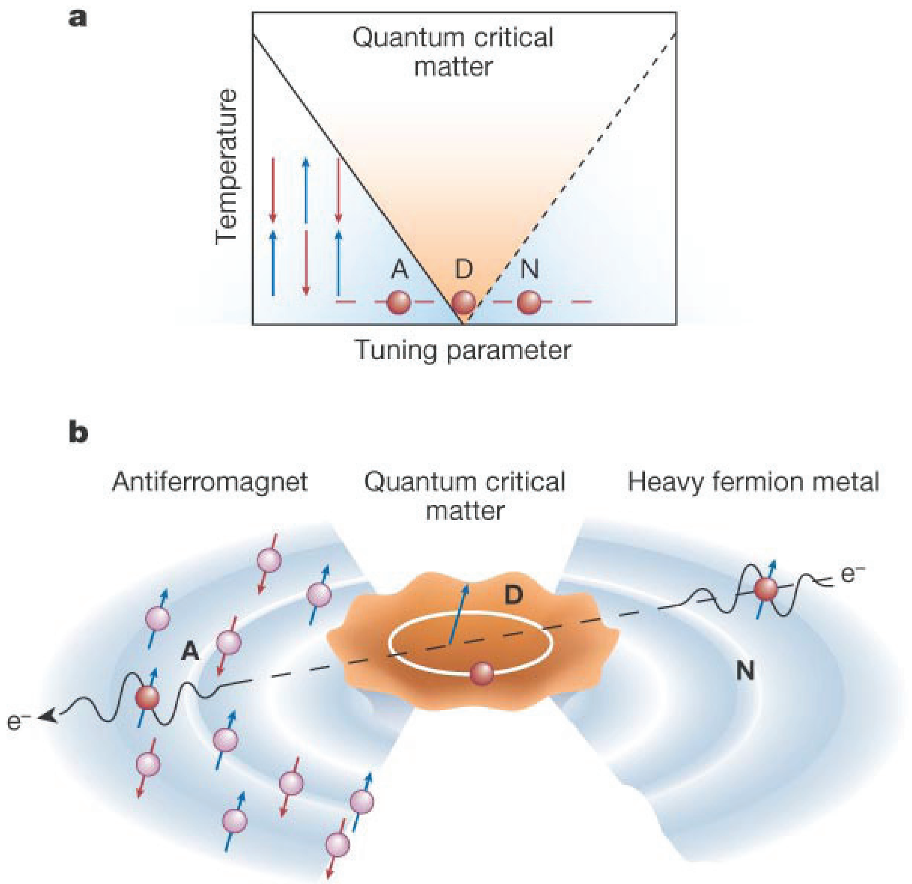
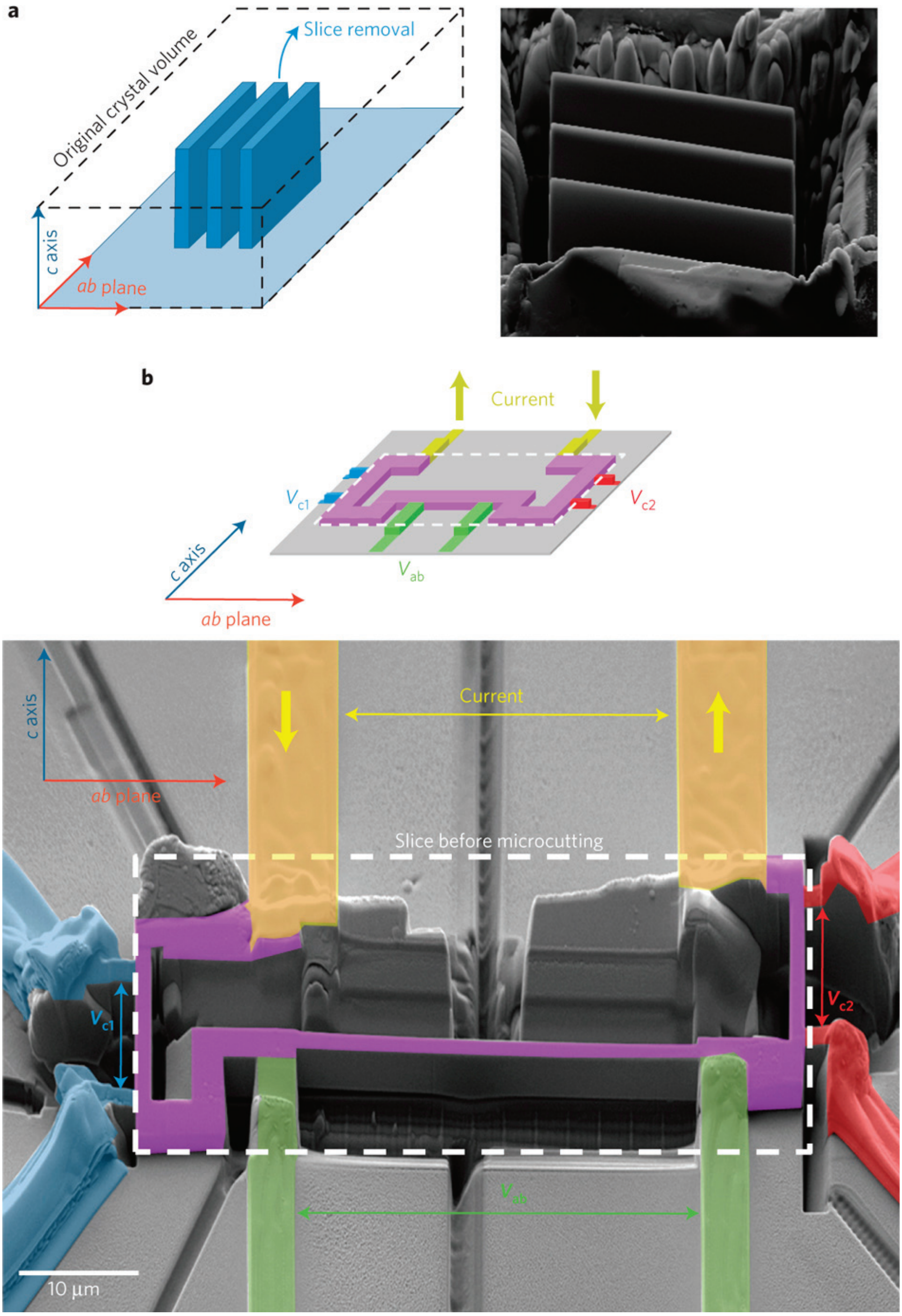


FIGURE 2.2 (*Below*) Schematic phase diagram near a QCP. QCPs distort the fabric of the phase diagrams creating a V-shaped phase of quantum critical matter fanning out to finite temperatures from the quantum critical point. As matter is tuned to quantum criticality, ever-larger droplets of nascent order develop. On length-scales greater than these droplets, electrons propagate as waves. Inside the droplet, the intense fluctuations radically modify the motion of the electron and may lead to its breaking up into its constituent spin and charge components. (*Above*) Physics inside the V-shaped region of the phase diagram probes the interior of the QCPs (D), whereas the physics in the normal metal (N) or antiferromagnet (A) reflects their exterior. If, as we suspect, quantum critical matter is universal, then no information about the microscopic nature of the material penetrates into the droplets. Making an analogy with a black hole, the passage from noncritical to critical quantum matter involves crossing a “material event horizon.” Experiments that tune a material from the normal metal past a QCP force electrons through the “horizon” in the phase diagram into the interior of the quantum critical matter, from which they ultimately reemerge through a second horizon on the other side into a new universe of magnetically ordered matter. SOURCE: Reprinted by permission from Macmillan Publishers Ltd.: Nature. P. Coleman and A.J. .Schofield, 2005, Quantum criticality, *Nature* 433: 226-229. Copyright 2005.

overcome using FIB to shape single crystal samples to have small cross sections, and by tailoring the sample dimensions and current to target the needed voltage levels for a successful measurement (Figure 2.3). FIB processing also allows the deposition of high-conductivity contacts, avoiding surface oxidation issues. It is possible that FIB processing of samples will also make high-pressure resistance measurements less challenging, possibly opening the door to the more routine use of high pressures and high dc fields for the exploration of QC matter. A range of new experimental applications can be contemplated, including quantum oscillation measurements (Sebastian et al., 2012), the implementation of devices where the sample charge and spin transport can be modified independently of the magnetic field, and even the simultaneous measurement of electrical transport with other quantities such as thermal conductivity or specific heat. One of the main constraints on pulsed magnets has been the need to provide slow rise times to avoid eddy current heating and similar experimental considerations. FIB has the potential to provide better control over these parameters, making experiments in magnets with faster rise times and thus higher peak fields feasible. It is generally believed that the next generation of higher field pulsed magnets for user science would require new innovations in the development of high strength/high conductivity materials for the magnet conductors. Implementation of FIB processing may mean that much higher pulsed fields could be available for user science soon, with the promise of expansion to even higher fields as improved magnet conductors become available.

FIGURE 2.3 Four-probe resistance bars for simultaneous *c*-axis and *ab*-plane resistivity measurements carved out of a SmFeAsO0.7F0.25 single crystal using the FIB. (*Top*) A crystal is positioned on a substrate with the *c* axis pointing perpendicular to the plane. The dashed volume indicates the original crystal that is removed during FIB cutting, leaving only the lamellar standing. (*Bottom*) The lamella is transferred to another substrate and flipped, so that its *c* axis is now aligned in the plane (short edge). Most of this lamella (dashed line) is again removed, leaving only the small current path standing (violet). Eight platinum leads are deposited onto the crystal edges (all other colors) that are connected to the resistance bars by narrow (~800 nm for *c* axis) crystal bridges. The common current is injected through the yellow contacts and traverses two *c*-axis resistance bars (blue and red voltage contacts) and one along the *ab* plane (green and violet contacts). Dimensions of resistance bars: length ~35 μm (*ab* plane), ~5 μm (*c* axis), cross section ~1.5 μm^2. SOURCE: Reprinted by permission from Macmillan Publishers Ltd.: Nature Materials. P.J.W. Moll, R. Puzniak, F. Balakirev, K. Rogacki, J. Karpinski, N.D. Zhigadlo, and B. Batlogg, 2010, High magnetic-field scales and critical currents in SmFeAs(O,F) crystals, *Nature Materials* 9:628-633. Copyright 2010.


a
Original crystal volume
Slice removal
c axis
ab plane
b
Current
V_{c1}
V_{c2}
V_{ab}
c axis
ab plane
c axis
ab plane
Current
Slice before microcutting
V_{c1}
V_{c2}
V_{ab}
10 µm

HIGH MAGNETIC FIELD STUDIES OF LOW-DIMENSIONAL, FRUSTRATED, AND QUANTUM MAGNETS

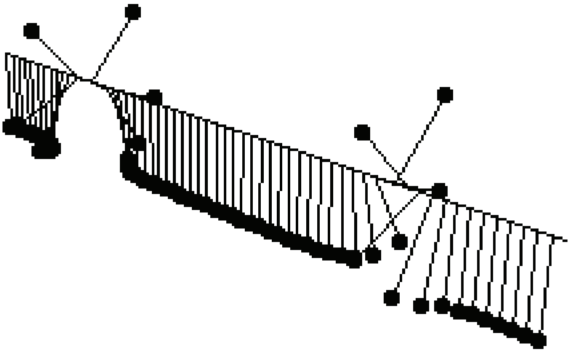
In conventional magnetic materials, such as ferromagnets and antiferromagnets, a quantity of immediate interest is the temperature at which there is an onset of long-range order among the atomic moments, or *spins*. Above this "critical" temperature, T_c, the spins are disordered in space and fluctuate randomly in time as a result of thermal fluctuations. Below T_c, the spins freeze into a static pattern with long-range order, wherein the identification of the orientation of a spin anywhere in the sample defines the orientation of all others. The simplest theory for predicting T_c is the so-called "mean field theory." In mean field theory, the magnitude of T_c is proportional to the interaction energy between neighboring spins and to the number of neighbors. An applied magnetic field will also change T_c in different ways depending on the type of long-range order and depending on the magnitude of the applied field. In order to assess whether a field is high enough to affect a change in T_c, one converts field strength to temperature by considering the energy difference between a spin that is aligned and one that is antialigned with the field. This energy is given by $g\mu_B H$, where $g \sim 2$, μ_B is the Bohr magneton (atomic unit of magnetism), and H the applied field. For H equal to 1 tesla, this energy is equivalent to a thermal energy of 1.3 K. Thus, in order to substantially affect a long-range ordered state, a field with strength equivalent to T_c must be applied. For most single investigators using helium-cooled superconducting solenoids, a field strength of 10 tesla is readily obtainable, thus allowing the modification of materials with T_c up to only ~13 K. In this section the committee considers classes of magnets where T_c is suppressed compared to predictions based on mean field theory. In some cases, this is accompanied by a smaller field scale, required to alter the ordered state.

The effects of low-dimensionality, frustration, and quantum zero point motion all conspire to suppress the mean field T_c in magnets by promoting fluctuations that destabilize the order. Such factors not only reduce T_c but can also give rise to new, previously unexpected states of matter as well as exotic excitations. Low dimensionality, frustration, and quantum zero point motion are all fixed by the material's composition and crystal structure so that their effects in suppressing long-range order can only be inferred from intermaterials comparisons. Applied magnetic fields offer a way to tune these effects, either by stabilizing them (as for ferromagnetic fluctuations) or destabilizing them (as for antiferromagnetic fluctuations). Thus, magnetic fields are essential tools for studying new phases of magnetic matter, and the committee discusses the role of *high* magnetic fields in understanding exotic states.

Low-Dimensional Magnets

The crystal structures allowed in our three-dimensional Euclidean space demonstrate a variety of low-dimensional substructures. For example, materials with a micaceous crystal structure can provide an effective two-dimensional (2D) space in which magnetic ions within a layer interact more strongly with one another than with ions in other layers. Structures also exist that promote 1D interactions along chains of ions. The most prominent difference between such quasi-1D or quasi-2D systems and 3D materials is a reduction of the critical temperature, T_c, at which long-range order appears. A decrease in T_c is expected from mean field theory since T_c varies with the number of nearest neighbors as well as the interaction energy between neighboring ions. In a simple 3D cubic lattice, every ion has six neighbors, whereas this number is four for a square 2D lattice and two for a chain 1D lattice. Theories that go beyond mean field theory and take into account *fluctuations* of ionic spins show that these fluctuations further reduce T_c. For instance, the Ising model of 1D magnets shows that T_c for a chain system is not just less than its 3D counterpart by a factor of three, rather it is zero, reflecting the fact that only one spin that is pointing in the wrong direction can destroy the ordered state, which is not too surprising since in 1D there is only one path to communicate the ordering information. In quasi-2D magnets, fluctuations that prevent traditional long-rage order can lead to exotic types of order, such as the Kosterlitz-Thouless state of quasi-long-range order, where the correlations among spins are not long range but decay as a power of their separation. Such low-dimensional systems also exhibit unusual excitations from the ground state that are not observed in 3D. One example in 1D is that of the sine-Gordon soliton, an excitation that travels without losing its shape—that is, it is dispersionless due to the mathematics of nonlinear fields in one dimension. Such excitations were observed 30 years ago in the quasi-1D system $CsNiF_3$, as distinct signatures in the magnetic field behavior of the thermodynamics of the Ni-centered spin. In quasi-2D systems, such as the $BaNi_2(PO_4)_2$, vortex excitations of a Kosterlitz-Thouless state are strongly implied by inelastic neutron scattering studies. In both materials, the Ni spins are constrained by microscopic electric fields to lie in a plane, a feature that stabilizes the topological soliton and vortex excitations for a reason similar to the reason one can lasso a zucchini but not an orange (see Figure 2.4).

Another example of the importance for high-field studies of quasi-1D magnets is given by the work of Oshikawa et al. (1997). They showed that for 1D spin chains with strong quantum fluctuations, the magnetization is topologically quantized as a function of magnetic field, a phenomenon that bears similarity to the quantum Hall effect observed in 2D electron metals in a magnetic field. A physical realization of this theory is found in the azurite structure compound $Cu_3(CO_3)_2(OH)_2$, shown in Figure 2.5. Here, the $s = ½$ Cu ions form a linear chain with alternating numbers



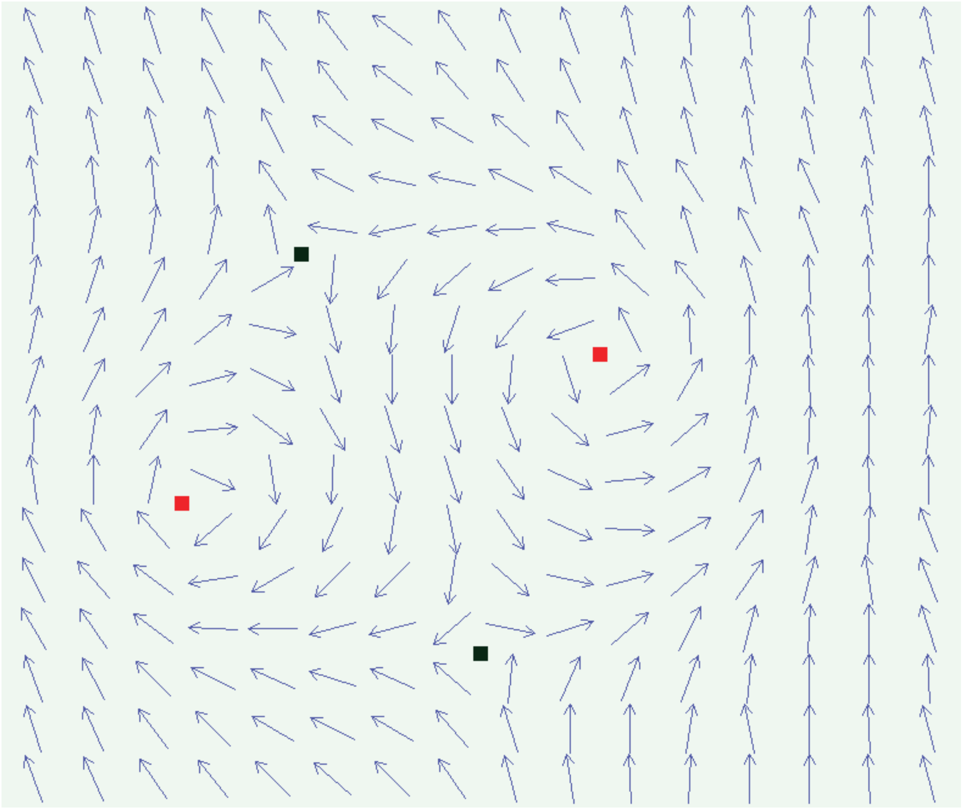


FIGURE 2.4 (*Top*) A pair of solitons of opposite sign in a 1D chain, where the pendula represents spins. (*Bottom*) Vortices on a 2D spin system. SOURCE: (*Top*) Courtesy of Kanehisa Takasaki, Kyoto University. (*Bottom*) Courtesy of Evgeny Demidov, Institute for Physics of Microstructures, Russian Academy of Sciences.

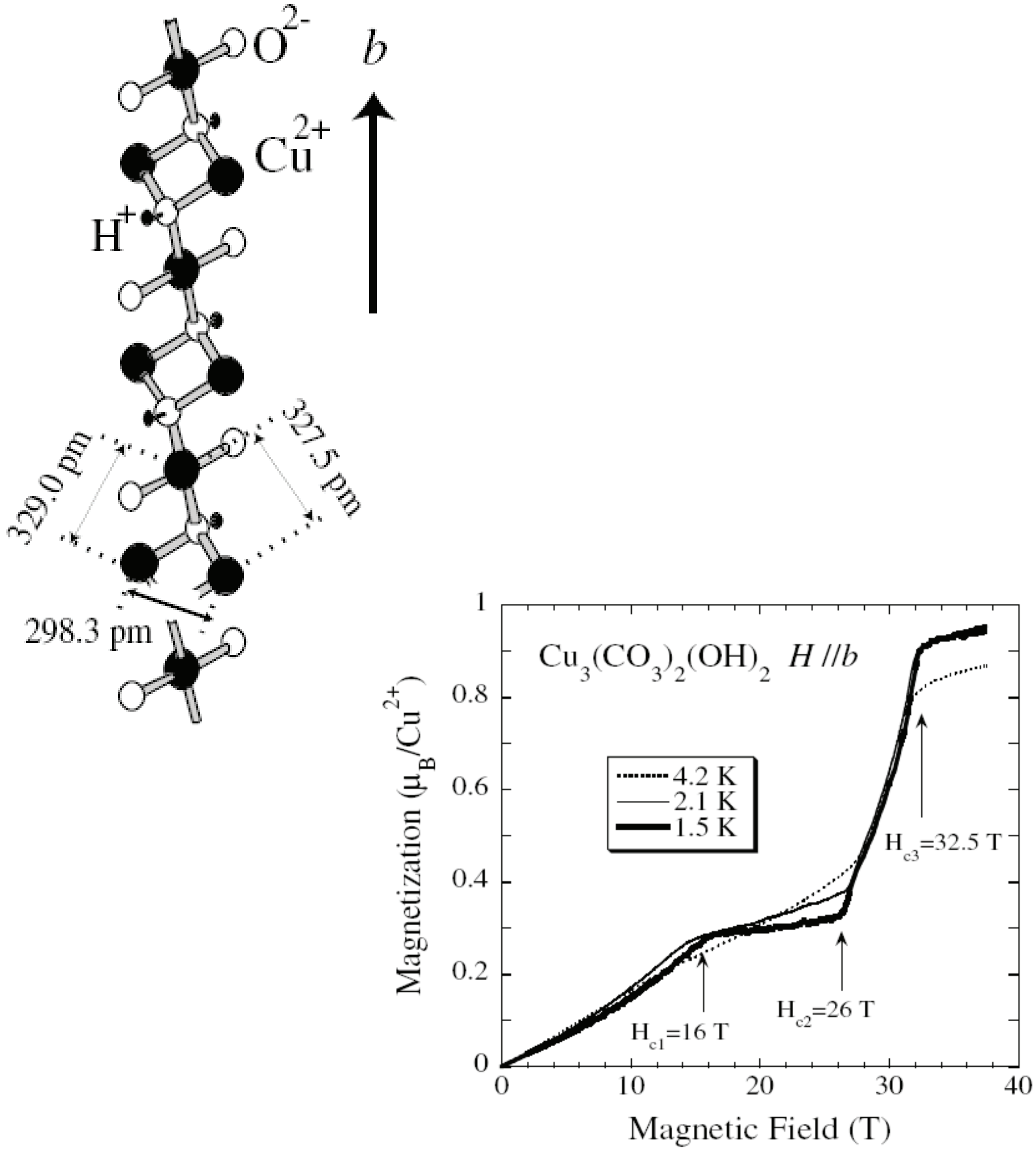


FIGURE 2.5 (*Left*) Schematic view of the crystal structure of the azurite $Cu_3(CO_3)_2(OH)_2$ along the b axis. (*Right*) The high-field magnetization of $Cu_3(CO_3)_2(OH)_2$ measured below 4.2 K. SOURCE: (*Left*) Reprinted figure with permission from H. Kikuchi, Y. Fujii, M. Chiba, S. Mitsudo, T. Idehara, T. Tonegawa, K. Okamoto, T. Sakai, T. Kuwai, and H. Ohta, 2005, Experimental observation of the 1/3 magnetization plateau in the diamond-chain compound $Cu^3(CO^3)^2(OH)^2$, *Physical Review Letters* 94:227201, Figure 1(b). Copyright 2005 by the American Physical Society. *(Right)* Reprinted figure with permission from the same source, Figure 2(a).

of nearest neighbors on the chain, the so-called “diamond spin chain.” The figure shows this structure and the magnetization, which demonstrates a field-induced state having ~ $^1/_3$ of the saturation magnetization. In the Oshikawa et al. picture, this plateau is associated with a periodic modulation of the local magnetization along the chain. This is one example of how magnetic fields can create exotic states of matter.

Another example of the importance of high magnetic fields for quasi-1D magnets is the spin chain system $CoNb_2O_6$. In this compound, the cobalt spins are of the Ising type, meaning that the spin direction is constrained by local atomic forces to point along a single direction, the Ising axis. For a spin ½ ion, such as divalent Co, such constraint leads to two distinct quantum states, aligned and anti-aligned when the magnetic field is applied along the Ising axis. When a magnetic field is applied perpendicular to this direction, however, the system’s eigenstates are a combination of the two original states. While the dominant interactions in $CoNb_2O_6$ are along the chain, weak interchain interactions induce antiferromagnetic 3D ordering below 2.95 K in zero field. This order can also be destroyed by applying a transverse magnetic field greater than 5.5 tesla near 0 K. At this quantum critical transverse field of the Ising chain, a degenerate spectrum of eight quasiparticles has been theoretically predicted. In order to observe these quasiparticles, a small additional field was applied along the Ising direction and inelastic neutron scattering was performed. As shown in Figure 2.6, left, peaks corresponding to the energy loss of the neutron beam are observed at well-defined energies. The ratio between the energies of these first two peaks is shown to the right, where it is seen that, as the transverse field approaches the critical value of 5.5 tesla, this ratio approaches the golden mean, as predicted by the theory. The emergence of a field theory with eight massive particles arising only from an Ising chain system in a magnetic field is a spectacular example of how complex states of matter can arise from a set of simple ingredients.

Organic Magnets

Organic molecules are the basis for a large number of molecular magnets. These molecules tend to be flat—C_{60} being a well-known exception—and thus the resulting crystal structures typically resemble stacks of molecules. In these structures, the shortest van der Waals bond between stack edges defines the dimensionality of charge transport or dominant magnetic order, and this dimensionality is often quasi-1D or quasi-2D. The prevalence of 1D interactions among organics makes them ideal systems in which to study Fermi-surface instabilities such as Peierls or spin-Peierls transitions. Also, due to the large effective distance between molecules containing a transition metal ion, the mean field energy scale for magnetism can be low and therefore easily destroyed by magnetic field. The interplay

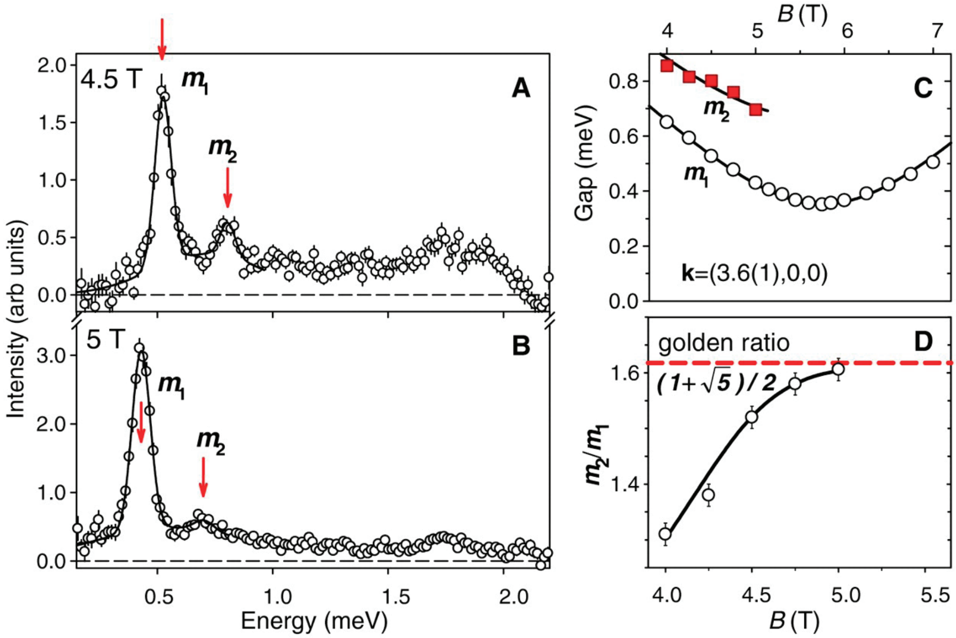


FIGURE 2.6 (*A and B*) Energy scans at the zone center at 4.5 and 5 tesla (T) showing two peaks, m_1 and m_2, at low energies. (*C*) softening of the two energy gaps near the critical field (above ~5 T the m_2 peak could no longer be resolved). The incomplete gap softening is attributed to the interchain couplings as described in the text. (*D*) The ratio m_2/m_1 approaches the golden ratio (dashed line) just below the critical field. SOURCE: From R. Coldea, D.A. Tennant, E.M. Wheeler, E. Wawrzynska, D. Prabhakaran, M. Telling, K. Habicht, P. Smeibidl, and K. Kiefer, 2010, Quantum criticality in an Ising chain: Experimental evidence for emergent E8 symmetry, *Science* 327:177-180. Reprinted with permission from AAAS.

between such magnetism and charge transport is demonstrated in the compound λ-$(BETS)_2FeCl_4$, which possesses a low-field antiferromagnetic state with BETS standing for bis(ethylenedithio)-tetraselenafulvalene. Near fields of 18 tesla, the antiferromagnetic state is destroyed and a superconducting state appears, eventually being destroyed itself at 41 T.

Organic crystalline systems are also well-suited to study magnetic quantum effects in low dimensions due to the commonality of free radicals, which have an unpaired electron, which often leads to a spin-½ moment on the molecule. In the quasi-2D organic system κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$ (BEDT-TTF stands for bis(ethylenedithio)tetrathiafulvalene), the presence of this spin-½ moment has led to the observation of quantum spin liquid behavior, related to the frustrating effects of a triangular lattice in this compound. The interplay of magnetism and superconductivity demonstrated in λ-$(BETS)_2FeCl_4$, mentioned above, suggests a compelling motivation for the continued study of organic compounds in high magnetic fields. The molecular nature of organics allows, in principle, the decoupling of the pairing excitation from the lattice, the so-called Little mechanism for superconductivity. This mechanism has never been confirmed as originally envisioned, although superconductivity in alkali-doped C_{60}, which is mediated by intra-molecular vibrations, bears some similarity. It is conceivable that ordinary magnetism in organics is a common mask for a superconducting state that is revealed only in very high magnetic fields. Superconductors uncovered in this manner would provide intriguing examples motivating possible synthetic routes for new superconductors in low fields.

Frustrated Magnets

The concept of frustration in magnetic materials is relatively simple. A conventional unfrustrated long-range-ordered antiferromagnetic state is depicted in the left hand side of Figure 2.7. Here, each arrow represents an ionic spin in a 2D Ising magnet, as would be realized in the low-temperature state of $CoCs_3Br_5$, for example. In such systems, the magnetic (antiferromagnetic) interaction is compatible with the lattice in the sense that there exists an ordered state in which each magnetic bond can minimize its energy. To the right is shown a counterexample, illustrating the basic conundrum behind geometrical frustration. Symmetry incompatibility between the magnetic interactions and the geometry of the triangle-based lattice implies that there exists no state in which each bond can minimize its energy. In

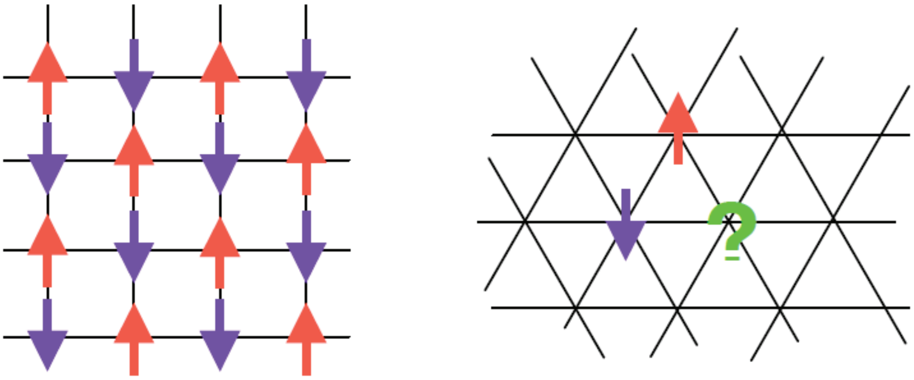


FIGURE 2.7 (*Left*) Unfrustrated antiferromagnetic structure on a square 2D lattice. (*Right*) Frustrating structure of the 2D triangular lattice for Ising spins.

the limit where a solid is built up from such triangles, the lowest energy state contains a nonzero fraction of high energy bonds. More importantly, as can be seen in Figure 2.7, for the triangle, there are three ways to achieve a spin configuration with one high energy bond. These multiple, or degenerate, states at the atomic level eventually lead to low energy states for the bulk solid that are different from the traditional long-range-ordered states. These frustrated states fall into one of two generic classes, depending on whether the spin can point continuously in any direction or point only along a given (Ising) axis defined by the other ions in the crystal. In the first case, the continuity of spin direction, combined with the degeneracy of available states, leads to "spin-liquid"-like behavior. In the second case, the high energy bond is in a different position from triangle to triangle and the resulting disorder is frozen in at low temperatures. This is a so-called "spin ice" state, by analogy with the disordered hydrogen positions in water ice.

Fortunately, there exist many crystal structures that provide a triangular atomic building block. Indeed the large mineral families of the pyrochlores, the spinels, and the delafossites contain several model compounds for the behavior implied above and the study of its interaction with magnetic field.

One example is found in the spinel compound $ZnCr_2O_4$, shown in Figure 2.8. This compound can be viewed as a 3D structure containing corner-sharing tetrahedra of trivalent Cr ions with spin $3/2$. The tetrahedron is the three-dimensional analogue of the triangle used above—namely, a frustrating unit out of which a lattice can be constructed, as shown in Figure 2.8 for the B-sites of the spinel lattice.

Measurements of the magnetic susceptibility of $ZnCr_2O_4$ in the temperature range 50-300 K can be described by mean field theory and suggest that antiferromagnetic ordering should have occurred at $T_c = 390$ K. Instead, antiferromagnetic order in $ZnCr_2O_4$ sets in at $T_c = 12$ K. Here, the magnetic interactions are so strong that ordering is accompanied by changes in the lattice constant and sound velocity. Despite possessing T_cs that are much lower than the mean field prediction, frustrated magnets are affected by magnetic fields on the scale of the spin-spin interactions, reflecting the local nature of the frustration phenomenon. For example, even though $ZnCr_2O_4$ orders at 12 K, suggesting that fields of order 10 tesla would be able to modulate T_c, such fields have almost no effect. In order to explore whether higher fields could affect $ZnCr_2O_4$, an experiment was performed using a field compression technique, and the magnetization probed using Faraday rotation, shown in Figure 2.9. At a temperature of 6 K, $ZnCr_2O_4$ exhibits a sharp increase in magnetization at about 130 T in the [111] direction with several smaller anomalies at higher fields, as shown. The anomalies at 240 T, 290 T, and 350 T correspond to $2/3$, $3/4$, and $5/6$ of the full moment, and while a theoretical understanding is not yet fully developed, the underlying kagome structure in the [111] direction suggests dimensional reduction might take place, leading to topological phases.

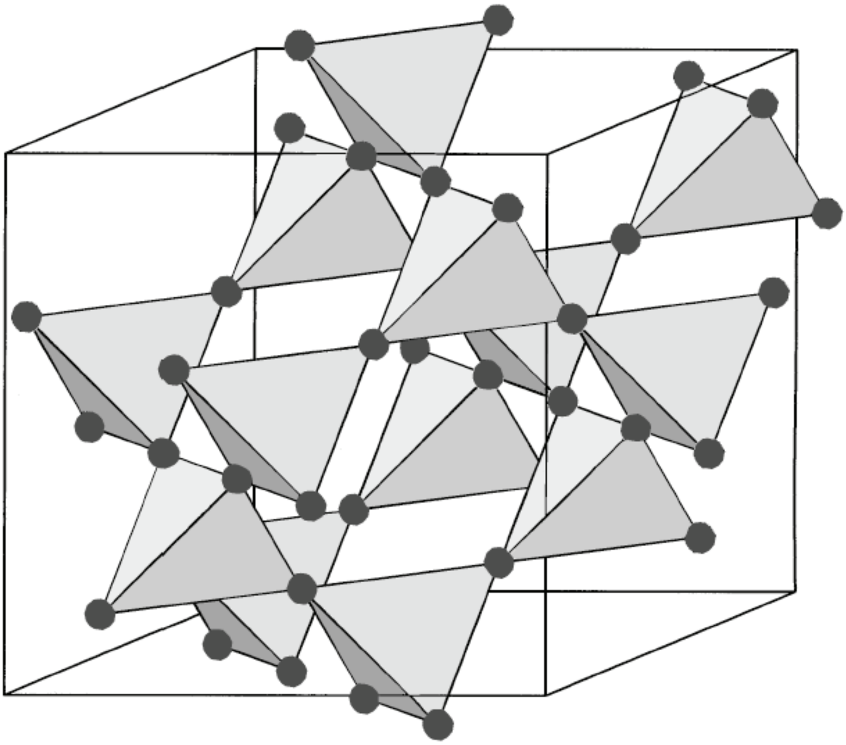


FIGURE 2.8 Lattice structure of the magnetic (A) sites in the pyrochlore compound $A_2B_2O_7$ or the B sites in the spinel compound AB_2O_4. SOURCE: S.T. Bramwell and M.J. Harris, 1998, Frustration in Ising-type spin models on the pyrochlore lattice, *Journal of Physics: Condensed Matter* 10:L215-L220. © IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved.

High Fields for Frustrated Multifunctional Materials

Researchers are presently searching for new materials that simultaneously possess the properties of ferromagnetism and ferroelectricity. The former property is used in information storage and the latter is used in sensors and actuators. The search for materials that not only possess both properties but where one property controls the other is motivated by applications such as electrically controlled information storage or electrodes on spintronics devices. These materials searches are uncovering a wealth of complex new phases, one example of which is $Ni_2V_3O_{8.}$ Originally identified as a possible frustrated magnet due to its "kagome staircase" structure, it was soon discovered to exhibit a ferroelectric phase at low fields, as shown in the phase diagram in Figure 2.10 as the C phase. Subsequent measurements above 20 tesla revealed a complex high-field phase diagram, with magnetization plateaus corresponding to ⅔, ¾, and 8⁄9 of the saturation magnetization.

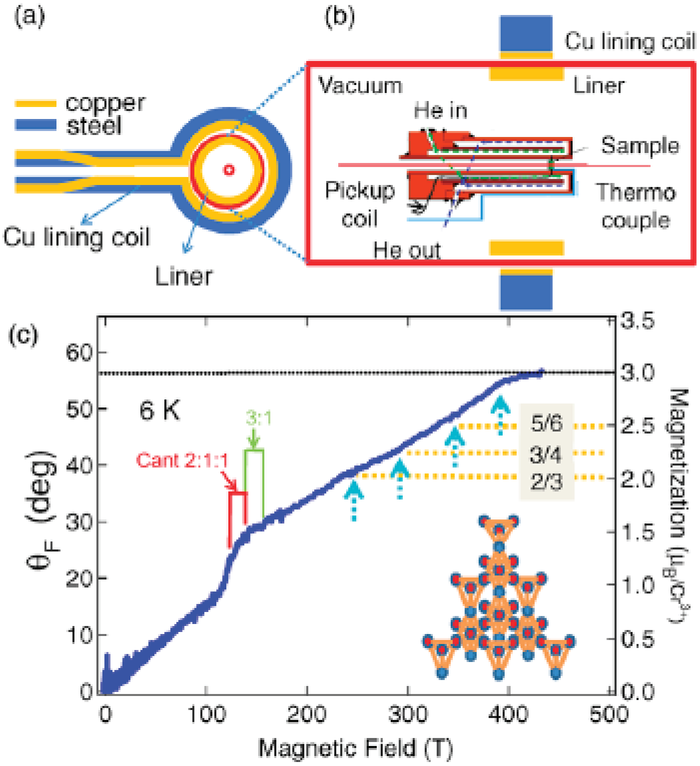


FIGURE 2.9 (*a*) Primary coil for the electromagnetic flux compression; (*b*) handmade optical cryostat made of “stycast” resin; (*c*) magnetization of $ZnCr_20_4$ measured by the Faraday rotation method at 6 K under ultrahigh magnetic fields generated by the flux compression. Arrows show the phase transitions above the plateau phase. SOURCE: With kind permission from Springer Science and Business Media: E. Kojima et al., 2010, Magnetic orders of highly frustrated spinel, $ZnCr_20_4$ in magnetic fields up to 400 T, *Journal of Low Temperature Physics* 159:3-6, Figure 1.

Quantum Matter Probed by High Magnetic Fields

In the example described earlier of high-field studies of the quasi 1D Ising system $CoNb_2O_6$, the effect of the magnetic field was to offset the effect of the mean ordering field. Since the energy between the ground state doublet and the next excited quartet state is about 300 cm^{-1}, the effect of the transverse applied field is to mix the Ising eigenstates en route to polarizing the spins at high field. This mixing involves quantum fluctuations, which ultimately destabilize the 3D order at a critical field of ~ 5 T. Another example of the balance between quantum fluctuations and long-range order induced by exchange interactions is found in

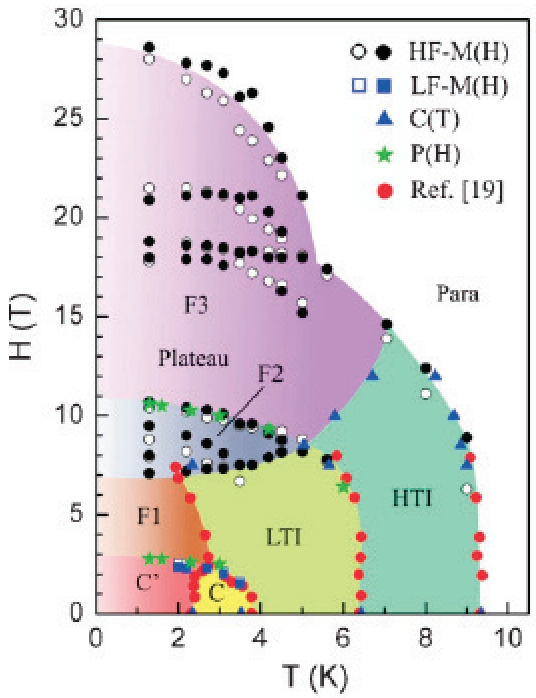


FIGURE 2.10 H-T phase diagram for $Ni_3V_2O_8$ for H || a, determined from magnetization (M), electric polarization (P), and specific heat (C) measurements. Open (closed) symbols are for increasing (decreasing) field. The phases are as follows: HTI, high temperature incommensurate; LTI, low temperature incommensurate; C and C′ are two different commensurate phases; F1, F2, and F3 are phases the nature of which is unknown at present. SOURCE: Reprinted figure with permission from J. Wang, M. Tokunaga, Z.Z. He, J.I. Yamaura, A. Matsuo, and K. Kindo, 2011, High magnetic field induced phases and half-magnetization plateau in the S=1 kagome compound $Ni_3V_2O_8$, *Physical Review B* 84:220407(R), Figure 3. Copyright 2011 by the American Physical Society.

$LiCuVO_4$. $LiCuVO_4$ possesses an inverse spinel structure with an orthorhombic distortion where the Cu^{2+} (s = ½) ions form chains separated by the nonmagnetic Li, V, and O ions. An antiferromagnetic phase with an incommensurate spiral spin structure sets in at 2.3 K. Zhitomirsky and Tsunetsugu predicted this structure to exhibit a quantum spin nematic phase at high fields by a magnetic analogy to the orientational ordering of needlelike molecules in liquid crystals. Figure 2.11 shows the magnetization of $LiCuVO_4$ using a pulsed-field technique. The kink at H_{c3} is interpreted as evidence for the appearance of the quantum spin nematic phase. Confirmation of this new state of magnetism will require neutron-scattering studies, but the fields required are beyond those presently available in neutron-scattering facilities.

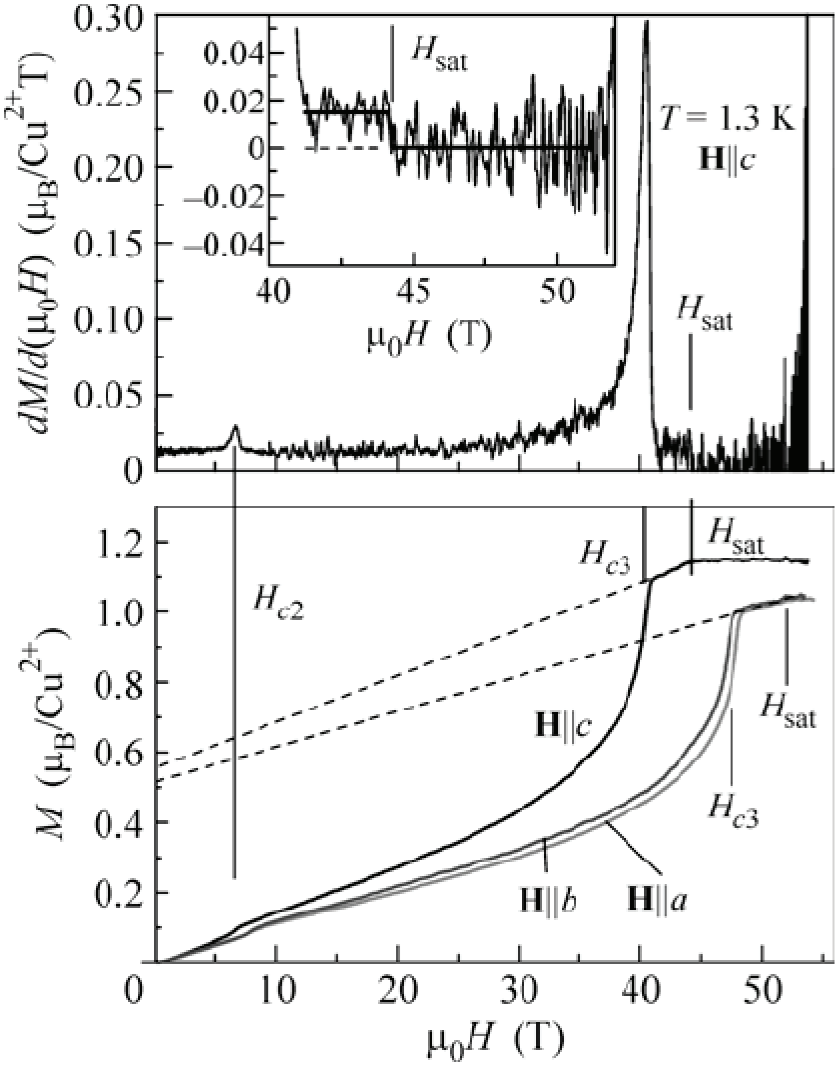


FIGURE 2.11 (*Upper panel*) *dM/dH* of $LiCuVO_4$ measured using a pulsed-field technique. The inset shows *dM/dH* near H_{sat}. The solid line is a fit to a step function. (*Lower panel*) *M(H)* at T = 1.3 K, obtained by integration for **H** || *a, b, c*. The solid lines correspond to the magnetization for the field-descending process. The straight dashed lines are linear fits in the range $H_{c3} < H < H_{sat}$ and extrapolations to these fits to zero field. SOURCE: With kind permission from Springer Science and Business Media: L.E. Svistov, T. Fujita, H. Yamaguchi, S. Kimura, K. Omura, A. Prokofiev, A.I. Smirnov, Z. Honda, and M. Hagiwara, 2011, New high magnetic field phase of the frustrated S=1/2 chain compound $LiCuVO_4$, *JETP Letters* 93:21, Figure 2.

The above examples illustrate the uniqueness of magnetic systems for studying phase transitions in condensed matter systems. With the variety of magnetic ions, effective dimensionalities, and reasonably precise knowledge of the spin-spin interactions, magnets are used to model generic problems in statistical physics. The ability to create magnetic fields over a wide range of energies allows us to continuously challenge and expand our understanding of matter.

