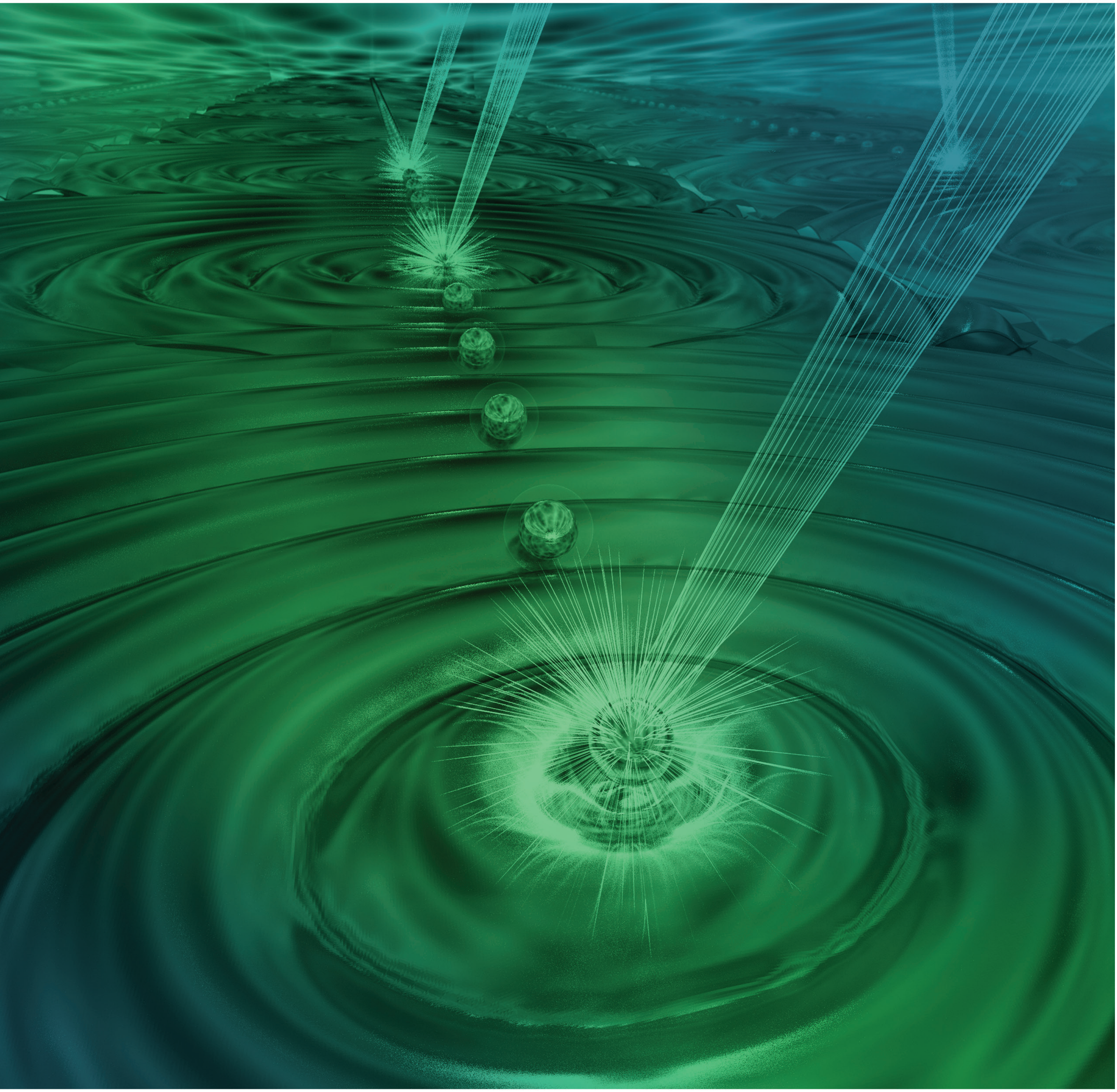
Nuclear Physics and Quantum Information Science

Report by the NSAC QIS Subcommittee *(October 2019)*



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A Report by the NSAC Quantum Information Science Subcommittee

October 2019

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Foreword

At the end of 2018, the US Congress enacted the National Quantum Initiative (NQI), making quantum information science (QIS) a high-priority research area in the United States. QIS is poised to bring about significant, and perhaps disruptive, changes in science, technology, national security, and societal infrastructure. This positioning follows from investigations into fundamental aspects of quantum mechanics, information, matter, and even space-time itself, across a number of science and computing domains, combined with improvements in the control of entanglement.

The Department of Energy (DOE) and the National Science Foundation (NSF) charged the Nuclear Science Advisory Committee (NSAC) with two tasks related to the Initiative. NSAC formed a subcommittee to provide an assessment of both the potential impact that QIS may have on nuclear physics (NP) research programs and new opportunities that may arise, and the identification of unique contributions that NP research could make to the development of QIS. This document is the report of the Subcommittee.

The Subcommittee held two information-gathering meetings in the spring of 2019. One focused on obtaining high-level information about the status of national and international QIS activities. This meeting included presentations from the Office of Science and Technology Policy, the DOE Office of Science, the NSF, the DOE Offices of Nuclear Physics and Advanced Scientific Computing Research, the National Institute of Standards and Technology, international programs, community reports from DOE Basic Energy Sciences and High Energy Physics, and the National Academies of Sciences, Engineering, and Medicine. The second meeting was a "deeper dive" into NP research activities that may be of importance to future QIS developments, and vice versa, as well as into potential engagements with other domain sciences and with technology companies and startups. There was an emphasis in the second meeting on quantum sensors and quantum computing and simulation. No attempt at a comprehensive summary of QIS has been made in this document. Rather, QIS has been discussed to the extent it is relevant for NP research and goals.

Among the experimental, theoretical and computational NP research activities, we have identified capabilities and expertise unique to NP that will aid in advancing QIS. Similarly, we have also identified NP scientific objectives and grand challenges expected to benefit from present and future developments in QIS. In the report, we make recommendations to support these goals. The work of the NP community in these areas can support strongly, and on strategic timescales, the national program established by the NQI.

Contents

Abbreviations, Acronyms, and Initialisms

0νββ	Neutrinoless double-beta (decay)
AMO	Atomic, molecular and optical physics
ANL	Argonne National Laboratory
ASCR	Advanced Scientific Computing Research
BES	Basic energy sciences
BNL	Brookhaven National Laboratory
BQP	Bounded-error, quantum, polynomial
CCD	Charge-coupled device
CP	Charge-conjugation-parity
DOE	Department of Energy
EC	European Commission
EDM	Electric dipole moment
EFT	Effective field theory
EIC	Electron ion collider
ESR	Electron spin resonance
FNAL	Fermi National Accelerator Laboratory
FRIB	Facility for Rare Isotope Beams
GPS	Geographic positioning system
GPU	Graphics processing unit
HEP	High energy physics
HPC	High performance computing
IDPRA	Isotope Development and Production for Research and Application (the DOE Isotope Program)
INT	Institute for Nuclear Theory
JLab	Thomas Jefferson National Accelerator Facility
JPA	Josephson parametric amplifier
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LHC	Large Hadron Collider
LLNL	Lawrence Livermore National Laboratory

LRP	*Long Range Plan for Nuclear Physics* (2015)
MKID	Microwave kinetic inductance detector
MMC	Magnetic microcalorimeter
NASEM	National Academies of Sciences, Engineering, and Medicine
NISQ	Noisy, Intermediate-Scale Quantum
NIST	National Institute of Standards and Technology
NMR	Nuclear magnetic resonance
NNSA	National Nuclear Security Administration
NP	Nuclear physics
NQI	National Quantum Initiative
NSAC	Nuclear Science Advisory Committee
NSF	National Science Foundation
NSTC	National Science and Technology Council
NV	Nitrogen vacancy
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
Q	Quality factor
QC	Quantum computing
QCD	Quantum chromodynamics
QCDC	Quantum Co-Development Consortia
QED-C	Quantum Economic Development Consortium
QIS	Quantum information science
QFT	Quantum field theory
QMC	Quantum Monte Carlo
QP	Quasiparticle
QPU	Quantum processing unit
R&D	Research and development
RF	Radio frequency
RHIC	Relativistic Heavy Ion Collider
SBIR	Small Business Innovation Research
SC	DOE Office of Science
SciDAC	Scientific Discovery through Advanced Computing

SLAC	Stanford Linear Accelerator Center
SNL	Sandia National Laboratories
SNSPD	Superconducting nanowire single photon detector
SQUID	Superconducting quantum interference device
STTR	Small Business Technology Transfer
SURF	Sanford Underground Research Facility
T	Time-reversal symmetry
TC	Topical collaboration
TES	Transition edge sensor
TWPA	Traveling wave parametric amplifier
UCN	Ultra-cold neutron

Executive Summary

Nuclear physics (NP) research spans a broad range of length scales and complexity. Our research encompasses environments and phenomena ranging from the extreme temperatures of the earliest moments of the universe through to the present day; from the most dense astrophysical environments emitting detectable gravitational waves to the fission of nuclei; and from the high-intensity beams created in research laboratories to ultra-sensitive, low-background experiments that probe the fundamental nature of matter. The techniques, tools, and expertise required for NP research are correspondingly diverse in nature. State-of-the-art detectors and sensing are developed and employed to perform precision measurements that probe the laws of nature, to discover new particles and states of matter, and to develop capabilities for national security needs. Similarly, analytical and computational methods are developed and employed in support of the experimental program; to explain how simple laws describe a complex world; to predict the nature and dynamics of systems and environments that are, as yet, inaccessible to experiment; and to chart a course for the future.

Quantum information science (QIS) is a rapidly developing field focused on the nature, acquisition, storage, manipulation, computing, transmission, and interpretation of information. It takes advantage of the fundamental laws of nature for which quantum mechanics is a defining framework. Entanglement and superposition, and their manifestation in quantum many-body systems, are the key ingredients that distinguish quantum information from classical information. Improving control of superposition and entanglement over macroscopic space-time volumes in the laboratory has produced the first devices useful for quantum computation and sensing.

The US government is initiating a broad-based, multidisciplinary, cross-agency program to build a sustained national quantum ecosystem and quantum economy (wherein the ecosystem will develop in support of this economy). Based upon more than two decades of research, development, and planning, the US government recognizes the importance of QIS and quantum computing (QC) to future scientific discoveries and to advances in technology, national security, and national infrastructure. This program will complement, integrate with, and in some ways parallel efforts of the semiconductor industry, which has been essential in advancing classical computing in myriad ways that are by now integral to much of today's economy and to national security. The **National Quantum Initiative** (NQI), enacted by the US Congress with bipartisan support and signed by President Donald Trump at the end of 2018, provides a framework to establish a national quantum ecosystem. The present report, solicited jointly by the Department of Energy (DOE) and the National Science Foundation (NSF), outlines the contributions NP could make to this national quantum ecosystem and assesses its benefits to the NP research programs. We explain that expansion of NP activities related to QIS and integrated into the national effort will be of mutual benefit both to this quantum ecosystem and to NP itself.

QIS and QC have the potential to disruptively change areas of NP research in the medium and long term. The evolution in the design and fabrication of materials and sensors that employ existing quantum technology will continue to provide enhancements in capability. However, improvements in the design and control of entanglement, defining a second impact-era of quantum mechanics, are expected to provide sensing and simulation capabilities far exceeding those possible through the evolution of existing technologies. Quantum systems from photons, electrons, nuclei, ions, and atoms, through to quantum dots in silicon are being used to advance entanglement protocols.

Rudimentary quantum computers and quantum analog simulators can now solve simple "toy" problems in fields from chemistry to materials science to high energy physics (HEP) to NP. However, all these problems can be solved with greater precision and accuracy with presently available classical computers. We have just entered the Noisy, Intermediate-Scale Quantum (NISQ) era in which quantum devices are noisy, with a modest number of "qubits," have imperfect controls, and may possess short coherence times. When combined, these factors limit the nature of current quantum computations. Establishing a "quantum advantage" for scientific applications is an activity currently being pursued with vigor. While there are deep ongoing efforts to identify the potential value of NISQ-era systems and technologies on the path to system and problem scaling, we anticipate that beyond-NISQ-era quantum devices with quantum error correction will be required to address grand challenge problems in NP research.

DOE and NSF charged the Nuclear Science Advisory Committee (NSAC) with two tasks related to the NQI. NSAC formed a subcommittee to provide an assessment of both the potential impact that QIS may have on NP research programs and new opportunities that may arise, and the identification of unique contributions that NP research could make to the development of QIS. This document is the report of the Subcommittee**. The Subcommittee expects the main research areas of mutual benefit to NP and to QIS to be quantum sensors and QC and simulation.** Sensors and detectors that employ quantum technology—such as atomic magnetometers, transition edge sensors (TESs), and Josephson parametric amplifiers (JPAs), developed in part by NP—are providing new capabilities. Quantum sensors will improve further with developing control of entanglement over increasing space-time volumes. NP can both benefit from, and contribute to, short- and longer-term developments in quantum sensing. The well-known "sign problems" in classical computations of finite-density systems—including modest and large nuclei—and in the real-time evolution of quantum many-body systems, enter calculations that would require classical computing resources beyond those currently envisioned. Quantum simulations using quantum devices are expected to help address some of these scientific questions. The direct impact of quantum simulation on NP experimental programs is likely to be a decade into the future, but conceptual impacts and improvements, both to quantum and to classical computing algorithms, are already beginning.

Addressing directly the charge to the Subcommittee, we provide here a pair of specific examples of potential contributions of QIS to NP programs; this subject will be discussed in more detail in Section 4, "Quantum Information Science, Quantum Computing and

Simulation for Nuclear Physics." We expect the adaptation of modern quantum sensors to enable the continued development of innovative cryogenic detectors. For example, improved capability in sensing both the heat and light generated by exceedingly rare sub-atomic events will improve sensitivity in the long-sought neutrinoless double-beta ($0\nu\beta\beta$) decay of nuclei. In the longer-term, beyond-NISQ-era, large-scale QC is expected to enable classically inaccessible calculations of, for example, early universe phase transitions, complex low-energy nuclear reactions, and hadron formation—all key elements of the NP research programs.

A number of activities and technologies in the diverse NP research portfolio can contribute to the emerging QIS and QC programs. For example, there is a long-standing component involving theory, high-performance computing (HPC), and experiment that is focused on strongly correlated quantum many-body systems and quantum field theories. The community also has expertise in the design and construction of highly instrumented, ultra-cold detection systems; ultra-low background experiments; the production and enrichment of nuclear isotopes; and the organization of a sustained community of researchers in the execution of multi-year collaborative research programs in theory, computing, and experiment.

Again addressing directly the charge to the Subcommittee, we provide here specific and unique examples of potential contributions of the NP research programs to QIS research; this subject is discussed more broadly in Section 5, "Nuclear Physics for Quantum Information Science and Quantum Computing and Simulation." Researchers in QIS are adopting techniques used in lattice quantum chromodynamics (QCD) calculations that were developed by NP and HEP researchers to elucidate features of carbon nanotubes and topological insulators, both of which may play significant roles in next-generation qubit technologies. The extensive expertise developed by nuclear physicists in shielding against cosmic rays, and in the fabrication of radio-pure materials to suppress backgrounds in rare event searches, can play an important role in increasing the coherence times of next-generation qubits. NP is also the steward of the US isotope program. In the future, isotopically pure materials will be required to improve qubit coherence times for a range of both computing and sensor applications, and to enhance the capabilities of quantum memories in which nuclear spin plays a key role.

To fully realize NP contributions to QIS, and vice versa, close collaboration among universities, technology companies and startups, national laboratories, and other government agencies will be essential. Such collaboration will be required to bring, for example, new sensor technologies to scale for implementation in the NP experimental program, as well as for uses in other sectors. The success of these efforts is pinned, in part, on developing and sustaining a quantum-ready workforce that comprises scientists, engineers, developers, laboratory technicians and others—with the full range of experience from novice to expert—through the continued integration of QIS into NP. Additional viable career paths are required to sustain a vibrant and effective quantum-ready NP workforce.

Stewarding the NP components of this multilateral effort will require regular and critical feedback, especially during the formative stages. Because of the fluid nature of the QIS field and because we are starting from what is effectively a "green field," we are convinced the NP activities will benefit from a formal, biennial evaluation for the next several years—a task that may be appropriate for an NSAC subcommittee.

The Subcommittee recommends that the funding agencies and the NP community take a number of actions to advance the community's contributions to QIS and to take advantage of developments in QIS. These actions will allow us to include, and optimally employ, potential enhancements to the NP research programs and to contribute effectively unique capabilities and expertise to the QIS and QC programs. **We recommend that DOE and NSF support the comprehensive package of initiatives in QC and simulation, quantum sensors, exploratory techniques and technologies in combined NP and QIS activities, and workforce development presented in this report.**

The recommendations presented below also appear with more detail in ***Path Forward for Nuclear Physics*** (Section 7) of the main body of the report.

Recommendation 1A: Quantum Computing and Simulation, and Nuclear Physics

Future developments in QIS, QC, and quantum simulators are expected to provide capabilities for specific applications that far exceed those possible with classical computation. Such capabilities, which likely require more than a decade of concerted effort to realize, would provide a unique path to address some of the computational challenges facing NP in quantum many-body physics and quantum field theory (QFT) research. In addition, quantum many-body and QFT techniques essential to addressing key problems in NP are anticipated to impact future developments in QIS and quantum devices. QIS will develop, in part, as a result of addressing new and difficult problems. The quantum many-body problems that NP has in common with other domain sciences such as materials and chemistry will help drive this development; NP also brings, for example, problems with non-Abelian symmetries. We anticipate this fortuitous feedback cycle to continue into the future.

Developing the capabilities to utilize QC and simulations for NP research requires a highly multidisciplinary approach. Furthermore, the intertwining of quantum device development, algorithm and application development, classical simulation of quantum devices, QC and simulation, and workforce development is essential to establish a sustainable NP quantum ecosystem. Close cooperation among scientists, engineers and developers with expertise in diverse areas—located at universities, technology companies and startups, national laboratories and other government agencies—is also required to tackle the substantial challenges that lie ahead.

We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for simulation. These Co-Development Consortia should pursue and facilitate the development of quantum simulation capabilities for NP research and utilize NP expertise in quantum many-body physics and quantum field theory to impact quantum information science and quantum computing.

The Quantum Co-Development Consortia (QCDC) for simulation should provide accessible expertise and quantum resources to the NP community, analogous to the cross-disciplinary benefits provided by the Scientific Discovery through Advanced Computing (SciDAC) Institutes for HPC in the domain sciences. The QCDC should strengthen partnerships among scientists, engineers, and developers at universities, technology companies and startups, national laboratories and other government agencies, as well as coordinate with DOE and NSF quantum test beds. They can take advantage of their combined resources to efficiently support and coordinate workforce development efforts in areas related to simulation. We envisage that, together, the QCDC will form a key part of the QC and simulation ecosystem for NP research. The co-development element of the QCDC will enable continuous feedback between application developments and quantum hardware design to realize the full scientific potential of this quantum ecosystem.

Recommendation 1B: Quantum Sensing in Nuclear Physics

Quantum sensors have diverse application in areas that include communication, imaging, medicine, deep-space exploration, national security, and research in NP, astrophysics, and HEP. Their implementation in NP applications is of direct benefit to NP research and aids in bringing QIS technologies to maturity. Fabricating and deploying quantum sensors—including those in solid-state, superconducting, atomic, nuclear, and optical systems—utilizes a range of technologies and breadth of expertise. Within the NP community, our expertise provides opportunities to drive forward the development of quantum sensors and other quantum devices.

Presently, the NP and QIS communities have developed natural interactions through the advancement of quantum sensors that are finding application in NP experiments. Quantum technologies such as superconducting quantum interference devices (SQUIDs) have long been critical to the success of a variety of NP experiments and are now becoming standard in many applications. Newer quantum sensor technologies—TESs, superconducting nanowire single photon detectors, microwave kinetic inductance detectors, and JPAs—are now finding their way into important experimental efforts. Programs including $0\nu\beta\beta$-decay experiments, nuclear materials analysis, electric dipole moment (EDM) searches, x-ray reference data, and neutrino mass measurement are all incorporating quantum sensors in critical roles. While this exploration of the applicability of quantum sensors in NP remains rather limited, as these specialized uses become successful and more broadly recognized, it is reasonable to expect that they will find a broader application in NP. Indeed, use of quantum sensors is expected to make transformative changes in the design of high-priority NP experiments.

We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for sensors focused on targeted, prioritized, cross-disciplinary developments in quantum-enhanced sensing for NP research.

We expect the QCDC for sensors to establish a base of support for an integrated NP community in quantum sensing. They will focus on select technologies to pursue vigorously and will work in partnership with researchers in QIS and QC, as well as other domain sciences. The sources of the sensor QCDC scientists, engineers, and developers will include universities, national laboratories and other government agencies, and technology companies and startups.

It is important for the NP portfolio of quantum sensing research to contribute to the US QIS and QC programs on relevant timescales, as it should complement and be competitive with quantum sensing programs in other domain sciences and the private sector. The sensor QCDC will target high-priority quantum sensing research that satisfies these criteria, is important in the NP research programs, and is expected to yield tangible results on timescales of a few years. These consortia, as those for simulation, can take advantage of their combined resources to efficiently support and coordinate workforce development efforts in areas related to sensors.

Beyond specific devices, nuclear physicists can bring unique expertise in a number of system-level areas to address problems in QIS, in QC, and in quantum sensors. Low-background methods, large-scale cryogenic techniques, and the ability to manage large, diverse collaborations are skills from which QIS and QC can benefit as they expand.

Applications of quantum sensors, in many instances relevant for NP applications, rely on devices being readily available in quantity and having standardized performance. To accommodate these needs, and to enhance quantum sensing in other science domains and QIS applications, it is desirable to have mechanisms enabling the commercialization of quantum sensing capabilities emerging from NP research. The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provide opportunities for supporting the commercialization of technology developed during research, and enable collaborations between research institutions and technology companies and startups on commercially viable projects of mutual benefit. The Quantum Economic Development Consortium (QED-C) led by the National Institute of Standards and Technology/SRI International should be considered in determining how best to support this emerging interface.

The DOE Nuclear Physics Program manages DOE's Isotope Development and Production for Research and Application program, which can uniquely support the supply of stable isotopes as raw materials important to QIS and QC development. These isotopes will play an increasing role in low-noise quantum sensing applications (as well as in devices for QC and for quantum memories). For example, the natural 1% abundance of ^{13}C limits the spin diffusion lifetime in nitrogen vacancy diamond sensors. On the other hand, here, as in other systems, the controlled deployment of atoms with nuclear spin, such as ^{13}C and ^{15}N, can be used to advantage for storage and readout of quantum information.

Recommendation 2: Exploratory Techniques and Technologies in Combined Nuclear Physics and Quantum Information Science Activities

We expect QIS research during the next decade, and beyond, to benefit programs that are currently part of the NP research portfolio, as well as those that are likely to emerge. These programs in turn will contribute to advances in QIS, including computing, simulation, and sensors. Currently, such "ancillary" efforts within NP are typically nascent and limited in scope. However, they have the potential to provide critical intellectual and training support for the overall NP program. These efforts, and the development of new efforts of similar scale, should be encouraged and supported.

We recommend that DOE and NSF encourage and support selected exploratory technologies and techniques that have promise to be of mutual benefit to NP and QIS research activities.

The scope of such projects ranges from experiment to HPC to theory. They encompass efforts that will feed the recommended QCDC in quantum sensing and quantum simulation, and efforts that may be independent, stand-alone projects. While these projects are expected to benefit from collaborations with QIS or QC experts and the QCDC, such collaborations need not be a requirement. Single-investigator, small- or medium-scale efforts are expected to provide unique or specialized workforce development opportunities. In particular, at the small scale, agency support for nascent new techniques and technologies in this domain (whether experimental, theoretical, or computational) should enable rapid and flexible NP response to newly apparent opportunities. We expect them to be a rich source of innovation and workforce development.

Recommendation 3: A Quantum-Ready Nuclear Physics Workforce

The US NQI recognizes that building a quantum-ready workforce is essential to a healthy ecosystem of impactful research to support the emerging quantum economy. We must give priority to the education, training, development, and sustainability of a quantum-knowledgeable and expert workforce at each professional, and pre-professional, level to enable NP to reap the benefits of developments in QIS and QC, and to establish long-term, co-development programs. Further, the inherent cross-disciplinary nature of QIS and QC suggests that broad engagement of nuclear physicists with scientists and engineers in other domains is essential to the development of a QIS-ready NP workforce. Participation by NP scientists and engineers in the anticipated NQI centers should also yield significant workforce benefits.

One should not underestimate the difficulty of this part of the task. Bootstrapping technical communication among the various disciplines will be among the first challenges. Each discipline naturally has its own language, and the substantial effort of translation will be required. This is often most effective with sustained, in-person contact—hence the array of steps recommended below. Effective workforce development will require the coordinated efforts of all stakeholders, including scientists, engineers, and developers; institutions; technology companies and startups; and funding agencies. The stakeholder roles will interlock and will not easily be separated.

Annual, multi-week summer schools and training programs continue to provide an effective means of workforce development within NP. Summer schools and training programs focused on QIS and QC in NP could provide a deep immersion in QIS and QC relevant to NP. The schools would draw presenters from universities, technology companies and startups, and national laboratories and other government agencies. The presenters' expertise should span the range from NP to materials, to exotic states of matter, to HEP, to quantum algorithms and error correction, to quantum programming, to quantum device design and fabrication. Further, the presenters should be involved in establishing the format and content, in addition to engaging with participants at the school. It is desirable to have participants engage in practical, independent projects, along with hands-on or remote access to quantum devices, simulators, and modeling and estimation tools. For large parts of the program, the NP community could make these activities available online.

The NSF has established the "Triplets" program, which connects graduate students with mentors and advisors in universities, national laboratories, and technology companies to guide them through their graduate careers. This innovative program appears well suited for developing, in part, the QIS-ready workforce for NP. A number of other countries are pursuing similar programs. The success of such collaboration will depend, in part, on establishing intellectual property agreements that allow for the mutually beneficial engagement and openness that are consistent with university environments.

The SciDAC programs have been successful in nurturing early career scientists in HPC within the domain sciences and could provide a useful model for QIS workforce development. They provide support for junior scientists and developers, at the level of graduate students and postdoctoral fellows, with expertise in HPC and algorithms to integrate with computationally demanding, domain science research projects.

The recommended QCDC in quantum sensing and simulation should play key roles in developing the QIS-ready workforce for NP through each of the universities, laboratories, government agencies, and technology companies and startups that participate in them. The QCDC will, in turn, adapt to and benefit from newfound expertise in the expanding QIS-ready workforce.

With the expectation of mutual benefit, we recommend strengthening the QIS and QC expertise in the NP workforce.

NP could develop this workforce with activities including the following:

- Annual summer schools and training programs in QIS and QC for NP
- Annual conferences focused on QIS, QC, and NP, to be established by the community
- Graduate fellowships that partner students with advisory teams of scientists, engineers, and developers from universities, national laboratories or other government agencies, and technology companies and startups
- Recruitment of postdoctoral fellows with expertise in QIS or QC to focus on NP research
- Bridge positions in NP for junior scientists, engineers, and developers with expertise in QIS or QC

- Visiting scholar positions to encourage engagement among the NP, QIS, and QC communities and to foster community-building and early collaborations

- Enlargement of the scope of the SciDAC program, or the establishment of analogous programs, to provide support for junior scientists, engineers, and developers with expertise in QIS and/or QC to work with NP scientists toward achieving NP objectives

In addition to our set of recommendations, the following are some synergistic comments for consideration primarily by the NP community.

