The National Academies of
SCIENCES • ENGINEERING • MEDICINE

BOARD ON PHYSICS AND ASTRONOMY (BPA)

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

A study under the auspices of the
U.S. National Academies of Sciences, Engineering, and Medicine

Jun Ye & Nergis Mavalvala, Co-Chairs

The study is supported by funding from the DOE, NSF, and AFOSR.
(Further information can be found at: https://www.nap.edu)

What is AMO?

- Basic fabric of light-matter interactions & window to the quantum world
- Plays a central role for other physical sciences and beyond
- Foundation for critical everyday technologies: such as lasers, MRI, GPS, fiber networks.
- Critical to emerging fields such as quantum computing, fundamental physics beyond standard model, astrophysics.
- Strong cycles between basic science, practical technologies, economic development, and societal impacts
- Unique training ground for future workforce.

Statement of Task - from the Agencies to AMO2020

The committee is charged with producing a comprehensive report on the status and future directions of atomic, molecular, and optical (AMO) science. The committee's report shall:

- Review the field of AMO science as a whole, emphasize **recent accomplishments**, and identify **new opportunities** and compelling scientific questions.
- Use case studies in selected, non-prioritized fields in AMO science to describe **the impact that AMO science has on other scientific fields**, identify opportunities and challenges associated with pursuing research in these fields because of their **interdisciplinary** nature, and inform recommendations for addressing these challenges.
- Identify the impacts of AMO science, now and in the near future, on **emerging technologies and in meeting national needs**.
- **Evaluate recent trends in investments** in AMO research in the United States relative to similar research that is taking place internationally, and provide recommendations for either securing leadership in the United States for certain subfields of AMO science, where appropriate, or for enhancing collaboration and coordination of such research support, where appropriate.
- Identify **future workforce, societal, and educational needs** for AMO science.
- Make recommendations on how the U.S. research enterprise might **realize the full potential** of AMO science.

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, and institutional and programmatic barriers.

Committee Composition

Jun Ye (NAS), *Co-chair*, JILA

Nergis Mavalvala (NAS), *Co-chair*, Massachusetts Institute of Technology

Louis DiMauro, Ohio State University
Ray Beausoleil, Hewlett Packard Enterprise
Patricia M. Dehmer, Department of Energy (Ret.)
Mette Gaarde, Louisiana State University
Chris H. Greene, Purdue University
Steve Girvin (NAS), Yale University
Taekjip Ha (NAS), Johns Hopkins University
Mark Kasevich, Stanford University
Michal Lipson, Columbia University
Mikhail Lukin (NAS), Harvard University
A. Marjatta Lyyra, Temple University
Peter J. Reynolds, Army Research Office
Marianna Safronova, University of Delaware
Peter Zoller (NAS), University of Innsbruck

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Report Process - Input and Deliberation

Meetings

First Committee Meeting
May 31-June 1, 2018
Ft. Lauderdale, FL

Second Committee Meeting
September 19-20, 2018
Washington, DC

Third Committee Meeting
November 29-30, 2018
Irvine, CA

Fourth Committee Meeting
Februrary 13-15, 2019
Washington, DC

Fifth Committee Meeting at DAMOP
May 29-30, 2019
Milwaukee, WI

Survey Town Halls

May 30, 2018
6-7 p.m.
APS Division of Atomic, Molecular and Optical Physics APS Meeting
Hilton Fort Lauderdale Marina
Ft. Lauderdale, Florida

September 19, 2018
9-10 a.m.
OSA Frontiers in Optics and Laser Science
Washington Hilton

White paper/input submitting information at http://nas.edu/AMO

Committee Telecons

August 08, 2019

January 04, 2019

January 07, 2019

January 30, 2019

March 07, 2019

April 16, 2019

August 19, 2019

August 22, 2019

September 12, 2019

October 21, 2019

Bottom Line

Key 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.

New Opportunities in Quantum Science

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 NSF, DoE, NIST, and DoD 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

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.

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 AMO science that are needed to address key questions in astronomy, astrophysics, and cosmology.

Education and Workforce

RECOMMENDATION: NSF, DoE, NIST, and DoD should increase opportunities for translating AMO 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.

