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Professor Harry Kimble

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ABSTRACT

One of the promising models for scalable quantum computation utilizes polarizations of single-photon pulses as qubits. The critical and difficult tasks for this approach include how to generate deterministically well-controlled single-photon pulses, how to make efficient single-photon detections, and in particular, how to realize controlled quantum gate operations between these pulses. Based on the state-of-the-art cavity technology, we propose to use a high-Q ?cavity with a single-trapped atom as the critical resource to fulfill all these difficult tasks. In particular:

We propose experiments to use a single atom in an optical cavity to generate deterministically single-photon pulses and multi-partite entanglement between the pulses.

We propose an efficient scheme for quantum gate operations between these photonic qubits by coherent interactions of the single-photon pulses from the single-atom cavity. This method is scalable, robust to important practical noise, and fits well the experimental capabilities. We will achieve proof-of-principle experiments for these quantum gate operations.

We propose to use the single-atom cavity as an efficient quantum non-demolition detector of single photon pulses. Its efficiency can be significantly higher than conventional detectors, and can detect the photon without destroying it. These features enable many important applications.

We propose to study efficient quantum error correction for our model of quantum computation. Due to its special noise properties, it is possible with this setup to find error thresholds significantly better than those in existing analyses for large-scale fault-tolerant quantum computation.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0

(c) Presentations

Number of Presentations: 0

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Number of Manuscripts:

Books

Number of Books:

Honors and Awards

Titles of Patents disclosed during the reporting period

Number of Patents disclosed during the reporting period:

Patents Awarded during the reporting period

Number of Patents awarded:

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Faculty

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Under Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Masters Degrees Awarded

NAME
Total Number:

PHDs Awarded

NAME
Total Number:

Other Research Staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Technology transfer (any specific interactions or developments which would constitute technology transfer of the research results). Examples include patents, initiation of a start-up company based on research results, interaction with industry/Army RD Lab

Scientific progress and accomplishments (Description should include significant theoretical or experimental advances)

The principal laboratory advances over the past year have been (1) the observation of strong coupling for the interaction of single Cesium atoms with a monolithic microresonator (i.e., the whispering-gallery modes of a toroidal, fused silica resonator) [T. Aoki, B. Dayan, E. Wilcut, W. P. Bowen, A. S. Parkins, H. J. Kimble, T. J. Kippenberg, and K. J. Vahala, Nature (in press, 2006); available as quant-ph/0606033] and (2) cooling to the ground of motion for one atom strongly coupled to an optical cavity, thereby bringing both the internal and external quantum degrees of freedom under control for the first time in cavity QED [A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, Phys. Rev. Lett. 97, 083602 (2006)]. On a theoretical front, the principal advances have been (1) a new scheme for efficient quantum computation with probabilistic gates that functions even if all the entangling quantum gates only succeed with an arbitrarily small probability p [L. M. Duan and R. Raussendorf, Phys. Rev. Lett. 95, 080503 (2005)] and (2) an extension of existing theoretical models of cavity QED to include now multiple hyperfine levels, which is essential as the coherent coupling of atom and cavity field becomes comparable to or larger than atomic hyperfine splittings [K. M. Birnbaum, A. S. Parkins, and H. J. Kimble, submitted to PRA; available as quant-ph/0606079].

Please note: the Forecast Expenditure section of the report indicates in the part "Anticipated Total Award" amount of $775,000. The proposal amount is $900,000. The forecast expenditures for the proposed period of extension are $125,000, **Agreement Period:** From: 01-Jun-2004 To: 31-May-2007. June 2006 Professor Kimble received $175,000 and anticipates receiving the final disbursement of $125,000 January 2007, which brings the total funding to $900,000.The same issue regarding the funding on the past, Aug. 2005, Interim Progress Report. The action taken was that Monica Williams faxed me, Scott Curtis, a corrected "Forecast Expenditure Report by Proposal" form for Dr. Kimble to review and sign, I faxed that form back on December 28, 2005 to fax# 919-549-4384. Dr. Kimble and I received an email from Ms. Monica Williams on December 28, 2005 at 6:22 a.m. stating the funds are available.

Scientific Progress and Accomplishments -- 2004-2005
[2004-2005]

The principal laboratory advances over the past year have been (1) the observation of the vacuum-Rabi spectrum for an individual atom trapped in an optical cavity [A. Boca, R. Miller, K. M. Birnbaum, A. D. Boozer, J. McKeever, and H. J. Kimble, Phys. Rev. Lett. 93, 233603 (2004)], (2) the attainment of photon blockade for an optical cavity containing a single trapped atom [K. M. Birnbaum, A. Boca, R. Miller, A. D. Boozer, T. E. Northup, and H. J. Kimble, Nature (in press, 2005)], and (3) the construction of a new apparatus for cavity QED with single atoms coupled to the fields of ultrahigh-Q toroidal microresonators [S. M. Spillane, T. J. Kippenberg, K. J. Vahala, K. W. Goh, E. Wilcut, and H. J. Kimble, Phys. Rev. A 71, 013817 (2005)].

The principal theoretical advances have been (1) the detailed characterization of our theoretical model for scalable photonic quantum computation [B. Wang and L.-M. Duan, in preparation for submission to PRA], (2) the development of a new scheme for engineering states of photon pulses, including Schroedinger cat states, through cavity-assisted interaction of coherent optical pulses [B. Wang and L.-M. Duan, Phys. Rev. A 72 (in press, 2005); available as quant-ph/0411139], and (3) the introduction of a new scheme to achieve quantum computation with neutral atoms whose interactions are catalyzed by single photons [L.-M. Duan, B. Wang, H. J. Kimble, Phys. Rev. A (in press, 2005); available as quant-ph/0505054].