Comment 1: QCDC and National Quantum Information Science Activities

QIS research is fundamentally interdisciplinary, and cross-pollination will be critical to serve the needs of the US. We envisage the NP QCDC as serving the needs of the NP community and providing vehicles to accelerate advances in NP, QIS, and QC in mutually beneficial ways. They could serve as natural conduits enabling integration of the NP-QIS activities, at the appropriate level, with the nation's larger-scale QIS effort. We strongly encourage the funding agencies to facilitate, as appropriate, these connections between NP and the anticipated NQI centers. Individual investigators from NP participating actively in the centers will enhance the integration of NP QIS activities. We expect NP simulation and sensing activities, together with the corresponding workforce development, to benefit significantly from these connections. Further, applications of QIS and QC to address grand challenge problems in NP will be similar to their applications to problems in other domain sciences, such as HEP and basic energy sciences, and therefore can both benefit from and aid advances in those areas.

The QCDC should engage, and enable collaboration among, all key elements of the future quantum ecosystem as well as facilitate effective QIS-workforce development**. The community and agencies should support QCDC only throughout the period in which they continue to accelerate advances in NP, QIS, and QC.**

Comment 2: The Nuclear Physics Community

Although NP can utilize and contribute to QIS and QC, future progress will depend critically on developing and sustaining a QIS-ready NP workforce. This effort will necessarily require establishing clear career paths for junior scientists that include, for example, leadership opportunities in support of promotion. The multidisciplinary nature of QIS and QC suggests that challenges to enjoying a successful career path in this area will be similar to those encountered by scientists in other multidisciplinary areas. Lessons from the past may therefore be helpful as the community builds the NP quantum ecosystem and grows the QIS-ready NP workforce.

As stated earlier, stakeholders of NP and QIS together should consider the following items:

- APS journals, particularly *Physical Review C* and other NP-related journals, should broaden their scope to consider manuscripts for publication that describe the results of research in QIS and QC for NP research.

- Universities and laboratories should be encouraged to hire scientists and engineers with expertise at the interface of QIS, QC, and NP into early-career positions that have long-term career opportunities.

- The NP community should organize summer schools, workshops, conferences, focused meetings, and other in-person and virtual venues for researchers to gather and learn from one another.

- Universities, together with national laboratories and other government agencies, should be encouraged to engage with technology companies and startups. To maximize the impact, special attention to intellectual property will be required and will perhaps involve conceptually new frameworks.

- Development and/or upgrading of undergraduate and graduate courses in NP to include QIS and QC should be encouraged by providing resources for university faculty.

- Engagement among the NP, QIS, and QC communities should be encouraged by making available visiting scholar positions to foster the early collaborations needed to build this community.

- NSF and DOE should consider forming an NSAC subcommittee to regularly evaluate the progress of QIS and QC efforts within the NP community. Such a committee could be empowered to recommend actions and investments to NSAC and to the broader NP community to optimize NP QIS and QC efforts.

Summary of Recommendations

- **R1A: We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for simulation. These Co-Development Consortia should pursue and facilitate the development of quantum simulation capabilities for NP research and utilize NP expertise in quantum many-body physics and quantum field theory to impact quantum information science and quantum computing;**

- **R1B: We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for sensors focused on targeted, prioritized, cross-disciplinary developments in quantum-enhanced sensing for NP research;**

- **R2: We recommend that DOE and NSF encourage and support selected exploratory technologies and techniques that have promise to be of mutual benefit to NP and QIS research activities;**

- **R3: With the expectation of mutual benefit, we recommend strengthening the QIS and QC expertise in the NP workforce.**

1. Introduction to the Report

Quantum information science (QIS) addresses the question of how to utilize quantum physics to enhance the acquisition, storage, manipulation, transmission, computation, and interpretation of information. It is a broad, interdisciplinary field spanning many topics, techniques and devices in fundamental science and technology. A central theme of QIS is the study of the properties and uses of *quantum entanglement*, the characteristic correlations among parts of a quantum system that have no analog in classical systems. The range of possible applications of QIS is wide. They include, for example, metrology with improved sensitivity and spatial resolution, cryptographic protocols that are secure against powerful eavesdropping attacks, quantum algorithms that can vastly speed up the time to solution for difficult computational problems, new insights into exotic states of highly correlated quantum matter, and even novel approaches to understanding the quantum structure of spacetime itself. It is likely that new and sometimes surprising applications will continue to emerge. QIS devices utilize physical systems that allow for coherent, high-precision manipulation of quantum states; among these systems are individual atoms and photons, spins of electrons and nuclei, and superconducting electrical circuits. Rapid advances in QIS research and technology during the past two decades, particularly in the control of quantum coherence and entanglement, suggest that revolutionary advances in scientific and other applications may be possible in the future.

Nuclear physics (NP) research seeks to answer fundamental scientific questions about the origin of the visible matter in the universe and about the nature and interactions of its basic constituents that, for example, give rise to the chemical elements. It is a broad research field that extends across all forms of matter. These forms include atomic nuclei, which are at the core of both the familiar matter around us and of the new elements at the limits of nuclear stability created in laboratories. They include the matter, and its symmetries, in the early universe; the very hot soup of quarks and gluons that existed a microsecond after the Big Bang; and the configurations of strongly correlated neutron and quantum chromodynamics (QCD) matter that exist inside neutron stars. Nuclear physicists make observations with an array of tools, from the high-intensity beams created in research laboratories to ultra-sensitive, low-background experiments that probe the fundamental nature of matter. Nuclear physicists predict and model complex matter and processes in terms of the fundamental laws of nature and verify observations using state-of-the-art theoretical approaches combined with high-performance computing (HPC).

Cross-fertilization between QIS and NP offers exciting opportunities for discovering new platforms, protocols, and approaches that can accelerate the advance of quantum technology and chart a quantum roadmap to address the fundamental science grand challenges highlighted in the 2015 *Long Range Plan for Nuclear Physics* (LRP). Of particular interest in this context, and therefore the focus of this report, is co-development of QIS and NP in two broad areas. (1) We foresee clear mutual benefit at the intersection of quantum computing (QC) and simulation with the existing tools and techniques of NP calculations; (2) the NP pursuit of frontiers of rare processes and precision measurements will increasingly involve development in the area of quantum sensing technologies, with possible applications in a broader range of experiments. There are also important implications of a better understanding of the manifestations of quantum mechanics in many-body systems, where important nuclear phenomena such as heavy-ion collisions, deep-inelastic scattering, and low-energy reactions of nuclei offer a rich testing ground. Meeting the LRP grand challenges in NP will require, among other resources, advances in computing and simulation, and in specialized sensing devices.

In the near term, computing and simulation in NP will rely on classical HPC. The 2017 "Exascale Requirements Review" established the range of resources required over the next several years. Solutions of NP problems are challenging for several reasons, including the nonlinearity and exchange symmetries of QCD, the exponential growth in the number of quantum states with increasing particle numbers, and the complex nature of the sum-over paths required to evolve quantum states in time. The solutions are complicated further by the range of distance scales in NP problems, from subatomic to astrophysical, and by the emergent nature of protons, neutrons, and nuclei themselves, as well as the hot quark soup from which they formed in the early universe. Even with exascale HPC resources, we are not able to explore NP systems and environments with the desired precision using current theoretical formulations and algorithms. NP problems, in part, drive continued expansion of these capabilities.

As suggested by Richard Feynman nearly 40 years ago, a way to efficiently simulate a quantum system might be to use a different quantum system whose parameters can be controlled. These ideas have matured to the point that now we have analog quantum simulators, quantum annealing computers, and modest gate-based quantum computers with from a few tens to just over a hundred qubits. We have recently solved several simple ("toy") NP problems using some of these devices. Whereas universal quantum computation with effective error correction is years away, there is a distinct possibility that various QC and simulation tools will make significant contributions to NP in the future. Even the early thinking in this area is leading to new ideas.

Quantum sensors utilize key aspects of quantum mechanics in an essential way to measure or to improve the measurement sensitivity of a physical quantity that may, itself, be classical or quantum. Although there is no accepted definition of "quantum sensing," it is generally understood to involve advantageous use of quantization (energy levels, angular momenta), and/or tunneling, and/or superposition of states (coherence) and/or entanglement. Historically, we have considered "classical" devices (e.g., photomultiplier tubes) to be quantum sensors as long as they measure a quantum phenomenon such as the absorption of a single photon. As discussed subsequently, there are a number of examples of NP experiments in which quantum sensors play important roles. Some of these devices rely on the class of phenomena associated with superposition; we are on the threshold of devices and measurements that rely on entanglement.

There is already a degree of integration of QIS and NP. Preliminary discussions about the role of QIS in NP research took place in a series of workshops organized by the NP community. They included Quantum Computing for Nuclear Physics, held at the Institute for Nuclear Theory (INT), University of Washington, on November 14–15, 2017; Intersections between Nuclear Physics and Quantum Information, held at Argonne National Laboratory on March 28–30, 2018; and Quantum Information Science and Quantum Computing for Nuclear Theory, held in Santa Fe, NM, on January 23–25, 2019. The first two of these workshops led to white papers, "Quantum Computing for Theoretical Nuclear Physics" and "Opportunities for Nuclear Physics and Quantum Information Science."

The present report is based on meetings of the Nuclear Science Advisory Committee (NSAC) Subcommittee on QIS. It includes an overview of information gathered during the Subcommittee's March 28–29, 2019, and April 30–May 1, 2019, meetings. Its structure is as follows: It begins with a brief survey of national and international activities in QIS and QC. Then, it provides an overview of QIS and QC as they relate to NP activities (this overview is not intended to be comprehensive). Following this general presentation, specific sections describe the potential applications of QIS and QC in NP research, and the contributions that NP activities could make to QIS and QC. Recommendations and additional comments are presented in the "Path Forward." **One of the most important observations one can make about the development of this field is that it moves quickly and often in unexpected directions; this report is, of necessity, based on current information and reasonable expectations.**

2. The US National Quantum Initiative and National Activities, International Quantum Activities, and National Security

2.1 The National Quantum Initiative

The National Quantum Information Act, passed in 2018, establishes a 10-year plan to accelerate basic research in QIS and relevant technological applications, with current research and development (R&D) efforts organized around three pillars: the civilian, defense, and intelligence communities. To comply with the Act, a presidential-level National Quantum Initiative (NQI) Advisory Committee was established. Additionally, the National Science and Technology Council (NSTC) Subcommittee on QIS—with DOE, the National Institute of Standards and Technology (NIST), and the National Science Foundation (NSF) as co-chairs—focuses on oversight of scientific and technical activities across federal agencies. This NSTC subcommittee has developed policy recommendations that emphasize a science-first approach to identifying and solving grand challenges. The NSTC also established a Subcommittee on Economic and Security Implications of Quantum Science, jointly chaired by the Department of Defense, the Department of Energy (DOE), and the National Security Agency. This coordinated national approach is critical to ensure the necessary government-sponsored research occurs in all relevant areas. It also recognizes that developing a quantum-ready and diverse workforce is critical to the long-term success of the NQI.

2.2 National Quantum Information Science Activities

The DOE Office of Science (SC) strategy for QIS leverages unique strengths to address crosscutting themes among the six SC program offices. DOE SC–wide collaborative programs are internationally recognized and have a demonstrated ability to execute large-scale, interdisciplinary projects, including facilities and centers. For QIS, a particularly important element of the SC mission is to provide foundational tools, equipment, and instrumentation. For example, the Office of Advanced Scientific Computing Research (ASCR) test beds program provides access to QC hardware for all SC programs and leverages the established methodologies for co-design in computer hardware development. SC is actively developing QIS application programs in QC, analog quantum simulation, and sensing and microscopy—a process driven by community engagement through workshops, study groups, and roundtables. Scientific requirements across the SC programs drive and focus innovation. Those involving QC and simulation speak, in part, to core NP scientific questions, including quantum field theories (QFTs) and dynamical nuclear many-body processes that are not tractable with classical computing systems. There is a recognized need for a crosscutting, SC-wide approach to the development of sensors and microscopy. SC has begun to invest in QIS, with $62M in FY 2018 and $123M in FY 2019. The FY 2020 request includes $168.5M to focus on the establishment of NQI centers.

NSF has been supporting QIS initiatives for over 35 years. The program has been active and comprehensive, with 2078 awards made to more than 1200 projects addressing the relevant areas supported by NSF. The current initiative, "The Quantum Leap: Leading the

Next Quantum Revolution," started in 2016, is framed in terms of three questions: What are the limits of quantum entanglement and coherence? What can be learned from the study of naturally occurring and engineered quantum systems? How can the science and engineering community be galvanized to develop the essential technologies? To date, NSF has made approximately $140M in multi-year awards in fundamental QIS R&D and scientific application development. Recognizing the critical role of workforce development in advancing QIS activities, NSF has initiated the QIS and Engineering Network (QISE-NET) of human resources, including the Quantum Leap Triplets program that links students with academic, industry and national laboratory mentors. The next awards in the Quantum Leap series will focus on Foundries for Quantum Materials Science, Engineering, and Information, an incubator program emphasizing small-team innovation; and the Quantum Leap Challenge Institutes, with 5 year funding, starting in FY 2020.

2.3 University, Laboratory, and Regional Programs

University-based investigators have driven conceptual advances in fundamental physics that have furthered the frontiers in QIS and QC from the very beginning. Many of the important breakthroughs in QIS have been accomplished at universities, in part, in collaboration with technology companies and national laboratories. During the past two decades, US universities have been growing their research activities in QIS to varying degrees. These have typically been cross-disciplinary activities involving a subset of physics, chemistry, engineering, and computer science departments. At a number of institutions, joint institutes and centers and technology hubs have been successfully established. On the experimental side, and to a lesser degree on the algorithmic side, some of these efforts have led to formation of technology startup companies. The NSF is supporting projects at universities in atomic, molecular, and optical physics (AMO), QC, QIS, and the quantum communication landscape, including the multi-institutional effort to build the world's first practical quantum computer. This report does not attempt to provide a complete summary of university-based activities, as efforts directly related to NP research activities are nascent.

The university-based activities have played an essential role in establishing the currently existing QIS and QC workforce, including scientists, engineers, and developers at national laboratories, technology companies, and startups. They have also been instrumental, along with the national laboratories, in training engineers and technical support for quantum infrastructure. Degree programs and specialty courses at universities, including online and evening masters programs, are growing rapidly to meet the demands and expected future needs of the emerging quantum economy.

The network of DOE national laboratories is an integral part of the vision outlined in the NQI. There are world-class technology and infrastructure resources at the national laboratories that support their diversified, multidisciplinary research programs. The laboratories are using some of these resources to help propel QIS development in the nation.

The range of capabilities of SC and the National Nuclear Security Administration (NNSA) laboratories is broad. They support facilities for the synthesis of novel materials, for example, the Nanoscale Science Research Centers at Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL). For the characterization of these materials, there are synchrotron and x-ray free electron laser light sources at ANL, BNL, LBNL, and Stanford Linear Accelerator Center (SLAC). For advanced quantum device fabrication, there are valuable facilities such as the Microsystem Science, Technology, and Components Center at Sandia National Laboratories (SNL). The Enriched Stable Isotope Pilot Plant at ORNL and the future U.S. Stable Isotope Production and Research Center, both part of the overall DOE Isotope Development and Production for Research and Applications (IDPRA) program, can produce crucial isotopes for various QIS applications, including qubits, atomic and nuclear clocks, magnetometers, ion-trap experiments, and quantum memories.

There are other unique capabilities at national laboratories. Research facilities for computing and networking enable collaborations among scientists, engineers, and developers from QIS, computational science, and other disciplines in the scientific community to develop algorithms and solutions for a range of problems. These facilities include commercial quantum annealer systems (e.g., D-Wave at LANL) and QC test beds (e.g., trapped-ion and superconducting test beds being developed at SNL, LANL, LBNL, and Lawrence Livermore National Laboratory [LLNL]); exploratory QC technologies for NP problems (e.g., qudits—quantum bits with *d*-levels—at LLNL and quantum frequency processors at ORNL); and research hubs providing access to quantum devices at technology companies and startups (e.g., the hub at ORNL). In support of their large-scale projects, national laboratories have unique engineering resources that could expedite research relevant to QIS. These resources include expertise and facilities for cryogenics and ultra-high vacuum, low-vibration platforms, and special laboratories with electromagnetic shielding.

The NNSA national laboratories have a long history of foundational research in QIS. More recently, national laboratories have taken a multipronged approach to broaden and hone their QIS capabilities. They have expanded their internal expertise by targeted staff hires and by supporting innovative QIS projects through their Laboratory Directed Research and Development funds. Some of these initiatives have led to crosscutting R&D portfolios supporting national QIS programs.

National laboratories, universities, and technology companies and startups have begun to convene consortia in various forms to extend capacity in QIS. National laboratories and universities have established agreements with technology companies and startups to provide them with mutually beneficial collaborative access to quantum devices and experts. The geographical span of regional partnerships varies in size, ranging from metropolitan to multi-state networks. The R&D scope of national laboratories typically encompasses elements integral to the QIS programs supported by the DOE ASCR, DOE

Basic Energy Sciences (BES) and DOE High Energy Physics (HEP)[1] Offices and by NSF. Participants in these partnerships benefit from the sharing of expertise and resources, which accelerates the development of new QIS-related ideas and empowers them to explore technologies built from these advances.

2.4 Technology Companies and Startups

Over the past few years, a number of US technology companies, such as Google, IBM, Intel, Microsoft, and Honeywell, and startups such as IonQ and Rigetti, have begun to invest in QIS, principally in QC. They are pursuing a range of qubit technologies (superconducting, trapped-ion, spin, and topological qubits) for gate-based machines, as well as development of quantum annealing (D-Wave). The US academic community has performed most of its exploratory quantum computation and simulation on devices developed by these companies. The technology companies and startups are working toward establishing a quantum ecosystem, in support of the ecosystem currently envisaged in the NQI.

Currently, the most significant connections of technology companies and startups to the academic community are related to quantum hardware. Microsoft, Google, and IBM have laboratories and facilities located within universities in the United States and internationally, which in some cases are connected to national laboratories. Another area of connection, but presently to a lesser extent, is algorithm development. There is a long history of advancing science and technology by expanding the application space, and technology companies are actively adopting this approach. They are supporting the development of existing users and drawing in new ones through activities including the development of user-friendly programming environments; sponsorship of workshops on algorithm development, materials science, and characterization; sponsorship of student internships; and direct support of faculty research. As the engagement between research communities and technology companies and startups grows, the range of challenging problems addressed will feed back to new approaches for quantum algorithms and hardware. This is a well-traveled path, for example, in the advance of HPC through the demands of lattice QCD. It is important to note the role of technology companies in creating economic opportunities. Developing QC, for example, will generate a need for spin-off or startup companies to provide components for "at-scale" production of systems in both the hardware and software arenas.

For the technology companies and startups to continue to advance the state of the art in capability and scale, it is essential for them to be able to recruit a workforce that is educated in quantum mechanics at a range of levels. However, there will also be increasing need for a workforce educated in relevant engineering capabilities and having expertise in materials, numerical modeling techniques, utilization of HPC systems, sensing, and more. Significant exchange between the academic and private sectors has already taken place at the level of senior personnel. Expanding the conversation about training between

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[1] The abbreviations BES and HEP are used to refer to science domains. DOE BES and DOE HEP are used to refer to the DOE offices.

technology companies and startups and the academic community is an important step toward accelerating the national development of QIS.

One mechanism for enhancing the connections among the academic and national laboratory communities and technology companies and startups will be the Quantum Economic Development Consortium (QED-C), an industry group led by SRI International with an interface to government agencies through NIST. The goal of the QED-C is to support broadly the transition from R&D to first-of-a-kind device prototypes through to system prototypes that can ultimately be deployed at scale. An important focus of the QED-C is to determine the QIS workforce needs.

2.5 Relevance for National Security

The new capabilities of QIS and QC are likely to significantly affect US security interests; new technologies may play a role in solutions to some of the most pressing US concerns. Specifically, with their potentially disruptive advantages in sensitivity and measurement range and robustness, quantum sensors could have far-reaching impacts on positioning, navigation, and timing technologies. One example is the quantum gyroscope based on atom interferometry. Such gyroscopes are orders of magnitude more stable against drift than those currently available. They enable GPS-free positioning and fully inertial navigation. A second example is atomic clocks that also enable GPS-free navigation. They too have strong overlaps with NP research programs, such as searches for time-variations of the fundamental constants of nature and searches for electric dipole moments (EDMs). Progress is being made in developing nuclear clocks, for example, the ^{229}Th clock, which is anticipated to be more precise owing to smaller interactions with the environment. Another type of atom-interferometry-based sensor can perform highly sensitive gravity measurements, complementing threat-detection techniques based on passive detection of radiation. This sensor has potentially far-reaching impact for the detection of hidden masses at close distances, for example, in the context of portal scans or in emergency response. In a similar vein, the types of atomic vapor magnetometers used in EDM experiments (see the sidebar *Using Quantum Mechanics to Measure Electric Dipole Moments*), which take advantage of coherent superpositions of states for their precision, are also of interest in remote sensing applications.

Conversely, new quantum technologies—primarily the potential development of large-scale quantum computers—may also pose challenges to national security. Their potential capability (demonstrated by Shor in 1994) to dramatically reduce the number of operations required to solve mathematical problems that are very difficult or intractable for classical computers poses a problem for communication encryption protocols. Today, this intractability promises the security of our global communication infrastructure, from key exchange to encryption to digital authentication. Cryptographic systems, such as RSA based on the difficulty of integer factorization, are particularly vulnerable to the construction of a large-scale quantum computer. The community is also investigating the implications of various quantum communication protocols, including, for example, those associated with eavesdropping. The search for information security systems capable of resisting quantum technology—termed "post-quantum cryptography"—has become a priority. There are schemes that appear resistant to quantum attacks, such as lattice-based cryptography, and NIST is currently working to develop and certify standards for such quantum-resistant algorithms.

2.6 The World Stage

Several regions of the world are taking ambitious approaches toward developing research programs and technologies to position themselves for a possible quantum revolution. There were substantial unclassified expenditures on QIS already in 2015, according to a McKinsey estimate (in US dollars): Australia $85M, Canada $110M, China $240M, European Union $600M, and US $400M, with total worldwide expenditures estimated at $1.7B. At the time of writing of this report, we estimate that these investments have approximately doubled.

Beginning in 2000, the Australian Research Council established the multi-university Centre for Quantum Computer Technology through its Centre of Excellence program. The Australian Research Council has subsequently funded the follow-on Centre for Quantum Computing and Communication Technology through 2025. The initial investment has led to expanded programs and diversified funding. The Sydney Quantum Academy, a consortium of four local universities with support from the state government, focuses on collaboration with industry. It hopes to support startup technology companies, create jobs in quantum technology, and train the workforce to fill them. The Australian Microsoft quantum research laboratory is co-located at the University of Sydney. The University of Melbourne has also entered a partnership with IBM Research–Australia, where a publicly accessible 14-qubit IBM-Q quantum device is located.

Canada has made long-term commitments to support QIS R&D. Its support began in 1984 with a university/industry partnership that outlined the first viable technique to utilize quantum mechanical principles to encrypt information. That early success has led to a decades-long investment in a "quantum future," with a coherent national approach leading to a rich ecosystem in QIS among universities, laboratories, and industry. Substantial private capital has been critical in the development of the Waterloo Quantum Valley, which includes both the Institute for Quantum Computing at the University of Waterloo and an incubator of quantum technology companies and startups. Federal and provincial resources fund three academic centers across Canada making up the Quantum Co-Laboratory. Through the Co-Laboratory, Canada is implementing a long-term strategy based on a full lifecycle approach, called the Quantum Innovation Cycle. This cycle spans the full chain of activities from development of innovative ideas through commercial production. In particular, it facilitates proofs of concept and prototyping. This model promotes broad participation by enabling access to specialized infrastructure. Canada is also committed to workforce development with outreach, training, and community building programs. This emphasis has led to a relatively large community of active researchers. Private foundations have been investing in QIS activities in Canada in innovative ways. In particular, the Canadian Institute for Advanced Research has been supporting international teams of scientists to collaborate on visionary, fundamental, and long-term objectives in QIS.

The Chinese Academy of Sciences (CAS) has established a CAS Center for QIS. The CAS Center has three principle physical locations: Beijing, Hefei, and Shanghai. The centers cover all significant topics in QIS, including QC and simulation, quantum communication, quantum sensors and metrology, and quantum materials. One emphasis—and a focus of industry, international, and academic partnerships—is the development of a global quantum communication network that will form the basis of a quantum internet. Steps in this strategy include the "National Quantum Communication Backbone Project," established in 2016, which has led to a quantum communication backbone between Beijing and Shanghai, with connections in Hefei and Jinan. China is investing, in addition, in quantum satellites. The Micius satellite, launched in 2016, provides the ability to test quantum key distribution and to study quantum communication more generally over large distances. In late 2017, scientists and engineers in China and Austria held a quantum video call between Beijing and Vienna. China has developed a roadmap and a set of R&D projects to begin to establish a "Global Quantum Communication Network," including the launch of a "Quantum Constellation" of satellites. Although the quantum communication efforts are more visible, there are substantial and broad activities in the exploration and development of qubits for quantum computers and sensing. These activities are of comparable scientific scope to those in the US and elsewhere and have similar strategic objectives.

Europe, through both the European Commission (EC) and national programs, is investing in an ambitious program of QIS research, building on the heritage of establishing quantum physics in the early 20th century. The current programs in QIS take a comprehensive approach, including linking fundamental and applied science with engineering and developing connections to industrial partners. Notably, European researchers are working to develop a robust supply chain in anticipation of a future in which QIS-based technologies are relatively common. The EC has made significant investments over the past 20 years, positioning its community for the launch in 2019 of the decade-long Future and Emerging Technologies Flagship activity in QIS. The EC has summarized its strategy in *Quantum Manifesto: A New Era of Technology*. It details a "Quantum Technology Timeline for Quantum Communication, Simulation, Sensors and Computers" with goals for near term, 5 to 10 year, and beyond-10-year time frame. The EC has established the Flagship projects with coordination and governance mechanisms as important components. Individual members of the European Union are also investing directly in national-level quantum technology programs, forming a backbone of investment for the EC Flagships.

Some US technology companies have established laboratories and connections abroad. For example, Microsoft has laboratories at the Niels Bohr Institute of the University of Copenhagen in Denmark, the Delft University of Technology in the Netherlands, and the University of Sydney in Australia. Similarly, Intel also has a location at Delft University of Technology.

Pacific Rim countries including Japan are now making significant per-capita investments in QIS and QC. While their investments are smaller than those of the US, Europe and China, they are emerging. Their QIS communities have been developing for more than a decade; for example, Singapore established the Center for Quantum Technologies in 2007.

3. Introduction to Quantum Information Science and Quantum Computing and Nuclear Physics

The diverse NP research portfolio encompasses physics from theoretical and computational explorations of strongly interacting, many-body systems with unique inter-particle forces, to highly sensitive experimental searches for rare events that would reveal violations of fundamental symmetries. This program emerged from the discovery of quantum mechanics and Rutherford's discovery that a nucleus was at the heart of every atom, both early in the 20th century. It was later, after advances in computing and classical information, that quantum mechanics, information theory, and computation moved toward becoming the unified field of QIS. With the major advances in QIS during the 21st century, and the national and international efforts to integrate QIS into the science domains and into society in general, QIS is now rapidly entering NP research activities. Importantly, it is anticipated to become a transformation driver in enhancing NP research, enabling scientific progress that was previously unimaginable, and enabling advances in QIS through unique contributions from NP research programs and expertise. In addition to anticipated conceptual developments and understanding from QIS that have the potential to substantially alter the way quantum systems are viewed, including nuclei, at a more practical level, QC and simulation and quantum sensing are expected to have a significant impact on NP research in the future. Although sensing may provide an earlier impact on the research program, QC and simulation will fundamentally change theoretical predictive capabilities when quantum devices of sufficient capability are developed.

