Final Progress Report to the Department of Energy

Project Identification
Project Title: AMO2010: Decadal Assessment and Outlook Report on Atomic, Molecular and Optical Science
Agency Award No.: DE-FG02-04ER15610
Reporting Period: 8/01/05 – 12/31/06

Participants

People
Participant’s Name: Donald C. Shapero
Project Role(s): Principal Investigator
>160 Hours: Yes

Partner Organizations
Department of Energy; Financial Support

Collaborators
(None)

Activities and Findings

Activities
Charge: AMO2010, a decadal assessment of and outlook for the field of Atomic, Molecular, and Optical Science, will be more than a simple review survey. Rather AMO2010 will result in a report that will (1) identify new opportunities and compelling scientific questions and themes that are arising from recent advances and accomplishments in the field; (2) identify connections between AMO science and other scientific fields, emerging technologies, and national needs; (3)
identify workforce, societal and educational needs for AMO science; and (4) make
recommendations on a strategy to fully realize the potential of the frontiers of AMO science.

Specifically, the committee is charged with the follow task:

**Statement of Task**

The committee will be charged to produce a comprehensive report on the status of AMO Science. The committee’s report shall:

1. Review the field of AMO science, emphasize recent accomplishments, and identify new opportunities and compelling scientific questions.

2. Identify the impact of AMO science on other scientific fields, emerging technologies, and national needs.

3. Identify future workforce, societal and educational needs for AMO science.

4. Make recommendations on how the US research enterprise might realize the full potential of AMO science.

5. Produce an intermediate report addressing key research issues and themes facing the research community, as well a full final report and a separate summary of its findings and recommendations.

In carrying out its charge, the committee might consider issues such as the state of the AMO research community, international models for support and collaboration, institutional and programmatic barriers, etc.

Within the reporting period the committee held 2 plenary meetings August 29/30, 2005 (Irvine, CA), and January 26/27, 2006 (Washington, DC). At its second meeting in August 2005 the committee finalized the content of its interim report that, following completion of the NRC’s review process, was released in November 15, 2005. In the report the committee identified six grand challenges and discussed how AMO Science has clear linkages to national R&D goals. Also at the second meeting the committee decided on the outline of the final report.

The committee subsequently divided into chapter-writing subgroups and at the committee’s third meeting the main elements of the conclusions and recommendations were agreed. Following the third committee meeting, a small writing group of 5 committee members—the two co-chairs and three committee members—met on March 7/8, 2006 (Menlo Park, CA) to complete the major drafting of the report from the earlier texts composed by sub-groups of the committee.

On April 11, 2006 the draft report was transmitted to a panel of 11 reviewers as part of the NRC’s report review process. The report in prepublication format, called *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons* was released to the sponsors at a briefing on July 10, 2007. The briefing meeting included the committee co-chairs Phil Bucksbaum and Robert Eisenstein, along with committee member William Phillips. Representatives from NSF, DOE, NIST, and NASA attended the briefing. Other briefings were held at OSTP and with representatives of the House Science Committee Staff. The report, again in prepublication format, was released to the public on July 24, 2006. Since then
the report has been in editing and production and the expected release date for the final printed book is within the first quarter of 2007.

**Future Activities:** Since the public release of prepublication of the report has been in editing and production and the expected release date for the final printed book is within the first quarter of 2007.

**Findings**
In its interim report the committee identified six grand challenges for AMO science which were described in terms of six compelling questions: *What is the nature of physical law? What happens at the lowest temperatures in the universe? What happens when we turn up the power? Can we control the inner workings of a molecule? How will we control and exploit the nanoworld? What lies beyond Moore’s law?*

The committee also concluded that AMO scientists contribute to the nation’s R&D priorities, as described by the Office of Science and Technology Policy and the Office of Management and Budget, in several key areas.

The final report, *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons* concluded that the federal government should reinforce its commitment to research in atomic, molecular, and optical (AMO) science, the study of atoms, molecules, and light, and related technologies such as lasers and fiber optics communications, says a new report from the National Academies' National Research Council. The report, highlights six main "challenges" in physics that could directly impact the technology and economy of the future. The report notes that during the past century, U.S. research in AMO science has benefited the country enormously through the development of global positioning systems, advanced medical equipment, and atomic clocks, to name just a few applications.

The report notes that AMO science is now poised to address many urgent needs, such as finding new sources of energy, detecting new diseases, and enhancing the security of codes that protect information over the Internet. This science will also play an important role in addressing challenges identified by the committee, which include gaining a better understanding of the laws of physics, probing the behavior of matter at high and low extreme temperatures, and learning about the properties of nanomaterials—man-made materials a billionth of a meter in size.

The report concludes that maintaining U.S. leadership in the physical sciences in general and AMO science in particular depends on more than simply money. The nation must be alert to new and more efficient ways of conducting research in AMO science, the committee said. For example, there has been a steady move over the years toward the creation of centers and large facilities where many teams of scientists gather and collaborate. Also, government agencies and universities have increased their financial support for teams led by a single investigator and expanded some single-investigator efforts into the activities of larger teams. The federal government should encourage these new approaches to doing research by creating appropriate grants and fostering cooperation between public institutions and the private sector, the committee said.

**Outreach Activities**
The AMO2010 committee has been engaged in significant outreach activities including community town meeting at the May 2005 Division of Atomic Molecular and Optical Physics of the American Physical Society and the CLEO/QELS May 2005 conference by the Optical Society of America and the Division of Laser Science of the American Physical Society. After the release of the interim report, the committee solicited public comment via a website and email contact to relevant professional societies, and conversations with peers and colleagues at their home institutions. The committee’s final report will be
published by the National Academies Press and distributed in a targeted manner to the sponsoring agencies, policymakers, and appropriate members of the research communities.

The report received notable coverage in the media including mention in an article in The Economist magazine. The attached PDF shows the news clippings to date.

**Internet Dissemination**

The committee launched a public website (available from [www.nas.edu/bpa](http://www.nas.edu/bpa)). This website serves as a gateway for electronic exchange with the scientific community. The committee has an e-mail box by which members of the public can offer comments. Meeting notices and solicitations for comment have been announced on the website. The website has played a key role in the data-gathering phase of the committee’s work after preparation of the interim report.

**Attachments**

- Committee membership roster
- Agenda for plenary committee meetings
- Copy of interim report
- Executive Summary and Overview Chapter of final report..
AMO2010

Committee Roster
COMMITTEE ON AMO2010: ATOMIC, MOLECULAR, AND OPTICAL SCIENCE
Terms expire on July 30 of year indicated.