Scientific Progress and Accomplishments -- 2005-2006
[2005-2006]

The principal laboratory advances over the past year have been (1) the observation of strong coupling for the interaction of single Cesium atoms with a monolithic microresonator (i.e., the whispering-gallery modes of a toroidal, fused silica resonator) [T. Aoki, B. Dayan, E. Wilcut, W. P. Bowen, A. S. Parkins, H. J. Kimble, T. J. Kippenberg, and K. J. Vahala, Nature (in press, 2006); available as quant-ph/0606033] and (2) cooling to the ground of motion for one atom strongly coupled to an optical cavity, thereby bringing both the internal and external quantum degrees of freedom under control for the first time in cavity QED [A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, Phys. Rev. Lett. **97**, 083602 (2006)]. On a theoretical front, the principal advances have been (1) a new scheme for efficient quantum computation with probabilistic gates that functions even if all the entangling quantum gates only succeed with an arbitrarily small probability p [L. M. Duan and R. Raussendorf, Phys. Rev. Lett. **95**, 080503 (2005)] and (2) an extension of existing theoretical models of cavity QED to include now multiple hyperfine levels, which is essential as the coherent coupling of atom and cavity field becomes comparable to or larger than atomic hyperfine splittings [K. M. Birnbaum, A. S. Parkins, and H. J. Kimble, submitted to PRA; available as quant-ph/0606079].

Report for the grant "Photonic Quantum Computation through Cavity Assisted Interaction" from DTO

Luming Duan

This is a grant in collaboration with Prof. Jeff Kimble at Caltech. The goal of this project is to propose and demonstrate a new approach to quantum information based on cavity assisted photon interaction. My team at Michigan is responsible for the theory part. Within this project, we have achieved our goals with the following advance:

- We have found a new scheme for photonic quantum computation with cavity assisted photon interaction, and have fully characterized the noise in this system and the noise influence on the quantum information protocols.
- We have found a more efficient method to correct the specific noise in this system, and have come up with a protocol to realize scalable quantum computation based on the use of probabilistic gates.
- We have found several other applications of this physical system, including the implementation of quantum finger printing and a scheme for scalable quantum state engineering.

We have published a number of papers associated with this project, which are listed as follows:

[1]. B. Wang, L.-M. Duan, Implementation of controlled SWAP gates for quantum fingerprinting and photonic quantum computation, quant-ph/0610035, **Phys. Rev. A (Rapid Communication) 75**, 050304 (R) (2007).

[2]. T. P. Bodiya, L.-M. Duan, Scalable Generation of Graph-State Entanglement through Realistic Linear Optics, quant-ph/0605058, **Phys. Rev. Lett.** 97, 143601 (2006).

[3]. L.-M. Duan and R. Raussendorf, Efficient quantum computation with probabilistic quantum gates, quant-ph/0502120, **Phys. Rev. Lett.** 95, 080503 (2005).

[4]. L.-M. Duan, B. Wang, H. J. Kimble, Robust quantum gates on neutral atoms with cavity-assisted photon-scattering, quant-ph/0505054, **Phys. Rev. A** 72, 032333 (2005).

[5]. B. Wang, L.-M. Duan, Engineering Schrodinger cat states through cavity-assisted interaction of coherent optical pulses, quant-ph/0411139, **Phys. Rev. A** 72, 022320 (2005).

[6]. L.-M. Duan, J. Kimble, *Scalable photonic quantum computation through cavity assisted interaction,* **Phys. Rev. Lett.** 92, 127902 (2004).

Photonic Quantum Computation through Cavity Assisted Interaction

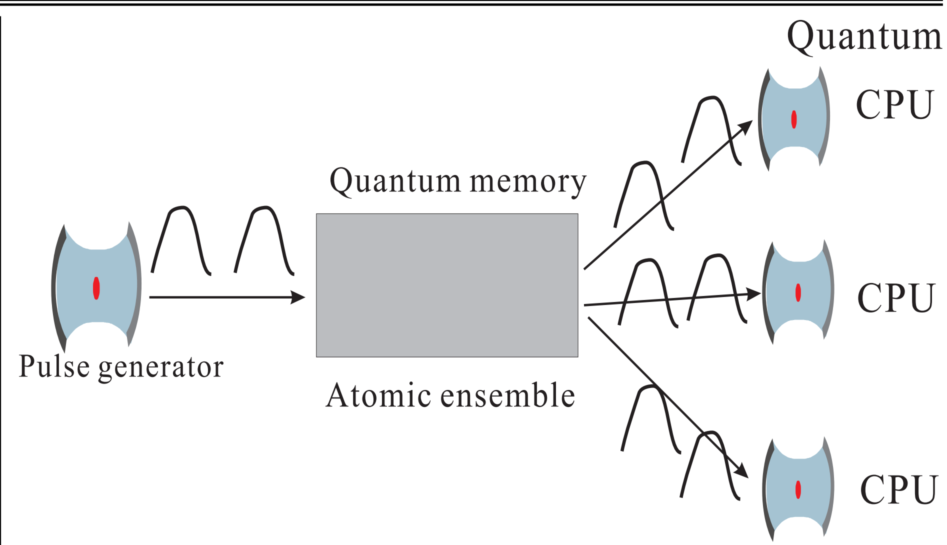
H. Jeff Kimble, Caltech; L.-M. Duan, U Michigan
hjkimble@caltech.edu / www.its.caltech.edu/~qoptics

