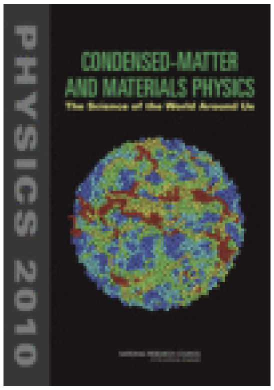
Free Executive Summary



Condensed-Matter and Materials Physics: The Science of the World Around Us

Committee on CMMP 2010, Solid State Sciences Committee, National Research Council

ISBN: 978-0-309-10969-7, 286 pages, 7 x 10, paperback (2007)

The development of transistors, the integrated circuit, liquid-crystal displays, and even DVD players can be traced back to fundamental research pioneered in the field of condensed-matter and materials physics (CMPP). The United States has been a leader in the field, but that status is now in jeopardy. Condensed-Matter and Materials Physics, part of the Physics 2010 decadal survey project, assesses the present state of the field in the United States, examines possible directions for the 21st century, offers a set of scientific challenges for American researchers to tackle, and makes recommendations for effective spending of federal funds. This book maintains that the field of CMPP is certain to be principle to both scientific and economic advances over the next decade and the lack of an achievable plan would leave the United States behind. This book's discussion of the intellectual and technological challenges of the coming decade centers around six grand challenges concerning energy demand, the physics of life, information technology, nanotechnology, complex phenomena, and behavior far from equilibrium. Policy makers, university administrators, industry research and development executives dependent upon developments in CMPP, and scientists working in the field will find this book of interest.

Summary

Condensed-matter and materials physics (CMMP) is the science of the material world around us. Long ago, curiosity about the natural world led to questions about condensed-matter systems, such as water, snow, ice, and rocks, and how these respond to light, heat, and mechanical forces. This thirst for fundamental understanding has been inextricably tied to the desire to manipulate nature by harnessing its properties or creating new materials to serve human needs. The inherent intertwining of pure and applied research defines and enriches the CMMP enterprise to this day. This report surveys the field of CMMP during the past decade, including the state of federal and private support of CMMP within the United States, and looks ahead to the intellectual and technological challenges of the coming decade.

The 20th century was a period of remarkable fundamental and technological progress in CMMP. Continued federal and private investments led to considerable advances in the basic understanding of condensed-matter phenomena. Years and often decades later, these advances led in turn to the invention of devices that now form the basis of much of our technological society, including the transistor, the integrated circuit, the laser, magnetic resonance imaging, liquid-crystal displays, and, more recently, high-efficiency solid-state lighting. U.S. leadership in nurturing invention, from initial scientific discoveries to commercial technological products, has contributed significantly to this nation's economic strength. In particular, the industrial development of many of these technologies has led to current U.S. leadership in computing and global communications. Although the relationship is difficult to measure quantitatively, there is a consensus among economists that

advances in technology have been the main driver of economic growth over the past 60 years.

In this report, the Committee on CMMP 2010 looks ahead to ask: What are the prospects for CMMP in the early part of the 21st century? One of the main findings of the report is the identification of six grand challenge areas in which CMMP research is poised to have a large and enduring impact in the next decade. These research areas reflect both fundamental intellectual challenges and societal challenges, in keeping with CMMP's dual pure and applied nature. While CMMP has been developing many of the key tools and is central to addressing many of these challenge areas, meeting all of the challenges successfully will require the combined efforts of researchers from many disciplines in order to succeed. The broad spectrum of research covered by CMMP includes many important problems beyond those identified in this report, and areas currently not foreseen are certain to arise from discoveries in the next decade. Nonetheless, as CMMP moves into the next decade, the intellectual vitality and breadth of the field are captured to a considerable extent in the following challenges:

- How do complex phenomena emerge from simple ingredients?
- How will the energy demands of future generations be met?
- What is the physics of life?
- What happens far from equilibrium and why?
- What new discoveries await us in the nanoworld?
- How will the information technology revolution be extended?