SUPERCONDUCTORS IN HIGH MAGNETIC FIELDS: AN EXPANDING FRONTIER

Early in the history of superconductivity (see Box 2.1), its relation to magnetic field became the object of enduring fascination. The Meissner effect, the full expulsion of the external magnetic field from a bulk superconductor below a certain maximum field strength, provided an early clue to the microscopic origin

BOX 2.1
Superconductors:
Low-T_c and High-T_c, Conventional and Unconventional

Superconductivity at critical temperature $T_c = 4.2$ K was discovered in 1911 in mercury. Numerous elemental metals (Pb, Al, Nb, and others) become superconducting at $T_c < 10$ K. The transition temperature of metallic alloys and compounds (e.g., Nb_3Sn) can exceed 15-20 K. The microscopic mechanism of superconductivity in these materials is understood within the Bardeen-Cooper-Schrieffer (BCS) theory epitomizing the key role of the electron-phonon interaction in superconducting pairing. The discovery of superconductivity in copper oxides (cuprates) in 1986 has revolutionized this field of research and all of condensed matter physics. Not only is the transition temperature of the cuprates high (the record is 160 K), but many electronic and magnetic properties of the cuprates reveal radical departures from the BCS scheme. Thus, cuprates are commonly referred to as high-T_c superconductors and also as unconventional superconductors. However, not all cuprates have high transition temperatures. For example, the $Re_{2-x}Ce_xCuO_4$ family has $T_c < 25$ K (Re, rare earth elements). And yet these particular cuprates are as unconventional as some of their counterparts with much higher T_c. Likewise, several other classes of low-T_c materials (organic compounds and heavy-fermion systems) possess exotic properties and are regarded as prototypical examples of unconventional superconductivity despite their low T_c in the range of 0.1-10 K. Iron-based superconducting pnictides and chalcogenides ($T_c < 60$ K) appear to have much in common with cuprates and other superconducting systems where magnetism is likely to be involved in a major way with superconductivity. It is therefore tempting to classify these two classes as unconventional superconductors. Other materials, including MgB_2 ($T_c = 40$ K) and A_3C_{60} ($T_c < 40$ K), show relatively high transition temperatures. However, because the electron-phonon interaction is believed to be responsible for superconductivity in both MgB_2 and A_3C_{60}, these systems are usually referred to as conventional superconductors (Choi et al., 2002, Gunnarsson, 1997).

of superconductivity as a state exhibiting coherent quantum behavior "over miles of dirty lead wire," in John Bardeen's words.

A new dimension of interplay between superconductivity and magnetic fields became apparent with the discovery of the so-called "type II" superconductors, which stand in contrast to the elemental type I superconductors. In the latter, the magnetic field is expelled until it completely suppresses superconductivity at a critical field H_c. On the contrary, in the case of the type II materials, above a lower critical field H_{c1}, the magnetic field intrudes into the superconductor in the form of quantized flux lines, each carrying a unit of fundamental flux quantum $H_c/2e$. This flux quantization signals the crucial role played in superconductivity by pairs of electrons of charge 2e (Cooper pairs) and is recognized as yet another universal property of type II superconductors, alongside the Meissner effect. Superconductivity is suppressed only when one reaches an upper critical field H_{c2}. In the region between the H_{c1} and H_{c2}, the fluxes are anchored to the locations of topological defects in the complex superconducting order parameter (i.e., vortices) and organize themselves into an ordered array, the Abrikosov lattice. Thus the field-temperature (H-T) phase diagram of conventional type II superconductors was completed (Figure 2.12) and became understood rather well (Tinkham, 1996; de Bruyn Ouboter, 1997). Because of their ability to carry electrical current with vanishing resistance, even in high magnetic fields, type II superconductors are *the* materials of choice for construction of high-field magnets for research, and also for a wide array of applications, including medical MRI.

High-Temperature Superconductivity in Copper Oxides

The discovery of high-temperature superconductivity (HTS) in copper oxides (Bednorz and Mueller, 1986) with T_c reaching 160 K, inaugurated the new era of extreme type II superconductivity (Figure 2.12). The main characteristic of these *extreme* type II superconductors is that H_{c2} is orders of magnitude larger than H_{c1}, often reaching into tens or even hundreds of tesla. Consequently, the ability to perform measurements in very high magnetic fields is an essential component of frontier research in HTS. In effect, the "mixed" state between H_{c1} and H_{c2}, where superconductivity coexists with magnetic field, became the dominant region in the phase diagram, while the Meissner state is found in only a tiny sliver at very low fields, below H_{c1}. Notably, T_c in HTS systems is comparable to the characteristic electronic energies, including the Fermi energy E_F. This is significant since $T_c << E_F$ is the key condition for the validity of the conventional BCS theory, perhaps the most successful "mean-field" theory in all of physics.

With T_c in cuprates routinely around 100 K, reaching fields of tens or even 100 T became both an experimental challenge and imperative. A worldwide effort

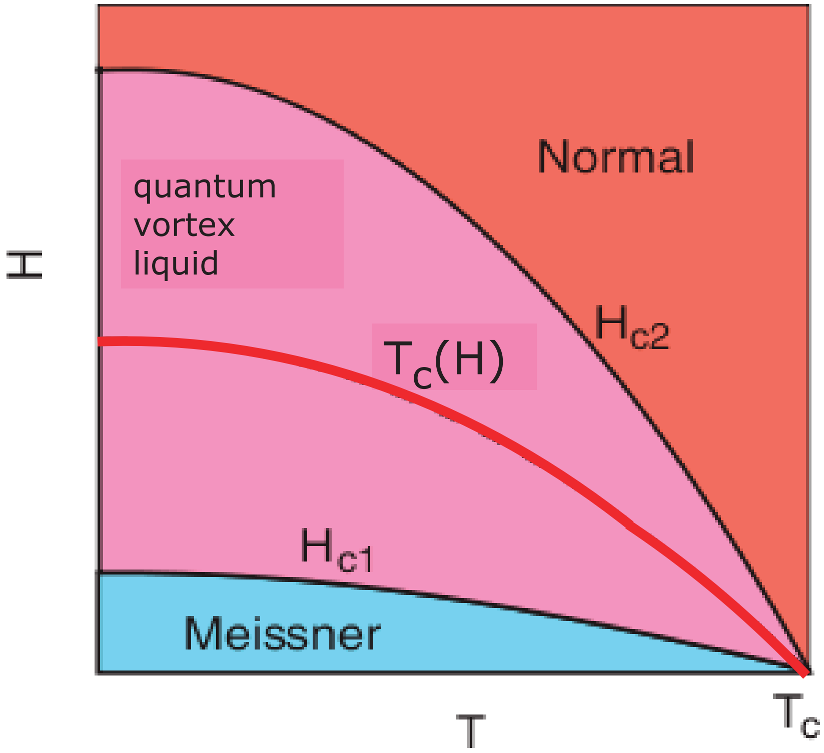


FIGURE 2.12 Phase diagram of extreme type II superconductors: In conventional type II superconductors, the magnetic field-temperature (H-T) phase diagram is marked by the upper and lower critical fields, H_{c1} and H_{c2}, respectively. For visual clarity, the size of H_{c1} relative to H_{c2} in extreme type II systems, routinely less than 1 percent, is intentionally exaggerated. At H_{c1} the magnetic field penetrates into a superconductor in the form of quantized fluxes, while at H_{c2} the Abrikosov lattice of such fluxes disappears along with the superconductivity itself. In extreme type II HTS these lines morph into gradual crossovers as strong thermal and quantum fluctuations erase the mean-field BCS features and replace them with phase transitions of an entirely different kind. For example, the true superconducting transition $T_c(H)$ is now the line where fluctuating vortices, already present in the normal state, turn from a liquidlike correlated state into some kind of a frozen arrangement, the precise nature of which involves an elaborate interplay among interactions, disorder, and materials features (the symmetry of the underlying crystal lattice, the symmetry of Cooper pairs, the presence or absence of gapless quasiparticles, etc.). The exploration of the vast regime between $T_c(H)$ and $H_{c2}(T)$, relying on magnetic fields as high as tens or even hundreds of tesla, has been one of the richest and intellectually most rewarding areas of research in physics during the past 10 to 15 years and is bound to remain so in the coming decade.

in studies of the interplay of superconductivity with high magnetic fields in the cuprates is at the cutting edge of research in condensed matter physics. Among the outcomes of this research is a refined understanding of superconducting fluctuations, phase transitions in vortex arrays, and quantum oscillations in superconductors. These efforts continue, recently reenergized by the discovery of HTS in iron pnictides and chalcogenides, multiband and less anisotropic relatives of cuprates, opening yet another window from which to view the fundamental phase diagram of Figure 2.12.

The cuprate high-T_c materials are a striking example of unconventional superconductors. Unlike conventional BCS superconductors, where the Cooper pairing of electrons is due to attractive interactions mediated by lattice vibrations, the Cooper pairing in these new materials is likely the product of *repulsion*. While there may not be a clear-cut experiment that would establish this directly beyond reasonable doubt, this point of view is strongly supported by the unconventional d-wave nature of Cooper pairs in cuprates, which has been explicitly demonstrated. Within the BCS theory, superconducting pairing impacts only a small fraction of electrons residing in the immediate vicinity of the Fermi surface: a surface of constant energy in the momentum space which separates empty and filled electron levels in the normal metallic state. In conventional BCS superconductors the Cooper pairs form in an s-wave state, which leads to a superconducting energy gap that is more or less uniform all around the Fermi surface. In the cuprates, however, the low-energy fermionic excitations are gapless at certain points or lines on the Fermi surface. These excitations lead to dramatic differences in thermodynamic and transport properties compared to the prescriptions of BCS theory.

Very importantly, as one looks for deviations from the mean-field BCS description, these low-energy quasiparticles and their interactions with superconducting vortices, through thermal and quantum fluctuations, become a fundamental problem in reconstructing the phase diagram of HTS. Various elements of this problem are the subject of intense ongoing research, much of which involves very high magnetic fields (some recent examples are in Riggs et al., 2011; Sebastian et al., 2008; Wu et al., 2011). Magnetic fields are crucial since, by weakening superconductivity, they usher in strong fluctuations.

Not only is the superconductivity of the cuprates unconventional, but their normal state properties are equally exotic. Common metals are described by the Fermi liquid theory establishing that, despite their high density in a metal, electrons behave as noninteracting quasiparticles. In the high-T_c cuprates, there are very strong correlations among the electrons even in the normal state, which render inapplicable existing approaches developed for weakly or noninteracting electronic systems. The strong correlations result from the fact that the superconducting cuprates are materials where a modest density of either electrons or holes have been introduced in the CuO_2 planes of an insulating antiferromagnetic

(AF) host. The high-T_c phenomenon involves a delicate balance of competing effects, including superconducting pairing, electronic correlations, and spin and/or charge order. These latter factors are at least partially responsible for anomalous sensitivity of HTS cuprates to external perturbations, including magnetic fields, as well as extreme dependence of observables upon composition and/or disorder. A remarkable property of many cuprates is a pseudogap, a partial gap dominating the excitation spectrum of underdoped materials. It is universally recognized that understanding the pseudogap physics is an imperative step toward uncovering the mystery of high-T_c superconductivity (Norman et al., 2005).

High magnetic fields are uniquely suited to address and resolve some of the most pressing issues in the field of cuprate superconductivity. Specifically, fields above the upper critical field suppress superconductivity and thus provide experimental access to the $T \rightarrow 0$ normal state properties in the absence of superconductivity. Data by Ando et al. (1995) obtained in pulsed magnetic fields in the mid-1990s indicated that, in some materials, the normal state transport at $T < T_c$ has a resemblance to insulators and is in stark contrast to that of ordinary metals (Ando et al., 1995). More recent high-field experiments performed for less disordered cuprate compounds have uncovered quantum oscillations, a phenomenon that is a hallmark of the well-defined Fermi surface (Doiron-Leyraud, 2007).

High magnetic fields will continue to play an essential role in superconductivity research. High fields allow access to the low-temperature regime of cuprates and pnictides, where quantum fluctuations away from the BCS theory dominate. Thus, entirely new quantum states of matter, not just uncovered by but *induced* by high magnetic fields, become a realistic possibility. One example of such a novel field-induced state is the formation of unidirectional charge- and/or spin-ordered regions in the cuprates, commonly referred to as stripes (Lake et al., 2002). This and other discoveries show that magnetic field research in cuprates is of high intellectual impact. Furthermore, this work is of unparalleled technological significance since in the background of the purely scientific quest, there is always the key issue of practical uses of extreme type II superconductors in energy generation, transmission, and storage, as well as numerous other applications from superfast trains to powerful particle accelerators. In particular, as detailed in Chapter 7 of this report, cuprate high-T_c material is the only viable material system for the development of all-superconducting magnets at 30 T and above.

High-Temperature Superconductivity in Iron Pnictides and Chalcogenides

Iron-based HTS burst onto the scene in 2008. This was a major serendipitous discovery that occurred subsequent to the 2005 NRC study on Opportunities in High Magnetic Field Science. As the first HTS materials that are not copper-based (Kamihara et al., 2008), iron-based superconductors have engendered a tsunami of activity. The iron-based systems continue to be a vibrant and rapidly evolving area, adding new facets to the field of unconventional high-T_c superconductivity. This much is known: these are multiband HTS, with a Fermi surface consisting of several distinct "pockets." The superconducting gap appears to have opposite signs on these pockets, suggesting that the interelectron repulsion is again a likely culprit behind the HTS mechanism. The cuprate and pnictide families appear to share a number of characteristics (Basov and Chubukov, 2011). Specifically, the normal state properties of both families of materials are dominated by strong correlations in the electronic system. Both cuprates and pnictides reveal quantum oscillations in high magnetic fields (Shishido et al., 2010). However, pnictides are less anisotropic than cuprates, bringing the *full* phase diagram of Figure 2.12 into the range reachable by available or soon-to-be-available magnetic fields. The pnictides show great promise for high-field applications, because their relatively high T_c, large critical fields, and weaker anisotropies are appealing virtues for such applications (Larbarestier et al., 2001).

Organic Superconductors

Organic superconductors were an early domain for high magnetic field research in superconductivity. While these materials nominally are not HTS, they *are* extreme type II systems, and their special anisotropic properties allow one to use high magnetic fields to enter into regimes that relate to the most interesting issues in cuprates and pnictides. In particular, the competition of superconductivity with spin and charge density-waves, quantum oscillations in the superconducting state indicating gapless excitations, along with other phenomena was first observed in these materials. This is still a very active subject of research, with high magnetic fields playing a key role (Lebed, 2008).

Topological Superconductors

Recently, there has been much excitement about a new distinct class of superconductors, said to exhibit topological superconductivity. Topological superconductors are expected to have a number of very peculiar properties, which could have unique applications. Further discussion of this subject, which is still in its infancy, may be found in the section Topological Phases.

The Next Ten Years for High-Temperature Superconductors

Here, the committee highlights some of the most promising research directions that it anticipates for the next decade:

- Transport experiments on unconventional superconductors in ultrahigh magnetic fields are likely to produce groundbreaking discoveries. With broader availability of intense magnetic fields, transport measurements can be performed in the regime where the applied magnetic field is comparable to the depairing (upper critical) field H_{c2}, even in the case of high-temperature superconductors. Transport studies in this regime are challenging but still much easier to carry out than often more informative but much more technically involved spectroscopic measurements.
- Correlated HTS such as cuprates and pnictides are among the most promising systems exhibiting fundamental departures from the mean-field, weak-coupling BCS theory. This is one of the looming intellectual challenges in condensed matter physics. Quantum and thermal fluctuations of vortices, their dynamics, and interactions with gapless quasi-particles will continue to be among the most active areas of inquiry. High magnetic field experiments are unique in their proven capacity to tune in to these phenomena—a direction that is likely to lead to vibrant new developments.
- The connection between topological insulators and superconductivity will surely be vigorously explored in the near future. In particular, possible Majorana fermion states in Tl-superconductor systems or in vortex cores of topological superconductors are bound to be a major new arena for high magnetic field research.
- Progress in the general area of unconventional superconductivity will be determined by close coordination of research at magnet facilities (dc and pulsed) and by material scientists. In this context, it may be an important question to ask why quantum oscillations in the cuprates were discovered by a Canadian-French collaborative group and not by a U.S. group, despite the fact that the National High Magnetic Field Laboratory (NHMFL) had worked on magnetotransport of YBCO in high fields before the competition. The answer will be familiar to many readers of this report: The Canadian-French team had unrestricted access to absolutely top-quality single crystals. This is an example of the United States lagging behind in integrating top new materials expertise into leading university physics programs.
- The vortex state is the electromagnetic face of superconductivity. Progress in this field will critically depend on spectroscopy and (nano)imaging techniques that will enable new insights into vortex dynamics.
- The problem of unconventional superconductivity is perhaps the most remarkable but not the only example of phase transitions in correlated metals. Ultrahigh magnetic fields will aid deeper understanding of these phase transitions, provided it becomes possible to apply spectroscopic

methods to tackle the problem. Unfortunately, one of the most informative spectroscopies in condensed matter physics, angular-resolved photoemission spectroscopy, is impossible in high magnetic fields. Therefore, one will need to rely on future advances of scanning tunneling microscopes and photon- and/or neutron-based spectroscopies.

- Unconventional superconductors are prone to phase separation on diverse length scales. Various imaging methods from atomic to meso-scale in ultrahigh magnetic fields are likely to make a decisive impact on the understanding of these phase separations.
- Advances in state-of-the-art characterization techniques compatible with ultrahigh magnetic fields will help to revolutionize materials for magnet technology.

SEMICONDUCTORS AND SEMIMETALS

Magnetic fields can have a particularly large effect in materials with a low density of charge carriers. In these systems, Planck's constant times the cyclotron frequency induced by a strong magnetic field can become comparable to the Fermi energies arising from quantum mechanical motion of the carriers, or to the energy scale of Coulomb interactions between the carriers. As a result, strong magnetic fields have long been used as a powerful tool for studying semimetals and semiconductors.

Semimetals are materials that would be insulating except for a small overlap between the energies of their valence and conduction bands, which causes a small number of electrons to be transferred from the valence band to the conduction band. Consequently, a semimetal has a small density of electron-like carriers arising from filled states in the conduction band and an equal number of holelike carriers due to empty states in the valence band. In semiconductors, the valence and conduction bands do not overlap, but carriers may be introduced by impurities or defects, whose concentration can be made very low in carefully grown material. A low-dimensional electron gas may be produced near the surface of a bulk semiconductor, or in other low-dimensional geometries, by a surface treatment or by application of an electrostatic potential via an external gate.

Low-Dimensional Semiconductor or Semimetal Systems

A general area that has remained at the frontier of physics research for the past three decades is that of low-dimensional systems. Spatial confinement of electrons to a plane, a line, or a small dot often dramatically alters the material's properties and gives rise to novel phenomena with no counterparts in bulk materials. In some cases, interactions among electrons can become dominant over their kinetic energies and can lead to exotic phases that are quite different from the phases encountered in bulk materials. Even in systems with weakly interacting electrons, confinement in a low-dimensional geometry can lead to striking differences from the behavior of the bulk material. Beyond its scientific interest, investigation of such low-dimensional systems also has tremendous practical implications: As the feature size of transistors becomes smaller and smaller, quantum phenomena are not only relevant, they are ubiquitous. High magnetic fields have been used both as a tool for studying new materials and structures, in order to elucidate the nature of the electronic structure that would be present in the absence of a field, and as an instrument for inducing behavior that is completely different from the behavior in zero field.

A low-dimensional system of particular interest is the two-dimensional electron system (2DES). Traditionally, such a system is achieved in semiconductor heterostructures—that is, by confining the charge carriers to the interface of two semiconductors that have different band gaps. More recently, new materials, such as graphene and the surface states of a topological insulator, have emerged as new 2D systems with novel properties that are promising for both understanding fundamental physics and exploring technological applications.

The prototypical 2D phenomena are the quantum Hall effects (QHE),[1] a collection of peculiar phenomena that occur in 2D electron systems, at low temperatures, in strong magnetic fields. Under these conditions, electrons' orbitals coalesce into Landau levels (LLs), which may give rise to the integer and fractional quantized Hall effects (IQHE and FQHE), where the Hall conductance is quantized at integer or fractional values of the conductance quantum $e^2/h = (25.9\ \mathrm{k}\Omega)^{-1}$, with e being the electron charge and h being Planck's constant. Other peculiar phenomena observed under these conditions include the unquantized QHE, where electrons in a strong magnetic field show properties similar to a Fermi liquid in zero magnetic field, highly anisotropic phases associated with formation of charge-density waves, and formation of collective states in bilayer systems where counter-propagating currents in the two layers can flow with zero resistance. FQHE states give rise to new types of collective excitations, including particles with charges that are a fraction of the charge of an electron and have quantum properties intermediate between fermions and bosons. In addition, certain FQHE states are believed to have particles with nonlocal hidden degrees of freedom, which lead to a phenomenon termed "non-abelian statistics," and which might be exploited for quantum computation. Owing to its precise quantization, the IQHE is now used as the standard of electrical resistance. The various QHE are signatures of novel states of matter, whose understanding has posed a major challenge to researchers over the past three decades.

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[1] For a review, see R.E. Prange and S.M. Girvin, eds., 1987, *The Quantum Hall Effect,* 1st ed., Graduate Texts in Contemporary Physics, Springer.

A very important parameter in the description of quantum Hall systems is the Landau level filling factor, $f = n\,\Phi_0/B$, where n is the two-dimensional electron density and $\Phi_0 = h/e$ is the quantum of magnetic flux. For example, the integer QHE is found when f is close to an integer, and the fractional QHE is seen, under appropriate conditions, when f is close to certain rational fractions, such as $\frac{1}{3}$, $\frac{2}{3}$ or $\frac{2}{5}$. The magnetic field necessary to achieve a given filling factor is therefore proportional to the electron density in the sample.

In order to observe quantized Hall effects, the electron mobility must be sufficiently high. For the integer QHE, the criterion is roughly $B > \sim \mu^{-1}$, where B is the magnetic field in tesla and μ is the mobility in m^2/Vs. For the fractional QHE, the required mobility is generally higher. Typically, the mobility in a given material increases with increasing electron density. With improved techniques of sample preparation, however, the density required to achieve a given mobility may be decreased. Due to these improvements, most experiments on quantized Hall effects in semiconductors are currently done in local laboratories, using commercial magnets with fields below 15 T. Much of this work is done using GaAs structures, where mobilities as high as 3,000 m^2 /Vs have been achieved, at electron densities such that even $f = \frac{1}{3}$ occurs below 15 T. However, higher magnetic fields become necessary if one wants to explore QHE in materials with lower mobility.

One specialized facility that has played a significant role in exploring aspects of the QHE is the NHMFL high B/T facility at the University of Florida. This facility enables one to reach extremely low temperatures, down 1 mK, using a nuclear demagnetization stage, in contrast to the base temperatures of 10-15 mK generally achievable with a dilution refrigerator.

Graphene

An area of recent study where very high fields have been crucial is in the observation of QHE in graphene. Graphene is a single layer of graphite, and thus is truly 2D, as it is precisely one atomic layer thick.[2] It is a unique material, whose many amazing material properties include some that are seldom found in the same material, such as high mechanical strength and elasticity, extraordinary electrical conductivity and 98 percent optical transparency, extremely high current-carrying capacity, chemical stability, and thermal conductivity. It is also nature's thinnest elastic membrane that is both transparent and conducting, which makes it perfect for applications as transparent electrodes and flexible electronics. Since its experimental isolation on insulating substrates in 2004 (Novoselov et al., 2004), graphene

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[2] For a review, see A.K. Geim and K.S. Novoselov, 2007, The rise of graphene, *Nature Materials* 6:183; M.S. Fuhrer, C.N. Lau, and A.H. MacDonald, 2010, Graphene: Materially better carbon, *MRS Bulletin* 35:289.

has quickly emerged as a most promising candidate for post-silicon electronic material, with a wide range of applications in electronics, sensors, displays, solar cells, miniaturized actuators, coatings, and composites (Novoselov et al., 2012).

In addition to its technological applications, graphene has a unique electronic band structure (Castro Neto et al., 2009; Das Sarma et al., 2011). The honeycomb lattice of carbon atoms gives rise to a peculiar energy-momentum dispersion: Instead of the parabolic bands normally found in semiconductors, metals, and insulators, the dispersion in graphene is linear, with the conduction and valence bands touching at two isolated points (the so-called Dirac points) in a plot of energy versus the x and y components of electron momentum (see Figure 2.13). Thus, graphene is either a zero band gap semiconductor or a zero-overlap semimetal, depending on one's perspective. Electron motions in graphene are described by Dirac's equation for zero-rest mass particles, $E(k) = \hbar v_F k$, with an effective "speed of light" v_F, where $v_F \sim 10^6$ m/s is the Fermi velocity. These massless electrons in graphene also have chirality or "handedness," much akin to that of neutrinos, which is not found in standard 2D electron gas (2DEG). Moreover, unlike standard 2DEG, which are buried below a surface, graphene is *all-surface*, enabling experiments that cannot be otherwise performed, such as optical spectroscopy, scanning tunneling microscopy, and mechanical manipulation. The 2010 Nobel prize in physics was awarded to André Geim and Kostya Novoselov for their groundbreaking experiments on graphene.

The first generation of graphene experiments was performed on Si/SiO_2 substrates, with a typical mobility of between ~ 0.1 and 1 m^2/Vs. Thus, compared to traditional 2DEG, higher magnetic fields were required to measure the Landau level gaps, break the fourfold degeneracy of the lowest Landau levels, and demonstrate the quantum Hall ferromagnetic state in graphene. Interestingly, the energetic separation between graphene's lowest Landau levels is unusually large, enabling

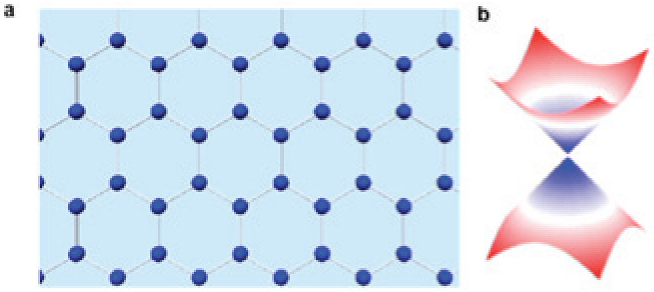

FIGURE 2.13 Atomic lattice and a portion of the electronic band structure of graphene. SOURCE: Reprinted from C.N. Lau, W. Bao, and J. Velasco, Jr., 2012, Properties of suspended graphene membranes, *Materials Today* 15:238, Copyright 2012, with permission from Elsevier.

the first observation of QHE at room temperature (performed at B = 30-45 T) (Novoselov, 2007). More recently, sample mobility has been improved to 10-100 m^2/Vs by either suspending graphene or using hexagonal boron nitride as the substrate, so that IQHE and FQHE have been observed using lower electron densities, at fields available in commercial magnets.

The knowledge and insights gained from the early quantum Hall measurements on graphene have been invaluable in elucidating the peculiar properties of that material, and high field studies of graphene continue to be indispensible today. The current outstanding questions include the nature of the QH states at $f = 0$, or zero charge density, which have diverging Hall and longitudinal resistance in both single-layer and bilayer graphene; quantum phase transitions among the symmetry-broken QH states; topologically nontrivial phases; presence of skyrmions (spin textures); Wigner crystals (electron solid); and FQHE with unusual fractions or sequence due to the approximate SU(4) symmetry of the electron states in graphene (see Figure 2.14). These questions can be answered only with transport

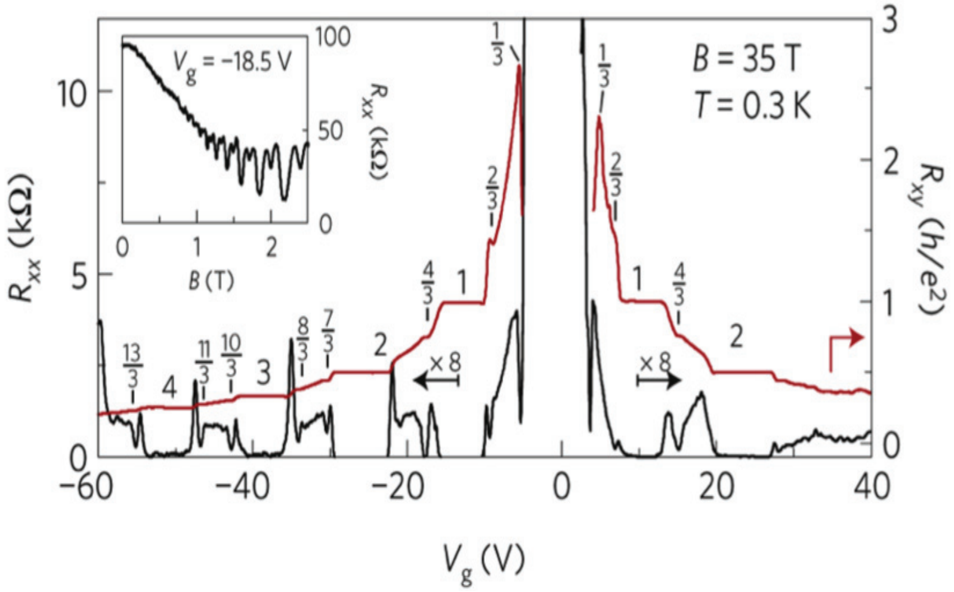

FIGURE 2.14 Longitudinal resistance (left axis) and Hall resistance (right axis) of a graphene sample versus gate voltage, which changes the carrier density, measured at B = 35 tesla. Quantized Hall conductance values are indicated. SOURCE: Reprinted by permission from Macmillan Publishers Ltd.: Nature Physics. C.R. Dean, A.F. Young, P. Cadden-Zimansky, L. Wang, H. Ren, K. Watanabe, T. Taniguchi, P. Kim, J. Hone, and K.L. Shepard, 2011, Multicomponent fractional quantum Hall effect in graphene, *Nature Physics* 7:693-696. Copyright 2011.

and/or optical measurements in dc and pulsed high magnetic fields with varying field angles and temperature.

A rather unique direction of graphene research is strain-based engineering of its electrical properties, which takes advantage of the "softer" side of graphene. Being both an excellent electrical conductor and an elastic membrane that can sustain more than 25 percent strain, graphene's electrical properties can be strongly affected by strain and morphology. Moreover, inhomogeneous strains in graphene affect the electronic motion in a similar way to an applied magnetic field. In fact, electrons in highly strained graphene have been observed to experience pseudomagnetic fields greater than 300 T (Levy et al., 2010). Thus, one can tailor graphene's electronic properties via careful design of strains. Interplay of such enormous pseudomagnetic field with the real magnetic field will be an exciting frontier and a step toward strain-based graphene electronics.

Carbon Nanotubes

A closely related allotrope of graphene is carbon nanotubes (Smalley et al., 2001), which can be visualized as seamless cylinders of graphene, with diameters ~1 nm for single-walled carbon nantoubes and up to hundreds of nanometers for multiwalled carbon nanotubes. Depending on the orientation of the cylinder axis relative to the atomic honeycomb lattice, a carbon nanotube can be either a one-dimensional metal or semiconductor. High magnetic fields have been employed to probe the spin-orbit interactions, to close band gaps in semiconducting nanotubes, and to induce spin polarization and Aharonov-Bohm quantum interference effects. These high field studies are expected to continue to yield important information on fundamental interactions in 1D wires.

Three-Dimensional Semimetals

One of the most interesting semimetal materials is bismuth, which has an unusual band structure consisting of one hole and three electron pockets. The electrons are massless, similar to graphene, except that here the degenerate Dirac point occurs slightly below the Fermi energy of the pure material. The density of electrons and holes in bismuth is exceptionally low. Consequently, the so-called "quantum limit," where all the charge carriers are confined to the lowest Landau level, can be achieved at relatively modest magnetic field ~ 10 T, above which electrical properties were expected to be featureless. Surprisingly, recent experiments at magnetic fields up to 31 T reveal striking oscillations and sharp rises in measurements of the Nernst effect, resistivity, and magnetization, as well as signatures for first-order phase transition induced by magnetic fields (Behnia et al., 2007; Li et al., 2008). Theoretical investigation (Alicea and Balents, 2009) suggests that the quantum limit is suppressed by an unusual spin-orbit induced Zeeman effect, and electron interactions at high magnetic fields may give rise to distinct phases such as Wigner crystals and charge density waves. Further investigation in high fields will be warranted to ascertain these behaviors and to uncover new phenomena in bismuth and other semimetals.

TOPOLOGICAL PHASES

During the last few years, a new class of materials, "topological phases," has emerged as an exciting frontier of science. These materials have a number of remarkable properties that were not previously envisaged, and strong magnetic fields have played an important role in their exploration.

Topological insulators and topological superconductors are materials that have an energy gap for electronic excitations in their interior, but of necessity have low-energy excitations located at their boundaries. Transport properties, such as electrical conduction, may be dominated by these surface excitations.

The quantum mechanical ground states of these materials are characterized by "topological quantum numbers," which cannot change their values as one continuously varies an external parameter such as the pressure applied to the system, unless the system undergoes a phase transition in which the energy gap closes and reopens again. Topological phases have quantum numbers that are different from those of ordinary, nontopological phases, so they represent a conceptually distinct state of matter. Mathematically, the topological quantum numbers characterize the way the ground state evolves if one changes certain parameters in the Hamiltonian, which affect its explicit form but do not affect the ground state energy. The set of such ground states forms a surface in the quantum-mechanical Hilbert space, and surfaces corresponding to different topological phases are distinguished from each other in much the same way as the surface of a sphere is topologically distinct from the surface of a donut—the surfaces cannot be deformed into each other without tearing and re-stitching.

The earliest known examples of topological insulators were in fact the quantized Hall states of 2D electron systems at low temperatures, and in a strong magnetic field. It was shown in the 1980s that the quantized Hall conductance of these systems is related to a winding number, which describes the way in which the ground-state wave function evolves when one varies the boundary conditions of the system. This winding number is an integer that, in principle, may be positive or negative and arbitrarily large.

By contrast, for the topological insulators of greatest current interest, the topological numbers have only two possible values, typically equal to 1 in the topological phase and 0 in the trivial non-topological phase. (Such numbers are often denoted Z_2 numbers, in contrast to the case of arbitrary integers, which are denoted

Z numbers.) These topological phases are strictly defined only in systems which preserve time-reversal symmetry—that is, systems in the absence of an external magnetic field, which do not have frozen local magnetic moments. Nevertheless, application of strong magnetic fields can be a strong tool for manipulating or probing these systems.

Originally it was thought that topological insulators could exist only in two-dimensional systems or in systems that were essentially a stack of weakly connected layers. However, we now know that there are different kinds of topological insulator that can exist in genuinely 3D systems. In fact, topological insulators can exist, mathematically, in any dimension, with appropriate classes of symmetry restrictions, and a complete classification of these phases has been developed, at least for models of weakly interacting electrons in a periodic potential.

Concrete examples of Z_2 topological insulators have been realized in both 2D and 3D. All these materials share a common trait—that is, a strong spin-orbit coupling, which causes band inversion and flips the parity of the valence band. Coincidentally, the nature of the edge/surface state of a topological insulator is dictated by the spin-orbit coupling, so that for a given momentum direction, only one direction is allowed for the electron spin. This type of spin polarization is often called "helical," although the spin direction is typically perpendicular to the direction of motion, in contrast to the case of a helical massless particle in high-energy physics, such as a neutrino. An interesting consequence of the helical spin polarization is the existence of dissipationless spin current at the edge/surface of a topological insulator. This property could have important implications for applications in spintronics. Also interesting is the fact that the edge/surface state consists of massless Dirac fermions, whose existence is guaranteed by the time-reversal symmetry. This aspect gives the two-dimensional surface states of a 3D topological insulator a close relation to graphene, but in topological insulators there is neither valley nor spin degeneracy, reducing the number degrees of freedom of the Dirac fermions to one quarter of those in graphene.

Transport studies of helically spin-polarized surface Dirac fermions inhabiting the surface of 3D topological insulators are a promising research frontier. One would expect various novel physics, including dissipationless spin current and topological protection from backscattering, to show up in transport properties of topological surface states. However, transport studies of the surface states have proved a challenge because of the coexistence of bulk transport channels due to doping by defects in available topological insulator samples. Nevertheless, experiments on thin samples in high magnetic fields, carried out at NHFML, were able to distinguish the surface from the bulk contributions. Surface quantum oscillations have been successfully observed, and the Dirac nature of the surface states has already been elucidated. Recent improvements in materials preparation have also contributed to a separation of bulk and surface contributions. More recently, the discovery of an intrinsically bulk-insulating material, Bi_2Te_2Se, gave a big boost to the surface transport studies. Furthermore, by improving the bulk-insulating properties of Bi_2Te_2Se in a $Bi_{2-x}Sb_xTe_{2-y}Se_y$ solid-solution system, researchers have already succeeded in preparing bulk single crystals showing surface-dominated transport (see Figure 2.15). Also, MBE growth of strained HgTe thick films has successfully provided 3D topological insulator samples showing surface-dominated transport. Using those samples, we may anticipate that novel quantum transport phenomena, including the fractional quantum Hall effect in topological surface states, will become an exciting realm of high magnetic field science.

The Dirac nature of the surface states of topological insulators has also been observed in STM and optical experiments involving high magnetic fields. In the next 10 years, those new types of high magnetic field experiments will become increasingly more important for the exploration of novel physics associated with nondegenerate Dirac fermions.

Intriguingly, it has been shown that the quantum field theory of topological insulators resembles that of a hypothetical particle in high-energy physics, called the "axion," and this theory leads to various interesting predictions such as the quantization of the magnetoelectric effect, the appearance of an image magnetic monopole, and the half-integer quantum Hall effect. All those phenomena are yet

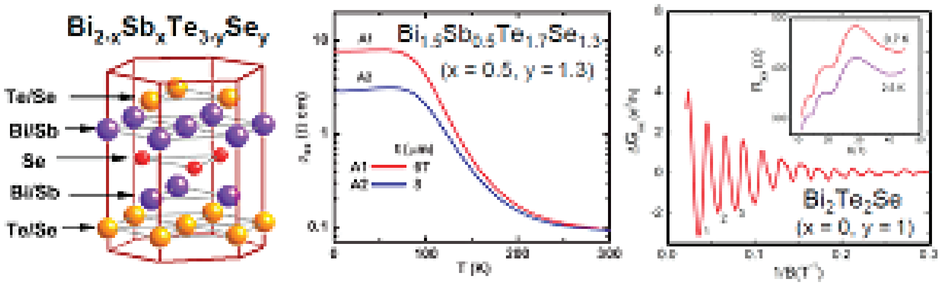

FIGURE 2.15 (*Left*) Basic crystal structure of a most promising topological-insulator material, the tetradymite $Bi_{2-x}Sb_xTe_{2-y}Se_y$ system. This material exhibits a highly bulk-insulating character and a tunable surface Dirac fermions. (*Center*) Since the surface transport is significant in this material, the apparent resistivity at cryogenic temperatures decreases when the sample thickness is reduced; the thickness dependence shown here suggests that the transport is 70 percent due to surface in the 8-μm thick crystal. (*Right*) Shubnikov-de Haas oscillations in high magnetic fields up to 45 tesla observed in this material reveal the Dirac nature of the surface state. SOURCE: (*Left and center*) reprinted figures with permission from A.A. Taskin, Z. Ren, S. Sasaki, K. Segawa, and Y. Ando, 2011, Observation of Dirac holes and electrons in a topological insulator, *Physical Review Letters* 107:016801, Figure 1(a) and Figure 4. Copyright 2011 by the American Physical Society. (*Right*) Courtesy of N. Phaun, Princeton University, adapted from J. Xiong, Y. Luo, Y. Khoo, S. Jia, R.J. Cava, and N.P. Ong, 2012, High-field Shubnikov–de Haas oscillations in the topological insulator Bi_2Te_2Se, *Physical Review B* 86:045314.

to be experimentally discovered, and an important prerequisite to the realization of those phenomena is to open a gap in the surface state. It has been proposed that high magnetic fields will be useful for this purpose, and the higher the field, the larger the gap, the easier the observation. This provides excellent opportunities for high magnetic field science to play a major role in the discovery of fundamentally new physics.

In a topological superconductor, the energy gap that protects the topological phase is actually the superconducting gap. The low-energy excitations at the boundary of a topological superconductor are exotic quasi-particles called Majorana fermions, which are their own antiparticles, and which should have a number of unusual properties. Notably, it has been proposed that, in appropriate situations, where Majorana excitations can be localized and kept well separated from each other, they could be useful for fault-tolerant quantum computing.

A promising way to materialize a topological superconductor is to induce electron pairing in the edge/surface state of a topological insulator via proximity effect of a conventional superconductor. One might also use a strongly spin-orbit-coupled semiconductor like InSb or InAs instead of topological insulators, but in this case a magnetic field is required to quench the spin degrees of freedom without suppressing the superconducting state. Recently there have been encouraging developments in realizing analogous topological superconductivity in 1D hybrid structures, where a nanowire of InSb or InAs is proximity coupled to a bulk superconductor.

Topological superconductivity may also be found in natural bulk superconductors when the superconducting order parameter is parity odd. For example, Sr_2RuO_4 is likely to have a time-reversal breaking, quasi-2D topological superconducting state, which would host Majorana fermions in the half-quantized vortices in magnetic fields. Also, $Cu_xBi_2Se_3$ was recently shown to be a time-reversal-invariant 3D topological superconductor, which hosts intriguing helical Majorana fermions on the surface. It is expected that more topological superconductors will be discovered in natural compounds or in artificially constructed hybrid systems. Considering the important roles that high magnetic fields have played in superconductivity research, we may expect that topological superconductors will naturally provide new exciting opportunities for high magnetic field science.

HIGH MAGNETIC FIELDS IN SOFT MATTER RESEARCH

As was mentioned in the overview to this chapter, applications of high magnetic fields to soft condensed matter research take advantage of the torques and forces on materials that can be exerted by a magnetic field. These may be used to align molecules or other small objects while they are being studied by one or another experimental probe, or they can be used to control materials preparation, such as crystal growth, in a desired way.

Magnetic Alignment

The main interaction with magnetic fields is caused by diamagnetism, the appearance of a weak magnetic moment in a material in opposition to an external magnetic field. This phenomenon is present in all materials and arises from the deformation of the electron orbits in atoms and molecules by the Lorentz force. To magnetically manipulate nanostructures, one takes advantage of the anisotropy of a material's diamagnetic response, which grows rapidly with size. For example, the increase in the magnetic energy by an object with N atoms or molecules is

$$\Delta E = N \chi B^2 / 2\mu_0$$

where μ_0 is the free space permeability and χ the susceptibility tensor per molecule. This energy may vary considerably depending on the relative orientation between the molecule and the magnetic field. Typically, for a single molecule, $|\chi|$ is miniscule ($<10^{-7}$) for all orientations, hence even at $B = 100$ T, the difference in energy between different orientations is negligible. However, for a benzene aggregate with 10^5 molecules (but which is still only ~ 5 nm in size), it becomes energetically favorable at room temperature to align to the direction of the magnetic field at $B = 20$ T. Similarly, nanoscale chemical aggregates or biological cells can be oriented using high magnetic fields and studied in situ or ex situ. Since the orientational torque is quadratic in B, high magnetic fields are required to study nanometer-sized aggregates (Maret and Dransfield, 1985).

In supramolecular chemistry and liquid crystals, relatively weak van der Waals forces or π-π bonding are involved in the process of self-assembly of targeted molecular building blocks into larger structures, like vesicles, dendrites, fibers, wires, etc. Magnetic fields may be used to probe these intermolecular interactions by determining the internal structure that is important for their properties. For instance, dye molecules can aggregate in solution in different geometries like stacked or herringbone structures, and their optical response strongly depends on the stacking. One type of aggregate shifts optical absorption or emission to the red while the other shifts it to the blue. Therefore it is possible to tune the absorption in a desired way. The stacking occurs usually in a liquid environment, and it is important to determine the structure under these conditions, which makes standard microscopy or light-scattering techniques hard to use. In a magnetic field the aggregates orient in a specific way with respect to the field while at the same time, optically, the light polarization with respect to this direction can be varied. In this way, the optical absorption along different axes can be determined in an in situ experiment. Molecular materials are considered as a possible element in photovoltaic devices, and it is important to match their optical properties to the optical spectrum of the sun, which makes a detailed knowledge of their structure necessary.

Another example is the study of optical properties of nanotubes in solution. A magnetic field readily aligns these tubes along the field axis and allows the study of their properties. In this way it has been possible to observe B-periodic Aharonov Bohm oscillations in the optical absorption of large-diameter carbon nanotubes as a function of magnetic field whenever an integer number of flux quanta fit in the cross section of the tube (Zaric et al., 2004).

It is also possible to use the magnetic forces to deform aggregate shapes like spheres or dendrites, and the deformation can be determined through optical experiments. In this way molecular forces on a nanometer scale can be quantitatively determined in a noninvasive manner. It is important to be aware of these diamagnetic forces. For example, molecular alignment in high fields produces observable effects in NMR spectra, which in principle can be used as constraints on the structures of macromolecules such as proteins.

It is of particular interest that the magnetic field experienced by a nano-object is practically identical to the applied field. Although it is easily possible to deform many objects with an electric field, the large values of typical dielectric constants mean that the local electric field may be very different from the externally applied field, which renders any quantitative analysis very difficult in that case.

Apart from aligning aggregates in solution with magnetic fields and studying them in situ, one may also use the fields to order matter in solution and then fix it in some way and study the ordered material ex situ afterwards. In general all collective states of soft matter like liquid crystals are very easily affected by magnetic orientation since domains in liquid crystalline material contain many molecules. Cooling liquid crystals in a field through the nematic phase transition leads to perfectly oriented materials since the first nuclei at the transition temperature can easily rotate in the magnetic field and aggregate after alignment. The cooled liquid crystalline film is fully transparent, free from domain boundaries, and shows a very high degree of birefringence. Strongly polarizing optically transparent films are useful optical components. Another example is that superior conducting polymers can be made from cylindrical stacks of coronene molecules that aggregate in solution and are then deposited on a substrate by evaporating the solution in a field. The resulting perfectly aligned stacks show a conductivity two orders of magnitude higher than the nonaligned stack, not aligned in a field. Such an increased mobility is very important for organic transistors (Shklyarevsky et al., 2005).

Magnetic Levitation

A very different application of diamagnetism is magnetic levitation. Since diamagnetic materials gain energy in a magnetic field, they experience a force F (per unit volume) toward the lower field region, given by

$$F = (\chi/2\mu_0) \text{ grad } B^2$$

which is proportional to the gradient of the square of the field strength. In a magnet with a vertical bore, this force acts against gravity and enables complete levitation of most diamagnetic organic materials for $B \sim 16\text{-}20$ T and gradients ~ 100 T/m (Beaugnon and Tournier, 1991). Such levitation, apart from being a striking demonstration of diamagnetism of living organisms, also allows study of materials under microgravity or artificially variable gravity, such as crystal growth under weightless conditions or fluid dynamical problems as a function of gravitational acceleration (Berry and Geim, 1997). An example of fluid dynamics is the study of cryogenic liquids like the ones used as rocket fuel. Understanding the behavior of these liquids in weightless conditions is important in rocket design, and such studies can easily be done with magnetic levitation.

Finally, many experiments have been done in microgravity in an attempt to improve the crystal quality of, in particular, protein crystals. High-quality protein crystals are essential for protein structure determination, which is an essential tool for the pharmaceutical application, for example. The idea is that in weightless conditions the convection plume occurring around the growing crystals is suppressed. This plume arises because the solution near the growing crystal has a different density since it is depleted because of the molecules that are deposited on the surface. The reduction of the growth velocity is known to lead to higher crystal quality. It is possible to suppress the growth plume also in high magnetic fields under the condition that the grad B^2 value suppresses the buoyancy of the depleted solution. This condition often requires much higher fields than the usual levitation condition (see Figure 2.16).

In summary, there are many as yet unexplored areas in research on soft matter in high magnetic fields since it is not widely recognized that at high magnetic fields diamagnetic energies may become important. Since these forces increase with B^2, higher fields will rapidly make them even more important and opportunities for unexpected results will be even greater. This area of application is interdisciplinary par excellence since it requires physicists, chemists, and possibly even biologists to work together.

