As part of the 2010 physics decadal survey project, DOE and NSF requested the NRC to assess opportunities, over roughly the next decade, in atomic, molecular, and optical (AMO) science and technology. In particular, the NRC was asked to cover the state of AMO science, emphasizing recent accomplishments and identify new and compelling scientific questions. The report presents discussions of the role of and challenges for AMO science in instrumentation; scientific research near absolute zero; development of extremely intense x-ray and laser sources; exploration and control of molecular processes; photonics at the nanoscale; and development of quantum information technology. The report also offers an assessment of and recommendations about critical issues concerning maintaining U.S. leadership in AMO science and technology.
Executive Summary

Atomic, molecular, and optical (AMO) science demonstrates powerfully the ties of fundamental physics to society. Its very name reflects three of 20th century physics’ greatest advances: the establishment of the atom as a building block of matter; the development of quantum mechanics, which made it possible to understand the inner workings of atoms and molecules; and the invention of the laser. Navigation by the stars gave way to navigation by clocks, which in turn has given way to today’s navigation by atomic clocks. Laser surgery has replaced the knife for the most delicate operations. Our nation’s defense depends on rapid deployment using global positioning satellites, laser-guided weapons, and secure communication, all derived directly from fundamental advances in AMO science. Homeland security relies on a multitude of screening technologies based on AMO research to detect toxins in the air and hidden weapons in luggage or on persons, to name a few. New drugs are now designed with the aid of x-ray scattering to determine their structure at the molecular level using AMO-based precision measurement techniques. And the global economy depends critically on high-speed telecommunication by laser light sent over thin optical fibers encircling the globe.1 These advances, made possible by the scientists in this field, touched many areas of societal importance in the past century, and AMO scientists have been rewarded with numerous Nobel prizes over the past decade, including the 2005 prize in physics.

The purpose of this report is to identify the most promising future opportunities in AMO science based on what is known at this time. Building on these findings, the report describes the most fertile avenues for the next decade’s research in this field.

Despite a century of phenomenal progress in science, the universe is still a mysterious place. Many fundamental questions remain. One of the most important is that the fundamental forces of nature that shape the universe are still not fully understood. New AMO technology will help provide answers in the coming decades—in precision laboratory measurements on the properties of atoms, in giant gravitational observatories on Earth, or in even larger observatories based in space. Tremendous advances in precision timekeeping also place us at the threshold of answering some of the central questions.

Society has other urgent needs that AMO physics is poised to address. How will we meet our energy needs as Earth’s natural resources become depleted and the environment changes? Solar energy collection and conversion, laser fusion, or molecular biophysics may offer solutions, and all of these have strong connections to AMO science. Health threats are likely to increase on our interconnected and highly populated planet, and rapid response to new contagions requires the development of ways to detect biomolecules remotely, possibly through advanced laser techniques, as well as ways to measure their structure and chemistry, a priority effort at advanced x-ray light sources. The future security of our nation’s most powerful weapons may depend on our ability to

reproduce the plasma conditions of a fusion bomb in the tiny focus of a powerful laser. And, controlling that plasma is key to harnessing its power for beneficial uses.

These last lines underscore how AMO science contributes strongly to the development of advanced technologies and tools. Instruments made possible by AMO science and related technical developments are today everywhere in experimental science—from astronomy to zoology. In many instances they enable revolutionary experiments or observations that lead to revolutionary new insights. A century of progress toward understanding the mysterious and counterintuitive nature of quantum mechanics now places AMO science at the vanguard of a new kind of quantum revolution, in which coherence and control are the watchwords.

