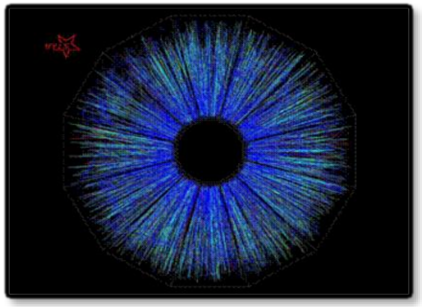
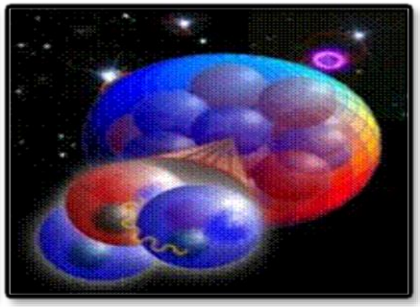
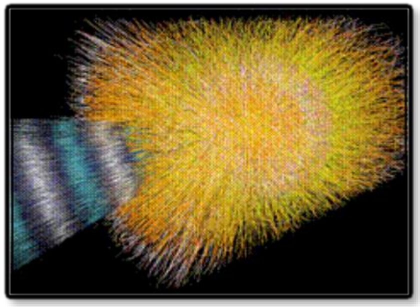
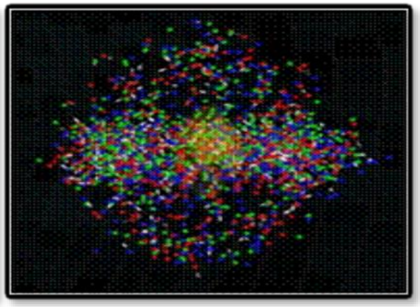
DOE/NSF QIS Charge to NSAC

November 2, 2018

Dr. Timothy J. Hallman
Associate Director for Nuclear Physics
DOE Office of Science

NSF & DOE SC/NP General Perspectives

The NSF PHY program that supports QIS is described at:

https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505446&org=PHY&from=home

and there are other programs outside of PHY. If something came in to the QIS (ENP) program that had a clear connection to ENP (QIS) and it reviewed well, it could possibly be considered for co-funding

"Quantum Information Science (QIS) supports theoretical and experimental proposals that explore quantum applications to new computing paradigms or that foster interactions between physicists, mathematicians, and computer scientists that push the frontiers of quantum-based information, transmission, and manipulation.

The quantum information science program is focused on investigations relevant to disciplines supported by the Physics Division, while encouraging broader impacts on other disciplines. Disciplines within the purview of the Physics Division include: atomic, molecular, optical, plasma, elementary particle, nuclear, gravitational and biological physics, particle astrophysics, and accelerator science.

Proposals with intellectual focus in areas supported by other NSF Divisions should be submitted to those divisions directly. Proposals that cross Divisional lines are welcome, but the Physics Division encourages PIs to request a co-review by naming other Divisional programs on the cover sheet. This facilitates the co-review and participation of other programs in the review process."

QIS/QC are Relatively New Areas of Interest and Investment Within DOE/SC/NP

QIS/QC Funding History in SC

Quantum Information Science						
	FY 2017	FY 2018	FY 2019			
	Enacted Approp.	Enacted Approp.	President's Request	House Mark	Senate Mark	Enacted
Quantum Information Science (non-add)						
Advanced Scientific Computing Research	5,801	20,609	33,507	33,507	33,666	33,666
Basic Energy Sciences	…	19,270	31,561	57,215	47,215	46,628
Biological and Environmental Research	…	4,500	4,500	4,500	4,500	4,500
Fusion Energy Sciences	…	…	…	…	…	…
High Energy Physics	…	18,000	27,500	27,500	27,500	27,500
Nuclear Physics	…	…	8,300	8,300	8,300	8,300
Total, Quantum Information Science (non-add)	5,801	62,379	105,368	131,022	121,181	120,594

