Testimony of

Carl J. Williams, Ph.D.

Acting Director
Physical Measurement Laboratory
National Institute of Standards and Technology
United States Department of Commerce

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Introduction

Chairwoman Comstock, Ranking Member Lipinski, Chairman Weber, Raking Member Veasey, and members of the Subcommittees, I am Dr. Carl Williams, the Acting Director of the Physical Measurement Laboratory (PML) at the Department of Commerce's National Institute of Standards and Technology (NIST). Thank you for the opportunity to appear before you today to discuss NIST's roles in quantum science and quantum computing.

As this nation's national metrology institute, NIST's overall mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. NIST does this through programs focused on national priorities from cybersecurity, advanced manufacturing and the digital economy to precision metrology, biosciences, and more.

NIST conducts basic and applied research in quantum science to advance the field of fundamental metrology as part of its core mission, by developing more precise measurement tools and technologies to address industry's increasingly challenging requirements. This work has positioned NIST both as a global leader among national metrology institutes, and as one of the world's leading centers of quantum research and engineering. While NIST's work in quantum science is revolutionizing the world of metrology, it also has direct application to quantum communications and quantum computation. Today, I'll describe in more detail some of NIST's quantum research efforts and how they are being leveraged to positively advance the field.

Quantum Computing and Quantum Information Science

Quantum mechanics revolutionized science in the 20th century, leading to technological breakthroughs including the invention of the laser and the transistor. Today's most advanced communication and computation technologies are based on those mid-20th century inventions.

Science and society is poised for a second quantum revolution in the 21st century, one in which we will employ our new-found ability to exploit quantum mechanical phenomena to push beyond the limits of classical computing and communications. Phenomena such as superposition (the ability of a particle to be in several different states at the same time) and entanglement (the ability of two particles to share information even at a distance) lie at the heart of what makes a quantum computer so much more powerful than even today's most advanced classical supercomputers.

So, what are quantum computing and quantum information? Unlike classical computers, which process high and low voltages as 1's and 0's to form bits of information that get shuttled around, quantum computers manipulate quantum bits of information, or qubits. A qubit's information is in the form of a discrete state, such as the magnetic spin of an electron. Due to quantum mechanical phenomena such as superposition, these qubits can be both a 1 and a 0 at the same time.

To understand this, we can imagine a normal classical bit as able to represent only two points on the surface of a sphere—such as the north and south poles of the earth. In contrast, a qubit could represent any point on the surface of that sphere. This superposition, together with the shared fate resulting from entanglement between multiple qubits together, is what gives a quantum computer the superior computational power that will make it uniquely capable of solving complex problems, including perhaps most notably the breaking of current encryption schemes.

NIST's expertise in quantum science is mainly focused on the use of quantized states of light and matter and their manipulation and interaction as quantum bits of information to make ultra-precise sensors and measurement tools. This application falls under a broader field of study that we refer to as "quantum information science," which lies at the intersection of computer science, mathematics, and quantum science. The breakthroughs that NIST is making in this field will have direct relevance and application to quantum computing.

Recent Investments and Advancements Abroad

Many nations view leadership in quantum computing as critical to making significant breakthroughs in medicine, manufacturing, artificial intelligence, and defense, and to reaping the rewards from those investments and breakthroughs. The U.S. has long been viewed as a leader in quantum science, information, and computing. Significant historic investment by the U.S. government has supported a robust base of fundamental research, and this has led to several transformational breakthroughs in the field.

Today, U.S. leadership in quantum science and technology is increasingly dependent on significant investments from U.S. technology giants and major defense companies with a natural interest in the many commercial applications of quantum technology beyond computing. These applications include quantum communications, quantum algorithms and software, data security, imaging, and quantum sensors, and could be applied to anything from national security to the Internet of Things, to advanced sensors for gas and oil exploration. Applications for quantum sensors include novel approaches to precision navigation and timing, as well as technologies that could provide a backup or holdover function for global positioning systems or GPS.

While the U.S. has made significant breakthroughs, the rest of the world has not been standing still—and U.S. companies are taking notice. Worldwide interest and investment in quantum computing and related technologies has spiked in recent years, following important and increasingly complex technological demonstrations by overseas research efforts.

