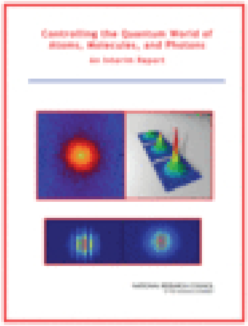

Controlling the Quantum World of Atoms, Molecules, and Photons: An Interim Report

Committee on AMO 2010, National Research Council

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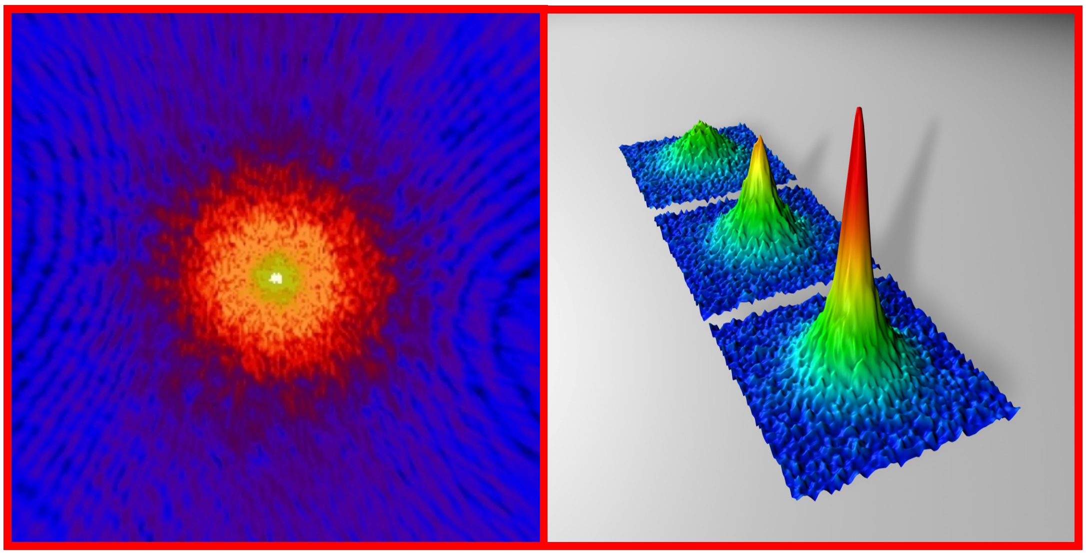

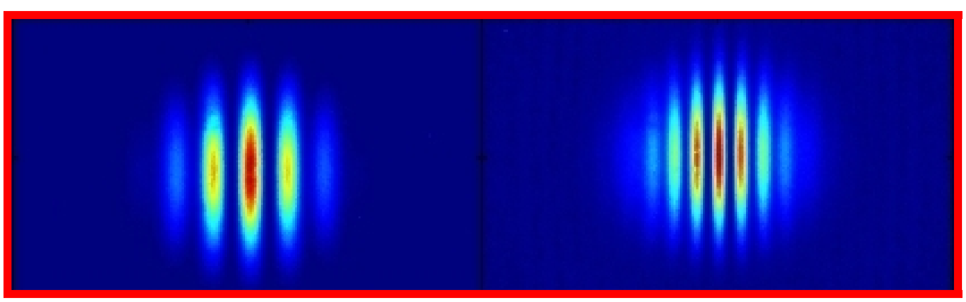

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Cover: *Upper left,* Simulation of X-ray diffraction pattern of anthrax from the Linear Coherent Light Source (courtesy of Lawrence Livermore National Laboratory). *Upper right,* Time-of-flight images showing a fermionic condensate (courtesy of JILA/University of Colorado). *Below,* Extreme ultraviolet (EUV) interferograms created by laserlike (or coherent) beams of short wavelength light centered at photon energies of 45 eV and diffracted by pinhole pairs at separations of 150 μm (left) and 250 μm (right) (courtesy of JILA/University of Colorado).

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

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

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:

Keith Burnett, Oxford University,
Alexander Dalgarno, Harvard-Smithsonian Center for Astrophysics,
Gerald Gabrielse, Harvard University,
Chris H. Greene, University of Colorado,
William Happer, Princeton University,
Wendell T. Hill, University of Maryland,
Erich P. Ippen, Massachusetts Institute of Technology,
Gerard J. Milburn, The University of Queensland, and
Richard 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.

CONTROLLING THE QUANTUM WORLD OF ATOMS, MOLECULES, AND PHOTONS: AN INTERIM REPORT

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 has 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

[1]For further detail on the connections between AMO science and society's needs, see National Research Council, *Atoms, Molecules, Light*: *AMO Science Enabling the Future*, Washington, D.C.: The National Academies Press (2002), available at <http://www.nap.edu/catalog/10516.html>.

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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.

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- *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

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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.[2] 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]<http://www7.nationalacademies.org/bpa/AMO2010_Home.html>.