T-4
Atomic & Optical Theory

The Theory of the Silicon-Based Nuclear Spin Quantum Computer

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A quantum computer is a device which stores information in quantum mechanical two-level systems ("qubits") and exploits fundamental quantum mechanical phenomena to vastly improve computational power. Such devices represent a revolutionary new computational paradigm that has seen tremendous growth since 1994, following the invention of quantum algorithms with compelling real-world applications, experimental realizations of systems with a few qubits, and the extension of the theory of error correction to quantum systems. Existing quantum computation experiments with trapped ions, optical interferometers and liquid-state nuclear magnetic resonance (NMR) systems provide a path to understanding the fundamentals of practical quantum computing on small or intermediate scales. However the long-term goal of this field is a quantum computer with the following features: a scaleable architecture (allowing large numbers of qubits); a high clock speed; the capability to perform quantum operations in parallel; and an "industrial" fabrication method.

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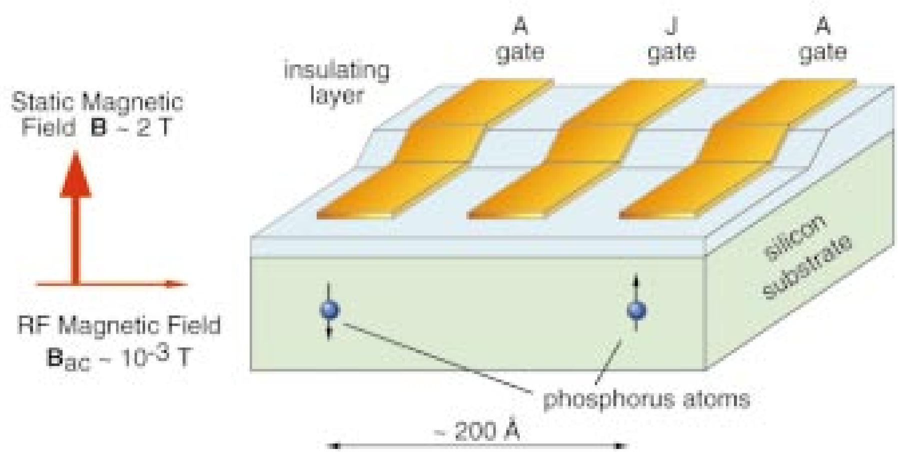
Solid state systems are the most promising candidates for meeting these demanding requirements. Kane recently published a break-through conceptual study for a silicon-based quantum computer that will meet many of these requirements [1]. The key elements of his proposed architecture (see figure) are an array of spin-1/2 phosphorus nuclei embedded in silicon and a series of surface gate electrodes. The spins of the phosphorus



nuclei, which constitute the qubits, will be addressed using a static electric field and manipulated using NMR techniques. Single spin interactions are achieved by changing the voltage on a metallic gate electrode (the "A" gate) positioned above each nucleus; spin-flips are then carried out by a pulse of RF field tuned to the appropriate Stark-shifted resonance frequency. The electron-mediated interaction between two nuclear spins can be turned on and off by applying a voltage to the electrode placed between them (the "J" gate); conditional spin flips can then be achieved again using the RF field. It is possible to show that any desired quantum state can be reached with these two types of interactions.

Los Alamos is currently embarking on a project to construct a prototype two-qubit device capable of investigating the principles of Kane's design. The program, headed by Chris Hammel and Bob Clark of MST Division, will be in close collaboration with the University of New South Wales, where the design originated and which has a state-of-the-art semiconductor fabrication facility. Other institutions taking part in the collaboration are CalTech, the University of Maryland and the University of Queensland.

The Los Alamos Theoretical Division will provide expertise crucial for the eventual success of this project. We have unique experience in the development of quantum computation technology [2], the theoretical[3] and experimental[4] study of errors and error correction in quantum computation and nuclear spin resonance systems and in the modeling of complex solid state devices[5]. Here are a few examples of the sort of problems we are going to be tackling: the basic physics of single spin measurements; the effects of impurities, lattice defects, boundary imperfections and vibrations on the behavior of qubits; the evaluation of different error mechanisms, and the identification of possible methods of overcoming them (such as the utilization of strategies developed in standard nuclear magnetic resonance, quantum control with feedback, and quantum error-correction). Although it would be foolhardy to underestimate the technical difficulties involved, this project is a bold initiative to develop a truly revolutionary new computational technology with stunning potential applications.

[1] Bruce E. Kane, “A Silicon-based Nuclear Spin Quantum Computer,” *Nature* **393**, 133 (1998).

[2] Daniel F. V. James, *Appl. Phys. B* **66**, 181 (1998)

[3] E. Knill, R. Laflamme and W. H. Zurek, *Science* **279**, 342 (1998).

[4] D. Cory, M. D. Price, W. Maas, E. Knill, R. Laflamme, W. H. Zurek, T. F. Havel and S. J. Somaroo, *Physical Review Letters* **81**, 2152 (1998); M. Nielsen, E. Knill and R. Laflamme, *Nature* **396**, 52 (1998).

[5] G. P. Berman, D. K. Campbell, G. P. Doolen and K. E. Hagaev, “Electron-Nuclear spin dynamics in a mesoscopic solid-state quantum computer”, 4th International Symposium on New Phenomena in Mesoscopic structures (NPMS’98), December 1998, Kauai, Hawaii, p. 311.

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