<table>
<thead>
<tr>
<th>NAS</th>
<th>Dr. Philip H. Bucksbaum, Co-chair</th>
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<tbody>
<tr>
<td></td>
<td>Stanford Linear Accelerator Center</td>
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<td>MS 69</td>
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<td>2575 Sand Hill Road</td>
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<td>Menlo Park, CA  94025</td>
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<td>Tel: 650/926-5337</td>
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<td>Fax: 650/725-2313</td>
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<td></td>
<td>E-mail: <a href="mailto:phb@SLAC.Stanford.edu">phb@SLAC.Stanford.edu</a></td>
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**Dr. Robert Eisenstein, Co-chair 2006**
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No Fax
E-mail: r.eisenstein@comcast.net

<table>
<thead>
<tr>
<th>NAS</th>
<th>Dr. Gordon A. Baym  2006</th>
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<td></td>
<td>Professor of Physics</td>
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<td></td>
<td>University of Illinois</td>
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<td>Department of Physics</td>
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<th>NAS</th>
<th>Dr. C. Lewis Cocke  2006</th>
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<td>University Distinguished Professor</td>
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<td>Kansas State University</td>
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<td>Physics Department</td>
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<td>Manhattan, KS  66503</td>
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<td>E-mail : <a href="mailto:cocke@phys.ksu.edu">cocke@phys.ksu.edu</a></td>
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<th>NAS</th>
<th>Dr. Eric A. Cornell  2006</th>
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<td>Staff Scientist, National Institute of Standards and Technology</td>
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<td>E-mail: <a href="mailto:fortson@phys.washington.edu">fortson@phys.washington.edu</a></td>
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<th>NAS</th>
<th>Dr. Keith Hodgson  2006</th>
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<td>Stanford Synchrotron Radiation Laboratory</td>
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<td>University of Maryland Baltimore County</td>
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<td>Cassius Lamb Kirk Professor in the Natural Sciences</td>
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<td>Professor of Physics</td>
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AMO2010

Plenary Meeting

Agendas
AMO 2010: An assessment of and outlook for Atomic Molecular and Optical Science
National Academies – Keck Center – Room 204 – Washington, DC

Monday April 4th, 2005

<table>
<thead>
<tr>
<th>Time</th>
<th>Session Type</th>
<th>Topic</th>
<th>Presenter(s)</th>
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<tr>
<td>8:00 am</td>
<td>CLOSED</td>
<td>Welcome/ Introductions, NRC Business, Committee Discussion</td>
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<tr>
<td>10.00 am</td>
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<td>Break</td>
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<tr>
<td>10.25 am</td>
<td>OPEN</td>
<td>Welcome and Introductions</td>
<td>Bob Eisenstein, co-Chair</td>
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<td>Phil Bucksbaum, co-Chair</td>
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<tr>
<td>10.30 am</td>
<td></td>
<td>Perspectives from National Science Foundation</td>
<td>Joseph Dehmer</td>
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<tr>
<td>11.10 am</td>
<td></td>
<td>Perspectives from Department of Energy</td>
<td>Eric Rohlfing / Michael Casassa</td>
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<tr>
<td>11.50 am</td>
<td></td>
<td>Setting Priorities: the Astronomy Decadal Survey</td>
<td>Chris McKee, UC Berkeley</td>
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<tr>
<td>12.20 pm</td>
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<td>Setting scientific priorities</td>
<td>J. Patrick Looney, OSTP</td>
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<td>Joel Parriott, OMB</td>
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<td>1:00 pm</td>
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<td>Lunch</td>
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<td>1:40 pm</td>
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<td>Perspectives from NIST</td>
<td>William Ott, NIST</td>
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<td>2:20 pm</td>
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<td>Perspectives on the AMO2010 study</td>
<td>Dan Kleppner, MIT</td>
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<tr>
<td>3:00 pm</td>
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<td>Break</td>
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<td>3:20 pm</td>
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<td>Quantum Information and National Security</td>
<td>Henry O. Everitt, ARO</td>
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<td>4:00 pm</td>
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<td>Perspective from Capitol Hill</td>
<td>Peter Rooney, House Science Committee</td>
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<td>4:30 pm</td>
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<td>Perspective from DARPA</td>
<td>Jay Lowell</td>
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<td>5:10 pm</td>
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<td>Open Microphone Discussion</td>
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<td>5:30 pm</td>
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<tr>
<td>5:30 pm</td>
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<td>Reception</td>
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Tuesday April 5th, 2005 (all in CLOSED SESSION)

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<th>Time</th>
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<th>Topic</th>
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<tr>
<td>8:30 am</td>
<td>Committee discussions</td>
<td>Committee discussions and breakout sessions</td>
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<td>3:30 pm</td>
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<td>Meeting closes</td>
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**AMO 2010 – 2\textsuperscript{nd} Meeting**

*National Academies – Beckman Center – Board Room – Irvine, CA*

**MEETING IS CLOSED IN ITS ENTIRETY**

**Monday August 29\textsuperscript{th}, 2005** (times are indicative except for break times)

<table>
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<th>Time</th>
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<td>7:45 am</td>
<td><em>Breakfast Buffet (Dining Room)</em></td>
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<tr>
<td>8:15 am</td>
<td><em>Welcome and Preview of the Meeting</em></td>
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<tr>
<td>9:00 am</td>
<td><em>Review of draft interim report</em></td>
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<tr>
<td>10.15 am</td>
<td><em>BREAK</em></td>
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<tr>
<td>10:30 am</td>
<td><em>Review of Draft Final Report</em></td>
</tr>
<tr>
<td>12:30 pm</td>
<td><em>Lunch Buffet</em></td>
</tr>
<tr>
<td>1:30 pm</td>
<td><em>Review of Draft Final Report</em></td>
</tr>
<tr>
<td>3:30 pm</td>
<td><em>BREAK</em></td>
</tr>
<tr>
<td>4:00 pm</td>
<td><em>Review of Draft Final Report</em></td>
</tr>
<tr>
<td>5:45 pm</td>
<td><em>Recess</em></td>
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**Tuesday August 30\textsuperscript{th}, 2005**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>8:00 am</td>
<td><em>Breakfast Buffet (Dining Room)</em></td>
</tr>
<tr>
<td>8:30 am</td>
<td><em>Final review and approval of draft interim report</em></td>
</tr>
<tr>
<td>9:15 am</td>
<td><em>First Discussion of conclusions and recommendations</em></td>
</tr>
<tr>
<td>10:30 am</td>
<td><em>Break</em></td>
</tr>
<tr>
<td>10:50 am</td>
<td><em>Planning the way ahead</em></td>
</tr>
<tr>
<td>12:30 pm</td>
<td><em>Lunch Buffet (Dining Room and Terrace)</em></td>
</tr>
<tr>
<td>1:30 pm</td>
<td><em>Planning the way ahead</em></td>
</tr>
<tr>
<td>3:00 pm</td>
<td><em>Meeting closes</em></td>
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### Thursday January 26 2006  The whole agenda is in closed session