The purpose of this section is not to provide a comprehensive view of QIS, but rather a basic overview to provide context for the connections with NP. For a brief overview of QC, see sidebar 3.1, *Quantum Computers.*

3.1 Aspects of Quantum Computing

Quantum computing has the potential to provide predictive capabilities for quantum many-body systems and QFTs that are inaccessible to HPC. The process of quantum computation corresponds to the application of a sequence of unitary operations to registers consisting of quantum particles, followed by measurements of the resulting quantum states. Typically, one thinks in terms of registers of two-level quantum systems called "qubits," the analog of registers of bits in classical computers; but d-dimensional "qudits" are also available. A qubit wave function can be written as a superposition, $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where α and β are complex numbers constrained to satisfy $\sqrt{|\alpha|^2 + |\beta|^2} = 1$ and $|0\rangle$ and $|1\rangle$ denote two independent quantum states (levels) spanning its Hilbert space. The number of complex amplitudes needed to describe a quantum state grows exponentially with the number of entangled qubits. Thus, for as few as 300 qubits, describing a highly entangled quantum state using classical data would require more bits than the number of atoms in the visible universe. For this reason, a quantum device is better suited for storing and processing highly entangled many-particle quantum states than any classical device. It is also important to recognize that, just like quantum measurements in general, quantum computations are probabilistic and typically involve ensemble averaging of repeated measurements to determine the desired quantities, or produce intermediate quantities that provide results when combined with other inputs.

Although QC has significant potential, to date, we have not demonstrated a quantum advantage through execution of any scientific application.[2] In other words, there is no calculation related to a physical system for which a present-day quantum device has outperformed an available classical computer. However, there are proposed quantum algorithms that are expected to provide a quantum advantage but which have not yet been executed on a quantum device. We must overcome many challenges, large and small, to achieve a quantum advantage. These challenges exist at all levels: from architecture to software, and from algorithms to hardware. It is presently unclear which technology, or sets of technologies, will ultimately prove to be required and successful in establishing QC at scale. Success in this endeavor will depend on the ability of scientists, engineers, developers, and funding agencies to adapt to new knowledge and innovation on appropriate timescales, to be willing to take risks with new technologies that might fail, and to maintain broad investments in the quantum program.

Progress in the field of QC is now at a level such that expanding current capabilities toward practical applications appears tenable. Operational systems now have from several qubits to, in a few instances, more than 100 qubits, with larger systems consistently being announced. These devices are defining the beginning of the Noisy, Intermediate-Scale Quantum (NISQ) era of QC. Indeed, NISQ systems have started to appear in the commercial sector to provide research-level or on-site (where the devices are) engagement with the broader community, but they are without commercial value at present. This is a positive sign of engagement and investment by industry and one that is necessary to make advances beyond the NISQ era and sustain research and progress to scale in QIS and QC. Unlike in modern classical computers, the performance and capabilities of NISQ-era systems are hardware-, algorithm-, problem-, and circuit-dependent quantities. While presently incapable of outperforming classical computers, NISQ devices with suitable hardware attributes, such as connectivity and gate fidelities, are expected to provide useful results from low-depth circuits for quantities that are not required to be determined with high precision. Computations of this nature have been performed for model NP systems. When the size and complexity of the target system is increased, existing NISQ systems run to completion but provide results that are dominated by noise from qubit errors and imperfect gates, preventing the extraction of scientifically meaningful results for those systems. Nonetheless, the experiences gained from mapping the problem to the quantum hardware and developing the algorithm and the quantum circuits, including optimization, are valuable to future calculations on more capable systems. In the case of trapped ions, it is expected that systems with a few hundred qubits that are able to execute tens of thousands of gate operations while retaining coherence, but without error correction, will become available during the NISQ era. These systems are anticipated to have simulation

[2] On October 23, 2019, after this report was accepted by NSAC, the journal *Nature* published an article from Google that claims to have achieved quantum supremacy in computations using 53 programmable superconducting qubits.

applications in the science domains and to provide an important resource for beginning to address problems of importance to NP research, with a system-dependent level of precision that will depend on details of the hardware.

The National Academies of Sciences, Engineering, and Medicine (NASEM) recently conducted a study of QC, outlining milestones for its next decade of development. First is the creation of a 100-qubit system with improved error rates (below 0.5%) that can carry out computations that are difficult to perform but still verifiable on a classical computer. The second milestone is the construction of a quantum annealer that demonstrates a quantum advantage using a benchmark calculation that cannot be carried out on a classical computer. The third milestone is the practical implementation of quantum error correction, including the required hardware, control, and software. The last milestone, strongly emphasized in the study, is the development of a *commercially* useful quantum computer.

These quantum devices will not stand alone, and they will require classical computing interfaces and control systems. They are expected to first enter the computing ecosystem, and remain for the foreseeable future, on a broad scale as hybrid QC-HPC systems, just as graphics processing units (GPUs) were incorporated into HPC and are now an integral component of the path to exascale computing. Consequently, algorithm development is important—in particular, the identification of elements of an overall calculation that would have a quantum advantage, even with re-integration into the classical workflow. Further, as the output from the quantum components will be classical numbers, HPC systems will be required to "receive" and interpret the results of quantum computation. Addressing optimization problems with variational methods using a NISQ-era device may be an early application suitable for a hybrid QC-HPC system, but, unfortunately, this particular technique is not expected to scale well in larger systems. In this technique, the quantum processing unit (QPU) executes a modest quantum circuit; the associated classical computer "makes measurements" and returns instructions to modify the quantum circuit—a loop that minimizes a "cost" function. Such variational methods have been used with such hybrid systems by quantum chemists and NP researchers, typically employing Bayesian estimation techniques, to successfully determine the potential energy between atoms in small molecules.

From the standpoint of considering present-day scientific applications, quantum devices currently under development fall into three main categories: universal quantum computers, analog quantum simulators, and quantum annealers. The following subsections briefly summarize the present state of the art for these three categories.

3.1.1 Universal Quantum Computers

A universal quantum computer performs calculations by manipulating qubits within a quantum register. Unitary operations corresponding to the desired Boolean logic, and implemented using external controls, transform the register state. In practice, a circuit containing the small set of universal quantum gates approximates an arbitrary unitary transformation. Eventually, universal quantum computers are expected to speed up calculations relative to classical digital computers, at least for certain special problems, fundamentally because of the relatively larger amount of information stored in a given number of qubits and the entanglement among them. Technology companies and startups are now aggressively pursuing this technology. Fabricating and connecting large networks of qubits are among the challenges to be faced. In the operation of a quantum device, there are inaccuracies in the unitary operations applied to the qubits, errors in the measurements of the qubits, and interactions with the environment leading to decoherence among the qubits, all of which lead to deviations from the exact result. Loss of coherence of the quantum computer ultimately limits its ability to compute.

Currently, the most advanced available platforms for universal QC are based on trapped atomic ions and superconducting circuits. In an ion trap, each qubit is a single atom, which can be in either its ground state ($|0\rangle$) or a long-lived excited state ($|1\rangle$). Laser pulses manipulate the individual qubits, and the Coulomb interaction between a pair of ions, also controlled by lasers, provides the mechanism for entangling the qubits. For trapped ions, "single qubit gate times," corresponding to sets of single unitary transformations, are a few microseconds. An advantage of this technology is that the appropriate laser modulation of the Coulomb forces between ions can entangle, in principle, any two qubits (ions) independent of their relative position up to some limit. Universities, national laboratories, technology companies and startups are developing ion-trap-based quantum computers with varying degrees of collaboration among them. For example, SNL fabricates the ion traps in IonQ's systems as well as in experiments at universities throughout the world. In superconducting-qubit quantum computers, each qubit is an anharmonic oscillator realized as an LC circuit containing a Josephson junction. The coupling between qubits can be capacitive, inductive, or mediated by microwave photons in a resonator; and single qubit gate times are 10 or more times faster than for ion trap devices. Microwave electronic devices control and read out the system of qubits. Such devices are becoming available with 50 or more qubits. They are being developed by IBM, Google, Rigetti, and other technology companies and startups, as well as in universities, national laboratories, and other government agencies. Present-day devices are noisy, with 2 qubit error rates at about the 1% level, about 10 times as large as for ion-trap devices.

Other QC technologies are advancing steadily and continue to have promise. Among them are spin qubits, which are realized as semiconductor quantum dots, in crystal defects, or by using donors in semiconductors. Intel is pursuing spin qubits, building on its long history of silicon-based devices. There have also been recent advances in optical-tweezer arrays of neutral atoms, with fast multi-qubit operations performed via atomic Rydberg transitions. There are currently efforts to create entangled many-photon states for measurement-based QC (in which, essentially, many measurements of a given entangled state substitute for the series of unitary operations on a given initial state). Microsoft is focusing on topological QC, in which pairs of Majorana fermion modes in quantum wires encode qubits. Because of their topological symmetry, Majorana qubits should have much lower error rates than other qubit realizations, significantly reducing the amount of quantum error correction required for a logical qubit. However, it is not well understood how to build or operate a system of topologically protected qubits. Presently, it is unclear which qubit technology has the best prospects for scalability to large devices. Neither is it clear what the optimum combination of CPUs/QPUs/GPUs will be in a hybrid machine. It is possible that the technology choices will be application-dependent; NP researchers may choose based on the capability to address NP grand challenges.

In the long term, limitations imposed by noisy quantum gates will be overcome by quantum error correction to protect quantum information from damage caused by noise. However, this approach has a substantial overhead cost in the number of qubits and the number of gates that are needed to execute a quantum circuit. Error correction, as currently conceived, involves representing each "logical" qubit in a quantum calculation using several "physical" qubits in a way that protects quantum information. An error-corrected quantum device therefore requires a relatively larger number of qubits and gate operations to be effective, depending strongly on the quality of the quantum hardware and the complexity of the algorithm. For example, given a two-qubit gate error rate of 0.1%, the factoring (Shor) algorithm that could be used to break widely used public key cryptosystems requires 20 million qubits. To reach scalable quantum computation, therefore, requires the scale of hundreds of qubits in near-term devices to grow to millions of qubits in future platforms.

3.1.2 Analog Quantum Simulators

Analog quantum computers (or simulators) provide an alternative path to solving quantum many-body systems. They are beginning to address aspects of quantum many-body systems that are not accessible with HPC. Rather than mapping models to qubit registers, a precisely designed and highly accessible quantum system models the target system directly. Ultra-cold atoms can model a wide range of bosonic and fermionic systems and provide for a compelling platform for such analog simulations. Classical simulations of systems of fermions are challenging because of the anti-symmetry of the many-body wave function, which typically gives rise to large cancellations (a sign problem) in Monte Carlo sampling. Explicit use of fermionic degrees of freedoms in analog quantum simulations may provide some advantages over other methods of quantum computation for these systems in the nearer term. However, further research is required in order to, among other things, understand how to quantify systematic uncertainties associated with the mapping of the target system to the analog simulator.

To carry out analog simulations of NP systems, it will be important to develop efficient, low-overhead mappings of relevant models to the analog quantum devices. Recent experiments using neutral atoms successfully demonstrated the programming of Hamiltonians with increasing complexity, including dynamical gauge fields. Existing simulation techniques, together with new tools such as programmable interactions (trapped ions, Rydberg atoms, dipolar molecules), provide a basis for realizing simulations of more complex models. The presently available interactions are typically two-body, and there is motivation to extend to multi-body interactions. The target model may involve three- or four-body interactions, and variational quantum simulations can allow for extensions to multi-body interactions, by including effects only in the classical parts of the computation.

3.1.3 Quantum Annealers

A quantum annealer solves optimization problems, i.e., finds the approximate ground state of a quantum Hamiltonian, using adiabatic evolution and exploiting both the coherence of coupled qubits and quantum tunneling. Scientists map the target system onto a spin model with distinct operator structures, for instance, the spin model employed by the commercially available D-Wave quantum annealing computers. To first order, parameters in the coefficients of these structures are adiabatically varied to evolve the system from the initial, known ground state, to that of the target system; the full system remains in its ground state throughout the process. Depending, in part, on the energy spacing of the low-lying levels of the target system, some solutions involve quantum tunneling and/or thermal activation to pass barriers that may appear as the initial Hamiltonian is evolved to the final Hamiltonian. The in-principle advantage of a quantum annealer relative to a classical computer is an open question that is now under active investigation. For example, the scaling behavior of the time to solution as a function of problem size—for certain classes of problems—is only now becoming accessible. Further, it remains to be shown how annealers could utilize error-correction techniques.

A number of applications involving optimization problems would benefit from a quantum advantage. These include, for example, radiotherapy, quantum chemistry, graph models and other quantum many-body systems, satellite placement, traffic flow, and unsupervised machine learning. In addition, given the nature of machine learning, optimization devices are expected to improve searches for particles in HEP and relativistic heavy ion collisions. Given the evolving flexibility of the architecture and of the underlying system Hamiltonian, the scope of applications of these systems will likely increase. We expect increased access to more capable quantum annealers in the near future.

Sidebar 3.1: Quantum Computers

Quantum computers are devices that employ the principles of quantum mechanics to perform computations. A superposition of states of quantum bits, qubits (or, more generally, d-dimensional qudits) defines the state of a quantum computer. It is this, and the associated control of entanglement, that endows a quantum computer with computational capabilities beyond those of a classical computer. The dimensionality of the space associated with a quantum register of n qubits is 2^n, the same dimensionality as a classical register of *n* bits. While a classical computer can be in one of these states at any given instant, a quantum computer can be in a superposition of some or all states, permitting “parallel” operations on all 2^n states while retaining relative phase information. Typical use of quantum computers involves initialization, a series of quantum operations, and measurements, followed by analysis. As a qubit measurement provides one of its eigenvalues, an ensemble of measurements performed by repeating the quantum computation multiple times is typically required to determine relevant quantities. State preparation, quantum control, and provision of tightly coupled feedback typically require HPC resources.

Various types of quantum computers are being developed. Gate-based (digital) quantum computers employ a finite set of quantum logic gate-based operations to perform unitary transformations of qubits (and, more generally, of qudits). Examples of digital quantum computers are trapped-ion systems and superconducting qubit systems (Figure 1). Analog quantum simulators tune the qubit interactions, such as superconducting loops or optical lattices of ultra-cold atoms, to simulate a target many-body quantum system (Figure 2).

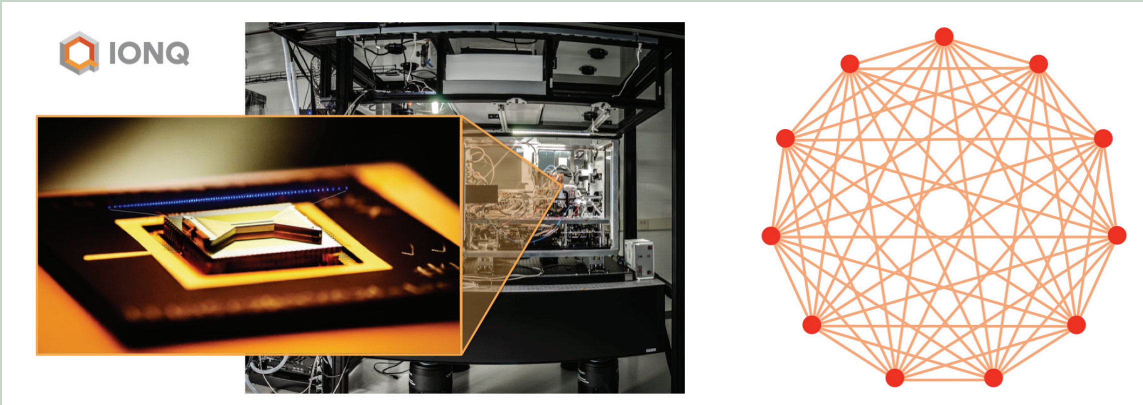

Figure 1: IonQ's trapped-ion digital quantum computer. The left panel shows the quantum computer along with an enlarged view of the ion trap (produced by SNL). The right panel shows the (all-to-all) connectivity map of the 11-qubit QC trapped ion systems that IonQ recently benchmarked. | *Images reproduced with permission from IonQ, via Jungsang Kim of Duke University.*

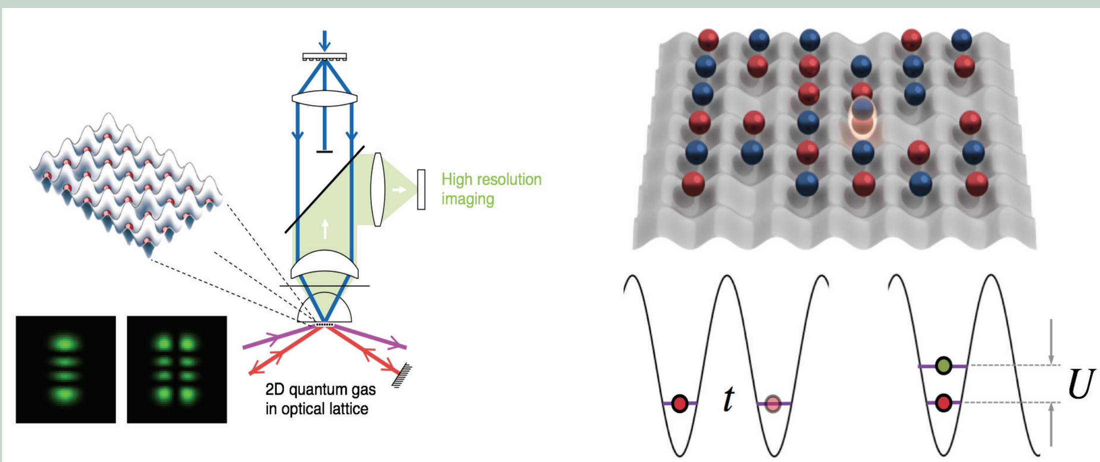

Figure 2: Elements of an optically trapped cold-atom analogue quantum simulator (left panel) and elements in simulating the Fermi Hubbard model. | *Images reproduced with permission from Markus Greiner, Harvard University.*

Because of the classical computing resources that are expected to be required to effectively operate a quantum processor(s), building heterogeneous (hybrid) classical-quantum computers that use classical and quantum components together to minimize the time-to-solution for sets of problems is a major objective. Scientists, engineers and developers are beginning to identify elements of computer codes and algorithms that would benefit from QPUs in heterogeneous computational systems. This approach is similar in spirit to the inclusion of accelerators in heterogeneous HPC systems.

Efficiently mapping a problem onto a quantum computer, developing algorithms to determine the operations necessary to arrive at the desired final state, and developing a set of measurements to interrogate that final state are all individually challenging problems. Note that effective use of supercomputers has an analogous set of elements: mapping the problem onto the architecture, data layout, parallelization, memory management, message passing, and effective use of accelerators such as GPUs. Each of these QC elements will require analogous developmental efforts.

There is now a concerted effort to develop, build, benchmark and operate quantum computers by technology companies and startups, national laboratories and other government agencies, and universities. Members of the NP community have performed calculations in toy model systems relevant to the NP mission on commercial, cloud-accessed, superconducting qubit quantum computers, for instance, IBM's Q Experience and Rigetti's Quantum Cloud Services, on IonQ's trapped-ion systems, and on ORNL's optical systems (Figure 3).

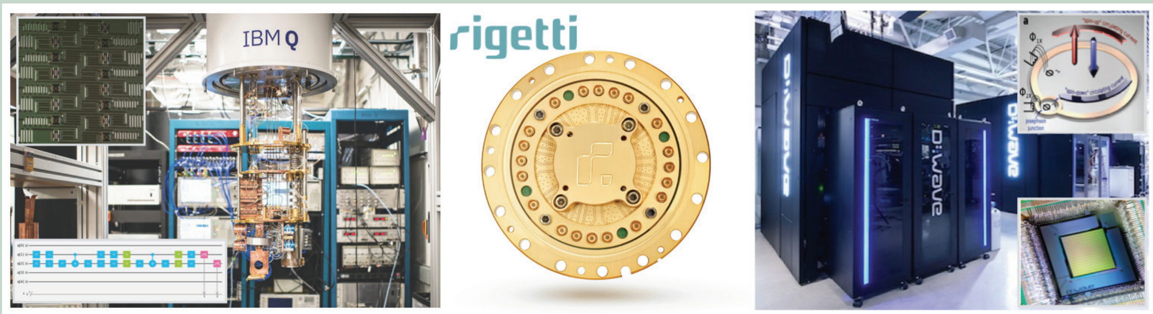

Figure 3: Components of quantum computers produced by IBM (left), Rigetti (center) and D-Wave (right). The upper inset of left panel is IBM's 16 qubit chip and the lower inset is a quantum circuit implemented through IBM's "qiskit" web-interface. The upper inset of the right panel is D-Wave's superconducting loop qubit and the lower inset is its 2000 qubit annealing processor. | *Images reproduced with permission from Nature Publishing Group. Nature, Hardware efficient variational quantum eigensolver for small molecules and quantum magnets, A. Kandala et al., copyright 2017.*

Although quantum computers will enable scientists to quantitatively address some physical systems that are inaccessible with classical computing, it is important to keep in mind that they are not a tool to address all systems and all problems. Computer scientists and quantum information scientists and engineers have understood the formal capabilities of compute devices, and their limitations, in terms of complexity classes. An illustrative cartoon outlining the relation between complexity classes and the capabilities of classical and quantum computers is shown in Figure 4. Note that the designation *NP* in the cartoon refers to the "nondeterministic, polynomial time" complexity class.

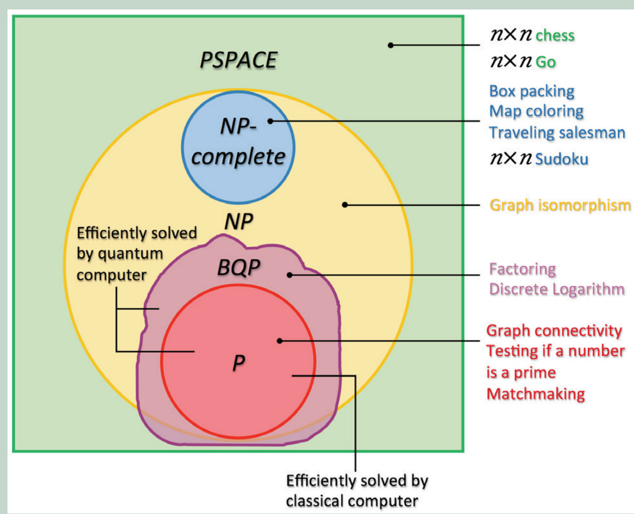

Figure 4: The relationship between complexity classes. | *Image reproduced from a 2008 Scientific American article with permission from Scott Aaronson.*

The cartoon in Figure 4 shows how different classes of problems quantum computers would solve efficiently (*BQP*—bounded-error, quantum, polynomial time) might relate to other fundamental classes of computational problems. *BQP* includes all the *P* problems (requiring a time to solution on a deterministic Turing machine that scales as a polynomial of problem size) and some *NP* problems (requiring polynomial-scaling time to solution on a nondeterministic Turing machine; not to be confused with NP denoting nuclear physics). Most other *NP* and all *NP*-complete problems are thought to lie outside *BQP,* meaning that a quantum computer would require more than polynomial-scaling resources to solve them.

It has only recently been shown (in 2018) that *BQP* extends beyond *P,* meaning that quantum computers may solve certain problems faster than classical computers and may also be able to check the solutions, such as integer factorization and simulations of quantum systems. *BQP* cannot extend beyond *PSPACE*, which also contains all *NP* problems. *PSPACE* problems are those that a classical computer can solve using only polynomial-scaling memory but which may require an exponentially scaling number of steps.

3.2 Quantum Sensing

The need for quantum sensors permeates the entire field of NP, encompassing the physics arguments and scientific objectives outlined in the preceding section. In a classical measurement, a probe interacts with the system under study and the outcome is recorded. Averaging the outcomes of a large number of repeated independent measurements reduces the statistical uncertainty of the average (as expected from the central limit theorem). Entangling qubit probes before their interactions with the system of interest produces a more favorable scaling factor in the uncertainty. Unlike the classical case, the uncertainty scales inversely with the number of probes ("Heisenberg limit"). As an example, entangling the particles (typically photons or atoms) in a Ramsey interferometer results in the phase sensitivity scaling with the number of particles.

In discussing the underlying physics mechanisms of sensors, it is convenient to define two categories of sensors, Quantum 1.0 and Quantum 2.0. Quantum 1.0 sensors are devices that measure an object or property related to quantization (e.g., energy or angular momentum or photon number) or devices whose performance depends explicitly on quantum phenomena. Quantum 2.0 sensors make use of superposition of states (coherence) and/or entanglement in performing measurements. For an overview of quantum sensors, see sidebar 3.2, *Quantum Sensors*.

In a quantum squeezed state, the reduced noise (uncertainty) in one measurement variable causes a corresponding increase in the noise of the conjugate variable, as constrained by the Heisenberg uncertainty principle. The use of squeezing has improved the sensitivity of experiments in many applications. For example, a near-term enhancement of the Laser Interferometer Gravitational-Wave Observatory involves squeezing the amplitude of the vacuum fluctuations in the mode to which the gravity waves couple, reducing the noise in the measurement.

Sidebar 3.2: Quantum Sensors

Detectors and sensors using quantum phenomena have existed for decades and have become critical components in essentially all areas of science and technology. They are not only tools of research but also are found ubiquitously in commercial products commonplace in everyday life. These quantum sensors are devices that measure physical quantities through properties that are unique to quantum mechanics. It is difficult to imagine research without the existence of such common instruments as photomultiplier tubes, lasers, semiconductor electronics, and nuclear magnetic resonance imaging. The list of devices that rely upon quantum-based technologies and have become the tools of everyday research is long, and these devices have found their way into major aspects of the economy, such as medicine, telecommunications, and computing. We often refer to these devices as belonging to the first quantum revolution, or more colloquially, Quantum 1.0.

Quantum 1.0 devices are essential in NP experiments and their performance continues to improve. Newer technologies show the promise of significant advances in both the scope of measurement possibilities and the ultimate precision that is achievable. Devices such as transition edge sensors (TESs), superconducting nanowire single photon detectors (SNSPDs), microwave kinetic inductance detectors (MKIDs), and Josephson parametric amplifiers (JPAs) are finding their way into important experimental efforts in physics. Their use essentially spans all subfields, including condensed matter, atomic, molecular and optical physics, NP, HEP, and astronomy. They play critical roles in cosmic microwave background searches, sub-millimeter astrophysics, and dark matter searches.

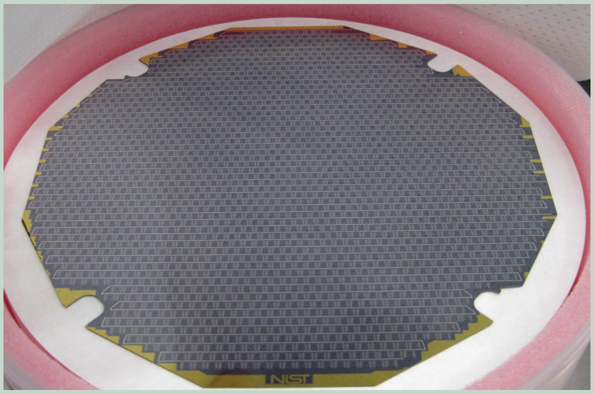

Figure 1: MKIDs on a 135 mm substrate measure small energies deposited in them by charged particles, phonons, and photons. These devices combine high sensitivity with large area coverage. The use of quantum-limited readout amplifiers improves their performance. | *Image reproduced by permission of Michael Vissers, NIST. From "The limits of quantum computers," Scientific American 298(3), 62–69, March 2008.*

A new, rapidly developing class of sensors has emerged during the past two decades for which the goal is a significant increase in sensitivity and precision. Broadly speaking, their operation depends explicitly on quantum phenomena such as superposition of states (coherence) and/or entanglement to achieve superior performance. These devices use quantum systems and quantum manipulations that frequently share basic elements with those used for QC with qubits. However, their design is specific to sensing applications. We sometimes refer to these sensors as part of the second quantum revolution, or Quantum 2.0.

Although the development and production of Quantum 2.0 sensors is nascent and still largely in the domain of basic research, the potential reach of new devices within the public realm may be profound. It is probable that they will affect communication technologies (random number generation, secure data transmission), computation (QFT, quantum chemistry, crypto-analysis, molecular dynamics), and precision metrology (magnetometry, timekeeping, navigation). These applications are still in their infancy, but the increased collaboration among academia, national laboratories, and industry is accelerating the pace of commercial development, and many countries are making substantial investments in the future of Quantum 2.0 sensors.

