STATEMENT BY

THE HONORABLE PAUL M. DABBAR

UNDER SECRETARY FOR SCIENCE

U.S. DEPARTMENT OF ENERGY

BEFORE THE

SENATE ENERGY AND NATURAL RESOURCES COMMITTEE

ON

AMERICAN LEADERSHIP IN QUANTUM TECHNOLOGY

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Thank you, Chairwoman Murkowski, Ranking Member Cantwell, and Members of the Committee. I am pleased to come before you today to discuss the emerging field of Quantum Information Science (QIS), to highlight its potential in our Nation's continued economic competitiveness, and to describe the Department of Energy's new initiatives in this area.

QIS represents a new frontier in information technology. Using elementary particles like photons and electrons to store and use data, quantum applications vary from classical computing, which relies on larger transistors and silicon chips.

While the potential of quantum computing has long been recognized in theory, the need to bring it to practice arises from the slowing down and predicted end of Moore's Law. Moore's Law is the famous 1965 prediction of Intel co-founder Gordon Moore that computing power would double every year; then every two years. For over half a century, Moore's Law has defined the trajectory of the Information Age. Moore's overall prediction is still holding, but the pace of growth in computing power is slowing down. There is general agreement that Moore's Law will eventually encounter unsurmountable barriers.

"Classical" physics contains physical limits, while quantum effects could potentially provide a way around these limitations.

Accessing the quantum world has been made possible through changes in the development of nanoscience, the increasing sophistication and capabilities of x-ray light sources and other instruments and our emerging ability to synthesize novel materials.

QIS can be viewed theoretically as a marriage of information theory—the mathematical foundation for information processing developed in the late 1940s—and quantum theory—a major revolution in physics from the early part of the 20th century. QIS applications differ from applications of quantum mechanics by exploiting distinct, non-classical behavior:

- Superposition—quantum particles or systems exist across all their possible states at the same time, with corresponding probabilities, until measured.
- Entanglement—a superposition of states of multiple particles in which the properties of each particle are correlated with the others, regardless of distance.
- Squeezing—a method of manipulating noise in systems that obey the Heisenberg uncertainty principle, by permitting large uncertainty in one variable to improve precision in another correlated variable.

Quantum computing depends on superposition. Instead of relying on bits with a definite value of 1 or 0, quantum computers are composed of qubits in an “in-between” state of superposition. QIS applicability extends well beyond computing and information processing. Other fundamental science topics are benefitting from advance in quantum information:

- Probes of biological cells for advanced drug development;
- the search for dark matter;
- the emergence of space-time;
- furthering Einstein’s interpretation of gravity;
- testing fundamental symmetries;
- materials design at the atomic level;
- calculations of molecular catalysis;
- nuclei and particle energy calculations;
- advanced sensor and detector fundamental research; and
- sensing and metrology.

Because QIS will open new vistas for both science and technology development, as well as new commercial markets, the U.S. and other countries are increasing investments in related basic research and technology development.

International Landscape

Worldwide interest in QIS has increased substantially in the past five years. Global investments and developed long-term strategies have shifted the distribution of top-tier research groups. Because many foreign governments are providing strong support to QIS and related technologies, academic researchers in the U.S. have expressed concern that their foreign counterparts have better access to novel materials and custom optics. Some foreign QIS activity follows:

- The largest quantum information science and technology programs outside the U.S. are in the European Union (EU) and China. In 2016, the EU announced a €1 billion ($1.1 billion USD), 10-year Flagship initiative . This is only the third EU Flagship project in future and emerging technologies; the prior ones, launched in 2013, are on Graphene and the Human Brain Project. China dominates Asian investment in QIS research and development with a large, rapidly growing program that initially focused on secure communication, including the widely publicized launch of an experimental quantum communications satellite in 2016, and is now expanding to other areas. The Chinese program includes industry partnership and lucrative offers to recruit top talent abroad.

- The U.K. and Canada have made high-profile budget investments in QIS. The U.K. has four hubs, partnering between universities and industry, on sensors, imaging, networking, and computing. The U.K. has also invested more than £200 million/$255 million USD in student and postdoctoral training. Canada's program was spearheaded by private investment aiming to make their Waterloo the quantum equivalent to Silicon Valley. Their Perimeter Institute and University of Waterloo lead QIS, ranging from blue-sky theory to practical devices and algorithms, and awarded $76 million CAD/$56 million USD in 2016 from the Canada First Research Excellence Fund.
- Australia and the Netherlands have made targeted, high-profile investments in quantum computing. Australia's 2016 National Innovation and Science Agenda included a $70 million AUD ($53 million USD) public-private partnership to advance quantum computing for commercial applications that is complementary to a new $33 million AUD ($25 million USD) fundamental research effort to support the scale-up of silicon quantum integrated circuits. The Netherlands is also home to a government-funded quantum software research center.
- A number of countries without a coordinated national QIS agenda or initiative nonetheless have strong, well-funded research groups, including Germany, Austria, Switzerland, Japan, and Singapore. Russia and Brazil also appear to be building national research communities.