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:30 am</td>
<td>Breakfast</td>
</tr>
<tr>
<td>8:00 am</td>
<td>Welcome and Overview of Agenda</td>
</tr>
<tr>
<td>8:15 am</td>
<td>Review of committee bias and conflict of interest forms</td>
</tr>
<tr>
<td>8:30 am</td>
<td>Where are we?</td>
</tr>
<tr>
<td>10:00 am</td>
<td>Break</td>
</tr>
<tr>
<td>10:30 am</td>
<td>Review of Draft Report</td>
</tr>
<tr>
<td>11:15 am</td>
<td>Introduction of the Discussion of Findings, Conclusions, and Recommendations</td>
</tr>
<tr>
<td>12:00 pm</td>
<td>Lunch</td>
</tr>
<tr>
<td>1:00 pm</td>
<td>Discussion of Findings, Conclusions, and Recommendations</td>
</tr>
<tr>
<td>3:00 pm</td>
<td>Break</td>
</tr>
<tr>
<td>3:30 pm</td>
<td>The Road Ahead – Getting the job done</td>
</tr>
<tr>
<td>5:00 pm</td>
<td>Meeting adjourns</td>
</tr>
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### Friday January 27 2006  The whole agenda is in closed session

<table>
<thead>
<tr>
<th>Time</th>
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</tr>
</thead>
<tbody>
<tr>
<td>7:30 am</td>
<td>Breakfast</td>
</tr>
<tr>
<td>8:00 am</td>
<td>Review and Continuation of Discussion of Findings, Conclusions, and Recommendations</td>
</tr>
<tr>
<td>10.00 am</td>
<td>Break</td>
</tr>
<tr>
<td>10.30 am</td>
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<tr>
<td>3:00 pm</td>
<td>Break</td>
</tr>
<tr>
<td>3:30 pm</td>
<td>Final Discussions and Next Steps</td>
</tr>
<tr>
<td>5:00 pm</td>
<td>Meeting adjourns</td>
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AMO2010

Interim Report
Controlling the Quantum World of Atoms, Molecules, and Photons
An Interim Report

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES
The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy’s purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.
COMMITTEE ON AMO 2010

PHILIP H. BUCKSBAUM, University of Michigan, Co-chair
ROBERT EISENSTEIN, Co-chair
GORDON A. BAYM, University of Illinois at Urbana-Champaign
C. LEWIS COCKE, Kansas State University
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MICHAEL H. MOLONEY, Study Director
BRIAN D. DEWHURST, Senior Program Associate
PAMELA A. LEWIS, Program Associate
VAN AN, Financial Associate
PREFACE

The National Research Council of the National Academies has undertaken a study of opportunities in atomic, molecular, and optical (AMO) science and technology over roughly the next decade. The charge for this study was devised by the Board on Physics and Astronomy’s standing committee on Atomic, Molecular, and Optical Science (CAMOS) in consultation with the study’s sponsors, the Department of Energy and the National Science Foundation. The committee carrying out the AMO 2010 study, has been asked to assess the state of AMO science, emphasizing recent accomplishments and identifying new and compelling scientific questions. The committee’s final report, which is scheduled for release in the summer of 2006, 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 purpose of this short interim report is to provide a preview of the final document. It summarizes the committee’s opinion on the key opportunities in forefront AMO science and in closely related critical technologies and discusses some of the broad-scale conclusions of the final report. It also identifies how AMO science supports national R&D priorities.

Significant effort has been made to solicit community input for this study. This has been done by means of town meetings, one of them held at the Annual Meeting of the Division of AMO Physics of the American Physical Society (APS) in Lincoln, Nebraska, in May 2005, and another held at the International Quantum Electronics Conference in Baltimore, Maryland, also in May 2005. The committee also solicited input from the community through a public Web site. It will welcome input for as long as possible following the release of this interim report.

The committee has also received valuable advice from its consultants, Neal Lane, Rice University, and Neil Calder, Stanford Linear Accelerator Center.

The committee’s work on the final report is continuing with an enthusiasm that is inspired by the tremendous excitement within the AMO science community about future R&D opportunities. It looks forward to sharing that compelling excitement with the broader R&D community and its sponsors, with the release of its final report in 2006.

Philip Bucksbaum
Co-chair

Robert Eisenstein
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:

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Chris H. Greene, University of Colorado,
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Wendell T. Hill, University of Maryland,
Erich P. Ippen, Massachusetts Institute of Technology,
Gerard J. Milburn, The University of Queensland, and
Richart E. Slusher, Lucent Technologies.

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.
Atomic, molecular, and optical (AMO) science illustrates powerfully the ties of fundamental physics to society. Its very name comes from three of the twentieth century’s greatest advances: the establishment of the atom as the 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. Advances made possible by the scientists in this field touch almost every sphere of societal importance in the past century. 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

AMO scientists are proud of their central role in science and society in the twentieth century, and they have been rewarded with numerous Nobel prizes over the past decade, including the 2005 prize in physics. But in this report we look to the future. At the beginning of the new millennium, what new answers do we seek? What knowledge must we obtain? Because of all that was learned in the last century about the mysterious and counterintuitive nature of quantum mechanics, we are now at the dawn of a new kind of quantum revolution, in which coherence and control are the watchwords.

The universe is still a mysterious place. How can we determine the properties of the fundamental forces of nature that shape the universe? What can we say about the most fundamental features of our natural world? What are the symmetries that govern the behavior of the universe from the subatomic scale to the cosmic? 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 these questions.

Society has other urgent needs, which AMO physics is poised to address. How will we meet our energy needs as Earth’s environment changes and its natural resources become depleted? AMO involvement in molecular biophysics, solar energy collection and conversion, or laser fusion may contribute to a solution. 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 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 thoughts underscore how much AMO science is also about 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 have made possible revolutionary experiments or observations and resulted in correspondingly revolutionary new understandings.

In approaching its charge, the committee identified, from among the many important and relevant issues, six broad grand challenges that succinctly describe key scientific opportunities available to AMO science. Surmounting these challenges will require important advances in both experiment and theory. Each of these science opportunities is linked closely to new tools that will also help in meeting critical national needs.

The six grand challenges, summarized below, will each form a chapter of the committee’s final report:

- **What is the nature of physical law?** What are the undiscovered laws of physics beyond our current model of the physical world? Recent advances in our understanding of the universe suggest the existence of an unexpected force that alters the fundamental symmetry of time. This tiny effect could be seen in the next decade in experiments that look for deviations in the nearly perfect symmetry found in atoms. Are the laws of physics constant over time or across the universe? A new generation of ultraprecise clocks will enable laboratory searches for time variation of fundamental constants. Answers will also come from AMO research that is helping to interpret astrophysical observations of the most exotic realms in the universe. The advanced technologies developed for fundamental physics experiments will also improve the accuracy of direct gravity-wave detection and of next-generation GPS satellites and will produce new medical diagnostics.