The European Union has launched an effort to invest 2 billion euros over the next 10 years in a recently launched EU Flagship Quantum Program. The United Kingdom has created a set of quantum hubs aimed at exploiting the various application spaces within quantum information science.

Perhaps even more noteworthy is China's rapid investment in quantum technology and the dramatic advances by China in the area of quantum communication. Earlier this year, China sent entangled photons from a satellite to the ground 1200 kilometers away, smashing several quantum communication distance records. More recently, China has demonstrated the world's first atomic clock in space using cold atoms, which can far outperform the atomic clocks in U.S. GPS, and can further support future advanced quantum networks.

NIST's History and Role in Quantum Computing and Information

At NIST, our researchers study and harness the quantum mechanical properties of light and matter in some of the most well-controlled and defined measurement environments to create the world's most sensitive and precise sensors and atomic clocks. NIST has been a leader in the field of quantum information from the beginning, and its multiple Nobel Prize-winning contributions have helped move quantum computing and quantum information from purely scientific fields of study to technological ones.

NIST scientists began researching quantum information in the early 1990s in their quest to make better atomic clocks. Qubits and atomic clocks may seem worlds apart, but experimentally they are very much the same thing. By 2000, NIST had established a formal quantum information program.

Atomic Clocks: The Power of One Qubit

Atomic clocks define the second and tell time with amazing precision. For example, the most accurate U.S. atomic clock currently used for defining the second is the NIST-F2. It keeps time to an accuracy of less than a millionth of a billionth of a second. Stated in another way, the NIST-F2 clock will not lose a second in at least 300 million years. And just this month, NIST published a description of a radically new atomic clock design—the three-dimensional (3-D) quantum gas atomic clock. With a precision of just 3.5 parts error in 10 quintillion (1 followed by 19 zeros) in about 2 hours, it is the first atomic clock to ever reach the 10 quintillion threshold, and promises to usher in an era of dramatically improved measurements and technologies across many areas based on controlled quantum systems.

These breakthroughs in precision timekeeping have critical real-world applications to navigation and timing. Today, commercial atomic clocks contained in GPS satellites provide the timekeeping precision that we take for granted when we use our GPS devices to pinpoint our location to within a meter almost anywhere on earth.

NIST's most advanced atomic clocks, so precise that they will not lose a second over the life of the universe, also are being applied to make the world's most sensitive measurements of quantities other than time. For example, NIST is actively pursuing the use of atomic clocks as quantum sensors, another application of quantum information, for a range of entirely new technologies. NIST is now able to detect the barely perceptible slowing of time in a large gravitational potential. This is the second form of time dilation predicted by Einstein in his general theory of relativity and may help scientists detect gravitational waves or prospectors find hidden oil reserves and mineral deposits. The technology might even have the potential to allow scientists to predict earthquakes days or even weeks before a cataclysmic event.

Quantum Logic

NIST's breakthroughs in the measurement of time also have laid the technological foundations for how to manipulate quantum information. NIST's pioneering work in the cooling and trapping of ions and atoms to improve timekeeping provided NIST researchers with the experimental platform to demonstrate the first two-qubit quantum logic gate in 1995, by controlling and entangling the energy levels of two ions. Logic gates in classical computers are used to process information. By analogy, quantum logic gates form the basic building block for quantum computing. Scaling up to experiments involving multiple logic gates provides a platform to test more complex quantum computing theory.

Other Quantum Computing Technologies

Atomic clocks are just one example of NIST's research focused on measurement science that has applications to quantum computing. NIST also is the world's leader in specially designed devices, made from superconductors, known as Josephson Junctions. Josephson Junction technology is used by NIST to realize and disseminate NIST's quantum voltage standard. The quantum voltage standard is also integral to the proposed 2019 effort to redefine the international system of units (colloquially, the metric system) to be based on fundamental constants of nature, as defined through world-leading experiments at NIST such as the "electronic kilogram". This same technology is being explored as a key competitor to trapped ions and atoms as another way to manipulate and store quantum information.