Education and Workforce

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.

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.

International Collaboration

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;
3. Mechanisms to remove excessive visa application delays for international students, collaborators, and speakers at U.S. conferences and workshops.

Report Organization

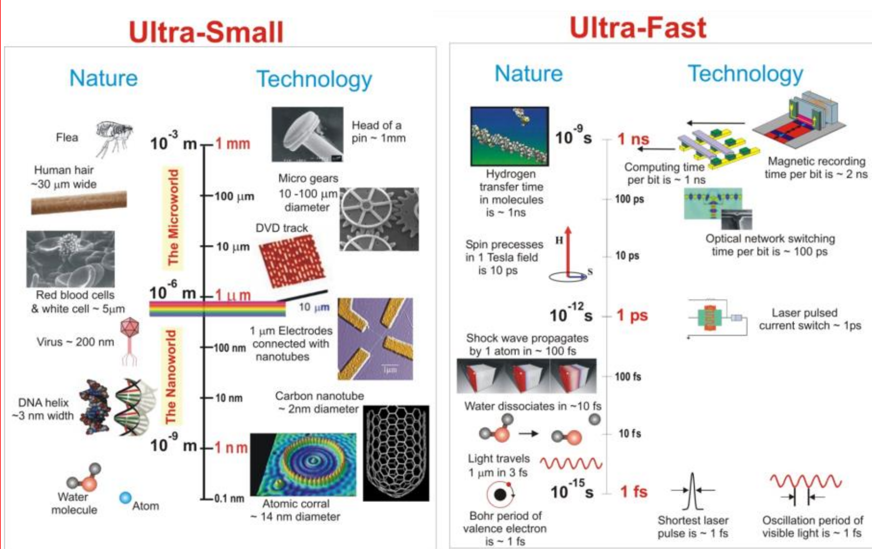
- Manipulating quantum systems: AMO science in the coming decade
- Tools made of light
- Emerging phenomena from few- to many-body systems
- Foundations of quantum information science and technology
- Harnessing quantum dynamics in the time and frequency domains
- Precision frontier and fundamental nature of the Universe
- Broader impact of AMO science
- AMO science: Part of the US economic and societal ecosystem

Ch 2: Tools made of light

Light is a ubiquitous tool in science, technology and everyday life

The past decade has seen revolutionary advancements in light source development that push new precision frontiers in time and frequency. The ability to control and manipulate these tools made of light is enabling new applications that extend beyond AMO physics.

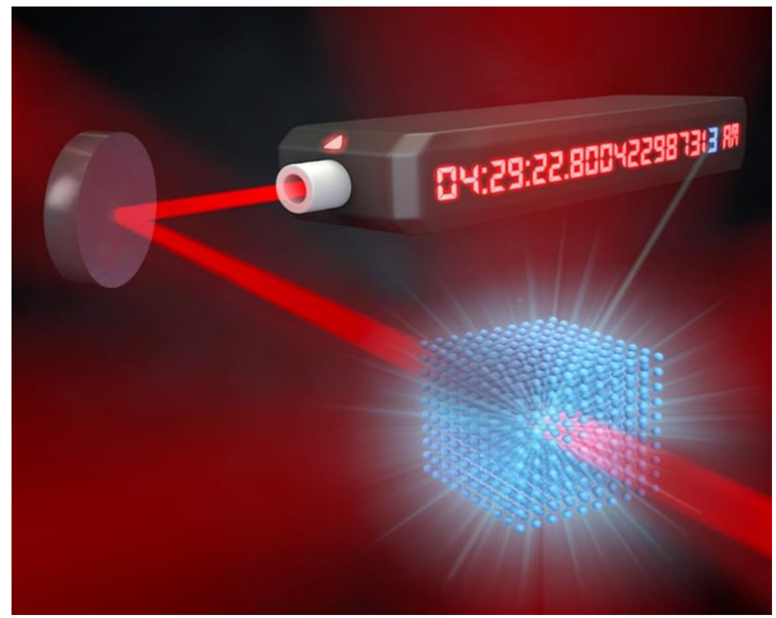
Ultrafast x-ray FEL sources



Now: ultra-fast (fs) meets the ultra-small (x-rays)