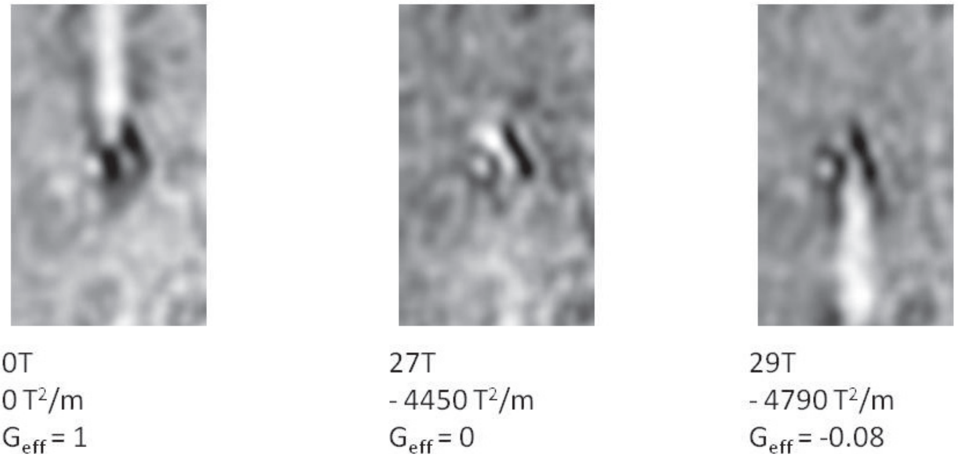

FIGURE 2.16 An image of the growth plume of growing lysozyme protein crystals at effective gravity $G = 1$ (normal gravity) and in a very high magnetic field gradient, showing that with field-induced effectively zero gravity ($G = 0$) convection can be suppressed and that gravity can even be inverted ($G = 0.08$). SOURCE: Reprinted with permission from M.C.R. Heijna, P.W.G. Poodt, K. Tsukamoto, W.J. de Grip, P.C.M. Christianen, J.C. Maan, J.L.A. Hendrix, W.J.P. Van Enckevort, and E. Vlieg, 2007, Magnetically controlled gravity for protein crystal growth, *Applied Physics Letters* 90:264105. Copyright 2007, American Institute of Physics.

CONCLUDING COMMENTS

High magnetic fields are a critical research tool in many areas of condensed matter and materials physics. Of the many examples of research in high magnetic fields cited in this chapter, a large fraction were carried out at facilities run by NHFML. The experiments were carried out by users from a large variety of universities and research institutions based in the United States and in other countries around the world. Those users may have brought with them samples, and in some cases measuring devices, prepared at their home institutions. In addition to magnet time, NHFML would have supplied technical support, as well as measurement instruments and cryogenic facilities for much of this work. The availability of higher magnetic fields, in both dc and pulsed modes, will be very important for continued progress in this area. (Specific magnet recommendations relevant to this research will be discussed in Chapter 7.) The use of high magnetic fields in soft matter research (biological cells, molecular aggregates, vesicles, polymers, some of them discussed in Chapter 3) has great promise but is largely underexploited. A close collaboration between the large facility and strongly interested chemists and biologists is necessary to fulfil these promises.

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3

High Magnetic Fields in Chemistry, Biochemistry, and Biology

High-field magnets that are near the cutting edge of technology play central roles in chemical, biochemical, and biological research, primarily through the techniques of nuclear magnetic resonance (NMR), electron paramagnetic resonance (EPR), and Fourier-transform ion cyclotron resonance (FT-ICR). In medical research and clinical medicine, high-field magnets are essential components of magnetic resonance imaging (MRI) systems, which create three-dimensional (3D) images of anatomical and diagnostic importance from NMR signals. (MRI is described in a separate section below.) In all of these techniques, current magnetic field strengths are somewhat below the level that is achieved in specialized high-field facilities devoted primarily to physics and materials research. The magnets are usually produced by commercial vendors rather than by research teams. Despite the commercial context of their construction, the magnets used for very high field NMR and other spectroscopies present ambitious design challenges: The magnets have exceptionally high homogeneity (~1 ppb) over large volumes (>1 cm^3 homogeneous volume), requiring highly specialized and sophisticated engineering to manage the concomitant structural stresses and stored energies. The magnets must also have exceptionally high stability for indefinite time periods (months to years), implying that they are typically constructed from persistent superconducting materials. Field strengths in NMR magnets are limited by the properties of these materials, making high-field NMR one of the important scientific drivers for the continuing development of advanced superconducting materials and magnet technology.

The National High Magnetic Field Laboratory (NHMFL) includes user facilities for NMR spectroscopy and FT-ICR, with state-of-the-art, but not unique, equipment. In addition, NHMFL has unique facilities based on magnet systems designed and built in-house. These include an ultra-wide-bore superconducting 900 MHz NMR magnet, which allows MRI studies on animals that are not possible elsewhere; high-field FT-ICR systems (including a 21 T system currently under construction through a joint effort with a commercial vendor), and high-field EPR systems. The high-field hybrid magnets and resistive magnets of NHMFL have also been used for NMR and EPR studies, principally of nonbiological systems to date.

It is impossible to overstate the importance of NMR as an analytical and structural tool in chemistry. When chemists synthesize new compounds with potential applications in medicine or technology, they always use NMR measurements to determine the chemical structure of these compounds and to optimize the synthetic approach. In the biological sciences, NMR measurements are one of the two main tools by which scientists determine full three-dimensional structures of proteins and nucleic acids, the other being X-ray crystallography. In materials science, NMR provides essential information not only about structure, but also about the electronic and magnetic properties that determine technological usefulness. For paramagnetic systems, including enzymes and supramolecular complexes that are crucial for numerous biological processes and materials that are important in industrial catalysis and energy storage, EPR measurements provide additional chemical, structural, and mechanistic information that cannot be obtained from NMR, crystallography, or other methods. In both chemistry and biochemistry, FT-ICR permits the determination of molecular masses with the highest available precision and accuracy, especially for the complex chemical mixtures that occur in such diverse fields as petroleum research, proteomics, and metabolomics.

PRINCIPLES OF NMR AND IMPORTANCE OF HIGH FIELDS IN NMR

Nuclei of certain atomic isotopes, including ^{1}H, ^{13}C, ^{15}N, ^{17}O, ^{29}Si, and ^{31}P, possess intrinsic angular momenta, called “nuclear spin,” and associated magnetic moments. In an external magnetic field, interaction between nuclear magnetic moments and the external field causes the nuclei to align with the field direction. NMR is a phenomenon in which the application of radio-frequency (RF) pulses induces a precession of the aligned nuclei about the external field direction, in turn resulting in the emission of RF signals at the characteristic precession frequencies. The precise frequencies and amplitudes of the emitted signals constitute the NMR spectrum. Although the basic phenomenon of NMR was demonstrated and explained over 60 years ago, the utility of NMR spectra in the physical, chemical, and biological sciences expanded substantially in each subsequent decade. The continuing expansion of NMR into new areas of science is a result of the fact that the details of NMR spectra are exquisitely sensitive to the chemical, structural, electronic, and motional properties of molecules and materials. A steady stream of advances in NMR methods and instrumentation, including but not limited to higher fields, has allowed NMR measurements to be performed on a progressively larger variety of systems with increasing complexity.

Higher magnetic fields lead to better NMR data for two main reasons. The first is spectral resolution: The NMR frequency of the nucleus of a particular atom in a molecule or material is proportional to the strength of the external field but is also affected by the atom's local chemical and structural environment. As the external field increases, differences between NMR frequencies of different atoms become proportionally larger and easier to measure. One of the most important advances in modern NMR methodology, beginning in the mid-1970s, is the development of "multidimensional" NMR spectroscopy, in which NMR frequencies detected in multiple time periods within a single RF pulse sequence are correlated with one another. In an N-dimensional NMR spectrum, the effect of increasing magnetic field on spectral resolution occurs in each dimension, so that the number of distinct NMR frequencies that can be measured (which determines the size and complexity of molecules and materials that can be studied by NMR) can increase as roughly the Nth power of the magnetic field strength (B^N). In practice, in a 3D NMR spectrum of a biological macromolecule such as a protein in aqueous solution in a field of approximately 20 T, NMR signals from more than 10,000 ^{1}H, ^{13}C, and ^{15}N nuclei can be resolved from one another and measured accurately.

The second main reason why higher fields lead to better NMR data is sensitivity: In available magnets, NMR frequencies typically lie in the 100-1000 MHz range, corresponding to photon energies of 4×10^{-7} to 4×10^{-6} eV (5-50 mK). These low energies imply that the degree of nuclear alignment induced by the magnetic field (i.e., the fractional difference between nuclear spin momenta parallel and antiparallel to the field direction, called the nuclear spin polarization) is typically only 10^{-6}-10^{-5} at ambient temperature and is proportional to the field strength. NMR signal amplitudes are proportional to the nuclear spin polarization. Because NMR signals are detected inductively, the signal amplitudes are also proportional to NMR frequencies themselves. Thus, signal-to-noise ratios in NMR spectra can be proportional to B^2. Additional factors affecting sensitivity include the temperatures of samples and electronics, the NMR linewidths, and the repetition rates of measurements (which are limited by spin-lattice relaxation rates, the rates at which nuclei align with the magnetic field before each measurement). In practice, an approximately linear dependence of NMR sensitivity on magnetic field strength is often observed. This produces an approximately linear decrease in sample quantities required for NMR measurements, an important consideration especially for biological samples that are difficult to obtain in large quantities.

Two distinct classes of NMR techniques are important in studies of chemical, biochemical, and biological systems. In each class, higher fields produce additional advantages for distinct reasons. The most common techniques, called "solution NMR," apply to molecules that are dissolved in an isotropic liquid (e.g., aqueous buffers or organic solvents). Rapid translational and rotational diffusion in an isotropic liquid make all molecules in the sample structurally equivalent on the nanosecond-to-microsecond timescale. Rapid rotational diffusion also averages out anisotropic nuclear spin interactions, resulting in exceptionally narrow NMR lines and high spectral resolution. However, when molecules become very large, as in the case of high-molecular-weight proteins and nucleic acids, rotational diffusion becomes too slow, resulting in greater linewidths that impair both resolution and sensitivity (because the NMR linewidths limit the efficiency of nuclear spin polarization transfers that are essential for multidimensional spectroscopy). However, in certain cases, higher fields reduce the NMR linewidths of high-molecular-weight proteins and nucleic acids through a partial cancellation between linewidth contributions from anisotropic magnetic dipole-dipole interactions, which are independent of field, and anisotropic chemical shielding interactions, which increase linearly with field. Thus, in the case of biologically important macromolecules in solution, higher fields enable multidimensional NMR measurements on high-molecular-weight systems that would otherwise be impossible. Very high fields can also produce a weak magnetic alignment of dissolved molecules, due to anisotropy in their magnetic susceptibility, which leads to incomplete averaging of dipole-dipole interactions among nuclei. Solution NMR measurements of these residual dipole-dipole interactions provide useful constraints on molecular structures, as has been demonstrated for proteins.

The second class of NMR techniques, called "solid state NMR," applies to bona fide solids, either crystalline or noncrystalline, that are of interest in materials science and organic and inorganic chemistry, as well as to solidlike biochemical and biological systems, including protein filaments and membrane-associated systems. The absence of isotropic translational and rotational diffusion (and, particularly at low temperatures, the absence of internal molecular motions) in a solid typically results in significantly greater NMR linewidths and poor spectral resolution. However, the technique of magic-angle spinning (MAS), first demonstrated in the late 1950s and improved dramatically in recent years, in which solid samples are rotated very rapidly about an axis at the "magic angle" $\theta_M = \cos^{-1}(1/\sqrt{3})$ to the magnetic field direction using a pneumatic turbine system, approximates the effects of rotational diffusion, producing solid state NMR linewidths that can approach the linewidths in solution NMR spectra. Some of the most exciting applications of solid-state NMR are possible only at very high magnetic fields. In solid-state NMR of organic and biological systems, strong dipole-dipole interactions among ^1H nuclei limit the achievable ^1H NMR linewidths, even under rapid MAS. Therefore, it is only at the highest available fields that ^1H NMR spectra of complex organic and biological systems become useful. Inorganic systems of practical and chemical interest (e.g., catalysts, glasses, battery materials) prominently contain elements whose NMR spectra are difficult or impossible to measure at low fields, because the nuclei have spin quantum numbers greater than ½ (e.g., ^{7}Li, ^{17}O, ^{27}Al). These nuclei possess electric quadrupole interactions, which are averaged out to lowest order by MAS but make a second-order contribution to the NMR linewidths that is inversely proportional to the magnetic field strength. For these reasons, NMR spectra of many technologically important materials are useful only if very high field equipment is used, and are increasingly informative as the field increases.

RECENT TRENDS AND ACHIEVEMENTS IN NMR

In studies of biological systems, NMR is one of the two major types of measurements that can be used to reveal the full 3D molecular structures of macromolecules, especially proteins and nucleic acids, the other being X-ray diffraction measurements on single crystals. In addition to purely structural information, NMR measurements have the unique capability of providing detailed, site-specific information about molecular motions in macromolecules, including motions that are essential for biological function. While X-ray diffraction measurements are largely restricted to highly structurally ordered molecules in crystalline environments, NMR methods are applicable to proteins and nucleic acids in fluid environments that more closely resemble the cytoplasmic and membrane environments of cells. Perturbations of NMR signals due to intermolecular interactions are used in the screening of molecular libraries for binding to pharmaceutically important macromolecular targets, providing an efficient approach to the identification of new lead compounds in drug development. NMR methods are also applicable to molecules that are intrinsically disordered, resistant to crystallization, and (in the case of solid-state NMR) inherently noncrystalline and insoluble.

Since the first demonstrations of protein structure determination by NMR in the early 1980s, methodological and technological advances have contributed to a steady increase in the size and diversity of systems that can be characterized by NMR. Among these are the development of multidimensional NMR techniques that allow NMR frequencies of essentially all ^{1}H, ^{15}N, and ^{13}C nuclei within a protein or nucleic acid to be measured and assigned to specific atoms; the identification and characterization of a variety of nuclear spin interactions that can be measured through NMR signals and interpreted as experimental constraints on molecular structure; and the development of highly stable and homogeneous superconducting magnets with fields up to 23.5 T. Some of the most significant new trends in biomolecular NMR that have appeared since the NRC report *Opportunities in High Magnetic Field Science* (NRC, 2005) include these:

- *Continued advances in the solution NMR methods for determining structure and dynamics, and integration of solution NMR measurements with measurements that provide complementary structural information, especially small-angle X-ray and neutron-scattering measurements.* Multidimensional solution NMR measurements are particularly powerful for obtaining short-range structural constraints that define the molecular structures of individual protein domains and specific interfaces between subunits within a supramolecular complex, while small-angle scattering data provide information about the overall configuration of a multidomain protein or multisubunit complex. Long-range structural constraints can also be obtained from EPR measurements, as described below, and from electron microscopy. As an example, by combining extensive NMR data sets with small-angle X-ray scattering data, NMR spectroscopists have recently succeeded in determining the complete 3D structure of an essential bacterial enzyme that exists as a homodimer, comprised of 1,148 amino acids, or nearly 18,000 atoms (Takayama et al., 2011). From a combination of NMR and cryo-electron microscopy measurements, NMR spectroscopists have determined the complete 3D structure of a large RNA structural motif, comprised of 131 nucleotide units or nearly 4,250 atoms, which is critical for packaging within retroviruses, of which HIV-1 is an example (Miyazaki et al., 2010).
- *Accelerated growth of biomolecular solid-state NMR.* Since solid-state NMR measurements are not limited by molecular rotational diffusion rates, solubility, or crystallinity, these measurements have the potential to address structural and dynamical problems in important classes of systems that are not amenable to any other techniques. The full potential of biomolecular solid-state NMR has begun to be realized only recently, in large part due to technological advances. Improvements in MAS technology allow sample rotation frequencies above 50 kHz to be achieved routinely; solid state NMR probes (the devices that contain the circuitry for application of RF pulses and detection of NMR signals) that work efficiently at the high NMR frequencies of high-field magnets have been developed; new isotopic labeling approaches have been introduced that lead to tractable solid-state NMR spectra for large proteins; new techniques for assigning solid-state NMR signals to specific atomic sites and for obtaining molecular structural constraints have been developed. In addition, a rapidly growing community of solid-state NMR spectroscopists has explored an increasing variety of biologically important systems. Significant achievements include the determination of complete molecular structures of filamentous protein assemblies, called amyloid fibrils, that are associated with Alzheimer's

disease and related diseases and with the transmissible protein-encoded biological states known as "prions" (Paravastu et al., 2008; Wasmer et al., 2008). Solid-state NMR measurements have also provided important new structural and mechanistic information about proteins that form ion channels in cell membranes (Bhate et al., 2010), and proteins that are involved in influenza infectivity and transmission (Cady et al., 2010).

- *Extension of NMR measurements to intact cells and subcellular structures.* Proteins and other macromolecules account for roughly 20 percent of the volume within cells, creating a highly congested, heterogeneous environment in which molecular structures and intermolecular interactions can in principle be significantly perturbed from their states in the simplified conditions of traditional in vitro studies. Improvements in the sensitivity and resolution of NMR are facilitating attempts to quantify the influence of the biological environment, through direct NMR measurements on proteins within bacteria or bacterial membranes (Renault et al., 2012; Fu et al., 2011).

A major new trend in both solution NMR and solid state NMR is the exploitation of dynamic nuclear polarization (DNP) for sensitivity enhancements. DNP is a process in which the large polarizations of electron spins in a strong magnetic field are partially transferred to nuclear spins by irradiation of EPR transitions, resulting in large enhancements of nuclear spin polarizations and hence NMR signals. Recent work has shown that NMR signal enhancements by a factor of more than 100 can be achieved through DNP in a variety of chemical and biochemical samples that are paramagnetically doped with stable free radical compounds. Among other applications, these signal enhancements have enabled new studies of metabolic and enzymatic pathways in cell cultures and whole organisms (Meier et al., 2012; Menichetti et al., 2012), have allowed solid state NMR studies of the structure and chemistry of catalyst surfaces (Lelli et al., 2011), and promise to enable structural studies of membrane-bound peptide/protein complexes that are available only in nanomole quantities (Reggie et al., 2011), including hormone/receptor complexes that are important pharmaceutical targets.

In recent years, NMR has developed a new role as one of the primary experimental tools in the burgeoning field of metabolomics, a term that encompasses efforts to identify and quantify all small-molecule metabolites within cells, tissue, and biological fluids and to correlate variations in metabolite profiles with gene expression, disease state, and environmental factors. The high resolution and high sensitivity of NMR at high fields allows ~100 compounds with ~10 μM concentrations to be quantified simultaneously within a single specimen (Psychogios et al., 2011).

In solid state chemistry and materials chemistry, NMR investigations of materials designed for energy storage applications have been an active area of research, including materials for fuel cells (Buannic et al., 2010) and batteries (Key et al., 2011; Hung et al., 2012). These studies particularly benefit from the highest available magnetic fields, due to the importance of elements such as lithium that possess large electric quadrupole moments.

FUTURE PROSPECTS AND INTERNATIONAL PERSPECTIVE ON NMR

There is no doubt that the importance of NMR measurements will continue to expand into new scientific areas as new variants of these measurements are invented and as higher fields lead to further improvements in resolution and sensitivity. Since the discovery of NMR (resulting in Nobel prizes to the American physicists I.I. Rabi, in 1944, and E.M. Purcell and F. Bloch, in 1952), the United States has played a leading role in the development of NMR spectroscopy. Many of the critical developments in multidimensional NMR, in solid-state NMR methods and their underlying theory, in DNP technology, and in the exploration of applications in chemistry, biochemistry, biology took place in this country. (MRI and functional MRI were also first proposed and demonstrated here.) However, there is a consensus in the NMR community that the U.S. leadership role has eroded over the past 10 years. This is certainly true in the area of high-field NMR magnets. When 900 MHz (21.1 T) NMR magnets became available around 2002, approximately 15 were installed in the United States, 10 of which were purchased with federal government funds (NIH or DOE, plus the wide-bore 900 MHz magnet constructed at NHMFL). Relatively few NMR magnets above 800 MHz (18.8 T) were installed here in subsequent years. Meanwhile, magnet technology has advanced to the point where a 1.0 GHz (23.5 T) NMR magnet was installed at the European Center for High Field NMR in Lyon, France, in 2010. Plans exist to install at least one 1.2 GHz (28.2 T) NMR magnet in Europe, at a new NMR center in the Netherlands. Additional 1.2 GHz NMR magnets are under negotiation for other European sites. Two 950 MHz NMR magnets were installed recently in this country, one with federal funding (NIH), the other purchased entirely by private funds.

Each increment in magnetic field strength produces an improvement in NMR data, through increased resolution and sensitivity, as explained above. Magnetic field strength is not the only significant parameter in an NMR-based research project. Innovations in ancillary technology and RF pulse sequence methods, new approaches to data analysis, improvements in sample quality, and clever choices of scientific problems are also highly significant. For these reasons, U.S. NMR research groups that do not have access to the highest available fields can continue to make important scientific contributions. However, if the country were to fall further behind in NMR magnet technology, the most interesting and important problems, involving systems with the greatest complexity, biological relevance, and technological impact, would be solved elsewhere. It would also become increasingly difficult for research groups here to attract the brightest and most productive Ph.D. students and postdoctoral fellows, as it is natural for young scientists to prefer better-equipped research labs for their training.

Investment in high-field NMR magnet technologies is highly leveraged. While this discussion is focused mainly on the importance of a small number of cutting-edge NMR magnets and spectrometers, it can be expected that demonstration of the scientific impact of these instruments will ultimately lead to the production of larger numbers of similar instruments, in more cost-effective ways and with enhanced technologies, to enable basic research in the chemical and biological sciences, in academic or national laboratories as well as the commercial sectors. Thus, the eventual impact of the initial cutting-edge instruments will expand beyond the results of specific experiments performed with these initial instruments. In addition, as magnet technology improves to meet the challenges of the next generation of NMR magnets, the cost of moderately high-field instruments, which are more widely distributed among individual research labs and institutions, is likely to decrease.

The cost of a 1.2 GHz NMR magnet is approximately $20 million. To satisfy the likely demand for measurement time on a 1.2 GHz NMR system in the United States, at least three such systems would need to be installed by early 2015. Moreover, planning for the next-generation instruments, likely a 1.5- or 1.6-GHz class system, should be under way now to allow for steady progress in instrument development. Given the size of the NMR community in the United States (more than 100 active research groups), the advantages of high-field NMR data discussed above, and the fact that each NMR data set requires hours to days of measurement time, the committee expects that three 1.2 GHz NMR systems would easily be used to full capacity. There is currently no mechanism by which funds on this scale can be obtained through the conventional peer-review processes at NIH or NSF or DOE. While the United States has historically held a leadership position not only in the applications of NMR in physics, chemistry, and biology but also in the development of NMR instrumentation and methodology, this privileged position is vulnerable. For this country to remain at the forefront of NMR-based research, new funding mechanisms must be developed.

FT-ICR MASS SPECTROMETRY

FT-ICR is a technique in which the mass-to-charge ratios of charged particles, especially molecular ions, are measured from the frequencies of their cyclotron motions in a strong magnetic field. Compared with other forms of mass spectrometry, FT-ICR has the highest demonstrated precision and resolution, making it the method of choice for complex mixtures of molecules and for distinguishing among chemical species with nominally identical masses but different elemental compositions. Magnets for FT-ICR have stability, homogeneity, and bore diameter requirements similar to those of NMR magnets, so that advances in NMR magnet technology have a direct impact on FT-ICR instrumentation. The resolving power (defined as M/ΔM, where M is the molecular mass and ΔM is the minimum mass difference that produces separate peaks in the mass spectrum) of an FT-ICR instrument increases linearly with increasing field; the accuracy of mass determinations and upper mass limit increases quadratically with field (Marshall and Guan, 1996). Thus, as with NMR, higher-field FT-ICR instruments have broader applications, yield data that are more informative, and permit experiments on systems with increasing complexity. Currently, the highest-field FT-ICR systems operate at 15 T and are located in several labs in the United States, Asia, and Europe. A 21 T system is under construction, through a joint effort involving NHMFL and Bruker Daltonics. The 21 T FT-ICR system will be made available to outside users as an NHMFL facility when completed.

In chemical applications, FT-ICR allows the chemical formulae of individual species to be determined in complex mixtures, such as mixtures produced by combinatorial chemistry, polydisperse synthetic polymers, and extracts from soil and plant matter. The FT-ICR group at NHMFL has pioneered the application of FT-ICR in petroleum chemistry, motivated by the fact that naturally occurring crude oil contains many thousands of chemical components, with distributions that vary with geographical location. Resolution and identification of these components requires the very high resolving power of a high-field FT-ICR instrument ($M/\Delta M > 10^5$ for a mass-to-charge ratio of 1,000 at 15 T). NHMFL scientists have recently used FT-ICR to analyze petroleum samples from the Gulf of Mexico, following the Macondo oil spill, in order to track the chemical transformations that this material undergoes through evaporation, microbial degradation, and photochemical degradation, at various locations (Rodgers, 2011).

In biological applications, FT-ICR mass spectrometry has emerged as a tool with immense impact in metabolomics (see discussion of NMR in metabolomics above) and proteomics, the study of protein structure and function via highly parallel large-scale data collection. ICR has particular advantages in the tandem Mass Spec-Mass Spec experiments, where proteins are identified not only by their total molecular weight but also by their patterns of fragmentation. FT-ICR is a forefront method because of the accuracy of the derived mass-to-charge ratios, and the measurement precision is currently limited by the availability of high magnetic field instrumentation (among other instrument issues). Development of higher magnetic field instruments is expected to increase the complexity of molecules amenable to analysis, and therefore more impact in human biology can be expected. It is furthermore expected that if instruments above 21 T can be implemented, single molecule analysis may become possible. The implications of studies at the single molecule level are many. Such highly sensitive analytic tools can be expected to allow better studies of the many microbes, including pathogenic microbes, that have not so far been successfully cultured in laboratories.

ELECTRON PARAMAGNETIC RESONANCE

EPR shares many of its basic principles with NMR, except that electron (rather than nuclear) spins are observed. Since the magnetic moments of electron spins (at $g = 2$) are 660 times larger than those of nuclear spins, EPR frequencies in chemical and biological applications are typically in the 9-400 GHz microwave range, with magnetic fields of 0.3-14 T. EPR at higher fields depends on somewhat exotic terahertz radiation sources but has been achieved in certain cases. Currently, high-field EPR is limited primarily by the properties and expense of the radiation sources, not by the properties of available magnets, so that EPR is not a major driver for magnet development. This situation could certainly change in the future. Nonetheless, high-field EPR is a growing field with important applications in chemistry and biology, as higher fields produce greater spectral resolution and provide sensitivity to molecular motions on a wider variety of timescales. In particular, in structural biology, measurements of magnetic dipole-dipole couplings between electron spins, using pulsed EPR techniques, have become increasingly common as a means of determining distances in the 10-100 Å range between electron spin labels in proteins and nucleic acids. Such measurements are complementary to the shorter-range distance information available from NMR. Challenges in biochemical preparative methods, magnet development, and microwave instrumentation are all important in the future of this field, and the development of higher field magnets for new high-field EPR spectrometers will be important for chemistry and structural biology over the next decade.

CONCLUSION AND RECOMMENDATION

> **Conclusion:** Nuclear magnetic resonance (NMR) spectroscopy is one of the most important and widely used techniques for structural, dynamical, and mechanistic studies in the chemical and biological sciences. However, in recent years, U.S. labs have failed to keep up with advances in commercial NMR magnet technology. If this trend continues, the United States will probably lose its leadership role, as scientific problems of greater complexity and impact are solved elsewhere.

NMR methods continue to improve, and new applications for NMR continue to be discovered and explored, driven in large part by the ongoing development of higher field superconducting magnets with high stability and homogeneity. Since the discovery of NMR, the United States has played a leading role in all aspects of NMR spectroscopy. However, the highest-field NMR magnets in this country are limited to the 900-950 MHz range (21.1-22.3 T), while a 1.0 GHz NMR system (23.5 T) was installed in Europe in 2010 and 1.2 GHz NMR systems (28.2 T) have been ordered by several European labs.

The cost of a 1.2 GHz NMR magnet is approximately $20 million. There is currently no mechanism by which funds on this scale can be obtained through the conventional peer-review processes at the National Institutes of Health or the National Science Foundation or the Department of Energy.

It is clear that new mechanisms must be devised in order to fund and site high-field NMR systems in the United States.

> **Recommendation: New mechanisms should be devised for funding and siting high-field NMR systems in the United States. To satisfy the likely demand for measurement time in a 1.2 GHz system, at least three such systems should be installed over a 2-year period. These instruments should be located at geographically separated sites, determined through careful consultation with the scientific community based on the estimated costs and the anticipated total and regional demand for such instruments, among other factors, and managed in a manner that maximizes their utility for the broad community. Moreover, planning for the next-generation instruments, likely a 1.5 or 1.6 GHz class system, should be under way now to allow for steady progress in instrument development.**

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4

Medical and Life Science Studies (MRI, fMRI, MRS) Enabled by 20 Tesla

INTRODUCTION

Development of Human Magnetic Resonance Imaging and Spectroscopy

This section is focused on in vivo studies of human beings and animals in health and disease enabled by very-high-field magnetic resonance imaging and spectroscopy. Much of the material presented here is based on the expectation that large magnets with fields as high as 20 T (1 tesla is 10,000 gauss) can be produced with a homogeneity of 1 ppm over a sphere of 16 cm diameter. The clear bore necessary for humans is at least 65 cm in diameter for head and extremity studies and 85 cm for other body parts. These magnets are for scientific research on fundamental medical and physiological problems ranging from cognitive science to aging, heart disease, and cancer. The opportunities opened by much higher magnetic fields than exist today are tremendous, because many human health conditions cannot be approached by any other methods, as discussed in the body of this chapter. The technologies presented here are meant for research and not for routine clinical use.

It is expected that a total of 40,000 clinical systems will have been installed worldwide by 2012. The majority (64 percent) of new installations is for 1.5 T, with the remainder equally divided between 3.0 T and less than 1.5 T. The number of magnets that have been sold having field strength at or above 7 T is 50 at 7 T, 5 at 9.4 T, 1 at 10.5 T, and 2 at 11.7 T. One 14 T magnet for human brain imaging is being funded for South Korea (Z. Cho, personal communication). Animal research systems with small bores and high fields are also in increasing demand worldwide.

Below is a brief history of the development of magnetic resonance imaging (MRI) and in vivo magnetic resonance spectroscopy (MRS) magnets, followed by a discussion of the medical and life science opportunities enabled by higher field magnets with wider bores and homogeneity than currently exist anywhere in the world. Appendix F provides information on safety and potential health effects of MRI.

Chronology of High-Field Developments Leading to High-Field MRI and MRS

Magnetic resonance applications in experimental science started soon after the discovery of proton nuclear magnetic resonance (NMR) in the 1950s. NMR instruments became important for physicists and chemists because the NMR signal carried information about the chemical structure of molecules. The field of MRS is now of major importance, particularly to chemistry (see discussion in Chapter 3). In 1972, chemist Paul Lauterbur of Stony Brook University showed that one can image the spatial distribution of the hydrogen nucleus concentration (mainly water) in objects, and this led to MRI (Lauterbur, 1973). MRI initially and, 10 years later, functional magnetic resonance imaging (fMRI) have become major modalities for research and diagnostic medicine, as well as for animal physiology studies, since the mid-1980s. The growth internationally has been from a few low-field magnets in the United States, Scotland, and England in the mid-1970s to 40,000 installations worldwide in 2012.

The field of NMR spectroscopy being pursued by chemists and physicists for research in molecular structure and dynamics has followed a parallel path of development, but with higher fields and much smaller samples (Figure 4.1).

The initial medical applications used horizontal bore electromagnets with a field strength of 0.04 to 0.15 T in the late 1970s. In the 1980s commercialization was successful for superconducting systems at 0.35 T. In the mid-1980s General Electric marketed worldwide superconducting whole body systems for clinical medicine at 1.5 T. Safety and health effects studies commenced in the late 1970s and continue to the present time while keeping pace with new methods of acquisition of the magnetic resonance signals and the increases in magnetic field strength (Appendix F).

Throughout the development of MRI and MRS, "each substantive increase in field strength has in time led to dramatic improvements in the quality of images and spectra obtainable, and usually to 'quantum leaps' in the information available about tissue structure and function [Figure 4.2]. Each major increase in field has also introduced new technical challenges and problems that have required creative scientific and engineering solutions in order to realize the potential to improve image quality." (Dula, 2010).

The evolution of higher field systems has continued. By 1988 success in development of a whole body 4 T system was reported (Barfuss et al., 1988; Bomsdorf

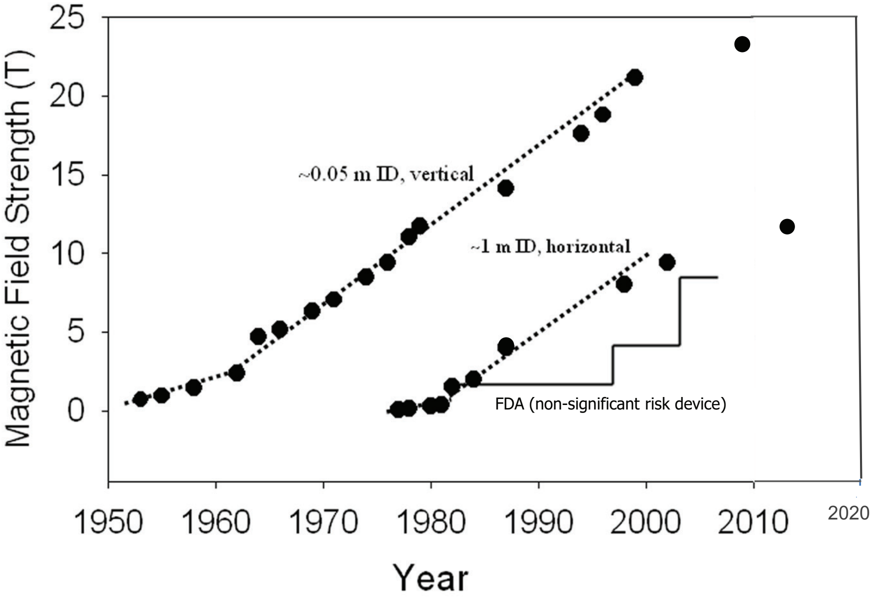

FIGURE 4.1 Flux density (tesla) of steady-state NMR-quality magnets relative to year first demonstrated. The upper group is magnets for analytical NMR applications. The lower set represents magnets suitable for human MRI/MRS. The step curve is the FDA guideline that does not denote a hazard threshold but only caution. SOURCE: Image used with permission from William Rooney, Oregon Health Sciences University; adapted from W.D. Rooney, G. Johnson, X. Li, E.R. Cohen, S.-G. Kim, K. Ugurbil, and C.S. Springer, 2007, The magnetic field and tissue dependences of human brain 1H2O longitudinal relaxation in vivo, *Magnetic Resonance in Medicine* 57:308-318.

et al., 1988; Schenck et al., 1992; Ugurbil et al., 1993), and commercial vendors made a small number of 4 T MRI magnets. However, ultimately the main industrial effort focused on developing scanners operating at 3 T, and these systems are replacing 1.5 T systems in many clinical applications. Much of the early 3 T developments emphasized brain imaging, partly motivated by the discovery of the benefits of blood oxygenation level-dependent susceptibility contrast as a measure of brain activity. This phenomenon is also known as fMRI.

The pioneering 8 T installation at Ohio State University (Robitaille et al., 1999) gave notice to the community that the current density limits of the magnet wire material then in use could be approached and that large bore magnets at 7 T could be developed with an expected commercial market. A compendium on ultrahigh-field magnetic resonance imaging was edited by Robitaille in 1988. Thus the major imaging equipment manufacturers, General Electric, Siemens, and Philips, along with vendors of research magnetic resonance (e.g., Varian) embarked on 7 T development, and academic researchers were successful in obtaining institutional and federal grant support to install these large-bore high-field magnets for medical science research and applications (e.g., Ugurbil et al., 1999). As already mentioned, there are approximately 50 human scanners operating at 7 T in the world today. An example of the demonstrable improvement in image quality over the past 30 years is shown in Figure 4.2.

By 2004 two human imaging systems at 9.4 T with warm bores of 65 cm diameter were being tested at the University of Minnesota and the University of Illinois in Chicago. Smaller scanners operating at higher fields are in extensive use in animal research. Systems with warm bores of 21 and 40 cm operating at 11.7 and 9.4 T are in widespread use, while smaller systems (11 cm bore) are used to image mice at 15.2 T. The 11.7 T installations require operation in liquid helium with reduced pressure and temperature of 2.5 K. One can conclude that 11.7 T is a realistic limit for large NbTi superconducting magnets even at reduced temperatures. This chronology is graphed in Figure 4.1.

While magnet manufacture technology was progressing, in parallel there had to be improvements in shimming techniques and hardware. These include radio-frequency (RF) transmission and reception coils; gradient coils and power supplies; spectrometer design and performance; and the associated pulse sequences needed

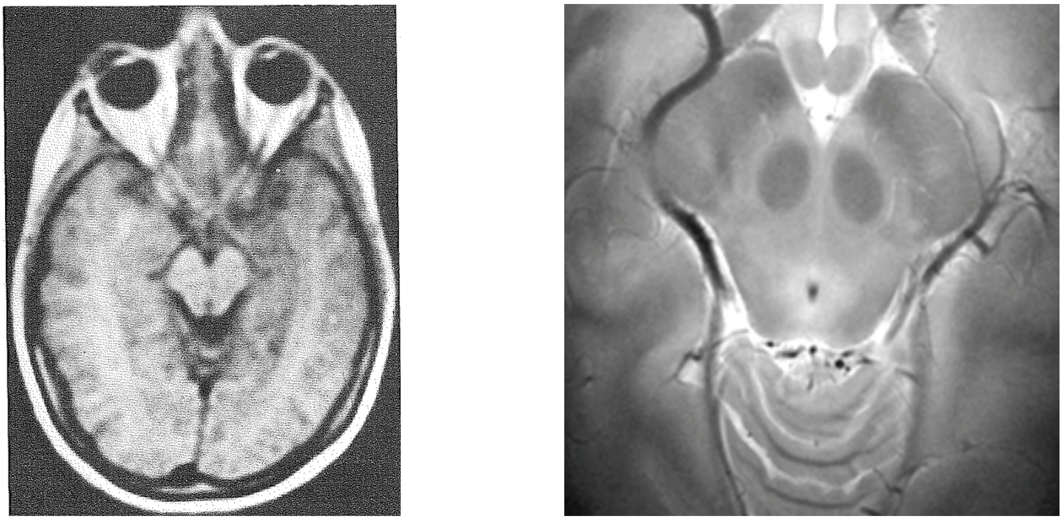

FIGURE 4.2 Increase in field and resolution for human brain proton MRI from 1984 to 2008. SOURCE: (*Left*) H.D. Sostman, D.D. Spencer, J.C. Gore, S.S. Spencer, W.G. Holcomb, P.D. Williamson, J. Prichard, C. Camputaro, R.H. Greenspan, and R.H. Mattson, 1984, Preliminary observations on NMR imaging in refractory epilepsy, *Magnetic Resonance Imaging* 2:301-306. (*Right*) Courtesy of John Gore, Vanderbilt University.

to obtain high-quality images with good contrast and high resolution in shorter experimental times. These advances have been and continue to be significant, with major new developments reported regularly. In the recent past, for example, parallel imaging using large numbers of receiver coils has emerged as an important improvement for imaging, providing new ways to reduce imaging times and increase signal to noise; at the same time, parallel transmission methods are also demonstrating how some limitations of RF fields at high frequencies can be overcome. Another notable innovation that arises only at very high fields (when RF wavelengths are shortened) is the use of traveling waves in MRI (e.g., Webb et al., 2010; Pang et al., 2011) to excite nuclei and detect their NMR signals using remote coils that are no longer closely coupled to the subject. This development suggests that a new class of experimental techniques may be developed, introducing some of the concepts of image formation from coherent optics such as holographic imaging and interferometry. These applications may develop significant importance as ultrahigh-field magnets and improvements in coil design arise.

The National High Magnetic Field Laboratory's (NHMFL's) role in meeting the needs of these research communities has been principally as a user facility. Currently, it has a range of wide-bore magnets at its Tallahassee and Gainesville facilities that are capable of performing MR using a variety of probes and scanners. The 21.1 T wide-bore spectrometer has been used for small-animal studies and is a resource for needed safety studies in planning for 20 T human studies. Other wide-bore magnets at NHMFL have sufficient homogeneity for exposures of animals in order to explore unforeseen physiological effects at static fields beyond 20 T.

The motivation for higher field imaging systems is to increase the signal-to-noise ratio (SNR) available for imaging, because the net nuclear magnetization induced in tissues scales linearly with the field, while the induced electromagnetic force (emf) in receiver coils also scales linearly with the frequency. Increased SNR leads to increased sensitivity for detecting changes within tissues, improved spatial resolution (imaging with smaller voxels), or shortening of data acquisition times. The main driver for development has been proton MRI, which largely depicts variations between tissues in proton (mainly water hydrogen nuclei) density and NMR relaxation times and provides exquisite anatomical images. In addition, there has been continual interest in the use of localized in vivo high-resolution NMR spectroscopy to study tissue metabolism and biochemistry. Proton magnetic resonance spectroscopy operates at the same frequency as proton MRI, but in addition there have been long-standing interest in and development of localized spectra from naturally occurring phosphorus-31 compounds (e.g., phosphomonesters, diesters, phosphocreatine, and adenosine phosphates involved in cellular energetics), as well as the metabolism of injected carbon-13-enriched agents. Next, the committee highlights the many opportunities for medical science advances using much higher fields than are currently available.

MEDICAL SCIENCE AND MAMMALIAN PHYSIOLOGY

Potentials for Studies of Eleven Species Other Than Protons

Whereas MRI and fMRI have been based on imaging proton spin density and intrinsic tissue relaxation rates as well as injected contrast-based relaxation rate changes, a major medical science window is opened by studies of other nuclei such as the spin ½ and spin $^3/_2$ nuclei of carbon-13, oxygen-17, sodium-23, phosphorus-31, potassium-39, and other nuclei present in the mammalian body (see Table 4.1) along with the resonant frequencies at 20 T. Note that many of the anticipated problems for proton studies at 20 T disappear for the other nuclei listed, as they have lower gyromagnetic ratios, hence lower NMR frequencies. Physics of NMR for low gamma nuclei shows the time to acquire equivalent SNR data at 20 T will be reduced by a factor of 8 from that at 7 T and of 33 from that at 3 T, and spectral dispersion and relaxation time changes will allow investigations of metabolites in vivo that cannot be observed by any other method. As shown in Table 4.1, the sensitivities for detection of these nuclei of interest are very much lower than the sensitivity of protons. Moreover, not shown are the abundances in tissues of these nuclei, so it is important to adjust our expectations for applications based on knowledge of the local concentration of nuclei of interest. For example, sodium concentration within cells is 10 *M* and in extracellular fluid is 130 m*M*,

TABLE 4.1 Resonant Frequencies of Relevant NMR Nuclei at 20 Tesla

Nucleus	Frequency (MHz)	Sensitivity	Spin
^{1}H	852	1.00	$^1/_2$
^{7}Li	331	0.29	$^3/_2$
^{13}C	214	0.02	$^1/_2$
^{15}N	184	0.001	$^1/_2$
^{17}O	115	0.03	$^5/_2$
^{23}Na	225	0.09	$^3/_2$
^{31}P	345	0.07	$^1/_2$
^{37}Cl	83	0.03	$^3/_2$
^{39}K	40	0.0005	$^3/_2$
^{57}Fe	28	0.00003	$^1/_2$
^{63}Cu	226	0.09	$^3/_2$
^{67}Zn	53	0.003	$^5/_2$
^{87}Rb	279	0.175	$^3/_2$

but intracellular potassium is 150 m*M* and extracellular potassium is 5 m*M*. This information, plus an assumption that the SNR is proportional to field strength, gyromagnetic ratio, and the square root of time, allows us to calculate the time and resolution obtainable.

Carbon-13 Spectroscopy

^{13}C MRS has great promise because of the richness of information to be gained by in vivo quantification of metabolites and the dynamics of metabolism. A principal advantage of ^{13}C spectroscopy is the fact that the chemical shifts are 20 times those of proton spectroscopy; however, ^{13}C's low natural abundance of 1.1 percent has led to the need to inject large quantities of ^{13}C-labeled substrates. Although hyperpolarized compounds offer significant improvements in detection, there are clear needs to improve the sensitivity for detecting ^{13}C-labeled substrates limited to their Boltzmann magnetization. New insights into neurochemistry have emerged from the ability to study the metabolism of labeled compounds such as glucose and the kinetics of major brain neurotransmitters such as glutamate and GABA, while the synthesis and metabolism of other compounds such as glutamine and choline are of compelling importance in understanding the behaviors of many tumors. Measurements of glycogen production and use are of great interest in metabolic studies of the brain, muscle, and liver. However, at its natural abundance, measurements of glycogen levels are possible but currently take too long and are poorly resolved.

Oxygen-17 for Oxygen Utilization in Brain and Heart

^{17}O is a stable isotope with a nuclear spin quantum number of $\frac{5}{2}$ and is detectable in vivo although its natural abundance is only 0.037 percent, which is almost 30 times lower than that of ^{13}C and about 3,000 times lower than that of protons. The gyromagnetic ratio is 7.4 times lower than that of ^{1}H; thus the resonance frequency at 20 T is 115 MHz. The ^{17}O nucleus possesses a quadrupolar moment that can interact with local electric field gradients. This mechanism leads to very short T1, T2, and T2* values (Zhu et al., 2005). In addition, relaxation times are field independent, so that ^{17}O sensitivity gain with higher magnetic fields will enable imaging the dynamics of $H_2{}^{17}O$ in vivo at 9.4 T and above (Zhu et al., 2001; Atkinson and Thulborn, 2010). This is a new method for noninvasive measurement of cerebral metabolism of oxygen.

Sodium, Potassium, and Chloride Ions

The importance of clinical studies of the local concentrations of sodium and potassium is a compelling reason for making available wide-bore magnets with field strengths significantly greater than available currently. The transmembrane $[Na^+]$ gradient is one of the major reservoirs of metabolic energy. Detecting and measuring this gradient in vivo have been an unattainable goal of importance not only to fundamental biology but also to clinical issues such as mental disorders; tumor biology and response to therapy; heart failure; and diseases of the lungs and kidneys. Theoretically, sodium and potassium can be imaged in human subjects (Parrish et al., 1997) and experience with imaging at low fields and at 9.4 T has been reported (Thulborn et al., 2009; Kopp et al., 2012). However, because these studies have not enabled quantification of intracellular versus extracellular sodium, detection of $[Na^+]$ gradients has not been achieved except in limited experiments. Using multiple quantum NMR techniques, it has been shown that the concentrations of intracellular sodium and extracellular sodium can be evaluated during normal and pathologic function (e.g., perfused heart studies) (Schepkin et al., 1996). It is possible to discriminate cation resonances using the difference in longitudinal relaxation values, which if sufficiently different in intracellular and extracellular environments allow simple inversion recovery pulse sequences (e.g., potassium in perfused heart studies) (Kuki et al., 1990). The most recent 21.1 T rodent studies of brain sodium and proton diffusion demonstrate the potentials at high field to study sodium physiology in the live animal (Schepkin et al., 2010).

Twenty years ago the concept of ^{23}Na relaxographic imaging was introduced to intracellular sodium imaging without the use of spectral shift reagents, most of which are toxic (Labadie et al., 1994). More recently, separation of signals representing intracellular and extracellular sodium has been demonstrated using longitudinal relaxometry on in vitro samples at 9.4 T (Zhang et al., 2010). Resolving the Na_e/Na_i components in human ^{23}Na data will represent a major accomplishment for in vivo NMR. There is even the possibility for determining the instantaneous, homeostatic flux of active trans-membrane Na^+ cycling (Charles Springer, personal communication).

An important potential clinical application is the investigation of migraine headaches, which affect 30 million U.S. citizens. Evidence for the importance of sodium extracellular concentration changes in migraine headache research comes from findings of an increase in $[Na^+]$ in cerebrospinal fluid of patients (Harrington et al., 2006) and the MRI demonstration of a significant increase in $[Na^+]$ in the brains of a rodent model of migraine at 21.1 T (Harrington et al., 2011). These are corroborated by the demonstration of increased excitability of neurons with increases of extracellular $[Na^+]$ (Arakaki et al., 2011).

Other recent studies have highlighted other compelling potential applications for Na, Cl, and K imaging, including provocative results suggesting that in hypertension and renal disorders, there can be a chronic accumulation and storage of ions within tissues such as skin (Titze, 2003), so that interstitial and intravascular levels of sodium are not the same. This has important implications for therapy in renal disease and the management of hypertension (Kopp, 2012), a condition that affects 30 percent of U.S. adults. Although sodium imaging at 3 T has been used to investigate these phenomena, higher fields would allow better resolution, shorter imaging times, and, most importantly, the ability to measure levels of the other relevant ions, chlorine and potassium.

