

Neutral Atom Approaches to Quantum Information Processing and Quantum Computing

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Section 6.3

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List of Acronyms and Abbreviations

3-D	three dimensional
BEC	Bose-Einstein condensate
GHZ	Greenberger, Horne, and Zeilinger
kHz	kilohertz
MHz	megahertz
NMR	nuclear magnetic resonance
QC	quantum computation/ computing
QED	quantum electrodynamics
TEP	Technology Experts Panel

1.0 Groups Pursuing This Approach

Note: This document constitutes the most recent draft of the Neutral Atom 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 Neutral Atom QC Research*

Research Leader(s)	Research Location	Research Focus
Chapman, M. S.	Georgia Tech, Atlanta	magnetic and optical trapping/cavity QED
Cirac, J. I.	Max-Planck-Institute, Garching	Theory
Cote, R.	U. of Connecticut, Storrs	Theory
Deutsch, I. H.	U. of New Mexico	Theory
Ertmer, W. & Birkl, G.	U. of Hannover	optical trapping with micro-optics
Gould, P.	U. of Connecticut, Storrs	optical trapping of Rydberg atoms
Grangier, P.	Institute d'Optique, Orsay	single-atom trapping
Haensch, T. W. & Bloch, I.	Max-Planck-Institute, Garching	BEC/optical trapping
Haroche, S.	Ecole Normale, Paris	cavity QED
Jessen, P. S.	U. of Arizona, Tucson	optical lattices
Kimble, H. J. & Mabuchi, H.	Caltech	cavity QED
Lukin, M.	Harvard, Massachusetts	Theory
Meschede, D.	U. of Bonn	single-atom trapping
Mølmer, K.	U. of Aarhus	Theory
Phillips, W. D. & Rolston, S. L.	NIST Gaithersburg, Maryland	optical lattices
Reichel, J.	U. of Mainz	magnetic microtraps
Saffman, M. & Walker, T. G.	U. of Wisconsin, Madison	optical trapping of Rydberg atoms
Schmiedmayer, J.	U. of Heidelberg	magnetic microtraps
Stamper-Kurn, D.	UC Berkeley, California	magnetic microtraps/cavity QED
Walther, H. & Rempe, G.	Max-Planck-Institute, Garching	cavity QED
Weiss, P.	Penn State, State College	optical lattice/Rydberg atoms
Williams, C. J.	NIST Gaithersburg, Maryland	Theory
You, L.	Georgia Tech, Atlanta	Theory
Zoller, P. & Briegel, H. J.	U. of Innsbruck	Theory

* Including neutral atoms trapped in optical lattices and/or magnetic guides and microtraps.

2.0 Background and Perspective

A system of trapped neutral atoms is a natural candidate for implementing scalable QC [1,2] given the

- simple quantum-level structure of atoms,
- isolation of neutrals from the environment, and
- present ability to trap and act on a very large ensemble of identical atoms.

In much the same way as the groundbreaking work on QC in ion traps [3], such a system builds on years of expertise in coherent spectroscopy developed by the atomic/optical community for application in precision measurements, most notably in atomic clocks. One might argue that a quantum computer is nothing more than a multiatom atomic clock, with controlled interactions between the constituent atoms. More recent advances in laser cooling and trapping technology open the door to unprecedented levels of coherence and control [4], as made evident [5] through the production of Bose-Einstein condensates (BECs) and Fermi degenerate gases.

The architecture of such a computer will depend strongly on the specific trapping techniques and the method for coupling atoms. Two basic interactions can be used to trap neutral atoms: fields interacting with the atom's induced electric dipole moment or with its permanent magnetic dipole moment. The best-studied trapping technology is the optical lattice [6], in which electric dipole-force potential wells are produced by the standing waves of intersecting laser beams. This virtual crystal can be dynamically controlled through the parameters of the trapping lasers or other external fields. Optical dipole forces can also be used to trap atoms in other configurations, such as through engineered micro-optics [7,8,9] and particular configurations of time-varying fields [10]. Magnetic trapping, especially in microtraps [11,12], though less mature, has also been demonstrated.

