STATEMENT TO THE
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American Leadership in Quantum Technology
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on behalf of the National Photonics Initiative

Thank you for the opportunity to testify, Mr. Chairman. I am honored to be here before you and the Committee to offer testimony on *American Leadership in Quantum Technology.* For your background, I am a quantum physicist and Professor at the University of Maryland, a fellow of the Joint Quantum Institute between the University of Maryland and the National Institute of Standards and Technology (NIST), and the chief scientist and co-founder of IonQ, Inc., with over two decades specializing in the field of quantum information science.

I am testifying today on behalf of the National Photonics Initiative, a collaborative alliance among industry, academia and government formed in 2013, by top scientific societies including the Optical Society, SPIE – the international society for optics and photonics – the IEEE Photonics Society, the Laser Institute of America and the American Physical Society. The mission of the National Photonics Initiative is to raise awareness of photonics – the science and application of light – and the impact of photonics on our everyday lives; increase cooperation and coordination among US industry, government and academia to advance photonics-driven fields such as quantum computing; and, drive US investment in areas of photonics critical to maintaining US economic competitiveness and national security.

Photonic devices, involving light or microwave fields, play essential roles in nearly all aspects of quantum information science. It is within that context and a desire to drive US competitiveness and national security that I am offering testimony on quantum computing and the need for our nation to create and support a National Quantum Initiative (NQI).

About Quantum Information Science

Exponential growth in the power of information technology – Moore's Law – has catalyzed US productivity and economic growth over the last 50 years. But, like much of our nation's aging infrastructure, this growth is now ending as scientific breakthroughs from the 1950s and 1960s reach their technological limits. This jeopardizes the safety and security of the American people and threatens what has been the backbone of US economic growth over the past several decades.

The demise of Moore's Law has mobilized the science and industry communities to search for fundamentally new approaches to information processing. Quantum technologies, based on fundamental particles of nature such as individual atoms and photons, are natural targets for innovation, as they hold great promise to become the computers, networks and sensors of tomorrow. Quantum information science is based on exploiting subtle aspects of quantum physics, such as "quantum superposition" and "entanglement" for valuable, real-world technologies. These technologies can handle computationally complex problems, provide communication security and enhance navigation, imaging and other sensing technologies in ways that are impossible using conventional hardware.

Quantum information science leverages the radical ability of quantum systems to store and process multiple pieces of information simultaneously in individual computing elements. For example, in a quantum computer, merely 300 atoms under full quantum control could store in a state of "superposition" more numbers than there are atoms in the universe. Quantum teleportation allows quantum information to flow securely between distant parties without occupying the space in-between. New applications and algorithms that exploit quantum capabilities are continually emerging, from code breaking, quantum cryptography and database searches to machine-learning algorithms and quantum simulations of biochemical processes and material properties. As quantum information science is developed in the future, the list of applications will continue to grow.

Nearly all implementations of quantum computers will use photonics in a key role for their operations. A quantum Internet will communicate data between quantum computers using pulses of light traveling on optical fibers. Quantum photonics is already used to operate the most accurate clocks on

Earth and the most sensitive probes for biomedical use and geo-exploration.

Efforts to Advance Quantum Information Science Domestically and Globally

Because of the great promise quantum information science holds for next-generation computing and processing, there are several independent federal and industry efforts underway to advance the research and technology. For example, widespread national interest in quantum information science also coincides with a new perspective on quantum sensors and quantum computing from the Department of Energy (DOE) and recent initiatives launched by the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST).

At the same time, publicly funded efforts in quantum information science are now complemented by growing industrial interest in quantum information technology, including efforts at Google, Honeywell, Hughes Research, IBM, Intel, Microsoft and Northrop-Grumman. Several startup companies, funded by venture capital and other equity sources, have risen near universities and laboratories throughout the country.

Perhaps most importantly, the United States is not alone in pursuing quantum research and technology development. In contrast to the decentralized funding structure of quantum information science in the United States, European entities have recently established large, focused, academic/industrial thrusts including the UK Quantum Hub Network ($400 million/five years), the Netherlands QuTech Initiative ($150 million/10 years) and the European Union (EU) Flagship Quantum Program ($1.3 billion/10 years). Outside of Europe, China is aggressive in its commitment to quantum; the country recently launched a satellite devoted to quantum communication protocols, and there is report of a $10 billion investment into a quantum laboratory in Hefei, China. Major initiatives are also underway in Australia and Canada.

This explosion of activity worldwide should be a call for action in the United States. To ensure competitiveness and national security in the field of quantum information science, the United States should dedicate resources to coordinating existing federal and private programs, and filling in critical gaps. Especially important are those gaps that exist between academic and government laboratories that lack systems engineering and product development expertise, and within the private industry, which lacks a trained quantum engineering workforce.

A National Quantum Initiative

A National Quantum Initiative (NQI) will address one of the Grand Challenges of the 21st century – harnessing quantum as a fundamentally new technology to serve national needs in information infrastructure, chemical and biomedical research and development (R&D), cybersecurity and defense capabilities. As quantum information sciences have the potential to touch nearly all areas of science and technology, its development and implementation through the NQI will naturally engage all STEM fields.

