LALP-04-037

The Quantum Institute

at Los Alamos National Laboratory

Los Alamos National Laboratory

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Quantum Information

Science for a new century

At the turn of the twentieth century, the science of physics underwent a critical transformation. The freshly minted theories of Max Planck, Albert Einstein, and Neils Bohr produced a premise for physics that considered atomic and subatomic systems, and their interactions with radiation, in terms of observable quantities. The notion that all forms of energy moved in discrete units called *quanta* was eventually constituted into a new subfield of physics called quantum mechanics. Over the course of that century, the work of scientists like Wolfgang Pauli, Werner Heisenberg, Erwin Schrödinger, Richard Feynman and others further fueled the scientific world's interest in and knowledge of quantum physics.

It seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds dominant sway.

Richard P. Feynman, 1985

By the turn of the twenty-first century, the study of quantum mechanics had evolved far beyond its modest origins and had engendered a number of different areas of inquiry, including a field called quantum information science. Quantum information science brought together physicists, mathematicians, computer scientists, chemists, and engineers in an interdisciplinary community working to develop advanced communication and information technologies based on or exploiting quantum physics theory. Today quantum information science research is taking place at institutions all over the world and advances have been made in both the theoretical and experimental realms. One of the principal goals of quantum information science has been the development of a quantum computer. If realized, a quantum computer could far surpass the speed and computational abilities of even the most powerful of conventional computers.

Los Alamos National Laboratory is one of the world's leading forces in the field of quantum information science. From theoretical studies of decoherence to experimental designs for the capture and manipulation of individual atoms for national security applications of quantum principles, researchers at the Laboratory are making significant contributions to every major area of quantum information science research. Although these researchers come from a number of different Laboratory divisions, including the Chemistry, Computer and Computational Sciences, International, Space and Response Technologies, Materials Science and Technology, Nuclear Nonproliferation, Physics, and Theoretical divisions, they are united together under the mission and auspices of the Los Alamos Quantum Institute.

The Quantum Institute

An institute to foster interdisciplinary research

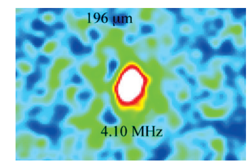
The Los Alamos Quantum Institute embodies the single largest multidisciplinary collection of quantum information science and technology researchers in the world. Drawing researchers from seven different Laboratory divisions, Los Alamos quantum research activities are responsible for roughly ten percent of the national quantum information science and technology budget.

Deputy Laboratory Director for Science and Technology William Press and former Laboratory Director John Browne officially opened the Quantum Institute on December 18, 2002.

The Quantum Institute was formally organized in 2002 with the mission of providing advocacy, information, coordination, and organizational support for quantum information science and technology programs and researchers at Los Alamos National Laboratory. The Laboratory provides a unique setting with access to both critical resources and national laboratory capabilities.

The goals of the Institute are:
To equitably represent the diverse Laboratory community of quantum information science and technology in basic and applied theoretical and experimental physics, mathematics, and computer science.

To foster a vigorous intellectual environment for quantum information science research by maintaining an active visitor program and seminar series and helping recruit and retain the best students, postdoctoral researchers, and technical staff.



Rubidium atom cooled to Bose-Einstein condensate

To identify and promote inter-divisional collaborative research and development opportunities and collaborations with researchers outside the Laboratory.

To promote the healthy, long-term development and support of the quantum information science and technology field and its contributions to the national security mission at Los Alamos through coordinated interactions with current and potential sponsors and with senior Laboratory management.

To help the Los Alamos quantum information science community identify resources, including internal and/or external research funding opportunities, required for organizational and individual success.

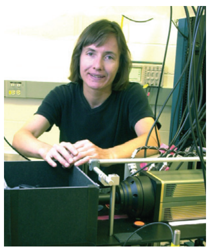
Los Alamos researchers had the most cited quantum information paper in 2002

The Quantum Institute

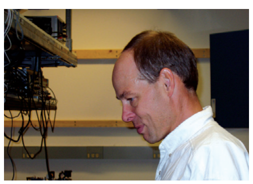
Fostering Interdisciplinary Research

The Los Alamos quantum information science and technology research activities are interdisciplinary. Meet just a few of the Laboratory's many notable quantum researchers who are recognized nationally and internationally for their leadership in both theoretical and experimental areas.