**SIX COMPELLING RESEARCH OPPORTUNITIES FOR AMO SCIENCE**

This report concludes that research in AMO science and technology is thriving. It identifies, from among the many important and relevant issues in AMO science, six broad grand challenges that succinctly describe key scientific opportunities available to AMO science:

- Revolutionary new methods to measure the nature of space and time with extremely high precision have emerged within the last decade from a convergence of technologies in the control of the coherence of ultrafast lasers and ultracold atoms. This new capability creates unprecedented new research opportunities.
- Ultracold AMO physics was the most spectacularly successful new AMO research area of the past decade and led to the development of coherent quantum gases. This new field is poised to make major contributions to resolving important fundamental problems in condensed matter science and in plasma physics, bringing with it new interdisciplinary opportunities.
- High-intensity and short-wavelength sources such as new x-ray free-electron lasers promise significant advances in AMO science, condensed matter physics and materials research, chemistry, medicine, and defense-related science.
- Ultrafast quantum control will unveil the internal motion of atoms within molecules, and of electrons within atoms, to a degree thought impossible only a decade ago. This is sparking a revolution in the imaging and coherent control of quantum processes and will be among the most fruitful new areas of AMO science in the next 10 years.
- Quantum engineering on the nanoscale of tens to hundreds of atomic diameters has led to new opportunities for atom-by-atom control of quantum structures using the techniques of AMO science. There are compelling opportunities in both molecular science and photon science that are expected to have far-reaching societal applications.
- Quantum information is a rapidly growing research area in AMO science and one that faces special challenges owing to its potential application in data security and encryption. Multiple approaches to quantum computing and communication are likely to be fruitful in the coming decade, and open international exchange of people and information is critical in order to realize the maximum benefit.

Surmounting these challenges will require important advances in both experiment and theory. Each of these science opportunities is linked closely to the new tools that will also help in meeting critical national needs. The key future opportunities for AMO science presented by these six grand challenges are based on the rapid and astounding developments in the field, a result of investments made by the federal R&D agencies in AMO research programs. These compelling grand challenges in AMO research are discussed in more detail in the report, which also highlights the broad impact of
AMO science and its strong connections to other branches of science and technology and discusses the strong coupling to national priorities in health care, economic development, the environment, national defense, and homeland security. Finally, the report analyzes trends in federal support for research, compiled from responses provided by AMO program officers at federal agencies.

The linkages between opportunities for AMO science and technology and national R&D goals are clear. The White House set forth the country’s R&D priorities in the July 8, 2005, memorandum of the science advisor to the President and the director of the Office of Management and Budget. These priorities were reiterated and strengthened in the President’s State of the Union Address in January 2006 and in the President’s Budget Request for FY2007. AMO scientists contribute to these national priorities in several key areas:

- Advancing fundamental scientific discovery to improve the quality of life.
- Providing critical knowledge and tools to address national security and homeland defense issues and to achieve and maintain energy independence.
- Enabling technological innovations that spur economic competitiveness and job growth.
- Contributing to the development of therapies and diagnostic systems that enhance the health of the nation’s people.
- Educating in science, mathematics, and engineering to ensure a scientifically literate population and qualified technical personnel who can meet national needs.
- Enhancing our ability to understand and respond to global environmental issues.
- Participating in international partnerships that foster the advancement of scientific frontiers and accelerate the progress of science across borders.
- Contributing to the mission goals of federal agencies.

In discussing the state of AMO science and its relation to the federal government, the report offers some observations and conclusions. Given the budget and programmatic constraints, generally the federal agencies questioned in this study have managed the research profile of their programs well in response to the opportunities in AMO science. In doing so, the agencies have developed a combination of modalities (large groups, centers and facilities, and expanded single-investigator programs). Much of the funding increase that has taken place at the Department of Energy (DOE), the National Institute of Standards and Technology (NIST), and the National Science Foundation (NSF) has served to benefit activities at research centers. The overall balance of the modalities for support of the field has led to outstanding scientific payoffs. In addition, the breadth of AMO science and the range of the agencies that support it are exceedingly important to future progress in the field and have been a key factor in its success so far.

On the other hand, the committee notes with concern the decline in research funding in general and in basic research funding in particular (the so-called 6.1 budget), at Department of Defense (DOD) agencies. This is troubling especially because fundamental scientific research has been a critical part of the nation’s defense strategy for more than half a century.

Since all of the agencies questioned by the committee reported that they receive substantially more proposals of excellent quality than they are able to fund, it appears that AMO science remains rich with promise for future progress. The committee concludes that AMO science will continue to make exceptional advancements in science and in technology for many years to come.

