# “Unique” Qubits Approaches to Quantum Information Processing and Quantum Computing

## A Quantum Information Science and Technology Roadmap

### Part 1: Quantum Computation

### Section 6.8

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## List of Acronyms and Abbreviations

| | | | |
|---|---|---|---|
| C-NOT | controlled-NOT (gate) | QDs | quantum dots |
| DFS | decoherence-free subspace | QED | quantum electrodynamics |
| GHz | gigahertz | QIP | quantum information processing |
| GHZ | Greenberger, Horne, and Zeilinger | rf | radio frequency |
| MEMS | micro-electro-mechanical systems | SHB | spectral hole burning |
| mK | milliKelvin | SPD | single-photon detector |
| NMR | nuclear magnetic resonance | SPS | single-photon source |
| NV | nitrogen-vacancy | TEP | Technology Experts Panel |
| QC | quantum computation/computing | UV | ultraviolet |

## 1.0 Introduction

In addition to the relatively well-established methods for performing quantum information processing (QIP) and quantum computing (QC) described in detail earlier in this document, there exist potentially fruitful approaches to QIP based on a variety of quantum technologies.

Virtually any quantum system that is addressable, controllable, and coherent has the potential to perform QC. The situation is reminiscent of the early days of digital computing, when switches and circuits were constructed from a variety of technologies, including electromechanical relays, vacuum tubes, and even from purely mechanical and hydraulic components in environments where electrical systems were inappropriate. Even today, when virtually all computers are based on integrated circuits, memory technologies exhibit considerable diversity. There are a variety of types of integrated circuits for memory, as well as magnetic memories (hard disks) and optical memories (CDs). Perhaps as a result of the diversity of different memory technologies, the Moore's law rate of increase of density of memory circuits has followed a more rapid pace than that of processing circuits. Similarly, we anticipate that a variety of different QIP technologies may be used for different purposes as the field matures further.

This section lists several such approaches to QIP. There exist tens of such "unique" approaches: not all will be described here. Rather, this section will concentrate on approaches that have current, funded research programs: these approaches have been thoroughly researched and found worth further investigation. It is anticipated that in the future more unique approaches will arise; these will be evaluated as they arrive. In addition, the ongoing research will serve to show which of these various approaches are the most promising. Summaries of existing efforts follow; which include general discussions of the state of the art for input-output, coherent computation, and decoherence. For two of these approaches, electronics on helium QC and spectral hole burning QC, short additional write-ups are included in the following sections.

**QIP using Nanotubes and Nanowires.**

Carbon nanotubes and silicon nanowires represent a well-developed nanotechnology. Such systems are known to exhibit significant degrees of quantum coherence for electron transport. Nanotubes can be used to create arrays of quantum dots (QDs) whose coupling can be turned on and off using silicon nanowires. Such systems share virtues and deficiencies with lithographed QD systems and potentially possess additional features, such as an enhanced degree of regularity of the dots due to the chemical synthesis of the nanotubes. Experimental efforts exist: further research is being performed on input-output, coherent control, and the properties of decoherence of electron spin in nanotube systems.

**Quantum Logic Using Electrons on the Surface of Liquid Helium.**

Electrons on the surface of liquid helium represent a clean system for registering and processing quantum information. The electrons effectively float above the surface of the helium, and their states can be manipulated by microwaves and by circuits embedded in the silicon substrate below the helium film. Experiments have been performed exhibiting single-electron detection, and are underway to exhibit coherent control of electrons on helium by the application of microwaves. Further investigations are taking place into the properties of decoherence and into the performance of quantum logic operations in such systems.

**Molecular Spin Arrays**

Chemical techniques can be used to produce self-assembled arrays of molecules containing electron spins. Such systems represent natural candidates for quantum computers with a cellular-automaton architecture. Experiments on such systems are in the initial phase. Issues of decoherence, input-output, and coherent control are understood to some degree in theory; more theoretical and experimental investigations are underway.