- **What happens at the lowest temperatures in the universe?** The coldest objects in the universe are the Bose-Einstein condensates developed by AMO physicists in the last decade. These remarkable new states of matter, typically a billionth of a degree above absolute zero, are much colder than the furthest reaches of outer space. Scientists have discovered that they have strange and wonderful properties, and in the next decade we can expect a rich harvest of interesting new physics ideas and applications—from technological breakthroughs such as clocks and inertial sensors of unprecedented accuracy, to insights into the physics of ordinary matter as well as matter under extreme conditions. We are entering an age when we can routinely and exquisitely control nature on the quantum level. This quantum coherent control has already produced a matter-wave laser, which could advance gravitational and environmental sensing.
• **What happens when we turn up the power?** Lasers in the next decade will reach peak powers of a million billion watts concentrated in a single beam of light for a little more than one millionth of a billionth of a second. For an instant this exceeds the entire electrical power consumption of Earth. The huge electric fields in these beams approach the conditions in particle accelerator collisions and overwhelm the forces that bind electrons in atoms and molecules, leading to exotic states of matter usually found only in stars or hydrogen bombs. These lasers will help us understand the violent forces we see in the universe around us. Bright new x-ray-laser sources currently under construction will also help unravel the mysteries of how complex biomolecules work. By irradiating proteins or viruses with a brief coherent flash from an x-ray laser, crucial details about their shape can be captured, to learn what makes them so efficient as they carry out the processes of life or the spread of disease. These exotic high-powered lasers have applications to many other important technological problems as well, ranging from the prospect of controlling nuclear fusion as a source of clean, abundant energy to next-generation compact x-ray microscopes with unprecedented resolution.

• **Can we control the inner workings of a molecule?** In the next decade we will begin to observe the processes of nature as they play out over times shorter than a millionth of a billionth of a second (less than 1 femtosecond—that is, in the attosecond regime). This remarkable new capability is enabled by advances in ultrafast laser- and accelerator-based x-ray strobes, which can detect the motion of electrons in atoms and molecules. Scientists anticipate the possibility of capturing images of motion inside a molecule or of using the laser to manipulate matter on the atomic scale. These previously unavailable tools of quantum control and feedback could help them to tailor new molecules for applications in health care, energy, and security.

• **How will we control and exploit the nanoworld?** The nanoworld lies in the transition region between our familiar classical world of relatively well-behaved macroscopic objects and the quantum world of atoms and molecules. These nanostructures have counterintuitive but useful optical properties that come from their subwavelength dimensions. Scientists see unique opportunities to tailor material properties for efficient optical switches, light sources, or photoelectric power generators. Negative index nanomaterials could dramatically improve optical microscopes or reduce the feature size in chip fabrication. Other applications include photonic crystals, single-photon sources and detectors, environmental monitoring, and biomedical optics, with applications such as killing cancerous cells via localized optical absorption and heating.

• **What lies beyond Moore’s law?** Today’s computers are doubling in performance every year or two. This will end when the ever-shrinking size of electronic components approaches the level of individual molecules and atoms. Quantum mechanics offers a radically different approach to information processing, whereby single atoms and photons could be the new hardware. This could lead to computers
controlling the quantum world of atoms, molecules, and photons: an interim report
capable of solving problems that are intractable on any imaginable extension of
today's computers but that are important in areas from basic science to national
security. Quantum communication might provide some security against interception
beyond anything possible in today's cyber infrastructure. These applications are based
on the strangest and least intuitive concepts of quantum physics, such as Einstein's
action-at-a-distance, which allows teleportation and the remote transfer of information
without physical contact. Quantum computing is forcing us to explore both theoretical
and experimental quantum mechanics at their deepest levels. Should quantum
computers be realized, they would be as different from today's high-speed digital
computers as those machines are from the ancient abacus.

These key future opportunities are based on rapid and astounding developments in the
field of AMO science, a result of investments made by the federal government’s R&D
agencies in the work of AMO researchers. The committee will discuss these compelling
research challenges in more detail in the final report and will highlight the broad impact of
AMO science and its strong connections to other branches of science and technology. The
strong coupling to national priorities in health care, economic development, the environment,
national defense, and homeland security will also be discussed.

The linkages to 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. 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.

An essential part of maintaining the country’s leadership in AMO science, and one of the
White House’s R&D priorities, is to train and to equip the next generation of American
scientists. The committee is compiling data on funding, demographics, and program
emphasis from the federal agencies to help it assess the current state of AMO science in the
United States. The committee’s conclusions will address priorities for investments in this
area, as well as how the U.S. research enterprise might realize the full potential of AMO
science.
The final AMO 2010 decadal report is scheduled for release in mid-2006. In the meantime, community input links and other public information about AMO 2010 can be found at the National Academies Web site. Each of the grand challenges identified by the committee in this interim report will be explored in depth in the final report. In the committee’s view, there can be no doubt that realizing these key opportunities in AMO science is a vital national priority.

\[^2\text{http://www7.nationalacademies.org/bpa/AMO2010_Home.html}.\]
Controlling the Quantum World:
The Science of Atoms, Molecule, and Photons

Preface
Executive Summary
Chapter 1: Overview
COMMITTEE ON AMO 2010

PHILIP H. BUCKSBAUM, Stanford University, Co-chair
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GORDON A. BAYM, University of Illinois at Urbana-Champaign
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NEAL F. LANE, Rice University

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BRIAN D. DEWHURST, Senior Program Associate
PAMELA A. LEWIS, Program Associate
VAN AN, Financial Associate
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
Co-chair

Robert Eisenstein
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:

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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

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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.

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.
Controlling the Quantum World:  
AMO Science in the Coming Decade

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, which changed everything from the way we think about light to the way we store and communicate information. The field encompasses the study of atoms, molecules, and light, including the discovery of related applications and techniques. This report illustrates how AMO science and technology touches almost every sphere of societal importance—navigation using the latest atomic clocks; surgery with a host of new laser tools; ensuring the nation’s defense using global positioning satellites and secure communication; defending the homeland with screening technologies to detect toxins in the air and hidden weapons in luggage or on persons; improving health care with improved drug design tools and new diagnostic scanners; and underpinning the world’s economies with a global communications network based on high-speed telecommunication by laser light.  

The immense advances in science over the past century have only just begun to explain the mysteries of the universe. One of the primary goals of AMO science is to reveal the workings of nature on a fundamental level. In addition, society continues to have many urgent challenges that AMO research seeks to address. The unifying thread between the pure and applied work is quantum mechanics: AMO research develops tools and seeks knowledge on the quantum level, enabling progress in many other fields of science, engineering, and medicine.

