Cavity QED Approaches
to
Quantum Information Processing
and
Quantum Computing

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Section 6.4

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List of Acronyms and Abbreviations

DFS	decoherence-free subspace
GHZ	Greenberger, Horne, and Zeilinger
LIGO	Laser Interferometer Gravitational Wave Observatory
QC	quantum computation/computing
QED	quantum electrodynamics
QIP	quantum information processing
rf	radio frequency
TEP	Technology Experts Panel

1.0 Groups Pursuing This Approach

Note: This document constitutes the most recent draft of the Cavity QED (quantum electrodynamics) detailed summary in the process of developing a roadmap for achieving quantum computation (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 1-1
Approaches to Cavity QED QC Research

Research Leader(s)	Research Location	Research Focus
Blatt, R.	U. of Innsbruck	Ca^+
Chapman, M.	Georgia Tech	Rb, Ba^+
Esslinger, T.	ETH, Zurich	Rb
Feld, M.	MIT	Ba
Haroche, S.	Ecole Normale Superiere, Paris	Rb (Rydberg)
Kimble, J.	Caltech	Cs
Kuga, T.	U. of Tokyo	Rb
Mabuchi, H.	Caltech	Cs
Meschede, D.	U. of Bonn	Cs
Orozco, L.	U. Maryland	Rb
Rempe, G.	Max-Planck Institute, Garching	Rb
Stamper-Kurn, D.	UC Berkeley	Rb
Walther, H.	Max-Planck Institute, Garching	Ca^+

2.0 Background and Perspective

In the context of quantum information 'cavity QED' refers to the coherent interaction of a material qubit (such as a trapped atom or semiconductor dot system) with the quantized (usually single photon) field of a high-finesse optical or microwave resonator. To achieve coherent dynamics with just a single photon and atom, a small, extremely low-loss build-up cavity is used to enhance the electric field per photon such that the coherent Rabi frequency of the atom-field interaction is faster than the spontaneous emission rate of the atom or the decay rate of the field in the cavity—this is known as the strong coupling regime. While this is very challenging, this limit has been achieved in ~10 labs over the past 15 years or so in both the microwave and optical domains (see [1,2,3,4,5] for recent overviews).

2.1 Importance to Quantum Information Processing

Applications of cavity QED systems to quantum information processing (QIP) derive mostly from the ability to coherently intra-convert quantum states between material qubits and photon qubits. Using this basic primitive, many two-qubit gate protocols have been developed for creating atom-photon, atom-atom, or photon-photon entanglements [6,7,8,9,10,11], and proof-of-principle experiments have been performed for some of these ideas [12,13]. Scalable architectures have also been suggested using these gates. More uniquely, cavity QED systems are featured in many ideas relating to distributed quantum information processing and communication [14,15,16,17,18,19,20,21,22,23] and provide a leading candidate for robust, controllable single and multiple photon sources [24,25,26,27,28,29,30]. Additionally, the system provides an attractive method for single atom detection [31,32,33,34,35].

2.2 Types of systems

Rydberg atoms in microwave cavities: the strong coupling limit has been achieved in microwave cavity QED experiments employing highly excited (Rydberg) states of neutral atoms. Some of the cleanest entanglement experiments performed to-date have been in these systems. The major obstacle to this implementation is scaling: microwave cavity QED experiments use atomic beams intersecting the cavity to deliver atoms and hence atomic delivery to the cavity is stochastic.

Neutral atoms in optical cavities: the strong coupling regime is also well-established in the neutral atom work with optical cavities. The principle obstacles to be overcome relate to incorporating a scalable trapping geometry using optical and/or magnetic trapping potentials, while still preserving the strong coupling regime. A key element to this challenge is controlling the atomic motion and atom localization so that the coupling is sufficiently well defined.

Trapped ion cavity QED: recently there has been experimental work incorporating linear ion traps with optical cavities [36,37]. Achieving the strong coupling regime is the major outstanding challenge facing this approach. This requires shrinking the cavity size, without adversely affecting the fields confining the ion.

Other systems: there are several related systems that are actively pursued by different groups. These are listed here, but are not included in this section of the roadmap

- Semiconductor quantum dots systems,
- Solid state ion vacancy systems,
- Superconducting junctions + cavity systems, and
- Neutral atom ensemble (many atom) based cavity QED system.