Quantum sensors can measure electromagnetic fields (e.g., atomic magnetometer), time or frequency (e.g., atomic clocks), displacement, pressure, and force (e.g., nano-cantilevers with single-electron transistor readout). The sensors are realized in different forms, utilizing, for example, atomic vapors, cold clouds of neutral atoms, trapped ions, and Rydberg atoms, electron spins in nitrogen vacancy (NV) centers, and nuclear spins in nuclear magnetic resonance (NMR). One of the most commonly used magnetic sensors is the superconducting quantum interference device (SQUID) that measures the phase shift induced by a magnetic field with a (phase-sensitive) Josephson junction. The intrinsic magnetic fields of materials can also be mapped using spins of elementary particles, such as muon spin rotation in muon magnetic resonance (μSR) and neutron spin polarization by Bragg reflection. New techniques are constantly emerging. For example, researchers have begun using "structured" neutron beams to investigate the bulk properties of magnetic materials. The goal is to create neutron spin-orbit beams (analogs of spin-orbit coupled light) and use them to study, for example, skyrmion (a type of topological quasiparticle [QP]) quantum materials. Research is in progress to tailor neutron waves to explore new avenues of entanglement and increase the number of degrees of freedom that a neutron beam can achieve, potentially leading, in turn, to the next generation of advanced materials for Quantum 2.0 devices. Quantum sensors are finding applications in areas as diverse as astrophysics, imaging, communication, medicine, and national security.

Quantum technologies such as SQUIDs have played critical roles in a variety of NP experiments and, in fact, have become essential in many applications. Recent quantum sensor technologies—TESs, SNSPDs, MKIDs, and JPAs—are now finding their way into important experimental efforts. Endeavors as varied as neutrinoless double-beta-decay ($0\nu\beta\beta$-decay) experiments, nuclear materials analysis, EDM searches, x-ray reference data, and neutrino mass measurement are all incorporating quantum sensors in critical roles within the experiments. Although this exploration of the applicability of quantum sensors in NP is still rather limited compared with the use of Quantum 1.0 devices, as these specialized uses become more broadly recognized, it is reasonable to expect that these sensors will find wider application in NP. At present, quantum sensors are used largely to detect phonons and photons, and their application to the detection of charged particles has yet to be explored. Indeed, the use of quantum sensors is expected to make transformative changes in the design of critical NP experiments.

The community must address some challenges before quantum sensors become more commonplace in NP. Whereas Quantum 1.0 devices are commercially available, given their recent development, Quantum 2.0 devices typically are not. At present, NP experimentalists usually collaborate with QIS researchers to obtain these devices, and this presents a natural barrier to their widespread use. Many, but not all, applications of quantum-enhanced sensing rely on the availability of a given device in sufficient quantity and with standardized performance. To accommodate this need, and to facilitate their use in other domain sciences and in QIS applications, mechanisms that enable the commercialization of devices are becoming increasingly important for NP research.

The NP and QIS communities have developed some natural interactions and collaborations centered on quantum sensors as they find application in NP experiments. Unique NP expertise in experimental techniques relevant to the development of QIS is playing a role in building these connections. For example, the QIS community has developed certain methods that require measurements with very low background noise or materials with high isotopic purity. The NP community has extensive expertise in both areas because of its longstanding work in underground science, e.g., in solar neutrino and double-beta decay experiments. Adapting such low-background detection techniques can satisfy some QIS needs. The NP community also has experience in large-scale cryogenic techniques through its work in the fields of $0\nu\beta\beta$-decay and dark matter detection. Finally, NP has developed effectively numerous large and diverse research collaborations, a skill from which QIS can benefit as the field expands.

3.3 Nuclear Physics and Entanglement

Entanglement is, in some sense, the attribute of quantum mechanics that is defining its Quantum 2.0 impact. NP has a distinguished history in this area, with the first actual test of Bell's inequalities.[3] The NP community is now starting to address the role of entanglement in more complex systems of importance to NP. The systems of interest range from heavy-ion collisions, proton-proton collisions, deep inelastic scattering and string breaking in fragmentation, to the low-energy structure and scattering of nucleons. These studies complement more formal investigations in the HEP and QIS communities and are also beginning to complement results obtained in QIS experimental programs. Experiments to improve understanding of the role of entanglement in NP can also inform quantum many-body theories and QFTs. At the same time, investigation of theoretical studies of entanglement in model theories is important in the near-term. These studies have already provided insights into fragmentation and the evolution of entanglement in scattering processes. Perhaps surprisingly, NISQ-era quantum devices provide effective platforms with which to study such model theories.

[3] Stuart J. Freedman and John F. Clauser, "Experimental Test of Local Hidden Variable Theories," Phys. Rev. Lett. **28** (1972) 938. Stuart Freedman received the APS Tom Bonner Prize for nuclear physics in 2007.

4. Quantum Information Science, Quantum Computing and Quantum Simulation for Nuclear Physics

Continued development of quantum sensing and QC and simulation, as well as a better understanding of quantum information, will likely provide a significant boost in addressing NP grand challenge problems over the coming years. Importantly, advances in QIS are likely to enable NP to address qualitatively new phenomena reliably, thus broadening the scope of experiments and theoretical investigations in the NP portfolio. Quantum computing, possibly combined with machine learning, artificial intelligence, data science and analytics, is expected to advance the ability to interpret experiments and to reveal phenomena that are not accessible to present-day theories and computation.

In this section, we identify and discuss areas of research in which advances in QIS are likely to benefit NP research. These examples are presented to illustrate the nature of the potential contributions, not as an exhaustive list.

4.1 Quantum Computation and Quantum Simulation for Nuclear Physics

As quantum devices become increasingly capable and our understanding of quantum information continues to improve, QC and simulations of many-body systems and QFTs are likely to provide significant and rapid advances in NP research. In the future, QC is expected to be able to provide more realistic and accurate studies of systems researchers now try to address with HPC. An example of such a system is the equation of state of neutron star matter. Its character changes substantially from very low densities at which it is similar to the unitary Fermi gas, to the very high densities at which it is predicted to be a color-flavor locked superfluid state of QCD. Another example is the set of dynamical processes, such as nuclear reactions and fission, important for the study of nuclear matter at the limits of stability, and for understanding the formation and role of nuclei in the universe. QC may allow us to calculate accurately the electroweak response functions of nucleons and nuclei over a range of kinematics, from those relevant to nuclear astrophysics to those addressed by the planned electron-ion collider (EIC).

Verification, validation, and uncertainty quantification are essential elements in providing reliable results with meaningful uncertainties using classical computers for scientific applications. They are equally important in providing reliable results from QC systems, and in going beyond classical computation. As current quantum systems more closely resemble physics experiments than classical computers, the suites of checks and calibrations required for NISQ-era systems will be significantly more extensive, including for users, than those required for classical computers.

Ultimately, calculations using programmable gate-based universal quantum computers are desirable because of their flexibility, in-principle scalability, and expected ultimate precision. However, simulations using analog devices may provide early results that extend qualitatively the work done with HPC, therefore exhibiting a quantum advantage. In the case of optimization problems, annealing devices may provide effective solutions ahead of analog and digital devices. The sections that follow elaborate on these discussions and extend them to other physical systems.

4.1.1 State of the Art of Quantum Information Science and Quantum Computing in Nuclear Theory

It is only recently that QC and QIS have started to enter the nuclear theory toolbox. Technological advances have made functional quantum hardware available to domain scientists. This newly available hardware has been used to solve simple model problems in quantum many-body systems for NP, QFT, condensed matter physics, quantum chemistry, and HEP.

In the near term, applications of QC to NP will employ NISQ devices; but such devices might soon comprise more qubits (with manageable error rates) than can be simulated on the most powerful HPC systems. This stage of development poses interesting challenges and opportunities for QC in nuclear theory. There is a need to develop efficient Hamiltonian formulations of nuclear systems that enable the application of low-depth quantum circuits. Researchers must also better understand and mitigate noise and explore how alternative QC protocols and hybrid algorithms that combine HPC and QC can accelerate the path to success. Software to program quantum hardware and simulators, supporting such developments, is becoming more publicly available. Companies such as D-Wave, IBM, Microsoft, Google, and Rigetti have been developing programming tools and simulators along with QC devices. Even laptops are useful for modest simulations, and access to quantum hardware is available via cloud servers and at some national laboratories.

Models of nuclei (toy models) and QFTs have been solved on existing quantum devices. Although these calculations are all easily performed on classical computers, they are initiating new thinking about quantum algorithms and quantum devices in the NP community. In some of these computations, wave functions were prepared on a quantum device and ground state properties computed using hybrid variational methods. These early calculations showed that, in working with a universal set of quantum gates, minimization of circuit depth, noise mitigation, and extrapolation techniques were all critical to an effective use of NISQ devices. This establishes an emerging need for programming techniques and quantum compilers, along with structured, device-independent software stacks, analogous to those in HPC, to enable scientists to address applications in an optimal way. Importantly, one of the near-term tasks for the NP community is to determine the complexity classes (see sidebar 3.1, *Quantum Computers*) of its important problems in order to make optimal use of QC resources.

An initial calculation of the deuteron binding energy, using the pionless effective field theory (EFT) mapped onto IBM and Rigetti superconducting qubit devices, provided a watershed moment for NP, showing that (simple) nuclei could begin to be addressed with QC. To be clear, these calculations produced results that have been obtained easily and with much higher precision and accuracy using present-day classical computers, but it was the first computation of a nucleus using a quantum device. This work was soon extended to ^{3}He and ^{4}He using an optical quantum frequency processor, and also using IonQ's trapped ion

QC. The Schwinger model (1+1 dimensional QED) was simulated on trapped ions by the Innsbruck group in 2016 and later on IBM's quantum devices, as well as on other trapped ion systems. In the US, this progress resulted from DOE ASCR support that brought together a diverse team of experts with access to quantum hardware, both cloud-accessed and on-site. For further details, see sidebar 4.1, *Simulating Quantum Many-Body Systems and Quantum Field Theories with Quantum Computers*.

Sidebar 4.1: Simulating Quantum Many-Body Systems and Quantum Field Theories with Quantum Computers

Quantum computing promises to perform computations in quantum many-body systems and QFTs of quantities that are important to NP and that are impossible to address with HPC. Richard Feynman first highlighted this potential in the early 1980s. These problems include the real-time dynamics of multi-particle systems, nuclear reactions, the structure of medium and large nuclei, the phase diagram of high-density matter, the propagation of neutrinos in high-density matter, and the direct evaluation of high-energy, inelastic S-matrix elements, such as in-medium fragmentation. Generally, for quantum computations to surpass the precision obtainable with HPC and complement the NP experimental program, large-scale quantum computers employing high-fidelity logical qubits with high-fidelity gate operations will be required, along with efficient quantum algorithms and problem mappings. We will be able to make substantial progress toward these objectives during the NISQ-era, learning valuable lessons in the process. We will also gain an understanding of the quantum ecosystem required to address NP problems. Quantum chemists have made good progress in the quantum simulation of small molecules, as shown in Figure 1, and are working toward systems of increasing complexity. High-precision results for NP problems will require more than a decade of focused effort.

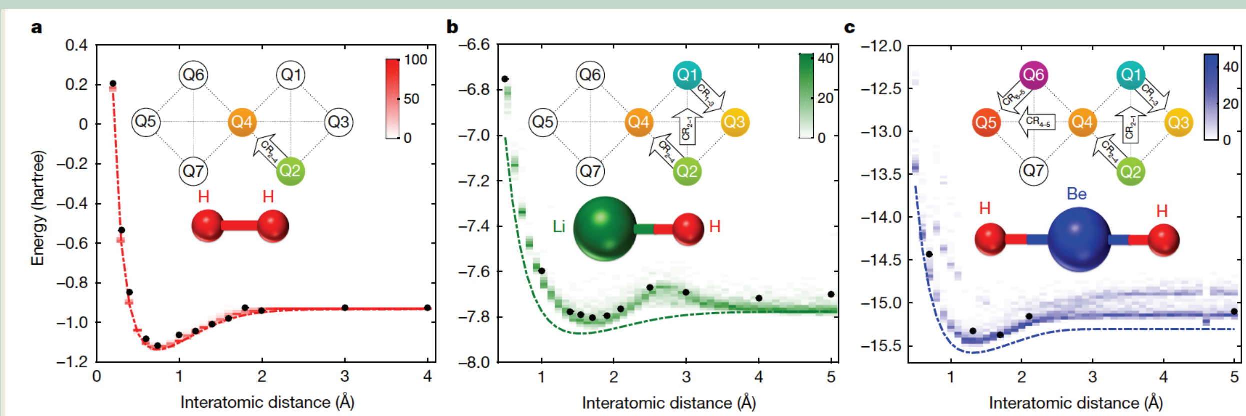

Figure 1: The potential energy between atoms in H_2, LiH and BeH_2 computed with IBMs quantum systems, compared with the known values. In each panel, the dot-dashed line corresponds to the exact (classically determined) result; the solid, black points are results obtained from the quantum calculations (after measurement and gate error mitigation); and the regions of varying color density correspond to results from 100 classical simulations of the quantum minimization process using the wavefunction ansatz employed for the quantum calculations at each separation distance. | *Images reproduced with permission from IBM and Nature Publishing Group. Nature,* Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets, A. Kandala et. al., copyright 2017. doi:10.1038/nature23879.

Building on a significant theoretical and algorithmic foundation, quantum simulations of model quantum many-body and quantum field theories of relevance to NP began in 2016. A limited range of quantum devices, quantum simulators, and quantum emulators has made these first calculations possible. The first such quantum simulation relevant to NP employed a small number of trapped ions to represent the occupation of electrons and positrons in 1-dimensional quantum electrodynamics (the Schwinger Model). The initially "empty" quantum state, evolving forward in time using Hamiltonian dynamics (with a discretized, or "Trotterized" time-evolution operator), produced a time-dependent number of electron-positron pairs (see Figure 2). While a laptop is also easily able to perform this particular computation, it provided a demonstration of a quantum simulation of real-time dynamics in a QFT. The promise of this calculation is that, although the HPC resources required to study much larger systems in higher dimensions grow exponentially with system size, the resources required for the same study on a quantum computer are expected to increase only as a polynomial. We note that this model QFT shares a number of features with QCD, including charge screening, a fermion condensate in the ground state, and bound states of "hadrons." Subsequently, it has been simulated with IBM's superconducting qubit quantum devices and other improved trapped-ion systems, and extended to include external charges.

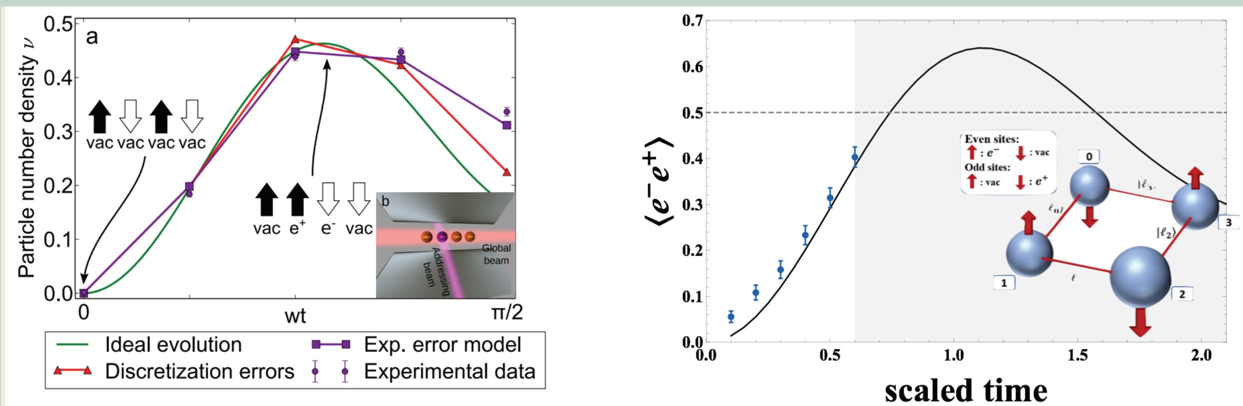

Figure 2: The number of electron-positron pairs in the vacuum as a function of time in 1+1 dimensional QED determined on quantum computers using Trotterized time-evolution. The left panel shows the results of the first calculation using a quantum device using trapped ions and the Kogut-Susskind Hamiltonian on a 2-qubit system describing two spatial lattice sites. | *Presented with permission from Nature Publishing Group. Nature, Real-time dynamics of lattice gauge theories with a few-qubit quantum computer, E. A Martinez et al. copyright 2016*. The right panel shows the analogous quantum simulation performed on IBM's superconducting qubit devices in 2018. | Image reproduced with permission from N. Klco et al., Quantum-classical computation of Schwinger model dynamics using quantum computers, Phys. Rev. A98 032331, September 28, 2018. *Image reproduced with permission from Christine Muschik (U. of Waterloo) and Natalie Klco (INT).*

Last year, a team of scientists from ORNL used quantum computation for the first time to recover the deuteron binding energy (E. F. Dumitrescu et al., Phys. Rev. Lett. 120 (2018) 210501). The experimentally measured nuclear interactions were implemented through a pionless EFT Hamiltonian in a truncated Hilbert space, and a classical-quantum hybrid variational quantum eigensolver was used to extremize the ground state wave function. The scientists have also calculated the binding energies of somewhat larger nuclei and have extended the calculations to other quantum devices as well. In the area of nuclear many-body systems, the first simplified calculations of the response of a many-body system to an interaction with a high-energy neutrino were performed. The real-time Hamiltonian evolution of the system, combined with a new quantum algorithm, permitted the determination of the spectral function for such a process.

Model systems, such as the "leading order" deuteron and the Schwinger models discussed above, provide frameworks and benchmarks to develop QC and QIS expertise. In addition, they allow us to compare, during the NISQ-era, quantum algorithms and quantum devices, aiding the design of future quantum devices and the preparation for high-fidelity, high-capability devices. They also enable us to estimate the resources required for the simulation of systems of importance to NP. These algorithmic and hardware activities will require HPC resources across a range of system scales.

NP researchers are making progress toward the use of more realistic nuclear forces in nuclear calculations and toward implementation of QFTs that are more complex. This progress involves improving understanding of how to map NP problems onto qubit registers (including the digitization of quantum fields and redundancies in gauge field theories), designing lower-depth quantum circuits, addressing more general quantum emulation and simulation issues, identifying bottlenecks on present devices, and designing enhanced devices to better simulate systems. Again, optimizing the productivity of these current activities has involved scientists, engineers, and developers with QC and QIS expertise working with those from NP.

Analog quantum simulation is also advancing in areas of interest to NP research, as a number of examples make clear. In nonequilibrium physics, for example, scientists are studying dynamical phase transitions and quantum thermalization and addressing open questions experimentally. A discovery—robust many-body revivals attributed to "quantum scars"—was made in spin models realized as arrays of Rydberg atoms. Strongly interacting fermionic atoms have been used to simulate a unitary Fermi gas, an s-wave superfluid, and a model system for neutron matter. Fermions in optical lattices provide a realization of lattice spin models that are important in condensed matter physics, NP, and elsewhere. Modern analog quantum simulations are using quantum gas microscopy to capture direct microscopic snapshots of many-body wave functions and to extract quantities such as high-order correlation functions and entanglement entropy. Significant theoretical progress has been made in developing the mappings of non-Abelian gauge field theories, including QCD, to cold atom systems, and their experimental implementations are under way.

4.1.2 Future Quantum Information Science and Quantum Computing Impact on Nuclear Theory

The application of QIS and QC to nuclear theory calculations and QFTs of increasing complexity has begun. The new techniques that are emerging from QIS and QC are likely to be valuable in a number of areas of NP, some examples of which follow.

Equation of State of Dense Matter and Neutron Stars

The equation of state of nuclear matter is critical to determine the properties of nuclei and neutron stars. At extremely low densities, it is quite similar to that of the unitary Fermi gas, where the s-wave pairing between neutrons is strong, even large enough to affect the equation of state. At these densities, cold atom experiments have essentially played the role of simulators in testing theories and calculations of both the unitary Fermi gas and neutron matter. At higher densities, the interaction between nucleons becomes repulsive; and at the highest densities a color-flavor locked phase is predicted in which the pairing among quarks with three flavors and three colors is particularly symmetric. At the intermediate and higher densities, where fermion sign problems are more substantial both in the interacting nucleon picture and in QCD, more progress is required.

QC is anticipated to eventually provide advances in this field, potentially first with quantum simulators and annealers and then with gate-based quantum computers. The long-term goal for this area is to produce an equation of state at high baryon densities (and low temperatures), with accurate characterization of phase changes that may occur with changing densities. Observations using the Laser Interferometer Gravitational-Wave Observatory and future gravitational wave observatories will test these theories, as the dynamics of neutron star mergers reflect the properties of dense, neutron-rich or deconfined QCD matter. At the same time, the theories must describe, for example, the neutron distributions across a range of nuclei as measured in parity-violating electron scattering and in coherent neutrino scattering.

Lattice QCD calculations performed with HPC have provided significant quantitative insight into the properties and structures of individual mesons and baryons, and recent advances have brought calculations of light nuclei within reach. They have also provided a quantitative understanding of the thermodynamics of hot QCD matter at zero baryon density (i.e., matter containing equal numbers of quarks and antiquarks). Introducing a chemical potential to study systems with non-zero baryon density (more quarks than anti-quarks), requires us to deal with the fermion sign problem, which, in turn, causes the scale of the calculation to grow exponentially with the volume of matter being simulated. Lattice calculations are, then, not tractable in this regime, which includes the parts of the QCD phase diagram now being explored in lower-energy heavy ion collisions. The sign problem becomes even more acute at high densities and low temperatures. This difficulty is a fundamental limitation of the way we formulate these calculations. In present-day formulations, the quantities of interest involve very-high-dimensional integrals that must be evaluated with stochastic sampling. On the other hand, the presence of a sign problem means that the integrand is oscillatory, and therefore the results arise through delicate cancellation among contributions from disparate regions throughout the high-dimensional integration region. These two aspects of how the problem is formulated make it essentially impossible to directly perform accurate calculations using HPC.

Although the challenge presented by sign problems appears to be an insurmountable obstacle, it is merely an artifact of current methods of calculation: nature does not encounter the same obstacle. This indicates, as Feynman highlighted in the early 1980s, that a fundamentally new way of computing such properties is needed, one that is closer to a simulation of what actually happens in nature. This is the vision behind the application of QC and simulation in this domain. As the ability to conduct quantum simulations advances, the first steps in this direction will involve simulation (both analog and digital) of simplified (i.e., simpler than QCD) low-dimensional gauge theories that include composite states—analogous to the mesons and baryons of QCD—and that have sign problems at nonzero density. Adiabatic methods might usefully simulate the ground states of these models at zero temperature, which is where sign problems are most acute in today's calculations. It is too early to say how long it will be before quantum simulations of QCD at nonzero density become possible, but we expect to gain considerable insight from simulating the model systems.

Electroweak Dynamics in Nucleons and Nuclei

The ability to understand and calculate electroweak processes in nuclear systems is critical to NP. The impact is far-reaching: from low-energy processes like beta decay and double-beta decay, to astrophysical regimes, to the high-energy electron and neutrino scattering studied in present-day and future experiments. Experimental searches for $0\nu\beta\beta$-decay inform us about the nature of neutrinos and the conservation of lepton number, which indirectly provides information about the origin of the matter-antimatter asymmetry of the universe. Heavy nuclei form in astrophysical environments in which both weak processes and nuclear structure play a role. Electroweak processes occurring at higher energies, probed in accelerator experiments, provide information about both the dynamics of QCD in different regimes and the fundamental properties of neutrino interactions.

In the particular case of neutrino interactions, a full simulation of the process is intractable with current lattice QCD methods, both because of the handedness of the neutrinos and because of the difficulty of dealing with scattering problems in the Euclidean time framework. However, for the processes in which researchers are interested, the electroweak dynamics can be included using EFT techniques involving matrix elements of local operators or their time-ordered products. The ability to perform QC calculations in real time resolves the second of these in-principle issues. A remaining challenge is to follow the evolution of the scattering system for a long enough time that the hadronic final state is resolved into the particles detected in the experiment. Note that the evolution from quantum to essentially classical degrees of freedom in dynamical processes is an intriguing question across many fields of physics.

Nuclear Dynamics

The complexity of protons and neutrons dynamically reorganizing into different shapes and partitioning into distinct subsystems adds to the challenge of precisely computing atomic nuclei and their interactions from the more fundamental interactions among the nucleons. For that reason, using classical computing resources, a predictive description of nuclear dynamical processes will remain intractable for all but the lightest systems. QC has the potential to provide solutions of dynamical nuclear processes that span the chart of the nuclides.

The scientific impact of the Facility for Rare Isotope Beams (FRIB) would be enhanced by reliable, precise, first-principles computations of nuclear reactions, including fission. HPC is limited in capability by the real-time dynamics and exponentially large Hilbert spaces of the many-body system. QC has the potential to address these reactions in the future, thereby magnifying the scientific footprint of FRIB. More broadly, use of the more sophisticated modeling capabilities of QC in this regime will be required for, among other topics, studying nuclear matter at the limits of stability, improving the predictive power of astrophysical models, and solving NP problems relevant to national security and other societal applications.

However, during the NISQ era, it is unlikely that QC tools will approach viability for calculations of complex nuclear reactions and fission processes. Realistic objectives for the near and intermediate time horizons are the identification and demonstration of QC protocols that would enable a successful computation of simple nuclear dynamical processes of modest size. NISQ-era hardware might be used, for example, to develop a microscopic description of scattering and reactions in few-nucleon systems. Presently, digital quantum computations of simple, low-dimensional quantum systems—including the ground state binding energies of light nuclei up to ^{8}He using nuclear forces systematized with EFT—face limitations from noise due to interactions of the qubits with their environment. The development of methods to reduce the coherence times required for a calculation by reducing the number of universal quantum gates required to realize each time step, combined with error correction techniques, will be essential for future computations. Similar efforts have recently emerged in exploring alternative QC protocols that trade the use of universal gates for the ability to implement each step of the unitary-time evolution with a single operation, reducing the adverse effect of noise. Analog quantum simulators offer another promising path for the simulation of nuclear dynamics. In general, the exploration of a variety of QC strategies, including hybrid quantum-classical approaches, is expected to play an important role in co-developing QC algorithms and hardware to provide a quantum advantage for these problems.

Dynamics of Jets and Hadronization in QCD

High-energy collisions of hadrons and nuclei are typically highly inelastic, resulting in the production of large numbers of pions, nucleons, other hadrons, and even light nuclei. In ultra-relativistic collisions, occasionally two incident quarks or gluons scatter off each other at a large angle—events that probe the microscopic physics of interest. In such collisions, the scattered quarks and gluons fragment into jets (collimated showers of many hadrons). The high-momentum transfer elements of jet production and the showering process are well-described by perturbative QCD; but the final, defining stage of the process, in which the quarks and gluons in the shower nonperturbatively form the detected hadrons, is essentially the same problem of dynamics discussed previously in other contexts. Currently, processes are modeled with sophisticated phenomenology constrained by high-precision experiments; better theoretical control and higher precision would be advantageous for the experimental programs in both NP and HEP. NP scientists are interested in measuring the modification of the shape and structure of the jets produced in heavy ion collisions and caused by their passage through the droplet of hot quark matter produced in those collisions. These modifications probe, in principle, the properties of this primordial phase of matter. To extract this information, however, they must account for jet evolution in a background of hot, strongly coupled matter as it rapidly expands and cools. As discussed earlier, lattice QCD is ill suited for these computations because of the intrinsic Minkowski-space nature of inelastic processes, fragmentation, and the interaction of jets with a dynamic medium. Although lattice QCD can be used to compute certain elements used in models of these highly inelastic dynamics, it cannot simulate the complete dynamics, as it can neither account for the complexity nor provide the precision needed to impact present and future experiments.

QC has the potential to provide results for highly inelastic processes directly from Hamiltonian QCD evolution from the initial high-energy state to the final state. The main feature distinguishing it from current modeling is quantum coherence: the retention of quantum phases among wave function components in an entangled system. Researchers using quantum simulators and gate-based quantum devices have performed a small number of calculations in small, low-dimensional model systems to explore such possibilities. The results indicate that such dynamical calculations may be possible with QC and with significant improvements in quantum algorithms.