Early FY 2018 NP QIS/QC Awards

Lead Insititution	PI	Title	Description
University of Washington	Martin Savage	Nuclear Physics Pre-Pilot Program in Quantum Computing	to support pre-pilot research activities that will begin to bring Quantum Computing (QC) and Quantum Information Science (QIS) expertise into the nuclear theory community, including starting to address scientific applications of importance for nuclear physics research. This pre-pilot proposal will organize the nuclear theory community at the national level in order to address Grand Challenge problems in nuclear physics through the use of QC and QIS.
MIT	Joseph Formaggio	Investigating Natural Radioactivity in Superconducting Qubits	to measure the impact of background radioactivity on qubit coherence times. MIT will be responsible for simulation of radiation transport models and development of calibration sources to be deployed in various qubit measurements. MIT will also coordinate this effort with Prof. William Oliver (MIT and Lincoln Labs). PNNL will be responsible for radioassay of materials using their calibrated measurement stations.
ANL	Ian Cloet	Quantum Simulators for Nuclear Physics: Theory	to support a postdoctoral fellow to work on the proposal for Quantum Simulations for Nuclear Physics. This pilot effort will begin to develop the expertise and knowledge that builds toward a QCD simulations on Quantum Computers and Analog Quantum Simulators.
ANL	Valentine Novosad	Superconducting Quantum Detectors for Nuclear Physics and QIS	to work on the proposal for Superconducting Quantum Detectors for Nuclear Physics and QIS.
LLNL	Stephan Frederich	Thorium 229mTh	to study of the feasibility of suppressing the internal conversion transition of 229mTh by implanting it in high band gap materials such as MgF2

FY 2018 Awards Made Through Annual Solicitation: Dr. Gulshan Rai, NP PM

NSAC Charge on QIS/QC

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.

NSAC Charge on QIS/QC

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].

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

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

NP is looking to avoid:

Re-inventing the Wheel

Turning into the “Office of Quantum Information Science”

Re-labeling Existing NP Research Scope as QIS/QC

The National Science and Technology Council

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Ted Wackler, Deputy Chief of Staff and Assistant Director, Office of Science and Technology Policy

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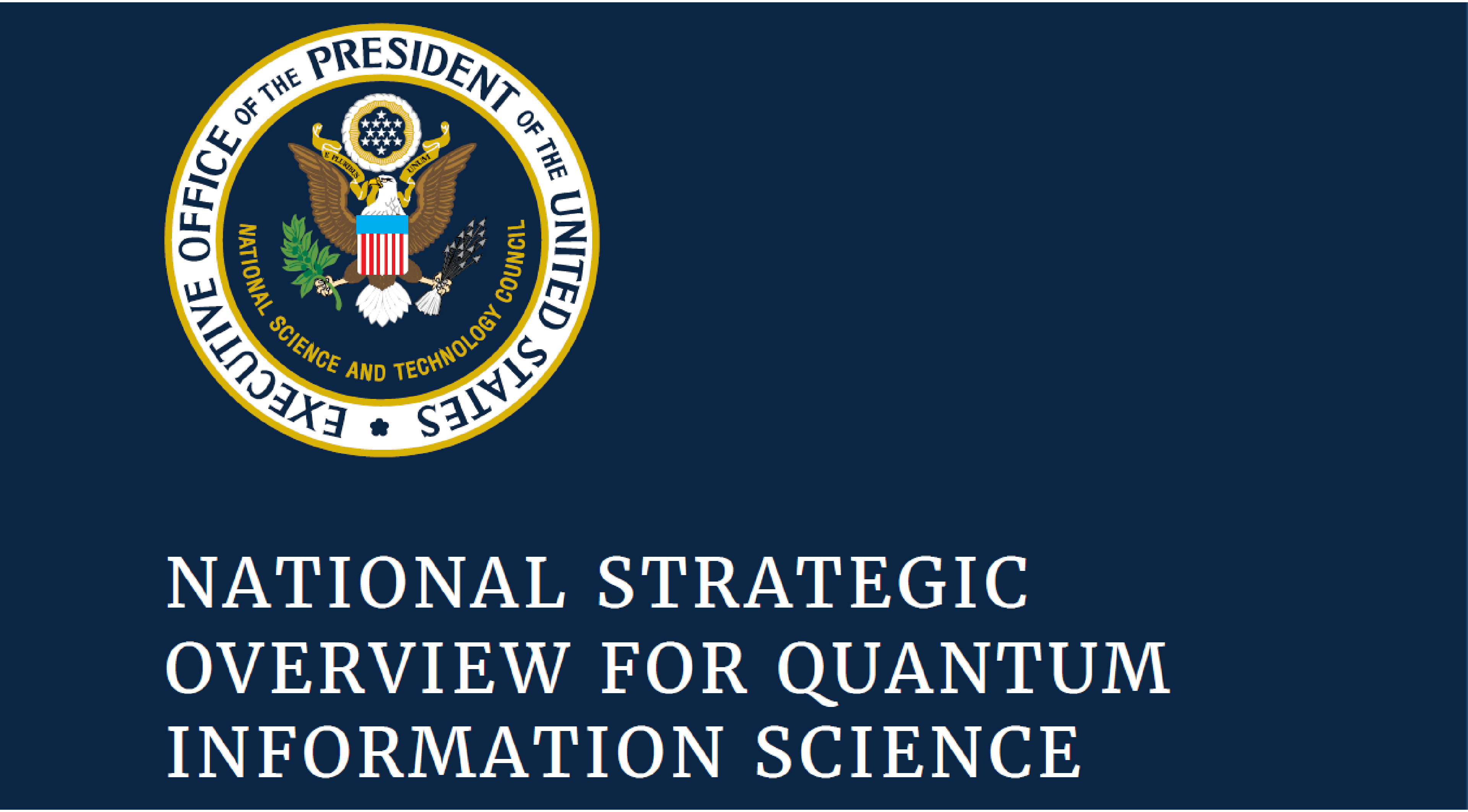