Trapped atoms can be cooled to the motional ground state of the potential wells, and the internal atomic states can be prepared in a desired initial state using standard techniques of laser spectroscopy. The motional and internal states provide a number of choices of levels for defining qubits. The trap itself and additional fields make available a variety of "handles" for coherent control of the motional and internal states. That the atoms are neutral means that they are relatively poorly coupled to the environment, thus reducing decoherence. By the same token, however, the atoms interact only weakly with one another. Proposals for two-qubit gates rely on

1. moving pairs of atoms into close proximity to increase their coupling (coherent transport of atoms in an optical lattice has been demonstrated [13],
2. turning on briefly much stronger electric-dipole or other interactions, or
3. both of these.

These techniques pose an inherent risk of opening up additional decoherence channels during gate operation.

To implement a neutral-atom quantum computer, the logical encoding for qubits, the method for performing logical operations, and the read-out strategy must all be addressed as a whole, with the design contingent on the specific atom to be used and the trapping technology. For example, parallel operations are natural in the lattice geometry, but because the atoms in a filled

optical lattice are spaced less than a trap-laser wavelength apart, there are difficult questions about how to address individual atoms. Various approaches might be used to overcome this difficulty. As another example, magnetic traps restrict the possible states available for logical encoding, but offer possible advantages for integrating with solid-state devices. Whichever approach proves superior, the highest priority for any experiment is to implement controlled high-fidelity quantum logic operations. This might be achieved in a geometry that does not provide the clearest route to a scalable quantum computer (e.g., ensemble operation without individual addressing), but nonetheless provide the proof-of-principle necessary to design such a scalable system.

3.0 Summary of Neutral Atom QC: The DiVincenzo Criteria

Recognizing that optical lattices are the most mature such technology, this section concentrates on optical lattices, while drawing attention in places to the potential of other trapping techniques.

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 Optical lattices can be loaded with many atoms from a laser-cooled sample or from a BEC.
 - 1.1.1 Approximately a million atoms have been loaded into an optical trap from a laser-cooled sample [14]. Loading of one atom per well in a three-dimensional (3-D) lattice has been achieved by using the transition to a Mott insulator [15]. Designer lattices in which the depth of the wells varies spatially provide the potential for loading more complex configurations. A notable feature for scalability is that the character and properties of the lattice and the trapped atoms don't change in any essential way when going from a smaller to a larger lattice.
 - 1.1.2 A potential problem exists in addressing individual atoms, which are separated by less than a wavelength of the trapping lasers. Possible solutions include the following:
 - 1.1.2.1 Designer lattices with wells separated by more than a wavelength [16].
 - 1.1.2.2 Trapping in a long-wavelength lattice. Resolution of individual Rb atoms has been demonstrated in a CO₂ lattice [17,18] and in a magnetic-trap storage ring [19].
 - 1.1.2.3 Controlled partial loading of the lattice, so that only a well defined subset of the potential wells is occupied [16].