Sufficiently capable QC could have impacted the existing heavy-ion programs at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). For example, quantum calculations that avoid the sign problem, if demonstrated, could predict the location of a possible QCD critical point, currently the focus of the beam-energy-scan program at RHIC. We expect such QC capabilities to arrive after the current experimental programs, but they may arrive in time to support future LHC and EIC programs. In both instances, fragmentation and hadronization play key roles. Further, the class of response functions including parton distribution functions, transverse momentum dependent distributions, and generalized parton distributions are all examples of quantities defined by light-like correlators in Minkowski space, again making them challenging to address using Euclidean-space lattice QCD techniques, but amenable to QC. Another class of response functions appropriate for QC would be those of the resonance program at the Thomas Jefferson National Accelerator Facility (JLab), as the computational capacity of QC devices may be suitable to address inelasticities in the kinematic regime relevant to the hadron resonance experimental program and the planned EIC.

Neutrino Dynamics in Astrophysical Environments

Particular astrophysical environments like neutron star mergers and core-collapse supernovae can be dense enough that neutrino-neutrino interactions may directly affect their flavor evolution as they emerge from these objects. The effects may, in turn, be large enough to affect the interpretation of the observed neutrino signals, or possibly alter the explosion mechanism of core-collapse supernovae or the r-process evolution of the elements. It is presently not possible to explore such a regime directly in terrestrial environments except through QC.

Neutrinos represent simple one- or two-qubit systems (two or three flavors) that evolve in a unitary manner, changing flavors through their weak interactions with other neutrinos and with the matter through which they propagate. The interacting system is difficult to treat in a fully quantum mechanical manner. Even simplified to a single neutrino field at each energy and angle of emission (going beyond a 1D to a 3D description), the quantum state involves an exponential number of amplitudes. Present-day studies use a mean-field level picture in which the description of the evolving state is a product state of the fields at different energies and angles. The general reliability of this approach is unknown at present. Again, we anticipate that QC will provide a means to understand the importance of the quantum mechanical phases in the problem. Incorporating the interaction of neutrinos with matter—electrons, nucleons, and nuclei—remains a challenge. At present, studies use quantum kinetic equations that describe the evolution of the relevant quantum density matrices at a mean-field level. A reliable understanding of the quantum evolution of the neutrinos in these environments is, however, very likely to require a fully quantum mechanical treatment.

4.1.3 Quantum Device Co-Development (Present-Day Nuclear Physics Examples)

Qubits are but one option for storing, manipulating, and computing quantum information. Qudits are alternative quantum register elements. Qudit systems can process an equivalent number of operations with fewer QPUs—interconnected sets of quantum bits. This capability motivates the exploration of hardware architectures in which multiple states within a single quantum device are simultaneously controlled. Although decreasing the number of connected quantum devices represents hardware and fabrication simplification, increasing the number of states in the qudit translates into more complicated quantum gates, and differences in error correction. A quantitative understanding of advantages and disadvantages of a qudit system requires an analysis of the entire compilation chain.

LLNL and Fermi National Accelerator Laboratory (FNAL), for example, are developing an alternative quantum architecture consisting of superconducting qudits and associated control systems. LLNL scientists and engineers, in collaboration with those at universities, are at early stages of using their device to compute the binding energy of light nuclei, with the eventual goal of, for example, computing reaction rates for light nuclear systems. Another example involving scientists in NP is the development of QC systems built around optical devices, e.g., quantum frequency processors, under way at ORNL. Using these devices, researchers have successfully computed both the ground state energies of the lightest few nuclei and solutions to the Schwinger model, using the variational quantum eigensolver technique in a hybrid classical-quantum system.

In general, both the structural design (e.g., qubits and qudits) and the physical realization (e.g., superconducting circuits, ion traps, or other) spaces for quantum hardware are large and essentially unexplored. Quite possibly, we have not yet invented the technology that will ultimately lead to a scalable, universal quantum computer.

4.1.4 Entanglement and Nuclear Physics

Drawing on developments in QIS, we are making initial progress in addressing the role of entanglement in systems of importance to NP, from high-energy processes—involving heavy ion collisions, proton-proton collisions, deep inelastic scattering, or string breaking in fragmentation—to the low-energy structure and scattering of nucleons. There have also been a number of investigations into more formal aspects of scattering, including the evolution of entanglement during the scattering of relativistic particles. When certain subsystems of the complete system are probed, they appear thermal, which is important for understanding, for example, the short apparent thermalization times in heavy ion collisions and exponential distributions found at low transverse momentum in proton-proton collisions. Heavy ion, proton-proton, and electron-ion collisions thus have potential for explorations of entanglement, as, during a collision, they engage only subsystems of the larger Hilbert space. Complementing these NP studies is pioneering work with optical lattices, in which entanglement creates local entropy from pure states, validating the use of statistical mechanics for such systems. These investigations, along with a number of other studies, motivate further theoretical investigations of the evolution of entanglement in quantum many-body systems and QFTs.

A complete understanding of entanglement in low-energy nuclear and hadron physics necessitates understanding its role in the structure of the nucleon. The symmetry structure of the nucleon and its spin have recently been connected to entanglement in the nucleon wave function. These considerations lead to the identification of entanglement entropy as an order parameter for chiral symmetry breaking. When the valence and sea quark-gluon components of the nucleon are modeled as subsystems, the principle of maximal entanglement power is consistent with a tree-level analysis of the electroweak sector. A principle of minimal entanglement power is also consistent with low-energy nucleon-nucleon scattering data and results of lattice QCD calculations. Points of vanishing entanglement power, where fluctuations in entanglement due to strong interactions are absent, correspond to enhanced, emergent symmetries of QCD. Many-body states have been prepared using these points of enhanced symmetry in Monte Carlo studies, as they are approximate in nuclear forces (i.e., they are spin-independent) and sampling does not have a sign problem at such points. This suggests a deeper connection between sampling techniques in classical computations and the structure of entanglement in QCD. Extension of these studies to understand the role of entanglement in the mass of the nucleon is only now beginning and is likely to complement explorations made possible with an EIC.

In addition to identification of experiments to better understand entanglement in NP, informing the general study of quantum many-body systems and QFTs, theoretical studies of entanglement in model theories are also important. Low-dimensional theories are particularly simple to explore and helpful in advancing qualitative understanding of theories of direct relevance to the NP program. Many can be profitably explored using matrix-product states and tensor methods, exploiting the fact that entanglement entropy in their low-lying states obeys area-law scaling. They have already provided insights into fragmentation and the evolution of entanglement in scattering processes. We might also profitably explore such theories with NISQ-era quantum devices with the range of available system attributes. Further, studies of these simple theories on quantum devices will inform state and operator preparation for classical Monte Carlo studies of these and more complex lattice theories.

4.2 Quantum Sensing for Nuclear Physics

Quantum sensors are devices that utilize quantum phenomena or systems to measure physical quantities. While many devices use quantum properties to perform measurements, for example photodiodes, a quantum sensor's performance depends explicitly on quantum phenomena, such as quantization (e.g., energy, angular momentum), and/or tunneling, and/or superposition of states, and/or entanglement. Within the past few decades, quantum sensors have found applications in a broad array of fields such as imaging, communication, medicine, space exploration, and national security. Their use in physics has essentially spanned all subfields, including BES, AMO, HEP, astronomy and NP. They play critical roles in cosmic microwave background studies, sub-millimeter astrophysics, and dark matter searches.

Within NP, quantum-sensing technologies have changed how researchers design and carry out some experiments. Efforts as varied as 0νββ-decay experiments, nuclear materials analysis, EDM searches, x-ray reference data, and neutrino mass measurement have incorporated quantum sensors in critical aspects of the experiments. Indeed, in some cases, the sensitivity, and even the feasibility, of the experiment may not be achievable without the use of these devices. Despite these notable applications, the exploration of the use of quantum sensors in NP is still rather limited. The NP community is integrating newer Quantum 1.0 sensors, e.g., TESs, SNSPDs, MKIDs, and JPAs, into important experimental efforts. As these applications become successful and more broadly recognized, however, one expects that they will find wider application in NP. Indeed, the use of quantum sensors is expected to make transformative changes in the design of critical experiments—a rare opportunity for the NP community. In x-ray spectroscopy, for example, micro-calorimetry has demonstrated dramatic improvement in energy resolution over silicon and germanium detectors. The potential applications of current devices in NP have clear importance. The expansion of such techniques into charged-particle detection may also be advantageous in some cases. NP has not yet developed or deployed Quantum 2.0 sensors that utilize entanglement and is only now beginning to explore this type of sensor.

4.2.1 Quantum Sensor Technologies

The following are brief descriptions of the technology and applications for some of the key quantum sensors in use in NP experiments.

Transition Edge Sensors

TESs are devices that leverage the superconducting phase transition to create a micro-calorimeter of considerable sensitivity. Applying a voltage and/or adjusting the temperature biases the TES so that it is in transition between the superconducting and normal phases. When a particle interacts with the material of the TES, the energy absorbed causes a small deviation from this equilibrium. Unlike SNSPDs, TESs operate in a *negative* feedback mode, so reduced bias voltage dissipation compensates the energy absorbed. The TES thereby converts energy absorption into an electrical signal. The inherently low temperature of operation suppresses thermal noise. As a result, such a detector has extraordinary resolution and small threshold energies. Experiments typically employ SQUID readout of TESs (to match the low TES impedance) and use multiplexed SQUIDs to read out TES arrays in order to minimize the number of amplifier channels.

Their energy resolution (as low as 0.1 eV and possibly lower) gives TESs potential applications throughout NP, including, for example, precision x-ray and gamma-ray spectroscopy to update reference databases. Researchers at NIST are currently using them as part of a micro-calorimetry system in a reassessment of many of the lanthanide x-ray lines, for which relative energy resolutions of 10^{-3}, and the ability to measure over a range of x-ray energies simultaneously, are advantageous.

Neutrino mass measurement is another NP application in which this type of quantum sensor plays an essential role. Several electron-capture–based experiments, such as HOLMES, ECHO, and NuMECS, have adopted quantum-sensing technology to achieve their technical requirements for micro-calorimetry. Although this concept for neutrino mass measurement is almost four decades old, it is only the recent development of TESs and related magnetic microcalorimeters (MMCs) that has made such experiments feasible. The approach is to measure the neutrino mass in the decay of ^{163}Ho, an ideal candidate isotope given its low end-point energy. The spectrum of the binding energies of the captured electrons is measured; the endpoint depends on the neutrino mass. These experiments also use TESs or MMCs read out with SQUIDs. Further, they use calorimeters implanted with ^{163}Ho, thereby eliminating two major sources of uncertainty in such experiments, external beta emitters and final state effects.

Future generations of $0\nu\beta\beta$-decay experiments such as CUORE and CUPID are also considering TESs for detection.

Superconducting Nanowire Single Photon Detectors

SNSPDs are similar to TESs; but applying a constant current, rather than a voltage bias, to the SNSPD causes a *positive* feedback in response to an energy deposition. Thus, a small energy deposition causes a runaway breakdown of the superconducting phase for the entire SNSPD. The timescale for this process is short, approximately 10 ps; thus, SNSPDs provide excellent timing resolution for the detection of even very low-energy particles. They also benefit from exceptional (single photon) quantum efficiencies, above 90%. Photon-based QC uses these devices to great advantage; in quantum cryptography, where the data rate increases because of the (compounding) high efficiencies, they are also valuable. Progress is being made in producing versions that are radiation hard and insensitive to high magnetic fields, possibly opening the door to SNSPD-based calorimeters suitable for accelerator-based experiments, e.g., at the future EIC.

Microwave Kinetic Inductance Detectors

The early 2000s saw the development of another class of sensitive superconducting photon detector, the MKID. Unlike other superconducting detectors, the MKID operates away from its superconducting transition. In this case, the energy of the incident particle is sufficient to break a Cooper pair, changing the superconductor's "kinetic inductance." Making the superconductor part of a resonant circuit in a transmission line causes a change in the kinetic inductance to shift the resonant frequency and increase the resonance width.

For a typical MKID, the resonant frequency is in the hundreds of MHz to few-GHz range. This limits the size of the sensitive area to, typically, a few square millimeters. Again, multiplexed readouts allow the implementation of MKID arrays with a minimum number of channels. In another approach effectively enlarging the sensitive area, incident photons convert to phonons in a substrate that has an array of MKIDs deposited on it. The MKIDs then absorb the phonons. The development program for the future CUPID 0νββ-decay experiment has successfully demonstrated detection of Cherenkov light from TeO_2 bolometers using an MKID array of this type.

Quantum Parametric Amplifiers

Amplifiers at the quantum limit (noise at the level of a single quantum), such as JPAs and the closely related (Josephson) traveling wave parametric amplifier (TWPA), use the nonlinear response of superconducting Josephson junctions to achieve broadband signal amplification. Such amplifiers have demonstrated noise temperatures as low as 600 mK. They have many applications for sensitive measurements in the radio frequency (RF) band, and work continues to reduce the noise temperature further. For instance, the cyclotron-resonance microwave spectroscopy technique requires extremely low-noise RF amplification. The Project-8 experiment will eventually require a noise temperature of approximately 100 mK to perform a measurement of the neutrino mass using tritium decay.

The nonlinear nature of JPAs also allows them to effect quadrature squeezing of RF and microwave fields, with additional implications for precision measurement. For example, in one idea for an axionic dark matter search, the axion converts to a (single) photon in a cold, resonant microwave cavity. A JPA squeezes the zero-point electromagnetic energy in the cavity, reducing the noise in the quadrature to which the axion couples. A second JPA then amplifies only that quadrature (while again squeezing noise to the conjugate quadrature). It turns out that this has the additional benefit of effectively relaxing the requirement on the cavity quality factor and thereby increasing the scan rate of the axion mass range.

Kinetic inductance traveling wave amplifiers have higher power-handling capabilities than TWPAs, in addition to a broad bandwidth. Their features make them potential tools for reading superconducting qubits and are now a focus of further research.

Electric Dipole Moment Experiments

Time-reversal invariance forbids permanent EDMs of (nondegenerate) energy eigenstates. However, theories of physics beyond the standard model and the observed baryon asymmetry of the Universe lead us to believe that our current picture of time-reversal symmetry violation is incomplete. There are, therefore, a number of searches for EDMs in a variety of quantum systems. These searches provide an example for which the "quantum sensor *is* the experiment." They use the concept of a quantum sensor in reverse—rather than exploiting a physical property of a quantum system to detect a field or particle (e.g., using a magnetic moment to measure magnetic fields), these experiments use a field to measure the putative existence of a physical property, the EDM. Experiments to measure the EDMs of elementary particles, atoms, and molecules continue to improve in sensitivity.

In fact, the upper limits established by this set of experiments provide some of the most stringent bounds on models of new physics. We can express one of the clear challenges for the field in terms of the language of quantum sensors: to adapt the Quantum 2.0 paradigm of superposition of states and/or entanglement to preparation of the EDM systems themselves. For more information about the quantum mechanics involved in searches for EDMs, see sidebar 4.2, *Using Quantum Mechanics to Measure Electric Dipole Moments.*

Quantum Defects

A quantum defect in a crystal lattice can introduce an optically active center with multiple quantum levels that exhibit enough coherence that it can be used as a quantum sensor. A classic example of such a defect is the diamond NV center, in which, typically, an electron or neutron beam creates vacancies in the diamond by "removing" some small fraction of the carbon atoms. Annealing causes a nitrogen atom, often naturally occurring in these synthetic diamonds, to couple to a vacancy. The resulting center behaves like a relatively simple spin-1 quantum system. It has spin, hyperfine levels, and optically accessible electronic transitions. Its quantum state is prepared by driving these transitions with visible lasers and/or microwaves; readout is often via the fluorescence of the decays. Quantum sensors built on such defects have many potential uses and have demonstrated utility as magnetometers, electrometers, and thermometers. The main advantage of these detectors is that they are solid-state structures that are robust, are inert, and can be small enough to operate inside a living cell. The ability to manipulate them optically extends their utility to include applications in which metallic leads are impractical. Further, they can be implemented in such a way as to take advantage of quantum coherence to enhance their sensitivity, e.g., in the mode of measuring electric fields using electromagnetically induced transparency. They have a natural application in some EDM experiments in which precision, all-optical sensors to map electric and magnetic fields are desirable. Finally, because they are an easily accessed (and stored), long-lived (typically ms scale) quantum state, they are also potentially useful both as qubits and as quantum memory elements for QC or quantum networking applications. Such long-lived quantum coherence generally relies on the nuclear spin degrees of freedom of the spin-1 ^{14}N nuclei. While nearby ^{13}C nuclear spins can act as a source of decoherence from effectively random dipole-dipole couplings to the target ^{14}N nucleus, with appropriate NMR pulse-shaping techniques, the ^{13}C nuclear spins can also be used coherently for extra qubit space, all connected to the central ^{14}N nucleus.

Sidebar 4.2: Using Quantum Mechanics to Measure Electric Dipole Moments

Among the properties common to elementary quantum systems that have spin, such as subatomic particles, atoms, and molecules, is the magnetic dipole moment. One might expect that such a system would also have an EDM, as the matter constituents of these objects all have electric charge. However, quantum mechanics combined with the symmetries of the standard model of particle physics nearly precludes the EDM. Just as electric and magnetic fields have opposite properties under time reversal, so too do the moments. EDMs of elementary systems are expected to be small because nature largely preserves time-reversal symmetry (T).

Because the predicted standard model values of EDMs are small, experiments to measure them are potentially sensitive to physics beyond the standard model. Indeed, models such as supersymmetry naturally predict relatively large amounts of combined charge-conjugation-parity (CP) symmetry violation, or equivalently, in current theories, T-violation. It is also possible that T-violation observed in future EDM experiments could play a role in explaining the observed matter–antimatter asymmetry in the universe. In one view of the early universe, CP-violating reactions played a key role in the asymmetric destruction of baryons and antibaryons, leaving the matter-dominated world we see today.

Experiments to measure EDMs take advantage of a number of purely quantum mechanical effects in order to improve sensitivity. These tools are in routine use in such experiments performed by the NP community and are examples of the broader class of detection techniques that rely on the distinct properties of quantum mechanics. The expansion of QIS will derive in part from the potentially accelerated development of such tools. This sidebar highlights four examples from neutron EDM experiments that illustrate both the nature of the quantum mechanical "points of departure" and the nature of some of the applications of these fundamental properties (Figure 1). They are not, perhaps, the most commonly discussed examples in QIS, but they illustrate some of the range and potential for expanding control of quantum systems even beyond the current scope.

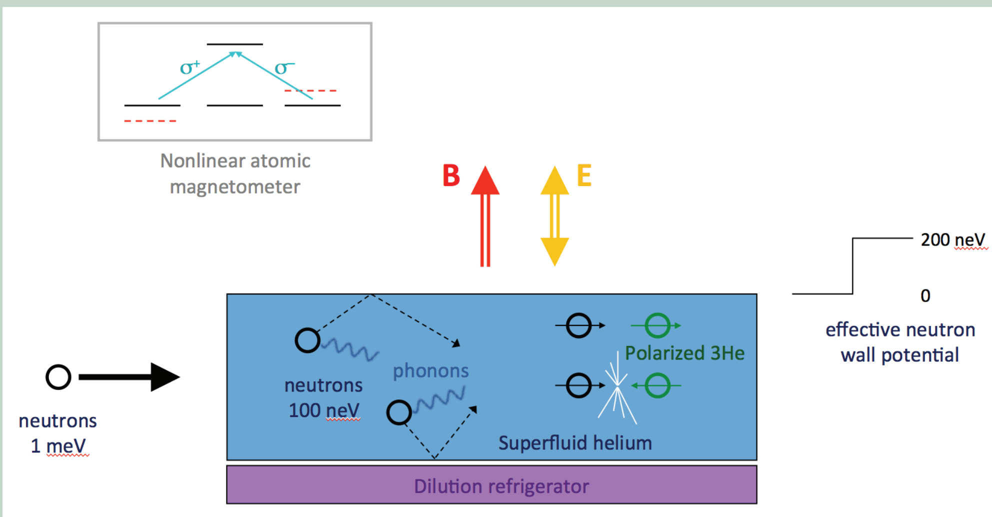

Figure 1: Quantum mechanical effects figure prominently in neutron EDM experiments: (1) Neutrons essentially stop in superfluid helium by transferring all their energy and momentum to the elementary excitations of the macroscopic quantum (superfluid) state. (2) These ultra-cold neutrons exhibit "total internal reflection" from the quantum potential of the container wall. (3) Polarized neutron capture on polarized ^{3}He atoms is highly spin dependent; the products of the reaction scintillate in the superfluid, producing an oscillating light signal at the precession frequency. (4) Atomic vapor magnetometers, whose sensitivity is enhanced through quantum coherence, monitor the magnetic field. | *Image reproduced with permission from Douglas Beck, University of Illinois, Urbana-Champaign.*

Refrigerating neutrons

Quantum mechanical particles differ from "classical" particles in that they are identical, i.e., every neutron is identical to every other. Therefore, any observed quantity for a wave function containing many quantum particles must not depend on which particle has which coordinates, i.e., it must have exchange invariance. Because it is the probability density, or the square of the wave function, that is the observable quantity, the sign (or, more generally, the phase) of the wave function is not defined by this exchange invariance. As a result, an infinite number of bosons (with a plus sign under exchange), like ^{4}He atoms, are allowed in the ground state. Indeed, there is a condensation of ^{4}He atoms into the ground state at low temperature, resulting in a macroscopic quantum system with a single (superfluid) wave function. The low-energy excitations are also collective states of the system—in this case, "phonons" with a linear dispersion relation. Fortuitously, the energy-momentum curve of low-energy neutrons intersects the phonon dispersion curve, leading to a situation in which the neutrons can transfer essentially all their energy and momentum to a collective mode of the quantum system. In neutron EDM experiments, starting with neutrons from either an accelerator or a nuclear reactor source, whose kinetic energies are about 1 meV, interactions with superfluid ^{4}He essentially stop the neutrons, reducing their kinetic energy by a factor of 10^4. The phonons produced are absorbed by a refrigerator—hence the notion that neutrons are refrigerated via a quantum fluid.

Ultra-cold neutrons

When the kinetic energy of neutrons is less than of order 100 neV (achieved using superfluid ^{4}He or another "cold moderator"), their de Broglie wavelength is large enough that their ordinary interactions with atomic nuclei are averaged out. The resulting (purely s-wave) scattering is effectively that from a simple potential step. For some materials, this "Fermi potential" is positive, totally reflecting neutrons with energy less than that of the potential. Thus, the wave-like properties of neutrons at very low energies govern their behavior. As there are materials with Fermi potentials of up to about 250 neV, neutrons can be stored in containers constructed of such materials; neutrons with energies low enough to be so confined are termed "ultra-cold." These are the materials used in modern neutron EDM experiments.

Low-energy neutron-^{3}He scattering

In the neutron EDM experiment planned for the ORNL Spallation Neutron Source, interactions with superfluid ^{4}He produce ultra-cold neutrons (UCNs) inside a plastic container, in which the UCNs are subsequently confined. In principle, we could measure the neutron precession frequency, which is sensitive to the EDM, directly with pickup coils (in a manner similar to that in a standard NMR experiment). However, the highest UCN densities attainable do not produce a measurable magnetic field even using the most sensitive SQUID detectors. Instead, we introduce polarized ^{3}He into the superfluid and take advantage of the very strongly spin-dependent interaction of ^{3}He and neutrons. This results from the deep ^{4}He nuclear bound state, accruing from filled s-orbitals for both protons and neutrons, and corresponding to a neutron and a ^{3}He nucleus in a spin zero initial state. The products of neutron-^{3}He capture scintillate in the superfluid and produce a light signal that oscillates depending on the relative spin of the two species. This oscillation gives the neutron precession frequency. We take advantage of the polarized ^{3}He in the system in another respect as well: its density is high enough that its magnetization signal is detectable with SQUIDs and provides a "co-magnetometer" to monitor the magnetic field seen by the neutrons.

Quantum coherence

In an EDM experiment, by far the dominant contribution to the precession frequency is that corresponding to the magnetic moment interaction with the external magnetic field (the EDM has an analogous contribution due to its interaction with the external electric field). Accordingly, we must monitor the magnetic field in the experiment very carefully. In addition to the average field seen by the neutrons, the shape of the field is important. For room-temperature EDM experiments, we can use external magnetometers based on, for example, the Zeeman effect in alkali atom vapors. To improve the precision of such devices, taking advantage of angular momentum selection rules, superpositions of atomic states can be excited coherently to produce a "dark state" with a long lifetime and narrow energy width, thus providing a more precise measurement of the magnetic field. Such quantum coherence can result in 1 Hz line-widths in situations when the natural linewidth is tens of MHz. This is but one example of a number of related effects based on quantum coherence—including coherent population trapping, electromagnetically induced transparency or absorption, slow and superluminal light, and others—useful for sources and sensing.

Quantum defects have some other natural connections to nuclear physics. Specifically, there are applications in which it is desirable to search optically for a rare isotope embedded in a crystal lattice, usually inert-gas ice. For instance, the nEXO collaboration, searching for $0\nu\beta\beta$-decay of ^{136}Xe, has worked to "tag" barium ions, since, together with measurement of expected decay products, the observed presence of a barium ion at a decay position within the liquid xenon detector would prove conclusively that a $0\nu\beta\beta$-decay event had been detected. A cold probe traps the ion in xenon ice (not strictly a quantum defect). A charge-coupled device (CCD) camera then images the barium fluorescence from the ice sample. Somewhat related is the detection of a trapped barium ion in a fluorescent molecule of a molecular matrix, which is being pursued for the NEXT experiment. Similarly, there is an effort to embed isotopes created at an NP accelerator into inert-gas ice, which would allow single-atom sensitivity for measurements of processes with extraordinarily small cross sections. These include nuclear reactions of astrophysical interest.

One possible area of cross-fertilization between these fields of research is the study of radiation damage. Production of these quantum defects, for either QIS or NP purposes, sometimes involves embedding a high-energy ion into a crystal lattice, which damages the lattice but results in potentially usable optical properties. Understanding and repairing radiation damage has a long history in NP, and the application here of that understanding could positively affect both fields.

5. Nuclear Physics for Quantum Information Science and Quantum Computing and Simulation

NP research strives to understand the nature of matter and forces: from the shortest distance scales in the early universe to the largest astrophysical distance scales. Diverse and highly effective experimental, theoretical, and computational capabilities focus on establishing precise and predictive descriptions of quantum systems: from the strongly correlated, many-body (or infinite) systems determined by unique and finely tuned nuclear forces, to systems exhibiting violations of the fundamental symmetries of nature. These vital and sustained research programs, ranging in scale from single-PI projects through large experimental collaborations, are the result of a talented and well-trained workforce and of community-wide planning and prioritization activities. Continuous interactions with scientists, engineers and developers in other domains, national and international collaborations, and partnerships with the private sector all nourish NP research. Strong connections between NP activities and the national QIS program in particular, including the anticipated NQI centers, will be of mutual benefit for QC and quantum sensing as well as for workforce development. The nature, scope, and complexity of the NP research programs, and their evolution with each discovery, present unique opportunities for NP to advance QIS research.

In considering the types of contributions that NP can make to QIS and QC development, we consider the following principles to be relevant: The activity should address scientific priorities within NP; the activity should, in some manner, be able to address one or more prominent areas in QIS and/or QC, such as those summarized in the previous sections; the activity should embrace tools or techniques in use by, or challenges posed by, NP; the activity would optimally involve members of the NP *and* QIS and/or QC communities.

Activities that this Subcommittee identified incorporated one or more of these principles. NP will contribute to advancing this field principally in the areas of QC and simulation and of quantum sensing. The sections that follow, based on the existing NP research portfolio, comment on these areas broadly, as well as on a number of specific examples of overlap.