**Quantum Hall Effect QC**

Quantum-Hall-effect systems are well-studied experimentally and represent good potential systems in which to perform QIP. Quantum information can be stored on highly coherent, long-lived nuclear spins, then transferred to electron spins and excitons for information transmission and readout. Coherence times have been measured in such systems and are favorable for QC. Detailed studies of input-output characteristics, decoherence, and quantum logic operations are underway.

**QC using Nonabelian Anyons**

Topological methods for QC have attracted considerable interest because of their intrinsically fault-tolerant properties. In such methods, quantum information is stored on nonabelian anyons, and quantum logic operations are performed by 'braiding' the anyons around each other in a two-dimensional plane. Nonabelian anyons are relatively exotic systems, which could potentially be constructed using arrays of quantum logic gates (e.g., superconducting quantum logic circuits) or implemented using the higher order fractional quantum Hall effect. Preliminary theoretical investigations of both types of approaches indicate their feasibility. Experiments are forthcoming.

**QC using the Fractional Quantum Hall Effect**

QC can also be performed in a topological fashion using abelian anyons, such as the usual fractional quantum Hall quasiparticles. Abelian anyons share some, though not all, of the fault-tolerance of the nonabelian anyons discussed above, and have the advantage that they have been investigated and manipulated experimentally. Theoretical and experimental investigations are currently underway to determine levels of decoherence for quantum Hall quasiparticles, and to perform simple quantum logic operations.

**Electro-Mechanical Systems for QIP**

Nanofabricated mechanical resonators exhibit high Qs and quantum coherence. Such mechanical devices represent natural structures on which to perform QIP. They can be coupled to electronic systems for measurement and control purposes. They can be interfaced, in principle, with superconducting quantum computers. Initial theoretical and experimental investigations on quantum control and decoherence for such systems have been performed; more extensive investigations are in progress.

**QC using Spectral Hole Burning**

Spectral hole burning is a well-established technique for addressing optically active atoms in solids. It allows for a potentially high density of quantum bits by using both spatial and frequency addressing techniques. A variety of models for quantum computing using spectral hole burning have been investigated, using optical cavities and/or dipolar coupling between spectral holes. Experimental investigations of the controllability and coherence properties of spectral holes have been performed and indicate a level of controllability comparable to normal quantum optical approaches to QC, with reduced coherence due to the solid-state nature of spectral hole systems. Current experimental investigations are aimed towards elucidating the coherence structure of spectral holes and towards coupling spectral holes to perform quantum logic operations.

## 2.0 Electrons on Helium Films Approaches to Quantum Information Processing and Quantum Computing

### 2.1 Groups Pursuing This Approach

**Note:** This document constitutes the most recent draft of the Electrons on Helium Films detailed summary in the process of developing a roadmap for achieving QC. Please submit any revisions to this detailed summary to Todd Heinrichs (tdh@lanl.gov) who will forward them to the relevant Technology Experts Panel (TEP) member. With your input can we improve this roadmap as a guidance tool for the continued development of QC research.

**Table 2.1-1**
**Approaches to Electrons on Helium Films QC Research**

| Research Leader(s) | Research Location |
|---|---|
| Goodkind, J. | UC-San Diego |
| Dahm, A. | Case Western Reserve |
| Dykman, M. | Michigan State U. |
| Platzman, P. | Bell Labs |
| Lea, M. | Royal Hollaway |
| Mukharsky, Y. | Saclay |
| Kono, K. | Riken, Japan |

### 2.2 Background and Perspective

Electrons on a helium surface are attracted to the surface by the helium dielectric image potential and occupy "hydrogenic" states associated with motion normal to the helium surface with a Rydberg energy of ~8K. A Pauli exclusion force prevents electrons from entering the liquid. Electrons are localized laterally by a microelectrode (post) located under each electron. The posts are separated by a distance *d* ~1 μm and are covered with an ~1-μm-thick helium film. The states for lateral motion are harmonic oscillator states in the post potential with an energy separation of ~1K. The ground and excited states in the hydrogenic potential are identified with the |0⟩ and |1⟩ components of a qubit.