3.0 Summary of Cavity QED 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
   1.1 Spin qubits: long-lived hyperfine states suitable for storing quantum information are available both for neutral atom systems and for trapped ion system. The challenges associated with implementing these qubits are largely the same as for the trapped ion and neutral atom approaches reviewed in other sections of the roadmap and the reader is referred to these sections for further discussion. Some of the distinguishing features and unique challenges are highlighted below.
      1.1.1 Trapped atoms in cavities: a principle challenge to developing this system is to be able to trap individual atoms/ions and arrays of atoms/ions inside the cavity. This has recently been accomplished for single neutral atoms in cavities in the strong coupling regime [38,39,40,41,42,43], and for trapped ions in the weak coupling regime [36,37]. Single atoms have been distinguishably trapped and translated in one-dimensional arrays (atom conveyors) without cavities [44,45], and single and many atoms have been delivered inside of cavities with similar conveyors [35]. Long-range dipole-dipole forces between distant intracavity atoms (but not in a controlled manner) have been observed in [46].
      1.1.2 Photon qubits: cavity QED systems offer photonic or 'flying' qubits as excitations of the cavity mode, or as single photon pulses escaping from through the cavity mirrors. Cavity QED systems can also provide nonlinear photon-photon interactions in the cavity for fields at the single photon level [12]. While optical photons leaking out of the cavity can be readily transported with fibers and can be directly detected efficiently, similarly capabilities are not available in the microwave regime.
   1.2 Motional qubits: motional qubits are also available for trapped ion cavity systems. For neutral atom systems, motional qubits are also available in principle, but experimental work is needed to assess their potential. The reader is referred to ion trapping and neutral atom sections of the roadmap for further discussion.
   1.3 Scalability: the scalability of cavity QED system faces similar challenges to the trapped ion and neutral atom approaches, with the additional constraint that the qubit trapping system and geometry has to be compatible with the small mode volume of the optical resonator. Translating arrays of atoms or ions can be used to enhance scaling, but at a potential cost in the speed of the system. This is a nontrivial constraint that will possibly limit individual cavity QED systems to smaller numbers than their free-space counterparts. Experiments are on-going to address this challenge [35]. Importantly, the cavity QED system lends itself to a distributed QC architecture, whereby relatively small QC nodes will be interconnected with quantum communication channels (optical fibers).

2. Ability to initialize the state of the qubits to a simple fiducial state
   2.1 Spin qubits: hyperfine states are readily initialized using standard optical pumping techniques widely used in atomic physics
   2.2 Motional qubits: motional states of trapped ions and neutral atoms have been initialized by cooling to the ground-state of the trapping potential, however, not yet in cavity QED experiments

2.3 Photon qubits: for optical cavities, initialization to the ground state ('vacuum') is trivial—the thermal occupation of an optical cavity is negligible at room temperature.

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

3.1 Spin coherence

3.1.1 Spin qubit memory: the spin coherence of trapped ions is very long (many minutes) for magnetically insensitive transitions. For neutral atoms, the coherence will be somewhat less due to differential stark shifts from the optical trapping fields [47]

3.1.2 Spin qubit coherence during operations: this relates to the achievement of the strong coupling requirement in cavity QED. This is/can be satisfied by a factor of 2–50 depending on the details of the cavity dimension and atomic transition.

3.2 Photon qubit coherence during operation: this also relates directly to the strong coupling condition. This has been satisfied by factors ranging from 2–50 in recent experiments.

3.3 Motional coherence: motional decoherence caused by trap fluctuation or environmental noise should be negligible on the time-scale of the gate operation. Motional decoherence caused by the gate operation itself needs to be further addressed theoretically [48,49,50] and evaluated experimentally.

4. Universal set of quantum gates

4.1 Single-bit rotations: these can be accomplished with excellent fidelity. These operations are not limited by qubit decoherence, but rather by external noise, noise in the driving field and differential stark shifts (in the case of neutral atom optical traps) [45,47]

4.2 Photon-photon phase gates: several gates have been proposed, and there has been a proof-of-principle demonstration using weak coherent states [12]

4.3 Atom-atom gates: several gates have been proposed [6–8,10,11] and there has been a demonstration experiment in the microwave domain [13]. Gate 'success' rates exceeding 90% are possible based on parameters in current experiments—employing high-efficiency photon detection to measure cavity decay can yield effective fidelities exceeding 99% [6,8,11]. Success rates are very dependent on the cavity geometry and mirror quality—the compromise between the small cavities for strong coupling and allowing for sufficient space for incorporating qubit arrays is a critical aspect of these systems.