5.1 Examples of Potential Nuclear Physics Contributions to Quantum Information Science

5.1.1 Quantum Field Theory, Quantum Many-Body Systems, Algorithms, and Simulations

With strong theoretical programs in QFT and quantum many-body physics, NP can provide expertise and techniques, and make outside-the-box innovations, to advance QIS. QC in particular will benefit from confronting new, difficult problems. NP has numerous many-body quantum problems in common with, for example chemistry and materials; NP, however, also has problems with fundamental non-Abelian symmetry—a new point-of-departure for QC. QCD is the theory of the strong interaction underlying the nuclear forces. Inherently nonlinear and quantum mechanical, QCD is most readily solved using numerical techniques. Using the techniques of lattice QCD, solutions incorporating the physical quark masses and including electroweak interactions are now routine. We have obtained results for hadron masses and matrix elements, low-energy scattering rates, the thermodynamics of very hot matter, and properties of light nuclei. Progress in lattice QCD has resulted from improvements in computer hardware and from innovative algorithm developments. There has been similar progress in the nuclear quantum many-body computations needed for heavier nuclei, resulting from new algorithms and new theoretical techniques, including those of the renormalization group framework. These NP-developed techniques and algorithms have enabled more efficient and broadly used computational methods. They are likely to provide a deeper insight into the general nature of entanglement and strongly correlated systems and a quantitative understanding of the evolution and delocalization of information (scrambling) in QFTs and quantum many-body systems. Just as the sharing of classical algorithms among interested domains has proved beneficial and successful, for instance with HEP and BES, we anticipate that such sharing will continue for quantum algorithms.

Efficiently mapping general physical systems onto quantum computers, or to hybrid quantum-classical systems, presents a significant challenge for a number of reasons. They range from state preparation requirements, to stability with regard to errors, to error-correcting protocols, to measurements, to moving results to classical computers. These issues, which are common across the domain sciences, will be addressed to a large extent by investments in quantum software by national laboratories and technology companies and startups. However, we anticipate, as has been the case in HPC, that the needs of NP research will require specific NP investments in these areas, analogous to those of the Scientific Discovery through Advanced Computing (SciDAC) projects and lattice QCD hardware projects for HPC. In addressing problems of importance to NP, effective mapping onto quantum computers will require significant effort. The variety of systems of interest to NP will require diverse sets of solutions in the mappings, and these solutions will likely have utility outside of NP, from applications in other domain sciences to influencing the operating systems of quantum computers. Examples are already emerging from NP research into efficient maps of NP systems onto NISQ-era quantum devices. Technology companies and startups have also expressed interest in these new ways of thinking about QC that result from NP research activities. There is expected to be significant benefit in maintaining the strong feedback loop between technology companies, startups, and NP quantum projects in these areas.

There is interplay between NP and quantum algorithms in advances associated with quantum Monte Carlo (QMC) calculations for NP currently performed on classical computers. As quantum computations generally involve ensemble averaging of repeated measurements to determine the desired quantities, or intermediate quantities that provide results when combined with other inputs, they have attributes similar to classical QMC calculations. Therefore, NP techniques and algorithms, extensively developed in classical computations, are of direct applicability to quantum computations. We anticipate these techniques will also be of use for QC in other domain science areas.

Examples of NP-developed techniques and expertise contributing to advances in QIS and QC already exist. Algorithms and techniques that have been developed in the lattice QCD community, particularly variants of the hybrid Monte Carlo algorithm, and correlation function analysis techniques have been used to study, for example, the electronic structure of carbon nanotubes. The latter might themselves play a role (potentially as qubits) for scalable quantum devices. Another interesting example of the impact of lattice QFT programs in NP on advances in QC and QIS is in the area of topological insulators. They are a physical realization of the domain-wall fermions[4] discovered in the context of lattice QCD and have been used, starting in the early 1990s, to enable chiral-symmetry-preserving lattice QCD calculations. Topological insulators are prime candidates for, as an example, use in constructing topologically protected qubits in quantum devices.

An area of NP research that holds particular promise for advancing QIS and QC is the application of lattice QCD techniques to describe lattices of physical qubits coupled to form robust logical qubits. The lattice QCD techniques in the NP community have applicability to the study of other lattice field theories, including, with a selection of particle content, lower-dimension QFTs. These are scientifically interesting and include systems of direct applicability to the error-correcting codes needed to advance the operation of quantum devices. For example, the Toric code and variants thereof are constructed from lattices of *physical* qubits. They represent lattice field theories defined with specified boundary conditions, in which the degenerate ground state sector contains one or more topologically stabilized *logical* qubits. The gap in the energy spectrum provides resilience to local qubit errors. [5] The phase structures and the topological properties of the lattice QFTs relevant to the operation and design of quantum devices are important to pursue. A high-level exploration of lattice QFTs to identify appropriate candidate theories would be beneficial.

Collaborations with technology companies and startups to optimize NP-specific scientific applications through the design and production of HPC hardware have proved valuable in advancing both HPC and NP. We anticipate NP co-development efforts will have analogous benefit in the development of quantum devices and algorithms, which will have impact on advances across the domain sciences and elsewhere. Such collaborations can provide junior scientists and engineers with an intimate experience of working with a technology company or startup and will lead to employment opportunities.

5.1.2 Quantum Sensing

Quantum sensing encompasses the development and deployment of devices and techniques to perform highly sensitive measurements of physical quantities. Although the categorization of sensors is not unique, quantum sensing is often used to describe methods that depend on quantization (e.g., energy levels, angular momenta), and/or tunneling, and/or superposition of states and/or entanglement to perform measurements. Utilization of these quantum features characterizes the techniques and devices; already a number of devices qualify. As discussed previously, NP experiments have started to take advantage of such sensors. Following established patterns with conventional instrumentation, as these sensors are adapted to meet the sometimes uniquely demanding applications in NP

[4] David B. Kaplan, "*A Method for Simulating Chiral Fermions on the Lattice*," Phys. Lett. **288B** (1992) 342.
[5] This scheme does not fully protect qubits from errors because the gap is finite. Work on implementation is ongoing and may be combined with, or supplanted by, other error correction protocols.

experiments (e.g., low noise, low levels of radioactive contamination, performance at cryogenic temperatures), the NP community contributes to their overall development. In addition to their diverse uses in a range of applications, quantum sensors are an integral part of devices for quantum computation. For example, further developments of JPAs may lead to more effective readout of superconducting qubit devices. See sidebar 5.1, *Josephson Technology for Ultra-Low Noise Experiments.*

EDM experiments rely on direct manipulation of nuclei, atoms, or even exotic molecules at the quantum level. Some of the clearest examples of NP research advancing quantum sensing are in such experiments. They typically deploy one or more types of quantum sensors to measure the EDM observable and/or to measure subtle aspects of, or changes in, the environment of the measurement. These tools include, e.g., laser cooling of molecules, single atom co-magnetometers, "environmental" atomic vapor magnetometers, and squeezed spin states. At present, EDM experiments are under way at a number of universities and national laboratories.

There have also been significant advances in developing and improving SQUIDs for particle detection. Such systems are used in a number of low-energy experiments, including searches for weakly interacting massive particles (e.g. CDMS, EDELWEISS), the detection of electron capture for neutrino mass experiments (e.g. ECHO, HOLMES, NuMECS), and the search for axion-like dark matter (e.g. ADMX, ABRACADABRA, DM Radio and HAYSTAC). In the near future, there will be considerable development associated with RF-SQUIDs and MKIDs in $0\nu\beta\beta$-decay experiments (e.g., CUPID). A number of such experiments also include detectors with low energy thresholds, such as MKIDs or TESs, overlapping with the types of devices used in QC systems.

Environmental Radiation and Qubit Performance

The QIS community has made considerable progress with regard to the coherence stability of qubits, particularly for trapped ions, semiconductors, and superconducting qubits. Despite these advances, coherence times in superconducting qubits currently fall short of theoretical projections. One candidate mechanism for decoherence is radioactivity from the environment and from cosmogenic activation. NP has a strong track record in understanding and reducing the impacts of environmental radiation on sensitive devices. For example, various neutrino and rare particle decay experiments require high-purity materials with the lowest possible concentration of alpha- and beta-emitting isotopes, as well as of stable isotopes activated by neutrons or cosmic rays. A major asset in NP is instrumentation for, and experience in, measurement of very low concentrations of such isotopes. NP has also made significant investment in producing such materials, e.g., copper for dark matter detectors. Presently, one NP group is studying the impact of radiation on superconducting qubits (see sidebar 5.2, *Superconducting Qubits, Cosmic Rays, and Naturally Occurring Radioactivity*). This research has the potential to extend qubit coherence times in quantum computations. AMO qubit systems typically couple through single photon detectors and CCD arrays for qubit state detection. Cosmic ray events in these components provide errors that currently limit qubit readout in such systems.

Sidebar 5.1: Josephson Technology for Ultra-Low Noise Experiments

QC readout and some fundamental physics experiments require measurements involving microwaves. Both blackbody radiation and the electronics of first-stage amplification contribute to the dominant noise in these measurements. In present devices, blackbody radiation is at the level of a few photons per second at the low temperatures obtained with dilution refrigeration, but transistor amplifiers add the equivalent of hundreds more photons. In the ADMX experiment search for axion dark matter, the use of quantum mechanics substantially reduces the amplifier noise (Figure 1). ADMX has pioneered the use of SQUID amplifiers in the gigahertz range with sensitivity to signals with power of less than 1 yoctowatt (10^{-24} W). SQUIDs, based on the low-loss and nonlinear properties of the Josephson junction, can operate at the standard quantum limit: the equivalent of 1/2 photon uncertainty per resolution bandwidth over a narrow frequency range. In the range of tens of gigahertz, the JPA has similar performance. ADMX is also developing and using these amplifiers. QIS devices also use JPAs for state preparation and for readout in quantum information experiments.

Figure 1: ADMX personnel assemble a cryo-electronics package containing a JPA and a TWPA for their axion search. | *Image reproduced with permission from Gray Rybka, University of Washington.*

The Project 8 neutrino mass experiment requires similar sensitivity to photons from electron cyclotron radiation but also needs to be sensitive to a wide range of frequencies to probe the entire tritium endpoint region. A recent development, the Josephson TWPA, greatly expands the bandwidth with low noise by using a traveling wave, as opposed to the resonant configuration of the JPA, allowing for multimode readout of quantum systems (Figure 2). This property should make Josephson TWPAs ideal for readout of the Project 8 signals.

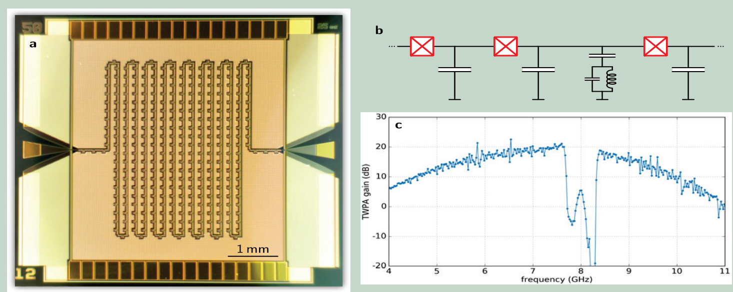

Figure 2: (a) A micrograph of a TWPA showing the path of traveling waves. (b) RF schematic for Josephson TWPAs. (c) Experimentally measured gains of a Josephson TWPA showing wideband performance. | *Images reproduced with permission from William Oliver, Massachusetts Institute of Technology, Lincoln Laboratory.*

Measurements that have an uncertainty below the standard quantum limit (generically, the limit of a single quantum, such as a photon in this case) can be achieved through squeezing (manipulating a quantum system to move, in the Heisenberg uncertainty relation, most of the uncertainty from one variable to its conjugate). Axion search experiments are exploring this technique using, essentially, a superconducting qubit, or "Josephson artificial atom," as is used in a number of QC technologies. For quantum sensing, we can detect the photon excitation amplitude of the artificial atom without measuring the phase (the variable conjugate to the amplitude)—a “perfect” squeezed measurement. Squeezing has a demonstrated improvement of a factor of two; so-called quantum non-demolition measurements (allowing repeated measurements) of single microwave photons are expected to provide further enhancements.

Sidebar 5.2: Superconducting Qubits, Cosmic Rays, and Naturally Occurring Radioactivity

The power of QC is inherent in the quantum mechanical properties of superposition and entanglement, leading to the possibility of coherent operations on all 2^n states in an n-qubit quantum register. Error rates and qubit coherence times are two factors limiting the complexity of calculations that quantum computers can perform.

How can cosmic rays and natural radioactivity affect qubit coherence? Since the first observation of nanosecond-scale coherence in a charge qubit in 1999, the coherence time of superconducting qubits has been, on average, doubling every year. However, we know that QPs are a dominant source of decoherence in these systems. When tunneling across a Josephson junction, for example, a QP can exchange energy with a qubit or modify its energy spectrum. In a wide variety of low-temperature devices, the observed concentration of QPs typically exceeds that predicted in a thermal equilibrium state by orders of magnitude. We have also observed bursts of QPs, which further limit qubit coherence times (Figure 1).

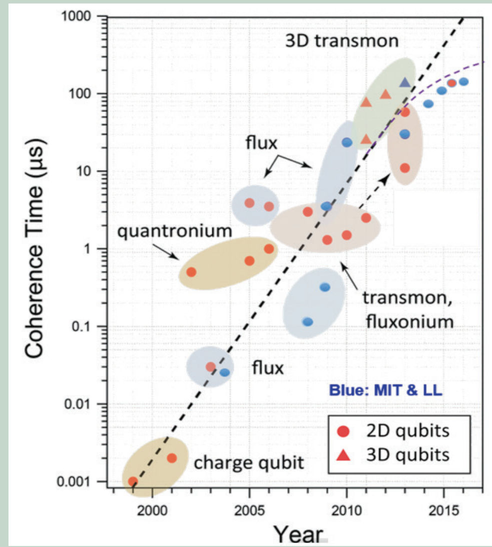

Figure 1: Quantum "Moore's Law" for superconducting qubit coherence times, T2. | *Image reproduced from Oliver and Welander, Materials in superconducting quantum bits, MRS Bulletin 38, 816-825 (2013), copyright by Materials Research Society. Updated by Brent VanDevender (2019). Reproduced with permission of Brent VanDevender (PNNL) and Will Oliver (MIT).*

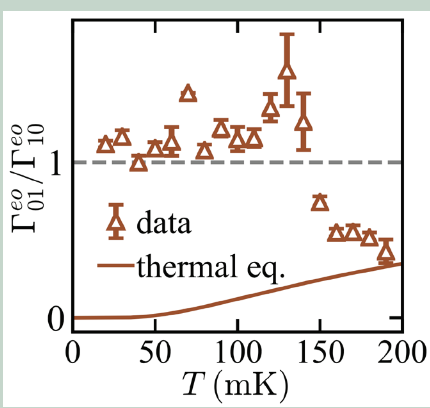

Figure 2: Non-thermal distribution of quasiparticles indicative of cosmic ray and natural sources of radioactivity. | *Reprinted figure with permission from M. Hayes et al., Phys. Rev. Lett 212, 157701, 2018. Copyright 2018 by the American Physical Society.*

Cosmic rays and natural radioactivity can create phonons in quantum devices (Figure 2), some of which reach the qubits and, for example, break Cooper pairs in superconducting devices. The subsequent production of QPs then degrades the coherence. Recent work has shown that QP losses in devices are comparable to losses from other mechanisms and that the rate of QP-induced excitations is greater than that of relaxations; i.e., these QPs are more energetic than, for example, thermal phonons. Many potential sources of the observed QP excesses have been eliminated, and the roles of cosmic rays and natural sources of radioactivity are being investigated. For example, 1 GeV cosmic muons with an observed flux of $1/cm^2$/min create about 10 QP/day/μm^3 and a persistence level of about 0.01 QP/μm^3. The latter value is consistent with experiments that eliminate other QP sources.

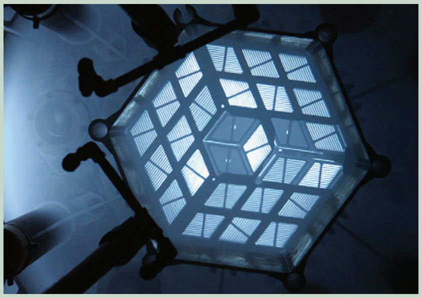

Figure 3: The MIT reactor being used to produce ^{64}Cu for use in controlled background experiments to measure the impact of radioactivity on quasi-particle distributions in superconducting qubits. | *Image reproduced with permission from Joseph Formaggio, MIT.*

Using NP techniques and a highly specialized workforce, NP researchers are working toward a better understanding of QP production mechanisms in superconducting qubits. Radioactive sources are used to measure QP distributions resulting from the energy deposited by the particles from the source. In those particular experiments, carried out at Pacific Northwest National Laboratory (PNNL) and Massachusetts Institute of Technology (MIT), a conducting foil of radioactive ^{64}Cu, produced in a reactor through thermal neutron activation of natural copper, is used to minimize interference in the functioning of the electromagnetic quantum device (Figure 3).

Shielding is being developed to prevent environmental radiation from reaching the sensitive volume of QP-sensitive devices, including the use of "Roman lead" (with a very low level of radioactive contamination) and low-radioactivity copper to attenuate external gamma radiation. For example, a recent experiment found a reduced rate of QP-triggered data in granular aluminum superconducting resonators after implementing basic material selection and cleaning procedures in the production process, followed by operation in a lead-shielded cryostat at the underground facility at Laboratori Nazionali del Gran Sasso in Italy.

Figure 4: The CUORE experiment used radon-free environments to assemble and install the bolometer towers. | *Image reproduced with permission from Yury Suvorov, University of California Los Angeles and Gran Sasso National Laboratory (Italy), and the CUORE Collaboration.*

NP has developed unique expertise and capabilities to support low-radioactive-background experiments such as measurements of solar neutrinos and searches for 0νββ decay and dark matter. Cosmic rays are a troublesome background in such experiments. Not only can they directly deposit energy that can mimic the signal of interest in the experiment, but they also produce radioisotopes whose subsequent decay can resemble real signals. One strategy employed for these low-radioactive-background experiments is locating them at deep underground facilities, for example, the Sanford Underground Research Facility (SURF) in South Dakota. Another class of naturally occurring background is radioactivity from the primordial uranium and thorium chains, present at trace levels in nearly all materials. NP has developed a variety of techniques to mitigate such backgrounds. Significant advances have been made in the development of ultra-low-radioactivity materials; for example, the Majorana Demonstrator project has developed the world's purest copper for constructing its cryostat. To mitigate the alpha decay background from radon, the fabrication, assembly, and storage of sensitive materials is undertaken in cleanrooms or in a radon-free environment.

The development of clean fabrication techniques and procedures has enabled low-radioactive-background experiments to achieve unprecedented sensitivities to very low-rate processes. These advances would not be possible without concurrent improvements of assay sensitivities in inductively coupled plasma mass spectroscopy and the direct counting of a very low level of alpha, beta, and gamma radiation in materials. NP has extensive capacity to support the radio-assay of components deployed in these experiments, from detection media (e.g., the bolometers in the CUORE experiment) and microelectronics, to the alloys in the supporting structure (Figure 4). We have compiled these radio-assay results for public access in a searchable online database (http://radiopurity.org).

High-Complexity Readout(s) in Extreme Environments

Public-sector research groups and technology companies and startups have been successful in implementing quantum circuits involving a few tens of qubits, with this number increasing regularly. As systems scale from tens to hundreds to thousands of qubits, the complexity of implementation also scales. These increasingly capable systems will require a large number of connections in a challenging cryogenic or vacuum environment, a situation sometimes referred to as "the tyranny of wires." Many of the challenges involved in such systems can also be found in sophisticated cryogenic experiments within NP and HEP. NP has considerable experience in such highly complex systems, for example in bolometer (CUORE) and TES readout systems (CUPID) for $0\nu\beta\beta$-decay, in direct neutrino-mass detection (e.g., NuMECS), and in charge and scintillation readout from large arrays of sensors (EXO-200 and nEXO). There is also considerable experience in NP in the readout and control of such complex systems, as experiments usually simultaneously deal with hundreds to tens of thousands of readout channels. There are opportunities for cross-collaboration among NP, QIS, and QC related to designing such system components as data acquisition systems, field-programmable gate arrays, and sensor and control readout.

Nuclear Clocks

The development of new atomic clocks lies at the intersections among NP, QIS, and QC. Currently, a collaboration among NIST, Ludwig-Maximilians-Universität München, Atominstitut–TU Wein, and University of California Los Angeles has started to develop a new nuclear clock using the ^{229}Th nucleus. This nucleus has an extremely low-lying meta-stable excited state, which is accessible to an ultraviolet laser. Such a system would be much less sensitive to cosmic rays and background electromagnetic fields (because it uses a nuclear rather than an electronic transition) compared with the state-of-the-art Al^+, Yb^+, and Sr clocks. Such a clock transition is configurable as a qubit, in this case, one having unique properties.

Isotope Enrichment and Rare Isotope Production

Silicon-based QIS and QC systems are attractive for potential scalability and the utilization of current microelectronics technology. However, the isotope ^{29}Si, with abundance 4.67%, has a nuclear spin and a magnetic moment that can lead to decreased coherence times in quantum devices. Therefore, there is interest in isotopic enrichment of ^{28}Si. If silicon-based devices become leading technologies, a need for additional isotope enrichment capabilities is to be expected. The DOE Nuclear Physics Program manages IDPRA, which can uniquely support the supply of stable isotopes as raw materials for a range of uses from fundamental research to medicine. In parallel, there are needs within NP for ton-scale quantities of enriched isotopes, such as ^{76}Ge and ^{136}Xe. An appropriate investment in new enrichment techniques and increased capacities would be of benefit to QIS, QC, and NP. QIS and QC development also requires small amounts of other specialized isotopes from the IDPRA facilities. These include, e.g., ^{229}Th for nuclear clocks and ^{167}Er, ^{171}Yb, and ^{133}Ba, which are being used in the development of quantum memory in solid state or ion trap platforms.

As a result of longstanding efforts focused on implanting nuclei with spin into doped silicon electronic devices, progress is being made toward a silicon-based, nuclear-spin (Kane) quantum computer. Electromagnetic fields, controlled using conventional techniques in silicon devices, entangle the implanted nuclear qubits. The initial proposal and development employed isotopically pure ^{31}P, which has been proven to have long coherence times. Recently, 2D lattices of ^{31}P implanted in silicon, sandwiched between two control layers arranged to facilitate error correction to create a logical qubit, have been successfully fabricated. In addition to implanting donor atoms into silicon, there have been successful efforts to implant silicon into diamond. For more detail, see sidebar 5.3, *Enriched Stable Isotopes for QIS and QC*.

Superconducting High Q-Cavities

Superconducting RF cavities specifically designed for QIS systems could provide a technological advance resulting from high quality factors (Q) and long coherence times. They are likely to be particularly useful as components of interfaces between quantum computers and the outside world, and potentially as components of quantum sensors. Significant R&D to design appropriate low-loss microwave resonator configurations is essential, as the modes and geometries in typical high-Q cavities optimized for particle acceleration are not generally suitable for QIS use. The development will involve both materials and surface treatments. Developing a process that would lead to production-quality cavities, at scale, for reliable operation in QIS test beds will also likely involve investigations into fabrication, machining, electron-beam welding, and potentially new assembly techniques. NP's JLab has extensive expertise and capability in the design and development of high-Q accelerator cavities. As part of the HEP research program, FNAL is also exploring the potential impact of high-Q cavities in QIS.

Training in Cryogenic Systems

Several experimental projects in NP and HEP employ advanced and complex cryogenic systems that are typically larger in scale than are those in QIS. One example is the CUORE experiment, which holds the record for the largest ultra-high vacuum, cold-instrumented volume (< 100 mK) in the world. Many systems used in NP research operate at liquid nitrogen, liquid helium, or milli-Kelvin temperatures; as a result, NP scientists and engineers involved in these experiments have valuable expertise in the design and operation of such systems. Demand for the cryo-engineering expertise and cryo-technical support that resides in NP is on the rise because of the growth of QIS-related activities in academia, national laboratories, technology companies, and startups. NP has the capability to provide, in principle, expertise and technical training to meet the increased demand for the QIS and QC communities. We believe leveraging and extending this NP expertise will be valuable for building a viable quantum workforce. Effective training of a cryo-ready workforce will require high-level coordination at universities and national laboratories. At the same time, it is important for NP to recognize that it will be competing for its own cryo-ready workforce in a way it has not previously experienced.

Sidebar 5.3: Enriched Stable Isotopes for QIS and QC

Some implementations of QC hardware rely on our ability to manipulate the quantum spin of an electron in, for example, a recently developed two-qubit system using electron spins in silicon quantum dots. One of the sources of noise in silicon-based devices is the odd-A nucleus ^{29}Si whose ground state is spin-1/2. This odd-spin nuclear ground state couples to the electron spin through the hyperfine interaction, causing decoherence within the system. For certain QIS devices, therefore, enriched stable isotopes are essential.

DOE's IDPRA, managed by the Office of Nuclear Physics within DOE-SC, recently embarked on reestablishing stable isotope enrichment capability within the United States. The DOE IDPRA mission includes producing and distributing radioactive and stable isotopes that are in short supply. IDPRA accomplishes its mission under the mandate provided in the 1990 Energy and Water Development Appropriations Act, which establishes a singular responsibility for isotope production, distribution, and sales of isotopes and related services. IDPRA's strategic approach includes planning, constructing, and operating production facilities at national laboratories and developing partnerships with industrial laboratories and universities.

As noted by the NSAC Isotopes Subcommittee in 2009, "Although significant stock of the stable isotopic nuclides of the heavier elements exists in current DOE inventory, some nuclide stocks have been exhausted." In addition, there is a very limited supply of many others. Since 2009, IDPRA has embarked on a project to reestablish stable isotope enrichment capability within the United States. The project has demonstrated both electromagnetic and centrifuge separation capability. These enrichment technologies are applicable to the provision of isotopes for QIS.

Figure 1: The ionized glow of different ruthenium isotopes upon separation. The electromagnetic ion separator system operates by vaporizing an element, such as ruthenium, into a gas phase, converting the molecules into an ion beam, and then channeling the beam through magnets to separate the different isotopes. | *Image reproduced with permission from Brian Egle and David J. Dean, Oak Ridge National Laboratory.*

The first such separation campaign involved production of the rare ^{96}Ru isotope for a RHIC experiment to understand better the properties of the quark-gluon plasma (Figure 1). The experiment required 500 mg of ^{96}Ru, which was not available anywhere in the world. Ruthenium metal itself is one of the rarest elements on earth, and the particular isotope required by BNL makes up less than 5% of naturally occurring supplies. The experiment required enrichment to greater than 92%, prompting researchers to use newly developed enrichment methods.

IDPRA receives funding from the DOE-SC QIS initiative to develop production capabilities of relevant isotopes. It is now constructing the Stable Isotope Production and Research Center, which will greatly enhance production capabilities of enriched stable isotopes in general.

Novel Qubits and Quantum Devices

The unique physical systems and challenges that are specific to NP motivate the design and prototyping of targeted hardware. Such activities have proved fruitful in HPC, specifically in the co-development of hardware for lattice QCD calculations. There are already examples of the potential for cross-pollination of ideas and expertise among the NP, QIS, and QC communities.

The first example is the development of optical systems built around quantum frequency processors that is under way at ORNL. NP researchers have used these devices to compute the ground-state energies of the lightest few nuclei using the variational quantum eigensolver technique in a hybrid classical-quantum system. As a second example, LLNL is pursuing quantum devices and support systems developed around superconducting qudits, with one of the main physics drivers being the calculation of low-energy inelastic nuclear reactions in few-body systems. A third example is the effort involving BNL to translate the understanding of charge separation in heavy-ion collisions, related to the so-called chiral magnetic effect, into the design and fabrication of "chiral qubits" by NP scientists and engineers.