The promise of imaging sodium, potassium, and chlorine such that, in principle, estimates can be made of the resting membrane potentials of the brain and heart in health and disease depends on the availability of fields approaching 20 T.

Phosphorus-31 Spectroscopy at High Fields

Though the frequency of ^{31}P at 20 T will present penetration and homogeneity problems greater than other spins, these problems are well understood from experience with ^{1}H at 7 T (300 MHz). The promise for high-field chemical exchange saturation transfer (^{31}P CEST) is that it could resolve all adenosine triphosphate (ATP), adenosine diphosphate (ADP), and adenosine monophosphate (AMP) signals and thus become an efficient, noninvasive diagnostic tool in heart disease. In addition, ^{13}C-CEST has the potential to redefine metabolic pathway phenotypes in human beings. Furthermore, 20 T will allow measurement of pH, redox, metabolite levels, temperature, reactive oxygen species (ROS), singlet oxygen, and others through the use of PARACEST agents that have exchange rates too fast at lower fields (Cherry and Malloy, University of Texas Southwestern Medical Center, personal communication, 2012).

Selected Horizons for Proton Studies at 20 T

Anatomical Imaging and Spectroscopy Advantages

Although radio-frequency penetration for studying proton relaxation differences and chemical shift spectroscopy currently experiences engineering design difficulties up to the highest human magnet fields of 11.7 T, the benefits of increases in sensitivity, anatomic resolution, and spectroscopy dispersion motivate proton studies at 20 T. In animals including nonhuman primates, cortical anatomic imaging at 7 T and 9.4 T is routinely accomplished with spatial resolutions of about 100 μm and with fMRI resolutions of about 300 μm. In the human at 7 T the attainable spatial and fMRI resolutions are currently 500 μm and 1,000 μm, respectively.

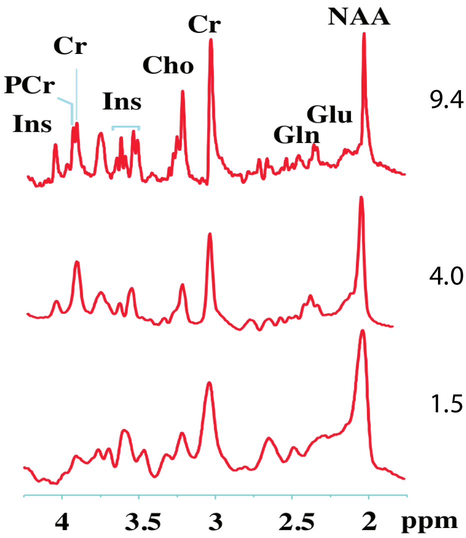

FIGURE 4.3 Comparison of the proton spectroscopy of a volume element of the brain that demonstrates the spectral resolution improvement in going from 1.5 T to 4 T to 9.4 T. The peaks of several of the compounds, such as glutamate (Glu) and glutamine (Gln), are just resolved at 9.4 T. SOURCE: Data courtesy of Michael Garwood, University of Minnesota, adapted from R. Gruetter, S.A. Weisdorf, V. Rajanayagan, M. Terpstra, et al., 1998, Resolution improvements in *in vivo* H NMR spectra with increased magnetic field strength, *Journal of Magnetic Resonance* 135:26-264.

There would be considerable value to being able to routinely image cortex with resolutions 2-4 times smaller—for example, to visualize cortical columns and cortical layers.

Experiments on small animals have resolutions of 50 μm at 21.1 T (Schepkin et al., 2010). Detailed anatomy, fMRI, and spectroscopic studies such as shown for lower fields in Figure 4.3 motivate higher fields than 7 T for proton MRI. One major important clinical goal would be to better understand dementia. Spectroscopic studies of the surface of the human heart for studies of congestive heart failure will most likely emphasize ^{13}C and ^{31}P. The gains in sensitivity for the lower gamma spins discussed above are substantially greater than will be experienced by the University of Minnesota when, as planned, it doubles the field of its human imaging magnet to 10.5 T. The dispersion increase can enable metabolic studies heretofore not possible.

Functional MRI (fMRI) at 20 T

During the past 20 years a method of mapping (imaging) the metabolic activity of the brain in response to activation uses signal changes associated with changes in oxy- and deoxyhemoglobin concentrations. This technique, known as the BOLD (blood oxygen level dependent) technique (Ogawa et al., 1992), or fMRI, has opened new horizons in the cognitive sciences and neurophysiology (Ugurbil et al., 1999). Development of high-field MRI, such as 7 T, is now the high-end research platform in neurosciences with the goal of studying the fundamental computational units that reside in submillimeter organizations (Ugurbil, 2012). Imaging these units and their connectivity employs functional MRI that provides regional information on the neuronal activity changes in the brain. The feasibility of this goal at 7 T was demonstrated by imaging noninvasively the ocular dominance columns (Yacoub et al., 2007). However, magnetic fields much higher than 7 T are needed to achieve the SNR and data acquisition times required to decipher the neural code at the scale of fundamental computations. Even though "physiological noise" increases at high magnetic fields (Triantafyllou et al., 2005), for high-resolution imaging the noise in an fMRI time series is dominated by thermal noise; thus, the effective signal-to-noise ratio for fMRI will increase at least linearly with magnetic fields.

Though functional MRI uses proton frequencies of 852 MHz, penetration to depths of 3 cm in the human skull is not expected to be a problem at 20 T. Studies of RF safety for cell phone frequencies (which are 2 to 3 times higher) show the RF field can penetrate through bone and tissues to and beyond the cortex. In addition, fMRI is an approach that requires minimal power deposition and should be feasible even at 20 T. The main technical challenges of performing fMRI at high magnetic field strengths have been solved for 7 T, and currently the whole brain can be imaged in subsecond intervals (Moeller et al., 2010; Feinberg et al., 2010). Potential future applications using new rapid acquisition techniques include whole-brain connectivity analysis, including the dynamics of brain networks as recently demonstrated (Smith et al., 2012).

Chemical Exchange Saturation Transfer Horizon

One of the most important applications of 20 T is in the use of CEST, as it will allow detection of exchangeable -NH protons or -OH protons within cells and, for example, the imaging of liver glycogen (Sherry and Woods, 2008). Combined proton and ^{13}C studies of lipid and amino acid metabolism in vivo in human subjects relative to nutrition, obesity, and diabetes is another area enabled by high-field studies of muscle and adipose tissue of the limbs.

New Opportunities for Exogenous Contrast Agents

Imaging the distribution of safe stable-isotope-based compounds at very high fields will open new horizons in the applications of contrast-enhanced MRI. The advances in MRI clinical applications have been enabled partly by advances in the design of paramagnetic contrast agents such as those using gadolinium. When these agents are in the intravascular blood pool, they allow visualization of the vascular tree analogous to X-ray angiography, because the presence of the agent reduces the T1 relaxation of water protons in the blood. If a tissue region has increased permeability such that more contrast agent accumulates in that region (e.g., breast or brain tumor), there will occur a temporal decrease in the local T1 (increase in tissue water relaxation rate). This allows identification of different tissue pathologies by MRI imaging methods used to bring out signals related to the relative decrease in T1. The barrier to improving sensitivity of the injected compounds is the inability to effectively restrict fast local motions of contrast agents attached to slow-tumbling scaffolds.

Synthesis of new agents to reach the maximum sensitivity is theoretically attainable at 20 T because the slow-tumbling requirement does not apply. For T2 and fluorine agents, sensitivity can be increased by at least an order of magnitude compared to current experience at clinical field strengths of 3 T. This translates to being able to image targets at subnanomolar concentrations (e.g., cell surface receptors).

Metals other than gadolinium become competitive in terms of sensitivity at 20 T because their fast electronic relaxation times no longer represent a limitation. Consequently, completely new classes of contrast agents become possible. In addition, the increased Curie spin of paramagnetic ions may allow for new ways of engineering more sensitive contrast agents. For PARACEST agents, the larger chemical shifts at 20 T would make multiplexing less challenging.

Proton Transverse Relaxation Rate Changes with Field

The anomalous behavior of the proton transverse relaxation rate (R2 = 1/T2) per gram of protein solutions in water as a function of the measurement field to 7 T (300 MHz) and beyond is shown in Figure 4.4. The implication is that although R2 decreases monotonically as field strength increases to 3 T (as does R1), consistent with the theory of a gradual fall in effectiveness of inter- and intramolecular dipole-dipole couplings that promote relaxation, some other mechanism(s) lead to an increase in R2. The primary candidate for this relaxation is chemical exchange between labile protons (notably -OH and -NH, $-NH_2$) and bulk water, which occurs at rates that depend on molecular structure, pH, and other factors and for which a quadratic field dependence may be predicted. Thus, Figure 4.4 suggests that the contrast mechanism of T2-weighted proton imaging is different than commonly observed at 3 T or at lower fields.

The underlying molecular properties that give rise to this contrast may be sensitive to a completely different set of influences than those known at lower fields. The transition to contrast that reflects chemical exchange is of particular relevance

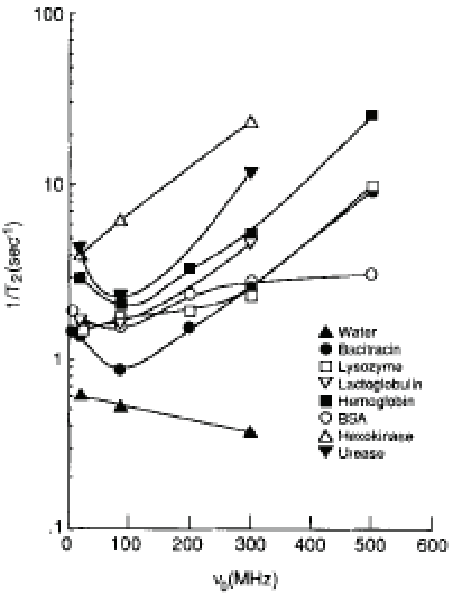

FIGURE 4.4 Transverse relaxation rates for protein solutions as a function of proton magnetic resonance frequencies. SOURCE: Reprinted with permission from John Wiley and Sons, Inc., J. Zhong, J.C. Gore, and I.M. Armitage, 1989, Contributions of chemical exchange and other relaxation mechanisms in protein solutions and tissues, *Magnetic Resonance in Medicine* 11(3):295-308. Copyright 1989 Wiley-Liss, Inc., A Wiley Company.

to new classes of molecular imaging techniques, including CEST and T1rho imaging. The manifestation of this mechanism will be at high magnetic fields.

Enhanced Contrast from Susceptibility Differences

Suppose two adjacent tissues have slightly different susceptibilities. This will result in a change in homogeneity that will increase linearly with field:

$$\Delta B_0 = (\chi_1 - \chi_2)\, B_{0.}$$

This local magnetic flux change leads to a signal phase difference over time:

$$\Delta\Phi \propto \gamma \cdot \Delta B_0 \cdot t$$

The phase difference can lead to image distortions and voids due to phase cancellation effects. The effects noted at 4 T and 7 T will be greater by factors of more than 2 at 20 T. However, the distortion can be viewed as an effective contrast enhancement depending on the amount of susceptibility difference and the volume of the tissue. This concept is already used at lower fields in susceptibility-weighted imaging, a technique that modulates the MRI signal intensity by local phase shifts to enhance vascular and other features. Moreover, tissue layers or domains having dimensions of tens of microns and small susceptibility differences from adjacent tissues might be visualized at higher fields than currently available. Animal experiments at very high fields can evaluate the extent of the benefits as well as problems of susceptibility differences between adjacent tissues because large differences in susceptibility can exist between paramagnetic tissues (e.g., ferritin-containing tissues) and adjacent normal diamagnetic tissues. The anisotropic magnetic susceptibility of neural tissues has already led to the development of imaging methods of the susceptibility tensor, from which new methods for mapping neural connectivity are emerging. Susceptibility anisotropy within macromolecules and assemblages of molecules is discussed in Appendix F.

Some of the potential benefits are related to the image contrast that results from bulk magnetic susceptibility differences in adjacent tissues due to compounds such as ferritin and myelin, both of which are found throughout brain tissue. In addition, the relative directional orientation of bundles of nerve fibers relative to the B_0 field will give an associated frequency shift that translates to image contrast, as shown in Figure 4.5.

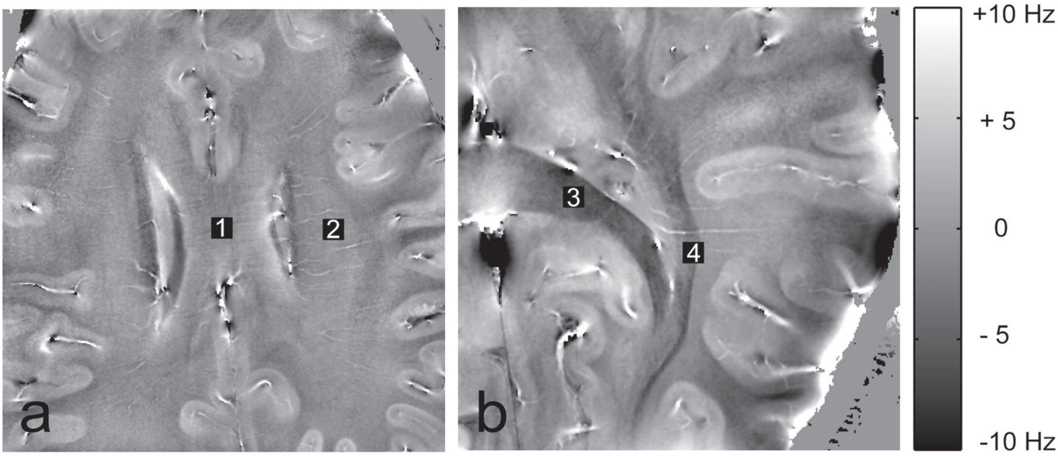

FIGURE 4.5 Contrast based on frequency differences from MRI at 7 T depends on susceptibility differences between adjacent tissues. In (a), the specimen is orientated with fiber tracks parallel to the B_0 field and in (b), the tracks are oriented both parallel and orthogonal to the B_0 field. The resolution is 0.25 × 0.25 mm for a 2 mm slice. SOURCE: J. Lee, K. Shmueli, M. Fukunaga, P. van Gelderen, H. Merkle, A. C. Silva, and J.H. Duyn, 2010, Sensitivity of MRI resonance frequency to the orientation of brain tissue microstructure, *Proceedings of the National Academy of Sciences* 107(11):5130-5135. Copyright 2010 National Academy of Sciences, U.S.A.

Potentials for Traveling Wave MRI at Short-Wavelength Proton Magnetic Resonance

As mentioned above, at very high fields (when RF wavelengths are shortened) traveling waves (e.g., Webb et al., 2010) may be used to excite nuclei and detect their NMR signals using remote coils that are no longer closely coupled to the subject. This development suggests that a new class of experimental techniques may be developed, introducing some of the concepts of image formation from coherent optics such as holographic imaging and interferometry. There will continue to be complications from the nonuniform distributions of relevant electromagnetic properties of tissues, but these may also open up opportunities for mapping such properties as new forms of tissue contrast. For example, measuring the nonuniform distributions of RF fields at 7 T has provided preliminary images of distributions of tissue conductivity and permittivity, and at higher fields these variations should be more easily distinguished. Traveling wave methods may be adapted for such acquisitions, and the fact that image data can be detected at a distance from the object provides a compelling reason to continue to develop these methods at higher fields.

ANTICIPATED PROBLEMS FROM INTERACTIONS BETWEEN HIGH MAGNETIC FIELDS AND MRI HARDWARE AND HUMAN SUBJECTS

Interactions of High Magnetic Fields with Imaging Gradients

Because of the well-known frequency vs. resistance and inductance dependencies, one expects a smooth variation of impedance vs. frequency, but at higher fields the Lorentz forces due to current flow in the gradient coils within the magnetic field not only cause loud acoustic noise but also result in a frequency-dependent resistance change (Schmitt et al., 2006). The emf generated by moving conductors in the magnet oppose the voltage of the gradient power amplifier. This phenomenon will be more problematic at 20 T than experienced at 7 T even though nuclei of lower gyromagnetic ratios than those of protons are being studied because the effect is dependent on field and gradient strength rather than NMR frequency.

Dielectric Effects

As magnetic resonance uses radio-frequency fields to excite nuclei, there are consequences from the interactions of the RF fields and the dielectric and resistive properties of the body (e.g., permittivity and conductivity) that vary with frequency and with tissue type. These effects alter the B_1 transmitted field and spatially modulate the sensitivity of coils in reception, leading to spatial inhomogeneities (Kangarlu et al., 1999; Roschmann, 1987). At RFs of 300 MHz, the effective wavelength in human tissue such as the brain with a dielectric coefficient of about 60 is 10 cm, so the wavelength is no longer larger than the object, leading to standing wave and interference effects. These can result in serious imaging artifacts. It is unknown how well one can deal with this problem at 20 T for protons at 852 MHz, where the limited penetration of RF at these frequencies is also more severe. Fortunately, previous studies at 7 T have coped with this problem for the proton frequency range of 300 MHz, and this range is appropriate for many of the other nuclei listed in Table 4.1 for 20 T.

Gradient Amplitude Requirements for Low γ Nuclei

Whereas very high fields open opportunities for imaging nuclei other than protons because the frequencies allow body penetration and to some extent reduce the RF power deposition, there is a penalty: The spatial resolution requires a spatially dependent frequency shift, and the magnitude of this shift is dependent on the product of the gyromagnetic ratio and the gradient. But this is not a serious consequence, because volumetric resolutions 10-50 times less than enjoyed from proton imaging can provide metabolic information not available by any other noninvasive method.

Shielding

If magnet installations do not use active shielding, between 400 and 800 tons of iron are required for setting up the magnet site. In 2010, Varian completed an actively shielded 7 T system in Palo Alto, California. The feasibility, engineering, and costs for an actively shielded 20 T installation should be part of a design study.

Safety and Health Effects

The effects of fields and magnetic field gradients on sensory functions, the induction of E-fields from switched gradients, and absorbed power from the RF fields are discussed in Appendix F.

FINDING, CONCLUSION, AND RECOMMENDATION

Finding: The development of magnetic resonance imaging, functional magnetic resonance imaging, and magnetic resonance spectroscopy in human studies since 1973 has led to major new human physiology information and significant improvements in diagnoses and treatments. The fields employed for human studies have increased from 0.04 T to 11.74 T over the last 40 years, but other possibilities would be opened by still higher fields.

> **Conclusion:** The current barriers in MRI medical science research would seem to call for an initiative to develop a 20 T magnet with capabilities to image and perform spectroscopy on the human head, large animals, and plants. Although this development would be for research and not for clinical applications, the research could lead to important clinical benefits.

The physics of NMR leads to an expectation that resolutions of 50 μm will be readily obtained in a field of 20 T, and the time to acquire equivalent SNR data will be reduced by a factor of 8 from that at 7 T and of 33 from that at 3 T. Changes in spectral dispersion and relaxation times will allow investigations of metabolites in vivo that cannot be observed by any other methods. A further horizon opened by 20 T is that of imaging nuclei such as ^{13}C, ^{15}N, ^{17}O, ^{23}Na, ^{31}P, ^{37}Cl, ^{39}K, and nuclei other than ^{1}H.

Limitations from absorbed power of RF frequencies restrict the depth of penetration for proton MRI and MRS, but this is not true for the other nuclei as the resonance frequencies of these nuclei at 20 T are in the range of currently successful proton MRI and MRS at lower fields. Potential human health effects at 20 T are not expected to go beyond temporary discomfort such as dizziness and short-term performance deficits. These observations from human subjects at fields up to 9.4 T do not present insurmountable barriers to safe studies. Continuation of human behavioral studies and animal research in small-bore magnets up to 20 T will lead to a better understanding of the mechanisms underlying the reversible symptoms and signs in animals and human subjects (cf. Appendix F).

A promising area will be ^{13}C in vivo spectroscopy because the polarization from higher fields than currently available for in vivo studies will allow direct detection of metabolites we cannot monitor at lower fields.

Another important application of 20 T is in the use of CEST, as it will allow detection of almost any exchangeable -NH protons or -OH protons within cells, thereby allowing, for example, imaging of liver glycogen. Heart disease is the major cause of death in North America. High-field MRS in human subjects using ^{31}P CEST can unlock the tissue and energy mysteries of heart failure (e.g., resolution of all ATP, ADP, and AMP signals). Studies using ^{13}C-CEST have the potential to redefine metabolic pathway phenotypes in human beings. In addition, 20 T will allow measurement of pH, metabolite levels, temperature, reactive oxygen species, singlet oxygen, etc. through the use of PARACEST agents that have exchange rates too fast to detect at lower fields.

At 20 T, imaging the human cortex using proton MRI at 50-μm resolution will be possible even though RF penetration at 852 MHz is limited to a few centimeters. The susceptibility differences between Alzheimer's plaques and adjacent tissues size should allow visualization of plaque-invested tissues even for particles of 20-μm size. fMRI studies at 7 T give confidence that fMRI at 20 T and new rapid acquisition techniques will allow nearly whole-brain connectivity analyses.

> **Recommendation: A design and feasibility study should be conducted for the construction of a 20 T, wide-bore (65 cm diameter) magnet suitable for large animal and human subject research. The required homogeneity is 1 ppm or better over a 16 cm diameter sphere. The appropriate sponsorship might be multiple agencies (e.g., NIH, NSF, and DOE). In parallel, an engineering feasibility study should be undertaken to identify appropriate radio frequency, gradient coils, and power supplies that will enable MRI and MRS and an extension of current health and safety research currently being conducted at lower fields.**

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5

Other High-Field Magnet Applications

INTRODUCTION

In this chapter, the committee reviews briefly several additional areas where high magnetic field science and technology is of great importance, or might be in the future. Two of these, high-energy physics and controlled nuclear fusion, are areas where magnetic fields already play a very large role. Particle accelerators and detectors, and devices for generation and control of hot hydrogen plasmas, require enormous magnets, with stringent demands on field geometries as well as requirements for the highest practical field strengths. In the United States, design and development of such magnets have largely been carried out at laboratories supported by the Department of Energy (DOE), but collaborations with the National Institute of Standards and Technology (NIST), universities, and the National High Magnetic Field Laboratory (NHMFL) have also been involved. A detailed discussion of the requirements of these magnets and the challenges they pose for high-field magnet technology will be discussed in Chapter 7 of this report. Here, we present a brief reminder of the scientific motivation for these projects.

In particle astrophysics, large magnets with strong magnetic fields have been employed in several ground-based experiments designed to look for axions, or axion-like particles, of solar or cosmological origin. Space-based experiments have, so far, made use of only magnetic fields that are rather weak relative to the scale considered in this report. However, improvements in the design of superconducting magnets, particularly a reduction in their consumption of helium and an extension of field lifetime, could give them an important role at some time in the future.

Particle accelerators using superconducting magnets could also play a role in health care in instruments for radiotherapy. In this chapter, the committee summarizes briefly the advantages that could be gained from such accelerators. The challenges involved are discussed more fully in Chapter 7, Magnet Technology Development.

HIGH-ENERGY PHYSICS

Reports of the recent success of the Large Hadron Collider (LHC) in facilitating the discovery of the long-sought-after Higgs boson of the Standard Model of particle physics have garnered much interest among physicists, in addition to capturing the imagination of many nonscientists worldwide. This achievement stands as a prominent example of the triumph of superconducting magnet technology. High magnetic fields are used both in the particle accelerator itself and at various places in the detectors used to observe the collision products. Magnets at the LHC are all superconducting, as the power and cooling requirements for resistive magnets would be entirely prohibitive.

Accelerators employ bending magnets to keep the particle beams in a circular track and use focusing magnets of various kinds to prevent the beams from spreading out in space as they circulate. The bending magnets use uniform magnetic fields, oriented in the vertical dimension, while the focusing magnets require nonuniform fields, with carefully designed gradients, in order to function properly. High fields for the bending magnets are necessary to achieve the highest possible beam energies for a given accelerator radius.

Although the magnetic field strengths of superconducting magnets for high-energy and nuclear physics applications do not approach the present level of laboratory research magnets, i.e., 1 GHz NMR, they do require mostly nonsolenoidal geometry to be useful for charged-particle beam bending (dipoles), focusing (quadrupoles), and error field correction (sextupoles and higher order). They have bore tube diameters on the order of 50 mm but with magnetic field lengths approaching 20 m. The largest detector magnets are often solenoids, but of unprecedented scale, complexity, and stored energy.

Accelerator physicists have already begun to envision the next generation of particle accelerators in the form of a muon collider enabled by high-temperature superconducting magnet technology. Such a device would require solenoidal magnets with a central field as high as 50 T. Several collaborations have been established, involving industry, universities, and government laboratories, to further the development of magnets necessary for such a project. An outline of these efforts may be found in Chapter 7.

PARTICLE ASTROPHYSICS

High magnetic fields could be useful in space-based detectors designed to analyze high-energy charged particles in cosmic rays. The experiment AMS-2, which was deployed on the International Space Station (ISS) in May 2011, employs a 1,200 kg $Nd_2Fe_{14}B$ permanent magnet with a field strength of around 0.125 T. Original plans called for a superconducting magnet using NbTi wire, which would have had a field strength about five times higher and which would have enabled the study of particles with proportionately higher energy. However, difficulties were encountered with the superconducting magnet, particularly a poorly understood heating effect, which would have increased the cryogenic cooling load and shortened the running time for the experiment. Consequently, the decision was made to employ the permanent magnet instead.

Presumably, the development of improved magnets, perhaps at much higher fields, could significantly increase the capability of a future space-based detector. However, a new detector is unlikely to be undertaken in the near future, for reasons unrelated to the magnet issue. The power requirements for the experiment are beyond the capabilities of any existing space platform other than the ISS, and AMS-02 was already too large to be carried by any vehicle other than the U.S. space shuttle, now retired.

High magnetic fields may also have a role in ground-based experiments to search for axion or axion-like particles as a possible constituent of cold dark matter. Strong magnetic fields are supposed to convert a small fraction of axions into observable photons. The Axion Dark Matter Experiment (ADMX), based at the University of Washington, employs a superconducting magnet that generates 8 T in a region that is 1 m long and 0.5 m in diameter. The experiment is designed to convert axions into microwave photons and would be sensitive to axions with a mass in the range of 2 to 20 μeV. Planned upgrades to this experiment, which should greatly increase sensitivity, do not involve stronger magnetic fields but rather involve improvements in the design of the microwave detectors and lowering of the temperature of the microwave cavity, by means of a dilution refrigeration system. However, stronger magnetic fields could have an important role in future experiments of this kind.

Another experiment, the CERN Axion Solar Telescope (CAST), is designed to look for axions produced in the core of the sun, with masses up to 10^4 eV. This experiment, which started operating at CERN in 2002, employs a magnet approximately 10 meters long, with a maximum field of 9.6 T, originally designed for the LHC (Aalseth et al., 2002). For masses below 0.02 eV, CAST has set an upper limit to the axion-photon coupling constant $g_{a\gamma}$ of $<8.8 \times 10^{-11}$ GeV^{-1}, with larger values for higher masses (Collar et al., 2012). Again, stronger magnetic fields will be important for achieving greater sensitivity in future experiments.

CONTROLLED NUCLEAR FUSION

If magnetic confinement fusion reactors are to become a viable source of energy for the future, this technology will require the development of magnets capable of generating large fields while being compact, lightweight, and, in some cases, of a novel geometry for special plasma field shaping. Fusion reactors that are currently operating or are in the planning or construction stages employ a variety of strategies, with different requirements on magnet design, as will be discussed further in Chapter 7.

RADIOTHERAPY USING CHARGED PARTICLES

Charged particles have been used for radiotherapy since the first proposal of Wilson at MIT in the 1940s and the implementation at Lawrence Berkeley National Laboratory at about the same time. The reason high magnetic field technologies are relevant to this health science program is that magnetic fields are used in the source beams of charged particles as well as in steering the beams to the patient.

Proton beams, the most commonly used mode, have the advantage over conventional photon radiotherapy in that the beams can be focused precisely to small tumors and the depth into tissue can be controlled by energy selection, thus allowing normal surrounding tissues to be spared radiation effects. Over the past 70 years, proton therapy systems have been commercialized throughout the world. The use of other charged particles such as helium, carbon, and neon has been shown to be efficacious in the treatment of cancers of the lung, liver, and prostate, while beams of protons, helium, and neon have successfully treated pituitary disorders and arteriovenous malformations. For example, current data, mostly from Japanese studies, show carbon ions are superior to protons in precise dose delivery and in the reduction in the number of times the patient must return for treatment (Kamada, 2012).

The installation of a patient-based accelerator and the supporting treatment devices and rooms is very expensive (approximately $200 million), so these facilities are found only in a few large medical centers. Superconducting technologies can play a major role in reducing the physical size and installation costs of the required particle accelerators and beam transport, as well as the operating costs.

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6

Combining High Magnetic Fields with Scattering and Optical Probes

In addition to the use of high magnetic fields as discussed in Chapters 2, 3, and 4, these fields can also be used in combination with other tools, such as scattering probes, to study the properties of materials. For instance, understanding the functionality of materials requires a deep and thorough knowledge of the spatial ordering of atoms—their charge, orbitals, and moments—as well as the fluctuations and collective modes of these quantities. This information can be obtained from neutron and X-ray scattering experiments that take place in magnetic fields. Similarly, because magnetic fields affect the electronic and magnetic properties of matter in a precise and reversible way, combining high magnetic fields with optical experiments can be used to explore these properties and how they change. In this chapter, the committee discusses opportunities for new science through scattering and optical probes of materials at high magnetic fields.

BRINGING HIGH MAGNETIC FIELDS TO NEUTRON AND X-RAY SCATTERING FACILITIES

Neutron and X-ray scattering experiments have seen some radical advances since the previous COHMAG review of high field facilities. The most dramatic developments in neutron and X-ray scattering in the United States have been the successful launch of the X-ray free electron laser Linac Coherent Light Source (LCLS) at Stanford Linear Accelerator Center (SLAC) and the pulsed spallation neutron source (SNS) at Oak Ridge, but new opportunities have also been provided by X-ray speckle experiments on magnetic materials, by Resonant Inelastic (soft) X-ray Scattering (RIXS), pioneered at the Swiss Light Source (SLS), and by the enormously efficient multi-angle crystal spectrometer (MACS) at the National Institute of Standards and Technology (NIST) for neutron spectroscopy. These advances in scattering capabilities need to be complemented by appropriate sample environments, including high-field magnets.

The science drivers that are described elsewhere in this report argue compellingly for the range of novel electronic phenomena and phases that can be found at high fields, and there can be no question that unleashing the full power of scattering techniques is imperative if we are to have the same understanding of these high-field phases that we have of those that are found in zero field. To give some idea of the potential impact that neutron and X-ray scattering tools might have for producing new scientific insight, the committee provides a few examples of the types of experiments that would be made possible with the combination of magnetic fields in the range of 20-40 T and scattering techniques, and also indicates some new opportunities at the interface with the life sciences:

- *Inelastic neutron scattering measurements.* Such measurements on the vortex state of YBCO probed the fundamental excitations of its normal state. It is not yet possible to carry out similar measurements in the bulk normal state of YBCO, which would require a field in excess of ~100 T. However, the critical fields can be much lower in other superconductors, such as the Fe pnictides and chalcogenides (20-40 T) or organic superconductors (10-15 T), making measurements of this sort well within the reach of pulsed-field magnets used for transport and magnetic measurements. However, critical fields above 15 T are totally inaccessible to even the largest superconducting magnets available at neutron scattering facilities today.
- *Magnetic critical fluctuations near quantum critical points (QCPs).* These have unusual properties, including scale-invariant fluctuations that may be the building blocks of the unconventional superconducting phases often found near QCPs. While QCPs associated with the loss of magnetic order are the most heavily studied at present, it has been shown that the charge response can also be driven critical in ferroelectric and multiferroic systems, to say nothing of Mott-Hubbard or other types of metal-insulator transitions. The electronic delocalization transition that is found in some QCP systems has received extensive theoretical attention, and there are specific predictions for the associated excitations and collective modes that are yet to be tested. Few systems are QC under ambient conditions, and in most cases a tuning parameter such as a field must be applied. In particular, there is a pressing need for spectroscopic information, and angle-resolved photoemission spectroscopy (ARPES) cannot be used in this circumstance, compounding the need for high field X-ray and neutron scattering studies.

- *Field-induced order and quantum effects.* There are a number of interesting systems where magnetic fields modify the local structures to induce moments that can subsequently order magnetically and/or reveal fundamental quantum phenomena of interest to a broad community, such as multispin entanglement, nuclear spin bath effects, and particle confinement, as in the theory of strong interactions (see Figure 6.1). Example compounds are $SrCu_2(BO_3)_2$, $TlCuCl_3$, $BaCuSi_2O_6$, $LiHoF_4$, and $CoNb_2O_6$. In some of these, magnetic order occurs via the Bose-Einstein condensation of moment bearing triplet states, at fields that can be small, as in Yb_2Pt_2Pb, or very large, as in $SrCu_2(BO_3)_2$. Inelastic neutron scattering measurements are required to understand their emergent plateaux phases, the evolution of the spin gap and its dispersion, and the subsequent excitations of the magnetic phase—particularly near the critical fields. A further feature of

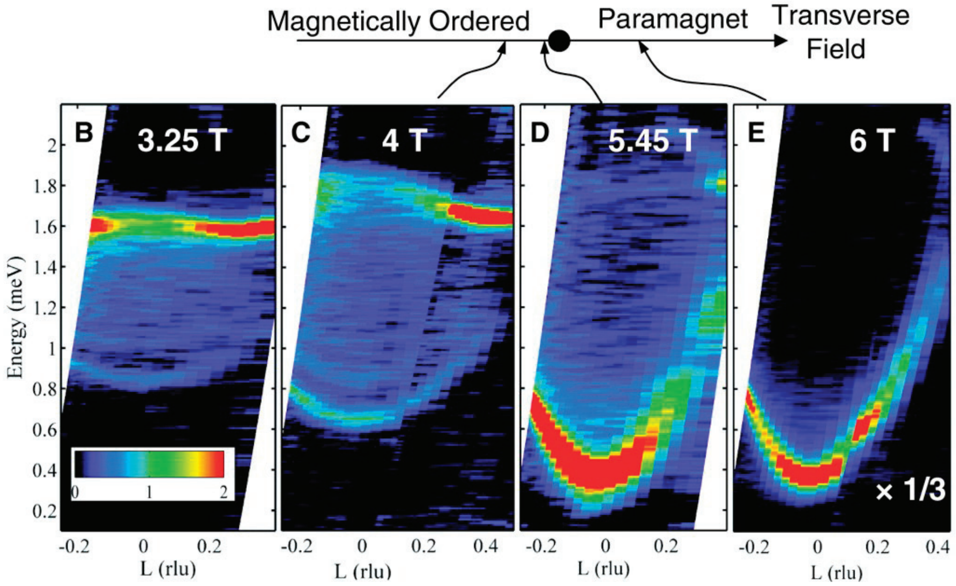

FIGURE 6.1 Inelastic neutron study of magnetic excitations near a quantum critical point induced by an applied magnetic field. By applying a transverse magnetic field to the quasi-one-dimensional Ising spin compound $CoNb_2O_6$, the system can be driven from a magnetically ordered phase to a nonmagnetic paramagnet. The quantum critical point separating the two phases, predicted to belong to an exotic symmetry class, characterized by the Lie group E_8 familiar to elementary particle theorists, gives rise to a peculiar spectrum of low energy excitations as the field is varied about its critical value. Neutron scattering results, shown in the figure, confirm these predictions. SOURCE: From R. Coldea, D.A. Tennant, E.M. Wheeler, E. Wawrzynska, D. Prabhakaran, M. Telling, K. Habicht, P. Smeibidl, and K. Kiefer, 2010, Quantum criticality in an Ising chain: Experimental evidence for emergent E8 symmetry, *Science* 327:177-180. Reprinted with permission from AAAS.

these quantum magnets, as well as spin ices and other frustrated magnets, is that they host cascades of first-order phase transitions among different ordered states as the magnetization approaches its saturation value. The combination of scattering tools with thermodynamic measurements for materials of this type can address frontier areas of quantum condensed matter physics.

- *New directions I.* Many effects in nanoscience and device physics and engineering have interesting magnetic field dependencies, and with the appearance of ever brighter X-ray beams, the examination of functional devices, using e.g., X-ray microscopy and coherent beam diffraction, in response to fields appears quite feasible. The first phenomena that we will be able to examine include strains in such structures, but one could imagine resonant diffraction to image the outer electrons therein as well.
- *New directions II.* It is quite common for physics needs to drive the development of new facilities, which then actually find much wider application in other fields, particularly chemistry and the life sciences. The committee believes that over the next decade we may well be on the threshold of a similar evolution for high field facilities at neutron and light sources. The implications of higher magnetic fields for the life sciences follow from the following energy scales: For an electron spin with $g = 2$, 40 T translates to a Zeeman resonance with energy of ~4 meV and for a proton, to a resonance at ~ 8 μeV. A variety of new possibilities will open up, including the manipulation of nuclear incoherent scattering as well as the possibility to perform magnetic resonance experiments without use of RF or microwave radiation, and even where these are used in pulsed schemes, it may be possible to avoid the use of resonators for detection. One of the simplest applications of the former will be to mitigate nuclear spin incoherent effects on diffraction data, thus obviating, for example, the need to deuterate systems of interest to biologists for neutron diffraction experiments.

While the measurement techniques and scattering facilities have undergone radical improvement since the last report, the maximum magnetic field available to experimenters at these facilities has remained fixed at 16 T. In the same time interval, a new user facility that combines a free electron laser and pulsed fields as large as 85 T has become operational in the Dresden High Magnetic Field Laboratory. A new facility is under construction at Helmholtz Zentrum Berlin (HZB), formerly the Hahn-Meitner Institut in Berlin, that will bring a series-connected hybrid magnet, constructed by the NHMFL in Tallahassee, to a neutron scattering center. Because HZB is a national user facility and has a peer-reviewed, merit-based proposal system, U.S. scientists and engineers can access its neutron measurement capabilities, based on the technical merit of their proposed experiments. When

TABLE 6.1 Magnetic Field Capabilities at Domestic Neutron and Light Sources[a]

Facility	Maximum Field[b]	Geometry	Temperature Range (K)
Domestic neutron sources			
Lujan Neutron Scattering Center (Los Alamos National Laboratory)	11 T	Vertical	1.6-300 (one-shot ^{3}He insert yields 300 mK base temperature)
High Flux Isotope Reactor (Oak Ridge National Laboratory)	7 T	Vertical	1.5-300
	5 T	Vertical	1.5-300
	11 T	Vertical	1.5-300
	8 T	Vertical	0.03-300
Spallation Neutron Source (Oak Ridge National Laboratory)	5 T	Vertical	1.5-300
	16 T	Vertical	1.5-300, 30-500
	30 T pulsed resistive	Horizontal	5-300
NIST Center for Neutron Research (National Institute of Standards and Technology)	7 T	Vertical	0.3-325
	9 T	Horizontal	2.8-325
	11.5 T	Vertical	0.02-40
	15 T	Vertical	0.05-300
Domestic light sources[c]			
Advanced Photon Source (Argonne National Laboratory)	30 T pulsed resistive	Vertical	3-325
	30 T pulsed resistive	Horizontal	2-325
	7 T	Horizontal	<4.5-325
	7 T	Horizontal	<4.5-325
Advanced Light Source (Lawrence Berkeley National Laboratory)	9 T	Vertical and horizontal orientations possible	8-300
	5 T	Arbitrary	8-300

[a] Only magnets whose maximum field equals or exceeds 5 T are listed in this table.

[b] Unless otherwise stated, the magnets listed in this table are superconducting.

[c] The facilities contacted for this report include those listed above and CHESS (Cornell), NSLS (Brookhaven National Laboratory), and the SSRL at Stanford University. Although most facilities responded, some did not have the magnetic field capabilities that warranted their addition to this list.

the series-connected hybrid magnet becomes operational, U.S. researchers should be able to submit proposals for access to the magnet/neutron scattering facility.

Table 6.1 lists the magnetic fields available at selected U.S. facilities, and Table 6.2 lists international scattering facilities. Most have superconducting magnets, while fewer can provide their users with constant fields as large as 16-17 T. Several have expanded the field range to 30 T and even 50 T using pulsed-field magnets, although this is limited largely to diffraction and perhaps small-angle neutron scattering experiments, except at the most intense sources. Improved pulsed-field magnets are being developed at several neutron sources domestically and internationally.

In view of the considerable new physics obtained from examining transport and bulk properties at the NHMFL and its peers worldwide, for which the corresponding correlation functions and fluctuation spectra are unknown, there is a

TABLE 6.2 Magnetic Field Capabilities at Selected Major International Neutron Sources[a]

Facility	Maximum Field[b] (T)	Geometry	Temperature Range (K)
SINQ (Paul Scherrer Institut, Switzerland)	14.9	Vertical	0.05-300
	11	Horizontal	0.05-300
	9	Vertical	0.05-300
	6.8	Horizontal	0.05-300
	6	Vertical	0.05-300
Helmholtz Zentrum Berlin (Germany)	14.5	Vertical	1.5-300 (0.05-1.2 with dilution insert)
	17 (with Dy booster)	Vertical	1.5-80
	15	Vertical	1.5-200 (0.05-1.2 with dilution insert)
	6.5	Vertical	1.5-300 (0.05-1.2 with dilution insert)
	5	Vertical	1.5-300 (0.05-1.2 with dilution insert)
	6	Horizontal	1.5-300 (0.05-1.5 with dilution insert)
	6.7	Horizontal	1.5-300 (0.05-1.5 with dilution insert)
Institut Laue-Langevin (France)	7	Horizontal	1.5-300
	17	Horizontal	1.6-300
	5	Vertical	0.04-300
	6	Vertical	0.04-300
	7	Vertical	1.5-300
	10	Vertical	0.04-300
	10	Vertical	0.04-300
	12	Vertical	0.04-300
	15	Vertical	0.04-300

clear impetus to build higher field capabilities at neutron and X-ray facilities. It is time to harness the developments in superconducting magnet and pulsed-field capabilities that the past decade has brought for scattering science applications. For elastic (diffraction) experiments, which measure order parameters in nonmetallic systems, using pulsed fields will be very informative. On the other hand, for inelastic spectroscopies, which are intrinsically flux-limited, and metallic samples affected by Eddy currents, these capabilities will need to be steady state.

Planning for the Future

There are multiple performance metrics for magnets, and this is especially true for beam experiments. Of particular significance are not only the absolute magnitudes H of the fields attained and the duty cycle (for pulsed-field magnets), but also the H/T ratios, where T is the sample temperature; the direction of the magnetic fields relative to momentum and polarization vectors; apertures and the

TABLE 6.2 Continued

Facility	Maximum Field[b] (T)	Geometry	Temperature Range (K)
ISIS (U.K.)	13.7	Vertical	0.03-300
	9	Vertical	0.03-300
	10	Vertical	0.03-300
	7.5	Vertical	0.03-500
JPARC-MLF (Japan)	7	Vertical	1.8-300 (0.05-1.5 with dilution insert)
	10	Vertical	RT - 1200°C
	14	Vertical	1.5-300 (^{3}He insert yields 400 mK base temperature)
	50 (pulsed resistive)	Horizontal	1.5-300
	30 (pulsed resistive)	Vertical	1.5-300
JRR3 (Japan)	6	Vertical	1.5-300
	6	Horizontal	2-300
	5	Vertical	0.05-1
	13.5	Vertical	RT bore with dilution insert and high-temperature options
	10	Vertical	RT bore and dilution insert and high-temperature options
	5	Vertical	4 K and dilution insert option
	30 (pulsed resistive)	Horizontal	1.5-300

NOTE: Many of the facilities that responded to the committee's requests for information also indicated that they had a number of additional magnets either in procurement or in the development stage. While those magnets are not listed here, the committee is very interested in progress in this area.

[a] Only magnets whose maximum field equal or exceed 5 T are listed in this table.

[b] Unless otherwise stated, the magnets listed in this table are superconducting.

arrangements of beam windows; sample cooling powers, taking into account the windows and beam heating effects; and mobility of the magnet/sample dewars, which are frequently mounted on the moving stages of spectrometers. RIXS, which depends on soft X-rays, will also demand suitable vacuum environments. Experiments themselves must be designed individually with this multidimensional phase space in mind (Figure 6.2). Their execution is of a difficulty that has prevented even experiments in modest 5 T fields from becoming any more routine than they were 20 years ago. The downgrading of traditional low-temperature physics skills among X-ray and neutron professionals since the era of high-temperature superconductors has also resulted in a skills gap, particularly at synchrotrons.

These considerations, together with the scientific opportunities described earlier, which could be exploited by a more vigorous program of high-field research at neutron and X-ray facilities, demand more than the simple procurement of large magnets for certain beam lines. There are new products such as "dry" dilution refrigerators and superconducting magnets exploiting new materials with higher

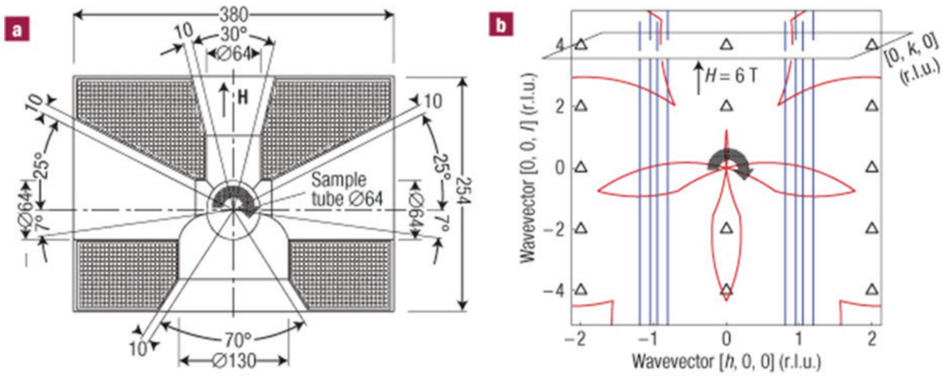

FIGURE 6.2 Planning issues for a high-field experiment using neutrons. Frame (a) shows restricted neutron flight paths into and away from sample centered in circle at middle, while frame (b) shows the highly restricted regions, enclosed by the red lines, accessible in reciprocal space for the $La_{2-x}Sr_xCuO_4$ superconducting crystal. The blue lines represent where the scattering for magnetic "stripe" order occurs in this crystal. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: Nature Materials. B. Lake, K. Lefmann, N. B. Christensen, G. Aeppli, D. F. McMorrow, H. M. Ronnow, P. Vorderwisch, P. Smeibidl, N. Mangkorntong, T. Sasagawa, M. Nohara and H. Takagi. Three-dimensionality of field-induced magnetism in a high-temperature superconductor. *Nature Materials* 4:658–662. Copyright 2005.

critical fields, and in vacuo magnet mounts, which effectively convert superconducting magnets into experimental consumables, all of which together will make it much easier to meet the experimental challenges than the currently installed base of magnet cryostats. Much important science would be enabled by the relatively simple and expeditious procurement of numerous modern 10-16 T magnet/cryostat systems for U.S. large facilities, together with the recruitment of low-temperature/high-field specialists from the "small science" communities, which already have significant practical experience with such systems. The resulting activity will then prepare the X-ray and neutron communities to properly manage and exploit more ambitious high-field systems such as hybrid and pulsed-field magnets.

> **Conclusion:** Neutron and X-ray scattering measurements have played a central role in explicating the behaviors of virtually every class of strongly interacting matter. However, there continues to be almost no progress in the United States on bringing higher fields to neutron and X-ray scattering user facilities. It is clear that difficulties in establishing and maintaining an effective steward-partner relationship between scattering facilities and the NHMFL, as well as their respective sponsors, have been a contributing factor to this lack of progress. This is rapidly becoming a lost opportunity for U.S. science, and bold action is needed now to take the lead in this important area.