Future: light at atomic length and time scales

Atomic clocks



Now: optical clocks vastly improves time keeping

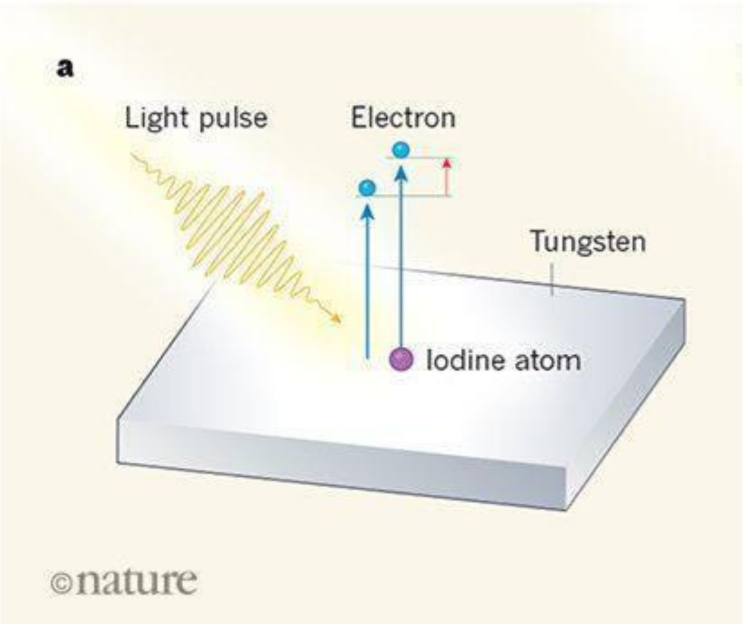
Future: Extreme spatial resolution for quantum & gravity

Ch 5: Harnessing Quantum Dynamics

Invest in science taking advantage of ultrafast XUV and X-ray light sources

Ultrafast sources allow tracking and controlling flow of energy from electronic excitation through structural and chemical changes. Scale up efforts to impact fundamental science through technology and photobiology. Single- and multi-PI funding mechanisms crucial.

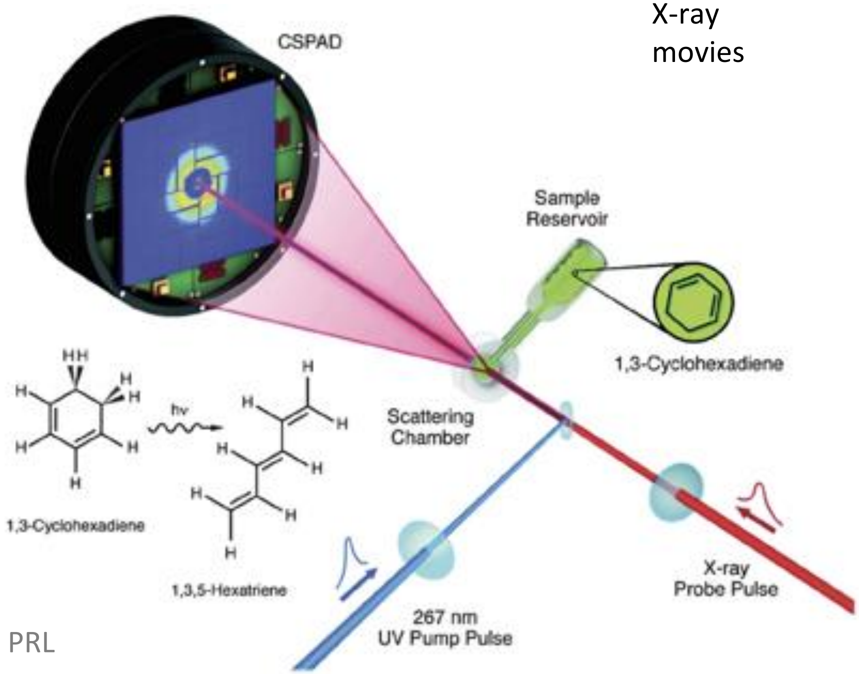
Attosecond science



Now: Timing emission of electrons from metal

Future: Lightwave electronics (PHz flop rate)