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

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Timothy Petty, DOI

Nathaniel Schaefle, State

1 Quantum information science: the next technological revolution

Quantum information science (QIS) applies the best understanding of the sub-atomic world—quantum theory—to generate new knowledge and technologies. Through developments in QIS, the United States can improve its industrial base, create jobs, and provide economic and national security benefits. Prior examples of QIS-related technologies include semiconductor microelectronics, photonics, the global positioning system (GPS), and magnetic resonance imaging (MRI). These underpin significant parts of the national economic and defense infrastructure. Future scientific and technological discoveries from QIS may be even more impactful. Long-running U.S. Government investments in QIS and more recent industry involvement have transformed this scientific field into a nascent pillar of the American research and development enterprise. The Trump administration is committed to maintaining and expanding American leadership in QIS to enable future long-term benefits from, and protection of, the science and technology created through this research. Based on the collective input of all the Government agencies invested or interested in QIS, this document presents a national strategic approach to achieving this goal.

Specifically, the United States will create a visible, systematic, national approach to quantum information research and development, organized under a single brand and coordinated by the National Science and Technology Council's (NSTC) Subcommittee on Quantum Information Science (SCQIS). These efforts will leverage existing programs and approaches, adapt to the changing and improving scientific and technical knowledge, reflect the best understanding of opportunities and challenges in QIS for the Nation, and take new steps where appropriate. The national effort will:

NSTC Strategic Overview for Quantum Information Science

- Focus on a science-first approach that aims to identify and solve Grand Challenges: problems whose solutions enable transformative scientific and industrial progress;
- Build a quantum-smart and diverse workforce to meet the needs of a growing field;
- Encourage industry engagement, providing appropriate mechanisms for public-private partnerships;
- Provide the key infrastructure and support needed to realize the scientific and technological opportunities;
- Drive economic growth;
- Maintain national security; and
- Continue to develop international collaboration and cooperation.

The key next step will be to develop agency-level plans that address the identified approaches and policy opportunities in the next section, which will be integrated into an overall strategic plan. This will enable new opportunities on a ten-year horizon, possibly including: the development of quantum processors which may enable limited computing applications; new sensors for biotechnology and defense; next-generation positioning, navigation, and timing systems for military and commercial applications; new approaches to understanding materials, chemistry, and even gravity through quantum information theory; novel algorithms for machine learning and optimization; and transformative cyber security systems including quantum-resistant cryptography in response to developments in QIS.

Additional Information

Quantum Information Science (QIS) in the DOE Office of Science (SC)

QIS is a thriving area of multidisciplinary science.

- It exploits particular quantum phenomena to measure, process, and transmit information in novel ways that greatly exceed existing capabilities.

QIS provides a basic foundation for numerous application areas.

- Potential transformative impact on SC grand challenges.

QIS is at a tipping point.

- Major companies are embracing QIS, foreign competition is expanding rapidly. Next-Generation advances will require new understanding of fundamental science.

