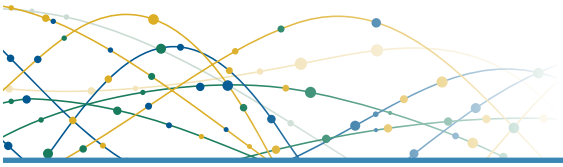

Consensus Study Report

HIGHLIGHTS

December 2019

Manipulating Quantum Systems: An Assessment of Atomic, Molecular, and Optical Physics in the United States

Discoveries in Atomic, Molecular, and Optical (AMO) physics have provided the foundation for critical everyday technologies that have transformed human society over the past few decades, from medical applications such as MRI to the lasers in consumer electronics. Over the next decade, AMO science will play a pivotal role in new advances ranging from the development of quantum computing to astrophysics. Due to the wide-reaching impact of AMO, the Department of Energy and the National Science Foundation asked the National Academies of Sciences, Engineering, and Medicine to survey the recent advances in AMO physics, identify future research directions, and make recommendations regarding funding and workforce.

WHAT IS ATOMIC, MOLECULAR, AND OPTICAL SCIENCE?

AMO scientists study the fundamental building blocks of matter to help advance our understanding of the universe. AMO physics is a foundational discipline within the physical sciences, relating to atoms and their constituents, to molecules, and to light at the quantum level. AMO physics combines theoretical research with practical application, sparking new technological advances, innovation, and commercialization.

AMO SCIENCE IS A CRITICAL INVESTMENT

The U.S. research community has enjoyed global leadership in AMO physics thanks to sustained support from the federal government and an AMO culture that fosters collaboration and open research. Yearly trends of research publications provide a good indicator that the United States maintains a strong position in AMO science globally, although many European nations along with China, South Korea, Japan, and Australia are rapidly catching up. However, U.S. funding has not kept up with growth in this field, causing U.S. global leadership to begin to erode as other countries increase their investments. Funding over the last decade for AMO science has seen little to no change, with large annual variations for certain programs, and flat budgets for others. Coordinated interagency support is needed for continued development and leadership of AMO science in the US. Given that the AMO research enterprise has been the driving force behind many new scientific discoveries and innovative technologies, the committee strongly urges continued national investment in AMO science. Funding for AMO science is particularly important because of the central role AMO science plays in advancing other physical science disciplines.

RECOMMENDATION: The U.S. government should vigorously continue investment in curiosity-driven atomic, molecular, and optical science to enable exploration of a diverse set of scientific ideas and approaches. AMO is a critical investment in our economic and national security interests.

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NEW OPPORTUNITIES IN QUANTUM SCIENCE

The development of quantum technologies brings important new opportunities in sensing and precision measurement that can have applications ranging from quantum computation to enhanced communication and navigation. With quantum information technology still at a very early stage, there is an increasing number of potential new systems and platforms one can exploit for the construction of quantum machines. Therefore, it is urgent that the research community develop platform-independent metrics to measure and characterize the performance of quantum technologies. Nurturing research into quantum information systems, work that will provide critical tools and insights for other areas of science, will require long-term investments that cross traditional disciplinary boundaries.

RECOMMENDATION: Basic research in science, engineering, and applications underlying both existing and emerging new platforms needs to be broadly supported, including research on techniques for cross-verification of quantum machines across different platforms for various applications. Specifically, the committee recommends that the National Science Foundation, Department of Energy, National Institute of Standards and Technology, and Department of Defense should provide coordinated support for scientific development, engineering, and early applications of AMO-based quantum information systems

RECOMMENDATION: The Department of Energy High Energy Physics, Nuclear Physics, and Basic Energy Sciences programs should fund research on quantum sensing and pursue beyond-the-standard-model fundamental physics questions through AMO-based projects.

CORE STRENGTHS AND NEW OPPORTUNITIES: A BALANCED PORTFOLIO

Creative science carried out by single-investigator groups is the heart of AMO science. The field has done well building on creative efforts of these individual investigators, but it is entering a new phase where collaborations with flexible-sized teams would enable exciting new discoveries. Therefore, it is important to maintain a good balance between large-scale national facilities, mid-scale university-hosted projects, and single-investigator programs, particularly in the fields of high-intensity lasers and quantum science.

RECOMMENDATION: U.S. federal agencies should invest in a broad range of science that takes advantage of ultrafast X-ray light source facilities, while maintaining a strong single principal investigator funding model. This includes the establishment of open user facilities in mid-scale university-hosted settings.