X-ray movies



PRL

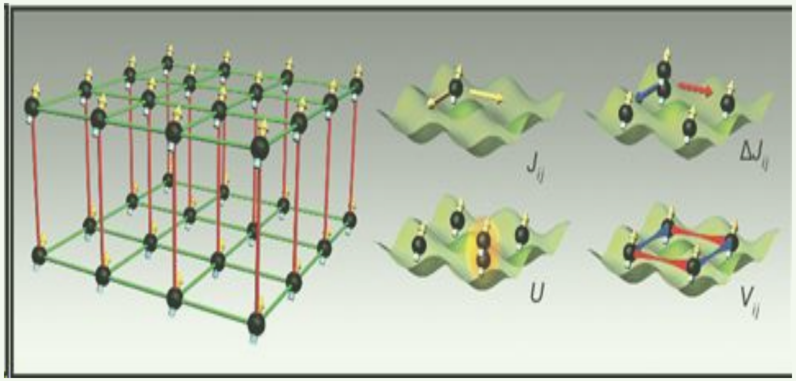
Now: X-ray laser movie of ring-opening reaction in gas

Future: From electrons to biology in single molecules

Ch 3: Emerging Phenomena from Few- to Many-Body Systems

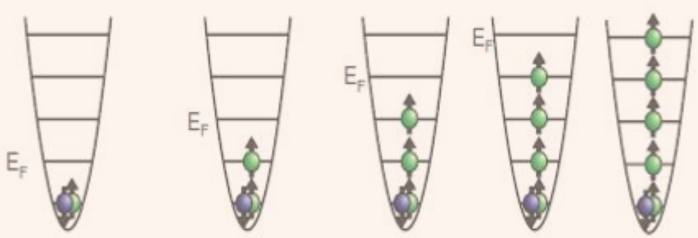
Fundamental research in the deep quantum limit opens the door to opportunities for atom-level control and understanding

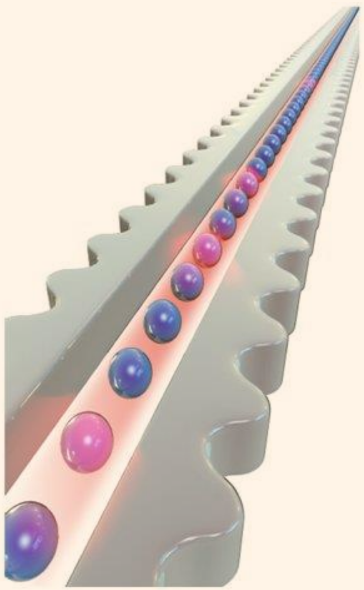
Tremendous progress illuminates the transition from a few quantum particles into the many-body limit. Strengthening basic theory and experimental investigations into the quantum phenomena of atoms and molecules, as well as quantum simulation, is a pre-requisite to implementing serious, large-scale quantum information protocols.



Optical lattice of magnetic atoms with long range interactions realizes a primary model of many-body dynamics

At what point do “a few” atoms become a “many-body system”? We now study this by adding atoms one at a time.





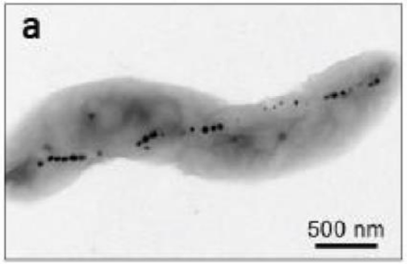
Artificial photonic crystal strongly couples atoms & light

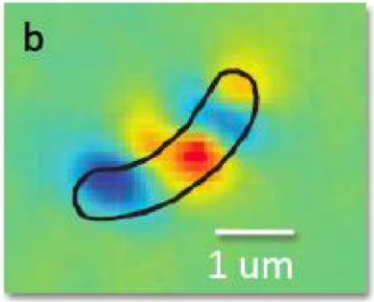
Ch 4: Foundations of Quantum Information Science and Technology

AMO systems are playing an essential role in laying the foundations of the second quantum revolution which will bring us radically new ways to process and communicate information, and sense the tiniest signals.