Objective

- Demonstration of a new protocol for scalable quantum computation and communication by way of photon – photon interactions mediated by 1 atom in a cavity
- Realization of efficient quantum error correction, with the possibility of significantly improved error thresholds for fault-tolerant quantum computation

Objective Approach

- Single atoms trapped in optical cavities in a regime of strong coupling
  - Source of single photons "on demand"
  - Implementation of controlled phase gates between any two photons *j*, *k*
- Intrinsic robustness against principal sources of error, including uncertainty in the atom-photon coupling rate and errors due to atomic spontaneous emission



Photonic Quantum Computation through Cavity-Assisted Interaction

H. Jeff Kimble, Caltech; L.-M. Duan, U Michigan

- Progress on last year's objectives

- New start – 1 June, 2004

- Research plan for the next 12 months

- To achieve an experimental demonstration of a controllable single-photon source from a single-trapped atom inside a high-finesse cavity in the region of strong coupling. The goal is to implement a source with full control of the spatial mode of the photon emission, and of the time and pulse shape for the emission. We will investigate the factors that degrade the efficiency of photon generation and which lead to multiple photon emissions in a single generation cycle. We will work to gain full control of the internal atomic state for coherent manipulation.

- To establish firmly a theoretical model of photonic quantum computation with detailed calculations of the influence of relevant experimental sources of noise. The goal is to determine optimal configurations for experimental implementations. For instance, we will consider the influence of temporally varying detunings of the various atomic levels due to random motion of the trapped atom. We will simulate numerically the influence on the conditional phase of asymmetry in the shape and detuning of the single-photon pulses. We will also consider multi-photon possibility in the input pulse, and propose methods to generate non-classical Schrodinger cat states from weak coherent-state inputs.

- Long term objectives (demonstrations)

- After this three-year project, we will have established an innovative and competitive approach to scalable quantum computation based on cavity assisted interaction through firm theoretical models and demonstration-of-principle experiments. We will also have achieved a deterministic and controllable single-photon source and a high-efficiency QND single-photon detector, which have wide applications for photonic quantum information processing.

- Because photons and optical cavities play a critical role for quantum communication, our approach to quantum computation naturally integrates quantum computation and communication, and will constitute an important avenue for building future scalable quantum computers and quantum networks.

Photonic Quantum Computation through Cavity Assisted Interaction

H. Jeff Kimble, Caltech; Luming Duan, U Michigan
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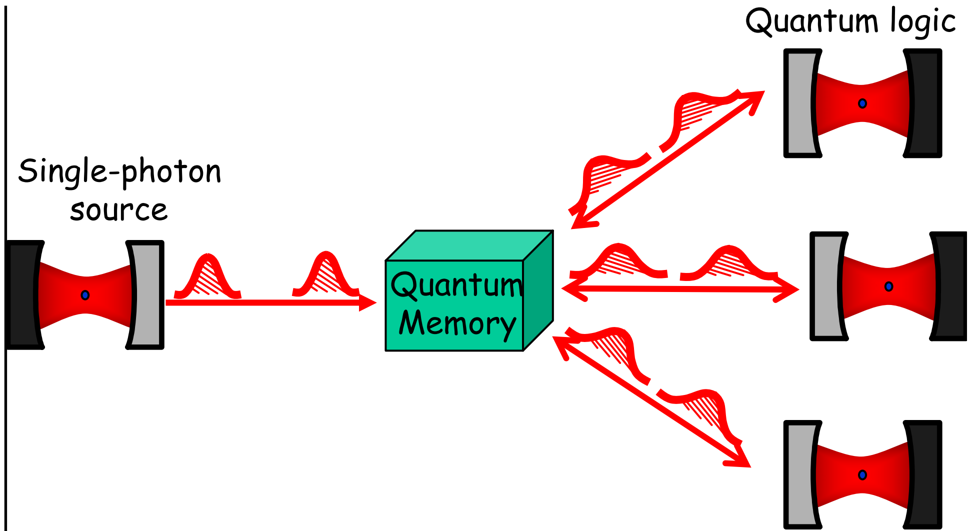
Objective

• Demonstration of a new protocol for scalable quantum computation and communication by way of photon–photon interactions mediated by 1 atom in a cavity
• Realization of efficient quantum noise reduction, with the possibility of significantly improved error thresholds for fault-tolerant quantum computation



Objective Approach

• Single atoms trapped in optical cavities in a regime of strong coupling
  • Source of single photons "on demand"
  • Implementation of controlled phase gates between any two photons *j*, *k*
• Intrinsic robustness against principal sources of error, including uncertainty in the atom-photon coupling rate and errors due to atomic spontaneous emission