Additionally, both space- and laboratory-based fundamental AMO science are needed to address key questions in astronomy, astrophysics, and cosmology. Recently developed AMO tools and technologies are also ready for deployment in space missions. However, addressing these opportunities will require strong inter-agency coordination that supports AMO and astrophysics.

RECOMMENDATION: The National Aeronautics and Space Administration, in coordination with other federal agencies, should increase investments in theory and experiment for both space- and laboratory-based fundamental atomic, molecular, and optical science that are needed to address key questions in astronomy, astrophysics, and cosmology.

EDUCATION AND WORKFORCE DEVELOPMENT

Academia needs to evolve to encourage cross-disciplinary hiring of both theorists and experimentalists at the rapidly growing interfaces between AMO and computer science, mathematics, chemistry, biology, astrophysics, engineering, and industry. Overall, education in preparation for a research career in AMO, as measured by the number of Ph.D.s granted, remains robust. However, interdisciplinary educational programs and funding mechanisms are needed so that other fields can take advantage of, and contribute to, cutting edge AMO science.

Strong collaboration between theorists and experimentalists is important for maintaining the health of AMO science. However, the number of faculty positions in AMO theory is limited. Additionally, experimental AMO science has become very expensive, and the starting cost of a new experimental program has become a deterrent for young AMO scientists being appointed as faculty in academia. Further-

more, departmental boundaries create barriers for young AMO-trained post-docs to move into related disciplines and departments, such as quantum information science and computer science, where their AMO training would play key roles in advancing those fields. In particular, quantum technology cuts across scientific fields and technologies beyond AMO, and so encounters barriers with traditional funding mechanisms.

RECOMMENDATION: The National Science Foundation, Department of Energy, National Institute of Standards and Technology, and Department of Defense should increase opportunities for translating atomic, molecular, and optical science advances to other fields by fostering collaboration with scientists and engineers from other disciplines through, for example, support of workshops and similar mechanisms for cross-disciplinary interactions.

RECOMMENDATION: The committee recommends that AMO funding agencies should develop portable fellowship grant models that support the transition of AMO science theorists and experimentalists into faculty positions.

RECOMMENDATION: To maximize the effectiveness of federal investment, academia should enable and encourage cross-disciplinary hiring of theorists and experimentalists at the rapidly growing interface between AMO science fields and computer science, mathematics, chemistry, biology, engineering, as well as industry.

AMO science, like other physics disciplines, continues to have difficulty in attracting women and underrepresented minorities at all levels. It is clear that education and workforce development in AMO is not keeping up with the demographics in the nation, and that this is a lost opportunity.

RECOMMENDATION: The entire AMO science enterprise should find ways to tap into the growing national talent pool of women and underrepresented minorities. The committee therefore endorses the relevant recommendations in the National Academies reports *Graduate STEM Education for the 21st Century* and *Expanding Underrepresented Minority Participation*, for example.

FACILITATING INTERNATIONAL COOPERATION IN ATOMIC, MOLECULAR, AND OPTICAL SCIENCE

The health of AMO science relies heavily on strong international collaborations, yet there are a number of technical and regulatory impediments that make it difficult to maintain U.S. leadership in research, education, and innovation globally. Some of these impediments include major differences in intellectual property ownership policies and conflict-of-interest rules between the U.S. and other countries, as well as currency exchange and audit requirements that make it difficult for U.S. universities to accept and administer grants from the EU.

In addition, despite security concerns, there is great national benefit in having intellectual leaders visiting the United States. This benefit is at risk due to continuing significant issues that international students, collaborators, and conference speakers experience in the United States, such as excessive visa delays and refusal of access to national research facilities. Open collaborations have been vital for the health of AMO physics, and the U.S. reputation as a welcoming place for the best international students and researchers has been key in attracting future leaders to the United States.

RECOMMENDATION: The committee recognizes the real security concerns in open, international collaboration. However, because open collaborations have been so vital for the health of atomic, molecular, and optical physics, the Office of Science and Technology Policy and federal funding agencies should work collaboratively with the Department of State and an academic consortium such as the Council on Governmental Relations to remove impediments to international cooperation. There is a critical need for

1. Blanket agreements for funding agencies in different countries to accept each other's grant administration regulations;
2. Standardized mechanisms for joint funding of cooperative projects; and
3. Mechanisms to remove excessive visa application delays for international students, collaborators, and speakers at U.S. conferences and workshops.

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