The overarching emerging theme in AMO science is control of the quantum world. The six broad grand challenges outlined in this report describe key scientific opportunities in the coming decade. They are: precision measurements; ultracold matter; ultra-high intensity and short-wavelength lasers; ultrafast control; nanophotonics; and quantum information science. These challenges will drive important advances in both experiment and theory. Each of these science

opportunities is linked closely to new tools that will also help in meeting critical national needs (see Figure 1-1).

**WHAT IS THE NATURE OF PHYSICAL LAW?**

What are the undiscovered laws of physics that lie beyond our current understanding of the physical world? What is the nature of space, time, matter, and energy? AMO science provides exquisitely sensitive tools to probe these questions. For example, a force that alters the fundamental forward-backward symmetry of time has been studied extensively by high energy physicists, but another such force beyond the current standard model of the universe is now widely expected to exist. This tiny but revolutionary effect could show up first in the next decade in AMO experiments that look for deviations in the nearly perfect spatial symmetry found in atoms. A second question asks whether the laws of physics are constant over time or across the universe. A new generation of ultraprecise clocks will enable laboratory searches for time variations of the fundamental constants of nature. Answers will also come from AMO research that is helping to interpret astrophysical observations of the most exotic and most distant realms in the universe. The advanced technologies developed for such fundamental physics experiments have many other uses: they will improve the accuracy of direct gravity-wave detection and of next-generation global positioning satellites and
will produce new medical diagnostics. These advances are described briefly in the next paragraphs and explored more fully in Chapter 2.

Since the atomic concept was finally accepted at the beginning of the 20th century, atoms have proven central to the discovery and understanding of the laws of physics. Today remarkably sensitive techniques probe the properties of atoms, molecules, and light over enormous ranges: from submicroscopic to cosmic distances, in both familiar environments and the most exotic realms in the universe. The unprecedented sensitivity with which these fundamental properties can be measured is not only advancing science but is also yielding new technology for applications as diverse as studying the brain and detecting lung disease, for terrestrial guidance and space navigation, and for mapping local gravitational fields and detecting subsurface features in the Earth.

Understanding a Fundamental Property of Time and Physical Law. How the laws of physics might change if time went backward is not just a whimsical question from science fiction; it is one of the most vigorously debated questions in the physics of fundamental forces. The measurement of atomic electric dipole moments (EDMs) could provide an answer to this question. The EDM is a tiny separation between the centers of positive and negative charges in an atom, which has been predicted by nearly every class of advanced theory in particle physics, including Supersymmetry. EDMs have never been observed and must be very tiny if they even exist; we do, however, possess the technology that could allow their detection in the next decade. They would reveal new physics beyond our current understanding of the subatomic nature of our universe, as described by the so-called Standard Model. While much of our knowledge about the Standard Model of fundamental interactions comes from high-energy particle accelerators, AMO experiments have provided critical complementary information.

Unprecedented precision has practical consequences. The techniques developed for these fundamental experiments are now surpassing low-temperature superconducting quantum interference devices (SQUIDs) in the precise measurement of magnetic fields, reaching sensitivities better than ten parts per trillion of Earth's magnetic field. Such sensitivity will improve our ability to measure more accurately the weak magnetic fields of the brain and the heart, thereby helping to diagnose epilepsy, cardiac arrhythmias, and other diseases. Similarly, advances in measuring the magnetic properties of the atoms of noble gases are opening up a new field in medical imaging that will allow high-resolution studies of the lung. Such images cannot be obtained using standard MRI techniques. Current devices based on this new diagnostic tool promise enormous improvement in the early diagnosis of lung disease.

Extraordinary advances in optical spectroscopy are leading to superb atomic clocks. Ultrashort pulsed laser sources have been exploited to create an “optical comb” spanning the entire visible and near-infrared spectrum. With this revolutionary development (recognized by the Nobel prize in 2005) it is possible to count optical frequencies (about $10^{15}$ Hz) literally in cycles per second and to measure the ratio of optical frequencies with unprecedented precision. New ultra-accurate clocks will test whether fundamental “constants” of nature are changing over time. They also have many direct and near-term technological impacts, including enhancement of the performance of high-end analog-to-digital converters in advanced radar, more accurate global positioning satellites, and many other applications.

Optical and atom interferometry will lead to new navigation tools and measurements of gravitation. New AMO devices are enabling ever more precise measurements of motion by detecting tiny changes in the interference not just between beams of light but also between beams of atoms, as discussed below. Interferometers are the cornerstone of gravitational wave observatories on Earth and in space that are expected to provide new insight into the structure of our universe. Ring laser and fiber-optic gyroscopes are now standard sensors that play a broad role in state-of-the-art navigation systems. Matter-wave interferometers promise a huge improvement in navigational
systems accuracy. Laser-based gravimeters are being used worldwide to characterize Earth’s gravitational field for the management of oil deposits and other resources. Future systems based on atom-wave interference will enable airborne characterization of gravitational anomalies at unprecedented levels to detect hostile underground structures and tunnels.

*Atomic data and atomic theory provide critical support in astrophysics exploration.* Our universe serves as an extraterrestrial laboratory in which to test the laws of physics under extreme conditions. Satellite observatories can probe the environments near black holes and the surfaces of neutron stars. Studying the universe can provide clues to the nature of fundamental physical laws at times and at energies than cannot be reached with today’s earthbound laboratory experiments. AMO science plays a central role in helping us to understand what the data from radio, optical, and x-ray telescopes are telling us about these extreme astrophysical environments. Collisions of atoms, molecules, electrons, and ions in these extreme regimes yield new spectral features that can be modeled by theorists and used to understand the full range of extraordinary conditions observed in the universe.

As the following chapters show, there are many areas in which AMO transcends disciplinary lines and provides techniques and data which improve both our understanding of the universe and our daily lives. For example, AMO data lie at the heart of development of plasma processing, efficient lighting and many other high-temperature chemical reactions. Exciting new developments in biology include results from electron-molecule scattering, where it has been recently discovered that resonant dissociative electron capture plays an important role in radiation damage through DNA strand breaking. A summary of some of these kinds of cross-cutting possibilities are discussed in the NRC report “Atoms, Molecules and Light: AMO Science Enabling the Future”.

**WHAT HAPPENS AT THE LOWEST TEMPERATURES IN THE UNIVERSE?**

The Bose-Einstein condensates (BECs) developed in the laboratories of AMO physicists in the last decade are the coldest objects that have ever existed anywhere in the universe. These remarkable clouds of trapped atoms are about a billionth of a degree above absolute zero, much colder than the dark, frigid, furthest reaches of intergalactic space. Furthermore, Bose-Einstein condensates and their close cousins, ultracold degenerate Fermi-Dirac gases, are not just cold; these quantum condensates are proving to be very special states of matter (see Figure 1-2). Scientists have discovered that they have strange and wonderful properties, and in the next decade we can expect a rich harvest of interesting new physics ideas and applications—from technological breakthroughs such as clocks and inertial sensors of unprecedented accuracy, to insights into the physics of ordinary matter as well as matter under extreme conditions. More information on cold quantum gases is contained in Chapter 3 and summarized below.