Status

• Generation of single photons "on demand"
  • J. McKeever et al., Science **303**, 1992 (2004)
• Observation of the vacuum-Rabi spectrum for 1trapped atom
  • A. Boca et al., Phys. Rev. Lett. **93**, 233603 (2004)
• Realization of photon blockade by an optical cavity with 1 atom
  • K. M. Birnbaum, Nature **436**, 87 (2005)
• Cavity QED with single atoms and micro-toroidal resonators
  • Theoretical analysis [Spillane et al., PRA **71**, 013817 (2005)]
  • New apparatus built with μ–toroids and cold atoms in place
• Detailed characterization of the theoretical model
  • Duan, Kimble, PRL **92**, 127902 (2004) ; B. Wang et al., in preparation for PRA
• Quantum state engineering of photons with the single-atom cavity
  •B. Wang, L.-M. Duan, PRA **72** (in press, 2005)

Photonic Quantum Computation through Cavity-Assisted Interaction

H. Jeff Kimble, Caltech; Luming Duan, U Michigan

• Progress on last year's objectives – FY04-05

- "To achieve an experimental demonstration of a controllable single-photon source"
  - Initial demonstration of single-photon generation "on demand" – J. McKeever et al., Science **303**, 1992 (2004)
  - Progress in control of external and internal degrees of freedom for 1 atom strongly coupled to optical cavity – A. Boca et al., Phys. Rev. Lett. **93**, 233603 (2004); K. M. Birnbaum, Nature **436**, 87 (2005)
  - Technical advances related to cooling and coherent control of internal degrees of freedom
    - Noise source identified for Raman cooling of axial motion and a new setup developed to eliminate the noise
    - New protocol for the generation of polarized photons
- "To establish firmly a theoretical model of photonic quantum computation"
  - Characterization of various noise and imperfections in the photonic quantum computation model – Duan, Kimble, PRL **92**, 127902 (2004); B. Wang et al., in preparation for PRA
  - Methods to engineer states of photon pulses with the single-atom setup – Wang & Duan, PRA **72**, in press 2005

• Research plan for the next 12 months – FY05-06

- Implement a new scheme for cooling to the ground state of axial motion for 1 strongly coupled atom
- Demonstrate strong coupling in cavity QED for single atoms coupled to the evanescent fields of μ–toroidal resonators
- Generate entanglement between 1 intracavity atom and 1 "flying" photon [atomic Zeeman and field polarization states]
- Extend our photonic quantum computation scheme for other applications, including atomic gates and tele-computation
- Investigate more efficient methods for combating noise in photonic quantum computation

•Long term objectives (demonstrations)

- To establish a competitive approach to scalable quantum computation based on cavity-assisted photonic interactions
- To achieve a deterministic and controllable single-photon source and a high-efficiency QND single-photon detector
- To integrate quantum computation and communication as an important avenue for building future scalable quantum computers and quantum networks

Photonic Quantum Computation through Cavity Assisted Interaction

H. Jeff Kimble, Caltech; Luming Duan, U Michigan

hjkimble@caltech.edu / www.its.caltech.edu/~qoptics

Objective

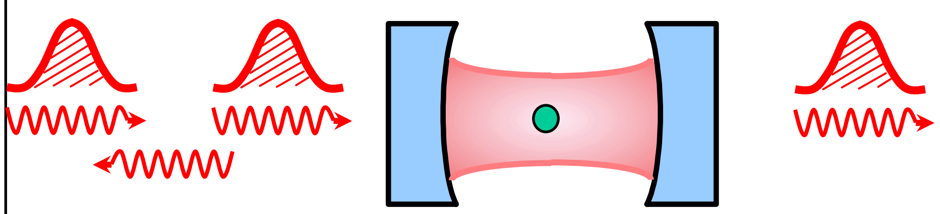
• Demonstration of a new protocol for scalable quantum computation and communication by way of photon–photon interactions mediated by 1 atom in a cavity

• Realization of efficient quantum noise reduction, with the possibility of significantly improved error thresholds for fault-tolerant quantum computation

<u>Photon Blockade</u>

Nature **436**, 87 (2005)

Beyond traditional nonlinear optics



Objective Approach

• Single atoms trapped in optical cavities in a regime of strong coupling

- • Source of single photons "on demand"
- • Implementation of controlled phase gates between any two photons *j*, *k*

• Intrinsic robustness against principal sources of error, including uncertainty in the atom-photon coupling rate and errors due to atomic spontaneous emission

Status

• Generation of single photons "on demand"

- • J. McKeever et al., Science **303**, 1992 (2004)

• Observation of the vacuum-Rabi spectrum for 1 trapped atom

- • A. Boca et al., Phys. Rev. Lett. **93**, 233603 (2004)

• Realization of photon blockade by an optical cavity with 1 atom

- • K. M. Birnbaum, Nature **436**, 87 (2005)

• Observation of single atoms strongly coupled to the evanescent field of a μ–toroidal resonator [Spillane et al., PRA **71**, 013817 (2005)]

- • Manuscript available as quant-ph/0606033

• Extension of the theoretical model

- • Duan, Kimble, PRL **92**, 127902 (2004); Duan, Wang, Kimble, PRA **72**, 032333 (2005)

• Quantum state engineering of photons with the single-atom cavity

- •B. Wang, L.-M. Duan, PRA **72**, 022320 (2005)