Large Collaborations and Organizations

Because of the complexity of the scientific challenges that NP addresses, some of the NP experimental programs naturally involve large, international collaborations. Such collaborations span tens to hundreds, and even, in some instances, thousands of scientists, engineers, developers, students, and technicians who are located around the globe. Collaborations between these experimental programs and industry on device development, quality control, and testing protocols are a common necessity. Such large-scale collaborative efforts are not unique to NP—they also evolved within the HEP community, in which collaborations are typically larger than those in NP, and in DOE's Office of Fusion Energy Science. Advances in QIS and QC, on the other hand, have typically emerged from smaller-scale collaborations embedded in other science domains, such as those in AMO and condensed matter physics; other government agencies; technology companies and startups; or science communities outside the US. To the extent that the NQI will benefit from an integrated effort with many participants, NP's institutional knowledge in successful, large-scale collaboration building may be a useful resource in this effort.

As discussed earlier in the context of cryogenic systems, NP has developed effective ways of integrating required engineering into its projects. Engineering training is not generally oriented to the challenges of our fields, which include one-off devices, or systems involving unusual constraints like extremely low temperatures and/or very pure materials. Again, the NP institutional knowledge might be a useful resource as engineering evolves to assume a more significant role in the national QIS effort.

The community of NP theorists has a number of important organizing structures that can also provide models and experience for future QIS and QC activities. The INT, established in the late 1980s, is a critical and long-standing component of the US (and international) theoretical and computational NP efforts. It provides a bridge to the NP experimental program, a center for NP planning, and an incubator for new ideas and techniques, and is highly successful in training the NP workforce. It hosts community-proposed workshops and programs, bringing together scientists from all over the world to address problems of importance to NP. It has been equally successful in gathering and integrating concepts and techniques from other domains into NP. The NP theory community also supports Topical Collaborations (TCs), which are delocalized, virtual collaborations of NP scientists focused on addressing specific scientific challenges in the field. The TCs have proved to be successful vehicles to target specific issues in a finite-duration framework. We anticipate the TCs in NP may provide models for similar collaborative mechanisms in QC.

SciDAC collaborations, focused partnerships between ASCR and NP, are essential for NP to make optimal use of HPC resources. NP currently has three SciDAC projects, one in lattice QCD, one in nuclear structure and reactions, and one in nuclear astrophysics. In this case, the lattice QCD project might be a particularly relevant example for QIS and QC as it supports, in part, the US Lattice Quantum Chromodynamics consortium (USQCD), which evolved in close collaboration with HEP. USQCD represents essentially all scientists working in the field of lattice QCD in the US. USQCD has both an Executive Committee responsible, for example, for writing funding proposals, and a separate Scientific Program Committee responsible, for example, for resource allocation within the consortium. It includes NP and HEP scientists, engineers, and developers at universities and national laboratories, together with counterparts in applied math, computer science, and statistics and in technology companies and startups. Similar collaborative arrangements among the domain sciences, such as NP, HEP, and BES, together with ASCR and with QIS and QC, would likely benefit all partners.

In establishing and sustaining collaborations of scientists and engineers, large or small, a crucial ingredient of success is that members of the collaborations be supportive of one another and of the scientific mission, and that members behave respectfully and with integrity and honesty. NP groups have found it valuable, as have other groups, to proactively establish guidelines such as codes of conduct that address sexual harassment and other forms of harassment and encourage inclusiveness and respect of all individuals. Consideration should be given to including guidelines pertaining to the appropriate treatment and attribution of data, algorithms, and codes and to the ethics associated with machine learning, artificial intelligence, and QC. The experiences and deliberations within the NP community are likely to benefit QIS and QC community building. For example, the APS Division of Nuclear Physics has established the Allies program to ensure meetings are appropriate and inclusive environments. While there has been significant forward progress in creating supportive communities, more improvement is needed. In particular, an important part of creating and maintaining a community in which all members can thrive is establishing mechanisms for feedback, accountability, and measurement of the efficacy of the community guidelines.

6. Synergies and Cross-Disciplinary Opportunities Across Science Domains

NP is an established science domain focused on developing predictive capabilities for the structure and behavior of matter in a diverse array of environments. The need for particle detection in its experimental program, the need for scientific computation to make reliable predictions, the need for a quantum-ready workforce, and the need for close ties to other scientific communities, including QIS and QC, is common to other science domains. Consequently, while there are differences in scientific directions, there are commonalities in scientific techniques, paths forward, and the organization required for achieving scientific objectives. Further, the developments that are required to address the scientific objectives of NP will, in many instances, lead to advances in QIS and QC.

As this report focuses on NP as it relates to QIS and QC, it does not discuss synergistic activities and opportunities for NP and other domain sciences in the absence of QIS impact. The previous sections have provided context and information to allow this section to be concise. It discusses potential synergies and cross-disciplinary opportunities in the areas of QC, simulation and algorithms, quantum sensing, and quantum-ready workforce.

6.1 Quantum Computing, Simulation, and Algorithms

The NP scientific objectives requiring QC and simulation have similarities to those in other domain sciences, such as BES, HEP, and scientific computing. All the fields share a basis in multi-particle dynamics, either in QFTs or in materials; the study of phase transitions; or the properties and dynamics of systems of fermions. The techniques currently employed for quantum simulation are similar at the conceptual level but differ in detail because of the underlying physics. In each of the domains, systems having large particle numbers, exhibiting a sign problem in sampling calculations, or undergoing real-time evolution typically require prohibitively large HPC resources to achieve the required precision. As an example, quantum chemistry is a research area that is anticipated to have a substantial overlap with NP in quantum algorithms. Although the nuclear force is qualitatively different from the Coulomb force, the quantum and hybrid classical-quantum algorithms used in quantum chemistry provide insight into the nature of quantum algorithms applicable to NP problems.

Lattice QFT and quantum many-body calculations in NP, which use an array of QMC techniques developed for classical HPC systems, require expertise that will benefit HEP and BES research, as well as QIS and QC. Close collaborations among these areas, including with scientists, engineers, and developers at technology companies and startups, will almost certainly be of mutual benefit. In the US, the first steps in such research programs resulted from collaborations among nuclear, high energy, and computational scientists. Recognizing the need for ever-more-capable computing devices, DOE ASCR established the Quantum Path Finder Testbeds and Hybrid Classical Quantum Algorithms programs in anticipation of future heterogeneous computing platforms that could include QPUs. Paralleling the development of HPC, the drive to solve a range of science problems, including those in NP, will in part guide the evolution of QC devices and systems. Algorithms implemented on cutting-edge quantum devices to address these NP problems, and their optimized tunings, will likely advance QIS and QC also.

6.2 Quantum Sensing

We anticipate the NP community will benefit increasingly from the design and development of new materials by BES programs. These programs have significant capabilities, and closer connections between NP and BES, focused on the development of materials for NP research, are desirable. These connections could be at the level of material design through simulation and also at the level of fabrication. Given the needs for ultra-low-background and high-sensitivity measurements, the design and fabrication of targeted materials is becoming increasingly important.

NP presently employs quantum-sensing techniques in a number of experiments. HEP is pursuing these and other quantum sensors for similar technical reasons but with different scientific motivations. For example, there are now numerous proposals for enhanced dark matter detection over a wide range of mass scales, some of which employ sensors similar to those that might be used to enhance $0\nu\beta\beta$–decay searches. A general class of charge, parity, and time-reversal violation measurements using clock-comparison techniques, which might be further enhanced by quantum sensing technologies, has commonalities with the techniques of EDM experiments.

There is significant overlap between sensors and techniques largely developed in AMO research and NP. NP experiments employ sensors using atomic systems, such as alkali vapor magnetometers that rely on quantum superposition to create long-lived "dark" states. In a number of important cases, the general tools and techniques for control of quantum systems are similar. Atom trapping played an important role in measuring the nuclear charge radii of ^{6}He and of ^{8}He (the most relatively neutron-rich nucleus known). Atomic clocks and various EDM experiments are closely related. Just as spin squeezing was used to enhance the precision of clocks, researchers are now exploring this and other techniques to increase the sensitivity of EDM measurements.

As examples in materials science, both muons and neutrons (sometimes at NP facilities) can map local magnetic fields and material magnetic spin properties. Another promising way to measure electric and magnetic fields in materials involves NV centers in diamond, using the nuclear spin. With potential applications in, for example, EDM experiments, continued development of NV diamond sensors across the communities is desirable.

6.3 Quantum-Ready Workforce

In training a quantum-ready workforce, consideration of the similarities and differences among fields, such as NP, HEP, and BES, may be helpful. In these domains, the QIS and QC expertise needs, as well as the nature of the collaboration with the QIS- and QC-fields-proper, will likely be similar, with possible differences at the technical level. The needs for vertical education and training in these communities, from undergraduates through faculty members and staff scientists, are similar; the mechanisms of summer schools, conferences, and postdoctoral and bridge positions discussed in this report might similarly be effective in other domains. European research communities have also implemented variants of the NSF's Triplets program. In this context, there can be value in bringing together scientists and engineers in the various scientific domains, in technology companies and startups, and in government agencies for broader discussions related to workforce development for QIS and QC. The NQI centers that are currently being organized may provide vehicles for the cross-disciplinary education and training that is required and may provide venues for collaboration in training a QIS-ready NP workforce.

7. Path Forward for Nuclear Physics

The preceding sections describe developments in NP that relate to QIS and QC; this section lays out a vision for accelerating that development. We are convinced NP has much to gain from, and contribute to, QIS and QC as these and related fields evolve together. Our emphasis is on ensuring that an augmented program focuses on the activities and the development of expertise that will most strongly benefit NP and, at the same time, support the development of QIS and QC. **The following sections detail a comprehensive package of three recommendations, expand on the context, and suggest strategies for NP community actions to take the best advantage of the opportunities at hand.**

7.1 Recommendation 1A: Quantum Computing and Simulation, and Nuclear Physics

Future developments in QIS, QC, and quantum simulators are expected to provide capabilities for specific applications that far exceed those possible with classical computation. Such capabilities, which likely require more than a decade of concerted effort to realize, would provide a unique path to address some of the computational challenges facing NP in quantum many-body physics and QFT research. In addition, quantum many-body and QFT techniques essential to addressing key problems in NP are anticipated to impact future developments in QIS and quantum devices. QIS will develop, in part, as a result of addressing new and difficult problems. The quantum many-body problems that NP has in common with other domain sciences such as materials and chemistry will help drive this development; NP also brings, for example, problems with non-Abelian symmetries. We anticipate this fortuitous feedback cycle to continue into the future.

Developing the capabilities to utilize QC and simulations for NP research requires a highly multidisciplinary approach. Furthermore, the intertwining of quantum device development, algorithm and application development, classical simulation of quantum devices, QC and simulation, and workforce development is essential to establish a sustainable NP quantum ecosystem. Close cooperation among scientists, engineers and developers with expertise in diverse areas—located at universities, technology companies, startups, national laboratories, and other government agencies—is also required to tackle the substantial challenges that lie ahead.

We recommend establishing one or more multi-institutional Quantum Co-Development Consortia (QCDC) for simulation. These Co-Development Consortia should pursue and facilitate the development of quantum simulation capabilities for NP research and utilize NP expertise in quantum many-body physics and quantum field theory to impact quantum information science and quantum computing.

The QCDC for simulation should provide accessible expertise and quantum resources to the NP community, analogous to the cross-disciplinary benefits provided by the SciDAC Institutes for HPC in the domain sciences. They should strengthen partnerships among scientists, engineers and developers at universities, technology companies and startups, national laboratories, and other government agencies, as well as coordinate with DOE and NSF quantum test beds. The consortia can take advantage of their combined resources to efficiently support and coordinate workforce development efforts in areas related to simulation. We envisage that, together, the QCDC will form a key part of the QC and simulation ecosystem for NP research. The co-development element of the QCDC will enable continuous feedback between application developments and quantum hardware design to realize the full scientific potential of this quantum ecosystem.

- Collectively, the QCDC for simulation should accomplish the following:

    - Identify a small number of high-priority objectives that could first establish a "quantum advantage" in NP, and coordinate their pursuit.
    - Identify and develop quantum many-body and QFT techniques within NP that have application in the design and operation of quantum devices.
    - Involve and work closely with scientists, engineers, and developers in QIS and in QC.
    - Involve and work closely with scientists, engineers, and developers in HEP and BES, who are anticipated to be addressing challenges with partial overlap in the quantum algorithms and quantum devices spaces, and potentially beyond, to address their scientific challenges.
    - Involve and work closely with scientists, engineers, and experts at technology companies and startups involved in developing quantum devices and quantum algorithms.
    - Facilitate access to quantum devices, tools, software, and expertise at universities, national laboratories, technology companies, and startups and to DOE and NSF platforms and test beds.
    - Support R&D of quantum device test beds at universities and/or national laboratories that are dedicated to NP research, complementing other DOE and NSF activities.
    - Grow a "quantum-simulation–capable" workforce.
    - Facilitate access to state-of-the-art classical HPC hardware, software, and tools for quantum device and algorithm simulation.

- The QCDC should develop and encourage quantum simulation capabilities in areas of importance to NP research, including, for example, the following:

    - Nuclear many-body systems, encompassing the structure of medium and large nuclei, nuclear reactions, and inelastic interactions with leptons;
    - Lattice QFTs, targeted toward QCD and the standard model, to complement classical lattice QFT calculations performed with HPC resources;
    - Low-dimensional field theories of relevance to QC, quantum algorithm design, and illustrative toy models on the path to QCD;
    - EFTs describing interactions between nucleons and between nucleons and mesons;
    - In-medium hadronic fragmentation and highly-inelastic processes;
    - Neutrino propagation in dense matter;
    - Finite-density systems exhibiting classes of sign problems in classical computations;
    - The dynamics of unitary systems;
    - Dark matter detection.

7.2 Recommendation 1B: Quantum Sensing in Nuclear Physics

Quantum sensors have diverse application in areas that include communication, imaging, medicine, deep-space exploration, national security, and research in NP, astrophysics, and HEP. Their implementation in NP applications is of direct benefit to NP research and aids in bringing QIS technologies to maturity. Fabricating and deploying quantum sensors—including those in solid-state, superconducting, atomic, nuclear, and optical systems—utilizes a range of technologies and breadth of expertise. Within the NP community, our expertise provides opportunities to drive forward the development of quantum sensors and other quantum devices.

Presently, the NP and QIS communities have developed natural interactions through the advancement of quantum sensors that are finding application in NP experiments. Quantum technologies such as SQUIDs have long been critical to the success of a variety of NP experiments and are now becoming standard in many applications. Newer quantum sensor technologies—TESs, SNSPDs, MKIDs, and JPAs—are now finding their way into important experimental efforts. Programs including $0\nu\beta\beta$-decay experiments, nuclear materials analysis, EDM searches, x-ray reference data, and neutrino mass measurement are all incorporating quantum sensors in critical roles. Although this exploration of the applicability of quantum sensors in NP remains rather limited, as these specialized uses become successful and more broadly recognized, it is reasonable to expect that they will find a broader application in NP. Indeed, use of quantum sensors is expected to enable transformative changes in the design of high-priority NP experiments.

We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for sensors focused on targeted, prioritized, cross-disciplinary developments in quantum-enhanced sensing for NP research.

We expect the QCDC for sensors to establish a base of support for an integrated NP community in quantum sensing. They will focus on select technologies to pursue vigorously and will work in partnership with researchers in QIS and QC, as well as other domain sciences. The sources of the sensor QCDC scientists, engineers and developers will include universities, national laboratories and other government agencies, and technology companies and startups.

It is important for the NP portfolio of quantum sensing research to contribute to the US QIS and QC programs on relevant timescales, as it should complement and be competitive with quantum sensing programs in other domain sciences and the private sector. The sensor QCDC will target high-priority quantum sensing research that satisfies these criteria, is important in the NP research programs, and is expected to yield tangible results on timescales of a few years. These consortia, as those for simulation, can take advantage of their combined resources to efficiently support and coordinate workforce development efforts in areas related to sensors.

Beyond specific devices, nuclear physicists can bring unique expertise in a number of system-level areas to address problems in QIS, in QC, and in quantum sensors. Low-background methods, large-scale cryogenic techniques, and the ability to manage large, diverse collaborations are skills from which QIS and QC can benefit as they expand.

Applications of quantum sensors, in many instances relevant for NP applications, rely on devices being readily available in quantity and having standardized performance. To accommodate this need, and to enhance quantum sensing in other science domains and QIS applications, it is desirable to have mechanisms enabling the commercialization of quantum sensing capabilities emerging from NP research. The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provide opportunities for supporting the commercialization of technology developed during research, and enable collaborations between research institutions and technology companies and startups on commercially viable projects of mutual benefit. The QED-C led by NIST/SRI International should be considered in determining how best to support this emerging interface.

The DOE Nuclear Physics Program manages IDPRA, which can uniquely support the supply of stable isotopes as raw materials important to QIS and QC development. These isotopes will play an increasing role in low-noise quantum sensing applications (as well as in devices for QC and for quantum memories). For example, the natural 1% abundance of ^{13}C limits the spin diffusion lifetime in NV diamond sensors. On the other hand, here, as in other systems, the controlled deployment of atoms with nuclear spin, such as ^{13}C and ^{15}N, can be used to advantage for storage and readout of quantum information.

- Collectively, the QCDC for sensors should
    - Complement and help coordinate individual efforts for quantum sensors with clear utility to NP, prioritizing those with the potential for near-term impact.
    - Facilitate collaboration between QIS and NP researchers—involving academia, national laboratories, and industry—to enable the co-development of quantum sensors for NP applications. Match capabilities and requirements and coordinate the development work needed for implementation of quantum sensing technology in NP experiments.
    - Pursue opportunities to apply NP expertise to advance quantum sensors in new directions, in part by facilitating interactions among NP researchers working with different sensor technologies.
    - Where feasible, find efficiencies by bringing together research with common needs, such as cryogenic capabilities or low-noise environments.
    - Grow a workforce familiar with the construction and application of quantum sensors, with materials capabilities and skills, and associated infrastructure.
    - Support and complement efforts from single-PI and small collaborative efforts.
- These QCDC should encourage the development of quantum sensor capabilities in areas of importance to NP research, including, for example,
    - TESs,
    - SNSPDs,

- MKIDs,
- Quantum-limited parametric amplifiers (e.g., JPAs, TWPAs),
- Quantum defects, such as NV centers in diamond.

7.2.1 Comments on Recommendations 1A and 1B:

We recommend to the community the following common framework for the proposed QCDC. Given the premium on acting effectively to make measurable gains in the near future, as well as to set the stage for success in the medium and longer term, we recommend a simple but formal structure. The structure is discussed below in the subsection "What Might Quantum Co-Development Consortia Look Like." The focused efforts undertaken by the members in the near term will define the consortia. Because the field is evolving quickly, and there are no guaranteed paths to success, we recommend a biennial scientific review by members of the broader community to guide choices and make course corrections as necessary. We view this as a key part of our commitment to the success of the consortia. An important part of the activities of the QCDC will be to host periodic workshops. The workshops will fold into the focused work of the consortia developments in QIS and QC proper, in related domain science fields, and in commercial technology efforts, as well as in activities in the ongoing NP program not associated directly with consortia. The latter function will help connect the activities supported as part of our second major recommendation to the QCDCs' more targeted work. Such workshops will also be critical elements of workforce development for NP and the broader community and will support the third major recommendation. The QCDC must also facilitate access for their members to, for example, test bed quantum computers and large-scale simulation platforms, software, tools, and data, as well as to sensor and device technologies that might only exist, for example, at particular national laboratories. Finally, we reiterate our support for strong connections between the QCDC and the NQI centers as appropriate, and for folding these connections into the QCDC structure.

It is important that there be continued progress in the development of both Quantum 1.0 and Quantum 2.0 sensors. As Quantum 2.0 technologies are at a significantly lower stage of readiness, there will be value in supporting projects to identify promising avenues of research. At the same time, the ongoing refinement of Quantum 1.0 technologies is more likely to have near-term impact for NP research.

7.3 Recommendation 2: Exploratory Techniques and Technologies in Combined Nuclear Physics and Quantum Information Science Activities

We expect QIS research during the next decade and beyond to benefit programs that are currently part of the NP research portfolio, as well as those that are likely to emerge. These programs in turn will contribute to advances in QIS (including computing, simulation, and sensors). Currently, such "ancillary" efforts within NP are typically nascent and limited in scope. However, they have the potential to provide critical intellectual and training support for the overall NP program. These efforts, and the development of new efforts of similar scale, should be encouraged and supported.

We recommend that DOE and NSF encourage and support selected exploratory technologies and techniques that have promise to be of mutual benefit to NP and QIS research activities.

The scope of such projects ranges from experiment to HPC to theory. They encompass efforts that will feed the recommended QCDC in quantum sensing and quantum simulation, and efforts that may be independent, stand-alone projects. While they are expected to benefit from collaborations with QIS or QC experts and the QCDC, such collaborations need not be a requirement. Single-investigator, small- or medium-scale efforts are expected to provide unique or specialized workforce development opportunities. In particular, at the small scale, agency support for nascent new techniques and technologies in this domain (whether experimental, theoretical, or computational) should enable rapid and flexible NP response to newly apparent opportunities. We expect them to be a rich source of innovation and workforce development.

- Examples of exploratory technologies and techniques include
  - Entangled qubits for field-gradient sensing;
  - Quantum algorithm and circuit design for QFT and quantum many-body calculations;
  - Nuclear clocks such as ^{229}Th;
  - EDM searches;
  - Opportunities to improve qubits or other quantum devices with NP expertise, e.g., with low-radiation-background environments or high-Q superconducting cavities;
  - Multiplexing in cryogenic environments for superconducting qubit readout;
  - Chiral qubits and microwave qudits.

7.4 Recommendation 3: A Quantum-Ready Nuclear Physics Workforce

The US NQI recognizes that building a quantum-ready workforce is essential to a healthy ecosystem of impactful research to support the emerging quantum economy. We must give priority to the education, training, development, and sustainability of a quantum-knowledgeable and expert workforce at each professional, and pre-professional, level to enable NP to reap the benefits of developments in QIS and QC, and to establish long-term, co-development programs. Further, the inherent cross-disciplinary nature of QIS and QC suggests that broad engagement of nuclear physicists with scientists and engineers in other domains is essential to the development of a QIS-ready NP workforce. Participation by NP scientists, engineers and developers in the anticipated NQI centers should also yield significant workforce benefits.

One should not underestimate the difficulty of this part of the task. Bootstrapping technical communication among the various disciplines will be among the first challenges. Each discipline naturally has its own language, and the substantial effort of translation will be required. This is often most effective with sustained, in-person contact—hence the array of steps recommended below. We also expand on other aspects of the challenges in Comment 4 below, "Developing the Quantum Workforce." Effective workforce development will require the coordinated efforts of all stakeholders, including scientists, engineers, and developers; institutions; technology companies and startups; and funding agencies. The stakeholder roles will interlock and will not easily be separated.

Annual, multi-week summer schools and training programs continue to provide an effective means of workforce development within NP. Summer schools and training programs focused on QIS and QC in NP could provide a deep immersion in QIS and QC relevant to NP. The schools would draw presenters from universities, technology companies and startups, national laboratories and other government agencies. The presenters' expertise should span the range from NP to materials, exotic states of matter, HEP, quantum algorithms and error correction, quantum programming, and quantum device design and fabrication. Further, the presenters should be involved in establishing the training format and content in addition to engaging with participants at the school. It is desirable to have participants engage in practical, independent projects, along with having hands-on or remote access to quantum devices, simulators, and modeling and estimation tools. For large parts of the program, the NP community could make these activities available on-line.

The NSF has established the Triplets program, which connects graduate students with mentors and advisors in universities, national laboratories, and technology companies and startups to guide them through their graduate careers. This innovative program appears well suited for developing, in part, a QIS-ready workforce for NP. A number of other countries are pursuing similar programs. The success of such collaborations will depend, in part, on establishing intellectual property agreements that allow for the mutually beneficial engagement and openness that are consistent with university environments.

The SciDAC programs have been successful in nurturing early-career scientists and developers in HPC within the domain sciences and could provide a useful model for QIS workforce development. They provide support for junior scientists and developers, at the level of graduate students and postdoctoral fellows, with expertise in HPC and algorithms to integrate with computationally demanding, domain science research projects.

The recommended QCDC in quantum sensing and simulation should play key roles in developing a QIS-ready workforce for NP through each of the universities, laboratories, government agencies, and technology companies and startups that participate in them. The QCDC will, in turn, adapt to and benefit from newfound expertise in the expanding QIS-ready workforce.

With the expectation of mutual benefit, we recommend strengthening the QIS and QC expertise in the NP workforce.

NP could develop this workforce with activities including the following:

- Annual summer schools and training programs in QIS and QC for NP;
- Annual conferences focused on QIS, QC, and NP to be established by the community;

- Graduate fellowships that partner students with advisory teams of scientists, engineers, and/or developers from universities, national laboratories or other government agencies, and technology companies and startups;

- Recruitment of postdoctoral fellows with expertise in QIS or QC to focus on NP research;

- Bridge positions in NP for junior scientists, engineers, and developers with expertise in QIS or QC;

- Visiting scholar positions to encourage engagement among the NP, QIS, and QC communities and to foster community building and early collaborations;

- Enlargement of the scope of the SciDAC program, or establishment of analogous programs, to provide support for junior scientists, engineers, and developers with expertise in QIS and/or QC to work with NP scientists toward achieving NP objectives.

Figure 7.1: Conferences and workshops that bring together scientists, engineers, and developers in NP, QIS, and QC and other domain sciences play an important role in the cross-pollination of concepts and technologies. | *Photograph from the Microsoft PhD Summit, October 28–30, 2018, which was held in Seattle. Permission to reproduce their photograph was given by Natalie Klco (INT/University of Washington) (foreground left) and Valerie Taylor (ANL) (foreground right).*

7.5 Comment 1: Quantum Co-Development Consortia and National Quantum Information Science Activities

QIS research is fundamentally interdisciplinary, and cross-pollination will be critical to serve the needs of the US. We envisage the NP QCDC as serving the needs of the NP community and providing vehicles to accelerate advances in NP, QIS, and QC in mutually beneficial ways. They could serve as natural conduits enabling integration of the NP-QIS activities, at the appropriate level, with the nation's larger-scale QIS effort. We strongly encourage the funding agencies to facilitate, as appropriate, these connections between NP and the anticipated NQI centers. Individual investigators from NP participating actively in the centers will enhance the integration of NP QIS activities. We expect NP simulation and sensing activities, together with the corresponding workforce development, to benefit significantly from these connections. Further, applications of QIS and QC to address grand challenge problems in NP will be similar to their applications to problems in other domain sciences, such as HEP and BES, and therefore can both benefit from and aid advances in those areas.

7.5.1 What Might Quantum Co-Development Consortia Look Like?

QCDC structure could follow previous successful models of consortia formed by scientists and engineers in NP and other domain sciences. A multi-institutional and multidisciplinary structure with a well-defined mission statement is expected. The Subcommittee expects, and indeed encourages, that the organization and structure of the QCDC will be driven to optimize achievement of their scientific goals and to support the activities of their members. Implementation of a QC and simulation consortium might differ from one focused on quantum sensing. This report does not prescribe a structure for the QCDC, but the Subcommittee has outlined some guiding principles and anticipated attributes; some are independent of the scientific focus of the consortia, while others are specific.

7.5.2 Desirable Quantum Co-Development Consortia Characteristics

Here we draw from the successful community-wide structures such as the SciDAC projects, various mid-scale experimental collaborations, NSF Physics Frontiers Centers, and active DOE theory TCs. The QCDC should provide an interface through which the agencies communicate and engage with scientists, engineers, and developers in the NP community. As discussed earlier, we envisage that to-be-defined, close collaborative relationships among the QCDC and anticipated NQI centers will be of significant mutual benefit.

The QCDC may require an initial term of approximately 5 years to become firmly established. We think the community and the agencies should support a QCDC only throughout the period in which it continues to accelerate advances in NP, QIS, and QC.

The QCDC should identify both near-term and longer-term research and engagement priorities, along with a strategy to achieve them. The QCDC should be able to respond dynamically to new opportunities on appropriate timescales and to capitalize on expertise in the growing QIS workforce. A QCDC would require a formal management structure, agreed-on bylaws, and metrics that define success. We anticipate that QCDC will address NP grand challenges, host relevant workshops, provide workforce training opportunities, and support mid- and long-term visiting arrangements for consortium members. They should enable researchers to carry out nimble and flexible small-to-medium-scale explorations, as well as larger, production-scale activities.