U.S. CMMP researchers will not be alone in tackling these challenges. The United States remains a leader in CMMP worldwide, but its premier position is in jeopardy. There are several contributing factors, which are detailed in Chapters 9 and 10 of this report:

- Other parts of the world are investing heavily in research and development (R&D) in CMMP.
- In the United States, industrial laboratories are now focused on much-shorter-term R&D goals, with little emphasis on fundamental, basic research.
- Federal research funding for CMMP has been approximately flat in the United States in inflation-adjusted dollars over the past decade.

The consequences of the decline of industrial involvement and nearly flat federal funding for CMMP are serious indeed:

- Many of the key technological innovations responsible for U.S. leadership in communications and computing were shepherded from fundamental research ideas to marketable products at the once-great industrial laboratories. The replacement of these industrial laboratories as sources of invention is a challenge.

- Many of today's leaders at the nation's universities, national laboratories, and other institutions came from industrial laboratories where they were able to conduct high-risk fundamental research with relatively little funding pressure. The opportunities for cooperation, leadership, and creativity experienced by researchers in these settings have greatly benefited the overall scientific enterprise. Currently, very few such research environments are available to young researchers to nurture their professional growth.
- At the National Science Foundation (NSF), a major supporter of university-based CMMP research, the chances of a grant application in CMMP being funded have dropped dramatically in the past 5 years, from 38 percent to 22 percent.[1] These low proposal-success rates greatly amplify the hidden "overhead" of writing and reviewing proposals and disrupt the continuity of scientific research. The corresponding numbers for new investigators show a drop from 28 percent to 12 percent; this lack of access to research funding severely impedes the establishment of viable research programs before tenure evaluation. These trends must be reversed.
- Strong support for principal investigators is particularly important for CMMP research, a field in which most investigators work in individual research groups or in small teams. Strong, healthy individual-investigator research programs are needed for effective, evolving collaborative efforts and for transitioning in and out of larger collective research activities.
- During the past 5 years, the size of grants increased only 15 percent, while the cost of supporting students increased by 25 percent, in as-spent dollars. Thus, the buying power of each dollar is also a concern.
- Over the past decade, the number of publications contributed by U.S. authors remained essentially flat in two major journals reporting CMMP research results worldwide (*Physical Review B* and *Physical Review E*), whereas foreign contributions nearly doubled in the same time frame.

RECOMMENDATIONS

The Committee on CMMP 2010 bases the following recommendations on its assessment regarding the most efficient use of resources and projected growth in funding for the field of 7 percent per year over the next 10 years. This rate of growth reflects levels recommended in the President's American Competitiveness

[1]These statistics are based on data gathered by the committee from the federal agencies and are discussed in further detail in Chapter 10.

Initiative, which seeks a doubling of the physical science research budget of the NSF, the Department of Energy (DOE), and the National Institute of Standards and Technology (NIST) in 10 years. In some cases, improved research quality and efficiency can be obtained through changes in the structure of funding. In other cases, additional funding is necessary in order to retain current expertise and to nurture emerging fields of science. Some new facilities are also required to advance science and to keep the U.S. research effort at the forefront. The committee's most important recommendations are presented below. More recommendations are found in Chapters 8 through 11 of the report.

Recommendation 1: Basic research in CMMP contributes to the economic strength and leadership of the United States. The following three recommendations to DOE and NSF (found in Chapter 10) are aimed at ensuring scientific progress toward meeting the challenges identified in this report and ensuring continued technological innovation to benefit the United States:

- Strong support should be maintained for individual and small groups of investigators, which are historically the primary source of innovation in CMMP. The ratio of support for individual and small groups of investigators relative to support for centers and facilities should not decline in the next decade.
- The average success rates for the funding of proposals should be increased to more than 30 percent over the next 5 years in order to give junior scientists the opportunity to obtain research results before the tenure decision and to enable currently funded researchers to maintain continuity in their research programs.
- The size of grants to individual and small groups of investigators should be increased to maintain the buying power of the average grant and to retain scientific talent in the United States.