4.4 Atom-photon gates: many of the photon-photon and atom-atom gates can be adapted to atom-photon entanglements

5. A qubit-specific measurement capability

5.1 Both individual neutral atoms [45] and trapped ions have been detected in state-sensitive means.

5.2 Cavity QED itself provides an excellent single atom detector that could be employed in other neutral atom-based systems [31–35]

6. The ability to interconvert stationary and flying qubits
   6.1 This is one of the strongest potential applications of cavity QED. The coherent dynamics of the atom—photon interaction has been one of the cornerstones of the field of quantum optics for the last 40 years.

7. The ability to faithfully transmit flying qubits between specified locations
   7.1 Photonic (optical) qubits are readily transported between sites using fibers.

4.0 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
      1.1.1 This has been accomplished for both trapped ion and neutral atom systems, although not in an experimental set-up with a cavity. In microwave cavity QED systems, single qubit preparation and readout has been accomplished for atoms transiting the cavity.
      1.1.2 Single photon 'guns' have been created in atom-cavity systems in both the optical [29,30] and microwave domains [27,28].

2. Single-qubit operations
   2.1 Demonstrate Rabi flops of a qubit
      2.1.1 Rabi flops are readily observed for single trapped ions (see Ion Trap section of Roadmap), and more recently, single trapped neutral atoms [45]
   2.2 Demonstrate high-Q of qubit transition
      2.2.1 Extremely high Q's have been observed in hyperfine transitions, and qubit coherence on the order of seconds to minutes is realistically achieved with proper control of external fields.
   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 operation
      3.1.1 In optical cavity QED, a quantum phase gate has been realized for weak coherent optical fields [12]. A quantum phase gate has also been realized in the microwave domain [13,51]. Both of these experiments utilized atomic beams to provide the atoms.

3.2 Produce and characterize Bell states

3.2.1 Atom-field Bell states have been produced and measured in a microwave cavity system [52]

3.3 Demonstrate decoherence times much longer than two-qubit gate times

3.4 Demonstrate quantum state and process tomography for two qubits.

3.5 Demonstrate a two-qubit decoherence-free subspace (DFS).

3.6 Demonstrate a two-qubit quantum algorithm

4. Operations on 3–10 physical qubits

4.1 Produce a Greenberger, Horne, and Zeilinger (GHZ) entangled state of three physical qubits.

4.1.1 GHZ states have been prepared in a microwave cavity QED system [53]

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.

5.0 Considerations

1. Special strengths

1.1 Ability to interconvert material and photonic qubits

1.2 Source of deterministic single photons and entangled photons
1.3 Cavity QED systems provide viable platforms for distributed quantum computing implementations for both neutral atom and trapped ions
1.4 Well understood systems from a theoretical standpoint. The cavity QED system has been an important paradigm of quantum optics

2. Unknowns, weaknesses
2.1 Ultimate performance of systems is dependent on advances in mirror coating and polishing technologies. Current mirror reflectivities, while adequate to achieve the strong coupling limit, are still ~100 times lower than the theoretical limit imposed by Rayleigh scattering in the coating. Additionally, smaller mirror curvature would provide for large coherent coupling rates.
2.2 The role of the atomic motional degree of freedom in the cavity gate operation and subsequent evolution needs to be better understood both experimentally and theoretically, see e.g. [48–50, 54].
2.3 Other emerging cavity technologies such as whispering gallery mode cavities [55,56] and photonic band gap cavities [57] may provide for stronger coupling and better performance.
2.4 Strategies for control of Rydberg atom localization and control in microwave cavity QED systems need to be developed. It is possible that advances in technology from Rydberg direct atom-atom coupling approaches (discussed in the neutral atom section of the roadmap) could be adapted for the cavity QED system

3. Goals 2002–2007
3.1 Demonstrate high quality single photon generator
3.2 Achieve deterministic entanglement between atoms/ions and photons in optical cavity QED
3.3 Achieve deterministic entanglement between two atoms or ions using the cavity field

4. Goals 2007–2012
4.1 Demonstrate high quality entangled photon pair generator
4.2 Distribute entanglement between two cavity QED based systems
4.3 Demonstrate scalability of system