Additionally, Superconductors are used by researchers at NIST to make ultra-sensitive single photon detectors used in precision photonic measurements at NIST and by external stakeholders. These specially designed sensors have become essential components in experiments at NIST to test the foundations of quantum mechanics and realize quantum teleportation. In quantum teleportation, quantum information gets transmitted instantaneously from one qubit to another. Discrete photons, like ions and atoms, can also be carefully controlled and entangled to form qubits. Prior to China's recent 1200 kilometer demonstration, NIST had held the distance record for quantum teleportation, transmitting information between photons separated by 100 kilometers. Progress in quantum teleportation is expected to be essential for eventual commercial quantum computing, and for other forms of quantum information transfer.

In the end, building a quantum computer will involve many disparate quantum technologies. Those technologies will need to be integrated to provide long-term storage and memory, transmission or teleportation, transduction, and detection of qubits while not corrupting the qubit's extremely delicate state.

Quantum Information Theory and Validation and Verification

In 2002, NIST hired its first quantum information theorist. This began a quantum information program which has led to new and improved approaches for quantum error correction, techniques for reliably characterizing quantum states produced in the laboratory, and concepts for randomized benchmarking of quantum gates. These concepts have provided crucial insights, which NIST has used to further improve our experimental efforts and those of other research groups. For example, randomized benchmarking has become the standard by which research groups around the world characterize and compare the quality of their computational paradigms.

Quantum Algorithms and Post-Quantum Cryptography

NIST programs on quantum algorithms and post-quantum cryptography further build on our core efforts in quantum information theory with a focus on addressing security challenges anticipated when practical quantum computers are realized. NIST, working with industry, has played a leading role since the 1970s in developing cryptography standards. Today's classical computers and computer networks employing Public Key Cryptography are using cryptography standardized by NIST. Unfortunately, these standards will not be resistant to attack by quantum computers. NIST researchers are using their understanding of quantum algorithms to create new classical encryption algorithms, commonly referred to as post-quantum cryptography, that will be resistant to quantum computing attacks.

NIST's Joint Institutes with Universities
NIST also supports joint centers with the University of Colorado Boulder (UC) and the University of Maryland (UMD). JILA at UC was founded in 1962 and has been doing research in quantum science and in atomic clocks and is evolving into quantum information science. Two joint centers in quantum information science at UMD were established more recently. The Joint Quantum Institute (JQI) was established in 2006 through a cooperative effort between NIST, UMD, and the Laboratory for Physical Sciences. The Joint Center for Quantum Information and Computer Science (QuICS) was established in 2014 to complement JQI's experimental and theoretical work by focusing the use of quantum systems to process, transmit and store quantum information. Taken together, NIST's joint institutes interact strongly to push the frontiers of quantum science, information, and computing and provide a training ground for industry's future quantum workforce.

Conclusion

NIST recognizes that it has an essential role to play in U.S. leadership in quantum computing and information. However, that role is not to build a quantum computer. NIST's role, consistent with its mission, is to develop the foundational knowledge and measurement science support for U.S. leadership in quantum computing, to create the basis for characterizing quantum logic gates, to explore approaches to quantum control and error correction, to develop rudimentary quantum processors that are capable of creating the exotic quantum states that will allow improvement of our measurements beyond the standard quantum limit, and to ensure that our cybersecurity infrastructure remains resilient in the quantum era. Part of this foundational knowledge will come from using NIST's measurement platforms to experimentally conduct quantum simulations and validate quantum computing theory. NIST also anticipates that the early adoption of the quantum technologies that emerge as NIST continues to develop the world's most precise atomic clocks (quantum logic clocks) and quantum based sensors will ultimately provide substantial support to the effort to build a quantum computer.

NIST is extremely proud of its world-class quantum science, quantum information, mathematics, and computer science programs, and we appreciate the support of this Committee for NIST's research efforts. Sustained advancements by NIST in these fields continue to underpin success in many parts of NIST's measurement science mission and contribute to U.S. leadership in quantum computing. Thank you for the opportunity to testify today. I would be happy to answer any questions you may have.