A substantial increase in the nation’s investment in the physical sciences has been identified as a national priority with vast importance for national security, economic strength, health care, and
As the President has indicated, a program of increased investment must be directed at both improving education in the physical sciences and mathematics at all levels as well as significantly strengthening the research effort. Such a program will enhance the nation’s ability to capture the benefits of AMO science. Support for basic research is a vital component of the nation’s defense strategy. The recent decline in research funding at the defense-related agencies, most particularly in funding for basic research, is harming the nation. Industry-sponsored basic research also plays a key role in enabling technological development, the committee concludes, and steps should be taken to reinvigorate it.

The report notes three key committee findings in programmatic issues:

- The extremely rapid increase in technical capabilities and the associated increase in the cost of scientific instrumentation have led to very significant added pressures (over and above the usual Consumer Price Index inflationary pressures) on research group budgets. In addition, not only has the cost of instrumentation increased, but also the complexity and challenge of the science makes investigation much more expensive. This “science inflator” effect means that while it is now possible to imagine research that was unimaginable in the past, finding the resources to pursue that research is becoming increasingly difficult.
- In any scientific field where progress is extremely rapid, it is important not to lose sight of the essential role played by theoretical research. Programs at the federal agencies that support AMO theory have been and remain of critical importance. NSF plays a critical and leading role in this area, but its support of AMO theoretical physics is not nearly enough.
- AMO science is an enabling component of astrophysics and plasma physics but is not adequately supported by the funding agencies charged with responsibility for those areas.

The committee made a number of findings on workforce issues. It agrees with many other observers that the number of American students choosing physical sciences as a career is dangerously low. Without remediation, this problem is likely to open up an unacceptable expertise gap between the United States and other countries. Since AMO science offers students an opportunity for exceptionally broad training in a field of great importance, and therefore of excellent job prospects, it is poised to contribute to a solution of the problem. The committee points out that any effort to attract more American-born students into the physical sciences must recognize that personnel adjustments occur on a time scale of decades. Reversing the decline will require a long-term effort.

It must be remembered, too, that it will always be in the national interest to attract and retain foreign students in the physical sciences. Similarly, the report notes that scientists and students in the United States derive great benefits from close contact with the scientists and students of other nations that takes the form of international collaborations, exchange visits, meetings, and conferences. These activities are invaluable for promoting both excellent science and better international understanding.

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and they support the economic, educational, and national security needs of the United States. It is, therefore, essential to U.S. interests that these activities continue.

RECOMMENDATIONS

Finally, the committee offers six recommendations that form a strategy to realize fully the potential at the frontiers of AMO science:

Recommendation. In view of the critical importance of the physical sciences to national economic strength, health care, defense, and domestic security, the federal government should embark on a substantially increased investment program to improve education in the physical sciences and mathematics at all levels and to strengthen significantly the research effort.

Recommendation. AMO science will continue to make exceptional contributions to many areas of science and technology. The federal government should therefore support programs in AMO science across disciplinary boundaries and through a multiplicity of agencies.

Recommendation. Basic research is a vital component of the nation’s defense strategy. The Department of Defense, therefore, should reverse recent declines in support for 6.1 research at its agencies.

Recommendation. The extremely rapid increase in the technical capability of scientific instrumentation and its cost has significantly increased pressures (over and above the usual Consumer Price Index inflationary pressures) on research budgets. The federal government should recognize this fact and plan budgets accordingly.

Recommendation. Given the critical role of theoretical research in AMO science, the funding agencies should reexamine their portfolios in this area to ensure that the effort is at proper strength in workforce and funding levels.

Recommendation. The federal government should implement incentives to encourage more American students, especially women and minorities, to study the physical sciences and take up careers in the field. It should continue to attract foreign students to study physical sciences and strongly encourage them to continue their scientific careers in the United States.
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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.