*When breakthrough science happens it defines a new frontier.* Today, AMO science is camped on one of the most exotic frontiers in science—the push toward ever lower temperatures obtained in atomic physics labs. In the last decade, six physicists have won the Nobel prize for their work at the frontier of ultracold atomic gases. The record low temperature stands, as of early 2006, at about a billionth of a degree above absolute zero. By contrast, intergalactic space is a relatively hot 2.7 degrees above absolute zero, owing to the existence of the cosmic microwave background.

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An ultra-low-temperature gas is a fruitful frontier to explore for two reasons: The atoms and molecules are nearly free from thermal fluctuations, and the quantum (or de Broglie) wavelength of the particles becomes extremely large. As a result, the field of ultracold atoms has become a remarkable meeting place for scientists of many different professional specialties, all of whom have come to realize how much can be learned from this new discipline, and all of whom bring their own expertise to the mix.

When a gas of atoms is cooled to “degeneracy,” meaning it becomes so cold that the quantum wave of one atom starts to overlap with that of its nearest neighbor, and the atoms in question are bosons, the result is a BEC. In such a gas, a macroscopic fraction of the particles can all occupy simultaneously the lowest-energy “wave” in the box in which the atoms are kept.

Ultracold gases offer the intriguing possibility of building completely controllable models for matter. They can be confined in a variety of geometries, including situations that are effectively one- or two-dimensional rather than three dimensional. It is also possible to confine them in ways that mimic the periodic structure in solid crystals. These uses of ultracold atoms as quantum simulators are among the most exciting recent developments in AMO science. They have a considerable impact on precision measurements, as discussed in Chapter 2, and on quantum information science, as discussed in Chapter 7. Also these applications occur at the intersection of AMO physics and condensed matter and indeed AMO physics and other fields of physics. These strengthening links between AMO and other parts of physics promises exciting new discoveries in AMO science in particular and in physics more broadly.

FIGURE 1-2 Atomic lithium matter waves produced at Rice University. The spikes are called matter-wave solitons. They occur because these ultracold atoms bunch together due to the quantum forces they exert on each other. SOURCE: K.E. Strecker and R.G. Hulet, Rice University.
WHAT HAPPENS AT THE HIGHEST TEMPERATURES IN THE UNIVERSE?

Lasers in the next decade will reach peak powers of a million billion watts concentrated in a single beam of light for a little more than a millionth of a billionth of a second. This power exceeds, for an instant, all the electrical power production on Earth. The huge electric fields in these focused beams overwhelm the forces that bind electrons in atoms and molecules, leading to exotic states of matter usually found only in neutron stars, the early universe, hydrogen bombs, and particle accelerators. These lasers will help unravel the violent forces we see in the universe around us. High-powered optical lasers have applications to many other important technological problems as well, ranging from the prospect of controlling nuclear fusion as a source of clean, abundant energy to creation of next-generation compact x-ray microscopes with unprecedented resolution.

Advanced lasers open new scientific and technological frontiers that benefit from two closely related technical advances: the development of optical-wavelength laser beams with unprecedented power and a new generation of lasers that produce coherent x rays. Both high-powered lasers and x-ray lasers will expand our knowledge as they extend our use of electromagnetic radiation. Bright ultrarfast sources of x rays will revolutionize the study of matter in the next decade. Synchrotron x-ray light sources have been important tools for determining structure at the atomic scale. Today there are dozens of accelerator storage rings around the world, heavily used and devoted to research in materials science, chemistry, as well as biology and medicine. Another revolutionary tool will become available in the next decade: the x-ray free-electron laser. These x-ray lasers will be more than one billion times brighter than the brightest synchrotrons, with pulses more than one thousand times shorter. This means that they will be capable of concentrating unprecedented energy on the atomic scale in chemicals, materials, and biological molecules. An important challenge of the next decade is to find ways to take full advantage of this new capability to advance chemistry, biology, and medicine. One particularly important application, biomolecular imaging, is discussed in Chapter 5. Other applications are covered in Chapter 4.

New scientific and technological frontiers will be explored using ultraintense visible laser that can reach peak powers in excess of one million billion watts. Focused beams from the highest powered lasers can concentrate the equivalent power of the entire electrical grid of the United States onto a spot only a tenth of a human hair in diameter. The enormous electric fields in these focused laser beams dwarf the forces that bind electrons in atoms and molecules, literally tearing them apart in an instant. Such energetic states of matter are usually found only in the most exotic places in the universe—in the center of stars or in the explosion of a nuclear weapon. Scientists are learning how to harness the electric fields generated by intense lasers to create directed beams of electrons, positrons, or neutrons for medical and materials diagnostics.

New ultraintense laser sources can accelerate electrons to high energies in shorter distances than any other method yet devised, opening up the possibility of building powerful particle accelerators in quite small spaces (see Figure 1-3). The accelerated beams have been employed to make radioisotopes for medical use. These lasers have also generated plasmas capable of nuclear fusion, and their light has been converted to x-rays for research on dynamics in laser-excited solids. These applications are discussed in more detail in Chapter 4. Any one of these demonstration experiments could become the basis for expanded research and technology in the coming decade.
FIGURE 1-3  A plasma channel shown in blue and white, about a millimeter long and denser toward the edges, guides the laser and allows it to form high-quality electron beams. As the laser pulse travels from left to right, it traps and accelerates bunches of electrons to high energies in very short distances. SOURCE: Lawrence Berkeley National Laboratory.

FIGURE 1-4  Workers stand within the target chamber of the National Ignition Facility, which measures 30 feet in diameter and will contain 192 high-power laser beams, all directed at one small target. NIF can thus deposit enormous amounts of energy in very small volumes over very short times. SOURCE: Lawrence Livermore National Laboratory.
Controlled thermonuclear fusion is one particularly important challenge from the past decade that will continue to be important in the next. Laser-heated plasmas for fusion energy have been under development in the United States and Europe for decades, but recent progress in ultrafast and high-field lasers holds particular promise for rapid advances toward a device that will produce more fusion energy than it consumes in heating the plasma (the so-called breakeven point). Advanced high-intensity lasers may be a key technology to achieve breakeven. This will be tested in the next decade (see Figure 1-4).

CAN WE CONTROL THE INNER WORKINGS OF A MOLECULE?