## 2.3 Summary of Electrons on Helium QC: The DiVincenzo Criteria

**Note:** For the five DiVincenzo QC criteria and the two DiVincenzo QC networkability criteria (numbers six and seven in this section), the symbols used have the following meanings:

a) = a potentially viable approach has achieved sufficient proof of principle;

b) = a potentially viable approach has been proposed, but there has not been sufficient proof of principle; and

c) = no viable approach is known.

1. A scalable physical system with well-characterized qubits

   Electrons on a helium surface are attracted to the surface by the helium dielectric image potential and occupy "hydrogenic" states associated with motion normal to the helium surface with a Rydberg energy of ~8K. A Pauli exclusion force prevents electrons from entering the liquid. Electrons are localized laterally by a microelectrode (post) located under each electron. The posts are separated by a distance *d* ~1 μm and are covered with an ~1-μm-thick helium film. The states for lateral motion are harmonic oscillator states in the post potential with an energy separation of ~1K. The ground and excited states in the hydrogenic potential are identified with the |0⟩ and |1⟩ components of a qubit. In principle, this system is scalable to an arbitrary number of qubits.

2. Ability to initialize the state of the qubits to a simple fiducial state

   Once placed on the helium surface, the electrons relax to the ground state in a time scale of ~1 ms. The energy separation of the excited state is controlled by a Stark field applied to the posts and is of order 100 gigahertz (GHz), so at the operating temperature of 10 milliKelvins (mK) (~0.2 GHz) all of the qubits are easily and reliably initialized into their ground states.

3. Long (relative) decoherence times, much longer than the gate-operation time

   Phonon emission into the liquid dominates the decay of the excited state with a lifetime of ~100 μs ($T_1$). Coupling is via phonon modulation of the surface level and image potential. The dephasing time ($T_2$) is estimated to be ~100 μs due to Nyquist noise on the electrodes, so decoherence/gate time ratios are ~$10^5$.

4. Universal set of quantum gates

   The operation begins with all qubits in the |0⟩ state. Single-qubit operations are preformed by Stark shifting qubits into resonance with an radio frequency (rf) field applied for a prescribed length of time. An expansion gives a dipolar interaction term between qubits $\mu\ e^2(z_2 - z_1)^2/d^3$. The computer will be operated at a temperature of 10mK. Quantum gates are implemented by bringing neighboring qubits into resonance alone (SWAP) or in conjunction with an rf field (C-NOT—controlled-NOT). The time required for a SWAP operation depends on the spacing between electrons (i.e., posts), and is ~1 ns for a 0.5 μm spacing between.

5. A qubit-specific measurement capability

   A simultaneous readout of all qubits will be accomplished by applying a moderate extracting field such that electrons in the |1⟩ state will tunnel from the surface. Subsequently, a large extracting field will be applied sequentially to each post such that electrons in the |0⟩ state will tunnel into the vacuum. Electrons detected (not detected) by the bolometer detector will register a |0⟩(|1⟩) for that post.

6. The ability to interconvert stationary and flying qubits

7. The ability to faithfully transmit flying qubits between specified locations

## 2.4 What Has Been Accomplished

**Note:** For the status of the metrics of QC described in this section, the symbols used have the following meanings:

a) = sufficient experimental demonstration;

b) = preliminary experimental demonstration, but further experimental work is required; and

c) = no experimental demonstration.

1. Creation of a qubit

   1.1 Demonstrate preparation and readout of both qubit states.

   The system consists of two parallel plates that form the upper and lower surfaces of an expanded waveguide. The microelectodes are incorporated in the lower plate that is covered with a helium film. A tungsten superconducting transition-edge bolometer able to detect 10 eV electrons in the read-out process and a tunnel-diode electron source for loading electrons onto the posts have been fabricated and are located above a small opening in the upper plate.