Grand Challenge: Realization of Large-Scale Quantum Machines and Networks

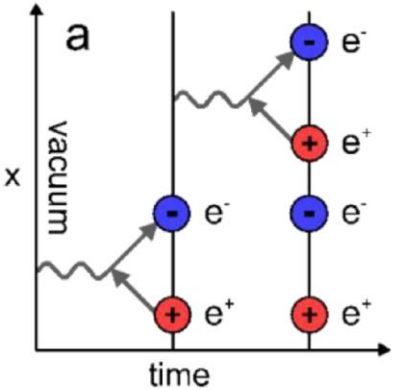
Basic research will generate the new ideas needed to meet this challenge

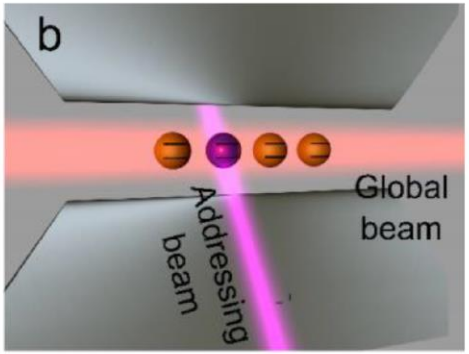




Now: NV-center quantum sensing of the magnetic domains in magnetotactic bacteria.

Future: Single-atom resolution MRI of molecules.





Now: Ion-trap quantum computer simulation of the Schwinger model of particle-antiparticle production.

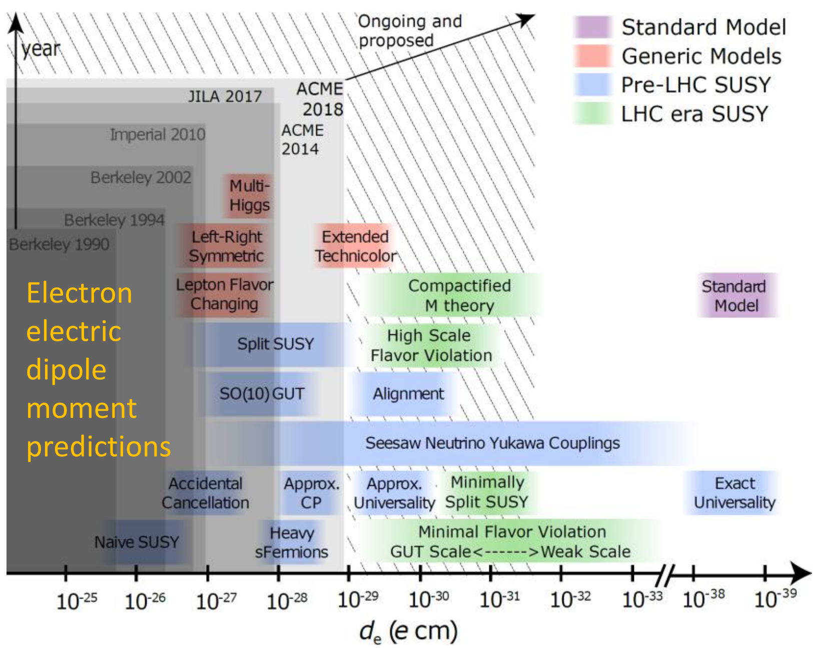
Future: Quantum simulation of strongly correlated lattice gauge theories and quantum chemistry of molecules far beyond the capabilities of conventional computers.

Ch 6: Precision Frontier and Fundamental Nature of the Universe

AMO provides precision measurement technologies, from atomic clocks to magnetometers

- Exceptionally high potential for **paradigm-shifting discoveries** of new physics phenomena
- Opened a new window on the Universe through gravitational wave detection
- Provides tools and techniques for industry and National Security
- Requires close collaboration between theory and experiment

New physics beyond the Standard Model



- AMO can probe new physics not accessible by colliders and other high-energy technologies
- Many new opportunities for dark matter searches