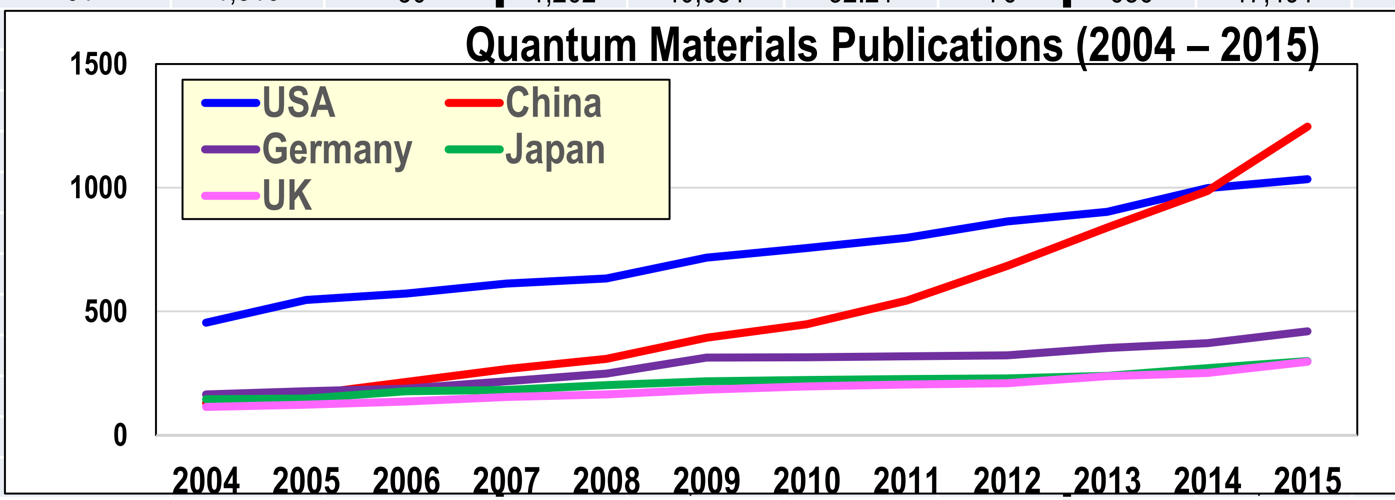
Progress in QIS is driven by basic research in physical sciences.

- DOE SC is the Nation's leading supporter of basic research in physical sciences.

Growth in Interest and Investment in QIS/QC has Been Dramatic

Quantum Materials & Quantum Chemistry: Web of Science Stats (2004 – 2015)

				Quantum Materials				Quantum Chemistry			
Country	Population (M)	GDP ($B)	GDP/PC ($K)	# papers	Total Citations	Avg. Citations	h-index	# papers	Total Citations	Avg. Citations	h-index
USA	322	18,036	56	8,887	435,947	49.05	266	4,459	173,140	38.06	163
China	1,373	11,182	8.1	6,225	157,889	25.36	155	2,709	48,366	17.85	90
Germany	82	3,365	41	3,406	107,079	31.44	135	2,029	72,044	35.51	100
Japan	127	4,124	32	2,559	72,391	28.29	115	851	17,397	20.44	57
UK	65	2,858	44	2,259	114,171	50.54	113	904	42,342	46.84	79
France	64	2,420	38	1,867	60,317	32.31	92	1,192	40,733	34.17	75
India	1,292	2,073	1.6	1,614	25,417	15.75	64	710	10,471	14.75	40
South Korea	51	1,378	27	1,515	42,562	28.09	81	255	9,625	37.75	41
Italy	61	1,816	30	1,262	40,651	32.21	76	686	17,491	25.5	59
Canada										2.79	58
Russia										0.72	37
Spain										4.14	58
Taiwan										3.28	30
Switzerland										1.18	56
Australia										9.58	43
Poland										6.31	36
Netherlands										7.09	47
Sweden										0.44	50
Brazil										4.11	27
Singapore										7.21	25
Belgium										2.11	41



Quantum Information Science and the Office of Science

SC Tools, Equipment, Instrumentation for QIS

Quantum Computing Hardware

ASCR's Testbeds Program:
- Research into device architectures and system integration optimized for science applications
- Development of hybrid platforms and quantum/classical coprocessors
- Early access to new quantum computing hardware for the research community