Photonic Quantum Computation through Cavity-Assisted Interaction

H. Jeff Kimble, Caltech; Luming Duan, U Michigan

• Progress on last year's objectives – FY05-06

- "Implement a new scheme for cooling to the ground state of axial motion for 1 strongly coupled atom"
    - *Measurements completed; manuscript in preparation. Observations are consistent with 1 trapped atom in the quantum ground state for axial motion with approximately 95% probability.*
- "Demonstrate strong coupling in cavity QED for single atoms coupled to the evanescent fields of μ–toroidal resonators"
    - *Manuscript describing the first observation of strong coupling for single atoms coupled to a monolithic optical cavity, here a micro-toroidal resonator – quant-ph/0606033*
- "Generate entanglement between 1 intracavity atom and 1 "flying" photon [atomic Zeeman and field polarization states]"
    - *Extensive effort still underway to achieve well-defined initial atomic Zeeman state and to implement an unambiguous measurement protocol for atom-photon entanglement.*
- "Extend our photonic quantum computation scheme for other applications, including atomic gates and tele-computation"
    - *A robust atomic gate catalyzed by cavity assisted photon interaction [Duan, Wang, Kimble, PRA 05]*
- "Investigate more efficient methods for combating noise in photonic quantum computation"
    - *Partial progress, engineering of graph states that tolerate large noise [Bodiya, Duan, in preparation]*

• Research plan for the next 12 months – FY06-07

- Generate entanglement between 1 intracavity atom and 1 "flying" photon [atomic Zeeman and field polarization states]
- Develop schemes for trapping single atoms in the evanescent fields of μ–toroidal resonators in a regime of strong coupling
- Demonstrate a "photon switchyard" suitable for the protocol of Duan-Kimble, Phys. Rev. Lett. **92**, 127902 (2004)
- A hybrid version of atomic-photonic gate for controlled swaps and quantum finger printing
- Noise-resilient photonic quantum computing and state engineering based on graph states

• Long term objectives (demonstrations)

- To establish a competitive approach to scalable quantum computation based on cavity-assisted photonic interactions
- To achieve a deterministic and controllable single-photon source and a high-efficiency QND single-photon detector
- To integrate quantum computation and communication as an important avenue for building future scalable quantum computers and quantum networks

Photonic Quantum Computation through Cavity Assisted Interaction

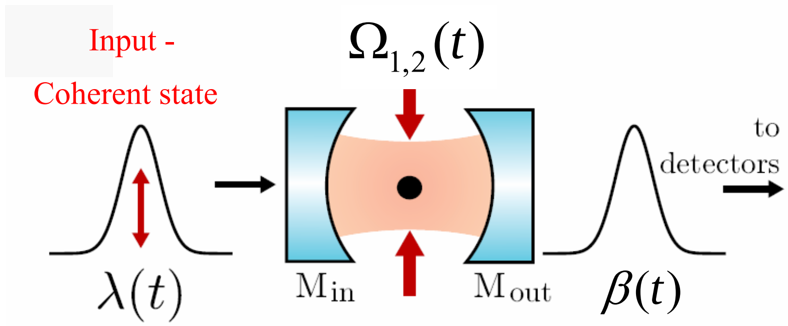
H. Jeff Kimble, Caltech; Luming Duan, U Michigan
hjkimble@caltech.edu / www.its.caltech.edu/~qoptics

Objective

• Demonstration of a new protocol for scalable quantum computation and communication by way of photon–photon interactions mediated by 1 atom in a cavity
• Realization of efficient quantum noise reduction, with the possibility of significantly improved error thresholds for fault-tolerant quantum computation

Reversible State Mapping

Phys. Rev. Lett. **98**, 193601 (2007)
An essential capability for quantum networks



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• Single atoms trapped in optical cavities in a regime of strong coupling
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  • J. McKeever et al., Science **303**, 1992 (2004)
• Realization of photon blockade by an optical cavity with 1 atom
  • K. M. Birnbaum, Nature **436**, 87 (2005)
• Observation of single atoms strongly coupled to the evanescent field of a μ–toroidal resonator [Spillane et al., PRA **71**, 013817 (2005)]
  • T. Aoki, Nature **443**, 671 (2006)
• Demonstration of reversible mapping: field → atom → field
  • A. D. Boozer et al., Phys. Rev. Lett. **98**, 193601 (2007)
• Extension of the theoretical model
  • Duan, Kimble, PRL **92**, 127902 (2004); Duan, Wang, Kimble, PRA **72**, 032333 (2005)
• Quantum state engineering of photons with the single-atom cavity
  •B. Wang, Duan, PRA **72**, 022320 (2005), Bodiya, Duan PRL, 97, 143601 (2006).

Photonic Quantum Computation through Cavity-Assisted Interaction

H. Jeff Kimble, Caltech; Luming Duan, U Michigan

• Progress on last year's objectives – FY06-07

- Generate entanglement between 1 intracavity atom and 1 "flying" photon [atomic Zeeman and field polarization states]
  - *As a step toward this goal, we have made the first demonstration of reversible transfer of quantum states to/from an atom trapped in a cavity [Boozer et. al, PRL **98**, 193601 (2007); available as quant-ph/0702248]*
- Develop schemes for trapping single atoms in the evanescent fields of μ–toroidal resonators in a regime of strong coupling
  - *Theoretical investigations are in progress, and a new apparatus is being built to test various schemes.*
- Demonstrate a "photon switchyard" suitable for the protocol of Duan-Kimble, Phys. Rev. Lett. **92**, 127902 (2004)
  - *Fiber optic components have been specially fabricated and implementation is underway.*
- A hybrid version of atomic-photonic gate for controlled swaps and quantum finger printing
  - *A scheme was found with theoretical characterization [Wang, Duan, quant-ph/0610035, under review]*
- Noise-resilient photonic quantum computing and state engineering based on graph states
  - *A method was found with a single-atom cavity as the photon source [Bodiya, Duan, PRL 97,143601 (2006).]*