Economic and National Security Implications

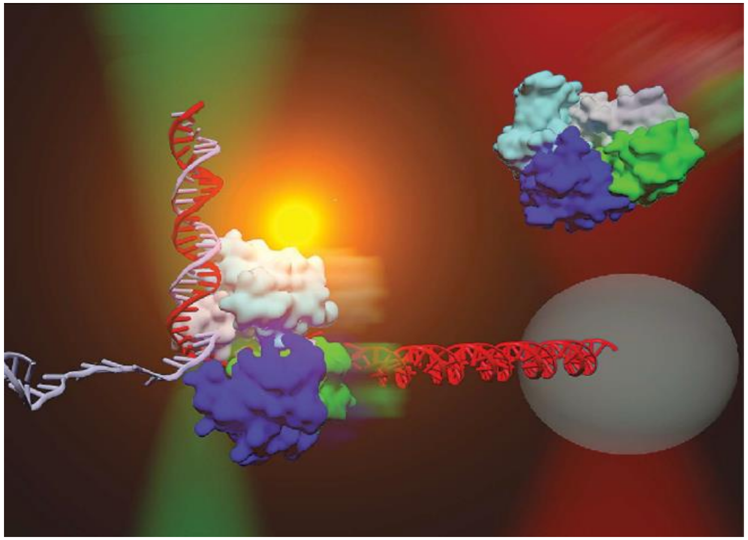
- International General Conference of Weights and Measures in 2018 redefined all measuring units in terms of fundamental constants
- Ultra-high quantum-based precision sensors
- New instrumentation for Industry

Ch 7: Broad Impact of AMO Science

Accelerate adoption of latest AMO technologies in other sciences and industry

- Single molecule and super-resolution imaging reveals new biology
- Image living systems near native conditions
- Search for earth-like exoplanets
- Fundamental science pushes industry into new technologies
- Commercial off-the-shelf technology enables new science

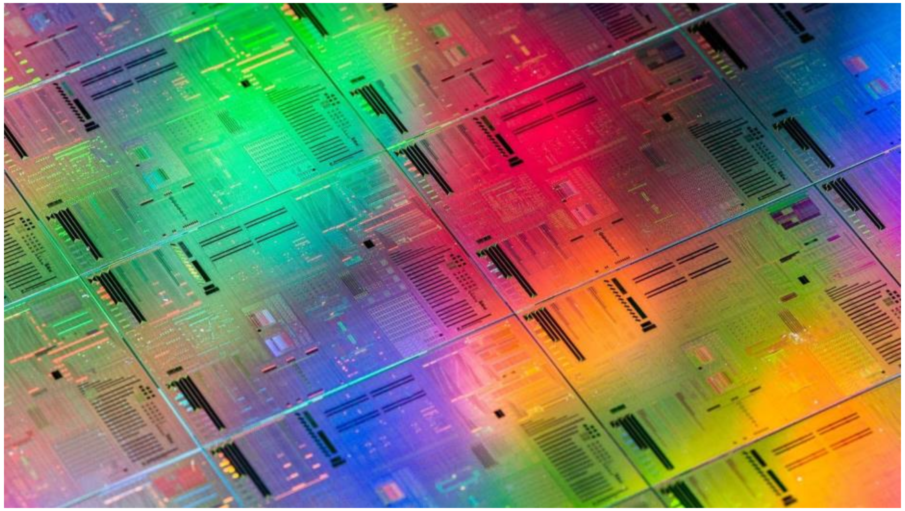
Biomolecule manipulation with light



Now: single enzyme optomechanics *in vitro*

Future: life at ever higher resolution *in situ*

Industry to science



Now: Interconnected nanophotonic circuits comprising thousands of integrated optical components