Recommendation: New types of magnets should be developed and implemented that will enable the broadest possible range of X-ray and neutron scattering measurements in fields in excess of 30 T. This requires as a first step the expeditious procurement of modern 10-16 T magnet/cryostat systems for U.S. facilities, together with the recruitment of low-temperature/ high-field specialists. Second, a 40 T pulsed-field magnet should be developed with a repetition rate of 30 s or less. Third, building on the development of a high-temperature all-superconducting magnet, which was recommended earlier, a wider-bore 40 T superconducting dc magnet should be developed specifically for use in conjunction with neutron scattering facilities. New partnerships among federal agencies, including the Department of Energy, the National Institute of Standards and Technology, and the National Science Foundation, will likely be required to fund and build these magnets, as well as to provide the funds and expertise that will be needed to operate these facilities for users once they are built. (See the discussion in Chapter 9.)

COMBINING OPTICAL PROBES AND HIGH MAGNETIC FIELDS

Magneto-optical experiments provide a powerful set of tools to obtain insights into the properties of materials, and such experiments are often an ideal way to study new physical phenomena. In this section we use magneto-optics as a general description of all experiments probing light-matter interaction over the extended frequency range from microwave frequencies to ultraviolet. Experimentally, light probes the complex refractive index that contains detailed information on low-energy excitations and collective modes in the studied system (Figure 6.3).

In the 1960s, an era when magnetic field research in specialized facilities started, interband and intraband magneto-optical experiments, most prominently at the Francis Bitter Magnet Laboratory in the United States, laid the basis of our knowledge of band structure of most semiconductors and inspired both theory and new experiments. This work evolved into impurity spectroscopy and the study of excitons in a huge number of semiconducting and insulating materials. At the basis of these studies lie the facts that impurity levels show Zeeman-like splitting in magnetic fields, and conduction and valence bands become Landau levels, all with characteristic energies and symmetries specific for the material studied and dictated by band parameters. These early experiments mainly entailed rather straightforward transmission and luminescence measurements, with optical sources for interband studies and infrared (IR) sources for intraband measurements (e.g., cyclotron and spin resonance) (Balkanski, 1994; Landsberg, 1994). This research has significantly contributed to the general understanding of metals and semiconductors and to the basis of much of the electronic and magnetic materials technology commonplace today.

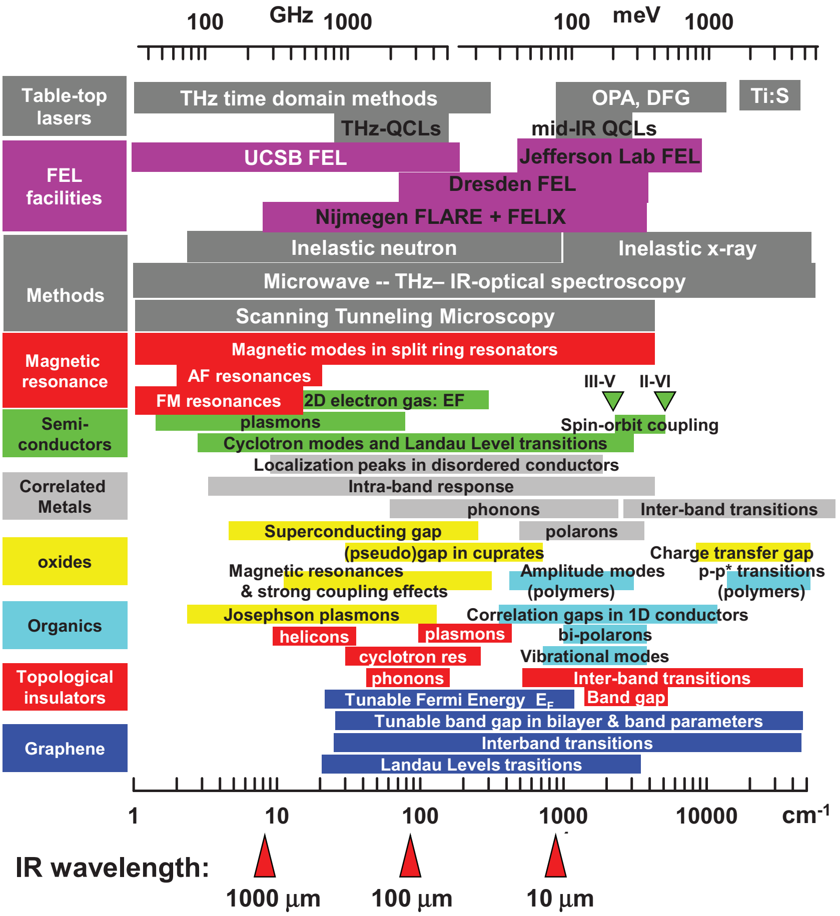

FIGURE 6.3 Characteristic energy scales in solids. NOTE: DFG, difference frequency generation; OPA, optical parametric amplifier; QCL, quantum cascade laser. SOURCE: Adapted with permission from D.N. Basov, R.D. Averitt, D. van der Marel, M. Dressel, and K. Haule, 2011, Electrodynamics of correlated electron materials, *Reviews of Modern Physics* 83:471, copyrighted by the American Physical Society.

Since the initially available samples of new materials are often of subpar quality, field-induced changes can be observed only at the very high magnetic fields, where magnetic energies exceed the disorder-broadening of the levels. For this reason, new materials are, in many cases, first studied at high magnetic field laboratories, thus making these facilities into antennas for advanced materials and condensed matter research. Magneto-optics or magnetospectroscopy remains a very important part of the work at high-field facilities, which are always focused on the newest materials or material structures. The set of experimental tools in the field of magneto-optics is being continuously expanded and becoming increasingly sophisticated.

In the 1970s and 1980s, semiconductor heterostructures were at the focus of magneto-spectroscopy research (Balkanski, 1994; Landsberg, 1994; Landwehr and Rashba, 1991). Current work is centered at the forefront of fundamental and applied physics, including zero-dimensional structures (quantum dots, quantum wires), oxide heterostructures, graphene, magnetic semiconductors, correlated electron systems, unconventional high-T_c superconductors, topological insulators, and many other systems. However, not only can material properties be studied but also new physical effects can be directly observed. For instance, the spin texture in semiconductor bilayer systems can be observed from the degree of polarization of transmitted light (Aifer et al., 1996). Also, many-body excitations responsible for the fractional quantum Hall effect can be investigated by Raman scattering experiments that allow probing of both energy and wavevector of the collective excitation (Blokland et al., 2011).

Over time, the performance of laser sources has increased dramatically, covering an ever-wider frequency range and allowing time-resolved studies in the femtosecond (fs) domain. These capabilities have enabled many nonlinear techniques (e.g., higher harmonic generation) to be done at high magnetic fields (Molter et al., 2010). Additionally, detectors have improved tremendously with the advent of charge-coupled device (CCD) arrays, allowing ever-weaker signals to be measured. Moreover, modern CCD detectors in combination with dispersive elements allow an entire high-resolution spectrum to be collected in a single-shot measurement. Finally, the development of low-loss single-mode fibers and compact optical components (lenses, polarizers, even nanometer-resolution translation stages) have allowed scientists to perform very advanced optical experiments at the highest possible magnetic fields and even at very low temperatures. For instance, single-object spectroscopy (single molecules, single quantum dots, nanowires) using confocal microscopy at very high fields with a subwavelength resolution are now possible (Htoon et al., 2009) and provide great promise for future discoveries. The use of single objects instead of ensembles of many dots has the enormous advantage in that spectral linewidth broadening due to unavoidable inhomogeneity of an ensemble of dots or molecules is eliminated, which increases resolution by orders of magnitude. Good examples are colloidal nanodots, made from II-VI elements by purely chemical means (Blokland et al., 2011). These dots may serve as coatings in LED sources or on top of solar cells, which convert the incoming solar photon energies to lower ones through absorption and re-emission in a very efficient way. Developing such an application requires a detailed knowledge of the electronic structure in these dots, and magneto-spectroscopy has contributed significantly to this crucial knowledge (Blokland et al., 2011).

Optical techniques in the past have had their greatest impact in advancing the physics of semiconducting materials. However, with nonlinear techniques becoming available due to better equipment, metallic materials can now be studied as well. Such studies are still in a relatively early phase but hold great promise for the future. Current active research in this vein includes small metallic particles and graphene microcrystals, both of which are of great interest in the areas of nanophotonics and nanoplasmonics (Crassee et al., 2012). The use of high magnetic fields in combination with advanced optical spectroscopy has therefore the potential of making great contributions to both science and technology. As mentioned before, a pioneering role is expected for dedicated high-field laboratories, since the highest fields are needed to provide the clearest data. Of particular interest here is that the quantum-mechanical magnetic length at high magnetic fields is in the nanometer range, so the interplay of magnetic fields and size effects in nanoscale structures may open new research areas.

In addition, many physical phenomena depend explicitly on the presence of a high magnetic field. Thus, spectroscopic studies of field-induced metal-insulator transitions, of the normal state of high-T_c superconductors, and of boundaries between different magnetic states in correlated electron systems are highly desirable.

Magneto-Optical Experiments in the Far Infrared

In the terahertz and far IR region (0.5-25 THz), progress has been more modest than in the mid-infrared and visible regime, largely because sources, detectors, and optical components here are far less developed. Yet, from a scientific viewpoint this energy region in high magnetic fields is of particular importance, since it covers the magnetic resonances (spin resonance, antiferromagnetic resonance, magnons, cyclotron resonance, and other important effects) in fields between 20 and 100 T (Figure 6.3). Recently completed IR magneto-optical studies of high-T_c superconductors (LaForge et al., 2008; Basov and Timusk, 2005) graphene (Jiang et al., 2007; Orlita and Potemski, 2010) and topological insulators (Valdés Aguilar et al., 2012; Schafgans et al., 2012) attest to unique capabilities of spectroscopic studies in far-IR and THz ranges. Phonon and molecular vibration energies are typically in this regime, allowing for the study of many types of coupled modes. Far IR radiation is of particular importance because its low energies (meV range) are such that electronic and magnetic states are probed very near their equilibrium state (measuring essentially ground state properties). This is a significant advantage compared to visible range optical spectroscopy, where excited states usually are studied. For all of these reasons, the Dresden facility and the Nijmegen high magnetic field laboratory of the EMFL have integrated free electron lasers (FELs), providing very high intensity, quasi-monochromatic, pulsed or quasi-continuous radiation, in exactly this frequency range, at their facilities. The much higher power of these sources (a 10^4- to 10^6-fold increase compared to traditionally available sources) and their tunability (instead of fixed frequencies with backward wave oscillators or molecular lasers) will lead to a wide range of new experiments hitherto impossible. Among them will be mode-selective excitation of phonons in correlated metal oxides triggering the transition from insulating to metallic state (Rini et al., 2007).

The NHMFL in Tallahassee has also recently put forward a proposal to combine its magnets with FEL dedicated sources. Serious consideration should be given to this provision of tunable radiation for pump-probe measurements in high magnetic fields at NHMFL. The NHMFL proposal presented to the committee is considerably more elaborate than the European FELs and would cover a broader range of wavelengths. But the estimated construction[1] and operating costs of this facility are significant, so less costly alternatives should be explored. A systematic approach to complete coverage of the terahertz regime by alternative methods, including, for example, a suite of quantum cascade lasers, should be explored, although it may be difficult to compete with FELs in optical field strength, wavelength, and time structure. Given the interest beyond the high-field community in such coverage, the committee suggests partnering with other agencies, including particularly those sponsored by the DOE or DOD. Another option that should be considered is to bring the high magnetic field capabilities to a source of terahertz radiation. A potentially cost-effective approach, one that would meet the needs of the scientific community, is to locate a moderately high field (commercially available, 10-20 T, all-superconducting) magnet at a centralized, tunable source of terahertz radiation. Although the very highest fields achievable at NHFML would not be reached at a centralized FEL facility, a significant breadth of scientific phenomena (including magnetic excitations, collective modes in correlated electron systems, lattice vibrations, and band gaps) could be studied even at lower fields.

Apart from FEL's recent developments in the ultrafast regime, nonlinear optics now allow one to generate intense THz fields using much more modestly priced tabletop setups (Yeh et al., 2007; Hirori et al., 2011). The attainable fields can exceed 1 MV/cm, which is sufficient to switch between the insulating and metallic state of correlated transition metal oxides (Liu et al., 2012). The anticipated progress in the technology of solid-state lasers directed towards enhancing spectroscopic and pump-probe capabilities will enable a broad range of breakthrough magneto-optics studies of new materials over the next decade.

At the high power densities enabled by state-of-the art laser sources, it is possible to break up Cooper pairs in films of high-T_c superconductors, meaning the phase transition line in the T_c-H_c plane can be spectroscopically studied. Furthermore, these power densities are sufficient to induce phase transitions, including superconducting transitions in nonsuperconducting compounds (Fausti et al.,

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[1] A cost estimate ($86 million) from 2008 for construction was presented to the committee by Greg Boebinger, NHMFL, on March 12, 2012.

2011). Magneto-spectroscopy offers tremendous opportunities to investigate the physics of these new states of matter. Novel spectroscopic capabilities when combined with ultrahigh magnetic fields will additionally enable cyclotron resonance studies of heavy Fermion systems (Dordevic et al., 2006) or even more complicated correlated electron systems.

Among other applications of high-power-density radiation sources in high magnetic field experiments, one may think of pulse probe experiments in the far IR, sum frequency and second harmonic generation, and spin-echo electron paramagnetic resonance at frequencies and field ranges at least 10 times higher than is possible now. Furthermore, the combination of far-IR radiation with scanning probe techniques that can position metallic nanometer-sized antennas with subwavelength precision may even allow far-IR spectroscopy of single objects. Continuous wave far-IR sources, together with high-field NMR, may also be used to create dynamic nuclear polarization, whereby the nuclear spin population is polarized by coupling to a set of electron spins that are polarized using far-IR light at terahertz frequencies. This technique promises orders-of-magnitude-enhanced sensitivity in NMR experiments.

As pulsed magnetic fields will always provide researchers with the highest fields, it is important to improve the set of optical characterization tools compatible with the stringent constraints of these experiments. Certain experiments already can be performed in ultrahigh (170 T) pulsed fields (Booshehri et al., 2012). Nevertheless, subsecond timescales are fundamentally insufficient to acquire quality spectroscopic data in the terahertz and far-IR ranges. Therefore, one can anticipate that the most significant breakthrough results will be obtained in dc fields enabling ample time for data acquisition. Furthermore, in order to take full advantage of IR/optical studies in high magnetic fields, it is imperative to be able to analyze the polarization state of transmitted, reflected, or scattered radiation. This latter requirement presents a significant challenge for broadband magnetospectroscopy. An ideal implementation of optical access to a sample in high magnetic field implies propagation of radiation in free space as opposed to fibers and waveguides.

A combination of far-IR radiation with scanning probe techniques that can position metallic nanometer-sized antennas with subwavelength precision enables infrared spectroscopy and imaging at the nanoscale (Bonnell et al., 2012). Extension of these studies to behavior in high magnetic fields would be quite interesting; however, extension to even to modest dc magnetic fields presents a considerable experimental challenge.

In summary, optical and far-IR spectroscopy with high magnetic fields present an ideal combination of experimental techniques that can probe and elucidate properties of the most advanced materials (see Figure 6.4). Furthermore, these techniques provide complementary information to the more commonly used

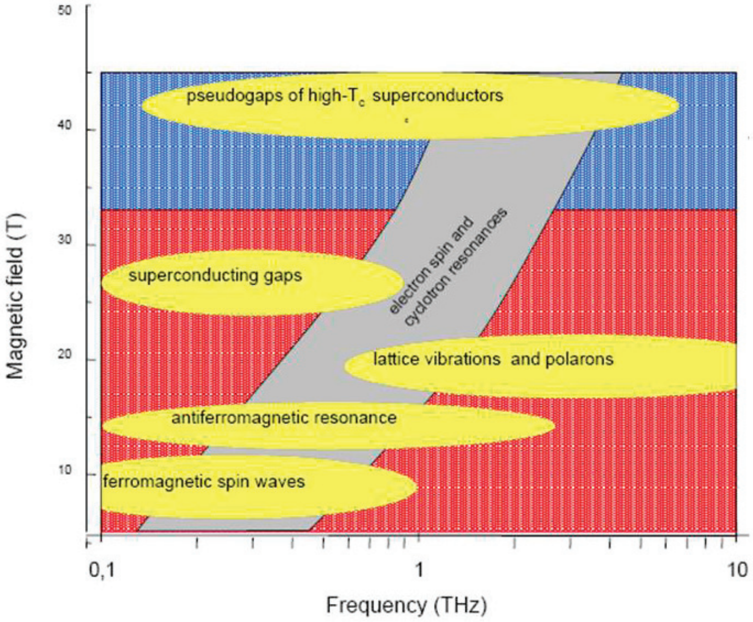

FIGURE 6.4 Typical energies, in terahertz, of various physical phenomena in fields up to 45 tesla (T), showing that the combination of intense far-infrared generated with free electron lasers combined with high magnetic fields has great promise for innovative research.

measurements of transport, magnetization, and thermodynamic properties. Any high magnetic field facility should have a strong program in this area.

Finding: Photons are one of the most important probes of high-field phenomena, ranging from magnetic resonance, which is of importance to all disciplines, including biology, chemistry, and physics, to excitation spectra in quantum solids, a central theme of modern condensed matter physics. Over the last decade, the use of photons for control as well as diagnostics of matter has become a major theme for condensed matter physics, and the committee expects that experiments entailing such control will place new demands on high field facilities. Photon sources in the frequency range 0.5 to 25 THz are of special importance for high-field experiments, as typical frequencies of electron spin resonances and cyclotron resonances fall in this range for fields between 20 and 100 T.

Recommendation: A full photon spectrum, covering at least all of the energies (from radio-frequency to far infrared) associated with accessible fields,

should be available for use with high magnetic fields for diagnostics and control. At any point in the spectrum, transform-limited pulses of variable amplitude, allowing access to linear and nonlinear response regimes, should be provided. Consideration should be given to a number of different options, including (1) providing a low-cost spectrum of terahertz radiation sources at the NHMFL, (2) construction of an appropriate free electron laser (FEL) at NHFML, or (3) providing an all-superconducting, high-field magnet at a centralized FEL facility with access to the terahertz radiation band.

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7

Magnet Technology Development

Magnet technology has advanced, year-over-year, pulled by the desire of scientists for ever-higher magnetic fields. But progress has been paced by new developments in properties of materials needed to build these high-field magnets and by innovations in overcoming the technical challenges that arise from integrating the materials into a stable, safe, and economical magnet.

The technology challenges can thus be grouped into advancing specific aspects of magnet materials properties and by applying intensive and clever engineering design innovations and manufacturing processes. All magnets must simultaneously satisfy a number of often competing electrical, electromagnetic, structural, thermal, and economic constraints.

High-field magnets are generally categorized as resistive, superconducting, and hybrid (i.e., an outer superconducting magnet and an inner resistive magnet). They can be further divided into steady-state (continuous wave, or CW) and pulsed (or transient). For high field research magnets, the coils are mostly solenoids generating primarily axial magnetic fields along the bore centerline. Both resistive and superconducting magnets are usually operated CW, but the highest magnetic fields are generated from pulsed resistive, cryogenically precooled coils. Cryogenic precooling permits significantly higher and longer pulse lengths than can be achieved with identical magnets operated without precooling.

For other high-field applications such as high energy physics accelerators, magnetic confinement fusion, and medical applications, the most advanced systems require large-scale superconducting magnets. Superconducting magnets permit the generation of very large magnetic field volumes with minimal electrical power input and can provide extremely stable temporal magnetic fields when the magnet leads are shorted through a superconducting switch. Superconducting magnets can either be operated CW (detector solenoids, toroidal field coils, magnetic resonance imaging, or MRI, magnets) or ramped (synchrotron dipoles and quadrupoles), or pulsed (ohmic heating coils, poloidal field coils).

The technology challenges are often different for each variety of magnet, but there is a basic subset of issues that all magnet designs must address to achieve higher fields.

TECHNOLOGY CHALLENGES

Materials Properties

Resistive electromagnets have been used industrially for well over a century and frequently have been designed for steady-state operations. For research applications, high-field (and high-stress), steady-state, water-cooled solenoid magnets constructed with Bitter plates were operating 50 years ago. They are the workhorse magnets of the National High Magnetic Field Laboratory (NHMFL) and other high-magnetic-field laboratories.

Resistive magnets can be simple, robust, and relatively inexpensive. For steady operation, it is only necessary to provide an electrical power source sufficient to overcome steady resistive losses in the magnets and a cooling system sufficient to remove the dissipated power from the magnets. In forced convection designs operating steadily at room temperature, pressurized coolant (frequently water) is pumped through passages in the magnet's copper conductors, then through a heat exchanger to eject heat into the environment, and then returned to the pump. Steady cooling at high power densities requires that coolant flow paths in the conductor must be kept very short and coolant flow rates kept very high.

The key point allowing resistive magnets to be used for steady-state applications in large sizes is that the required electromagnet current density decreases with increases in the designed size of the electromagnet, as $J \propto B/R$. Power density decreases even more, as $\eta J^2 \propto \eta (B/R)^2$, so cooling large magnets becomes relatively easier. Furthermore, with the total conductor volume proportional to R^3, it follows that total magnet power varies as $P_{magnet} \propto B^2 R$.

For resistive magnets the conductor challenge is to balance high electrical conductivity with high mechanical strength since they are in opposition for practical materials (Figure 7.1). Higher-strength copper alloys or copper strengthened with nanoparticles or filaments have higher resistance than pure copper while offering higher yield stress and modulus. Thus, to achieve higher magnetic fields, the required electrical power and cooling power must also be substantially increased

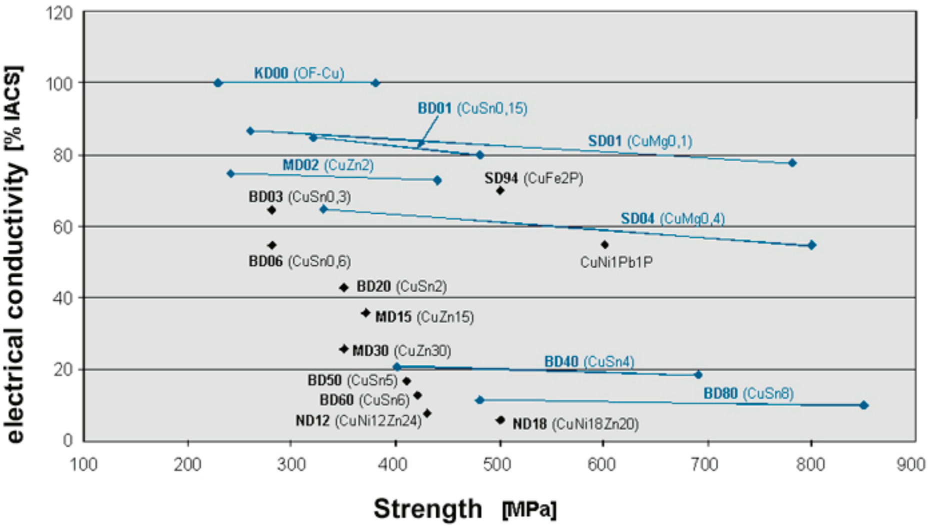


FIGURE 7.1 Electrical conductivity relative to International Annealed Copper Standard versus tensile strength of copper alloys. SOURCE: Data from Diehl Metall.

to keep the working stresses within limits. The CW Bitter magnets at NHMFL are water cooled, while the pulsed-field magnets at Los Alamos National Laboratory (LANL) are precooled by liquid nitrogen and then operated adiabatically during the pulse. The pulse rate is limited by the time required to recool the magnet.

Superconducting magnets usually are more complicated to design and build than resistive magnets and also are more expensive. On the other hand, operating costs are lower because they require only a small amount of electrical power to keep them cold by their cryogenic refrigeration system. There are many technical challenges and considerations for high field superconducting magnets, including the following:

Critical current density is a function of field, temperature, strain, mechanical strength, and wire piece length. Cost and availability have become a major issue particularly when evaluating the trade-offs between high-temperature superconductors (HTS) and low-temperature superconductors (LTS) because the number of manufacturers is limited and the fabrication and processing methods are still under development.

The most commonly used LTS conductors are ductile alloys of NbTi (47 wt% Ti, $T_c \sim 9$ K) and the brittle intermetallic compound of Nb_3Sn. Manufacture is quite complex since the conductors are most useful as multifilamentary composites requiring many assembly, processing, and control steps. This requires sophisticated quality control (QC) and quality assurance (QA) programs that result in high costs. Owing to the highly brittle nature of Nb_3Sn, the wires must be processed to small final diameters while the Nb and Sn elements are separate, and then the Nb_3Sn compound is formed by a high-temperature reaction treatment, typically in the range of 650°C for as long as 100 hours. This process usually requires that the coil be wound from the unreacted wire while it is still ductile, then the entire coil undergoes reaction heat treatment so as not to mechanically strain the reacted wire. The reaction heat treatment poses additional problems for the electrical insulation, which often is applied to the wire before winding and thus must survive the reaction stage.

For high-field applications of interest, NbTi is used for the lower field portion of the coil windings, typically up to 9 T, with Nb_3Sn used in the inner, high-field layers with peak fields now up to ~23.5 T for the highest field nuclear magnetic resonance (NMR) magnets in operation at a proton frequency of 1.0 GHz.

Operation of a superconducting magnet in a cryogenic environment requires the use of a sophisticated cryostat and refrigeration system. The majority of magnets operate at or near 4.2 K, which is the boiling point of liquid helium at 1 atm. The highest field NMR magnets are subcooled to ~2 K to achieve a higher critical current density, but this requires an even more complex cryogenic system, because helium becomes a superfluid below 2.2 K at atmospheric pressure.

To achieve magnetic fields higher than 24 T from an all-superconducting magnet, it will be necessary to utilize a HTS conductor for the portion of the coil operating in higher magnetic fields. Figure 7.2 shows a variety of the best-performing LTS and HTS superconductors that are presently in commercial production.

As noted earlier, NbTi and Nb_3Sn wire production are highly mature and are available in long piece lengths suitable for contemporary magnets. The HTS conductors, on the other hand, still have a long way to go before realizing their full potential. The best performance highlighted in Figure 7.2 may not be available now with the properties stable over piece lengths required to build a magnet. Superconducting tapes produced by powder-in-tube methods such as $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10-x}$ (Bi-2223) ($T_c \approx 110$ K) have seen the widest application so far. The highly anisotropic critical current density has, however, limited its use in high-field applications. More attractive for high-field magnet applications is $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) ($T_c \approx 90$ K), which has high critical current density and low anisotropy at high magnetic fields and can be fabricated as a round wire, making coil winding much easier. Bi-2212 is presently made only in limited quantity for research purposes and is primarily considered for high-field use by the U.S. high-energy physics community.

The HTS material with greatest potential high-field application is the coated conductor $YBa_2Cu_3O_{7-\delta}$ (YBCO), with a $T_c \approx 92$ K. These tapes use a strong metallic substrate such as Hastelloy or a Ni-W alloy, providing very high tensile strength.

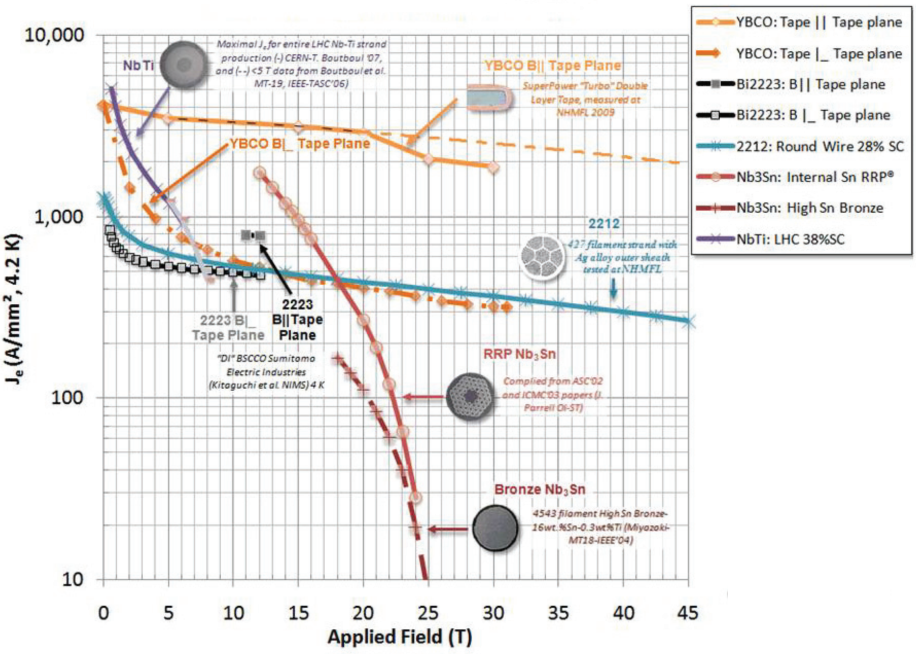


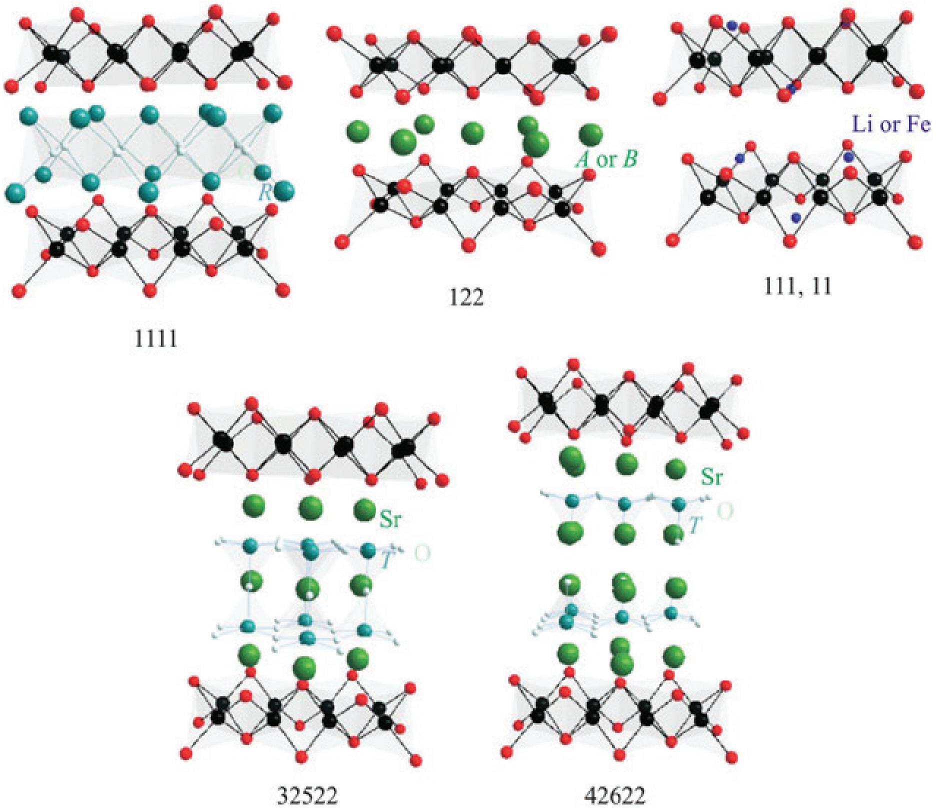
FIGURE 7.2 The critical current density versus magnetic field at 4.2 K for the best-performing LTS and HTS conductors presently in commercial production or development. Critical current densities for YBCO tape with B parallel to the plane of the tape (not shown in figure) are higher than 1,000 A/mm^2 for all fields plotted on the graph (up to 31 T). SOURCE: Courtesy of David Larbalestier, Florida State University/NHMFL.

Presently these conductors can be made only as thin flat tapes. They exhibit a strong anisotropic critical current density in the presence of transverse magnetic fields. Doping the compound with zirconium and substituting gadolinium for yttrium have resulted in reduction and modification of this effect (Selvamanickam et al., 2012). This is very important for magnet operation since the performance of coils using YBCO has often been limited by the transverse magnetic field generated near ends of the coil rather than by the highest magnetic field, which is located at the coil inner radius, axial centerline, and parallel to the c-axis.

Iron-Based Superconductors

The 2008 discovery of superconductivity in fluorine-doped LaOFeAs was highly significant because, as it turned out, the quaternary compound was only the tip of the iceberg for a new class of iron-based superconductors that include a number of families of binaries, ternaries, and the other more structurally complex pnictide and chalcogenide compounds that soon followed. In the classification by structure, the six families that have been discovered to date are known as 11, 111, 1111, 122, 32522, and 42622 compounds [1-13] (Selvamanickam et al., 2012; Sefat and Singh, 2011; Kumar et al., 2009; Yuan et al., 2009; Jaroszynski et al., 2008; Putti et al., 2010; Ozaki et al., 2012a, 2012b, 2011; Weiss et al., 2012; Gao et al., 2011; Wang et al., 2010; Qi et al., 2010) (see Figure 7.3).

One of the main features of the iron-based superconductors that have generated much interest is the unconventional multiband superconductivity originating from d-orbitals in the layers of paramagnetic iron ions, which would normally be antithetical to superconductivity by pair-breaking in the traditional mechanism of s-wave Cooper pairing. The relationship of the quintessential magnetic ion to superconductivity in these materials was surprising and motivated a focus on understanding the mechanisms of superconductivity and magnetic ordering in



1111

122

111, 11

32522

42622

FIGURE 7.3 Structural variation of the six families of iron-based superconductors. SOURCE: A. Sefat and D. Singh, 2011, Chemistry and electronic structure of iron-based superconductors, *MRS Bulletin* 36(8):615, reproduced with permission.

addition to the fundamental interplay between these two phenomena. The observation of antiferromagnetic ordering in the form of stripes versus the checkerboard pattern observed with the cuprates prompted further comparisons of similarities and differences between the iron-based superconductors and the cuprates. Magnetic correlations appear strongly in these families of materials so for this reason the iron-based superconductors are ideal for the study of the fundamental relationship between magnetism and superconductivity. Since some aspects of high-temperature superconductivity are still under debate a quarter of a century after the discovery of the cuprates, the iron-based superconductors offer another opportunity for the development of a fundamental understanding of the mechanism of high-temperature superconductivity.

The availability of high magnetic fields, particularly the 45 T hybrid dc field magnet in addition to the pulsed-field magnets at LANL, played a critical role in the exploration of many of the interesting characteristics exhibited by these superconductors. Experimental evidence of multiband superconductivity also quickly revealed that the higher-critical-temperature members of this new class of unconventional superconductors exhibited very high upper critical fields comparable to the cuprates. During this flurry of discoveries, it was the fortuitous availability of high magnetic fields in both dc and pulsed modes that sustained the pace of the investigation of these materials. Table 7.1 gives the upper critical temperature and upper critical field for selected iron-based superconductors.

The upper critical field phase diagram of several superconductors having potential for commercialization in high-field magnets, including the LTS and HTS conductors already in production, are shown in Figure 7.4.

Superconducting magnet design also must take into account electrothermal stability, ac losses (magnetic hysteresis) if cycled, quench detection and protection, and stress management. A magnet design that resolves all these issues simultaneously and in an integrated fashion requires a high level of engineering and manufacturing sophistication. This becomes increasingly more difficult as magnetic fields are pushed ever higher. This is fundamental because all of these issues scale with the magnetic field B, or with the magnetic pressure B^2.

Clearly, the critical current density J_c decreases with increasing field B. This then requires the use of more superconductor at lower overall winding current density, leading to use of more materials and higher cost. As the size of the coil winding increases, the conductor turns are placed at larger radius, decreasing the effectiveness for generating axial field in the magnet bore. Operation at these high fields also increases the probability and consequences of unstable behavior as operating margins are reduced.

Two of the most significant impacts, though, are (1) difficulty in protecting the magnet from damage in event of a quench and (2) management of the coil stresses from the Lorentz forces. Quench protection becomes more difficult because the

TABLE 7.1 Critical Temperature, Upper Critical Field, and Structure Classification for Iron-Based Superconductors

Material	T_c (K)	H_{c2} II ab(T) at Temp (K)	H_{c2} II c(T) at Temp (K)	J_c(Local) at Temp (K)	J_c(Global) at Temp (K)	Structure Classification	Source
$LaFeAsO_{0.89}F_{0.11}$	26 K		60-63 T			1111	1
$CeFeAsO_{0.88}F_{0.12}$	30 K	48.8 T (31.61 K)		1.5 × 10^6 A/cm^2 (5 K)		1111	3
$SmFeAsO_{0.85}$	53.25 K		30.48 T (36.9 K)	7.3 × 10^6 A/cm^2 (5 K) 1.0 × 10^5 A/cm^2 (53 K)	3,850 A/cm^2 (5.4 K)	1111	2, 10
$NdFeAsO_{0.94}F_{0.06}$	53 K		45 T (33 K)	6.7 × 10^6 A/cm^2 (5 K) 1.08 x 10^5 A/cm^2 (49 K)	2,090 A/cm^2 (4.75 K)	1111	2, 10
$(Ba,K)Fe_2As_2$	34 K	90 T (20 K)	68 T (20 K)		5 × 10^5 A/cm^2 (5 K)	122	4
$Sr(Fe,Co)_2As_2$	20 K	42 T (8 K)	38 T			122	5
$FeSe_{0.5}Te_{0.5}$	14 K		14 T (14 K)		10^5-10^6 A/cm^2 (4.2 K)	111	6, 8
FeSe	8 K	50 T			600 A/cm^2 (4.2 K)	11	7,9

SOURCE: (1) Hunte et al., 2008; (2) Jaroszynski et al., 2008; (3) Chong et al., 2008; (4) Weiss et al., 2012; (5) Y. Kohama et al., 2008; (6) Kawale et al., 2013; (7) Ding et al., 2012; (8) Tsukada et al., 2011; (9) Jung et al., 2010; (10) Putti et al., 2010.

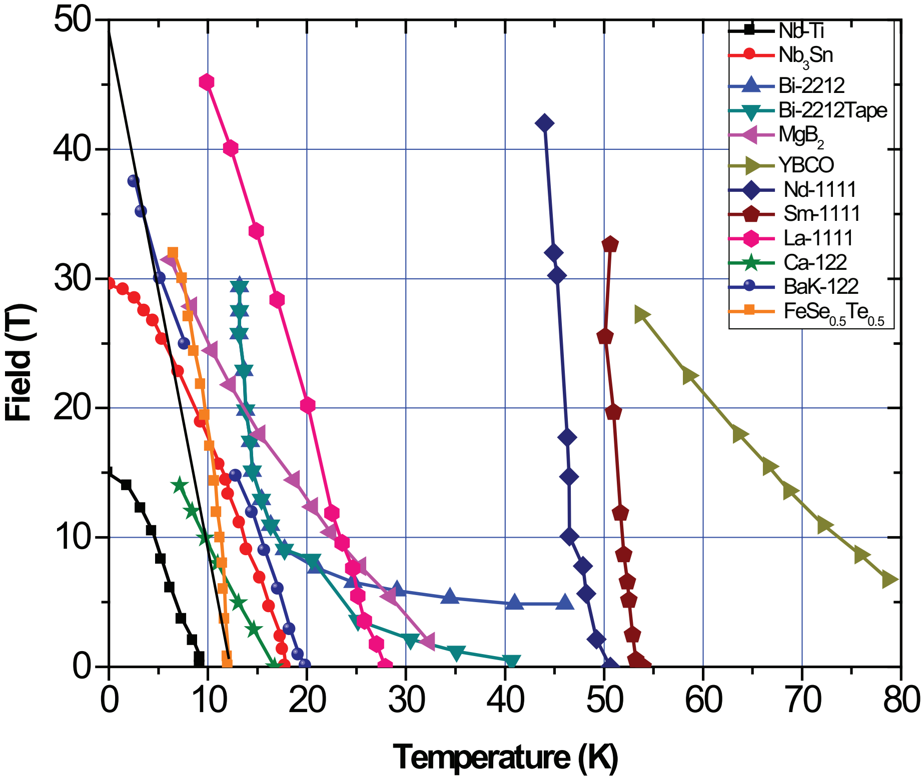


FIGURE 7.4 Upper critical field phase diagram of several superconductors having potential for commercialization in high field magnets. SOURCE: Courtesy of David Larbalestier, Florida State University/NHMFL.

stored energy per unit volume of the magnet increases with B^2, and along with it comes an increase of internal mechanical stresses. A quench in superconductor parlance refers to an unplanned transition of the conductor to its resistive state, which is generally initiated by an abrupt excursion of the superconductor beyond its critical surface.

For an NMR magnet that is operated in persistent mode, all quench energy must be safely dissipated within the winding pack at cryogenic temperature. Keeping stresses within acceptable design criteria may mean the addition of stronger materials and/or more structure with subsequent reduction of overall current density.

These issues require intensive engineering design and analysis. Implementation of any new materials or designs requires substantial R&D and testing. This type of expertise is available at only a few highly select laboratories in the United States and abroad, the NHMFL being premier among them.

TECHNOLOGY STATUS

Resistive Magnets

Resistive magnet technology of the Bitter plate type (e.g., Florida Bitter) is highly developed. Presently generating CW fields to 33 T, the limit is primarily availability of cooling water and electric power, with the cost of power a major issue. This technology requires large infrastructure to operate and maintain and thus is available only in a limited number of laboratories such as NHMFL. Any increase in magnetic field will require upgrade of both cooling and electric power capability at significant cost. Increased magnet time availability would require either operation during more shifts (e.g., three shifts) or building more magnets and power supplies.

Pulsed-Field Magnets

All very high field pulsed magnets are resistive. They are also limited by the availability of cooling and electric power. With stresses increasing with B^2, engineering design and materials properties are major issues. The conductor resistance (usually a copper alloy) increases with temperature and magnetic field, depending on the alloy composition. Resistive magnets require high power to reach high field and high stored energy in the pulsed power source to achieve long, peak field durations. Here 100 ms is considered a long time. This relatively short duration pulse requires advanced methods for instrumentation and diagnostics of the sample under test and methods to prevent excessive heating of the test sample. Now only a few laboratories worldwide are available to provide this type of magnet system. The most powerful system is located at NHMFL/LANL, which takes advantage of a major electrical power generator as the power and energy storage source, coupled with a large capacitor bank and switching circuits. Recently, a world record 100 T pulse was achieved at LANL.

Presently available pulsed field magnets include the following:

- Capacitor driven—Field strength: 50-70 T, duration: 20-800 ms (total pulse length, including decay, available now at NHMFL);
- AC power driven (long-pulse, adjustable pulse shape)—Field strength: 40-60 T, duration: 2 s (>100 ms duration at constant field (flat-top), available now at NHMFL);
- Capacitor + ac power—Field strength: 80-100 T, duration: 20 ms (100 T recently achieved at NHMFL); and
- Destructive—Capacitor + chemical 100 T – 250 T.

The highest magnetic field values (up to 1,000 T) can be obtained during microsecond pulses with destructive techniques. Fields up to 200 T can be reached with the so-called single-turn coils. A very steep high-voltage pulse is provided to a relatively simple and cheap copper single-turn coil, inducing a large current in it. During the pulse the copper is evaporated, and the current is carried by the ionized plasma, which is pushed outward by the Lorentz force. Due to inertia, during a few microseconds the high current density is maintained near the center, and a high-field pulse of the same duration is experienced by the sample. The coil is destroyed, but since the debris is projected outwards, it is usually possible to save the sample and additional experimental infrastructure. At the LNCMI in Toulouse (France) and the MegaGauss laboratory in Kashiwa (Japan), this technique is routinely used in optical and simple transport experiments. Even higher fields can be obtained using flux compression. Here, with a relatively slow pulse in an outer coil, a small seed field is fed into a small inner copper ring (the liner). Subsequently the flux in this liner is compressed, thus increasing the field in the center. The flux compression can be achieved with explosives, as was done in the Dirac experiment in Los Alamos, where field values of 1,000 T have been reported. Alternatively, flux compression can also be achieved by applying a second, huge electrical pulse to the outer coil, which is destroyed in the process but generates a short-duration high-field pulse on the inner coil, which compresses it and which generates the high field by flux compression. This technique has been pioneered by the MegaGauss laboratory in Kashiwa, which has also reported scientific data from such experiments up to several hundreds of tesla. This facility is being used to study magnetic phases of spinel oxides such as $ZnCr_2O_4$ at ultrahigh magnetic fields (Miyata et al., 2012). Obviously, the flux compression technique is destructive for the outer coil, the liner, the sample, and any apparatus near the field center.

The amount of information that one can extract from a pulsed experiment is proportional to the product of the pulse duration, the bandwidth of the experiment, and the binary logarithm of the signal-to-noise ratio (SNR). Obviously, all things being equal, less information can be extracted in shorter times. Fast data acquisition can only partially alleviate these problems, because increasing the bandwidth also will increase noise and thus a deterioration of the SNR. Furthermore, the technique is limited to physical effects that have shorter timescales than the pulse duration. Therefore no extensive and precise data at these high fields may be expected, and not all experiments are suitable. Nevertheless, very useful data might be obtained under these unique conditions, and exploring this field is very promising.

Superconducting Magnets

The 2005 NRC report of the Committee on Opportunities in High Magnetic Field Science (COHMAG) included recommendations for specific magnet development goals. Among them was the goal of developing a 30 T superconducting, high-resolution, small-bore (54 mm) magnet for nuclear magnetic resonance (NMR). Recently the NHMFL demonstrated an HTS (YBCO) coil operating at 35.4 T (Trociewitz et al., 2011). The test coil comprised an insert HTS coil generating 4.2 T at 1.8 K, within the bore of a resistive magnet generating a 31.2 T background field. Although this magnet system was not all superconducting, it served to demonstrate that coated conductor YBCO tape has sufficient engineering current density as well as mechanical strength to be used as the high-field insert coil of a future, graded, all-superconducting small 32 T research magnet (Weijers et al., 2010).

NMR magnets to 950 MHz are presently commercially available. The first 1 GHz NMR magnet was brought into service by Bruker in 2009 at the European Center for High Field NMR, at the University of Lyon. The central field of this magnet is 23.5 T, achieved with a NbTi outsert and a Nb_3Sn insert cooled to ~1.5 K (Bruker Biospin Corporation, 2009). Several organizations are now designing 1.3 GHz small-bore NMR magnets, including the National Institute for Materials Science in Tsukuba, Japan (Otsuka et al., 2010). This magnet requires generating a central field of 30.5 T and thus will require the use of a YBCO insert coil. Iwasa and co-workers at the Francis Bitter Magnet laboratory at MIT are designing and building a prototype 1.3 GHz (30.5 T) NMR magnet based on using BSCCO-2223 tape for a 600 MHz insert coil in combination with a 700 MHz LTS coil (Bascuñán et al., 2011).

Hybrid Magnets

The status of hybrid magnet development is summarized in Table 7.2.

The NHMFL Magnet Technology Division is presently constructing the NHMFL II, the Berlin, and Nijmegen III hybrids.

OTHER HIGH-FIELD MAGNET APPLICATIONS

High-Energy Physics

With the major goal of bringing the Large Hadron Collider (LHC) into scientific operation having been achieved several years ago, magnet technology R&D programs have been reoriented to achieving even more powerful superconducting beam bending and focusing magnets. The dipole magnets will likely operate with peak fields well beyond 12 T and strong focusing magnets with high-field gradients operating at similarly higher peak fields in the windings. This next step requires a change in focus from magnets using NbTi superconductor at 4.2 K and 2.0 K, to

TABLE 7.2 Resistive-Superconducting Hybrid Magnets Built, in Operation, or Under Construction

Magnet	Total Field (T)	Year of First Operation	Outsert Field (T)	Energy (M)	Technology
First Generation					
MIT I	20	1972	5.8		Ventilated, cryostable?
McGill	25	1972	15		
Oxford I	16-25	1973	6.5		Stabilized NbTi
Moscow	25	1973	6.3	4	Ventilated multifilamentary strip
Second Generation					
Nijmegen I	25-30	1977	8.5		Ventilated, cryostable
MIT II	25-30	1981	7.5	3.5	Ventilated, cryostable
Sendai I	20	1983	8	1	No ventilation
Sendai II	24	1984	8	5	
Sendai III	31	1985	12	19	
Nijmegen II	30	1985	10.5	10	Ventilated, cryostable
Grenoble I	31	1987	11	22	Ventilated
Hefei I	20	1992	7	1.4	Adiabatic
Third Generation					
MIT III	34-35	1991	13	21	"Quasi-adiabatic"
Tsukuba	31-37	1995	15	63	"Fully stable" monolithic
NHMFL I	45	1999	14.2	100	CICC
Sendai IV	23	2003	6	2	Cryogen-free
Sendai V	30	2005	11	8	Cryogen-free
Under Construction					
NHMFL II	36-41	2014	13	52	CICC
Grenoble II	42+	2016	8.5	76	Quench-shield, RCOCC
Nijmegen III	45	2016	12	40	CICC
Hefei II	40	2013	11		CICC
Berlin	25	2013	13	52	CICC

NOTE: CICC, cable in conduit conductor; RCOCC, Rutherford Cable on Conduit Conductor.
SOURCE: Courtesy of the National High Magnetic Field Laboratory.

an Nb_3Sn superconductor operating at 4.5 K. Unlike NbTi, which is a ductile alloy, Nb_3Sn is a brittle compound, requiring a high-temperature reaction heat treatment to form the superconducting phase. This imposes a significant additional step in the integrated magnet fabrication of the conductor, coil, and insulation, which requires important changes in manufacturing processes and handling from those used for past accelerators. Operation at higher magnetic fields leads also to increased stored energy and magnetic forces necessitating stronger and better-integrated structural reinforcing materials. In the United States a new program in applying HTS conductors to accelerator magnets requires R&D to accommodate the complexity of working with this new material.