5. Necessary achievements
5.1 Demonstrate qubit array storage in neutral cavity QED system
5.2 Achieve strong coupling limit in ion trap cavity QED systems
5.3 Further develop mirror technology to increase mirror reflectivity and reduce the mode volume by reducing the mirror curvature

6. Trophies
6.1 Demonstration of a deterministic single photon gun
6.2 Demonstration of atom-field entanglement in an optical cavity QED system
6.3 Demonstration of atom-atom entanglement in an optical cavity QED system

6.4 Demonstration of a deterministic entangled photon source

6.5 Demonstration of entanglement distribution between two cavity systems

7. Connections with other quantum information science technologies

   7.1 Cavity QED is a universal paradigm for intra-converting material-based and photonic-based quantum information

   7.2 Cavity QED systems are some of the cleanest, best-understood 'open' quantum systems to be studied. The lessons learned in cavity QED systems will be widely applicable across different QI implementations

8. Subsidiary developments

   8.1 Improvements in cavity technology will lead to more accurate optical clocks and positively impact a host of precision measurements in both fundamental and applied physics (e.g. LIGO, precision spectroscopy, inertial sensing).

   8.2 Development of high quality optical polishing and coating technologies that will benefit many laser based industrial applications.

   8.3 Improved atomic control can be used to improve atomic clock technologies

9. Role of theory

   9.1 The cavity QED system is one of the foundations of quantum optics. Theoretical research in this field has been prodigious and the general methods and formalisms developed are applicable to many physical implementations of QIP systems.

   9.2 Investigate different 2-qubit gate protocols

   9.3 Develop error-correcting protocols adapted to the decoherence mechanisms specific to the cavity QED system

   9.4 Explore distributed QC architectures employing photonic quantum communication

   9.5 Develop and analyze algorithms and architectures specifically tailored to cavity QED systems

6.0 Timeline

1. Timeline for 2002–2007
   1.1 Refer to the Excel timeline chart below and #3 of "Considerations" (above).

2. Timeline for 2007–2012
   2.1 Refer to the Excel timeline chart below and #4 of "Considerations" (above).

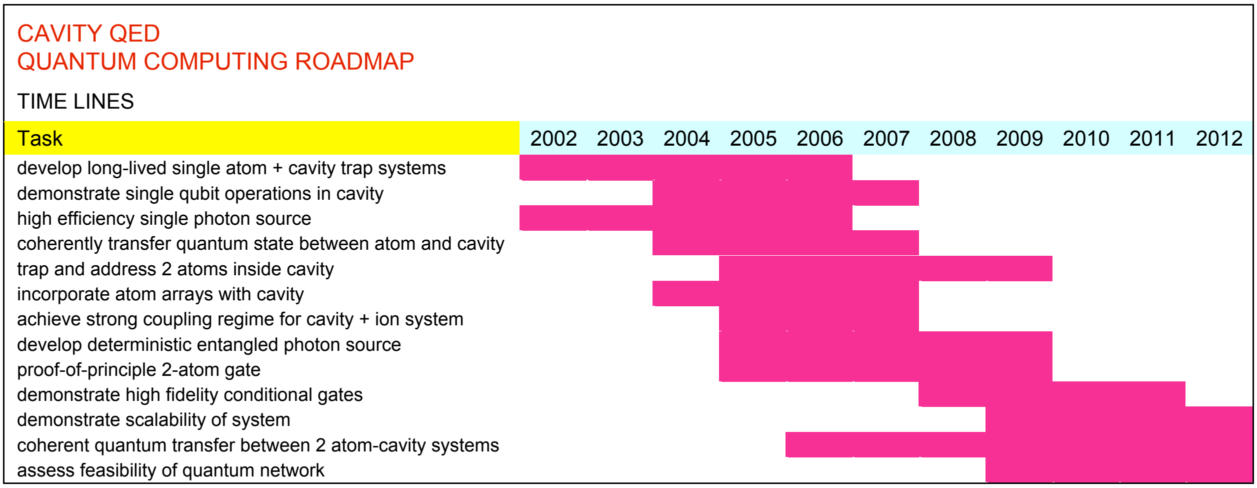

Figure 6-1. Cavity QED QC developmental timeline

7.0 Glossary

8.0 References

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