2. Single-qubit operations

   2.1 Demonstrate Rabi flops of a qubit.

   2.2 Demonstrate high-Q of qubit transition.

   2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.

3. Two-qubit operations
   - 3.1 Implement coherent two-qubit quantum logic operations.
   - 3.2 Produce and characterize Bell states.
   - 3.3 Demonstrate decoherence times much longer than two-qubit gate times.

4. Operations on 3–10 physical qubits
   - 4.1 Produce a Greenberger, Horne, & Zeilinger (GHZ)-state of three physical qubits.
   - 4.2 Produce maximally entangled states of four and more physical qubits.
   - 4.3 Quantum state and process tomography.
   - 4.4 Demonstrate DFSs.
   - 4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations, etc.) between physical qubits.
   - 4.6 Demonstrate quantum error correcting codes.
   - 4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza).
   - 4.8 Demonstrate quantum logic operations with fault-tolerant precision.

5. Operations on one logical qubit
   - 5.1 Create a single logical qubit and "keep it alive" using repetitive error correction.
   - 5.2 Demonstrate fault-tolerant quantum control of a single logical qubit.

6. Operations on two logical qubits
   - 6.1 Implement two-logical-qubit operations.
   - 6.2 Produce two-logical-qubit Bell states.
   - 6.3 Demonstrate fault-tolerant two-logical-qubit operations.

7. Operations on 3–10 logical qubits
   - 7.1 Produce a GHZ-state of three logical qubits.
   - 7.2 Produce maximally-entangled states of four and more logical qubits.
   - 7.3 Demonstrate the transfer of quantum information between logical qubits.
   - 7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.
   - 7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

## 2.5 Considerations

1. Special strengths
   - 1.1 The physics is well-understood and has been experimentally explored.
   - 1.2 The system naturally presents long decoherence times due to intrinsic cleanliness of helium films.
   - 1.3 The qubit separation of ~1 μm is lithographically well within reach.

1.4 The range of interaction energy between qubits in the presence of a ground plane is $\mu\, e^2/r^3$, a short range interaction that improves controllability of qubit interactions.

2. Unknowns, weaknesses

3. Five-year goals

3.1 Within the next year, we expect to localize electrons above posts and detect electrons that tunnel from the surface in an extracting field, and perform single and two-qubit operations.

3.2 Explore materials other than helium, such as neon, which have larger excited-state separations allowing use of lasers to couple to qubits.

## 3.0 Spectral Hole Burning Approaches to Quantum Information Processing and Quantum Computing

**Note:** This document constitutes the most recent draft of the Spectral Hole Burning detailed summary in the process of developing a roadmap for achieving QC. Please submit any revisions to this detailed summary to Todd Heinrichs (tdh@lanl.gov) who will forward them to the relevant Technology Experts Panel (TEP) member. With your input can we improve this roadmap as a guidance tool for the continued development of QC research.

### 3.1 Summary of Spectral Hole Burning QC: The DiVincenzo Criteria

**Note:** For the five DiVincenzo QC criteria and the two DiVincenzo QC networkability criteria (numbers six and seven in this section), the symbols used have the following meanings:

a)  = a potentially viable approach has achieved sufficient proof of principle;

b)  = a potentially viable approach has been proposed, but there has not been sufficient proof of principle; and

c)  = no viable approach is known.