A laboratory-university-industry collaboration has been established for the development of magnets with fields >22 T. This Very High Field Superconducting Magnet Collaboration (VHFSMC) includes Fermi National Accelerator Laboratory (FNAL), Lawrence Berkeley National Laboratory (LBNL), LANL, Brookhaven National Laboratory (BNL), NHMFL, North Carolina State University, Texas A&M, and National Institute of Standards and Technology (NIST) (Clements, 2009). The focus of the research is to design and build HEP relevant magnets based on round-wire, multifilament Bi-2212 to complement other ongoing work with YBCO-coated conductors.

The U.S. LHC Accelerator Research Program (US-LARP) was established as a consortium of U.S. national laboratories, BNL, FNAL, LBNL, and SLAC, to collaborate with the European Organization for Nuclear Research (CERN) on development of accelerator technology to increase the luminosity of the LHC and to upgrade the interaction regions, through advanced superconducting magnet technology (Gourlay et al., 2006). US-LARP also serves as a programmatic vehicle to advance U.S. accelerator science and technology, including forefront accelerator research, improving capabilities and skills, and preparing the U.S. scientists to design the next generation of particle colliders. Present research is focused on using advanced, very high critical current density Nb_3Sn strands and cables to design, build, and operate high-gradient focusing quadrupole magnets.

The NHMFL fulfills an important role in the development of high-energy particle (HEP) accelerator magnets, both by serving as a national resource for performing high magnetic field tests of advanced, state-of-the-art superconducting materials, conductors, and cables, and conducting research at the Applied Superconductivity Center (ASC). Research at ASC, in particular, and in collaboration with the Department of Energy-HEP laboratories, has been highly effective in advancing the development of round-wire, multifilament Bi-2212, making it a leading candidate for very high field accelerator magnets of the future.

Magnetic Confinement Fusion

Technologies for magnetic confinement fusion applications are designed in various shapes and sizes to provide plasma confinement, shaping, heating, and stabilization. Depending on the plasma configuration, the magnet geometries vary from simple rings and long solenoids, toroids, helical coils, and, sometimes, three-dimensional twisted shapes. Although most of the magnetic fusion experiments built in the past and still operating use pulsed, adiabatic resistive magnets recooled with either water or liquid nitrogen, several new superconducting devices have come into operation in the past few years. A working fusion power reactor has always been envisaged to require the use of large-scale superconducting magnets, since creating very high fields over large volumes would make resistive magnets impractical because of their large electrical and cooling power requirements. The international fusion community has put great effort into development of large-scale NbTi and Nb_3Sn superconducting magnets over the past four decades. Fusion magnet research programs in the United States, Europe, and Asia are now beginning to focus magnet development on using HTS conductors for some plasma confinement coils.

Since the COHMAG report was written, two new, all-superconducting fusion experimental systems have been built and are operational. These are both of the tokamak configuration that is presently demonstrating the most advanced plasma confinement. The EAST tokamak in Hefei, China, is made from all-NbTi cable-in-conduit conductors (CICC) (Wan et al., 2006; Wei et al., 2010). The KSTAR tokamak in Taejon, South Korea, is also made from all-CICC conductors, but the toroidal field (TF) magnets and the central solenoid (CS) use Nb_3Sn strand while the poloidal field (PF) coils employ NbTi strand (Kim et al., 2005). Although the peak magnetic field in these machines is relatively low, ~ 7 T, compared with the most advanced high-field research and NMR magnets, the magnetic field volumes are very large, on the order of cubic meters. Thus the stored energy of the magnet system is 1-2 orders of magnitude greater than, say, a 1 GHz (23.5 T) NMR magnet. This results in very high Lorentz forces and mechanical stresses that in most cases require the use of external supporting structure. The very high stored energy also makes quench detection more difficult, forcing magnet designers to use high current (~10's kA) conductors and external quench protection circuits operating at ~5-10 kV.

Although the tokamak configuration offers the most progress to date in plasma confinement, there are several other magnetic configurations that have significant advantages worth pursuing. Of these, a helical magnetic field is foremost in technology development, including the all-superconducting Large Helical Device (LHD) now in operation at the National Institute for Fusion Studies (NIFS) (Satow and Motojima, 2002), in Toki, Japan, and the Wendelstein 7-X (W7-X) stellarator nearing completion of construction at the Max Planck Institute for Plasma Physics (MPIPP) in Greifswald, Germany (Rummel et al., 2012). Again, although both devices operate at relatively low magnetic field, 6-7 T, using NbTi, their challenge has been to construct large-scale superconducting magnets of very complex geometry.

The W-7X is shown during construction in Figure 7.5 as well as one of its convoluted superconducting magnets.

The largest and most significant large-scale application of superconducting magnets for magnetic confinement fusion is the ITER project. ITER is a large-scale scientific experiment that aims to demonstrate the feasibility of producing fusion power in a sustained burning plasma, while also demonstrating some of the key technology components (ITER Project). It is probably the most ambitious international scientific project ever undertaken, both in the scale of the device and in the complexity of the international collaboration. Over half the world's population is represented by the seven countries participating in the project, including China, the European Union, Japan, India, South Korea, Russia, and the United States. Among the goals of ITER is the production of 500 MW of fusion thermal power using deuterium-tritium fuel, while consuming no more than 50 MW of heating input power, to give a ratio of $Q \geq 10$ for at least 300 s. Another goal is to demonstrate long pulse sustainment for at least 1,000 s with a $Q \geq 5$.

A drawing of the fusion tokamak core is shown in Figure 7.6. Its immense scale requires production of ~500 metric tons of Nb_3Sn strand, supplied by most of the world's LTS suppliers. This amount is more than 10 times the total integrated amount of Nb_3Sn produced since first commercialization in the 1960s. It will also require about 250 metric tons of NbTi strand (Devred et al., 2012).

The ITER TF magnets generate a peak magnetic field of 11.8 T at an operating current of 68 kA and store 41 GJ of magnetic energy. The CS magnet generates a peak field of 13 T and operates with 40 kA current in a pulsed, fully bipolar cycle. It is over 13 m tall and is lifted as a single unit weighing over 900 metric tons (Mitchell et al., 2012). Although the magnitude of these magnetic fields does not approach that of the very highest fields required for NMR studies and scientific research, the huge scale of the magnets imposes extremely stringent design criteria and requires an extremely comprehensive and interdisciplinary engineering and technology approach.

The U.S. fusion base program for magnet technology is now focused on developing magnet technology for fusion reactors beyond ITER. The present magnet program is focused on developing high current, high field, and HTS conductors for fusion magnets. This requires development of 50 kA class conductors that can operate in magnetic fields in the range 16-20 T. Recent studies performed at the Massachusetts Institute of Technology indicate that the use of demountable magnets is a feasible option for future devices that incorporate magnets made with HTS conductors (Hartwig et al., 2012). This could have a major impact on the ability to maintain the machine and increase reliability and availability; however, much more development is required. Similar research is being done in Japan (Yanagi et al., 2012) and Germany (Schlachter et al., 2011). Among the innovations waiting to be explored are structural materials with strengths and elastic moduli much higher than present stainless steels and other alloys. Developing better structural materials is the only viable way to increase the overall magnet current density in a tokamak inner leg, with subsequent savings in machine cost and size.

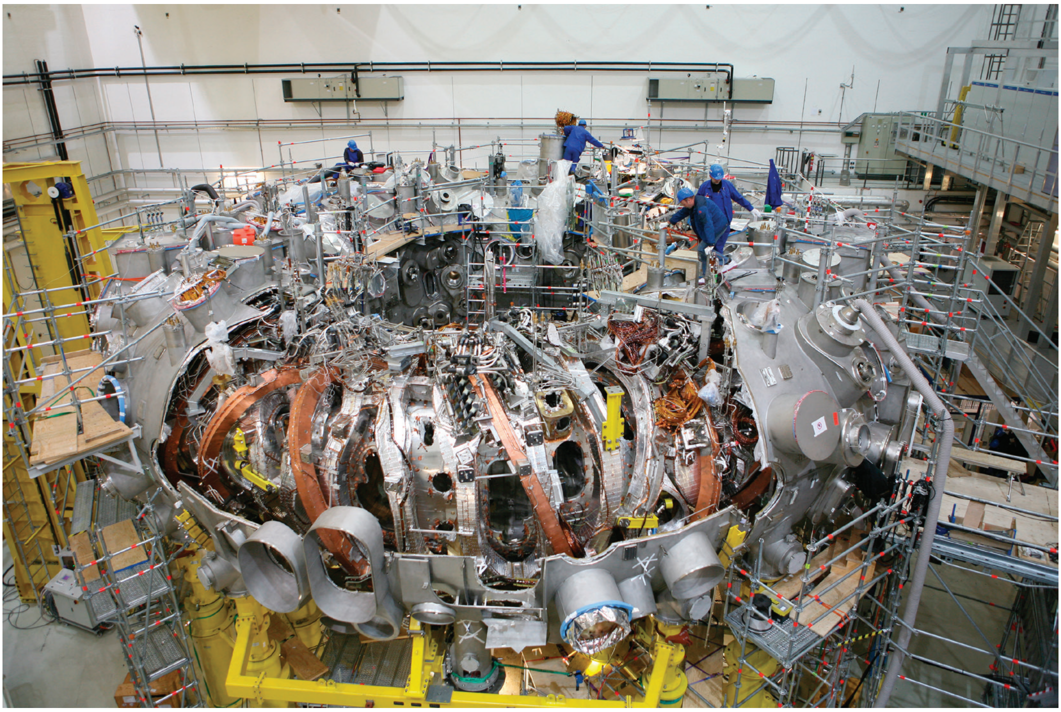
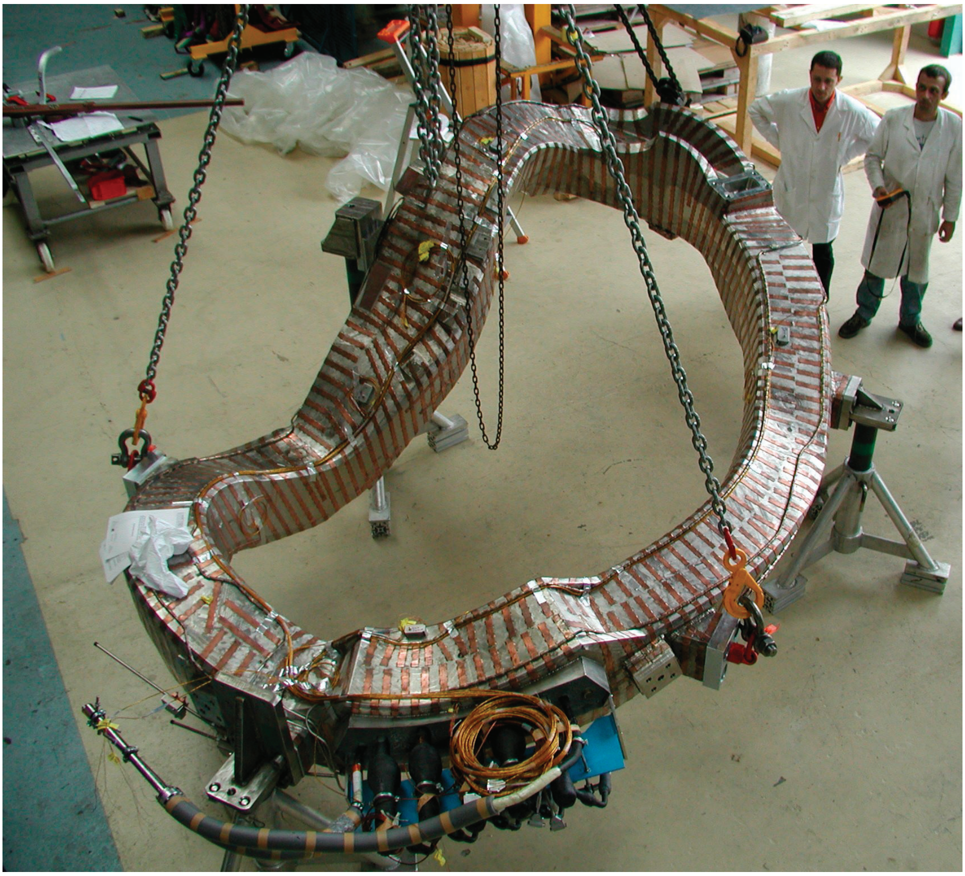


FIGURE 7.5 (*Left*) Overview of the Wendelstein 7-X stellarator during construction. (*Right*) One of the superconducting magnets comprising the complicated main confinement magnetic field. SOURCE: Courtesy of Max-Planck-Institut für Plasmaphysik.

Charged Particle Radiotherapy and Radionuclide Production Medical Applications

The largest commercial application of superconductors today is for NMR magnets in chemistry and biology and magnetic resonance imaging (MRI) magnets in life science. Two new medical applications that can benefit from using superconducting magnets are compact cyclotrons for charged-particle radiotherapy and compact cyclotrons for production of radionuclides used in nuclear medicine.

Radiotherapy using protons to deposit ionizing radiation in tumors has been shown to be very effective in the treatment of cancer. A major feature and advantage of proton therapy is that this method takes advantage of the Bragg peak of energy loss when transiting the body. An example of energy deposition versus depth is shown in Figure 7.7, which compares photon energy versus depth with proton energy versus depth (Yock and Tarbell, 2004). Depth of maximum energy deposition can be controlled by proton energy, and magnetic steering enables



precise targeting, thus the radiation dose can be precisely targeted to the tumor, minimizing damage to surrounding tissues (Kaderka et al., 2012), especially when the lateral energy deposition profiles are compared to those from photon radiations, as shown in Figure 7.8. Proton radiotherapy's main use is for treating tumors where surrounding tissue has a low ionizing radiation tolerance. This is often the case for childhood cancers and for tumors near the eye, the spinal cord, or in the brain. Another potential benefit is reduced probability of secondary tumors resulting from the radiation treatment. A maximum proton energy of 250 MeV will penetrate tissue to a depth of ~30 cm, which is sufficient to treat deep tumors in a human patient.

Ernest O. Lawrence invented the cyclotron in 1930 at the University of California at Berkeley. It was one of the earliest types of particle accelerators for scientific research. In 1946 Robert R. Wilson first suggested using a proton cyclotron, then

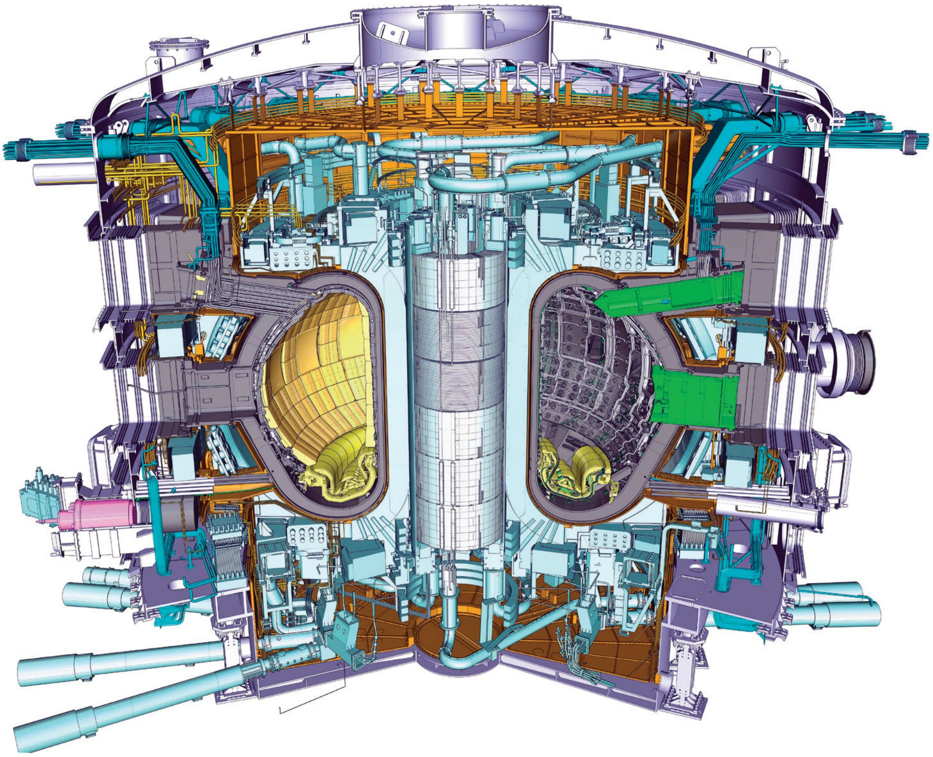


FIGURE 7.6 A detailed model of the ITER device. The 18 D-shaped toroidal field magnets are 17.5 m tall by 9 m wide. The two largest outer ring poloidal field magnets are 24 m in diameter, each weighing 300 metric tons. SOURCE: © ITER Organization, http://www.iter.org/.

under construction at the Harvard Cyclotron Laboratory (HCL) to treat tumors (Wilson, 1946; Geisler et al., 2005). The first treatment of patients occurred in the 1950s using existing scientific research accelerators. While working at HCL, Wilson began a collaboration with the Massachusetts General Hospital (MGH) in Boston to treat patients using the cyclotron at Harvard. The major proton and heavier ion treatments commenced at the Donner Laboratory of the University of California and the Lawrence Berkeley National Laboratory, now supported by the Department of Energy and the National Institutes of Health (NIH). Treatments by radiation ablation of the pituitary gland were successful for acromegaly (gigantism) and Cushing's disease. That work from 1950s to 1990s was moved to Loma Linda Medical Center in California for the first hospital-based proton treatment in 1990. The radiation source was not a cyclotron, but rather a synchrotron designed and constructed by scientists from FNAL. The Northeast Proton Therapy Center

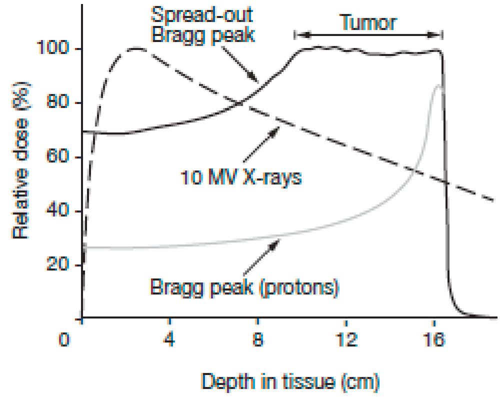


FIGURE 7.7 Comparison of relative photon dose with proton dose versus tissue depth. The Bragg peak occurs at the end of proton travel. By varying proton energy to generate different Bragg peaks and superposing them, the radiation dose can be constrained to the tumor volume. SOURCE: Adapted from R.R. Wilson, 1946, Radiological use of fast protons, *Radiology* 47:487-491.

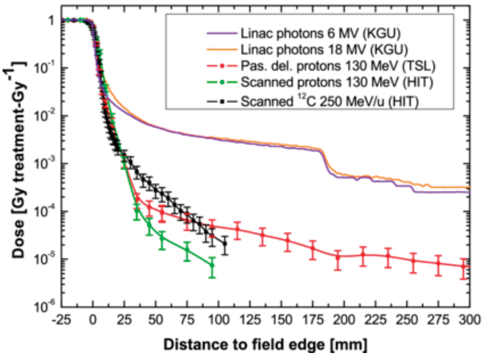


FIGURE 7.8 Overview of the lateral dose profiles measured for radiation types and delivery techniques. SOURCE: R. Kaderka, D. Schardt, M. Durante, T. Berger, U. Ramm, J. Licher, and C. LaTessa, 2012, Out-of-field dose measurements in a water phantom using different radiotherapy modalities, *Physics in Medicine and Biology* 57:5059, © Institute of Physics and Engineering in Medicine, published on behalf of IPEM by IOP Publishing Ltd., all rights reserved.

opened at MGH in 2001 using a conventional (resistive) proton cyclotron. This center was partially funded by the National Cancer Institute. Since then, more than 36 proton radiotherapy centers have gone into operation worldwide, 24 of which are cyclotrons and 12, synchrotrons. Most new facilities that are opening now use cyclotron accelerators (Krischel, 2012).

A major impediment to rapid expansion of this highly effective treatment is the $100 million to $200 million cost of a treatment center that includes the necessary infrastructure. A significant part of this high cost is due to the very large size, mass, and cost of the conventional cyclotron, the long beam transport system, and the huge rotatable gantry required to direct the proton beam to the patient. The use of superconducting cyclotrons begins to address the size and cost issue by reducing the size of the cyclotron and potentially leading to easier beam transport solutions and substantially less shielding and siting costs.

This reduction is a consequence of the inverse relationship between the radius of the cyclotron and the magnetic field, as shown below:

$$E_f \approx Kr^2B^2$$

where E_f is energy, K is a constant, r is the cyclotron radius, and B is the magnetic field. Thus cyclotrons can be made very compact by going to high magnetic fields. Currently two superconducting cyclotrons have been built for proton radiotherapy and are treating patients on a regular basis (MSU, 1993; Miyata et al., 2012). One machine is at the Paul Scherrer Institute in Villigen, Switzerland (PROSCAN) and the other is installed at the Reinecker Proton Therapy Center in Munich, Germany. Both machines are isochronous cyclotrons built by the same company and based on a 1993 design done by the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. They are cooled with liquid helium but maintained cold by cryocoolers in a closed cryogenic system, similar to the methods used to cool MRI magnets. These machines are more compact than resistive cyclotrons, reducing the size and weight from 4.3 m and 220 metric tons down to 3.1 m diameter and 90 metric tons.

Although this is a factor of 2 reduction in weight, these machines used NbTi superconductor and limited the central gap field to 2.4 T. Newer designs by other organizations are capitalizing on the very high current density and high critical field of Nb_3Sn to develop much more compact synchrocyclotrons. The most advanced of these designs is the Mevion S250 proton synchrocyclotron built by Mevion Medical Systems, Inc., based on technology licensed by MIT. The concept developed at MIT is based on using a Nb_3Sn magnet generating 9 T at the pole gap with a peak field at the windings of ~11 T. This design takes advantage of a very high current density superconducting wire developed by U.S. industry using funding from the U.S. high-energy physics research program.

The device built by Mevion Medical Systems has a diameter of only 1.8 m and weighs about 20 metric tons. It is small enough and light enough to be placed on the treatment gantry so that the entire cyclotron rotates around the patient, as shown in Figure 7.9. The compact size and light weight of the cyclotron not only reduce cost but also eliminate the stationary beam transport system as well as the heavy gantry-mounted beam transport magnets, thus reducing the gantry weight as well. These systems can be installed as individual treatment machines instead of the contemporary device, which uses a single accelerator with beam line transport of protons to multiple rooms. Thus the initial capital investment in establishing a center that can scale to multiple treatment rooms is reduced by a factor of 10. This

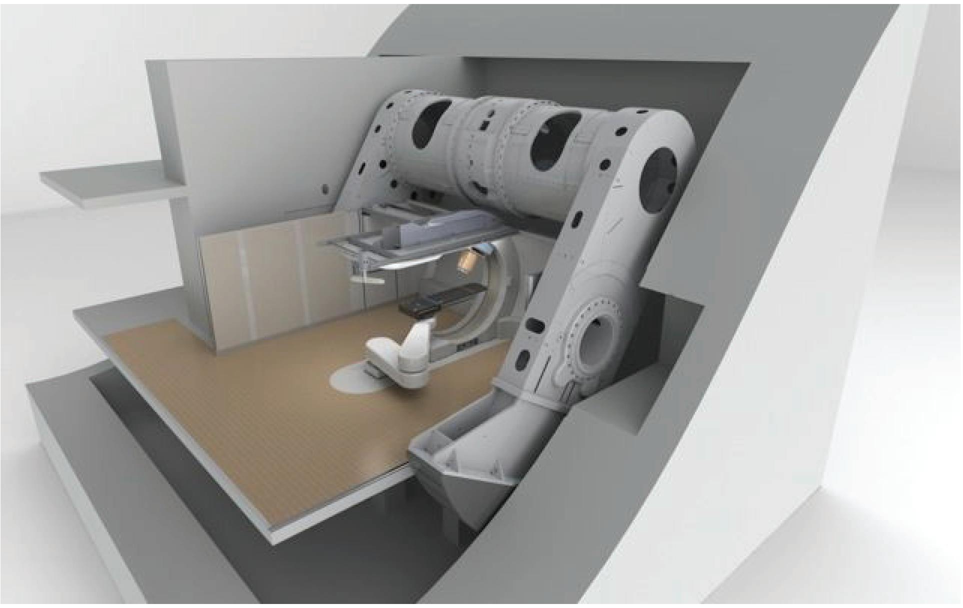


FIGURE 7.9 Mevion S250 compact superconducting proton synchrocyclotron mounted on a rotating gantry for a single treatment room. SOURCE: Courtesy of Mevion Medical Systems.

lower cost makes introduction of this treatment therapy more widely available to medical centers and patients.

Although proton beam radiotherapy is expanding in clinical use, other charged particles such as helium, carbon, and neon have also been used for the treatment of cancers. These charged particles have heavier mass than a single proton and thus require more powerful particle accelerators to achieve effective treatment energies. Ongoing activities include efforts in Japan at the Heavy-Ion Medical Accelerator in Chiba (HIMAC), which uses a range of charged particles for cancer therapy, and studies at high-energy-physics laboratories in Europe that have used carbon beams. Several organizations in the United States are considering using carbon and other heavy ions for radiotherapy, but there is no existing and mature commercially available accelerator technology ready to satisfy this wish. It is possible that advances in superconducting technology can be used to develop a medically and economically feasible solution, but this will require a substantial investment in accelerator technology. At present, NIH continues to provide research and development funds for the purpose of developing and installing more powerful MRI magnet systems, and it seems reasonable to extrapolate that support to the development of advanced heavy ion accelerators for radiotherapy applications. This support would be especially efficacious at this early stage of exploratory medical research since it could affect the future direction of application and development of this technology.

Nuclear medicine radionuclide production for research and clinical studies depends for the most part on accelerator and reactor facilities that are remote from clinics and research institutions. This has severely limited the application of the short-lived nuclides ^{11}C, ^{13}N, ^{15}O to those institutions with a local cyclotron that usually operates with a 1 to 1.5 T resistive magnet. The siting costs are dominated by shielding requirements and the size of the installation. These costs as well as cyclotron costs typically necessitate a $4 million investment. Thus for studies that take advantage of positron emission tomography, long half-life radionuclides are used, but even these cannot achieve the needed specificity to enable clinical studies in addiction, aging, heart disease, and some cancers where radionuclides such as ^{11}C, ^{14}N,^{15}O, and ^{89}Zr must be produced locally using a particle accelerator. To overcome this problem, superconducting cyclotron technology is being employed in the production of small cyclotrons at 5 to 9 T with modern cryostats and turnkey operations. A commercial prototype is being developed by Ionetix, Inc., with expected clinical installations in 2014.

The horizons for increasing field strengths in chemical, biological, and medical research studies are discussed in Chapters 3 and 4 as well as in the recommendations of this report.

SPECIFIC MAGNET GOALS

High fields define a scientific frontier, and the new phases that are discovered as higher fields are made available are the feedstock for new materials and devices that reproduce these new behaviors at low or even zero field. Increased field strength inevitably leads to enhanced sensitivity and new experimental techniques that in turn increase the tempo of scientific discovery. Each breakthrough in magnet technology and experimental capability leads to a new flurry of scientific revelation and discovery, which in turn enables the next round of technological breakthrough. This virtuous cycle is nowhere more evident than in the bootstrap process by which new magnets are themselves developed, where access to higher magnetic fields provides the means for testing and improving the new concepts and components that will make possible the next generation of magnets.

It is imperative that magnet technology be constantly challenged—and also supported!—to provide the innovation that enables the ever higher fields that fuel these discoveries. It is in this spirit that the committee recommends here three magnet development goals. Each is a novel and first-in-class project, and significant development efforts will be required to reach the stated goals. These magnets also represent significant investments in the national research infrastructure, because in some cases new research and funding partnerships must be formed in order to take full advantage of these new capabilities. The committee anticipates that it may take as long as a decade until these magnets become available for researchers. As discussed in Chapter 2 of this report, access to higher magnetic fields, both in dc and pulsed modes, will be crucial for progress in many aspects of condensed matter and material physics.

An additional recommendation calling for a design and feasibility study for a 20 T magnet for use in MRI studies of humans was discussed earlier, at the end of Chapter 4, and recommendations for the development and installation of new types of magnets for use at X-ray and neutron scattering facilities is presented in Chapter 6.

> **Finding:** Recent advances in high-temperature superconductor (HTS) magnet technology are an important step forward, with the potential for making possible a new generation of all-superconducting high-field magnets that would be transformational in many research areas.

Such magnets will enable steady-state physics measurements at very high magnetic fields without the constraints and attendant costs of huge power supplies and a large-scale cooling facility. This means that significant reductions in both the construction and operation costs of a 40-T class magnet can be envisioned, making it possible to locate these magnets in regional centers, built around teams of users with specific measurement needs. The improved accessibility to the 40-T class magnet will greatly facilitate the advancement of sciences that require steady-state measurements in magnetic fields significantly higher than the ordinary laboratory fields; furthermore, all-superconducting magnets can be used in the persistent-current mode, which provides a noise-free environment and makes it possible to perform ultrahigh-sensitivity measurements that have not been possible in hybrid-type magnets. It seems likely that the availability of these magnets would significantly change the mix of users at NHMFL-Tallahassee and would free that facility to develop new and complementary capabilities that cannot be reproduced elsewhere.

As the committee has discussed elsewhere in this report, the United States has largely ceded leadership in constructing high-field superconducting magnets for NMR to Europe, where there is a closer relationship between the national labs that provide the required technology and the companies that will build these magnets. In part, this reflects a long-term underfunding of both magnet technology research in this country and the research in high-strength materials that underlies this important area. Surmounting the technological challenges associated with realizing a 40 T all-superconducting magnet will be a big step toward making U.S.

industry competitive in the production of NMR/MRI magnets and the associated superconducting wires and cables.

> **Recommendation: A 40 T all-superconducting magnet should be designed and constructed, building on recent advances in high-temperature superconducting magnet technology.**

> **Finding:** The veritable explosion of new materials with new functionalities that we have witnessed in the past decade is a potent driving force for the need to push experimentation to higher fields, where new phases and new behaviors are invariably found. Although pulsed fields will always provide the highest peak fields, many of the most revealing measurement techniques have inherent timescales or sensitivity requirements that make them practical only in constant magnetic fields.

Techniques requiring dc magnetic fields include ultrasensitive voltage measurements that allow high-precision parametric studies of electrical resistance, heat capacity, susceptibility, and thermopower; scanned probe microscopies that provide both atomic-scale imaging and spectroscopic information; and optical spectroscopies performed over a wide range of frequencies. The ability to carry out these measurements, already proven in zero field to provide crucial information, has the potential to open up whole new fields of research and technology. Some examples include the exploration of the normal state that precedes the unconventional superconductivity in the cuprates and iron pnictides and chalcogenides, the manipulation of symmetry-broken phases and unconventional quantum Hall effects in single-layer and few-layer graphene, and the investigation of the interplay between topological insulators and superconductivity. The ability to bring these measurements to new generations of materials and devices in increasingly high magnetic fields would define a world-leading capability and confer a distinct advantage to the researchers who can exploit them.

> **Recommendation: A 60 T dc hybrid magnet should be designed and built that will capitalize on the success of the current 45 T hybrid magnet at the NHMFL-Tallahassee.**

> **Finding:** Many crucial measurements requiring the highest attainable fields can be performed in pulsed magnetic fields with durations on the order of 10 ms. Similar measurements at higher fields than are currently available would allow investigation of phenomena that are now beyond reach.

With the March 2012 attainment of 100 T in a nondestructive 15 ms pulse at the pulsed-field facility of the NHMFL in Los Alamos, new terrain in high-field research has been opened up to researchers. The ability to routinely access 100 T fields will enable unprecedented research in topological insulators, quantum matter, and electronic structure determination.

Fields much higher than 100 T have been achieved in very short pulsed field magnets (microseconds duration), which destroy the magnet coil and in many cases also the sample. However, the types of measurements that can be performed on microsecond timescales are much too limited to provide the type of information needed for elucidating the most pressing research problems.

From a scientific point of view, a desirable long-term goal would be the ability to extend the suite of measurements now available at 100 T to fields on the order of 200 T or beyond. As one measure of magnetic field strengths, it can be noted that at 225 T, the energy difference between the two states of an electron's spin is equal to the thermal energy at room temperature. Fields of this magnitude would allow direct investigations of unusual phases and phase transitions in quantum spin systems with strong exchange couplings. They would also enable investigations of some of the most important high-temperature superconductors by allowing field-induced suppression of superconductivity in the ground state of these materials.

Unfortunately, no clear route currently exists for producing nondestructive fields as high as 200 T. Among other limitations, magnets of this strength would have to sustain forces well beyond the yield strengths of any known material. Nevertheless, important advantages could be obtained already by extending the availability of nondestructive pulsed fields in a series of smaller steps, perhaps achieving 150 T by the year 2023. Higher-field magnet technology might be developed hand-in-hand with the ability to make required measurements on smaller samples and in shorter times.

> **Recommendation: Higher-field pulsed magnets should be developed, together with the necessary instrumentation, in a series of steps, to provide facilities available to users that might eventually extend the current suite of thermal, transport, and optical measurements to fields of 150 T and beyond.**

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8

International Landscape of High-Magnetic-Field Facilities

SCALE OF HIGH-MAGNETIC-FIELD FACILITIES

This chapter describes the international landscape of large, high-magnetic-field facilities, with a discussion at the end on opportunities for collaboration among these facilities.

High magnetic field installations are expensive and therefore rare. A rough estimate of the investment needed to finance the construction of a facility providing dc fields similar to the U.S. National High Magnetic Field Laboratory (NHMFL) in Tallahassee is several hundred million U.S. dollars. This would include the costs for basic infractructure, specialized hybrid magnets, and full instrumentation for conducting experiments. A pulsed-field facility similar to NHMFL's laboratory at Los Alamos National Laboratory would cost roughly half this amount. Annual operating costs for such facilities depend significantly on the intensity of their use and on how much of the personnel costs are included but are nevertheless in the tens of millions of U.S. dollars. The development of specialized new magnets such as hybrids or high-temperature superconducting coils is estimated to cost between $10 million and $20 million each.

Because of their size and the costs of building and operating such installations, only a few of these large facilities are in operation worldwide, and most function as user facilities that host external guest researchers. Typically their funding sources are more stable and of a longer-term nature than other projects that might be funded locally or whose funding is project-related. Access to these facilities normally entails submitting a proposal for evaluation by an external project review panel. Selection criteria include the scientific merit (innovativeness and excellence) of the proposed project and whether the unique resources provided by the facility are needed for the planned experiments.

Appendix G summarizes the main characteristics of large research facilities for high magnetic fields available worldwide. Also included in that appendix are the yearly number of projects executed, the number of different projects executed, and the number of external researchers involved. These numbers provide some indication of the worldwide demand for these fields. It can be seen that the number of such facilities worldwide is quite limited and that their characteristics are similar. All facilities that are in full operation (primarily located in Europe and the United States) have a successful, oversubscribed user program and produce many excellent groundbreaking publications every year.

TECHNICAL CHALLENGES IN MAKING THE HIGHEST MAGNETIC FIELDS

In addition to the financial constraints associated with constructing and operating such facilities, these research resources are limited because of the technological difficulty of producing the highest possible magnetic fields.

Producing such magnetic fields requires not only world-class engineering but also the development of rare materials that must combine strength with good electrical conductance. The demands on magnets due to the Lorentz force are huge, and controlling them in all parts of the magnets—the winding body, the housing, and other components such as current leads—is a major design challenge. Design requirements are further complicated by the need to have the largest possible currents, and hence the largest forces, in a small volume near the magnet's central bore. The design of dc magnets is further complicated by the need to use some of the space in the magnet body for the flow of coolants to uniformly counter the heat generated by the currents flowing through the magnet. In the design of superconducting magnets, one must take into account not only the constraints imposed by the Lorentz force, which are the same as in resistive magnets, but also the very poor mechanical properties of the superconducting material. This requires including in the design an external reinforcing structure that sufficiently strengthens the magnet against the substantial Lorentz forces. Furthermore, because superconducting magnets must be operated at low temperatures, they must be able to withstand thermal cycling over a large temperature range, where thermal expansion of materials can be significant.

For all magnets, regardless of which technology is used, the amount of energy stored in the magnet depends on natural constants (the permeability of free space), the square of the magnetic field, and the volume where this field is present. Therefore, in all high-field magnets with a reasonable measuring volume the amount of energy stored is enormous. For larger magnets such as hybrids, 100-200 MJ of stored energy is not uncommon. This enormous amount of stored energy requires that important safety precautions be implemented in the magnet's operations, since release of that stored energy over a short time period is comparable to the energy released by a small bomb. This energy is of particular concern for superconducting magnets since their relatively large self-inductance means they are unable to rapidly carry away that stored energy.

Because of these challenging conditions, magnet technology for high-field magnets requires very specialized engineering, and the safe use and maintenance of high fields for research requires having a dedicated and skilled staff. These rather unique conditions are another reason why only a few high-magnetic-field laboratories exist. In fact, the continuous increase in maximum fields over the last decades has gone hand-in-hand with the concentration of those very high field-producing magnets in only a few large facilities in the United States, Japan, Europe, and, recently, China. As described below, interactions between these laboratories are quite extensive, and there is a general awareness that future-generation magnets can be developed only by fostering a widespread expertise in magnet technology worldwide.

OPPORTUNITIES FOR COLLABORATION

Interactions among the large magnet laboratories around the world are ongoing, with laboratory representatives informally exchanging information during frequent visits to each others' laboratories or at conferences. Personnel are also frequently exchanged (even between laboratories located on different continents), and most laboratories employ people who have worked in one of the other laboratories. For instance, the NHMFL at Tallahassee has hired staff who previously worked at the Laboratoire National des Champs Magnétiques Intenses (LNCMI-G) in Grenoble, France, and key engineers at the new magnet laboratories in China—the Chinese High Magnetic Field Laboratory (CHMFL) in Hefei and the Wuhan High Magnetic Field Center (WHMFC) in Wuhan—were trained in the United States and Europe. Furthermore, new magnet designs from one laboratory often are reviewed by chief engineers at other laboratories in order to profit from all of the expertise available. Regular mutual visits ensure the sharing of developments in technology and the layout of new systems. It is therefore not surprising that key parameters of the larger installations, such as the amount of energy stored, the capacitive voltage for pulsed installations, maximum currents and voltages, and the hydraulic parameters in cooling circuits for dc magnets, are rather similar in all the laboratories. Such similarities also make the exchange of magnet systems between laboratories rather easy. Technology for making magnets is shared on a regular basis, and magnet parts, and at times entire magnets, are provided by one laboratory to another.

The dc laboratory at the NHMFL plays a particularly important role among large-scale magnet laboratories. The laboratory has closely collaborated with LNCMI-G from the time that NHMFL opened. The earliest NHMFL dc magnets were provided by LNCMI-G, while NHMFL later developed its own very successful resistive magnets based on what has come to be known as Florida-Bitter technology. This technique has been adopted at the High Field Magnet Laboratory (HFML) in Nijmegen, Netherlands, and the Tsukuba Magnet Laboratory (TML) in Tsukuba, Japan, which have acquired magnets from the NHMFL. This technology in Nijmegen was developed further and improvements have found their way back to NHMFL. Rigid housings that can handle the forces and withstand the high water pressure while still having low vibrations are complex engineering objects. Working together, NHMFL and LNCMI-G developed a 24 MW housing for dc magnets for which each laboratory then constructed its own inserts. NHMFL pioneered the cable in conduit conductor (CICC) for use in superconducting outserts for hybrid magnets. It also built a 25 T hybrid magnet with conical access for installation at the Helmholtz-Zentrum Berlin (HZB), which is designed to be operated in combination with a neutron beam. Representatives from NHMFL have also provided advice on the building of the infrastructure at HZB. At the time this report was being written, Nijmegen and NHMFL were entering into a collaboration in which the Nijmegen hybrid magnet will be jointly designed and the cold body (the actual magnet inside the cryostat) will be produced at NHMFL's facility in Tallahassee. This choice is largely based on the experience NHMFL has developed in this technology. As mentioned earlier, key engineers in laboratories in China earlier worked at the NHMFL and in European laboratories, and the experience these engineers acquired during their stays at those laboratories is now being used to build the Hefei and Wuhan laboratories.

All magnet laboratories have close connections to various industries that develop systems for installation at the laboratories or provide specific materials needed to produce high-field magnets. The extreme conditions required to produce and use the highest fields (high energy or power densities, extreme mechanical loads, high current densities, high stability of the power source, etc.) often go beyond what is needed for standard industrial products and thus push the limits of the industries involved. Information about possible suppliers is shared among the laboratories, which often leads to orders for these industries. Parts like housings and cables for the CICC require specialized windings and jacketing facilities that often are fabricated on different continents and shipped back and forth between the laboratories. In summary, there is a very intense informal collaboration among the main high-magnetic-field facilities worldwide, and knowledge is shared very effectively. It is clear that even higher magnetic fields like 50 T or even 60 T hybrids or pulsed fields higher than 100 T will constitute an enormous financial and technological challenge. It will be necessary to combine all global experience and financial clout in this field to succeed. Encouraging international collaboration as much as possible will help to ensure that the conditions needed to meet these challenges are in place.

PERSPECTIVES

To produce even higher fields than are now available will be very costly. Fields around 30 T that are produced by all-superconducting magnets should become available in the coming decade. Such magnets will cost around $10 million and will require a specialized staff and environment to operate them. Such magnets probably will be installed in existing facilities and possibly in some new regional facilities. It is not realistic to expect that such magnets will become affordable for many smaller research groups, in contrast to the case when the 20 T superconducting magnets became commercially available.

At present, purely resistive dc magnets typically use around 24 MW of power at maximum field. Increasing the power will only marginally increase the maximum attainable field, so this type of magnet is becoming economically unattractive. The highest dc fields will therefore be produced with hybrid magnets. The operation of hybrid magnets requires the same power supply and cooling as purely resistive dc magnets, but they are operated in combination with a superconducting outer coil. The record for the highest field produced using such a magnet (as of the time of this report) is 45 T using 28 MW of power at the NHMFL; a 45 T magnet expected to require 22 MW of power is being built at Nijmegen. Higher-field hybrid magnets capable of producing fields at 50 T or even 60 T could easily cost more than $100 million. This is a very rough guess, since no realistic design with cost estimates has been produced to date. It is clear that such magnets will be very large (a minimum of several meters in all dimensions) and will require enormous amounts of materials. The size of such a project presumably will require global cooperation among the large magnet facilities. Consequently, the highest dc magnetic fields will be available at only a few dedicated facilities. It is expected that while these facilities work on the development of even better performing magnets, they will run a guest program for external users providing both the field and the necessary infrastructure and will maintain their own research program in order to stay at the forefront of science. This last point is essential to guarantee the availability of the most advanced instrumentation and the scientific excellence of the work done at the facility.

Regional centers with lower fields, possibly with new high-T_c magnets in the 30 T range, may also be created, since these magnets are too costly and cumbersome to become a normal laboratory commodity but could still be provided in dispersed facilities.

In pulsed fields, the 100 T record has now been established at the Los Alamos facility of the NHMFL. Much higher fields are not expected to be reached in the near term using nondestructive techniques. Development in the near term will probably concentrate on increasing reliability and user accessibility so that these record fields will become more widely available. It is expected that these top-end pulsed magnetic fields will be found only in a few facilities worldwide. As with dc laboratories, the central pulsed facilities will continue to work on magnet technology, provide service to external users, and pursue their own research programs.

RECOMMENDATIONS AND CONCLUSION

Recommendation: High-field facilities worldwide should be encouraged to collaborate as much as possible to improve the quality of magnets and service for users. This can be accomplished through the establishment of a global forum for high magnetic fields that consists of representatives of large magnetic field facilities from all continents. Such a forum would further stimulate collaboration and the exchange of expertise and personnel, thereby providing better service to the scientific community and magnet technology development. The forum should establish a roadmap for future magnets and stimulate the realization of the defined targets on this roadmap.

Recommendation: Large high-magnetic-field facilities should also have strong collaborations with smaller regional centers, providing them with support and expertise. Users of these regional centers may need the higher fields available in the large facilities, while users of the large facilities could be referred to the regional centers if their proposed experiments are better suited for those centers.

Conclusion: Success requires that the large facilities have a threefold mission: (1) to generate the highest possible magnetic fields by developing new magnets needed to produce those fields (magnet technology); (2) to make these fields, together with experimental support and expertise, available to qualified external users (act as a facility); and (3) to perform world-class research led by the facility staff.

9

Stewardship and Related Issues

High magnetic fields for research are made available through special, purpose-built facilities requiring significant infrastructure investments. Effective stewardship of these facilities is critical to the vitality of the research that requires use of these high fields, and the facilities must be managed and operated in the most robust manner to provide the greatest benefit to and highest impact on the research community.

High-magnetic-field science is similar to X-ray and neutron science in two regards: (1) It is manifestly multidisciplinary and (2) it utilizes unique facilities requiring a significant federal investment. The National High Magnetic Field Facility (NHMFL) is the nation's flagship facility for carrying out high-magnetic-field science and represents a substantial and continuing investment for the United States. The National Science Foundation (NSF) provides the majority of operating funds for the NHMFL and thus is the principal steward for high-magnetic-field science in the United States.

Effective stewardship of large facilities, particularly those that serve research communities spanning multiple scientific disciplines, is critical to the vitality of the scientific enterprise. However, complexities in the operations and management of these facilities could threaten the effectiveness of the facility in serving the community. Some challenges include stability and adequacy of funding, adequacy of instrumentation, and changing user demographics. An agency's strategy for managing a major user facility is a major factor in the success or failure in addressing these challenges. Before discussing the relative advantages of various models for stewardship of magnetic field science in the United States, however, the committee addresses the related issue of centralized versus de-centralized facilities.

CENTRALIZATION VERSUS DE-CENTRALIZATION

A centralized national user facility that provides the highest magnetic fields in the world for the purposes of research offers numerous benefits to the scientific community; it is an essential part of our national prestige and, as a centralized entity, is a cost-effective resource (more so than an *equivalent* decentralized set of capabilities). The NHMFL provides high-magnetic-field measurement capabilities that are not available anywhere else in the United States. Indeed some of the NHMFL's measurement capabilities cannot be matched anywhere else in the world. By offering these capabilities to the U.S. scientific community, cutting-edge research is enabled, and the nation's competitiveness is enhanced. These magnets, and the associated scientific experiments employing these fields, require a substantial infrastructure such as electricity and cooling. Locating these at a centralized facility, such as at the NHMFL, is a highly cost-effective approach. Moreover, developing high-field magnets requires a special and rare combination of expertise in, and extensive knowledge of, materials properties, physics, electrical engineering, mechanical engineering, and engineering design. Locating these magnet developers at a centralized facility is cost-effective and ensures they are well connected to the needs of a national user facility.

> **Conclusion:** There is a continuing need for a centralized facility like the NHMFL because (1) it is a cost-effective national resource supporting user experiments and thus advancing the scientific frontiers and (2) it is a natural central location with expert staff available to develop the next generation of high-field magnets.