- 1.1.2.4 Use of gradient fields to distinguish atoms in different wells and thus provide individual addressing.
- 1.1.2.5 Use of other trapping techniques for neutral atoms, which provide tighter confinement and/or greater separation. Individual addressing has been achieved with neutrals trapped in optical micro-traps [17], where the atoms are separated by many wavelengths.
- 1.2 The many motional and internal atomic states provide a number of choices for defining qubits.
 - 1.2.1 Internal-state qubits are formed from the ground hyperfine states, which are well characterized by atomic spectroscopy and atomic-clock technology.
 - 1.2.2 Motional qubits are formed from the well characterized quantized levels in the trapping potential.
 - 1.2.3 The many atomic levels other than those chosen to define qubits pose a problem for quantum control because of the potential for leakage outside the qubit state space. The additional levels might be used to advantage, however, as intermediate states in conditional logic operations or in quantum logic involving more than two levels (qudits, instead of qubits).
- 2. The ability to initialize the state of the qubits to a simple fiducial state 
 - 2.1 Internal-state qubits can be prepared reliably in a standard initial state using optical-pumping techniques in use since the 1950s. These techniques can achieve populations in the desired state >0.9999 .
 - 2.2 Motional qubits can be cooled to the motional ground state using techniques of laser cooling and Raman sideband cooling [14,20,21,22,23]. Ground-state populations greater than 95% have been achieved [14].
 - 2.3 Loading of a lattice from a precooled BEC through use of the superfluid–Mott-insulator phase transition has the potential to prepare both internal and motional states reliably.
- 3. Long (relative) decoherence times, much longer than the gate operation time 
 - 3.1 Memory decoherence.
 - 3.1.1 For internal-state qubits (hyperfine states), coherence times are known to be long (μs , ms ~ many minutes), but have not yet been measured and are expected to be highly system specific.
 - 3.1.2 Motional qubits are expected to have a long coherence time because of neutrals' weak coupling to the environment, but the time has not yet been measured.
 - 3.1.3 The fundamental decoherence mechanism for both kinds of qubits in an optical trap is photon scattering. Technical decoherence mechanisms, such as stray magnetic fields, trapping-field fluctuations, and inelastic collisions with background gas, are likely to play a role. Long-term trapping times in an optical lattice are unknown.

- 3.2 Decoherence during gate operations is likely to be a greater problem than memory decoherence. Additional decoherence channels are opened up during gate operations, especially in two-qubit gates, as a consequence of the strong couplings introduced to perform the gate. Issues that need to be addressed experimentally and theoretically for gate-operation decoherence include
- laser-beam intensity stability,
 - pulse timing stability,
 - spontaneous emission during gates that populate levels outside the qubit state space,
 - molecular chemistry during gates that rely on close atomic encounters,
 - unwanted entanglement between internal and motional degrees of freedom, and
 - transitions out of the qubit state space during gate operation.

Fundamental decoherence mechanisms giving decoherence times $\sim 1 \mu\text{s}$, when combined with gate times of $0.1 \mu\text{s}$ to $100 \mu\text{s}$ (determined by lattice trapping frequencies), give a decoherence time/gate time ratio of $10:10^4$. Experiments are needed to get a handle on what is possible.

4. A universal set of quantum gates 
- Single-qubit rotations on atomic systems have been carried out in nuclear magnetic resonance (NMR) and laser spectroscopy since the 1940s.
 - No two-qubit gates have as yet been implemented. Proposals for two-qubit gates are listed below. The speed of gates that involve moving atoms (all except #4.2.1.2 in the following list) is limited by the trap frequency, which lies in the range $10 \text{ kHz} - 10 \text{ MHz}$. Coherent transport of atoms in an optical lattice has been demonstrated [13].
 - Gates based on electric-dipole interactions between pairs of atoms.
 - Optically induced conditional electric-dipole interaction between pairs of atoms brought into close proximity [24,25,26].
 - Electric-dipole interaction via conditional excitation to a Rydberg state [27]. Because this gate does not involve moving atoms, its speed can be set by the strength of the electric-dipole interaction. This gate is potentially insensitive to motional heating. Collective versions of this gate have also been proposed [28].
 - Gates based on ground-state elastic collisions.
 - Cold collisions between atoms conditioned on internal states [29,30].
 - Cold collisions between atoms conditioned on motional-state tunneling [31].
 - Gates based on magnetic dipole interactions between pairs of atoms brought into close proximity [32].
 - Parallel operations for both single-qubit and two-qubit gates are the natural method of operation in optical lattices.

5. A qubit-specific measurement capability 
 - 5.1 The “quantum-jump” method of detection via cycling transitions is a standard technique in atomic physics.
6. The ability to interconvert stationary and flying qubits 
 - 6.1 Cavity-QED (quantum electrodynamics) techniques can be used to convert between atomic-state qubits and photons, although it is not clear whether this capability would be useful in neutral-atom QC.
7. The ability to faithfully transmit flying qubits between specified locations 
 - 7.1 Standard optical techniques can be used to transmit photons from one location to another.