Tool R&D for QIS

- Extensive nanoscience tools for quantum structure synthesis and integration
- Detectors and metrology
- Quantum sensors enabling precision measurements
- Quantum computational tools
- Superconducting RF cavities, laser cooling, neutral ion traps, spin manipulation technology, and isotope production

Key DOE-SC Contributions:

- Well-established co-design practices in computer hardware development
- History of fundamental research leading to prototype devices, characterization and synthesis tools, and techniques
- Experience in collaborations with industry and core competencies in delivering major projects involving equipment, tools, and instrumentation for discovery and implementation
- Demonstrated success in generating leading scientific tools with and for the international user community

Fundamental Science That Advances QIS

ASCR	BES	HEP	NP
Quantum algorithms; uncertainty quantification and verification & validation methods; software stack; quantum networks	Synthesis, characterization, theory, modeling, and instrumentation to advance quantum materials & chemical phenomena	Black hole physics; quantum gravity and quantum error correction; fundamental aspects of entanglement	Isotopes; trapped ions for quantum devices; lattice quantum chromodynamics; fundamentals of nuclear spin-based

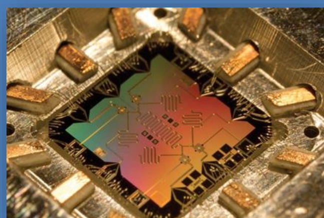
Quantum Field Theory and Topology

Control of Quantum Phenomena

SC Unique Strengths

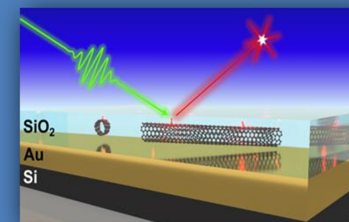
- Intellectual capital accumulated for more than a half-century
- Successful track record of forming interdisciplinary yet focused science teams for large-scale and long-term investments
- Demonstrated leadership in launching internationally-recognized SC-wide collaborative programs

Sensing and Microscopy



Superconducting qubit sensors for x-ray spectroscopy. As sensors improve, single-photon detection may become possible at far infrared and microwave wavelengths.

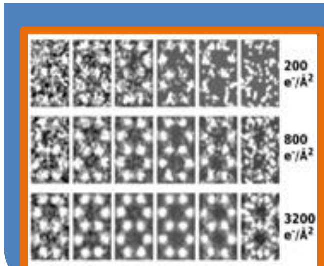
Nanostructured single photon emitters and detectors could be integrated for sensing, communications, and computing systems at room temperature.



Quantum sensors to perform dynamic, non-invasive visualization of subcellular biological processes

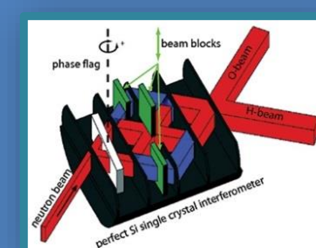
Cross-Cutting Applications in BER, BES, HEP, NP

Quantum devices for environmental sensing in field settings for integrating multi-model and multi-scale data (e.g. quantum lidar)



Quantum electron microscope for high resolution at very low doses for imaging of sensitive materials

Single photon detectors can expand the range of discovery for dark universe, non-Newtonian gravity, and new forces. Quantum error correction reduces noise in matter wave interferometry for such searches.



Fundamental Science That Advances QIS

SC will leverage the groundwork already established in DOE National Labs and the academic groups to maximize SC's impact on QIS. Examples include:

In April 2017, the researchers have successfully run the largest ever simulation of a quantum computer at NERSC, LBNL. The simulation was made possible by the performance boost gained through the use of Roofline model during the optimization process. The Roofline model was developed by SciDAC Institutes; a flagship ASCR program.