At present NSF provides more than half of funding for the NHMFL and thus is the steward for high-magnetic-field science in this country. By many measures, the NHMFL continues to be a scientifically productive facility. Numerous advances in magnet technology have been achieved as a result of the development work at the NHMFL (including reaching 100 T pulsed), justifying a continued investment by NSF.

> **Recommendation: The National Science Foundation should continue to provide support for the operations of the National High Magnetic Field Facility and the development of the next generation of high-field magnets.**

Assuming successful completion of the 32 T all-superconducting magnet under development at the NHMFL, one can envision a time shortly thereafter when this technology will become available as a standard commercial product. At that time, it might be feasible to consider establishing satellite magnet user facilities at locations around the country. The 32 T magnet technology would provide the basis for these satellite sites, since they would not require the extensive infrastructure to power, cool, operate, and maintain the dc resistive magnets.

> **Conclusion:** There are benefits to decentralized facilities with convenient access to high magnetic fields for ongoing scientific research. Such facilities need not engage in expanding the frontiers of high-magnetic-field science or lead the way in new magnet technology; instead, they should provide the broad user community with the up-to-date high-field magnets to relieve the shortage of user time at the NHMFL-style central facility.

The need for a centralized magnet user facility such as the NHMFL is still essential. This flagship facility will develop the most advanced superconducting, resistive, and pulsed-field magnets and provide them to qualified users, while also maintaining a leading magnet science program.

> **Recommendation: Taking into account, among other factors, the estimated costs and anticipated total and regional demand for such facilities, federal funding agencies should evaluate the feasibility of setting up some smaller regional facilities, ideally centered around 32 T superconducting magnets as the technology becomes available and at geographic locations optimized for easy user access. These would be in addition to the premier centralized facility, which would remain, with its unique mission of expanding the frontiers of high-magnetic-field science.**

The need for decentralized facilities for high-field nuclear magnetic resonance (NMR) measurements, with magnets in the range of 28 T, was discussed in Chapter 3.

STEWARDSHIP OF HIGH-MAGNETIC-FIELD SCIENCE IN THE UNITED STATES

A National Academies study investigated a variety of models for the management of scientific research, together with their strengths and weaknesses, and recommended a management model for the future in the concise *Cooperative Stewardship* report (NRC, 1999).

Of the models described in that report, the model that best describes the management of the NHMFL is the *simple steward model,* in which a single entity has primary responsibility for funding the management and operations of the facility. In the case of the NHMFL, NSF is the dominant financial supporter of management and operating costs. At the time that the *Cooperative Stewardship* report was released, the NHFML was receiving distributed financial and management support, which was considered adequate at that time because sufficient funds were available. The report argued that an alternative model of management and support should be used when there is a rapid growth in the number of users, a growing diversity of scientific interests, and significant financial constraints. In the cooperative stewardship model, a single entity, the steward, is solely responsible for the construction and operations of the core facility and some of the individual experimental units. In the context of a high-magnetic-field laboratory, the core facility includes the infrastructure and the high-field magnets. The individual experimental units include the instrumentation used with the magnets. The remaining individual experimental units would then be funded by government agencies, industry, or other interested parties. These other funding entities are the partners. The steward is responsible for design, construction, operation, maintenance, and upgrading the core of the facility. The partners are stakeholders in decisions regarding the need for an experimental capability (e.g., a new magnet or new instrumentation for a magnet), site selection for the magnet, user instrumentation, performing R&D for the instrumentation improvement, construction, and performance evaluation. Partners are responsible for the construction and operations of individual experimental units (see Box 9.1).

NSF management described mounting pressures on the portion of the NSF-Division of Materials Research (DMR) budget that is the primary source of NHMFL support. In particular, a 2011 Committee of Visitors (COV) report "expressed concern about the balance within facilities and instrumentation, where instrumentation is underweighted." They went on to state that "instrumentation should grow at the expense of facilities stewardship, unless support from outside DMR can be increased for national facilities" (NSF, 2011a). NSF responded (NSF, 2011b) that a full strategic plan for its facilities and instrumentation programs was under way and that they would gather broad community input, use recent community reports, and consult with advisory groups. Part of this strategy was undertaken with the Materials 2022 DMR advisory panel (NSF, 2011c). As part of its response, NSF-DMR was going to explore the "possibility of joint stewardship and funding of facilities with other NSF divisions and agencies." It is important to note that NSF is the steward for the NHMFL facilities. As the steward for the NHMFL, NSF is also the principal steward for the nation in high magnetic field science, which includes, but is not limited to, the materials science community. Therefore the committee strongly endorses all efforts that would broaden research partnerships that leverage expertise that is complementary to that currently at NHMFL, and cost-share the

BOX 9.1
Steward-Partner Model for User Facilities

Steward Responsibility: Core Facility
- Construction,
- Operation,
- Facility performance reviews,
- Performance reviews of partner subfacilities and/or instrumentation,
- Facility upgrades and R&D,
- Laboratories (general),
- General training (e.g., safety and general facilities),
- Facility staffing, and
- User support for facility-related issues.

Partner Responsibility: Individual Experimental Units (Subfacilities and Instrumentation)
- Construction,
- Operation,
- Laboratories (specific),
- Instrumentation (development, upgrades, and provision),
- Training (for users at subfacilities and magnets), and
- User support for experiment-related issues.

SOURCE: Adapted from NRC (1999).

operating expenses for experimental capabilities where appropriate and consistent with the cooperative stewardship model.

One measure that would be attractive to potential partners of the NHMFL (and would address a concern mentioned in the NSF-DMR COV report) is to ensure that sufficient funds are available within DMR's facilities and instrumentation budget for the design and construction of new, cutting-edge, high magnetic field experimental capabilities, including instrumentation. Such funding could be pursued from prospective partners from other agencies or institutions with a design concept (and sufficient scientific justification) and a commitment to fund the operations once constructed. This strategy could have a number of benefits, including (1) attracting prospective partners from other agencies, (2) broadening research participation through the development of new scientific measurement capabilities with new applications, and (3) increasing the measurement capacity and capability without increasing the operational costs incurred by the steward agency. Additionally, the NSF instrumentation funding line item could be used to support the design and construction costs for new high-magnetic-field capabilities that would be sited at one or more of the national scattering facilities. As described elsewhere in this report, combining high magnetic fields with probes such as X-rays and neutrons can yield insights into entirely new states of matter that cannot be observed by other approaches. There are clear and compelling opportunities to study the structure and dynamics of such new phases of matter via scattering techniques.

Conclusion: Optimization of the broad spectrum of research opportunities in high-magnetic-field science can be best achieved through strategic research partnerships.

Given the inherently multidisciplinary nature of high field science, the committee is concerned that there are almost no examples of partnerships between the NSF-stewarded NHMFL and other agencies that could support the construction and operation of new facilities that would bring new users and new science to the NHMFL. In addition, in the past decade there have been no new substantive or sustained partnerships of the type that would bring new high-field magnets to neutron or X-ray scattering facilities. A lack of clarity about the steward-partner relationship may have impeded the formation of effective partnerships that would advance research requiring high magnetic fields. The committee believes that the steward-partner relationship described in *Cooperative Stewardship* should be the basis for defining these relationships. It is beyond doubt that the NHMFL is world-leading in magnet technology development and will bring to partnerships the unique ability to design and construct new magnets, even if those magnets are to be located away from NHMFL. On the other hand, for these remotely sited magnets, the stewards of the host facility should commission their construction and installation and, if appropriate, they should be encouraged to enter into partnerships with other funding agencies to operate these specialized magnet facilities.

Recommendation: The National Science Foundation (NSF), the National High Magnetic Field Facility (NHMFL), and other interested entities that benefit from the use of high magnetic fields should adopt the steward-partner model as the basis for defining roles in future partnerships in high-magnetic-field science. For magnets not sited at NHMFL, the host institution is in most cases the natural steward, especially for the significant facility-specific infrastructure required for magnet operations. For magnets sited at the NHMFL, NSF should be the steward, although the partner organization could fund the construction and operation of these facilities.

The National Science Board drafted a resolution in 2008 stating as follows: "Therefore, be it RESOLVED that the National Science Board (the Board) endorsed strongly the principle that all expiring awards are to be recompeted, because rarely will it be in the best interest of U.S. science and engineering research and education not to do so" (NSB, 2008). As written, this resolution applies to the major research facilities such as the NHMFL and is implemented by NSF such that recompetition is required every 5 years. However, a major multidisciplinary research facility like the NHMFL necessarily involves considerations far different than a single-investigator research grant. These complicating factors include partnerships with other stakeholders, site-specific factors, infrastructural concerns, and/or any other encumbrances on the facility.

> **Conclusion:** Recompetition on timescales as short as 5 years places at risk the substantial national investment in high-field research that is embodied in a facility like NHMFL and could have disastrous effects on the research communities that rely on uninterrupted access to these facilities. Although the committee believes that recompetition of facilities is appropriate, it also believes a flexible approach should be taken in implementing recompetition of the NHMFL to fulfill its role as a steward and to avoid potential negative consequences of a short time interval between recompetitions.

Funding decisions at NSF and other federal agencies are appropriately based on peer review of facilities like the NHMFL. This is crucial to ensure the highest-quality science. The committee observes that NHMFL has realized over its almost two decades of existence many, if not all, of its initial aspirations and has evolved in new directions. It recognizes the need for a mechanism by which the long-term accomplishments and direction of the facility, the evolution of the facility users' needs and interests, and the efficacy of its management can be critically evaluated, in a way that is beyond the accepted scope of periodic review. Periodic recompetition may be an appropriate mechanism to obtain such an assessment, particularly if a substantial new investment in the facility is contemplated. However, the policy should not be so rigid as to specify a fixed period, especially one as short as 5 years. This will likely have the unintended consequences of discouraging potential partners and hindering the pursuit of projects requiring a sustained effort that could significantly advance the measurement capabilities of the facility.

> **Conclusion***:* The committee strongly endorses the consideration given to this matter by the Subcommittee on Recompetition of Major Research Facilities (NSF, 2012). It endorses the need for evaluating the long-term strategy and direction of national facilities, as well as for effective periodic reviews of their scientific programs.

It is important to make a meaningful distinction between nascent and mature facilities, particularly those facilities that have a significant infrastructure investment like the NHMFL, recognizing that recompetition plays a very different role than regular peer review in determining the future development of the facility. The latter ensures the continued quality of the scientific program of the facility and its users, while the potential negative consequences of recompetition mandates that it must be reserved for enforcing longer-term course corrections and future major developments of a facility, which involve substantially longer timescales.

WORKFORCE EDUCATION AND TRAINING

In order to facilitate the long-term viability of the research laboratories and industries that stand to benefit from advancements in the development of magnet technology, there needs to be a highly trained workforce that is specialized in the knowledge and expertise of magnet design and construction. High-field magnet design requires comprehensive interdisciplinary engineering skills, including mechanical engineering, electrical engineering, materials science, and engineering design. This requires rigorous academic and laboratory training with a focus on magnet technology issues. Unfortunately, with the exception of an occasional single-term class in superconducting magnets or applied superconductivity, there are no formalized university curricula available to graduate and post-graduate students. The traditional route to developing expertise in magnet technology is through some combination of self-study, internship, or on-the-job training at a few select companies, universities, or national laboratories. There is no unified structure to this type of learning, and often what is learned may be particular to a specific magnet application, and thus highly specialized and narrow in scope.

The NHMFL presently hosts a 1-week summer school for measurement techniques and instrumentation. This school offers a valuable and necessary education in these skills, but it is only a small part of the education required if the nation is to have world-leading expertise in magnet technology.

If significant and rapid progress is desired to advance magnet technology, much more support should be provided for education and training in these subjects, particularly at the graduate and postdoctoral level. The committee notes that several U.S. Department of Energy (DOE) sites, in collaboration with several other government agencies, support internships, graduate studies, and fellowship programs in broad technology areas through the Oak Ridge Institute for Science and Education. But these are not necessarily focused on magnet technology.

One way to achieve a more focused path to magnet technology expertise is to establish basic, but broad, curricula in magnet science and technology. An analogous program has already been established for education and training in the science of particle beams and their associated accelerator technologies through the U.S. Particle Accelerator School (USPAS).[1] The USPAS is governed by a consortium of

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[1] See http://uspas.fnal.gov and Barletta et al. (2012).

national laboratories and universities with programs in nuclear and high-energy physics and is funded primarily by DOE, but with significant support from NSF. The program is organized as a university course program, and it has recently been expanded and strengthened to offer homework, exams, and academic course credit from host universities. There are two 2-week sessions per year at rotating sites, usually at hotels. The USPAS has a permanent home at Fermi National Accelerator Laboratory and an academic director not necessarily stationed at the home site. The director engages volunteer experts who conduct 1- or 2-week courses concurrent with other experts who teach in the same general area of particle accelerator technology.

This program could serve as a model for establishing a U.S. high-field magnet science and technology school. Such a program would educate students in the basic elements of applied superconductivity and resistive and superconducting magnet design, with a focus on fundamental engineering subjects in electromagnetics, heat transfer and thermal design, cryogenics, structural analysis, materials properties, laboratory measurement methods, diagnostics, and instrumentation, among others. Students could be drawn from universities, scientific laboratories, and industry, both national and international. Faculty with expertise in the field would be invited from similar organizations.

Ideally, several government agencies—for example, NSF, the National Institutes of Health, DOE—with interests in high-magnetic-field science would sponsor and support this school. As a practical matter, the commercial sector that develops technology or applications that rely on high-field-magnet technology could be engaged as a funding partner in this educational program. The school could provide training and serve as a talent resource that promises to have an important impact on future innovation in the field.

> **Finding:** The absence of an efficient education and training system for magnet science and technology has been a hindrance to advancement of the field.
>
> **Recommendation: A high-field-magnet science and technology school should be established in the United States. The school could use the U.S. Particle Accelerator School as a model for its organization. Oversight and support should be drawn from a consortium of government agencies, laboratories, universities, and, possibly, industry. The National High Magnetic Field Facility could be the initial host site, with the laboratory facilities providing an excellent resource for laboratory courses.**

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Appendixes

A

Charge to the Committee

The committee will assess the needs of the U.S. research community for high magnetic fields. The committee will determine the status and identify trends in the use of high magnetic fields throughout science and technology.

1. What is the current state of high-field magnet science, engineering, and technology in the United States, and are there any conspicuous needs to be addressed?
2. What are the current science drivers and which scientific opportunities and challenges can be anticipated over the next ten years?
3. What are the principal existing and planned high magnetic field facilities outside of the United States, what roles have U.S. high-field magnet development efforts played in developing those facilities, and what potentials exist for further international collaboration in this area?

Based on this assessment, the committee will provide guidance for the future of both magnetic-field research and technology development in the United States. It will address trends in the disciplinary makeup of the user base and consider how the infrastructure should be optimized to meet the needs of the next decades.

1. On what areas of magnetic field research and development should the United States focus its efforts over the next decade?

2. What new capabilities should be provided in the United States (taking into account worldwide capabilities and any potential for international collaborations or cooperative arrangements)?
3. What is the best model for the infrastructure supporting high magnetic field science in the United States? Among the issues the committee might consider addressing are-
    i. To what extent should facilities be centralized?
    ii. Would the program benefit from distributing a portion of the high magnetic field capability to other locations?
    iii. How should the issue of providing magnetic fields to light source and neutron facilities be handled? Conversely, what experimental capabilities should be co-located at high field labs?
    iv. For facilities that remain centralized, should the programs remain divided among the current three locations or be combined?
    v. What are the trends in providing support for outside users versus supporting in-house independent research programs and do those trends optimally meet the needs of the user base?
4. What is the best infrastructure model for supporting high magnetic field technology development and U.S. industrial competitiveness?
5. How can the operational and financial stewardship of the research and facilities be optimized to address changes in the disciplinary spectrum and user needs?

In responding to these questions, the committee may make recommendations on organizational structure, program balance, and funding.

B

Input from the Community

A broad call for community input to the committee was issued in spring 2012 as a "Dear Colleague" letter, shortly after the committee's second meeting. The announcement was sent by e-mail to the users of the National High Magnetic Field Facility (NHMFL) and colleagues of committee members, and appeared on the committee's public Web page. The letter is excerpted below.

> Dear Colleague,
>
> The National Research Council (NRC) has established a committee called the Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States (MagSci), which will produce a report on the current status and trends in the U.S. research community for high magnetic fields throughout science and technology, and guidance for the future of both the scientific disciplines that use high field magnets and the magnetic-technology development community in the United States. More information about the study can be found at http://sites.nationalacademies.org/BPA/BPA_067287. With this message, the MagSci committee invites you to send it any information or opinions you feel should be taken into account during its deliberations.
>
> Specifically, how have high magnetic fields had an impact on your research? What scientific advances might your research lead to? How have you taken advantage of facilities at the National High Magnetic Field Laboratory (NHMFL) or other high-field magnet centers? Have you utilized international high magnet field facilities for your research? What new facilities or new capabilities would be most valuable to you? In what new areas of research are high magnetic fields likely to have a large impact? Are the challenges related to the current status of high magnetic field science impacting your research? Do you have any other comments? How does support for magnetic field research compare with support elsewhere?

By way of background, we note that when the NSF created the National High Magnetic Field Laboratory (NHMFL) in 1990, the original drivers principally resided in physics and materials science. Since then, the instrumentation available through the NHMFL has become increasingly used by other disciplines, including biology, chemistry, and geology. The NHMFL also has found applications beyond basic science, serving many applied fields from medicine to the petroleum industry. Consequently, in 2011, the NSF commissioned the NRC to generate an assessment of the current status and future direction of both high magnetic field science and technology development in the United States.

The MagSci committee is distributing this message to as many members of the high magnetic field community as possible, using several different organizations, because it wants to be sure that all voices have been heard before it issues its report. We apologize if you have received multiple copies of this letter.

If you have information you want to transmit to the MagSci committee, please send it by e-mail to NRCMagSci2012@nas.edu. It would be helpful to have your comments by June 20, 2012. Please note that in accord with government regulations for federal advisory committees, all information submitted to the committee will be made available to the public. Thank you for your help.

For MagSci,

Bertrand Halperin, *Chair*
Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States

Written responses were received from the following individuals:

Núria Aliaga-Alcalde
Michael S. Chapman
Sang-Wook Cheong
Juliana D'Andrilli
K.-P. Dinse
Jack H. Freed
William P. Halperin
Michael Harrington
Jeffrey Hoch
Mei Hong
Trudy Lehner
James McKnight
Gavin Morley
Tatyana Polenova
Ayyalusamy Ramamoorthy
Raphael Raptis
Dan Reger
Bertaina Sylvian

Joshua Telser
David Valentine
Patrick van der Wel
En-Che Yang
Joe Zardrozny

C

Committee Meeting Agendas

MEETING 1: MARCH 12-13, 2012
KECK CENTER, WASHINGTON D.C.

March 12, 2012

CLOSED SESSION

8:00 am	Committee Discussion

OPEN SESSION

12:55 pm	Welcome and Introductions *Bert Halperin, Chair*
1:00	Perspectives from National Science Foundation (NSF) *Ian Robertson and G.X. Tessema, NSF*
1:30	Perspectives from Department of Energy (DOE) *Andrew Schwartz, DOE*
2:00	Perspectives from the Committee on Opportunities in High Magnetic Field Science (COHMAG) Study *Peter Moore, Yale University*

2:45	Science Drivers and Magnet Facilities: Present and Future *Greg Boebinger and Lucio Frydman, National High Magnetic Field Laboratory (NHMFL)*
4:15	Magnet Technologies: Superconducting, DC, and Pulsed *David Larbalestier and Charles Mielke, NHMFL*
5:00	Open Discussion
5:30	Session Closes

March 13, 2012

The committee was in closed session all day.

MEETING 2: MAY 17-18, 2012
KECK CENTER, WASHINGTON D.C.

May 17, 2012

CLOSED SESSION

8:00 am	Committee Discussion

OPEN SESSION

9:00	Welcome *Bert Halperin, Chair*
	Perspectives from DOE High-Energy Physics (HEP) *Glen Crawford, DOE-HEP*
9:30	Perspectives from DOE Office of Fusion Energy Science (OFES) *Barry Sullivan, DOE-OFES*
10:00	Perspectives from National Institutes of Health (NIH) National Institute of Biomedical Imaging and Bioengineering (NIBIB) *Alan McLaughlin, NIBIB, and Alan Koretsky, National Institute of Neurological Disorders and Stroke (NINDS)*

10:45 Magnet Technology: American Superconductor Corporation (AMSC)
Alexis Malozemoff, Consultant to AMSC

11:15 Magnet Technology: Agilent
Jim Hollenhurst, Agilent Technology

11:45 Magnet Technology: Bruker
Gerhard Roth, Bruker BioSpin

12:15 pm Open Discussion with Agency and Magnet Technology Speakers

1:00 Science Drivers: Ion Cyclotron Resonance
Peter O'Connor, University of Warwick (U.K.)

1:45 Science Drivers: Neutron Scattering
Collin Broholm, Johns Hopkins University

CLOSED SESSION

2:45 Committee Discussion

6:45 Adjourn for Dinner

May 18, 2012

CLOSED SESSION

7:45 am Review Agenda and Committee Discussion

OPEN SESSION

8:30 Welcome
Bert Halperin, Chair

8:35 A Perspective on Facilities Stewardship
Ed Seidel, NSF

9:00 A Perspective on Facilities Stewardship
Pat Dehmer, DOE

9:25	A Perspective on Facilities Stewardship *Pat Gallagher, National Institute of Standards and Technology*
9:50	Open Discussion with Presenter on Facilities Stewardship
10:30	Perspectives from the NHMFL Users Committee *Janice Musfeldt, University of Tennessee and NHMFL Users Committee, Chair*
11:00	Science Drivers: Soft Matter *Jim Valles, Brown University*

CLOSED SESSION

11:45	Committee Discussion
4:30 pm	Adjourn Meeting

MEETING 3: JULY 19-20, 2012
ARNOLD AND MABEL BECKMAN CENTER, IRVINE, CALIFORNIA

This meeting was closed in its entirety.

MEETING 4: SEPTEMBER 29-30, 2012
ARNOLD AND MABEL BECKMAN CENTER, IRVINE, CALIFORNIA

This meeting was closed in its entirety.

D

Committee Member Biographies

Bertrand I. Halperin, *Chair,* is the Hollis Professor of Mathematics and Natural Philosophy at Harvard University and a professor of physics. His current research involves the theory of electron states and transport in structures of semiconductor or metal with restricted geometries, and topological aspects of condensed matter systems. Focus areas include the properties of two-dimensional electron systems at low temperatures in strong magnetic fields and the physics of interacting electron and nuclear spins in nanoscale semiconductor devices. Previous research interests included transport in inhomogeneous systems, quantum magnets and one-dimensional metals, low-temperature properties of glasses, melting and other phase transitions in two-dimensional systems, and the theory of dynamic phenomena near a phase transition. Dr. Halperin is a member of the National Academy of Sciences (NAS) and of the American Philosophical Society and is a fellow of the American Physical Society (APS) and the American Academy of Arts and Sciences. He was the recipient of the Lars Onsager Medal and Lecture (2009) of the Norwegian University of Science and Technology, the Dannie Heineman Prize of the Göttingen Akademie der Wissenschaften (2007), the Wolf Prize in Physics (2003), and the Lars Onsager Prize (2001) and the Oliver Buckley Prize (1982) of the APS.

Gabriel Aeppli is the Quain Professor of Physics and director of the London Centre for Nanotechnology. He obtained a B.Sc. in mathematics and Ph.D., M.Sc. and B.Sc. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT). Prior to taking up his current posts in the autumn of 2002, he was a senior research scientist for NEC Laboratories America, a Distinguished Member of the

Technical Staff at Bell Laboratories, a research assistant at MIT, and an industrial co-op student at IBM. Honors include a fellowship of the Royal Society (2010), the Institute of Physics Mott Prize (2008), the APS Oliver Buckley Prize (2005), the Majumdar Memorial Award of the Indian Association for the Cultivation of Science (2005), the IUPAP Magnetism Prize/Neel Medal (2003), Riso National Laboratory fellow (2002), Royal Society Wolfson Research Merit Award (2002), fellow of the APS (1997), and fellow of the Japan Society for the Promotion of Science (1996). In addition, he has been a member and chair of many panels sponsored by the DOE, APS, Engineering and Physical Science Research Council (EPSRC) (U.K.), and the National Research Council, among others. Dr. Aeppli's experience and involvement with nanotechnology are both managerial and scientific. He cofounded the interdisciplinary and interuniversity (Imperial and University Colleges) London Centre for Nanotechnology (LCN), developed its overall problem-solving strategy, arranged for the procurement of a new laboratory/office facility dedicated to nanotechnology in central London, defined the operating model in collaboration with colleagues at both colleges, and is now managing operations and future programme development. His personal research is currently focused on the implications of nanotechnology for information processing and health care. He is also a cofounder of Bio-Nano Consulting (BNC), a firm spun off from the LCN and the Institute for Bio-Engineering at Imperial College, which provides a range of services from due diligence to testing and prototyping in the nanotechnology arena.

Yoichi Ando is a professor of quantum functional materials at the Institute of Scientific and Industrial Resarch at Osaka University. He received his B.S., M.S., and Ph.D. in physics from the University of Tokyo. Dr. Ando's resarch is foucsed on materials presenting useful functionalities based on novel quantum-mechancal principles, such as high-temperature superconductors and topological insulators. To uncover the operating principles of those materials, his group grows high-quality single crystals and characterizes their transport and thermodynamic properties down to very low temperatures in high magnetic fields. He did his postdoc at Bell Laboratories and then led a research group at the Central Research Institute of the Electric Power Industry in Japan. He moved to Osaka University to found an interdisciplinary laboratory where physicists and chemists work together to reveal novel aspects of superconductors and semiconductors. Dr. Ando received the Superconductivity Science and Technology Award and the JSPS Prize. He is currently a coeditor of *Europhysics Letters.*

Meigan Aronson is a professor in the Department of Physics and Astronomy at Stony Brook University, as well as a group leader of the Correlated Electron Materials Group in the Condensed Matter Physics and Materials Science Department at Brookhaven National Laboratory. She received her A.B. from Bryn Mawr College and M.S and Ph.D. degrees from the University of Illinois at Urbana-Champaign. Subsequently, she held a postdoc at Los Alamos National Laboratory and a visiting appointment at the University of Amsterdam before joining the faculty of the Physics Department at the University of Michigan as an assistant professor in 1990. After receiving tenure in 1996, and being promoted to professor of physics in 2000, she served as associate dean for natural sciences in the College of Literature, Science, and Arts from 2004 to 2006. She moved to her current appointments at Stony Brook University and Brookhaven National Laboratory in 2007. Her research in experimental condensed matter physics focus on the interplay of superconductivity and magnetism with electronic delocalization in systems with strong electronic correlations like heavy fermions and transition-metal-based systems like the iron pnictides and chalcogenides. She is a fellow of the APS and the Committee on Institutional Cooperation (CIC) and has received a National Security Science and Engineering Faculty fellowship.

Dimitri Basov is the chair of the Department of Physics at the University of California, San Diego. He received an M.S. from the Moscow Engineering Physics Institute and a Ph.D. from the Lebedev Physics Institute, Academy of Sciences of Russia. He was a postdoctoral research associate at the University of Regensburg and McMaster University and held an assistant physicist appointment at Brookhaven National Laboratory. He joined the faculty of the University of California, San Diego, as an assistant professor and was promoted to professor in 2001. His research involves the use of infrared spectroscopy to study the physics of a wide range of materials, including strongly correlated materials, magnetic semiconductors, molecular and organic nano-electronics, electromagnetic metamaterials, superconductivity, memristors, and charge dynamics in graphene. Dr. Basov has received the Frank Isakson Prize for Optical Effects in Solids of the APS, a Humboldt Research Award, and the Ludwig Genzel Prize, among others. He is a fellow of the APS.

Thomas F. Budinger (NAE, IOM) is a professor emeritus at the graduate school of the University of California, Berkeley (UC Berkeley), as well as professor and chair of the Department of Bioengineering and Professor in Residence, University of California, San Francisco, and department head, Department of Nuclear Medicine and Functional Imaging, Lawrence Berkeley National Laboratory (LBNL), professor emeritus of the Department of Radiology at the University of California, San Francisco, and senior faculty scientist in the Department of Nuclear Medicine and Functional Imaging at LBNL. He received his B.S. in chemistry from Regis College, an M.S. in physical oceanography from the University of Washington, Seattle, an M.D. from the University of Colorado, and a Ph.D. in medical physics from UC Berkeley. He has received numerous honors and awards for his research contributions to nuclear medicine and imaging techniques and was elected as a member to the National Academy of Engineering (NAE) in 1996.

Robert Dimeo is the director of the National Institute of Standards and Technology's (NIST) Center for Neutron Research (NCNR), a national user facility for neutron scattering on the NIST Gaithersburg campus. Dr. Dimeo received an M.S. in electrical engineering in 1994 and a Ph.D. in physics from the Pennsylvania State University in 1999. His research interests include the dynamics of quantum fluids, quantum rotations in molecular solids, software development for the visualization and analysis of neutron scattering data, and the development of neutron instrumentation. Dr. Dimeo served as the Assistant Director for Physical Sciences and Engineering at the Office of Science and Technology Policy from 2005 until 2007. He was responsible for working on policy matters involving major research facilities in materials science, interagency cooperation on large-scale research activities, and other interagency working groups.

John C. Gore (NAE) is the director of the Institute of Imaging Science and the Hertha Ramsey Cress University Professor of Radiology and Radiological Sciences, Biomedical Engineering, Physics and Astronomy, and Molecular Physiology and Biophysics at Vanderbilt University. Dr. Gore obtained his Ph.D. in physics at the University of London in the U.K. in 1976 and has been an active leader in imaging research and applications for over 30 years. He also holds a degree in law. In addition to being an elected member of the NAE, he is also an elected fellow of the American Association for the Advancement of Science, the American Institute of Medical and Biological Engineering, the International Society for Magnetic Resonance in Medicine (ISMRM), and the Institute of Physics (U.K.). In 2004 Dr. Gore was awarded the Gold Medal of the ISMRM for his contributions to the field of magnetic resonance imaging. He has served twice as a trustee of the ISMRM and is editor in chief of *Magnetic Resonance Imaging*. He is currently a member of the National Advisory Council for Biomedical Imaging and Bioengineering at the National Institutes of Health (NIH). He has published over 500 original papers and contributions within the medical imaging field. His research interests include the development and application of imaging methods for understanding tissue physiology and structure, molecular imaging, and functional brain imaging.

Frank Hunte is an assistant professor in the Department of Materials Science and Engineering at North Carolina State University (NCSU). He received B.S. and M.S. degrees in physics from Florida Agricultural and Mechanical University and a Ph.D. in physics from the University of Minnesota. Prior to coming to NCSU he was a visiting assistant scholar/scientist at the Applied Superconductivity Center in the Magnets and Materials Division of the National High Magnetic Field Laboratory at Florida State University. His research investigates magnetic materials and thin film heterostructures, including semiconductors and superconductors, processing methods, functionality, and operating environments (thermal, mechanical, electromagnetic), from basic materials physics to technological applications. He is currently focused on dilute magnetic semiconductors, which retain ferromagnetism at room temperature, and memristors. Hunte also studies the relationship between magnetism and superconductivity in the iron-based unconventional multiband superconductors, where magnetic correlations appear strongly. His experimental research employs characterization methods including magnetotransport, magnetometry, XRD, microscopy (SEM, AFM, MFM), and magneto-optical imaging (MOI).

Chung Ning (Jeanie) Lau is an associate professor of physics at the University of California, Riverside (UCR). She received her B.A. from the University of Chicago and her Ph.D. from Harvard University. Before joining UCR in 2004 as an assistant professor, she was a research associate at Hewlett-Packard Laboratories in Palo Alto, California. Her research interests center on the thermal, electrical, and mechanical properties of carbon nanomaterials. She is recipient of the NSF CAREER award and the 2008 Presidential Early Career Award for Scientists and Engineers.

Jan Cornelis Maan is a professor in experimental solid state physics and director of the Nijmegen High Field Magnet Laboratory (HFML). He received a B.S. in physics engineering from Delft Technical University and a Ph.D. in solid state physics from the University of Nijmegen. His research interests include fundamental properties of condensed matter in high magnetic fields, with emphasis on transport measurements and optical spectroscopy (visible to far infrared), as well as manipulation and study of molecular materials with magnetic fields. He has coauthored more than 340 publications (cited more than 5,000 times) in refereed journals or invited book contributions. In 2003 he was appointed Ridder in de Orde van de Nederlandse Leeuw (Knight in the Order of the Dutch Lion) by the Queen of the Netherlands, for the realization of the new HFML.

Ann E. McDermott is a professor of chemistry at Columbia University. She received a B.Sc. in chemistry from Harvey Mudd College and a Ph.D. in chemistry from UC Berkeley. Her research group studies the mechanisms of several enzymes, principally through solid-state NMR spectroscopy. She has studied the opening of the active site flexible loop of the glycolytic enzyme, triosephosphate isomerase, and its coupling to the appearance of product, using a range of biophysical probes. The compressed "non-bonded" interactions of the prereactive substrate on the active site of this enzyme, and the conformational dynamics, have been experimentally probed at high resolution. Analogous studies are under way for bacterial cytochrome P450, where conformational flexibility impacts the range of chemistry carried out by the enzyme. These studies involve recent advances in high-resolution solid-state NMR spectra of uniformly or selectively isotopically enriched proteins wherein site-specific assignments allow for efficient structural, dynamic, and mechanistic studies. She also studies the photosynthetic reaction center and demonstrated for the first time a coherent quantum mechanical-photochemical mechanism for enhancement of NMR detection sensitivity by three orders of magnitude involving the primary players of electron transfer.

Joseph Minervini is division head for technology and engineering in the Plasma Science and Fusion Center at the MIT. He also holds an academic appointment as senior research engineer in the Nuclear Science and Engineering Department at MIT, where he teaches a course and supervises graduate student research. Dr. Minervini received his master's and Ph.D. in mechnical engineering from MIT. Dr. Minervini has played a leading role in the field of large-scale applications of superconductors for more than 30 years. His research interests include applied superconductivity, electromagnetics, cryogenic heat transfer, supercritical helium fluid dynamics, and low-temperature measurements. Dr. Minervini served as principal investigator for the US ITER magnetics R&D program, and a major achievement of the engineering design activity (EDA) was the design, fabrication, and testing of the Central Solenoid Model Coil, the world's largest and most powerful pulsed superconducting magnet. He now serves as spokesperson for the U.S. Magnetics Program organized under the Virtual Laboratory for Technology of the DOE Office of Fusion Energy Science (OFES). Dr. Minervini has worked on magnet systems for nearly every major application of large-scale superconductivity, including fusion energy, magnetic levitation, energy storage, power generation and transmission, magnetic separation, and high-energy and nuclear physics, as well as medical applications. He has management and technical responsibility for an interdisciplinary division of approximately 20 engineers, technicians, and students devoted to magnet technology and engineering and development of advanced applications of superconductivity.

Arthur Ramirez is the dean of the Jack Baskin School of Engineering at the University of California at Santa Cruz and previously was director of the condensed matter physics department at Bell Laboratories of Lucent Technologies, leader of the Materials Integration Science Laboratory at Los Alamos National Laboratory, and co-director for the University of California's Institute for Complex Adaptive Matter. Dr. Ramirez received his Ph.D. in physics from Yale University in 1984. His research interests in experimental condensed matter physics include low-dimensional magnetism, heavy fermion systems, thermoelectric materials, colossal magnetoresistive materials, high dielectric constant materials, geometrically frustrated systems, molecular electronics, and superconductivity in various systems including molecular compounds, intermetallics, and oxides. Dr. Ramirez is a fellow of the APS and has served in a number of positions with the APS's Division of Condensed Matter Physics.

Zlatko B. Tesanovic was a professor in the Henry A. Rowland Department of Physics and Astronomy of the Johns Hopkins University (JHU) until his death on July 26, 2012. Previously, he served as director of the TIPAC Theory Center at JHU. He received a B.Sci. in physics from the University of Sarajevo, Yugoslavia, and a Ph.D. in physics from the University of Minnesota. His research interests were in theoretical condensed matter physics, revolving primarily around iron- and copper-based high-temperature superconductors and related materials, quantum Hall effects, and other manifestations of strong correlations and emergent behavior in quantum many-particle systems. He was a foreign member of the Royal Norwegian Society of Sciences and Letters and a fellow of the APS Division of Condensed Matter Physics. He gave more than 100 invited talks at scientific meetings, including major international conferences, and authored more than 120 journal articles.

Robert Tycko is senior investigator in the Laboratory of Chemical Physics of the National Institute of Diabetes and Digestive and Kidney Diseases, NIH. His research focuses primarily on solid-state NMR spectroscopy and its applications in biophysics and structural biology. Current research includes structural studies of amyloid fibrils and proteins and peptide/protein complexes associated with HIV. Dr. Tycko received the APS's Earle K. Plyler Prize for Molecular Spectroscopy in 2005, the Chemical Society of Washington's Hillebrand Prize in 2007, and an NIH Director's Award in 2001. He is a fellow of the APS, the American Association for the Advancement of Science, and the International Society of Magnetic Resonance. Dr. Tycko has served on the editorial boards of the *Journal of Chemical Physics*, the *Journal of Magnetic Resonance*, the *Journal of Biomolecular NMR*, and *Molecular Physics* and chaired the Gordon Research Conference on Magnetic Resonance in 2001.

E

Glossary

antiferromagnetism: In substances known as antiferromagnets, the magnetic moments of adjacent atoms tend to line up antiparallel, yielding an ordered state with no net magnetic moment. Consequently, such materials display almost no response to an external magnetic field at low temperatures.

band structure, bandgap: Theory describing the collective organization and interaction of atoms (and notably their valence electrons) in a solid. The band structure of a solid is the continuous range of states with different energies that are filled by the charge carriers in an extended solid. In insulators and semiconductors, a bandgap separates the last filled state from the first excited state, unoccupied at zero temperature. The electrical properties of a material at room temperature can be influenced by the (temperature-dependent) population of charge carriers near the bandgap. For instance, materials without a bandgap (i.e., metals) or with a bandgap comparable to the thermal energy (i.e., semiconductors) are typically conductors, while materials with a very wide bandgap are typically insulators.

Bitter magnet: Design for direct current resistive magnets invented by Francis Bitter in the late 1930s. Bitter's design meets the high conductivity and cooling requirements of high-field resistive magnets using perforated copper plates that are sandwiched between insulating layers, a small region of electrical contact being allowed between plates so that current can flow from one plate to the next. Electrical current flows through the resulting copper spiral, and coolant flows through perforations in the conductors, which are aligned vertically.

bore, magnet: Inner diameter of a cylindrical magnet where the magnetic field is available for use. The bore of a magnet constrains the volume that can be utilized for experimental measurements.

coil, magnet(ic): Electric current in most electromagnets passes through coils of wire. Since the coils of all such magnets are their active component, the terms *coil* and *magnet* are often used as synonyms.

coherence length: Characteristic scale of a Cooper pair in a superconducting material. The coherence length effectively represents the longest distance over which the two electrons of the Cooper pair act in tandem and is typically on the order of 1.5 nm for high-field materials.

conductor: Material such as Cu or Al in which charge carriers can move under the influence of an electrical voltage. Unlike superconductors, conductors have finite, nonzero resistance.

Cooper pair: Entity believed to explain the superconductivity of many materials. A Cooper pair consists of two electrons that are paired together into a new state with zero net charge and angular momentum. Below the superconducting transition temperature, Cooper pairs form a condensate—a macroscopically occupied single quantum state—in which current flows without resistance.

correlated electron systems: A many-particle system in which strong interactions between electrons play a crucial role in determining fundamental properties. Electronic correlations can cause striking many-body effects like superconductivity, electronic localization, magnetism, and charge ordering, which cannot be described using the simpler independent particle picture. These properties and dynamics arise from the collective interactions of the electrons with one another. Also "strongly correlated electron systems."

critical current density (J_c): At a certain temperature, the maximum electrical current density that a superconductor can carry before it quenches and enters the normal state. In general, as the current flowing through a superconductor increases, the T_c (see below) will usually decrease.

critical field (H_c): At zero applied current, the maximum magnetic field (at a given temperature) that a superconductor can transport before it quenches and returns to a nonsuperconducting state. Typically, a higher T_c (see below) is associated with a higher H_c. (For the superconductors of interest to this report, the critical field is technically the *upper critical field*, properly denoted as H_{c2}.)

cryogenically cooled probe: Device installed in the bore of an NMR magnet that carries the samples to be studied as well as the electronics necessary both for perturbing the orientation of nuclear spins in samples and for detecting the consequences of those perturbations electromagnetically. Probes may include additional devices for controlling the sample environment. In a cryogenically cooled probe, in order to improve signal-to-noise ratio, electronic components are cooled to liquid helium temperatures, which minimizes shot noise.

cuprates (copper oxides): Materials or chemical compounds that contain copper anions.

cyclotron: Device for experimental particle physics that uses an oscillating electric field to accelerate charged particles and a magnetic field to control particle trajectories.

cyclotron frequency: Charged carriers of all kinds follow cyclotron-like spiral trajectories in strong magnetic fields, with a frequency proportional to the field strength. In doped semiconductors and metals, measurements of the cyclotron frequency give information about the effective mass of the mobile carriers.

dc magnet: A steady-state magnet; dc stands for direct current, meaning that the flow of current in the magnet's coils is constant in time.

diamagnetism: The property of some materials that causes them to create a magnetic field that opposes an externally applied magnetic field and therefore are slightly repelled by that external field.

dynamic nuclear polarization (DNP): DNP is a process in which the large polarizations of electron spins in a strong magnetic field are partially transferred to nuclear spins by irradiation of EPR (see below) transitions, resulting in large enhancements of nuclear spin polarizations and hence NMR signals.

electromagnet: Device designed to generate a magnetic field by having electric current passed through it.

electron paramagnetic resonance (EPR): EPR, also known as electron spin resonance (ESR) or electron magnetic resonance (EMR), is the resonant absorption of microwave radiation by paramagnetic ions or molecules with at least one unpaired electron spin in the presence of a static magnetic field. It has a wide range of applications in chemistry, physics, biology, and medicine. For example, it may be used to probe the static structure of solid and liquid systems and is also very useful in investigating dynamic processes.

Faraday rotation: An interaction between light and a magnetic field by which the plane of polarization of the light rotates.

Fermi surface: Separates occupied electron states, whose energies lie below a cutoff (the *Fermi energy*), from unoccupied or empty states, whose energies lie above the cutoff. Electrons close to the Fermi surface are of particular interest because they play a dominant role in electrical transport and many other properties of the material.

ferromagnetism/ferromagnetic materials: In substances known as ferromagnets, the magnetic moments of adjacent atoms tend to line up in parallel, yielding an ordered state that has a macroscopic magnetic moment. Once the magnetic domains in a ferromagnetic substance have become aligned by a small field, the magnetic moment of the bulk material may persist even in the absence of an external magnetic field, a property unique to ferromagnets. Consequently, ferromagnetic materials can be used to make permanent magnets that deliver fields as large as 1-2 T. Elements such as iron, nickel, and cobalt are ferromagnetic at room temperature.

Fourier transform-ion cyclotron resonance (FT-ICR) mass spectrometry: FT-ICR is a technique in which the mass-to-charge ratios of charged particles, especially molecular ions, are measured from the frequencies of their cyclotron motions in a strong magnetic field. Compared with other forms of mass spectrometry, FT-ICR has the highest demonstrated precision and resolution, making it the method of choice for complex mixtures of molecules and for distinguishing among chemical species with nominally identical masses but different elemental compositions.

functional magnetic resonance imaging (fMRI): A form of magnetic resonance imaging that registers changes in blood oxygenation and flow to areas of the brain, thereby measuring brain activity.

fusion: Nuclear reaction in which nuclei combine to form more massive nuclei with the simultaneous release of energy.

gauss (G): Unit of measure for magnetic field strength in the cgs system of units. Earth's magnetic field is about 0.5 G. One G is equal to 0.0001 tesla (T), the mks unit of magnetic field.

hybrid magnet: In a hybrid magnet system, resistive and superconducting magnet technologies are combined. The superconducting magnet takes the place of the outer portion of the resistive coil. The resistive portion operates as an insert to the superconducting magnet and produces the portion of the field that exceeds the critical current and field limits of the superconducting magnet.

hybrid magnet, series-connected: Hybrid magnet system where the current supplied to the resistive insert travels first through the superconducting outer magnet.

ion cyclotron resonance mass spectroscopy (ICRMS): Method for precisely measuring the mass of a collection of ions originating from the chemical dissociation of complex molecules and solids. It depends on cyclotron resonance. Ions with a range of mass-to-charge ratios are exposed to a high-frequency electric field in the presence of a constant magnetic field perpendicular to the varying electric field. Maximum energy is gained by the ions that satisfy the cyclotron resonance condition and that can be separated on that basis from ions that have only a slightly different mass-to-charge ratio.

ITER: ITER is a large-scale scientific experiment being built in the south of France that aims to demonstrate the feasibility of producing fusion power in a sustained burning plasma, while also demonstrating some of the key technology components.

J_c: See *critical current density*

linewidth: Energy resolution of a feature in an experimental measurement; typically, a peak observed in a spectrum.

Los Alamos National Laboratory (LANL): National laboratory in northern New Mexico operated by the University of California for the Department of Energy.

macromolecule: Molecule of high relative molecular mass the structure of which usually consists of multiply repeated units that are derived—actually or conceptually—from molecules of low relative molecular mass. Particularly, a molecule of this kind that is of biological origin.

magnetic confinement fusion reactors: One of the two major avenues along which fusion energy research is proceeding (the other being inertial confinement fusion), magnetic confinement fusion relies on magnetic fields to confine a plasma at sufficient densities and appropriate conditions so that fusion reactions take place.

magnetic field: Modification of free space or vacuum caused by the presence of moving charges that results in a force being exerted on other moving charges. Magnetic fields are caused by electrical currents, which may be either microscopic (e.g., due to electron spins or orbital motion within atoms) or macroscopic, as in case of currents in the coils of an electromagnet.

magnetic moment: Property of a magnetic dipole that determines the amount of torque exerted on it when it is placed in a magnetic field.

magnetic order: Systematic arrangement of magnetic moments in a material that forms a long-range pattern.

magnetic resonance imaging (MRI): Noninvasive medical technique based on nuclear magnetic resonance for imaging the interior of objects. The sample to be imaged is placed in a strong magnetic field that varies across its volume in a known manner; it is then exposed to electromagnetic radiation of appropriate frequency. In this environment the frequency of the NMR signals generated by all the magnetically active atoms in the sample will vary with location in the sample. The three-dimensional distributions of molecules of a particular type in a sample can be reconstructed from the frequency distributions.

magnetic susceptibility: a dimensionless proportionality constant that indicates the extent to which a material is magnetized in response to a given, external magnetic field.

magnetism: The attractive and repulsive forces magnets exert on each other. Commonly taken as synonymous with ferromagnetism—that is, the intrinsic magnetic fields characteristic of ferromagnetic materials. More generally, magnetism spans the whole range of phenomena displayed by materials with constituents having magnetic dipoles, including antiferromagnetism and other forms of short-range permanent or ephemeral order.

magnetoresistance: In some materials, electrical resistance depends dramatically on external magnetic field. Antiferromagnetically coupled magnetic layers separated by nonmagnetic spacers can display an extreme form of magnetoresistance called giant magnetoresistance, which is taken advantage of in the magnetic sensors used in high-density disk drives.

megavolt ampere (MVA): measures the apparent power in a power supply.

Meissner effect: The active exclusion of magnetic fields from the interior of materials as they transition from the normal to a superconducting state.

MgB_2: Magnesium diboride is a superconductor that has conventional superconducting properties despite having two types of electrons that participate in its superconductivity. Its critical temperature (about 39 K) is the highest of all known phonon-mediated superconductors. This relatively inexpensive material was first synthesized in 1953, but its superconducting properties were not discovered until 2001.

molecular beam epitaxy (MBE): A process widely used in the semiconductor industry for growing single crystals on a heated crystalline substrate.

nanophotonics: The study and use of light and optics at the nanometer scale.