Future: Programmable photonics beyond Moore's Law

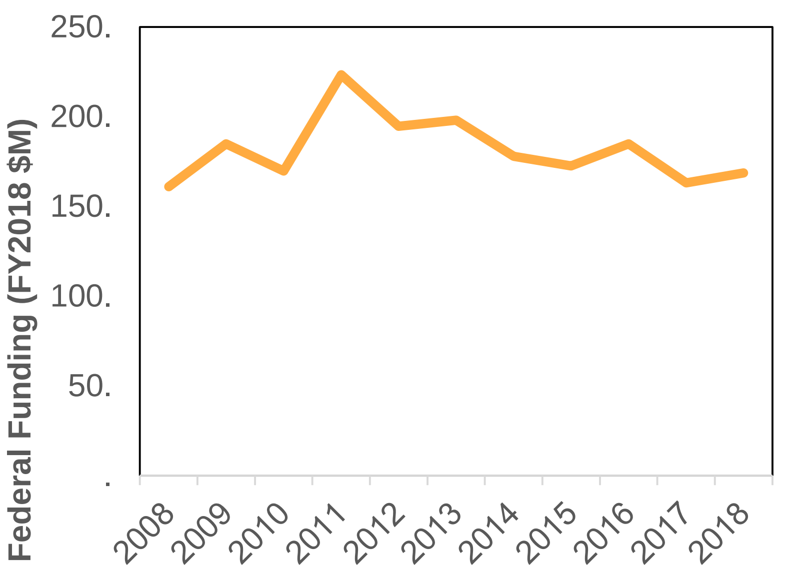
Ch 8 – AMO science: Part of the US economic and societal ecosystem

Sustained financial investments with flexible funding models are critical to maintain US leadership in AMO science

The US is at risk of losing its leading position as investments internationally are on the rise, and visa delays and denials are hindering the pace of progress the US

Significant opportunities exist to capture an untapped talent pool by increasing participation by women and underrepresented groups

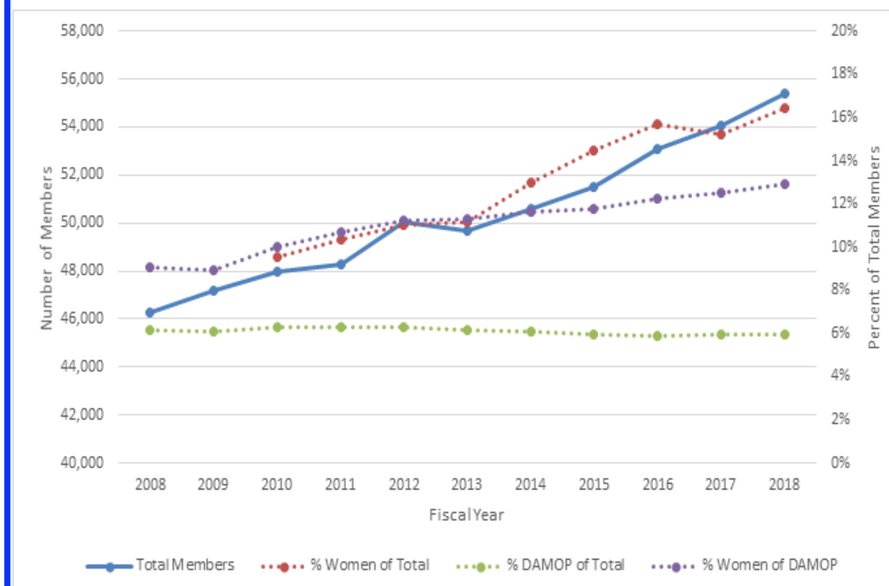
Federal research funding trends



Now: Little or no increase in federal funding for AMO

Future: Maintain robust funding with flexible funding models and coordination among agencies

Demographic opportunities



Now: Participation of women and URMs remains low

Future: Incentivize recruitment and retention of these groups and monitor progress

Bottom Line

Key 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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Manipulating Quantum Systems

An Assessment of Atomic, Molecular, and Optical Science in the United States

Download the report at nap.edu

BACKUP SLIDES

Chapter 2 Recommendations

Key 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 user facilities in mid-scale university-hosted settings.

Recommendation: The federal government should provide funding opportunities for both basic and applied research that enables the development of industrial platforms, such as foundry offerings, and interdisciplinary academic laboratories to support the integration of photonics and engineered quantum matter.

Chapter 3 Recommendations

Recommendation: The atomic, molecular, and optical science community should aggressively pursue, and federal agencies should support, the development of enhanced control of cold atoms and molecules, which is the foundational work for future advances in quantum information processing, precision measurement, and many-body physics.

Recommendation: Federal funding agencies should initiate new programs to support interdisciplinary research on both highly correlated equilibrium phases and non-equilibrium many-body systems and novel applications.