To maintain leadership in this "next frontier" of science, the U.S. must build on its investment in QIS to generate new technologies and, ultimately, important new commercial opportunities. Federal agencies have supported research in QIS and related areas since the field emerged over 20 years ago, with basic and applied federally-funded research now supported at more than $200 million annually from agencies such as the Department of Defense, the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the Department of Energy (DOE). In FY2018 DOE invested $62.38 million, and DOE is working on the FY2019 plan at this time at a level of approximately $120 million.

Summary of Scientific Challenges and Office of Science-Specific Efforts to Date

Several program offices in the Department of Energy's Office of SC (SC) have important roles in QIS research and development.

Quantum Science—Coherence and Entanglement of Quantum States

Materials and Synthesis

The SC's Office of Basic Energy Sciences (BES) is focusing on research for materials synthesis and processing. Materials synthesis is required for quantum systems to address a basic science gap preventing "synthesis by design." This requires establishing generalized rules of assembly for complex materials in different platforms, to understand and control phases of quantum materials. New functionalities could include superconductivity and robust entangled states approaching room temperature, or dissipationless charge and spin transport relevant to quantum computation, neuromorphic computing, and ultra-low loss digital computation beyond silicon. Conversely, understanding of fundamentals of competitive heat/electron transfer could demonstrate limitations on quantum computation.

Instrumentation for Quantum Control: Sensing and Metrology
Two offices in SC are addressing instrumentation development for measurement and control of quantum phenomena. The Office of High Energy Physics (HEP) is developing specialized cavity sensors for detecting new particles and quanta in previously inaccessible frequencies and with greater sensitivity. Such quantum technologies could inform particle physics experiments. BES is characterizing quantum materials through scattering, spectroscopy, and imaging of quantum materials using neutrons, x-rays, and electrons as probes. This could lead to the discovery of new materials and inform theories that predict and explain their properties.

Theory and Modeling of Quantum Entanglement
QIS research has informed particle physics work on relationships among quantum fields, black hole physics, and information entanglement, invoking quantum error correction codes and quantum gravity. Tensor networks provide new models to understand fields, particles, and their interactions. BES is exploring quantum computing to enable fast algorithms for computation of quantum entanglement. Decoherence in entangled systems could potentially be understood via molecular magnets. SC's Office of Advanced Scientific Computing Research (ASCR) plans to explore partnerships with other SC offices to develop tools and algorithms for modeling and simulations, in order to accelerate the computation and understanding of quantum entanglement in different systems.

Quantum Devices and Systems for Computing, Information, and Other Applications

Qubit Technologies
Qubits are the basic building blocks for quantum computing that embody superposition of states. Implementing these systems involves a variety of issues, including specific material properties, manufacturability, scalability, stability, integration, and other concerns. Some potentially useful materials for qubit systems include high-temperature superconductors, trapped ions, quantum dots, nitrogen-vacancy complexes (NV centers) in localized defect structures, topological insulators and two-dimensional electron gas (2DEG) systems that support the fractional quantum Hall effect, miniaturized skyrmions, and nano-magnets. BES research and facilities already encompass investigations in many of these areas, including the five Nanoscale Science Research Center (NSRC) user facilities to advance the fabrication and testing of these materials.

Quantum Sensors and Detectors
Many devices developed as a qubit system for quantum computing can also be used as a quantum sensor, with potential applications to precision measurements and detection of particles across the entire range of SC topics. Electronic, magnetic, and structural properties and ultrafast dynamics can be investigated with tools including pump-probe experiments at femtosecond resolution, ultra-high field neutron scattering, angle-resolved photoemission, and scanning probe imaging. Ultrasensitive magnetometers can be constructed based on NV centers, and single-photon detectors based on quantum aspects of superconducting materials. The NSRCs supported

by BES can fabricate over the necessary spatial and temporal scales, and utilize extensive characterization capabilities through SC user facilities and National Laboratory capabilities. Detectors and superconducting radio-frequency technology for nuclear physics experiments also may be relevant to instrumentation for quantum control.

Fabrication and Testbeds

Testbeds provide the research community with access to early stage devices, accelerating the development of hardware well-suited to scientific computing as well as applications that make effective use of new hardware. They can potentially serve as standardized environments for preserving coherence, extent of entanglement, and other key criteria. Testbeds can also facilitate comparison of different devices and can develop production-quality software for novel computing architectures.

ASCR issued a program announcement to DOE National Laboratories for research into development of quantum testbeds in April 2018. Multidisciplinary efforts to explore the suitability of implementations of quantum devices for science applications will advance engineering of quantum information systems and perhaps overcome practical limitations. Strong collaboration among government agencies, academia, and industry will enable device fabrication and testbeds. National Laboratory facilities are well-positioned in capabilities and infrastructure to enable the needed collaborative integration of advanced synthesis, fabrication, characterization, theory, modeling, testing, benchmarking, and development-to-scale.