In the next decade we will begin to observe the processes of nature as they play out over times shorter than a millionth of a billionth of a second (less than 1 femtosecond—that is, in the attosecond regime). This remarkable new capability is enabled by advances in ultrafast laser- and accelerator-based x-ray strobes, which can detect the motion of electrons in atoms and molecules. Scientists anticipate the possibility of capturing images of motion inside a molecule or taking a snapshot of a protein or virus (see Figure 1-5). We will also be able to control physical phenomena on all of the timescales relevant to atomic and molecular physics, chemistry, biology, and materials science. These previously unavailable tools of quantum control could help tailor new molecules for applications in health care, energy, and security.

A frontier of AMO science is to observe the basic processes of chemistry and biology on the scale of a single molecule. A key ingredient in taking slow-motion pictures is the ability to freeze the action by recording images with a shutter speed much faster than the motion of the object of interest. In atomic and molecular motion, as elsewhere in high-speed photography, the mechanical shutter has been replaced by a short pulse of light, which acts as a stroboscope. The picosecond (or faster) processes within molecules require very short pulses that can only be produced by a laser. The rotational motion of the molecules in a gas cell can be captured by illuminating the gas with laser pulses that are a fraction of a picosecond in duration, while freezing the vibrational motion of

![Figure 1-5: An x-ray free-electron laser (xfel) can image single biomolecules. Left: a simulated model of the anthrax lethal factor. Right: A simulation of the diffraction pattern of the molecule on the left, which can be processed by a computer to generate an image of the molecular structure with atomic resolution. SOURCE: Lawrence Livermore National Laboratory](image-url)
molecules requires pulses of a few femtoseconds. Freezing the motion of electrons as they move about the molecule requires subfemtosecond, or attosecond laser pulses.

*Capturing the motion of atoms in the attosecond regime is now possible.* Rapid molecular vibrations can be observed with a sequence of two subpicosecond pulses in which the first pulse excites the molecule and the second pulse probes the resulting molecular response as a function of the time interval between the pulses. The science breakthroughs brought about by this advance were recognized by the 1999 Nobel prize in chemistry. At the beginning of 2006 strobes as short as one hundred attoseconds have even captured the motion of the electrons within an atom. This motion is the fundamental physical basis for chemistry. Why do some atoms bind, and others not? Why do reactions take the time they do, and why do molecules bend one way but not another? Watching the steps in the dance of electrons will provide a wealth of new insight into the mechanisms of chemistry.

*Ultrafast pulses of x rays show great promise for investigating the structure of complex molecules.* X rays are very short wavelength light rays with two important differences from ordinary light: They can penetrate ordinary matter and reveal the interiors of solid objects and they can resolve very small objects, down to single atoms. X rays were used to reveal the double helix shape of the DNA molecule, which encodes the genetic information for all living things. Currently the brightest x-ray sources can reveal the atomic details of complex molecules and solids in a static or resting state but are not bright enough to capture changes such as chemical catalysis or absorption of sunlight in photosynthesis.

The new x-ray laser tools of 2010 and beyond will help scientists understand, manipulate, and exploit the molecular universe. What makes the molecules in all living organisms so efficient at carrying out particular tasks? Can we design other molecules to be as efficient as the ones that nature has optimized? What makes certain materials effective catalysts in chemical reactions or gives them the remarkable ability to capture sunlight efficiently and turn it into chemical energy?

*New 21st century tools also place us on the verge of the new discipline of quantum control.* This development is enabled by key advances in laser technology, which let us generate light pulses whose shape, intensity, and color can be programmed with unprecedented flexibility. Our ability to control the positions, velocities, and relative spatial orientations of individual atoms and molecules has led to a broad array of precision measurement technologies and devices, leading to a wide range of experiments and discussed throughout this report, that reveal qualitatively new phenomena. A new capability to manipulate the inner workings of molecules is emerging: Lasers can now be used to control the outcome of selected chemical reactions. This control technology may ultimately lead to powerful tools for creating new molecules and materials tailored for applications in health care, nanoscience, environmental science, energy, and national security.

**HOW WILL WE CONTROL AND EXPLOIT THE NANOWORLD?**

The nanoworld lies in between the familiar classical world of macroscopic objects and the quantum world of atoms and molecules. Nanostructures can have counter-intuitive but useful optical properties that arise because they are smaller than the wavelength of light used to observe them. Scientists see unique opportunities to tailor material properties for efficient optical switches, light sources, and photovoltaic power generators. Nanomaterials promise the development of single-photon sources and detectors, photonic crystals, environmental sensors, biomedical optics, and novel cancer therapies involving localized optical absorption. These opportunities are described in Chapter 6 and briefly summarized below.

* A myriad of powerful new tools are now available to create, visualize, and control structures on the nanoscale. Nanoscience includes fundamental research on the unique phenomena and
processes that occur at the nanometer scale (see Figure 1-6). Opportunities that lie in this region, between the quantum scale and the classical scale, involve AMO science in a number of ways. Nanostructures can be constructed from the bottom up using chemical and optical techniques, or from the top down using techniques such as optical lithography. The structures often have novel optical features, including special absorption properties and negative refractive indices. Nanomaterials with negative indices of refraction could dramatically improve optical microscopes or reduce the feature size in chip fabrication. A new field is growing up to take advantage of these opportunities: nanophotonics.

Size is everything in the nanoworld. The physical, chemical, and biological properties of nanostructured materials can vary substantially at the nanoscale. This dimensional dependence means that physical properties can be controlled by varying the size of the nanoparticles. Until recently, our ability to view or to control the nanoworld was so limited that harnessing it was impossible. However, owing to recent technological developments—many of which are coming from AMO science—efficient and practical nanoscale synthesis and assembly methods will be developed in the coming decade.

Nanofabrication promises to exploit the properties of lasers and optics to improve the production of nanomaterials. Laser ablation is one of the easiest and most widely understood methods for producing nanoparticles from solids. A new twist on this old method is the use of shaped ultrafast pulses to control the size and other characteristics of the nanoparticles. “Atomtronics” is a very new technology that employs trapped ultracold atoms above the surface of a microchip, one aim of which might be to create a single-atom transistor. Nanoscale engineering will allow the creation of new nanostructured media with exceptionally large optical nonlinearities, allowing efficient detection of infrared light. It will also allow the realization of optical nanoparticles, whose size and shape
determine their absorption, transmission, and reflection properties. In addition, nanoscale engineering will also allow new optical fibers that can carry the shortest ultrafast pulses without distortion, new lenses that can focus light far more tightly than allowed by the conventional rules of physical optics, and it will allow the construction of new optical displays with unprecedented ruggedness and low cost.

WHAT LIES BEYOND MOORE’S LAW?