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. 
2. Single-qubit operations
 - 2.1 Demonstrate Rabi flops of a qubit. 
 - 2.2 Demonstrate decoherence times much longer than Rabi oscillation period. 
 - 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. 
 - 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, & 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. 

Tomography of the quantum states of the large angular-momentum hyperfine spaces of Cs atoms trapped in an optical lattice has been demonstrated by Klose [33].

- 4.4 Demonstrate decoherence-free subspaces. 
- 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). 
- 4.9 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. Neutral atoms have a simple well-characterized energy-level structure.
 - 1.2. Neutral atoms start with the obvious advantage of being uncharged, which gives a substantial advantage in terms of weak coupling to the environment and consequent low decoherence for both internal and motional states.
 - 1.3. Laser-cooling and laser-spectroscopy techniques make available high-fidelity initial-state preparation.
 - 1.4. Standard “quantum jump” detection techniques provide efficient readout.
 - 1.5. The lattice geometry makes it easy to perform massively parallel operations.
 - 1.6. There are straightforward paths to scalability—*provided* individual addressing can be achieved or rendered unnecessary by new models for QC.
 - 1.7. Neutral atoms are relatively clean systems for theoretical analysis, particularly compared to condensed systems. Well-developed, often first-principles theoretical understanding and techniques can be used to analyze state preparation, quantum control, and decoherence in neutral-atom systems.

2. Unknowns, weaknesses
 - 2.1. The interactions required for two-qubit gates are less straightforward than, say, for ions. Though theoretical estimates of decoherence times and achievable gate fidelities are encouraging, these need to be demonstrated and measured in experiments.
 - 2.2. Whether individual addressing can be achieved and the extent to which it is necessary is a major open question.
 - 2.3. Error-correction protocols and fault-tolerant computation suitable for the lattice geometry have not yet been designed, although the lattice geometry seems natural for robust “topological” codes.
 - 2.4. Long-term trapping times are unknown.
 - 2.5. To achieve quantum-information-processing goals in this, as in other approaches to quantum computing, generally requires a period of basic research and technology development in the laboratory. Though it is difficult to predict the outcome of such technology development, it must be supported as an essential part of the process of achieving the more glamorous information-processing goals.
3. Goals 2002–2007
 - 3.1. Demonstrate full (arbitrary) two-qubit state manipulation.
 - 3.2. Characterize relevant decoherence mechanisms, especially those that become important during gate operations.
 - 3.3. Demonstrate individual addressing in a trapping environment suitable for quantum information processing or a scheme that circumvents the need for individual addressing.
 - 3.4. Assemble ingredients for simple error correction, say, for spontaneous emission.
4. Goals 2007–2012
 - 4.1. Demonstrate full error correction for several logical qubits.
 - 4.2. Provide a clear path to a scalable system.
5. Necessary achievements
 - 5.1. Demonstrate controlled loading of optical lattice.
 - 5.2. Demonstrate one or more of the proposed two-qubit gates with high enough fidelity to warrant further development.
 - 5.2. Demonstrate one or more of the schemes for individual addressing in a trapping environment suitable for quantum information processing or an alternative scheme that circumvents or reduces the need for individual addressing.
6. Trophies
 - 6.1. Entanglement between motional and internal atomic degrees of freedom in neutral-atom systems.
 - 6.2. Entanglement among two or more qubits as a consequence of one or more two-qubit gate operations.