Quantum research has conventionally been led by academic institutes and government laboratories. Examples of successful demonstrations of quantum hardware include sensors for gravity and for electromagnetic fields with quantum-limited sensitivity; small quantum networks for the point-to-point sharing of information with guaranteed security; and small quantum processors comprised of 10 to 20 quantum bits. However, the transition from quantum research to usable quantum technology in the marketplace is impeded by several challenges:

- The mismatch between the quantum research community, which does not engineer or manufacture products, and the industrial engineering community, which does not have a sizable workforce with training in the quantum sciences.

- The disparity between small-company innovators and their yet-to-be developed marketplaces.

- An ecosystem of conventional technologies to support quantum devices that has not been developed because quantum technologies are not yet used in high-volume applications.

- Conventional device manufacturers typically do not have the expertise to develop products targeted at quantum systems.

A catalyst is urgently needed to bootstrap the quantum economy, much like early investments by government sparked the development and growth of the Internet. The overarching goal of the NQI is to remedy these gaps in capabilities and marketplaces in order to hasten the development and deployment of quantum information technology, while propelling the United States into a continued leadership role in this vital field.

It is envisioned that the NQI will concentrate on three pillars of quantum technology:

1. *Quantum-enhanced sensors.* Advanced electronic and photonic sensors will be developed and deployed that reach fundamental quantum noise levels of sensitivity and, in some cases, use tailored quantum states of light and matter to reach below these noise floors or enable distributed sensors across space. Examples include the detection of gravitational forces for remote sensing and imaging of subsurface material composition (caves, minerals, underground infrastructure), the sensing of proximal magnetic fields in biomedical imaging, absolute navigation in GPS-deprived environments and networks of portable atomic clocks for navigation and communication.

2. *Optical photonic quantum communication networks.* Similar to its use in the fiber-optics-based Internet that spans the world, light is ideal for the communication of quantum information over distance. Photonic quantum channels between spatially separated systems can exploit the laws of quantum physics to ensure information security or distribute information in new ways for communication protocols that are impossible using non-quantum approaches. Examples include the establishment of a fiber-optic network of quantum entangled nodes for communication including remote, secure access to centralized quantum computers, remote imaging, and multiparty quantum communication to optimize decision-making protocols.

3. *Quantum computers.* In a quantum computer, information is stored as quantum bits, which can represent and process information in an exponentially large space of possible states. This ability holds great promise for solving problems intractable for conventional computers. Apart from widely known quantum algorithms such as factoring large numbers into primes for use in message decryption, quantum algorithms promise to speed the search of unstructured databases or optimize complex functions for applications from logistics to machine learning and pattern recognition for autonomous navigation. Quantum

computers can also be applied to simulate the complex functionality of novel materials, biomolecular processes or complex economic models. One example is minimizing economic cost functions that depend on a complex maze of interacting forces, such as a marketplace that may involve a nearly uncountable number of factors.

About Quantum Innovation Labs

Under the NQI, several Quantum Innovation Labs will need to be established, each created to address aspects of a particular technology and its potential applications. Quantum Innovation Labs will attack the hardest challenges in quantum technology, to help bring the new capabilities to the marketplace. Crucially, they will also train a new generation of quantum engineers armed with the foundation of quantum mechanics combined with computer science, while embedding industrial engineers in government and academic laboratory settings.

The physical basis of quantum information science assumes several forms involving fundamental entities such as photons, atoms, atomic-scale impurities in solids or superconducting circuits. Each of these platforms has certain advantages that are suitable for particular applications and, as a result, a successful national portfolio will involve several concurrent approaches. Each platform will require the advanced engineering of very specific fabrication and operation procedures, such as the fabrication of optical waveguide circuits on a chip, superconducting circuit integration, ultra-high vacuum environments and ultra-low temperature devices.

As envisioned, the Quantum Innovation Labs will serve as a collaborative space shared by academic, government and industrial researchers to create complete systems – quantum “testbeds” – consisting of hardware and software aimed at practical applications. The Labs will be encouraged to integrate sensor, communication and computing technologies, where appropriate. Each Quantum Innovation Lab will include an educational component, closely integrated with the development and innovation activities, to train the next generation of quantum engineers. This may include the establishment of Quantum Engineering degrees granted from partner universities.

For the NQI to succeed, Quantum Innovation Labs will need be located proximal to, but not necessarily embedded in, existing government laboratories, universities and other appropriate facilities. Labs will support efforts at specific sites or may be distributed across collaborating teams at different locations. The number of Quantum Innovation Labs should ideally be four, as deployable quantum technology is now sufficiently defined so that the Labs can specialize in certain physical platforms and goals. Distinct labs may specialize in superconducting circuit quantum computing; trapped-ion quantum computing; silicon-based quantum computing; and, integration between platforms using optical interfaces and interconnects, among other capabilities.