Possible science-specific attributes might include the following:

- Quantum sensing–focused consortia are likely to benefit from infrastructure for device fabrication and testing. This cross-community topic should draw from disciplines well outside traditional NP groups.

- For QC and simulation consortia, we can imagine that providing access to cloud-based QC platforms at technology companies and startups and to test beds at national laboratories will be critical. They are expected to be important in providing pathways to effect quantum device design that can result in useful platforms for NP quantum computation.

7.6 Comment 2: The Nuclear Physics Community

Although NP can utilize and contribute to QIS and QC, future progress will depend critically on developing and sustaining a QIS-ready NP workforce. This will necessarily require establishing clear career paths for junior scientists, engineers, and developers that include, for example, leadership opportunities in support of promotion. The multidisciplinary nature of QIS and QC suggests that challenges to a successful career path in this area will be similar to those encountered by researchers in other multidisciplinary areas. Lessons from the past may therefore be helpful as the community builds the NP quantum ecosystem and grows a QIS-ready NP workforce.

We expect it to be beneficial for workforce development in this area if APS journals, particularly *Physical Review C* and other NP-related journals, broaden their scope to consider manuscripts for publication describing the results of research in QIS and QC for NP programs. Without a path to the publication of research results in journals and conference proceedings, hiring and promoting university faculty and national laboratory staff may be hampered.

A sustained QIS-ready workforce in NP is likely to require additional mechanisms to encourage universities, in particular, to hire scientists, engineers, and developers with expertise at the interface of QIS, QC, and NP into junior faculty positions and to keep in mind the complications of multidisciplinary efforts in promotion. This may include bridge positions that are joint between national laboratories and universities, or involve the emerging mechanism of partnerships with technology companies and startups. Such mechanisms will be crucial in retention and in sustaining a vital "vertical" workforce. We should find funding for these and other mechanisms to enable a clear career path from the undergraduate through the senior ranks, including leadership opportunities at the junior levels.

QIS is a field that is developing quickly and in fascinating ways. We think that for NP connections to QIS to develop in the most effective and coherent manner, we must evaluate our investment choices on a regular basis. This is particularly important because of the speed with which QIS is developing. We suggest that a committee of community members be charged with such review as a part of the commitment to move forward with programs to support this endeavor.

As stated earlier, the stakeholders of NP and QIS together should consider the following items:

- APS journals, particularly *Physical Review C* and other NP-related journals, should broaden their scope with regard to QIS.

- Universities and laboratories should be encouraged to hire scientists, engineers, and developers with expertise at the interface of QIS, QC, and NP into early-career positions that have long-term career opportunities.

- The NP community should organize summer schools, workshops, conferences, focused meetings, and other in-person and virtual venues for researchers to gather and learn from one another.

- Universities, together with national laboratories, and other government agencies should be encouraged to engage with technology companies and startups. To maximize the impact, special attention to intellectual property, perhaps involving conceptually new frameworks, will be required.

- Development and/or upgrade of undergraduate and graduate courses in NP to include QIS and QC should be encouraged by providing resources for university faculty.

- Engagement among the NP, QIS, and QC communities should be encouraged by making available visiting scholar positions to foster the early collaborations needed to build this community.

- DOE and NSF should consider forming an NSAC subcommittee to regularly evaluate the progress of QIS and QC efforts within the NP community. Such a committee could be empowered to recommend actions and investments to NSAC and to the broader NP community to optimize NP QIS and QC efforts.

7.7 Comment 3: Future-Proofing Quantum Computing and Simulations

One of the issues we think needs much more scrutiny and deliberation is that of "future-proofing." Currently, technology companies and startups are pushing ahead in the development of hardware and software for QC. They are providing access through both open and restricted hubs, through proposals, through connections with universities or national laboratories, or through a combination of these. DOE ASCR, and NSF are establishing quantum test beds that, as part of their mission, will provide domain scientists access to their quantum devices. Such devices will likely evolve rapidly in the near future, posing opportunities and challenges for the scientists and engineers using them.

One issue to consider is reliance on access to quantum devices located and operated at technology companies and startups. Whereas NP will likely benefit from active connections to such companies, there is significant risk to the NP scientific mission in relying on technology companies and startups to provide sustained access and high-quality support. Given the success of DOE and NSF in providing HPC resources to scientists through large-scale facilities and smaller community clusters at "computationally inclined" universities, it may be helpful to explore a similar infrastructure for quantum resources.

NP has played an active role in the development of HPC and has ongoing needs to support its own medium-scale HPC resources, beyond those made available by ASCR, as discussed in the 2015 LRP. There is no strong motivation for NP to develop specific QC resources in isolation from other efforts in DOE and NSF, but there probably are motivations to develop some complementary quantum capabilities to address problems specific to NP. This issue has broader ramifications. The NP research program should generally avoid single points of failure in growing its quantum ecosystem (e.g., points that are associated with significant reliance on technology companies and startups) but should not expend resources to duplicate efforts within DOE and NSF. The previous discussions suggest that many aspects of the QC and simulation ecosystem will resemble those in the HPC ecosystem. Therefore, we see compelling reasons for the NP community and agencies to start preparing to provide QC resources to the community, along with the open-source software and tools with which to use them, following the successful HPC model for providing resources.

7.8 Comment 4: Developing the Quantum-Ready Workforce

The challenge of creating a workforce to support a significant research sector, and possibly a significant technology sector, is substantial. Although a strong thread of many-body quantum mechanics runs through NP—a natural advantage—as discussed previously, NP is relatively new to the QIS and QC fields. As a community, NP should consider how to take advantage of this background to support the broader effort that is only now starting. If this workforce development is to be successful, it is likely to include a number of key aspects. There will be an initial need to invest in mechanisms to bring PhD students, postdoctoral fellows, and professional scientists, engineers, and developers who are new to the QIS and QC fields up to speed—hence our recommendations of conferences, workshops and summer schools. Programs must follow to support graduate students and postdoctoral fellows to pursue the type of typically interdisciplinary projects necessary to advance the fields.

An important aspect of all these activities will be the interface with the technology companies and startups that are currently playing an important role in advancing QIS and QC. NP should consider how best to support this emerging interface, for example, through the QED-C led by NIST/SRI International.

In the slightly longer term, it would be beneficial for the community to be actively engaged in helping their institutions develop classes and programs for a variety of educational purposes. We teach quantum mechanics to physics undergraduates, but few learn the quantum mechanics of QC and simulation or of quantum devices. There will be an increasing demand for courses like, for example, Quantum Physics for Electrical and Computer Engineering and Computer Science; conversely, there are likely to be aspects of computing and devices that would be beneficial for physics undergraduates contemplating a future in the QIS and QC fields. Further, there is likely to be increasing demand from professionals in the technology and/or business sectors for master's degrees in the QIS and QC space. Strong connections to the national QIS program, including the anticipated NQI centers, will enhance the effectiveness of these educational efforts. Given the welldocumented difficulty of becoming comfortable and proficient with quantum mechanics, this classroom component alone will present a challenge to our collective communities.

The fields of QIS and QC are in many ways defined by new thinking. It is difficult to overstate the importance of bringing young people into the field to create and explore the new ideas that will be required. At the same time, we must take care to ensure this workforce development sequence is whole, from educating undergraduates, to nurturing young professionals and researchers, to establishing fulfilling permanent positions.

8. Glossary of Terms

Bloch sphere: A geometrical representation of the pure state space of a qubit (named after Felix Bloch).

Complexity class: The set of all computational problems that can be solved with given computational resources. For example, complexity class **P** contains decision problems that can be solved with a polynomial amount of deterministic Turing machine compute resource. **NP** contains problems that can be solved with a polynomial amount of non-deterministic Turing machine compute resource, and with solutions that are verifiable with polynomial resources by a deterministic Turing machine.

Consortium: An association of two or more individuals, companies, organizations or governments (or any combination thereof) with the objective of participating in a common activity or pooling their resources for achieving a common goal. [*Wikipedia*]

Dilution refrigerator: A refrigerator in common use in quantum computing and sensing applications that relies on both the binding energy of ^{3}He in (superfluid) ^{4}He and the larger zero point motion of ^{3}He that enhances its evaporation rate relative to that of ^{4}He. Typical operating temperatures can range from a few to a few 10s of milliKelvin.

Entanglement: A phenomenon that occurs when particles are generated or interact in ways such that the quantum state of each particle is not independent and cannot be separated from the others. In particular, if the quantum state of one particle is determined by measuring it, doing so modifies the quantum states of one or more other particles.

Eigenvalues and eigenvectors: A linear operator **A,** has eigenvectors **x** and eigenvalues **λ** such that **A x= λ x**, where the multiplication by **λ** corresponds to a rescaling of the vector **x.**

Error correction: See quantum error correction.

High performance computing (HPC): Current and future classical supercomputers.

Hubbard Model: The Hubbard model provides insight, through model forces, into how the interactions between electrons can give insulating, magnetic, and even superconducting effects in solids. Its Hamiltonian consists of a hopping term and a number-density local-interaction term.

Jordan-Wigner transformations: These transformations map fermion annihilation and creation operators defining one-dimensional systems onto strings of spin operators.

Kinetic inductance: The manifestation of the inertial mass of mobile charge carriers in alternating electric fields as an equivalent series inductance. Kinetic inductance is observed in high carrier mobility conductors (e.g., superconductors) and at very high frequencies. [*Wikipedia*]

Lepton number: The number of leptons (electrons, muons and taus, and corresponding neutrinos) minus the number of anti-leptons (positrons, anti-muons, anti-taus, and corresponding anti-neutrinos).

Logical qubit: An effective two-level system, formed from individual *physical* qubits, which mitigate certain types of decoherence by quantum error correction mechanisms.

Majorana qubit: Majorana fermions are their own antiparticles. In condensed matter, topological insulators provide an environment to support Majorana modes, with, for example, localized support at either end of a one-dimensional system, enabling the storage of information at two separated locations.

Measurement-based quantum computing: A method of QC that first prepares an entangled *resource state*, usually a cluster state or graph state, then performs single qubit measurements on it. It is "one-way" because the resource state is destroyed by the measurement. [*Wikipedia*]

Minimum noise limit: The least amount of noise in a signal that is set by quantum mechanics.

Neutrino: A weakly interacting, electrically neutral, spin-half particle, denoted by ν.

Neutrinoless double-beta (0νββ) decay: A nuclear process in which two neutrons transform into two protons and two electrons without associated neutrinos, explicitly violating lepton number.

Optical lattice: Interference of oppositely propagating laser beams that creates a spatially periodic modulation of energy density in the electromagnetic field. This pattern can be used to trap atoms by their interaction with the light.

Physical qubit: A single quantum object employed as a qubit. See "logical qubit."

Quantum 1.0: A quantum sensor that relies on measuring an object or property related to quantization (e.g., energy or angular momenta) such as a single photon, or on quantum tunneling (as in, for example, a scanning tunneling microscope or an atomic force microscope).

Quantum 2.0: A quantum sensor that makes use of superposition of states (coherence) and/or entanglement in performing a measurement.

Quantum advantage (for an application): The situation when a quantum device can provide a faster time to solution of an application than any classical computer using any algorithm.

Quantum chromodynamics (QCD): An asymptotically free, confining quantum field theory constructed in terms of quarks and gluons. When combined with the standard model of electroweak interactions, it is responsible for the nature and dynamics of nucleons and nuclei.

Quantum circuit: A sequence of quantum gates, which together combine to complete a useful calculation. Usually the final step of a quantum circuit is measurement of the qubit states, which collapses the wave function and gives the desired solution with a certain probability. Besides this measurement step, quantum circuits are generally equivalent to a unitary many-body operation and are therefore reversible.

Quantum computer: A device that uses superposition and entanglement of qubits or qudits to perform some calculation. A *digital* quantum computer uses some defined set of discrete quantum gates to accomplish this, while an *analog* quantum computer utilizes more general kinds of interactions.

Quantum decoherence time: The timescale over which the information in a quantum system is lost.

Quantum error correction: An approach to protecting quantum information by distributing it among many qubits in a way that makes it robust against *specific* kinds of errors, such as a phase error or a spin flip. The *threshold theorem* proves that a computation of arbitrary length is possible with quantum error correction, provided the single-step error rate is below a certain threshold. Quantum error correction is generally considered indispensable for future complex quantum computations, although simple and noisy calculations are routinely performed without it today.

Quantum gate: The basic element of a quantum circuit. Its function is to perform a unitary operation on a small number of qubits, usually one or two. By operating on more than one qubit, a quantum gate is able to transform the system into a state where the individual qubit states are not separable, and therefore entangled.

Quantum information science (QIS): "A field of science and technology that combines and draws on the disciplines of physical science, mathematics, computer science, and engineering. Its aim is to understand how certain fundamental laws of physics discovered earlier in this [sic] century can be harnessed to dramatically improve the acquisition, transmission, and processing of information." (*NSF report from QIS workshop, 1999)*

Quantum sensor: "Quantum sensor" encompasses a rather broad area of devices and techniques used to perform measurements of physical quantities of interest. Although the exact definition is somewhat elusive because of the pervasive nature of these devices, quantum sensing is often used to describe methods that use (a) quantum properties (e.g., energy levels or angular momenta), (b) superposition of states (i.e., coherence), or (c) entanglement to measure a desired physical quantity. [C. L. Degen, F. Reinhard, and P. Cappellaro, *Quantum sensing*, Rev. Mod. Phys. **89**, 035002 (2017)].

Quantum superposition: Quantum states can be added to produce another valid quantum state and, conversely, a quantum state can be decomposed into a sum of valid quantum states. In particular, if a certain measurement on a qubit can yield only two possible outcomes, call them 0 and 1, this does not mean that the qubit can be in only one or the other of these states. The possible quantum states of a qubit include any superposition of the 0-state and the 1-state, with the particular quantum state determining the probability of measuring a 0-state or a 1-state.

Qubit: A unit of quantum information, the quantum analogue of the classical bit. A qubit is any two-state quantum-mechanical system in which the specifics of the physical system used are merely incidental to QC. Examples of a physical representation include the polarization states of a single photon or the spin-states of a spin-1/2 fermionic system. For a qubit to be useful to quantum computation, it must be possible to measure each qubit's state, perform controllable state rotations, and create controllable interactions between qubits.

Qudit: A unit like a qubit, but with more than two states. There are various proposals for how such a system might provide benefit compared with qubits, although any computation possible with some qudits is, in principle, computable with a larger number of qubits.

Rydberg atom: A highly excited atom with valence electron energy near the ionization threshold. These atoms have several potentially useful properties for quantum sensing, including large electric polarizability.

Superconducting nanowire single photon detector (SNSPD): A microcalorimetric device that uses the runaway breakdown of a superconducting phase transition to detect very low-energy photons. They have excellent detection efficiency and timing resolution but no energy resolution.

Squeezed state: State that occurs when the noise in one variable is reduced below the symmetric limit at the expense of the increased noise in its conjugate variable, so that the Heisenberg uncertainty relation remains satisfied.

Superconducting quantum interference device (SQUID): A sensitive magnetometer able to measure extremely small changes in magnetic fields. It is formed from a superconducting loop using Josephson junctions.

Transition edge sensor (TES): A device that utilizes the rapid temperature variation of the conductivity of metals near a superconducting phase transition.

Topological quantum computing: A way to store and manipulate quantum information using QPs with (effectively) fractional spin.

Trotterized time evolution: An adiabatic way to evolve quantum states forward in time through the repeated application of a unitary operator that, generally, is close to the identity operator.

Unitary Fermi gas: An idealized finite density system consisting of fermions that have zero-range interactions but an infinitely large two-body scattering length.

Universal quantum computer: A quantum computer that implements a complete set of universal quantum gates and is therefore capable of executing, in principle, any quantum algorithm. A universal quantum computer does not necessarily implement quantum error correction.

Universal gate set: A selection of quantum gates that is sufficient to execute any unitary operation on a collection of qubits in a finite number of steps (with arbitrary precision). There are many known universal gate sets, which are usually chosen to best match the physical qubit implementation.

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This bibliography is provided as a guide to the current literature related to this report. It is not comprehensive or complete. It contains duplications in cases where references are relevant to two or more sections.

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We would also like to thank the **Double-Tree Hilton in Bethesda, Maryland,** and the **Faculty Club at the University of Washington** for providing pleasant venues for the Subcommittee's information-gathering meetings.

Appendix A: Members of the NSAC QIS Subcommittee

Douglas Beck	University of Illinois at Urbana-Champaign
Amber Boehnlein	Thomas Jefferson National Accelerator Facility
Joseph Carlson	Los Alamos National Laboratory
David Dean	Oak Ridge National Laboratory
Matthew Dietrich (co-chair)	Argonne National Laboratory
William Fairbanks, Jr.	Colorado State University
Joseph Formaggio	Massachusetts Institute of Technology
Markus Greiner	Harvard University
David Hertzog (NSAC chair)	University of Washington
Christine Muschik	University of Waterloo
Jeffrey Nico	National Institute of Standards and Technology
Alan Poon	Lawrence Berkeley National Laboratory
John Preskill	California Institute of Technology
Sofia Quaglioni	Lawrence Livermore National Laboratory
Krishna Rajagopal	Massachusetts Institute of Technology
Martin Savage (chair)	Institute for Nuclear Theory and University of Washington

Back Row, L to R: Krishna Rajagopal, Douglas Beck, David Hertzog, Joseph Carlson, David Dean, Matthias Dietrich, Markus Greiner, William Fairbanks, Jr., and Jeffrey Nico.
Front Row, L to R: Alan Poon, Joseph Formaggio, Sofia Quaglioni, Amber Boehnlein, John Preskill, Christine Muschik, and Martin Savage.

Appendix B: Agenda of Meeting 1

NP Exploration of the Quantum Landscape
March 28–29, 2019
Doubletree Hotel, Bethesda, Maryland

Day 1 (Thursday, March 28)

08:00 – 08:30	Executive Session
08:30 – 09:00	Welcome and Subcommittee Orientation **Timothy Hallman (DOE), David Hertzog (UW), Martin Savage (INT and UW)**
09:00 – 09:35	OSTP/NSTC National Strategic Overview for QIS and QC **Jake Taylor (OSTP)**
09:35 – 10:10	The National Quantum Initiative Act **David Dean (Oak Ridge National Laboratory)**
10:10 – 10:35	Coffee Break
10:35 – 11:05	QIS and QC Perspective from NSF **Anne Kinney (NSF)**
11:05 – 11:40	QIS and QC Perspective from NIST **Carl Williams (NIST)**
11:40 – 12:15	QIS and QC Perspective from DOE **Steve Binkley (DOE)**
12:15 – 13:30	Working Lunch
13:30 – 14:05	Overview of the HEP QIS and QC Report **Maria Spiropulu (California Institute of Technology)**
14:05 – 14:40	Overview of the BES QIS and QC Report/Zoom **Giulia Galli (University of Chicago)**
14:40 – 15:15	Overview of the NAS QC Report **Mark Horowitz (Stanford University)**
15:15 – 15:35	Coffee Break
15:35 – 16:10	Overview of the Nuclear Physics QIS and QC Workshops at INT and ANL **Mathew Dietrich (Argonne National Laboratory)**
16:10 – 17:30	Executive Session
17:30	Adjourn Day 1

Day 2 (Friday, March 29)

8:15 – 8:45	An Overview of QIS and QC Programs in Europe/Zoom **Tommaso Colarco (Forschungszentrum Juelich)**
8:45 – 9:15	An Overview of QIS and QC Programs in China/Zoom **Jian-Wei Pan (University of Science and Technology of China)**
9:15 – 9:45	An Overview of QIS and QC Programs in Canada **David Cory (University of Waterloo)**
9:45 – 10:05	Coffee Break
10:05 –10:35	QIS and QC Interest of Laboratories in the Northeast **Eden Figueroa (Stony Brook University and Brookhaven National Laboratory)**
10:35 –11:05	QIS and QC Interest of Laboratories in the Midwest/Zoom **Salman Habib (Argonne National Laboratory)**
11:05 –11:35	QIS and QC Interest of Laboratories in the West Coast **Irfan Siddiqi (University of California Berkeley)**
11:35 –12:05	QIS and QC Interest of Laboratories in the Southeast **David Dean (Oak Ridge National Laboratory)**
12:05 – 13:30	Working Lunch
13:30 – 14:00	Overview of ASCR QIS and QC Programs **Barbara Helland (DOE–ASCR)**
14:00 – 14:30	Overview of NP QIS and QC Programs **Timothy Hallman (DOE–NP)**
14:30 – 15:00	Isotopes for QIS and QC **Joel Grimm (DOE–NP)**
15:00 – 15:20	Coffee Break
15:20 – 16:20	Executive Session
16:20	Adjourn Meeting

Appendix C: Agenda of Meeting 2

A Deep Dive
April 30–May 1, 2019
UW Club, Yukon Room, University of Washington, Seattle

Day 1 (Thursday, April 30)

08.00 – 08.30: Executive Session

08.30 – 09.00: Technology for EDM Detection **Matthew Dietrich (ANL)**

09:00 – 09.30: Superconducting Qubits for QIS and QC **Brent VanDevender (PNNL)**

09:30 – 10.00: Superconducting Cavities and QIS **Alexander Romanenko (FermiLab)**

10:00 – 10:30	Coffee Break

10:30 – 11:00: Quantum Electron Microscopy **Mark Kasevich (Stanford)**

11:00 – 11:30: Quantum Encryption and Quantum Communication
Christine Muschik (University of Waterloo)

11:30 – 12:00: Quantum Defects for Sensing and Computing, and Isotopic Purity
Xing Rong (University of Science and Technology in China)

12:00 – 12:30: Overview of Quantum Sensors **Joel Ullom (University of Colorado/NIST)**

12:30 – 13:30	Lunch

13:30 – 14:00: QIS and QC Interests of LANL, LANL and Sandia **Richard Muller (Sandia)**

14.00 – 14.30: Superconducting Nanowire Single-Photon Detectors and Transition Edge Sensors
Aaron Miller (Quantum OPUS)

14.30 – 15.00: Quantum Sensors in High-Sensitivity Experiments
Gray Rybka (University of Washington)

15:00 – 15:30	Coffee Break

15:30 – 16:45: **Technology Panel** on Engagement and Collaboration with Universities and Labs

45 minutes: presentations by each panel member (**15** minutes each), followed by

30 minutes of Q&A

Panelists: (1) D-Wave—**Eric Ladizinsky**, (2) Google—**Dave Bacon, (**3) IBM—**Jerry Chow**

16:45 – 18:30: Executive Session

18.30: **Adjourn Day 1**

Day 2 (Friday, May 1)

08.00 – 08.30: **Executive Session**

08.30 – 09.00: Quantum Simulation **Matthias Troyer (Microsoft)**

09:00 – 09.30: Atoms, and Engineering Challenges **Markus Greiner (Harvard)**

09:30 – 10.00: Ions, RF, and Optical Engineering—IonQ **Jungsang Kim (Duke/IonQ)**

10:00 – 10:30	Coffee Break

10:30 – 11:00: QIS and QC with Photons **Pavel Lougovski (ORNL)**

11:00 – 11:30: Qudits @ LLNL **Jonathan Dubois (LLNL)**

11:30 – 12:00: Theoretical Advances for QIS and QC **John Preskill (Caltech)**

12:00 – 12:30: Overview of Quantum Simulations for NP **David Kaplan (INT)**

12:30 – 13:30	Lunch

13:30 – 15:00: Subcommittee Deliberations

- Compile Subcommittee Comments
- Establish Findings for the Report

15:00 – 15:30	Coffee Break

15:30 –16.30: Subcommittee Deliberations

16.30 – 17.30: Formulate Draft Recommendations

- Finalize Report Writing Assignments

17.30: **Adjourn Day 2**

Appendix D: Charge to NSAC from DOE and NSF

U.S. Department of Energy
and the
National Science Foundation

October 29, 2018

Professor David Hertzog
Chair
DOE/NSF Nuclear Science Advisory Committee
Department of Physics
University of Washington
Seattle, Washington 98195

Dear Professor Hertzog:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a study to identify unique opportunities for U.S. nuclear physics research to contribute to advances in Quantum Computing and Quantum Information Science (QIS). In carrying out this study, NSAC should provide information assessing the relative importance and potential benefits of QIS to nuclear physics and the potential contributions that nuclear physics can make to QIS.

QIS research is playing an increasingly central role in the vision for the future of U.S. science and technology. Emerging QIS priority areas provide promising new avenues for addressing challenges of enormous complexity, including, for example dramatic extensions of the application of Quantum Field Theory to the analysis of physical systems at scale with heretofore intractably large numbers of degrees of freedom that cannot be addressed by conventional computing. In another area of rapid development, quantum entanglement in multi-particle states is opening new horizons in quantum sensing, quantum communication, quantum computing, and quantum simulations.

Decades of accumulated intellectual capital, extensive experience in interdisciplinary research, considerable technical infrastructure at labs and universities, and a long history of international leadership in collaborative research have positioned the DOE Office of Nuclear Physics and the NSF nuclear physics research programs to engage in QIS relevant research. However, QIS is newly emergent as a priority area for Research & Development (R&D) investment in nuclear science. Furthermore, private sector R&D investment in QIS, as well as investment by other Federal agencies, has been ongoing for some time. NSAC is therefore requested, in the context of Federal and private sector research efforts already underway, to articulate the unique role nuclear science research, aligned with the DOE and NSF nuclear physics programs, can and should play in Quantum Information Science. While unique, this role should nevertheless align broadly with the goals outlined in the national strategy for QIS[1].

[1] https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf

Please submit your report to DOE and NSF by summer of 2019. The agencies very much appreciate NSAC's willingness to undertake this task and anticipate that the information provided in this report will be important in guiding DOE and NSF nuclear physics investments in this newly emergent area for Federal R&D.

Sincerely,

J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Anne L. Kinney
Assistant Director, Directorate for
Mathematical and Physical Sciences
National Science Foundation

Appendix E: Charge to NSAC QIS Subcommittee from NSAC

DEPARTMENT OF PHYSICS
UNIVERSITY of WASHINGTON
College of Arts & Sciences

Box 351560
Seattle, WA 98195
Tel: 206-543-1493

January 9, 2019

Professor Martin Savage
Institute of Nuclear Theory
University of Washington

Dear Martin,

J. Stephen Binkley, Deputy Director for Science Programs at the Department of Energy, and Anne L. Kinney, Assistant Director of Mathematical and Physical Sciences at the National Science Foundation, have requested that NSAC form a Subcommittee to identify unique opportunities for the U.S. nuclear physics research community to contribute to advances in Quantum Computing (QC) and Quantum Information Science (QIS) and to identify potential benefits of QIS and QC to Nuclear Physics. Their charge letter is attached.

I am writing to formally ask you to serve as the Chair of this new NSAC Subcommittee, and to help me establish a broad and diverse membership having a collective expertise across a wide range of QIS and QC subjects. As you are well aware, Quantum Information Science – broadly defined – is now a high-priority, multi-disciplinary initiative within the U.S. science and technology community at large.

Significant funding opportunities have been enabled by recent legislation with the aim to widely distribute support to different specialty areas. In that context, your committee should develop guidance as to how the Nuclear Science community can most effectively contribute to the advancement of QIS; for example, one anticipates topics ranging from quantum computing for science applications to development of sensitive quantum sensors. These are areas for which U.S. nuclear scientists are already beginning to make valuable contributions. Your committee will likely need to host one or more information meetings with the aim of acquiring expert input and advice that will be folded into your report. To be most useful, NSAC would appreciate receiving your report by early Summer 2019.

I realize this is a heavy responsibility and a burden on your time and that of the Subcommittee. I, and our whole community, will owe you an enormous debt of gratitude.

Sincerely yours,

David W Hertzog,
Chair NSAC

Attachment: Charge Letter

National Science Foundation

U.S. DEPARTMENT OF ENERGY

Office of Science