1. A scalable physical system with well-characterized qubits 

To illustrate the basic mechanism behind the spectral-hole-burning (SHB) approach to quantum computing, consider a small volume of a medium such as nitrogen-vacancy (NV) color centers in diamond [1]. A laser beam incident on this volume can interact with all the centers in this volume. However, each center has a transition frequency that is slightly different from that of the others, a feature known as inhomogeneous broadening. This implies that individual centers can be addressed distinctively by tuning the laser, if the system is prepared so that only a single center is present in each spectral band. This enables single-qubit operations [1,2]. In order to perform two qubit operations, such as the C-NOT, it is necessary to couple two centers that are spectrally adjacent [1]. One mechanism for such a coupling is the dipole-dipole interaction [3]. However, because the spectral neighbors are not necessarily close to each other spatially, it is necessary to enhance this interaction artificially. This can be achieved by embedding the centers in a high-Q optical cavity. The number of qubits that can be realized this way in a single diffraction-limited spot can be as high as $10^5$ for realistic parameters, making this scheme a good candidate for **scalable QC**. Many spots on a single crystal, each containing a quantum computer, can also be used for the so-called type II quantum computing for efficient simulation of lattice gas dynamics [4,5]. Furthermore, this approach is readily suited for coupling the individual quantum computers via optical means [6].

The qubit in this process is a spin transition that is excited by a Raman interaction. In order to realize distinct qubits, we must have at most one atom per spectral channel**.** As discuss in detail in reference 1, this can be achieved in NV-diamond by making use of a storage level where all but one atom from each channel can be transferred to for a long time (hours). As such, this system can be claimed to have a **well characterized qubit**.

2. Ability to initialize the state of the qubits to a simple fiducial state

This criterion pertains to the ability to prepare the quantum bits in a pure (0 or 1) state. At the onset, there are two metastable states in NV-Diamond [7] that are both occupied, with the normalized population difference determined by the exponent of the negative of the ratio of □ and the product of the temperature and the Boltzmann constant. For the case of nuclear magnetic resonance (NMR) at room temperature, this implies that the number of spins that are in a pure state is very small. For other systems such as phosphorous in QDs, this problem requires that the quantum computer be operated at temperatures in the mK regime. In our model, near-perfect alignment can be produced at much higher temperatures (at least up to 15K, accessible by compressor-based closed-cycle cryostats), via a process known as the two-photon induced coherent population trapping, or the dark resonance [1,2].

3. Long (relative) decoherence times, much longer than the gate-operation time

This criterion requires that the time needed to perform a single operation should be much less than the dephasing time of the qubits. In NV-diamond, the dephasing time is about 0.1 ms, while the time for a single operation can be as low as 100 ns. The number of operations that can be performed before dephasing can thus be as high as $10^3$. The dephasing time can be reduced further by

a. using samples that are free from $^{13}C$ and
b. using techniques of dynamic noise suppression developed in the context of NMR quantum computing [8].

4. Universal set of quantum gates

We have identified in explicit detail two different methods for realizing a C-NOT operation between two nearest-neighbor qubits in NV-diamond. The first method [3], applicable to high-density of color centers, uses the direct optical dipole-dipole coupling between two qubits that are very close to each other spatially and can be turned into spectral neighbors via applying a magnetic field. This method is somewhat limited in the number of bits that can be coupled. The second method [1], applicable to low-density of color centers, uses a high-finesse optical cavity, resonant with a transition common to both bits, in order to enhance the optical dipole-dipole coupling. The number of qubits that can be realized this way can be as high as $10^5$.

5. A qubit-specific measurement capability
In the model of reference 1, the two laser photons used to excite the qubit can be encoded (in the form of the amplitude and phase of the beat between the two frequencies) with the quantum information during the input process. The information then can be transferred to a distinct qubit occupying the matching spectral channel. The reversal of this process enables the retrieval of the quantum information from distinct qubits.

6. The ability to interconvert stationary and flying qubits
The SHB model inherently satisfies this criterion, because the quantum bit can be copied in to the state of a cavity photon, which in turn can transmit the bit to another system upon exiting the cavity. This converts a stationery qubit in to a flying one. The reverse process enables the conversion of a flying qubit in to a stationery qubit.

7. The ability to faithfully transmit flying qubits between specified locations
Once the flying qubit exits in the cavity at one location, it can then be transmitted to the other location via free-space or via an optical fiber, and then coupled to the cavity at the other location for conversion into a stationery qubit, in a manner analogous to reference 8.

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