- 6.3. Continuous measurement of feedback control of atomic dynamics.
 - 6.4. Controlled loading of lattices with complex, well-defined configurations of atoms.
 - 6.5. Demonstration of error-correction protocol for correction of spontaneous-emission errors.
 - 6.6. Demonstration of quantum teleportation in an optical lattice.
 - 6.6. Loading of an optical lattice from a BEC.
 - 6.7. Individual addressing of atoms in an optical lattice for purposes of quantum information processing.
7. Connections with other quantum information science technologies
 - 7.1. Trapping in optical lattices can be married with magnetic microtraps, to take advantage of tighter confinement and thus potentially stronger interactions between atoms, and with cavity QED technology, to take advantage of coupling to photons (flying qubits).
 - 7.2. BECs provide a method for loading traps and might also provide additional possibilities for quantum control.
8. Subsidiary developments
 - 8.1. Trapped neutral atoms provide an avenue to improved signal-to-noise in atomic spectroscopy, with applications to atomic clocks.
 - 8.2. QC techniques can be applied to cooling, state preparation, state manipulation, and detection of the atoms in atomic clocks.
 - 8.3. Developments in quantum control of trapped neutral atoms for QC can be used to control collisions of neutral atoms for study of chemical reactions and of molecular physics.
 - 8.4. Developments in quantum control of trapped neutral atoms can be used to study new states of matters, such as BECs and Mott insulators.
9. Role of theory
 - 9.1. Design and analyze additional two-qubit gates for neutral atoms.
 - 9.2. Study atomic/molecular interactions between neutrals for application to analysis of quantum gates.
 - 9.3. Develop and analyze control tools (e.g., feedback and adaptive measurements, for trapped neutrals).
 - 9.4. Model and characterize decoherence and noise, including effects of molecular chemistry in close collisions.
 - 9.5. Develop error-correction and fault-tolerant protocols suited to optical-lattice geometry.
 - 9.6. Explore QC paradigms suited to massively parallel operations available in lattice geometry (e.g., cellular automata) thereby circumventing the need for individual addressing.

- 9.7. Develop algorithms tailored to the particular sources of decoherence found in neutral-atom traps.
- 9.8. Develop quantum-computing architectures appropriate to neutral atoms.

6.0 Timeline

Each section of the timeline (5-year and 10-year) is broken out by period, with tasks for each period. *Critical-path, necessary achievements* are indicated by italics.

1. Timeline for 2002–2007
 - 1.1 Period 1: 2002–2004
 - 1.1.1 3-D lattice cooled to the motional ground state
 - 1.1.2 Preparation of internal states
 - 1.1.3 Arbitrary single-qubit control
 - 1.1.4 *Proof-of-principle two-qubit gates*
 - 1.1.5 Projective measurements on ensemble of lattice atoms
 - 1.1.6 Ensemble process tomography
 - 1.2 Period 2: 2005–2007
 - 1.2.1 *Controlled loading of lattice*
 - 1.2.2 High-fidelity two-qubit gates
 - 1.2.3 *Full (arbitrary) two-qubit control*
 - 1.2.4 *Individual addressing or alternative*
 - 1.2.5 *Measurements of individual atoms*
 - 1.2.6 Continuous measurement and feedback
 - 1.2.7 Individual-atom process tomography
2. Timeline for 2007–2012
 - 2.1 Period 1: 2008–2009
 - 2.1.1 Encoding logical qubit
 - 2.1.2 Using ancilla to diagnose errors
 - 2.1.3 *Simple error-correction protocol*
 - 2.1.4 Additional cooling beyond initialization
 - 2.1.5 Refreshing ancilla
 - 2.2 Period 2: 2010–2012
 - 2.2.1 Full error correction for several logical qubits
 - 2.2.2 Begin full-system integration