Chapter 4 Recommendations

Recommendation: In support of the National Quantum Initiative, federal funding agencies should broadly support the basic research underlying quantum information science.

Recommendation: Academia and industry should work together to enable, support, and integrate cutting-edge basic research, complemented by focused engineering efforts for the most advanced quantum information science platforms.

Chapter 4 Recommendations

Recommendation: The Department of Energy and other federal agencies should encourage medium-scale collaborations in quantum information science among academia, national laboratories, and industry.

Recommendation: (a) The Department of Defense (DoD) should continue both this foundational support for novel developments and the exploitation of the resulting technologies. (b) U.S. funding agencies participating in the National Quantum Initiative (NQI) should collaborate with each other and with DoD to build on the long history in quantum information science when developing their plans under NQI. (c) Department of Energy and its laboratories should develop strong collaborations with leading academic institutions and other U.S. funding agencies to realize the full potential of QIS.

Chapter 5 Recommendations

Key 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.

Recommendation: National laboratories and NASA should secure the continuation of collision physics and spectroscopy expertise in their research portfolios.

Chapter 6 Recommendations

Key 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.

Recommendation: Federal funding agencies should modify funding structures to allow for theoretical and experimental collaborations aimed at atomic, molecular, and optical science-based searches for new physics and development of diverse set of atomic, molecular, and optical precision measurement platforms including larger (more than five principal investigators) and long-term (10-year) projects.

Chapter 6 Recommendations

Recommendation: Funding agencies should establish funding structures for continued support for collaborative efforts of atomic, molecular, and optical theory and experiment with particle physics and other fields, including joint projects, joint summer schools, dedicated annual conferences, and so on.

Recommendation: U.S. federal agencies should establish mechanisms to co-fund international collaborations in precision searches for new physics with other worldwide funding agencies.

Chapter 7 Recommendations

Recommendation: Federal agencies should improve the availability and raise the awareness of the latest atomic, molecular, and optical (AMO) technologies for researchers in other fields of science. Additionally, agencies should create funding opportunities to bridge the latest AMO technologies to other disciplines, specifically targeting early adopters.

Recommendation: State governments should encourage the exploitation of opportunities to compete for economic development in atomic, molecular, and optical (AMO)-related science and engineering user facilities at universities using state funding and/or industrial joint support.

Chapter 7 Recommendations

Recommendation: The National Science Foundation and Defense Advanced Research Projects Agency should create funding opportunities that target strong multidisciplinary collaboration between academia and industry to transfer current e-beam lithography methods in engineered quantum matter to advanced photolithography pilot lines.

Recommendation: The National Science Foundation Research Trainee Program should be expanded to ensure that the next generation of post-doctoral fellows are prepared to handle research and innovation challenges across the engineering and physical sciences landscape, particularly in quantum engineering.

Chapter 7 Recommendations

Recommendation: The federal government should provide funding opportunities for basic research that enables the development of industrial platforms, such as foundry offerings, to support the integration of photonics and engineered quantum matter.

Recommendation: NSF, DoE, and NASA should support a strengthened community of faculty with the capability to carry out laboratory-based experiments, to develop theory, and to carry out computations in order to maximize the payoff from astrophysical observations and to encourage enhanced support from other funding agencies.

Chapter 8 Recommendations

Recommendation: It is vital that the U.S. government continue to invest as a nation in curiosity-driven atomic, molecular, and optical science that enables a diverse set of scientific ideas and approaches to be explored.

Recommendation: The federal government should develop seed funding and portable fellowship grant models that support the transition of atomic, molecular, and optical theorists and experimentalists into faculty positions.

Recommendation: A vibrant theory program needs to be incentivized through funding opportunities, such as a portable fellowship grant program, and through a sustained campaign of educating and hiring theoretical atomic, molecular, and optical physicists.

Chapter 8 Recommendations

Recommendation: Institutions receiving federal funding should implement stronger mechanisms to ensure a high standard of accountability in creating an inclusive workplace environment. Funding agencies may seek ways to incentivize this as well.

Recommendation: The entire atomic, molecular, and optical science enterprise should find a multitude of ways to tap into this growing talent pool.