Dana Berkeland works in the Physics Division studying the ways in which atomic traps can be used as tools for understanding quantum mechanical systems. Because these traps tightly confine single ions almost indefinitely, Berkeland is using the traps to test whether the result of measurement of a quantum mechanical system in a superposition of states is unpredictable. The results of this test are important to interpreting the nature of information in a quantum system.

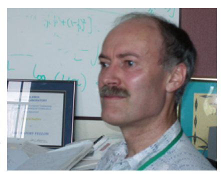


Malcolm Boshier is part of a team attempting to harness atoms provided by a Bose-Einstein condensate to build a waveguide atom interferometer. Such a device would be extremely sensitive to any interaction that affects the energies of atoms and could be miniaturized to dimensions of just a few millimeters, which might make possible a new generation of ultra-sensitive miniature sensors. He was recently recruited to the Physics Division from The University of Sussex, U.K.



Marilyn Hawley of the Materials Science and Technology Division is exploring a novel "bottom-up" fabrication approach to using a scanning tunneling microscope to create a solid-state, silicon-based, quantum computer. The approach involves the fabrication of atoms in a spin array, which could be the functional basis of a quantum computer.

Richard Hughes is a quantum information physicist who works on quantum cryptography and with the quantum computing teams at the Laboratory. A member of the Laboratory's Physics Division, he is also currently the chair of two panels of eminent scientists who are engaged in creating national roadmaps to help guide the future development of those two fields. He also serves as the Scientific Director of the Quantum Institute.



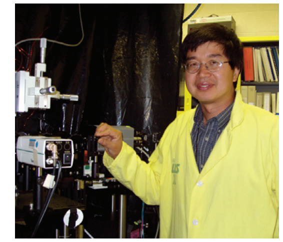
Daniel James of the Theoretical Division investigates theories underlying quantum computing technologies such as ion traps. He also studies the theory behind optical technology such as single-photon sources and detectors and is interested in optical measurement and readout of quantum computing in the solid state.

Juan Pablo Paz is a theorist who works on the quantum algorithms used for developing and studying physics simulations on physical systems. Assigned to the Laboratory's Theoretical Division, he is also involved in the study of decoherence and the role of decoherence in the context of how classical laws emerge from the quantum realm in what is called the quantum-classical transition. He was recently recruited from the University of Buenos Aires, Argentina.

Toni Taylor is a physicist working in the Laboratory's Materials Science and Technology Division. Taylor is interested in the ways in which ultrafast optical pulses of light might be used to selectively excite such complex materials systems as nonlinear optical crystals, semiconductor quantum dots, and bulk materials, in order to prepare and manipulate specific electronic and photonic quantum states which may be of critical importance for building future quantum electronic and photonic devices.

David Vieira is a nuclear chemist in the Chemistry Division who conducts fundamental atomic and nuclear physics experiments involving trapped radioactive atoms, ultrasensitive detection, and quantum information and control. He also carries out investigations into fundamental symmetries, radioactive beams, and neutron-induced cross section measurements.

Xinxin Zhao, of the Chemistry Division, conducts research on novel atom cooling and trapping techniques. Using recent advances in laser cooling and atom trapping, Zhao's team at Los Alamos has adapted cooling and trapping techniques to make measurements of parity violation in radioactive atoms as a means to test the Standard Model of electroweak interactions.



Wojciech Zurek of the Theoretical Division is known internationally for his seminal contributions to theory of decoherence. His interests also include physics of information, quantum error correction, the transition from quantum to classical, as well as other subjects such as cosmology and dynamics of phase transformations. In the photo, Zurek (left), **Raymond Laflamme**, (center) University of Waterloo, Canada, and **Emmanuel (Manny) Knill** (right) is shown discussing resilient quantum computation, a strategy was proposed by the three collaborators to enable error-free quantum computations using quantum gates. Knill is a mathematician in the Computer and Computational Sciences Division and works on the theory and practice of quantum information processing.

The Quantum Institute's National Security Mission at Los Alamos

. . . the development of a fully operational quantum computer would demolish the concept of national security. Whichever country gets there first will have the ability to eavesdrop on the plans of its enemies. Although still in its infancy, quantum computing presents a potential threat to global security.