Recommendation 2 (from Chapter 8): Funding agencies should develop more-effective approaches to nurturing emerging interdisciplinary areas for which no established reviewer base now exists. The CMMP community should organize sessions at national meetings to engage funding agencies and the community in a dialogue on best practices for proposal review and for the support of nontraditional, rapidly evolving areas.

Recommendation 3 (from Chapter 8): Outreach, K-12, and undergraduate science education initiatives should be supported through supplemental or stand-alone grants administered by separate NSF and DOE programs, instead of through individual research grant awards. In the present system, the quality of outreach programs is a criterion in the evaluation of NSF/Division of Materials Research grants. The present approach confuses two conceptually distinct goals to the point that neither is optimally served. The funding agencies and the research community both want outreach programs to succeed, and they should confer to determine how best to implement an effort to achieve that goal.

Recommendation 4 (from Chapter 10): The CMMP community should work to improve the representation of women and underrepresented minorities in CMMP through mentoring; providing flexible working conditions, day-care opportunities, and viable career paths; and developing outreach programs targeted to students and the public and aimed at increasing the numbers of prospective researchers.

Recommendation 5 (from Chapter 10): The Office of Science and Technology Policy (OSTP) should convene a study with participation from DOE, the Department of Defense, NSF, NIST, the physics community, and U.S. corporations to evaluate the performance of research and development activities that might replace the basic science previously done by the large industrial laboratories and the contributions that those laboratories made to the training of future scientific leaders and educators. This next decade will involve a series of new approaches to long-term R&D designed to recapture the ability to work on large difficult projects based on fundamental CMMP research. Such an evaluation should be an ongoing activity of OSTP since it may be several years before the performance of these activities can be adequately evaluated.

Recommendation 6 (from Chapter 11): DOE and NSF should develop distributed national facilities in support of the design, discovery, and growth of new materials for both fundamental and applied CMMP research.[2]

Recommendation 7: State-of-the-art instrumentation and facilities are critical to CMMP and will be even more critical during the next decade. The committee's top-priority recommendations for instrumentation and facilities (all taken from Chapter 11) follow below. The committee also recommends action on the priorities for mid-scale instrumentation identified in a recent National Research Council (NRC) report.[3] Further recommendations on light sources, neutron sources, electron microscopy, magnetic field facilities, and nanocenters are offered in Chapter 11.

[2]A current National Research Council study, "Assessment of and Outlook for New Materials Synthesis and Crystal Growth," will make detailed recommendations on how best to support this need. The report is expected to be released in the summer of 2008.

[3]National Research Council, *Midsize Facilities: The Infrastructure for Materials Research*, Washington, D.C.: The National Academies Press, 2006.

- DOE and NSF, partnering with the National Institutes of Health and NIST, should create a consortium[4] focused on research and development needs required for next-generation light sources. The consortium, with an independent chairperson, should include stakeholders from universities, industry, and government (both laboratories and agencies). The consortium should formulate a light source technology roadmap and make recommendations on the research and development needed to reach milestones on the roadmap for a new generation of light sources, such as seeded x-ray free-electron lasers, energy-recovery linear-accelerator-driven devices, and other promising concepts. The consortium should also take into account cost containment and the internationalization of research facilities. The sponsoring agencies of the consortium should fund the R&D needed to reach the milestones on the roadmap.
- DOE should complete the instrument suite for the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, together with provision of state-of-the-art ancillary equipment for these instruments, in order to gain the maximum benefit from the recent investment in the SNS.
- DOE and NSF should support the CMMP community's needs for electron microscopy instrumentation at universities on a competitive basis. Cutting-edge electron microscopy technique development (such as the DOE TEAM [Transmission Electron Aberration-corrected Microscope] project) should be continued in order to fully reestablish U.S. competitiveness in developing the next generation of electron microscopes.
- NSF should continue the support of the National High Magnetic Field Laboratory and high-magnetic-field instrumentation development following the priorities recommended by the NRC report *Opportunities in High Magnetic Field Science*.[5]

Without strong support for basic research, U.S. leadership in CMMP is unlikely to survive. Such a loss could cause the United States to miss critical opportunities in growing new markets and could significantly hamper U.S. economic innovation. The recommendations of the Committee on CMMP 2010 focus on ensuring U.S. leadership in this intellectually exciting field that is technologically and economically vital to the nation.