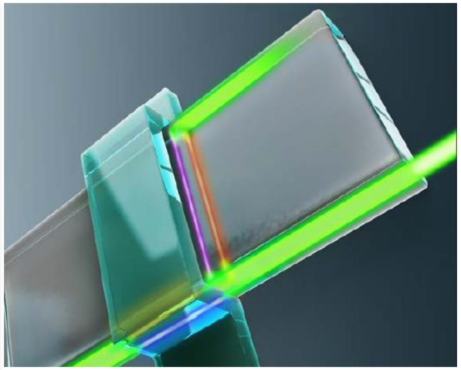
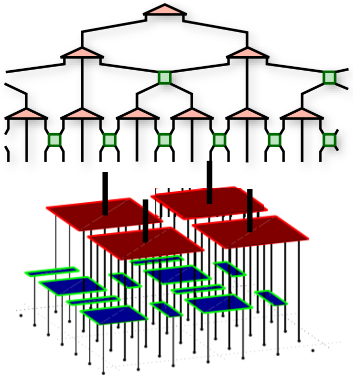
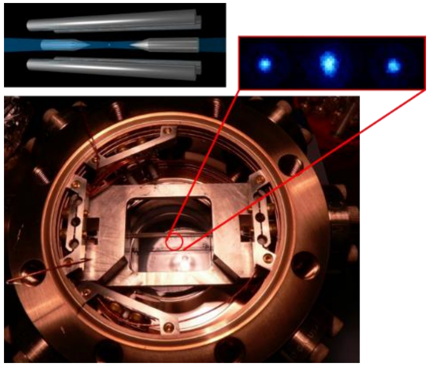


Illustration of a topological insulator with a superconducting layer on top for detection of Majorana fermions (colored lines). Once identified and isolated, Majorana fermions could form the basis of qubits. Electrons (green) travel along the edges of the structure. Supported in part by the BES Energy Frontier Research Center (EFRC) program.



Tensor networks are a key theoretical tool for understanding entanglement, topological order, and other aspects of quantum systems. They comprise a broad family of techniques (2D Multi-scale Entanglement Renormalization Ansatz (MERA) shown here).

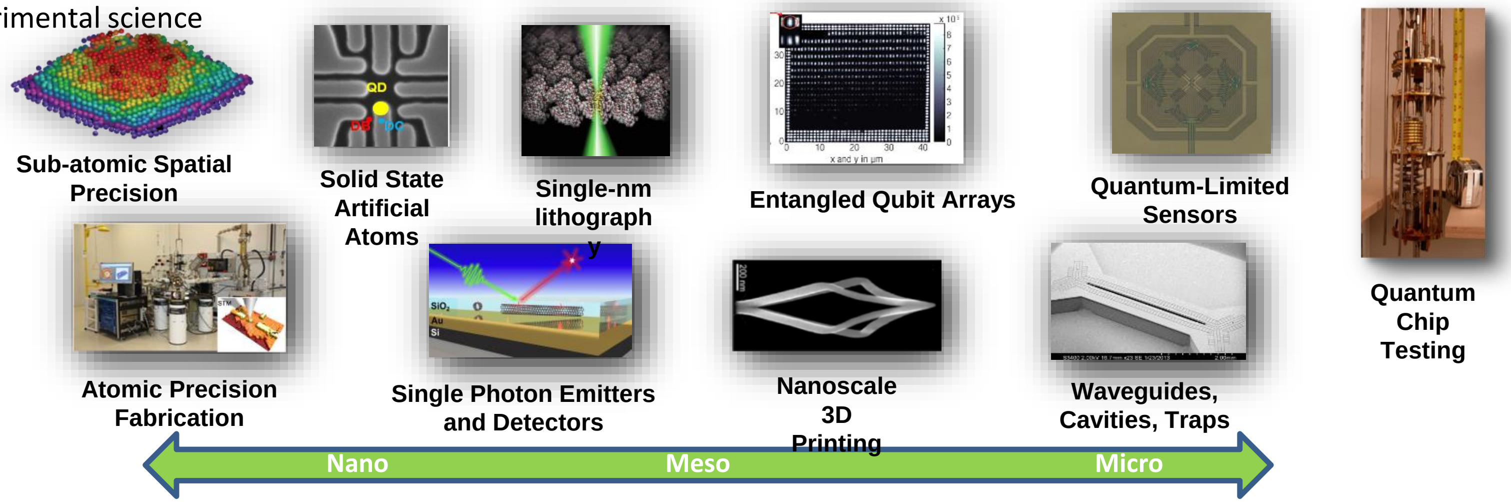


A laser cooled, RF confined ion trap at Argonne National Laboratory: trapped ions can be used as qubits and as quantum simulators.