National High Magnetic Field Laboratory (NHMFL): National laboratory for the production of high and specialized magnetic fields for scientific research. It is operated by the National Science Foundation. Its steady-state magnetic field facility is located in Tallahassee, Florida, its pulsed-field facility is based at Los Alamos National Laboratory in New Mexico, and it has an MRI facility and a high field-to-temperature-ratio experimental facility at Gainesville, Florida. The NHMFL develops and operates high-magnetic-field facilities that scientists use for research in physics, biology, bioengineering, chemistry, geochemistry, biochemistry, materials science, and engineering. It is the only facility of its kind in the United States and one of about a dozen in the world.

Nb_3Sn: Niobium-tin (T_c of about 18 K) is a superconducting compound that has been widely used for the construction of high-field magnets with field greater than 10 tesla or so.

Nb-Ti: Niobium-titanium (T_c of about 9 K) is the workhorse superconducting material in the high-field-magnet industry.

Neel temperature: The temperature at which the thermal energy is large enough above which an antiferromagnetic or ferrimagnetic material becomes paramagnetic.

neutron source: A nuclear reactor or accelerator-based facility that generates beams of neutrons of (usually) modest energy that have high intensity and flux. Neutrons are important probes of the microstructure of matter because (1) having no net charge, they interact with the nuclei of atoms, not their electron clouds; (2) they interact weakly with matter and therefore can probe deeply into the interior of samples; and (3) their energies are well suited to the scales of electronic and atomic processes. Moreover, because they are spin-½ particles having a magnetic moment, they can be used to study the magnetic microstructure of matter.

NMR spectrometer: Instrument used to measure the frequencies of NMR transitions. A modern NMR spectrometer usually includes (1) a superconducting magnet; (2) a probe for holding the sample in the magnet that includes coils for irradiating it with electromagnetic radiation and detecting the electromagnetic radiation emitted by the sample; and (3) a console that contains the electronics necessary to operate the probe and a computer to control what happens in the probe and analyze the data returned from the probe.

nuclear magnetic resonance (NMR): When an atomic nucleus in a magnetic field is exposed to photons that have an energy corresponding to the difference in energy between two possible orientations of its magnetic moment, it will resonate—that is, its magnetic moment will rapidly change orientation, in the process first absorbing energy and then radiating it. Only a finite number of different orientations are possible for the magnetic moments of any such nucleus in a magnetic field, each orientation having its own characteristic energy. This behavior is efficient enough that it can be detected over only a narrow range of photon energies (frequencies). The frequencies at which resonances are seen in some specified magnetic field not only identify the kinds of atom responsible for them but can also provide valuable information about the molecular environment in which the atoms are found.

organic superconductors: Class of organic conductors that superconduct at low temperature. They include molecular salts, polymers, and even pure carbon systems—for example, carbon nanotubes and C60 compounds. They are also sometimes called molecular superconductors. They are typically large, carbon-based molecules of 20 or more atoms and consist of a planar organic molecule and a nonorganic anion.

pulsed-field magnet: Resistive magnet designed to provide transient magnetic fields, often for durations as short as microseconds but occasionally for as long as several seconds. Because it is active for only short times, a pulsed magnet uses less power and needs less cooling than a dc magnet of similar bore and maximum field strength. Today, research magnets with the highest fields are pulsed magnets.

quantum critical point: Phase transitions of any sort that occur at absolute zero; thought to be a characteristic feature of all strongly correlated electron systems. The novel behaviors that are observed signal the dominance of quantum fluctuations over the thermal fluctuations that are characteristic of phase transitions at finite temperatures. Many believe that the unconventional properties of high-temperature superconductors may be related to a hidden quantum critical point in these materials.

quantum Hall effect (QHE): When a magnetic field is applied perpendicularly to a thin metal film or a semiconductor film that is conducting an electric current, a voltage will be observed that is perpendicular to the axis of both the film and the magnetic field. Discovered in 1879, this phenomenon was named for its discoverer, Edwin H. Hall. Classically, this voltage is proportional to the strength of the applied magnetic field. However, it was later observed that certain two-dimensional semiconducting devices display precisely quantized plateaus in their Hall resistance—that is, the ratio of Hall voltage to current—which reflect the tuning of charge carrier occupancy states by the external magnetic field. K. Von Klitzing was awarded the Nobel prize in physics in 1985 for his demonstration of this phenomenon, which is known as the integer quantum Hall effect.

quantum Hall effect, fractional (FQHE): The fractional version of QHE, in which the Hall resistance progresses in fractions of integer quanta, was discovered in 1982 by D. Tsui and H. Störmer in experiments performed on gallium arsenide heterostructures. This behavior was explained by R. Laughlin in 1983 in terms of a novel quantum liquid phase that accounts for the effects of interactions between electrons. The three were awarded the 1998 Nobel prize in physics for this work.

quench: Transition, often sudden, in a superconducting material from its superconducting state to its normal, resistive conducting state. It occurs when either the critical current density (J_c) of the material or its critical temperature (T_c) is exceeded.

resistive magnet: Electromagnet that generates a magnetic field by the passage of electric current through resistive conductors.

resistivity: Property of a material that inhibits the flow of electricity, usually because of collisions between the charge carriers and the material's internal lattice structure.

scanning tunneling microscopy (STM): An instrument that uses quantum tunneling to image surfaces at the atomic level.

soft condensed matter: Encompasses a variety of physical systems that are soft in the sense that they can be easily deformed by mechanical or thermal stress, or by electric and magnetic fields. Such systems include polymers, gels, colloids, membranes, and biological cells or organisms. The binding between molecules in these mostly organic or biological materials (hydrogen bonding, van der Waals, or π-π bonding), is much weaker than in normal solids. High magnetic fields can be used to assemble and align functional, organic or inorganic, nano- and microstructures, and to probe their structures, properties, and dynamics, with potential applications in drug delivery, optics, sensors, and nanoelectronics.

solenoid: Magnetic solenoid; the most common type of magnet, formed by wrapping coils of conductor around a central cylindrical volume.

Spallation Neutron Source (SNS): Large research facility at the Oak Ridge National Laboratory, completed in 2006, which provides the most powerful pulsed neutron source in the world. The neutrons produced by a spallation source are knocked out of a target (spalled), which is usually a mass of some high-atomic-weight metal, by high-energy protons generated by an accelerator of some kind.

spectroscopy: (Usually) the experimental study of the energy levels of materials. More generally, a spectrum is a display of the dependence of some property of a sample as a function of some other parameter—for example, energy absorption versus energy or abundance versus molecular mass. Any experimental activity that generates such plots can be described as spectroscopy.

stored energy: Potential energy; energy that can be released to do work, as in an electric motor. A magnet's energy is stored in its magnetic field.

superconducting magnet: Electromagnet whose conductor is made of superconducting material.

superconductivity: Phenomenon that occurs in certain materials at low temperatures. It is characterized by the complete loss of electrical resistance and the complete expulsion of weak externally applied magnetic fields (the Meissner effect).

superconductor: Any material that will conduct electricity without resistance.

superconductor, high-temperature (HTS): Superconducting material that has a high critical temperature, typically above 30 K. However, there is no specific temperature separating HTS from low-temperature superconducting materials. HTS is now frequently used to mean superconductors where the pairing mechanism is believed to arise from electron-electron interactions, such as the copper-oxide- and iron-pnictide-based superconductors, as opposed to materials where the superconductivity is believed due to phonon-mediated interactions.

superconductor, low-temperature (LTS): Superconducting materials whose T_c is below about 30 K, though many now call MgB_2 a low-temperature superconductor even though its T_c can be as high as 40 K, because its superconductivity is believed to arise from conventional phonon-mediated pairing. See preceeding entry, *HTS.*

synchrotron light source: Relativistic charged particles traveling in circular trajectories emit electromagnetic radiation, known as synchrotron radiation. Although this phenomenon can result in a serious loss of particle energy in circular accelerators used by the high-energy physics community, the emitted radiation can be a powerful source of photons, with energies ranging from the infrared to X-rays. A synchrotron light source is an electron storage ring, typically fed by a separate accelerator, which is designed and operated for the electromagnetic radiation it produces.

T_c: Scientific notation for the critical transition temperature (at zero applied magnetic field and current) below which a material begins to superconduct.

tesla (T): Unit of measure for magnetic field strength in the SI system of units. One tesla is equivalent to 10,000 gauss.

THz radiation: Electromagnetic radiation at frequencies around 1 terahertz (10^{12} Hz), with the upper and lower boundaries not clearly designated. A range of 0.1 THz (100 gigahertz) to 10 THz has a corresponding wavelength range of 3 mm to 0.03 mm (or 30 μm).

topological insulator: A material whose interior behaves as an insulator but whose surface contains conducting states.

transition temperature: See T_c.

van der Waals bond: The weak attractive or repulsive forces between atoms or molecules that arise principally from induced or permanent dipoles existing in the particles.

YBCO: Acronym for a well-known high-temperature ceramic superconductor composed of yttrium, barium, copper, and oxygen.

F

MRI—Safety and Potential Health Effects

This appendix discusses possible physiological effects in human subjects from 20 T exposures and related MRI experiments. There have been temporary sensory effects noted by human subjects at lower fields, and extrapolation of these to much higher fields requires evaluations of the biophysics and additional experimentation with tissues, animals, and human subjects. The committee presents a short history of the health effects controversy followed by physiological and perception observations and then a synopsis of the physics behind these experimental observations of effects of static, radiofrequency fields, and switched magnetic field gradients.

SCOPE OF THE PROBLEM

Investigations of health effects from magnetic field exposures have been placed into three categories: static field effects, switched gradient effects, and radio-frequency (RF) heating effects. Experiments commenced in earnest 30 years ago, when the promise of widespread use of magnetic resonance imaging of humans became clear from the 1973 initial experiments demonstrating the imaging potentials by Lauterbur (Lauterber, 1973). Health effects studies include effects on molecular enzyme kinetics of genotoxic experiments up to 10 T and whole human body exposures up to 9.4 T. The conclusions from these investigations are that there are no harmful effects from static fields up to 9.4 T. There are known nerve stimulations from induced E-fields following rapid gradient switching with a threshold near 6 V/m. The RF thermal effects are dependent on calculated specific absorbed power. Though the health effects observed are reversible and not considered harmful, there is no question that high static magnetic fields do have a temporary physiological effect on the central nervous system, as detailed in the next section on static field effects.

The issue before the committee is—What are the potential effects of fields that are two times those to which human beings have been exposed, particularly when the theoretical expectation involves a force or energy dependence on the B-field squared? The health effects emphasis is on static field effect potentials, because for nuclei other than protons, the RF frequencies are in the range already experienced, and with respect to imaging gradients, no major differences in the gradient-switched field rates are expected. But for protons, the anatomical distribution of power deposition and dielectric resonance effects need investigation for imaging and spectroscopy at 20 T. The relative permittivity of tissues at frequencies above 400 MHz is known, and both theoretical and experimental work can explore the potentials for hazards. Proton magnetic resonance functional imaging becomes important at 20 T, where RF penetration (1/e) at 860 MHz of 6-10 mm allows examination of the human cortex. Next, the committee gives a short history of inquiry into static and RF fields and then synopsizes the observations made using human subjects at fields above 4 T as well as animal behavior results.

STATIC FIELD EFFECTS: HISTORICAL PERSPECTIVE AND SCIENTIFIC LITERATURE

Public awareness of potential problems from electromagnetic fields dates from the publication of a statistical relationship between childhood leukemia and the presumed increases in magnetic fields in their homes. The magnetic fields were those related to electric power line inputs, and the method of quantification was the configuration of wires from the main high-voltage lines to the transformers to the homes. These were codified by a "wire code" for the homes in a particular neighborhood. Magnetic fields that epidemiologists were investigating are 60 Hz sinusoidal fields with only generally less than 3 μT amplitude associated with ac power lines. Though there was no compelling evidence that the wire codes and actual fields in the homes were strongly correlated, the controversy persisted for a number of years in the 1980s. These concerns and related concerns about electric fields near homes from overhead power lines led to a NRC committee evaluation and report. That committee concluded that there are no known human health effects from oscillating magnetic fields with an amplitude in the range to be expected in public places (NRC, 1997). An exception is the physiological effect of increased bone healing from the induced electric fields associated with exposure of bone fractures to oscillating magnetic fields of low amplitude (Bassett et al., 1974). Nearly 300 literature citations comprise this report on cell, animal, human, and epidemiology studies. Concerns about industrial operations (e.g., induction heating, aluminum plants) and high-energy physics accelerators, where fields of 0.05 to 1.0 T are experienced by technicians and scientists for a few hours each day, led to an epidemiology study, which found no increased incidence of cancers. But this, like many other studies, had limited power even though almost 1,600 individuals were evaluated (Budinger et al., 1986). Epidemiology studies that endeavor to show effects must limit the claims to statements such as this: The results show that there was not an increase in prevalence of disease X beyond a factor of Y, where Y in the case of static fields is 2 for cardiovascular effects and 3 for cancer. Because disease incidences are low, a proper study to show, say, a 1.5-fold increase in incidence or measurable change in prevalence requires large groups (100,000 for most diseases) and, for diseases of very low prevalence, such as brain tumors and some leukemias, millions of subjects.

When nuclear magnetic resonance (NMR) was found to have major applications to human health but involved whole body exposure to fields more than 10,000 times Earth's magnetic field, the scientific community began extensive investigations on cells, animals, and humans, with exposures approaching 10 T. The most extensive compendium of studies was published by the Advisory Group on Non-ionizing Radiation as a document of the Health Protection Agency of Great Britain (Health Protection Agency, 2008). The focus of that investigation is on static fields. But because the MRI and fMRI procedure involves use of rapidly changing magnetic fields to acquire spatial information and RF oscillating fields to achieve the resonance condition, the evaluation of safety of MRI and spectroscopy must include the slew rate of magnetic field changes and the RF power. These three aspects are discussed below.

MAGNETIC FORCES

A first concern surrounding very high magnetic fields is the danger from projectiles, including tools, metal furniture, and other ferromagnetic objects that can become projectiles (Schenck, 1992; Schenck, 2000). A life-threatening danger is to personnel with metallic implants, including pacemakers and wound clips. But other than the fact that the forces will be greater when the field and the field gradient become larger, one does not expect increased hazards from forces at 20 T. The current screening of individuals before entering the magnet is an adequate safeguard from harm from pacemakers and other implanted ferromagnetic objects.

Field Effects on Diamagnetic Materials (Water and Tissues)

The force for saturated ferromagnetic objects is proportional to the gradient, and this can be as high as 10-40 T/m depending on the magnet and the position of the subject, but there is no force on ferromagnetic objects in a homogeneous field. For diamagnetic and paramagnetic materials the force is proportional to the product of the B-field and the gradient of the field. Even in a homogeneous field the turning torque can exist depending on the magnetic susceptibility anisotropy. Though the forces on diamagnetic materials are smaller than those on ferromagnetic materials, they are sufficient to levitate frogs in the fringe fields of a 16 T spectrometer (Berry and Geim, 1997). The levitation effect on diamagnetic materials, including water, ethanol, wood, plastic, acetone, and graphite, was noted in 1991 (Beaugnon and Tourier, 1991). One can expect a liquid surface profile to change significantly from a level surface in very high magnetic fields. For example, the surface of pure water (diamagnetic susceptibility of -9.031×10^{-6}) will decrease at the field center and rise at the edges of a magnetic field of 10 T in a 200 mm diameter, 1,300 mm long magnet (Hirota et al., 1995). The amplitude of the surface profile is almost 40 mm. The change in heights from one part of the field to another is the result of the conservation of potential energy.

Whether this phenomenon affects the inner ear sense of gravity direction is not known but will be discussed further in the next section.

Magnetic Field Effects on Vestibular Apparati of Fish, Birds, and Mammals

A wide variety of experimental observations implicate the vestibular apparatus for the variety of symptoms and signs manifested by animals and human subjects in high magnetic fields as well as in the fringe fields of high-field magnets, where forces can cause small but physiologically significant relative tissue motion. Observed symptoms and signs include avoidance by animals of high fields and field gradients (Weiss et al., 1992; Houpt et al., 2007), animal head tilt while in a homogeneous field (Houpt et al., 2003), and turning behavior of animals after exiting high magnetic fields (Houpt et al., 2003). Human subjects have definite symptoms of nausea, vertigo, nystagmatism, and some reversible decline in cognitive function at fields of 4 T, 7 T, 8 T, and 9.4 T (Schenck, 1992; Patel et al., 2008; Theysohn et al., 2008; Kangarlu et al., 1999; Glover et al., 2007; van Nierop et al., 2012). Effects on the vestibular system are believed to underlie these phenomena.

The vestibular apparatus is the size of a children's marble imbedded in the bony structure of the skull and comprises the inner ear. The vestibular organ is the master sensor for balance and motion, acting in coordination with the brain and spinal cord and using the visual system and body proprioception. The structure shown in Figure F.1 has three units: three orthogonally oriented circular canals (sacs) filled with fluid to sense angular motion (semicircular canals); two linear force detectors for gravity and linear acceleration (utrical and saccule); and a spiral structure that detects sound pressure waves over a wide band of frequencies (cochlea). All three systems use the deflection of hair cells to stimulate nerve impulses. Inertial forces of the endolymph fluid in the semicircular canals result in the bending of a structure at the base of each semicircular canal; multiple calcium

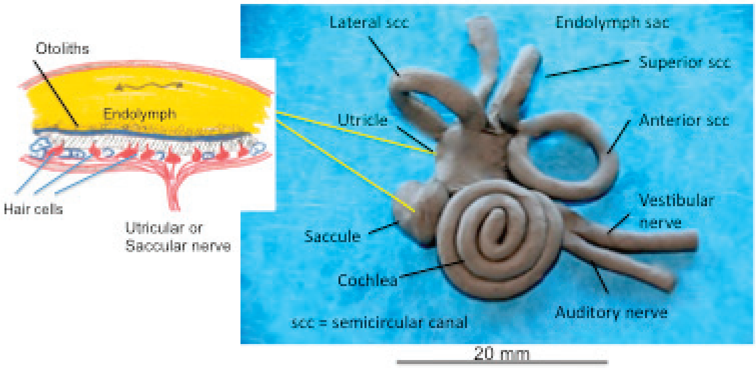

FIGURE F.1 Vestibular apparatus is about 20 mm in width and height. The semicircular canals sense angular motion, the two ball-like structures sense gravity and linear acceleration, and the spiral is the sound pressure transducer. The inset shows the otoliths embedded in a gel matrix whose motion stimulates the hair cells of the utricle and saccule. SOURCE: Courtesy of Thomas Budinger, University of California, Berkeley.

carbonate particles (10-100 μm) embedded in a gelatin platform move hair cells in response to gravity and linear motion in the utrical and saccule; and the motion of fluid in response to sound pressure waves stimulates hair cells lining the channels of the cochlea. The calcium carbonate particles (known as otoliths) in birds and fish contain some magnetite and thus are thought to play a role in navigation as well as balance (Harada et al., 2001). Definitive experiments that implicate the vestibular system in animal behavior showed no effects if the vestibular system is ablated (Carson et al., 2009).

There is no agreement regarding the predominant mechanism between Lorentz forces associated with movement of ions in a magnetic field (Roberts et al., 2011; Antunes et al., 2012), nerve conduction effects from changes in magnetic field (Glover et al., 2007), or magnetic field torque associated with susceptibility anisotropy of diamagnetic tissues (Budinger, 1981). Sensors in the utricule and saccule are hair cells driven by a small structure containing particles composed of mostly calcium carbonate (otoliths). Sensors in the semicircular canals are cells that distort from relative motion of fluid and the cell surface. Pressures of 2 mPa are sufficient to stimulate nystagmus (Kassemi et al., 2005).

Anticipated Human Responses to 20 T Magnet Exposures

The actual force on diamagnetic tissues of the body is dependent on field, field gradient, free space permeability, and susceptibility of the tissues. The susceptibility of tissues is in the range of that of diamagnetic water, ca. -10^{-6}, but some tissues such as those containing ferritin protein can have a paramagnetic susceptibility, which means that the forces on these tissues will be in the opposite direction to those of diamagnetic susceptibility (Schenck, 1996). The magnetization of tissues is given by $\chi B_0/m_0$, where χ is the susceptibility and B_0 is the magnetic field. The presence of heterogeneous susceptibility is manifest in the contrast in images that show the associated phase differences.

The fringe field of a 20 T magnet will have a product of field and field gradient of 17 T^2/m based on extrapolated values from measurements made for a 7 T fringe field as shown in Figure 2 of van Nierop et al. (2012). Our extrapolated values are 4.5 T/m and a field of 3.75 T at 0.5 m from the bore of 20 T magnet. We can compare this value to that at which rodents demonstrate avoidance on entering the 14.1 T magnet. From Figure 1 of Houpt et al. (2007), it was calculated that the field and gradient at the avoidance level were 2 T and 35 T/m, respectively, thus, the product is 70 T^2/m. This force threshold is much greater than that estimated for a 20 T fringe field, but within the bore of a 20 T magnet the gradients could be much greater depending on the magnet design. If the maximum gradient on entering the magnet is 15 T/m when the local field is 10 T, the value of field times field gradient will be 150 T^2/m. The dimensions T^2/m when divided by the permeability and modified by susceptibility of the specific tissue give the volume force in N/m^3.

Animal experiments as well as recent human subject exposures have shown the effects are temporary. But the neurological network of which the vestibular system is part has a tremendous plasticity, so that damage to the vestibular system might be hidden through adaptation. Animal exposure studies in addition to tissue exposure studies and mathematical simulations will be necessary in order to assure the safety of expected exposure periods. As already shown, pressure thresholds for activation of parts of the vestibular apparatus are in the range of 2 mPa, and adjacent tissues (e.g., ferritin-loaded brain tissue vs. normal tissue) are expected to have a 200-fold increase in susceptibility (extrapolated from Schenck, 1992).

Turning Torque on Macromolecules and Large Molecular Assemblages

In addition to high magnetic field effects from susceptibility differences between tissues, there is an important effect of high fields on molecules or tissue elements with large susceptibility differences between major and minor axes of molecular assemblages (e.g., retinal rods, chloroplasts, platelets). The energy is given by

$$W = \frac{V}{2} - \left(| \chi_r | + | \chi_i - \chi_r | \cos^2 [\theta] \right) | B^2 |$$

where V is the volume of the unit, χ_l and χ_r are the susceptibility for the long and radial directions, and θ is the angle between the radial axis and the B-field. It is well known that, under conditions of negligible viscosity, fields of 1 T will orient chloroplasts, blood platelets, retinal rods, and even large macromolecules. The potential for unwanted effects on molecular systems in animals and human beings requires investigation at fields of 20 T because the turning torque scales as B-field squared. The orientation effect on molecular assemblages and macromolecules has been demonstrated in studies of stimulating bone formation to grow in specified directions (Kotani et al., 2002). The origin of diamagnetic anisotropy in proteins and polypeptides is attributed to diamagnetic anisotropy of the planar peptide bonds (Worcester, 1978).

Lorentz Force Movement of Conducting Nerves

The Lorentz force, per unit volume, on conducting nerves in a magnetic field is given by

$$\mathrm{F} = J \times B$$

where J is the current density. The maximum displacement, as modeled by Roth and Baser (2009), is given by $(JB/4\mu)\ a^2 \ln(b/a)$, where the current density J is 10 A/m^2, the field is 20 T, and μ is the tissue shear modulus of 10 kPa. The nerve radius a is assumed to be 2 mm and that of the surrounding tissue return ion flow b is 25 mm. The calculated displacement is only 0.05 µm.

Effects of High Magnetic Fields on Nerve Conduction Speed

The Lorentz effect of force on moving ions in a magnetic field can slow nerve conduction velocity. The motion of sodium and potassium ions during nerve conduction can be pictured as small current loops along the axis of the conducting nerve fiber. If a field is applied at right angles to the nerve fiber, one can expect the ion current paths will be distorted. An ion of charge e in an electric field, E, and a magnetic field, B, will have forces $\mathrm{F_e} = \mathrm{eE}$ and $\mathrm{F_m} = e\mathrm{V_d B}$, respectively. Here, $\mathrm{V_d}$ is the drift velocity of the ions. Wikswo (1980) shows $\mathrm{V_d}$ is between 0.033 m/s and 6.6×10^{-5} m/s depending on the values chosen for estimation. This suggests that a 10 percent change in nerve conduction velocity will occur at 24 T. Verification of this can be done now at fields available at NHFML.

Cardiovascular Electrical Signal Artifacts

Electrocardiogram (ECG) signals at high field show artifacts associated with external wire conductors moving in the external field, and these temporal changes in recorded voltages are not associated with a physiological effect. There are two additional effects of importance as they do induce E-fields within the body that are proportional to field strength. With each heartbeat as much as about 70 ml of blood is ejected into the aorta with a cross section of 17 mm. The initial velocity is 0.3 m/s. In a static magnetic field the potential across the aorta is about 1 V (i.e., 20 T × 0.3 m/s × 0.17 m). This potential will be detected by the ECG leads and give a signal that will occur mostly at the T wave, but a complex wave form occurs due to the varying directions of blood flow through the chambers of the heart and main vessels of the thorax (Tenforde et al., 1983). A result is the magnetocardiogram.

Another time-varying signal is that associated with breathing, where now the induced voltage is proportional to the rate of change of area orthogonal to the field direction. At 20 T, breathing at 15 per minute and a chest expansion of 2 cm, this is only 1.5 mV ($3.14\ \mathrm{cm}^2/4\ \mathrm{s} \times 20\ \mathrm{T} \times 10^{-4}\mathrm{m}^2/\mathrm{cm}^2$). This potential will appear as a rise and fall of the ECG in synchrony with breathing. None of these effects is of physiological significance.

Magnetohydrodynamic Effects

A flowing conductor in a magnetic field will experience charge separation, and this E-field when acted upon by the magnetic field will result in a force counter to the flow of the fluid. Flowing mercury can be stopped by magnetic fields. The question arose years ago regarding the retarding force that might increase peripheral resistance, causing a rise in blood pressure if human subjects are exposed to high fields. Theoretical studies published before 1990 concluded the magnetohydrodynamic effect would be prohibitive. The correct theory for magnetohydrodynamic effects has shown that earlier literature did not take into account viscous forces and all of the induced magnetic field (Keltner et al., 1990). This theory and experimental work at 4.7 T showed the magnetohydrodynamic effect is not significant at physiological flows in the aorta where the largest effect is expected.

SPECIFIC ABSORBED POWER AND RAPIDLY CHANGING GRADIENTS

Major safety issues that underpin limiting guidelines for magnetic resonance imaging and spectroscopy of human subjects are the RF heating effects, whose metric is the specific absorbed power. A second limitation on the pulse sequences is the magnitude of induced electric fields from rapidly changing magnetic fields. Whereas the known thresholds from the experiences over the last 40 years are not expected to be exceeded at 20 T, these thresholds will limit the power density and therefore the depth of penetration at the higher proton frequencies required for 20 T. The physiological thresholds of nerve stimulation will limit the use of some desired pulse sequences.

Specific Absorbed Power

The oscillating magnetic fields for the radio-frequency pulses used in imaging and spectroscopy induce oscillating electric fields in accord with Faraday induction. The E field is proportional to the frequency and the conducting body loop. The average electric field is $E/\sqrt{2}$, so that the absorbed power, SAR, by a mass of tissue is as follows:

$$\mathrm{SAR} = |\mathrm{E}|^2\, \sigma/2\rho$$

where |E| is the magnitude of the E-field, σ is the conductivity, and ρ is the density.

An increase in field leads to an increase in the magnetic resonance frequency for a given spin. In turn the increase in frequency leads to an increase in induced E-field, and SAR is expected to increase with field. The conductivity of tissues also increases with frequency (a factor of 2 can be expected between 300 MHz (7 T) and 852 MHz (20 T) While this is the case for proton MRI, fMRI, and MRS, and will be the case for other spins, but these other spins (see Table 4.1 in Chapter 4) have frequency requirements many times lower than the resonant frequency of protons for a given field. The scientific community (e.g., Tang and Ibrahim, 2007) and regulatory advisors involved in safety are experienced with frequencies below 300 MHz and as one can see from Table 4.1, most of the nuclei comprising the human body have resonant frequencies below 300 MHz.

Induced E-Fields from Time-Varying Gradients

An E-field of 6 V/m induced by 60 T/s near a 30 cm diameter body part will cause a sensation of an electric shock (Budinger et al., 1991). The governing physics is the Maxwell-Faraday equation, which equates the electric field to the diameter of a loop defining the body being exposed to a rapid change in the magnetic field.

$$\text{Volt/meter} = -\, dB/dt \times r/2$$

where dB/dt is the rate of the magnetic field gradient change associated with MRI pulse sequences and r is the object radius.

Visual sensations known as magnetophosphenes can be induced at about 2 T/s. This phenomenon has been studied since visual phosphenes were noted by d'Arsonval (1896), who moved the magnetic field source near the eyes. The mechanism is not as simple as suggested by equation (Carson et al., 2009). Because the threshold for visual sensations is dependent on reaching a field of at least 10 mT with a rise time of approximately 2 ms and a repetition rate less than 30 per second (Lövsund et al., 1980). These dependencies can be understood if the mechanism is a mechanical distortion of retinal components from susceptibility anisotropy. Direct electric voltage application to the head can induce phosphenes, but the current densities of 17 μA/cm^2 are much greater than the 2 μA/cm^2 that is inferred from magnetic field changes. The emphasis on the mechanisms for phosphene observations is relevant to understanding other sensory phenomena that might manifest at 20 T, where larger fringe fields and B-fields are expected than experienced in the last 40 years of investigations.

New problems are not expected to arise with pulse sequences needed for imaging at high fields. Power requirements for RF transmit and receive coils and requirements for the gradient coils involved in applications at 20 T will not present serious engineering problems if the frequencies are restricted to less than 400 MHz. Going beyond low gamma spins to proton imaging and spectroscopy at 20 T, 852 MHz, will be a challenge.

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Short Description of Large Research Facilities for High Magnetic Fields

The large research facilities described in this appendix are limited to facilities that provide magnetic fields that are substantially higher than available in common well-equipped laboratories. Technically, the boundary between small laboratory magnets and large research facilities is drawn as follows. For dc fields (constant field at least during several minutes), available fields must be higher than 21 T, that is, beyond values reached for commercially available magnets, while pulsed fields must be operated with capacitor banks having stored energies of more than 2 MJ. Lower stored energies allowing shorter pulses or lower fields are also affordable for well-equipped research groups. For dc fields >21 T and up to 45 T, large dc power supplies and cooling systems (>20 MW) are necessary. Such dc field facilities are expensive in both investment and operational costs (electricity, infrastructure, and personnel). Pulsed fields with longer pulses, larger-bore magnets, and higher maximum fields (up to 100 T is possible) require large energy storage (much higher than >2 MJ), and such installations require similar investments, running budgets, and costly safety precautions (limited access and reinforced cells and building) to be operated reliably. This definition excludes all NMR facilities (with the exception of the 1 GHz, 23.5 T one at the Centre de RMN à Très Hauts Champs in Lyon, France, installed July 2009).

Due to the size, the necessary investments, and the operational costs, there are only a few large-scale facilities for high magnetic fields in the world. Most of them function as a user facility hosting external guest researchers. They receive central and longer-term (as opposed to local and project-related) funding to fulfill their role. Practically all facilities have a selection procedure through an external project review panel for users to obtain access. Selection criteria are the scientific merit (innovation and excellence) of the project and the proven need to use such unique resources for the experiments planned.

CHINA

Hefei

The Chinese High Magnetic Field Laboratory (CHMFL) of the Chinese Academy of Sciences was founded on April 30, 2008. It is located in Hefei, the capital city of Anhui Province. CHMFL was founded to provide first-class, steady high-magnetic-field facilities to researchers and to better develop high-magnetic-field science. The Steady High Magnetic Field Facility (SHMFF) is the steady field component of the National Key Science and Technology Basic Establishment Project for high-magnetic-field facilities and is funded by the National Development and Reform Commission. The principal objectives of SHMFF are to build a 40 T hybrid magnet, a series of high-power resistive magnets for multiple uses, including a resistive high-homogeneity magnet for NMR, and superconducting magnets. A 28 MW high-stability power supply and a deionized water cooling system have been built for the resistive magnets. Scientific experimental measurement systems of many kinds will be provided to researchers. A local research program is now being set up that will cover the most promising research areas. All hardware and buildings have been acquired or built, and the laboratory was expected to be operational by the end of 2012.

Wuhan

The Wuhan High Magnetic Field Center (WHMFC) was established in 2005 for the development of pulsed magnets and their application to scientific research. The pulsed high-magnetic-field facility is the first major science and technology infrastructure project that will be built by the Huazhong University of Science and Technology under the direct leadership of the Ministry of Education as part of the National Key Science and Technology Basic Establishment Project for high magnetic field facilities. The total investment for the pulsed magnetic field facility is ¥180 million. It is planned to open the new facility with its own building for external users in 2012. A 12 MJ capacitor bank and a 100 MJ/100 MVA pulse generator power supply will be developed and built in order to generate pulsed magnetic fields from 50 to 80 T with pulse lasting from 15 ms to 1,000 ms. In seven experimental stations that can be used in parallel, special equipment will be provided such as low-temperature cryostats(from 30 mK to 300 K), high-pressure cells, and various lasers with associated optical systems. The facility will provide high-level research opportunities in the areas of physics, chemistry, life science, and materials science. Experienced in-house staff will provide the necessary assistance to researchers from China and all over the world. In addition, the development of new technology for electromagnetic equipment will be further pursued.

JAPAN

Kashiwa

The International MegaGauss Science Laboratory (IMGSL) of the Institute for Solid State Physics at the University of Tokyo was started in 1972. Researchers at MGL study properties of matter in very high magnetic fields—that is, at several hundred tesla—in a very short time. All external users are required to collaborate with staff researchers and to obtain the approval of the facility's directors. The electromagnetic flux compression method has been improved to establish the world's highest indoor field of about 750 T, but at the expense of destroying the sample and its environment. Fields up to 300 T can be generated with single-turn coils where the coil is destroyed but the sample and cryostat are usually conserved. In addition to the destructive methods (where either only the coil or, in other cases, the coil and the sample are destroyed), a new project aiming at the nondestructive generation of both long pulsed and 100 T fields is progressing along the lines as other pulsed field laboratories. Many kinds of coils have been developed, not only for the highest field but also for various experiments.

IMGSL has five separate measuring stations with advanced infrastructure, such as optical multichannel analyzers, far-infrared optics, and helium-3 refrigerators. Activities include study of the origin of the magnetism in magnetic materials and the mechanisms underlying magnetically induced properties. Interesting phenomena observed at high fields and high pressures are studied using cyclotron resonance, far-infrared and millimeter-wave spectroscopy, magneto-optical spectroscopy, Faraday rotation, magnetization, and transport measurements. Materials under investigation include semiconductors, semimetals, superconductors, organic conductors, magnetic materials, and low-dimensional spin systems.

Sendai

The High Field Laboratory for Superconducting Materials at the Institute for Materials Research at Tohoku University was established in April 1981 to provide facilities for research into superconducting materials for the construction of the superconducting magnets needed for fusion reactors. The laboratory has a hybrid magnet of 31 T with an 8 MW, 32 mm resistive insert, and developed the first cryogen-free hybrid magnet generating 27.5 T. The laboratory has developed several superconducting cryogen-free magnets (up to 20 T). Construction for a similar 25 T magnet is in progress. Cooperative research programs are under way nationwide. Basic research and high-temperature superconductor development are the most important research areas at this laboratory.

Tsukuba

The Tsukuba Magnet Laboratory (TML) is located at the National Institute for Materials Science. TML has been a user facility since 1998, and it provides domestic and international users access to 17 different magnet systems, including resistive and hybrid magnets operated with a 15 MW power converter and fields up to 37.9 T; 30 mm (hybrid), pulsed magnets 30 to 50 T; and NMR systems up to 930 MHz. There is a vigorous research program in magnet development for 1 GHz NMR. TML is also a base for the international standardization of superconducting materials; a Cu-Ag wire codeveloped at TML has held the world record for nondestructive pulsed magnetic field strength. The in-house research program at TML includes a variety of subjects, such as NMR, magnetic separation, protein crystal growth, and studies on chemical and metallurgical reactions in high fields. Outside users come primarily from universities, and they prefer the high-field superconducting magnets, closely followed by the high-field resistive magnets.

EUROPE

In Europe the four main laboratories for high magnetic fields (Grenoble and Nijmegen for dc fields and Toulouse and Dresden for pulsed fields) have in the past decade developed a very strong cooperation. In the European Union programs EuroMagNET I (2003-2008) and EuroMagNET II (2008-2012), a common selection procedure with a single selection committee for all four labs was established. Furthermore, research topics of common interest (nanoprobing, high-field NMR, magnet technology, IR spectroscopy in pulsed fields, soft matter research) have been worked upon jointly. Magnet technology relies for the moment on strategies developed by the laboratories individually in the past, but coordination is pursued actively to ensure an efficient use of available resources. A common user committee has been formed, several topical workshops are being organized yearly, and biyearly a school has been held for young scientists working in high magnetic fields. In 2008 the laboratories were selected as a European priority on the European Strategic Forum for Research Infrastructures (ESFRI) and it was proposed the four establishments should become a single laboratory (European Magnetic Field Laboratory, or EMFL). As a consequence of this, a structure for the new EMFL has been developed as a multisite research facility under a common direction. In the process, major new investments have been made in Toulouse, Grenoble, Dresden, and Nijmegen to strengthen the EMFL. EMFL is the European counterpart to the very successful NHMFL in the United States.

The Laboratoire National des Champs Magnétiques Intenses (France)

The Laboratoire National des Champs Magnétiques Intenses (LNCMI), with a dc facility in Grenoble and a pulsed field facility in Toulouse, is a French national laboratory operated by the Centre National de la Recherche Scientifique (CNRS) as a user facility. Both sites started their activities in the 1960s and in 2009 the two sites were united in a single structure. The three missions of the LNCMI are (1) to serve as a user facility for the French and European scientific communities; (2) to develop techniques for high magnetic field production; and (3) to develop innovative research activities in high magnetic fields, which involve a permanent staff of 100 scientists and engineers. Around 200 external users come to the LNCMI yearly. The LNCMI is part of the French large research facility roadmap and collaborates closely with other large facilities to combine high magnetic fields with X-ray, neutron, and intense laser sources.

Grenoble Site (LNCMI-G)

The LNCMI-G operates several resistive magnets that produce dc magnetic fields up to 35 T with a 34 mm bore, and a new 42-T hybrid magnet that is under construction, using a 24 MW power supply. Primary research activities include work with two-dimensional electron systems, nanostructures, bulk semiconductors, magneto-science, and nuclear and paramagnetic resonance on magnetic systems.

Toulouse Site (LNCMI-T)

The LNCMI-T is a European pioneer for pulsed magnetic fields, offering non-destructive field strengths up to 82 T, and longer pulsed fields at a lower strengths, with pulse durations up to 0.2 s. Semi-destructive fields up to 180 T are also provided. The primary research interests are high-T_c superconductors, organic conductors, quantum magnetism, and low-dimensional (semi)conductors. The LNCMI-T has 10 pulsed magnet sites ranging in field strength from 38 to 82 T; its high-voltage generator can store 14 MJ at 24 kV. The laboratory is currently building an extension to house new magnets.

Dresden (Germany)

The HLD (Hochfeld-Magnetlabor Dresden) is part of the Helmholtz-Zentrum Dresden-Rossendorf and in 2006 the building and the construction of the new laboratory were finished, making the HLD now the largest pulsed field laboratory in Europe, with five measuring stations for pulsed magnets. The laboratory features an unprecedented 50 MJ capacitor bank power supply that energizes its magnets with a record field of 94.2 T, achieved in early 2012. Presently the laboratory is involved in a further extension, including additional magnet sites and a separate capacitor bank. The main research topics are superconductivity, highly correlated electron systems, semiconductors, and magnetism. HLD has rapidly grown out to a popular user facility with an increasing user demand every year. The HLD facility is coupled to an adjacent free-electron laser facility (ELBE) generating radiation in the near- and mid-infrared that will offer unique high-resolution capabilities for spectroscopy that greatly increase the science potential of both facilities.

Nijmegen (Netherlands)

The High Field Magnet Laboratory (HMFL) at Radboud University Nijmegen reopened in June 2003 after a substantial upgrade to provide continuous fields. From 2011 the laboratory is operated jointly by the Radboud University Nijmegen and the Dutch Foundation for Fundamental Research on Matter (FOM) and has had an increased running budget. In 2012 it was selected as a Dutch priority on the Roadmap for Large Research Infrastructures and has received much additional funding. A key feature of the 2003 upgrade was the construction of a 20 MW power supply and the construction of a dedicated new building that houses the magnets and the auxiliary experimental equipment. The laboratory has four resistive magnets, with two providing fields of 33 T. The HFML is constructing a 45 T hybrid magnet (2016) and will commission two 38 T resistive magnets in 2013. It serves as a European user facility and receives yearly some 80 researchers from external institutions, a number steadily increasing in the last years. The local research program centers on low-dimensional systems and semiconductors, strongly correlated electron systems, and soft matter. Adjacent to the HFML the free electron lasers (FLARE, FELIX, and FELICE) housed in a separate building provide very intense light (more than 100 W in quasi-continuous wave operation or kilojoule pulses in microsecond bursts) in the infrared to far-infrared region (from 10 μm to 2 mm) to the HFML magnets. This frequency range covers the major excitations (electron spin resonances, cyclotron resonances, rotational and vibrational excitations, superconducting gaps, and so on) in solids and molecules up to 45 T.

UNITED STATES

In the United States the NHMFL is the single institution that coordinates all U.S. activities in high magnetic fields at the different sites. The NHMFL is the main player in the world in the area of high magnetic fields. NHMFL has played a very positive role in stimulating research in high magnetic fields on other continents and has close ties to practically all the laboratories mentioned in this survey. A very concrete exchange of information, even of entire magnet systems (or parts of one), has taken place with the dc laboratories of Tsukuba, Nijmegen, and Grenoble, and magnet builders from these sites are in continuous close contact related to new magnet systems and design reviews, and also to very practical matters such as identifying vendors of parts in the different countries.

Los Alamos, New Mexico

The Pulsed Field Facility at Los Alamos National Laboratory (LANL) is one of the three campuses of the NHMFL, the other two being at Florida State University in Tallahassee, Florida (continuous fields, magnetic resonance, and general headquarters), and the University of Florida in Gainesville, Florida (ultralow temperatures at high magnetic fields). The NHMFL is sponsored primarily by the National Science Foundation, Division of Materials Research, with additional support from the State of Florida and the U.S. Department of Energy. The Pulsed Field Facility is the only facility of its kind in the country because of its 1.4 GW motor generator. The facility operates both short- and long-pulse magnets and a broad library of programmable waveform shapes in between; a record 80 T was achieved in 1999. A unique 100 T nondestructive pulsed hybrid magnet was realized and successfully tested at a record field of 100.4 T in 2012. Users also have access to the high fields generated using destructive pulsed magnets. Supporting instrumentation at the LANL facility is also extensive and state of the art.

Tallahassee and Gainesville, Florida

The NHMFL was established in 1990 with support from the National Science Foundation and the State of Florida and is a collaboration between the University of Florida, Florida State University, and LANL. The laboratories in Florida provide users access to continuous field magnets, and that facility is the world's largest magnet laboratory. NHMFL developed and operates the strongest hybrid magnet in the world (45 T, 32 mm) and has a strong development program for resistive magnets (presently up to 35 T). It also recently installed a powerful radial access magnet. To provide the community with NMR-grade resistive magnets, highly homogeneous magnets have been built, with a highly homogeneous, series-connected hybrid under construction. In addition to an active research program in static high magnetic fields, there is an extensive program in NMR, ion cyclotron resonance (ICR), electron magnetic resonance (EMR), and other advanced high-field magnetic resonance research. The laboratory has a very strong and successful user program and receives visitors from all over the world. In recent years the electrical and cooling installation has been upgraded, and the laboratory can now provide 2 × 28 MW to the magnets.

Tallahassee has a very strong magnet technology program that develops special magnets for external facilities (split coil, three-dimensional rotating field, a 25 T hybrid for the Helmholtz Zentrum Berlin to work with a neutron source) and new magnets for its own facility (high-homogeneity magnets and series-connected hybrid magnets). Contrary to the other dc laboratories, which concentrate on their core activities of providing the highest possible fields only and leave lower fields to be provided by commercially available magnets, Tallahassee has defined its mission more broadly, as a magnet center promoting high-field research in all areas. It, therefore, has (1) a Center for Interdisciplinary Magnetic Resonance, (2) a center on ion cyclotron resonance, and (3) geochemistry facilities located on the main campus in Tallahassee. The high B/T (magnetic field/temperature) and the magnetic resonance/imaging spectroscopy (using commercially available 20 T magnets) facilities are located in Gainesville.

The information was distilled from a combination of personal communication with facility staff, information from Web pages, and asking the facilities for information.

TABLE G.1 High Magnetic Field Facilities in the World

Location	Facility	Magnets Bore Size, Pulse Length,[a] (Type) [future magnet]	Energy/Power Source	Additional Details
CHINA				
Hefei	Chinese High Magnetic Field Laboratory (CHMFL)	27 T, 32 mm 25 T, 50 mm 20 T, 200 mm [36 T, 32mm] [43 T, 32 mm (hybrid), 2015]	28 MW	Magnet hours/shots starting in 2013.
Wuhan	Wuhan High Magnetic Field Center (WHMFC)	50–75 T	1 MJ [+12 MJ], 25 kV; 100 MVA generator 100 MJ pulse	Magnet hours/shots starting in 2012.
JAPAN				
Kashiwa	International MegaGauss Science Laboratory (IMGSL)	50 T, 22 mm, 50 ms 50 T, 20 mm, 20 ms 50 T, 20 mm, 18 ms		
Sendai	High Field Laboratory for Superconducting Materials (HFLSM)	20 T, 52 mm (resistive) 31 T, 32 mm (hybrid) [25 T, 52 mm (cryocooled superconductor)]	8 MW	
Tsukuba	Tskuba Magnet Laboratory (TML)	33 T, 32 mm (resistive) 38 T, 32 mm (hybrid)	15 MW	
FRANCE				
Grenoble	Laboratoire National des Champs Magnétiques Intenses (LNCMI-G)	35 T, 34 mm (resistive) 3 x 30 T, 34 mm 30 T, 55 mm [42 T, 34 mm (hybrid)]	24 MW	
Toulouse	Laboratoire National des Champs Magnétiques Intenses (LNCMI-T)	82 T, 15 mm, 10 ms 61 T, 11 mm, 150 ms 58 T, 19 mm, 282 ms 45 T, 120 mm, 500 ms	14 MJ	

TABLE G.1 Continued

Location	Facility	Magnets Bore Size, Pulse Length,[a] (Type) [future magnet]	Energy/Power Source	Additional Details
GERMANY				
Dresden	Hochfeld-Magnetlabor (HLD)	50 T, 24 mm, 75 ms 60 T, 20 mm, 25 ms 70 T, 24 mm, 150 ms 94 T, 16 mm, 10 ms 60 T, 40 mm, 1000 ms [100 T, 10 mm, 10 ms]	50 MJ [14 MJ]	
NETHERLANDS				
Nijmegen	High Field Magnet Laboratory (HFML)	2 x 33 T, 32 mm 2 x 32 T, 50 mm [45 T – 32 mm (hybrid), 2016] [38 T, 32 mm, 2012]	20 MW [22 MW]	Number of magnet hours/shots: 1,600 h yearly; 2,400 h >2014. Number of projects: 60 yearly; 100 >2014. Number of external visitors: 90 yearly; 140 >2014.
UNITED STATES				
Los Alamos, New Mexico	National High Magnetic Field Laboratory (NHMFL)	60 T, 15 mm, 35 ms 50 T, 15 mm, 350 ms 100 T, 10 mm, 10 ms	1.4 GW generator, 5 MJ (?)	
Tallahassee and Gainesville, Florida	National High Magnetic Field Laboratory(NHMFL)	33 T, 32 mm (resistive) 45 T, 32 mm (hybrid)	2 × 28 MW	Magnet hours/shots: 6,000 h yearly. Number of projects: 200 yearly. Number of external visitors : 300 yearly.

[a] If applicable.

SOURCE: Information compiled by committee from publicly available information and private conversations with staff of facilities.