[4]The committee used the term "consortium" in the sense of a partnership among the stakeholders described in the recommendation for developing a light source technology roadmap. The committee expects that the "consortium" will follow federal rules for providing advice to federal agencies.

[5]National Research Council, *Opportunities in High Magnetic Field Science*, Washington, D.C.: The National Academies Press, 2005.

CONDENSED-MATTER AND MATERIALS PHYSICS

The Science of the World Around Us

Committee on CMMP 2010

Solid State Sciences Committee

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study is based on work supported by Contract No. DE-FG02-05ER46206 between the National Academy of Sciences and the Department of Energy and Grant No. DMR-0525628 between the National Academy of Sciences and the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Library of Congress Cataloging-in-Publication Data

National Research Council (U.S.). Board on Physics and Astronomy. Committee on CMMP 2010.
Condensed-matter and materials physics : the science of the world around us / Committee on CMMP 2010, Board on Physics and Astronomy, Division on Engineering and Physical Sciences.
p. cm.
Includes bibliographical references.
ISBN 978-0-309-10969-7 (pbk.) — ISBN 978-0-309-10970-3 (pdf) 1. Condensed matter—Research—United States. 2. Power resources—Research—United States. 3. Materials—Research—United States. 4. Technological innovations—United States—Forecasting. I. Title.
QC173.456.N38 2007
530.4′1—dc22
2007041250

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu; and the Board on Physics and Astronomy, National Research Council, 500 Fifth Street, N.W., Washington, DC 20001; Internet, http://www.national-academies.org/bpa.

Cover: Correlated motion of densely packed, air-driven steel spheres showing that driven granular systems near a jamming transition behave like supercooled liquids near a glass transition. Colors indicate mobility (red = high, blue = low) and arrows show direction of motion of highly mobile spheres. Courtesy of A.S. Keys, University of Michigan; A. Abate, University of Pennsylvania; S.C. Glotzer, University of Michigan; and D.J. Durian, University of Pennsylvania.

Printed in the United States of America

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[1]Laura Garwin resigned from the committee in October 2006.
[2]Frances Hellman resigned from the committee in September 2006.

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Preface

The National Research Council (NRC) of the National Academies convened the Committee on CMMP 2010 to study the opportunities and challenges in condensed-matter and materials physics (CMMP) in the next decade. The Solid State Sciences Committee (SSSC) of the NRC's Board on Physics and Astronomy developed the charge for this study in consultation with the study's sponsors at the Department of Energy and the National Science Foundation. The Committee on CMMP 2010 was charged to identify recent accomplishments, compelling scientific questions, and new opportunities in the field; to identify CMMP's potential future impact on other scientific fields; to consider how CMMP contributes to meeting national societal needs; to identify, discuss, and suggest priorities for the construction, purchase, and operation of tools and facilities; to examine the structure and level of the current research effort and funding for research; and to make recommendations on how to realize the full potential of CMMP research. The complete charge is presented in Appendix A. The report is part of the ongoing Physics 2010 survey, the latest decadal assessment of and future outlook for the field of physics conducted under the auspices of the Board on Physics and Astronomy.