• Research plans for coming year – FY07-08

- DTO/ARO STIC grant "Photonic Quantum Computation through Cavity-Assisted Interaction" expires October 1, 2007
- New funding has been requested from DTO/ARO
  - "Quantum Logic and Communication with Single Atoms and Photons"
- Research goals for this proposal include the following:
  - Nonlinear interactions between single photons and atoms in a microtoriodal resonator
  - Generation of nonclassical fields from the interaction of one atom with the field of a microtoroidal resonator
  - Trapping one atom in the evanescent field of the microtoroid
  - Improvement in quality factors for microtoroidal resonators from $Q \leq 10^8$ to $Q > 10^9$ at 850 nm
  - Quantum interactions of multiple atom-resonator systems mediated by single-photon pulses

Final Progress Report Presentation List
Grant No.: W911NF-04-1-0201
Title: "STIC: Photonic Quantum Computation through Cavity Assisted Interaction"

1. "Cavity QED with Single Atoms and Photons," H. J. Kimble, FOCUS Workshop on Building Computational Devices Using Coherent Control (invited speaker), Ann Arbor, Michigan, (6/9/04).

2. "Cavity QED with Single Atoms and Photons," H. J. Kimble, 2004 IEEE/LEOS Summer Topical Meeting (invited speaker), San Diego, California, (6/28/04).

3. "Cavity QED with Single Atoms and Photons," H. J. Kimble, International Conference on Atomic Physics (invited speaker), Rio de Janeiro, (7/26/04).

4. "Cavity QED with Single Atoms and Photons," H. J. Kimble, Workshop on Microcavities in Quantum Optics (invited speaker), Lake Tegernsee, Bavaria, Germany, (9/23/04).

5. "Cavity QED -- from Purcell and Casimir to the Era of Strong Coupling for Single Atoms and Photons," H. J. Kimble, Quantum Information & Coherence (QUIC) Seminar Series (invited speaker), Naval Research Lab, Washington DC, (11/5/04).

6. "Quantum Information Science Enabled by Quantum Optics," H. J. Kimble, Complexity, Entropy and the Physics of Information (CEPI) Seminar Series (invited speaker), Santa Fe Institute, Santa Fe, New Mexico, (1/19/05).

7. "Cavity QED -- from Purcell and Casimir to the Era of Strong Coupling for Single Atoms and Photons," H. J. Kimble, Physics Colloquium (invited speaker), University of British Columbia, Vancouver, Canada, (2/10/05).

8. "Cavity QED with Single Atoms and Photons," H. J. Kimble, 2005 APS March Meeting (invited speaker), Los Angeles, California, (3/21/05).

9. "Exploring the Jaynes-Cummings ladder: experiments in cavity QED," T. Northup, Physics Colloquium (invited speaker), U.S. Air Force Academy, Colorado Springs, Colorado, (3/31/05).

10. "The Quantum Optics Circus -- Flying Photons, Acrobatic Atoms, and Teleported Tuataras," H. J. Kimble, Year of Physics Series, CosmoCaixa Science Museum (invited speaker), Barcelona, Spain, (4/7/05).

11. "Cavity QED with Single Atoms and Photons," H. J. Kimble, Seminar, Universitat Autonoma de Barcelona (invited speaker), Barcelona, Spain, (4/8/05).

12. "The New Science of Quantum Information: From Quantum Computers to Teleportation of Quantum States," H. J. Kimble, Public Lecture, Welsh Lecture (invited speaker), University of Toronto, Toronto, Canada, (4/21/05).

13. "Quantum Dynamics with Single Atoms and Photons," H. J. Kimble, Colloquium, Welsh Lecture (invited speaker), University of Toronto, Toronto, Canada, (4/21/05).

14. "Cavity QED with single atoms and photons," T. Northup, JILA (invited speaker), University of Colorado at Boulder, Boulder, CO, (4/22/05).

15. "Observation of the Vacuum-Rabi Spectrum for One-and-the-Same Trapped Atom," H. J. Kimble, APS DAMOP Meeting (invited speaker), Lincoln, NE, (05/21/05).

16. "Quantum Optics as Enabling for Quantum Information Science," H. J. Kimble, SPIE Meeting on Fluctuations and Noise FaN05 (plenary lecture), Austin, TX, (5/24/05).

17. "Progress in Cavity QED with Single Trapped Atoms," R. Miller, IQEC/CLEO-PR (invited speaker), Tokyo, Japan, (7/15/05).

18. "Quantum Control of Single Atoms and Photons in Cavity QED," H. J. Kimble, 2005 GRC: Quantum Control of Light and Matter (invited speaker), Waterville, ME, (8/5/2005).

19. "Cavity QED with Single Atoms and Photons," H. J. Kimble, 8th International Symposium on Foundations of Quantum Mechanics in the Light of New Technology (invited speaker), Tokyo, Japan, (8/20/2005).

20. "Quantum Optics as Enabling for Quantum Information Science," H. J. Kimble, FOCUS Distinguished Lecturer Colloquium (invited speaker), University of Michigan, Detroit, MI, (10/7/2005).