Fundamental Science That Advances QIS

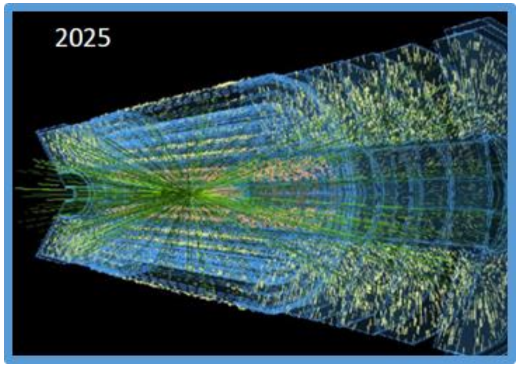
Quantum Integration Across Scales

- BES Nanoscale Science Research Centers user facilities are key to the synthesis and characterization of materials and structures from nano-components to prototype-scale quantum systems.
    - Integration and testing couple closely to theory, design, and systems efforts
    - Co-located with National Lab x-ray, neutron, computing, and microfabrication facilities for understanding and scale-up of quantum structures
    - Next-generation qubits and sensors
- BES research broadly advances understanding and use of quantum materials and chemical phenomena, integrating theory and experimental science

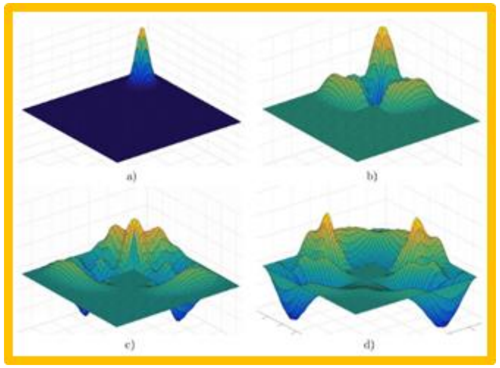


Initial SC Research on Quantum Computing Applications

SC Pilot Projects



Quantum pattern recognition for real time data tracking & quantum algorithms for exponentially increased storage (HEP/LBNL)



Simulated particle scattering off a complex boundary condition by quantum algorithms *(HEP-ASCR Pilot/U Maryland)*

ASCR Programs

Quantum Algorithm Teams (QATs)
Aims to stimulate early investigations of quantum simulation and machine learning algorithms by focusing on key topics of research with relevance to problems of interest to SC. In FY17, 3 interdisciplinary teams led by LBNL, ORNL, and SNL were funded.

Quantum Testbed Pathfinder
Aims to initiate an exploration of the suitability of various implementations of quantum computing hardware for science applications. In FY17, 2 teams led by LBNL and ORNL were funded.

FY 2017: Quantum Testbed Pathfinder

Purpose: To provide decision support for future investments in quantum computing (QC) hardware and increase both breadth and depth of expertise in QC hardware in the DOE community

Emphasis: Research in the relationship between device architecture and application performance, including development of meaningful metrics for evaluating device performance.

Timeline & Proposals: A DOE National Laboratory Announcement was issued in June 2017. 6 proposals were received in July 2017.

2 Awards:

Advanced Quantum-Enabled Simulation (LBNL, LLNL, UC Berkeley);

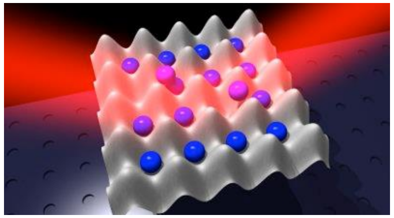
Methods and Interfaces for Quantum Acceleration of Scientific Applications (ORNL, IBM, IonQ, Georgia Tech);

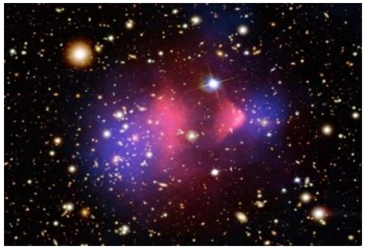
HEP-QIS Pilots & Partnerships -Fundamental Science

The intersection of HEP-QIS research connects study of the universe including black holes and quantum gravity with information encoding and quantum error correction in quantum systems such as qubits

- **HEP and DOD Basic Research (BR)** are exploring this area of shared interest in partnership via an open research coordinated pilot at Caltech (HEP) and Stanford University (DOD).
- Additional **HEP pilot at LBNL** is studying thermalization and signal transfer in qubit systems by invoking black hole physics techniques

HEP has also partnered with BES Condensed Matter Physics (CMP)Theory to pursue HEP-QIS studies in entanglement, quantum chaos, and fundamental field theories with similar CMP interests including tensor networks, holography, and spin chains (Publications -4)