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PREFACE

This report is an accounting of the AMO 2010 study undertaken by the National Research Council of the National Academies to assess opportunities in atomic, molecular, and optical (AMO) science and technology over roughly the next decade. The charge for this study was devised by a Board on Physics and Astronomy standing committee, the Committee on Atomic, Molecular, and Optical Sciences, in consultation with the study’s sponsors, the Department of Energy and the National Science Foundation. The Committee on AMO 2010, which carried out the study, was asked to assess the state of the field of AMO science, emphasizing recent accomplishments and identifying new and compelling scientific questions. The report is a part of the ongoing Physics 2010 decadal survey that is being undertaken by the National Academy’s Board on Physics and Astronomy.

The committee that carried out this study and wrote this report is composed of leaders from many different subfields within the AMO physics community, as well as prominent scientists from outside the field. The committee also received valuable advice from consultants Neal Lane, Rice University, and Neil Calder, Stanford Linear Accelerator Center. In addition, the committee received valuable input from the following colleagues: Laura P. Bautz, Nora Berrah, Joshua Bienfang, John Bollinger, Gavin Brennen, Denise Caldwell, John Cary, Michael Casassa, Henry Chapman, Michael Chapman, Charles Clark, Paul Corkum, Philippe Crane, Roman Czujko, Joseph Dehmer, Brian DeMarco, David DeMille, Todd Ditmire, John Doyle, Henry Everitt, Aimee Gibbons, Janos Hajdu, Hashima Hassan, Robert R. Jones, William Krueer, Chan Joshi, Anthony Leggett, Wim Leemans, Steve Leone, Heather Lewandowski, Jay Lowell, Lute Maleki, Anne Matsuura, Harold Metcalf, Roberta Morris, Gerard Mourou, William Ott, Steve Rolston, Peter Reynolds, Eric Rohlfing, Michael Salamon, Howard Schlossberg, Barry Schneider, David Schultz, Thomas Stoehlker, David Villeneuve, Carl Williams, and Jun Ye.

Significant effort has been made to solicit community input for this study. This has been done via town meetings held at the Annual Meeting of the Division of AMO Physics of the American Physical Society (APS) in Lincoln, Nebraska, in May 2005 and the International Quantum Electronics Conference (jointly sponsored by the APS Division of Laser Science, the Optical Society of America, and the Lasers and Electro-optics Society of the Institute of Electrical and Electronics Engineers) in May 2005 in Baltimore, Maryland. The committee also solicited input from the community through a public Web site. The comments supplied by the AMO community through this site and at the town meetings were extremely valuable primary input to the committee.

The federal agencies that fund AMO research in the United States were also solicited for input, through their direct testimony at open meetings and their written responses to requests for information on funding patterns and other statistical data. These data are summarized in Chapter 8 and in the appendixes to the report. Finally, the committee is grateful to the staff at the White House Office of Science and Technology Policy and the Office of Management and Budget, as well as staff from committees of the Congress concerned with funding legislation, who provided important background on connections between AMO science and national science policy.

In November 2005, the National Research Council released a short interim report from the AMO 2010 Committee, which was intended as a preview of this final document. It summarized the key opportunities in forefront AMO science and in closely related critical technologies, and it discussed some of the broad-scale conclusions of the final report. It also identified how AMO science
supports national R&D priorities. The present report reinforces the preliminary conclusions of the interim report and adds a wealth of detail as well as recommendations.

This report reflects the committee’s enthusiasm, inspired by the tremendous excitement within the AMO science community about future R&D opportunities. It would not have been written without the extensive and unselfish work of the entire committee, its many consultants, and the NRC staff. We thank them all for their efforts. We particularly wish to thank Michael Moloney for his expertise and dedication and Don Shapero for his experience and wisdom in assisting us to produce this report.

Philip Bucksbaum             Robert Eisenstein
Co-chair                     Co-chair
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 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:

Keith Burnett, University of Oxford
Alexander Dalgarno, Harvard-Smithsonian Center for Astrophysics
David P. DeMille, Yale University
Chris H. Greene, University of Colorado
William Happer, Princeton University
Wendell T. Hill III, University of Maryland
Tin-Lun Ho, The Ohio State University
Gerard J. Milburn, The University of Queensland
Richart E. Slusher, Lucent Technologies
David J. Wineland, National Institute of Standards and Technology

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 Daniel Kleppner, Massachusetts Institute of Technology. Appointed by the National Research Council, 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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