21. "Scalable Quantum Networks with Atoms and Photons," H. J. Kimble, 2005 Frontiers in Optics-89th OSA Annual Meeting & APS Laser Science XXI (invited tutorial lecture), Tucson, AZ, (10/17/2005).

22. "Cavity QED and Atomic Ensembles," H. J. Kimble, Quantum Repeater Workshop for Long-Distance Communication (invited speaker), Harvard University, Cambridge, MA, (11/3/2005).

23. "The Quantum Optics Circus: Flying Photons, Acrobatic Atoms, and Entangled Ensembles," H. J. Kimble, Department of Physics Colloquium, Niels Bohr Institute (invited speaker), Copenhagen, Denmark, (11/17/2005).

24. "The Light-Matter Interface: Atoms in Cavities and Atomic Ensembles," H. J. Kimble, Symposium on Quantum Information, Royal Danish Academy of Sciences and Letters (invited speaker), Copenhagen, Denmark, (11/18/2005).

25. "The Quantum Optics Circus – Flying Photons, Acrobatic Atoms, and Entanglement Ensembles," H. J. Kimble, ACU Math/Science Centennial Conference, Abilene Christian University (invited plenary speaker), Abilene, TX, (1/27/2006).

26. "Quantum Optics with Single Atoms and Photons," H. J. Kimble, Stanford Physics Colloquium, Stanford University (invited speaker), Stanford, CA, (2/14/2006).

27. "The Quantum Optics Circus – Flying Photons, Acrobatic Atoms, and Entanglement Ensembles," H. J. Kimble, Center for Ultracold Atoms (CUA) Seminar, MIT (invited speaker), Cambridge, MA, (3/7/2006).

28. "The Quantum Optics Circus – Flying Photons, Acrobatic Atoms, and Entanglement Ensembles," H. J. Kimble, Distinguished Lecture Series, Joint Quantum Information (JQI) Seminar, JQI/NIST, University of Maryland (invited speaker), College Park, MD, (4/19/2006).

29. "The Quantum Optics Circus – Flying Photons, Acrobatic Atoms, and Entanglement Ensembles," H. J. Kimble, Physics Colloquium, Princeton University (invited speaker), Princeton, NJ, (4/20/2006).

30. "The New Science of Quantum Information – From Quantum Computers to Teleportation of Quantum States," H. J. Kimble, 2nd Annual Hermann Anton Haus Lecture, MIT (invited speaker), Cambridge, MA, (4/26/2006).

31. Invited discussion leader on Atomic Systems I, H. J. Kimble, Gordon Research Conference 2006: Quantum Information Science, Il Ciocco, Italy, (5/8/2006).

32. "Scalable Quantum Networks with Atoms and Photons," H. J. Kimble, Applied Physics Seminar, Stanford University (invited speaker), Stanford, CA, (5/15/2006).

33. "The Quantum Optics Circus – Flying Photons, Acrobatic Atoms, and Entangled Ensembles," H. J. Kimble, 69th Annual Seminar Day, California Institute of Technology (invited speaker), Pasadena, CA, (5/20/2006).

34. "Photon Blockade in an Optical Cavity with One Trapped Atom," A. Boca, poster presentation, Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (CLEO/QELS-06), Long Beach, CA (May 21-26, 2006).

35. "Photonic Quantum Computation through Cavity Assisted Interaction," H. J. Kimble, (invited speaker) (6/6/2006); "DLCZ Communications," (invited speaker) (6/9/2006), 2006 ARO/DTO Quantum Information Science and Technology Conference and Program Review, San Antonio, TX, (6/6-9/2006).

36. "Cooling to the Ground State of Axial Motion for One Atom Strongly Coupled to an Optical Cavity, " R. Miller, oral presentation and poster presentation with the same title, 2006 ARO/DTO Quantum Information Science and Technology Conference and Program Review, San Antonio, TX (June 6-9, 2006).

37. "New Interactions of Light and Matter," H. J. Kimble, Award Ceremony upon Receipt of the Berthold Leibinger Zukunftspreis ("Future Prize"), Ditzingen, Germany, (7/3/2006).

38. "Ground State Cooling of Axial Motion for One Atom Strongly Coupled to an Optical Cavity," A. Boca and A. D. Boozer, poster presentation, 20th International Conference on Atomic Physics (ICAP-2006), University of Innsbruck in Austria, (July 16-21, 2006).

39. "Demonstration of Strong Coupling between Single Atoms and High-Q Microresonator," B. Dayan, poster presentation, 20th International Conference on Atomic Physics (ICAP-2006), University of Innsbruck in Austria, (July 16-21, 2006).

40. "Quantum Optics with Atomic Ensembles and Single Atoms in Cavities," H. J. Kimble, 20th International Conference on Atomic Physics (ICAP-2006) (invited speaker), University of Innsbruck in Austria, (7/19/2006).

41. Invited speaker on the topic of Cavity QED, H. J. Kimble, 2006 US-Japan Workshop on Quantum Information Science, Maui, HI, (10/18/2006).

42. "Nonclassical Light – An Assessment of the Voyage into Hilbert Space," H. J. Kimble, Sudarshan: 7 Science Quests Symposium (invited speaker), Austin, TX, (11/7/2006).

43. "Quantum Optics with Atomic Ensembles and Single Atoms in Cavities," H. J. Kimble, invited speaker (11/29/2006) and serving on the Scientific Committee, Quantum Optics III Conference, Pucón, Chile, (11/29/2006).