Novel Architectures, Quantum Simulators/Emulators, and Systems-Level Control

Exploring novel architectures from the device level through the system level will allow DOE to invest in the quantum computing technologies best-suited to mission needs. Some applications, such as quantum chemistry, appear to benefit from an approach that pairs classical feedback with inherently quantum processing. Other applications may run best on a larger quantum processor with classical computing only required for control. Qubit simulators will facilitate early exploration of architectures; emulators that parameterize key features of larger quantum devices will allow efficient system-level design that can proceed hand-in-hand with research and development in systems-level control.

Algorithms

DOE generally, and its SC programs in particular, have extensive computational problems to solve; quantum computing can support a robust and versatile set of algorithms. Research into quantum speedups for linear algebra, integration, optimization, and graph theory could ultimately facilitate performing a wide variety of scientific computing tasks. An initial program announcement to DOE National Laboratories regarding the development of quantum algorithm teams was released by ASCR in May 2017.

Software Implementation and Reliability

Realizing quantum computing’s potential will require advances in hardware and algorithms, and advances in optimizing languages and compilers to translate these abstract algorithms into concrete sequences. A systematic research agenda to develop a software infrastructure from high-level languages to debuggers and benchmarking metrics, when executed in coordination with hardware and architecture design, will also lead to effective strategies that find balance between systems-level control and error correction.

Quantum Networks and Complexity
Significant research effort is needed to develop, test, and deploy continental scale Quantum Wide Area Networks composed of many nodes, multi-hops, multi-users, and high-speed optical quantum channels. High-performance quantum communication network components are needed to secure distributed quantum systems processing and sharing data sets over continental distances. Critical components include quantum communication network hardware, architectures, and protocols; quantum-enabled software defined networks; and all-optical network extension for quantum key distribution (QKD) and understanding QKD security loopholes.

FY 2018 DOE Office of Science Initiative in QIS

The Department recently announced $218 million for new research awards in QIS sponsored by ASCR, BES, and HEP at both universities and national laboratories.

ASCR's awards (total $81 million) will support the development of both hardware and software for quantum computing, and the creation of two additional Quantum Testbed sites, one at Sandia National Laboratories and the other at Lawrence Berkeley National Laboratory. These sites will provide prototype quantum computers and related instrumentation on an open, competitive basis to a community of outside users, similar to the Office of Science X-ray light sources or the Leadership Computing Facilities at Argonne and Oak Ridge National Laboratories Users will harness quantum computing in the effort to address real-world research problems. ASCR is also providing substantial support for algorithm and software application development for quantum computing.

BES awards (total $106 million) cover both research and facilities. Areas of research include: controlling the quantum dynamics of nonequilibrium chemical and materials systems; unraveling the physics and chemistry of strongly correlated electron systems; embedding quantum hardware in classical frameworks; and bridging the classical–quantum computing divide.

To address the challenge of new materials synthesis, a second category focuses on basic experimental and theoretical research on the discovery and characterization of quantum phenomena to enable the design and discovery of novel quantum materials and information systems. Areas of research include: synthesis of materials for the development of quantum coherent systems that involve *in situ* characterization and real-time machine learning and target quantum information functionality; creation and control of coherent phenomena in quantum systems emphasizing an improved understanding of entanglement and enhanced coherence lifetimes; and transduction of quantum coherent states between disparate physical systems (light, charge, spin) with high fidelity. BES is also providing $33 million for the Department's five NSRCs, focused primarily on synthesis of new quantum materials at the nanoscale.

HEP awards (total $31 million) focus on connections between cosmic phenomena like information scrambling in black holes and quantum error correcting codes, in five areas: collaborative research on quantum gravity, information theory, and entanglement, with simulations on qubit systems aimed at study of the universe; foundational field theory development, along with tests on nascent quantum computers and emulators; quantum computing for innovative data analysis and to model cosmic quantum phenomena; potential adaptation of HEP developed tools and technology such as superconducting radiofrequency cavities and quantum controls for improved qubit performance; and exploration of the potential of highly sensitive quantum-based sensors to detect elusive phenomena such as neutrinos or candidate dark matter particles.

The Path Forward

DOE is committed to a strategic approach to the next steps in QIS. The Department of Energy's Office of Science has unparalleled capacity to support foundational, and therefore path-breaking, original research—leveraging the strengths of the nation's higher-learning institutions, and the unique capabilities of the DOE National Laboratories, with their unsurpassed scientists, intellectual property, and suite of scientific user facilities and other advanced instrumentation. It is critical for American economic competitiveness that U.S. research efforts in QIS systematically capture the valuable intellectual property likely to flow from new discoveries.

Conclusion

The DOE QIS FY 2018 awards are a strong first step, with very enthusiastic response to these QIS solicitations from scientists in the ASCR, BES, and HEP communities. Universities and the DOE National Laboratories are poised to generate new insights and approaches to information processing and other technologies. With strategic investments, America can remain on the leading edge of this next frontier of Information Age science and technology. I look forward to answering questions from the Committee.