In preparing for the decadal survey of CMMP, the SSSC called on the community for input on opportunities and challenges in the field. This input was compiled and presented to the Committee on CMMP 2010 at its first meeting, in February 2006. In addition, the committee received direct input from the community at five town meetings held at professional society meetings—the March (2006) meeting of the American Physical Society in Baltimore, Maryland; the spring meeting (March 2006) of the American Chemical Society in Atlanta, Georgia; the spring meeting

(April 2006) of the Materials Research Society in San Francisco, California; the fall meeting (November 2006) of the Materials Research Society in Boston, Massachusetts; and the March (2007) meeting of the American Physical Society in Denver, Colorado. The committee thanks the professional societies for their support and encouragement in helping to arrange these town meetings. The committee also solicited community input through nine focus groups at universities and national laboratories, each with an attendance of between 10 and 15 researchers. The committee thanks the hosts at these institutions for arranging these important sessions, at which the discussions were lively and enlightening. The committee also solicited input through a public Web site. The comments supplied by the CMMP community through these venues provided extremely valuable primary input to the committee.

The committee that prepared this report is composed of experts from many different areas of CMMP research, prominent scientists from outside the field, and leaders from industry (see Appendix D for biographical sketches of the committee members). The committee met in person four times (see Appendix B) to address its charge, forming subcommittees to study different aspects in greater depth. The committee thanks the speakers who made formal presentations at its meetings; those presentations and the ensuing discussions strongly informed the committee's deliberations.

The federal agencies that fund CMMP research in the United States also provided input to the committee, through their direct testimony at committee meetings and their written responses to requests for information on funding trends and other statistical data. These data are summarized in Chapter 10 of the report. The committee is also grateful to the staffs at the Office of Science and Technology Policy and the Office of Management and Budget for their input on connections between CMMP and national science policy.

In September 2006, the committee released a short interim report that summarized important opportunities and challenges for CMMP research in the coming decade.[1] That report was used as a basis for subsequent discussion with the CMMP community at town meetings and focus groups. This, the committee's final report, expands on these themes, discusses them in further detail, and provides recommendations for further advancement of the field.

To help address the charge to identify, discuss, and suggest priorities for the construction, purchase, and operation of tools and facilities, the committee convened a workshop in January 2007 to hear from members of the community and the federal agencies on future facility needs for CMMP researchers. Appendix C provides further details on this workshop. The committee expresses its apprecia-

[1]National Research Council, *Condensed-Matter and Materials Physics: The Science of the World Around Us: An Interim Report*, Washington, D.C.: The National Academies Press, 2006.

tion for the input received from the 30 presenters and more than 70 participants in that workshop.

As co-chairs, we are grateful to the committee members for their wisdom, cooperation, and commitment to ensuring the development of a comprehensive report. The report reflects the committee's heartfelt enthusiasm for the field of CMMP and its future potential and past accomplishments. Finally, we also thank the NRC staff (Natalia Melcer, Donald Shapero, Phillip Long, and Caryn Knutsen) for their guidance and assistance throughout the development of this report.

Mildred S. Dresselhaus, *Co-Chair*
Committee on CMMP 2010

William J. Spencer, *Co-Chair*
Committee on CMMP 2010

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:

Gordon A. Baym, University of Illinois at Urbana-Champaign,
Malcolm R. Beasley, Stanford University,
Paul M. Chaikin, New York University,
Elbio Dagotto, University of Tennessee and Oak Ridge National Laboratory,
Robert R. Doering, Texas Instruments, Inc.,
Martha A. Krebs, California Energy Commission,
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Sunil K. Sinha, University of California at San Diego,
Maury Tigner, Cornell University,
John Tranquada, Brookhaven National Laboratory,

Dale J. Van Harlingen, University of Illinois at Urbana-Champaign, and
Thomas A. Witten, University of Chicago.

We also wish to thank the following individuals for their review of the committee's interim report:

Elihu Abrahams, Rutgers University,
Frank S. Bates, University of Minnesota,
Gordon A. Baym, University of Illinois at Urbana-Champaign,
Arthur I. Bienenstock, Stanford University,
J.C. Séamus Davis, Cornell University,
Barbara A. Jones, IBM Almaden Research Center,
Marc A. Kastner, Massachusetts Institute of Technology,
Hyla S. Napadensky, Napadensky Energetics, Inc.,
Julia M. Phillips, Sandia National Laboratories, and
Peter G. Wolynes, University of California at San Diego.

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 Venkatesh Narayanamurti, Harvard University. 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.

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