Simon Singh, *The Code Book*

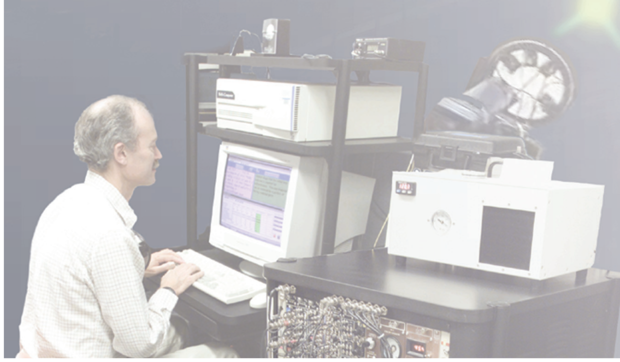
Quantum information science and technology research is conducted not only at Los Alamos National Laboratory, but also at outstanding universities and laboratories around the world. At Los Alamos, however, even the most basic quantum research often has national security implications or connections.

Although the Quantum Institute's national security mission at Los Alamos is manifest in many areas, it is perhaps most evident in two of the Laboratory's most successful quantum technology initiatives—quantum cryptography and the race for a quantum computer.

Quantum Computing

Quantum computing is a global race to conceive and create the ultimate computing machine. If fully-functional quantum computers can be built, and there is still somewhat of a question that they can, they will be able to rapidly factor extremely large numbers, making them extremely useful for solving certain large mathematical problems at speeds faster than today's fastest supercomputers and for cracking secret codes that have been encrypted by traditional methods. A functional quantum computer would put much of the world's past and present encrypted information at risk of being quickly deciphered.

Los Alamos researchers were among the first to make tangible advances in quantum computation. In 1998, Los Alamos scientists used nuclear magnetic resonance techniques to create a prototype liquid-based quantum computer within trichloroethylene molecules. They went on to build a slightly larger device in 2000, but the technology is far from the desired end state.



From the Manhattan Project to quantum cryptography, Los Alamos has often been called on to solve the most complex problems of national security.

More recent research efforts have focused on constructing a quantum computer as a solid-state device. This will require the ability to manipulate individual atoms in some kind of a solid matrix or lattice and Los Alamos researchers are exploring this technology in collaboration with researchers from the University of New South Wales in Sydney, Australia, California Institute of Technology, and the University of Maryland.

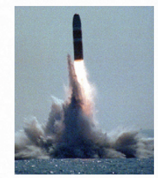
Quantum Cryptography

In quantum key distribution (QKD), two parties use single photons that are randomly polarized to states representing ones and zeroes to transmit a series of random number sequences that are used as keys in cryptographic communications. This string of numbers becomes a quantum key that locks or unlocks encrypted messages sent via normal communication channels. Because the transmitted photons cannot be intercepted without being destroyed, and the act of interception then tips off the message receiver, QKD is considered the most powerful data encryption scheme ever developed and its codes are, by all indications, virtually unbreakable.

Although the quantum key distribution technique was not created at Los Alamos, laboratory researchers have taken the technology, quite literally, to new lengths in the interest of national security. In 1999, Los Alamos researchers set a world record when they sent a quantum key through a 31-mile-long optical fiber. While this distance proved sufficiently far enough to create QKD networks connecting closely-spaced government offices or localized bank branches, the system failed at greater distances when signal loss increased to the point at which the photons were absorbed by normal optical fiber noise. To achieve longer distances, Los Alamos researchers developed a free-space quantum cryptography system that could send keys through the air.

Los Alamos quantum scientists developed a transportable, self-contained QKD system that used polarized photons to send information through the air for distances of up to 10 miles. This mobile trailer-based QKD system could be quickly deployed in the field and was capable of continuous, automated transmission in both daylight and darkness. Today, Los Alamos researchers are in the process of taking this technology even further by developing a smaller scale version that is capable of being put on an Earth-orbiting satellite for transmitting quantum keys distances of hundreds of miles between the satellite and a ground station.

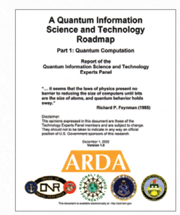
Manhattan Project



Cold-war deterrence

Non-proliferation space technology

Advanced computing



A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Report of the Quantum Information Science and Technology Experts Panel

"... it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds sway."

Richard P. Feynman (1985)

Disclaimer:
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December 1, 2002
Version 1.0

ARDA

Leading the international effort to plan the future of quantum information science.