NP-QIS Collaborations - Fundamental Science

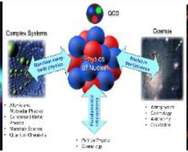
NP-QIS research activities:

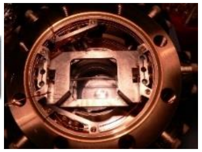
- **NP and Microsoft Research** are in the early stages of collaborating on learning circuits and algorithms, and implementations of time –evolution. Shared interest in Field Theory applications. *The first steps towards a quantum simulator of gauge theories are being taken now.*

- **NP's Institute for Nuclear Theory** studying ground states of many-body systems via Spectral Combing on a Quantum Computer. Spectral Combing requires fewer quantum gates to realize than the Quantum Adiabatic Algorithm. (1-publication).

- **Heterogeneous Digital-Analog Quantum Dynamics Simulations** (**ASCR**). Collaborator: University of Washington, Seattle, (**NP**) exploring Quantum Algorithms.

- **Ion-Trap Quantum Computing.** NP pioneered development of magneto-optical traps and cryogenic polarized nuclear targets. NP is in early stages of exploring chip traps, for ionic or neutral qubits. Miniaturization of atom traps is critical to scalability of this technology. Accelerator R&D applied to RF/Microwave design - a non-trivial component of building a chip traps.





Where Do Things in NP Stand Now?

Early activities involving nuclear scientists

- INT workshop took place
- Calculation of the binding Energy of the Deuteron
- Workshop at ANL: Intersections between Nuclear Physics and Quantum Information Physics Division, Argonne National Laboratory, 28–30 March 2018

NP ∩ QI

Requested Resources:

- FY18 PR: $45M requested by SC
  - NP may have some resources in FY2018
  - Proposals should be submitted to the open solicitation pursuant to the :Dear Colleague" Letter: …"DOE SC encourages submission of innovative research ideas via <u>any appropriate existing mechanism</u>
- FY19 PR: $121M SC request; $8.3M requested by NP
- NP POC: Gulshan Rai

Institute For Nuclear Theory Report 18-008

QUANTUM COMPUTING FOR THEORETICAL NUCLEAR PHYSICS

A White Paper prepared for the U.S. Department of Energy, Office of Science, Office of Nuclear Physics

Joseph Carlson (Los Alamos National Laboratory)
David J. Dean (Oak Ridge National Laboratory)
Morten Hjorth-Jensen (Michigan State University)
David Kaplan (Institute for Nuclear Theory)
John Preskill (California Institute of Technology)
Kenneth Roche (Pacific Northwest National Laboratory)
Martin J. Savage (Institute for Nuclear Theory)
Matthias Troyer (Microsoft)

Cloud Quantum Computing of an Atomic Nucleus*

E. F. Dumitrescu,[1] A. J. McCaskey,[2] G. Hagen,[3,4] G. R. Jansen,[5,3] T. D. Morris,[4,3] T. Papenbrock,[4,3,†] R. C. Pooser,[1,4] D. J. Dean,[3] and P. Lougovski[1,‡]

arXiv:1801.03897v1 [quant-ph] 11 Jan 2018

SC's QIS Strategy Builds On Community Engagement

- ASCR Quantum Computing Discussion, January 15, 2014, Germantown MD
- LANL Workshop on Materials Opportunities for Quantum Computing, October 7-8, 2014, Los Alamos NM
- ASCR-HEP Study Group: Grand Challenges at the Interface of QIS, Particle Physics, and Computing, December 11, 2014, Germantown MD
- BES-HEP Roundtable: Common Problems in Condensed Matter and High Energy Physics, February 2, 2015, Germantown MD
- ASCR Workshop on Quantum Computing in Scientific Applications, February 17-18, 2015, Bethesda MD
- BES Basic Research Needs on Quantum Materials, February 8-10, 2016, Gaithersburg MD
- ASCR-HEP Quantum Sensors at the Intersections of Fundamental Science, QIS & Computing, February 25, 2016, Gaithersburg MD
- Computing Beyond 2025, August 15-16, 2016, Chicago IL
- ASCR Quantum Testbeds Study Group, August 23, 2016, Germantown MD
- The 1st International Workshop on Post-Moore Era Supercomputing (PMES), November 14, 2016, Salt Lake City UT
- LBNL Workshop on Quantum Simulations 101, January 11, 2017, Berkeley CA