Government and Industry Collaboration

It is envisioned that the NQI will be administered by an inter-agency quantum working group, with funding directly flowing through the federal science agencies such as DOE and NSF, as well as NIST. The Labs should be semi-autonomous (within federal oversight constraints) to enable a flexible and innovative mode of operation. High interest in quantum technologies has also been shown by Department of Defense (DOD) agencies and laboratories including Defense Advanced Research Projects Agency (DARPA) and the US intelligence community, including the Intelligence Advanced Research Projects Activity (IARPA), National Security Agency (NSA) and the National Reconnaissance Office (NRO). These should also act as partners and advisors of the NQI.

Industrial participation in the Quantum Innovation Labs is a critical component of the NQI, and this requires special consideration in three key areas:

1. *Embedded industry engineers.* Industry engineers will be embedded in the Labs and funded by their home companies or through the NQI. This will provide industry players in quantum information technology the opportunity to work alongside experts in a variety of quantum platforms, while exposing the Labs to systems engineering approaches to product development. Additionally, industry participants will be exposed to a trained potential workforce of academic and government NQI researchers and students. It is expected that industry staff would rotate in the Labs for various terms and return to their industry settings armed with new expertise that can be transferred to others.

These scientists and engineers may also spend time at participating universities for studies toward new degrees in Quantum Engineering.

2. *Direct funding of industry quantum efforts.* Industry groups developing quantum hardware that relates to Quantum Innovation Lab efforts could be funded directly from agencies in close coordination with the Labs themselves, perhaps through targeted Small Business Innovation Research (SBIR) or Small Business Technology Transfer (STTR) grants. Such an arrangement may be preferable for certain technologies that require extensive existing infrastructure or involve proprietary processes. Such funding will also assist in bootstrapping companies as they develop marketplaces for new products. Labs will provide bridge funding for accelerated commercialization of the most mature quantum technologies as well as interface with conventional IT, biomedical, military markets and private equity communities.

3. *Intellectual property (IP).* The Quantum Innovation Labs are expected to be fruitful incubators of US intellectual property in quantum technology. IP-sharing and nondisclosure agreements will be negotiated so that industrial players need not expose existing internal IP portfolios. IP created at the Labs themselves will be shared between all entities (including multiple industrial players) while respecting the inventors. In cases where IP generated at the Quantum Innovation Labs involves fundamental quantum device characteristics or functionality, IP-sharing arrangements would be crafted to benefit all industrial players. For higher-level IP that deals with applications for particular markets or pertains directly to products, care will be taken to ensure that each industrial player is able to leverage its activity in the Labs in order to pursue its own IP outside the NQI.

Recommended Funding and Timeline

The proposed federal budget for the NQI over its first five-year period (Phase I) is $500 million, which will fund each of the four Quantum Innovation Labs at $25 to $35 million per year plus support for companies and academic institutions that will collaborate directly with Lab efforts. Proposals for developing a Quantum Innovation Lab will be evaluated by the interagency quantum working group, using an external review process organized jointly through the relevant federal science agencies. In the early stages, these funds will establish the Quantum Innovation Lab administrative structures, facilities infrastructure (e.g. advanced laboratories, materials fabrication facilities, low-noise controlled environments) and equipment (e.g. electronic instrumentation and high-performance computers). In the later stages, the NQI funds will be primarily devoted to Laboratory staff, embedded industry and other personnel, and possible private funding from outside groups collaborating on the use and testing of the developed technology.

After Phase I, the NQI will have shown significant progress in the performance of quantum sensors, quantum communication systems and quantum computers as described above, with clear demonstrations of deployable systems that can be used by others or, in some cases, evolve into commercial products. Embedded personnel at Quantum Innovation Labs are expected to return expertise to their academic, government or industrial homes, with long-standing ties between these entities.

In Phase II (years six and beyond), the NQI will be devoted to new scientific and technological applications of hardware and software developed in the Labs, while also pressing on new technological platforms that may arise. In these ways, the NQI will play a crucial role in the engineering and deployment of quantum devices, as well as the training of a new quantum STEM workforce that will propel quantum technology through the 21st century and assure that the US leads the world in the future of quantum information technology.

Conclusion

Now is a critical time for federal investment to initiate moving quantum technology from its current research status to real-world applications. Such investment will create the infrastructure – both physical and workforce – needed to move the United States into a leadership position in quantum information technology, a technology that will create vast opportunities for workforce creation, economic growth and betterment of society across areas as diverse as health outcomes and information security.

The National Photonics Initiative, and its consortium of leaders from industry and academia with knowledge in information technology and quantum science and technology, strongly recommends the United States establish a quantum information technology base that will lead to new opportunities in communication, sensing and computing; develop a marketplace for companies – small and large – to sell new products based on quantum information science; and, build the much-needed quantum workforce to grow this new industry.

I thank you, Mr. Chairman and members of the Committee, for the opportunity to speak on quantum computing and the need for a nationally focused effort to advance quantum information science in the United States. With extensive reach into the science R&D community, I and the National Photonics Initiative stand ready to work with the government as it considers the recommendations put forth in this testimony.