Today’s computers are doubling in performance every year or two. This will end when the ever-shrinking size of electronic components approaches the level of individual molecules and atoms. While it is still uncertain whether a working large scale “quantum computer” (as we understand the word computer today) will ever be built, it is clear that quantum mechanics offers a radically different approach to information processing, in which single atoms and photons would be the new hardware. This could lead to computers capable of solving problems that are intractable on any imaginable extension of today's computers, but which are important in areas ranging from basic science to national security. Quantum communication might provide security against interception beyond anything possible in today’s cyber infrastructure. These applications are based on the strangest and least intuitive concepts of quantum physics, such as Einstein’s “spooky action-at-a-distance,” which allows “teleportation”, or the transfer of information (as opposed to actual physical objects) between remote quantum systems without any physical contact between the quantum hardware during the communication. The possibility of quantum computing is forcing us to explore both theoretical and experimental quantum mechanics at their deepest levels. Should quantum computers be realized, they would be more different from today’s high-speed digital computers than those machines are from the ancient abacus. These opportunities are described in Chapter 7 and summarized briefly below.

Quantum mechanics and information theory were two of the scientific cornerstones of the 20th century. One describes physics at very small scales, from molecules and atoms to electrons and photons; the other is a mathematical description of data communication and storage. With the last decades having witnessed the remarkable shrinking of electronic components that carry and process information to near-atomic scales, these two disciplines are naturally beginning to merge. Moore’s law of exponentially shrinking computer chip components will soon slow, as individual electronic transistors approach the atomic scale, where there is no more room for packing additional components. However, the revolutionary principles of quantum mechanics could offer a way out: quantum information science may have profound and far-reaching relevance to economic growth, secure communication, and specialized number-crunching. The quantum hardware now found in atomic, molecular, and optical systems is the key to realizing future quantum devices and will be crucial to the understanding and development of quantum hardware in complex condensed matter systems.

Quantum mechanics contains radical features not found in any other physical theory. The quantum mechanical concept of superposition, where objects can exist in many states simultaneously, is at center stage. When multiple systems are prepared in certain types of “entangled” superpositions, there is a linkage between the systems that does not involve any apparent physical interaction. Einstein called this “spooky action-at-a-distance,” and it is the key to the information processing power of quantum information science. The binary digits or bits from conventional information theory now take the form of quantum bits (“qubits”), which can store and process superpositions of numbers in a way that is impossible in any conceivable conventional information processor.

Quantum information theory is a young and rapidly developing field, spanning many areas of science and engineering. Conventional techniques such as logic gate families and error-correction
are being adapted to the quantum realm. The landscape of possible quantum applications is still evolving. The best known application is Shor’s quantum factoring algorithm, which uses a quantum computer to factor a large number exponentially faster than any known classical algorithm. This has far-reaching implications in the world of cryptography, where most public-key current encryption standards are based on the inability to factor large numbers efficiently. The availability of a quantum factoring machine would render obsolete most of today’s encryption standards.

Quantum mechanics offers a remarkable new method for secure data transmission. Quantum cryptography exploits the fundamental tenets of quantum mechanics to allow the secure transmission of information with no physical possibility of undetected eavesdropping. Quantum cryptographic instruments are already available commercially, featuring the use of small numbers of photons traversing a length of optical fiber. There is a rich array of other quantum communication protocols that allow the movement and networking of data in ways that are more efficient than corresponding classical procedures.

AMO physics is concerned with the control and manipulation of atoms, molecules, and photons and is therefore well placed for the development of quantum hardware. Individual atoms confined with electromagnetic fields can be laser-cooled to be nearly motionless, and to act as ideal qubit carriers of quantum information (see Figure 1-7). These atoms can be linked by implementing quantum logic gates through direct atom-atom interactions or through individual photons that couple atoms. In this way, large-scale entangled superpositions can be prepared. The use of atomic ion traps, optical lattices, and photons confined between closely spaced mirrors are but a few of the systems that are just starting to show promise for use as future quantum devices.

The grand challenge of quantum information science is the scaling of these AMO systems to the quantum control of even more complex systems. In the realm of condensed-matter systems, both superconducting devices that support quantized levels of currents or charges and spin-based devices are now being developed to show rudimentary quantum operations akin to their AMO cousins. While the development of quantum computing and communications hardware currently focuses on AMO...

FIGURE 1-7 At NIST, an ultraviolet laser beam is used to manipulate ions in a high-vacuum apparatus containing an ion trap. These devices have been used to demonstrate the basic operations required for a quantum computer and for “teleportation” of the quantum state of one atom onto another. SOURCE: National Institute of Standards and Technology.
science, the future of quantum information science will involve an exciting confluence of scientists and engineers of all stripes.

CONCLUSIONS AND RECOMMENDATIONS

The research field of AMO science and technology is thriving. The committee offers the following conclusions on the opportunities in AMO R&D:

- Revolutionary new methods to measure space and time have emerged within the last decade from a convergence of technologies in coherent control 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 contribute significantly to the resolution of 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 capability 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. Compelling opportunities in both molecular science and photon science 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 for 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.

The key future opportunities for AMO science contained in this report are based on rapid and astounding developments in the field that are a result of investments made by the federal government’s R&D agencies in the work of AMO researchers. These compelling research challenges are discussed in more detail in the following chapters which also highlight the broad impact of AMO science on other branches of science and technology, and its strong coupling to national priorities in health care, economic development, the environment, national defense, and homeland security.
The linkages to 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 on January 31, 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.

An essential part of maintaining the country’s leadership in AMO science, and one of the White House’s R&D priorities, is to train and to equip the next generation of American scientists. The committee has compiled data on funding, demographics, and program emphasis from the federal agencies to help it assess the current state of AMO science in the United States. In summary, the committee offers the following conclusions on federal support for AMO science:

- 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 DOE, NIST, and NSF has been to benefit activities at research centers. The overall balance of the modalities for support of the field has led to outstanding scientific payoffs.

- The breadth of AMO science and of the agencies that support it is very important to future progress in the field and has been a key factor in its success so far.

- Since all of the agencies report that they receive many more proposals of excellent quality than they are able to fund, it is clear that AMO science remains rich with promise for outstanding future progress. AMO science will continue to make exceptional advances in science and in technology for many years to come.

- In view of its tremendous importance to the national well being, broadly defined—that is to our nation’s economic strength, health care, defense, education, and domestic security—an enhanced investment program in research and education in physical science is critical and such a program will improve the country’s ability to capture the benefits of AMO science.
Historically, support for basic research has been a vital component of the nation’s defense strategy. Therefore, the recent decline in funding for basic research at the defense-related agencies is troubling.

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 insufficient.

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 number of American students choosing physical science as a career is dangerously low. Without remediation, this problem is likely to create an unacceptable “expertise gap” between the United States and other countries.

Scientists and students in the United States benefit greatly from close contact with the scientists and students of other nations. Vital interactions include the training of foreign graduate students, international collaborations, exchange visits, and meetings and conferences. These interactions promote excellent science, and improve international understanding, and support the economic, educational, and national security needs of the United States.

Finally, the committee offers the following recommendations which, as a whole form a strategy to fully realize 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.