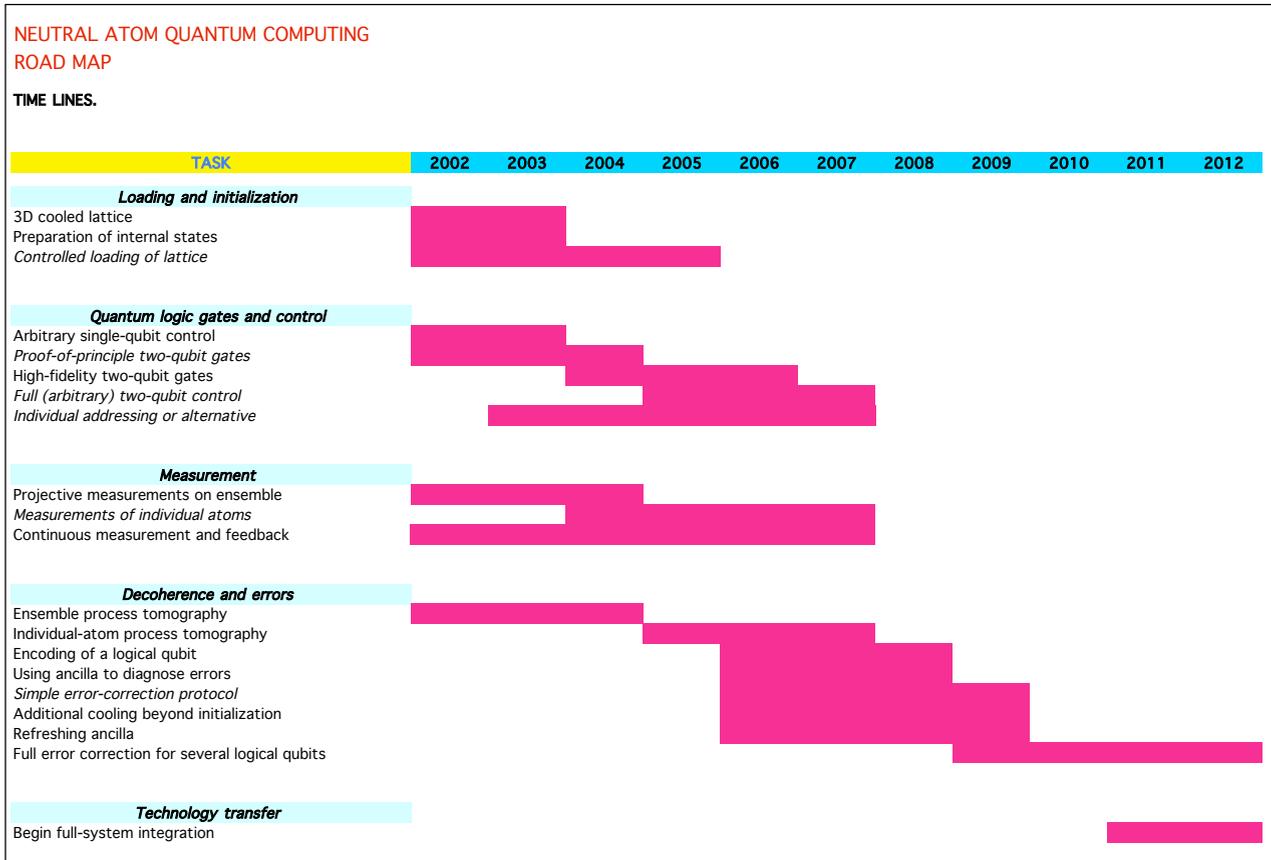


Figure 6-1. Neutral atom QC developmental timeline

7.0 Glossary

Bose-Einstein condensate

A state of a tenuous, very low-temperature gas in which all the atoms occupy the same motional quantum state; typically all the atoms are essentially at rest.

cavity quantum electrodynamics (QED)

Individual atoms interacting with the strong electromagnetic field inside a small optical-frequency cavity.

magnetic microtrap

A configuration of magnetic fields in which atoms can be trapped in the regions of strongest field strength via the interaction of the atomic magnetic-dipole moments with the magnetic field.

optical dipole force

When an atom is exposed to light, the electric field of the light induces an optical-frequency electric-dipole moment in the atom, and then the electric field exerts a DC optical dipole force on the induced dipole.

optical lattice

A pattern of standing light waves created by the interference of intersecting laser beams; neutral atoms can be trapped in the standing-wave pattern by optical dipole forces.

optical microtrap

A configuration of tightly focused light beams; atoms can be trapped by optical dipole forces in the regions of greatest light intensity.

qudit

A quantum system where more than two Hilbert-space dimensions are used for quantum information processing, as opposed to the two dimensions used in a qubit.

Rydberg atom

An atom with one valence electron that has been excited to a high-lying (Rydberg) energy level.

8.0 References

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