44. "Cavity QED with a Monolithic Microresonator," B. Dayan, poster presentation, Workshop on Quantum Electromechanical Systems (QEM-2), Morro Bay, CA (12/13-15/2006).

45. "Quantum Optics with Atomic Ensembles and Single Atoms in Cavities," H. J. Kimble, Workshop on Quantum Electromechanical Systems (QEM-2) (invited speaker), Morro Bay, CA, (12/15/2006).

46. "Quantum Information/Computation/Communication," H. J. Kimble, 37th Winter Colloquium on the Physics of Quantum Electronics (PQE XXXVII) (invited speaker), Snowbird, UT, (1/3/2007).

47. "Cavity QED with Cold Atoms and Chip-Based Toroidal Microresonators," B. Dayan, oral presentation, Israel Technological Institute in Haifa, Israel, (2/7/2007).

48. "The Quantum Optics Circus – Flying Photons, Acrobatic Atoms, and Entangled Ensembles," H. J. Kimble, 2007 NIST Colloquium Series (invited speaker), University of Colorado at Boulder, Boulder, CO, (2/9/2007).

49. "Cavity QED in the Regime of Strong Coupling with Chip-Based Toroidal Microresonators," B. Dayan, oral presentation, French-Israeli Symposium on Non-Linear & Quantum Optics (FRISNO-9), Les Houches, France, (2/12-16/2007).

50. “Coherent State Transfer between a Classical Pulse and a Trapped Atom in Cavity QED,” T. Northup, poster presentation, Ninth Annual Meeting Southwest Quantum Information and Technology (SQuInt) Workshop, California Institute of Technology, Pasadena, CA, (2/16-18/2007).

51. “Cavity QED with Cold Atoms and Chip-Based Toroidal Microresonators,” B. Dayan, oral presentation, University of Geneva, Geneva, Switzerland, (2/19/2007).

52. “Cavity QED with Cold Atoms and Chip-Based Toroidal Microresonators,” B. Dayan, oral presentation, Ben-Gurion University, Be’er-Shev, Israel, (2/25/2007).

53. “Cavity QED with Cold Atoms and Chip-Based Toroidal Microresonators,” B. Dayan, oral presentation, Tel Aviv University, Tel Aviv, Israel, (2/26/2007).

54. “Cavity QED with Cold Atoms and Chip-Based Toroidal Microresonators,” B. Dayan, oral presentation, Bar-Ilan University, Ramat-Gan, Israel, (2/27/2007).

55. “Cavity QED with Cold Atoms and Chip-Based Toroidal Microresonators,” B. Dayan, oral presentation, Weizmann Institute of Science, Rehovot, Israel, (2/28/2007).

56. “Reversible Transfer of Optical to Atomic States,” A. Boca, poster presentation, American Physical Society (APS) March Meeting, Denver, CO, (3/7/2007).

57. “Scalable Quantum Networks with Atoms and Photons,” H. J. Kimble, Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (CLEO/QELS-07) (invited tutorial), Baltimore, MD, (5/8/2007).

58. “Ground state cooling and reversible state transfer in cavity QED,” T. Northup, poster presentation, The Ninth Rochester Conference on Coherence and Quantum Optics/The International Conference on Quantum Information (CQ09/ICQI), Rochester, NY, (6/10-15/07).

59. "Quantum Optics with Single Atoms and Photons,” H. J. Kimble, CQ09/ICQI: The Ninth Annual Conference on Coherence and Quantum Optics/ The International Conference on Quantum Information (ICQI) (plenary speaker), Rochester, NY, (6/13/07).

60. “Ground state cooling and reversible state transfer in cavity QED,” T. Northup, poster presentation, 18th International Conference on Laser Spectroscopy (ICOLS07), Telluride, CO, (6/24-29/07).

61. "Quantum Optics with Single Atoms and Photons," H. J. Kimble, 18th International Conference on laser Spectroscopy (ICOLS07) (invited speaker), Telluride, CO, (6/28/07).

62. "Reversible State Transfer between Light and a Single Trapped Atom in Cavity Quantum Electrodynamics," R. Miller, poster presentation, Gordon Research Conference: 2007 Atomic Physics, Tilton, NH, (7/1-6/07).

63. "Strong Coupling between Single Atoms and Photons," H. J. Kimble, 2007 Atomic Physics Gordon Conference (invited speaker), Tilton, NH, (7/2/07).

64. "Cavity QED with Single Atoms and Photons," H. J. Kimble, Fundamental Optical Processes in Semiconductors (FOPS 2007) (invited speaker), Big Sky, MT, (7/26/07).

65. 2007 Quantum Computing (QC) & Quantum Algorithms (QA) Program Review. DTO: ARO/STIC award. Russ Miller speaking on behalf of H. J. Kimble on the STIC: Photonic Quantum Computation through Cavity Assisted Interaction Grant: W911NF-04-1-0201, Minneapolis, MN, (8/11-13/07).

66. "Quantum optics with single atoms and photons," H. J. Kimble, 2007 Photons, Atoms, and Qubits Conference (PAQ07) (invited speaker), London, UK, (9/4/07).

67. "Cooling of an Atom in a Cavity to the Quantum Ground State of Axial Motion," D. Boozer presented a talk on behalf of H. J. Kimble, Frontiers in Optics 2007/Laser Science XXIII (invited speaker), San Jose, CA, (9/16-20/07).

68. "Cavity QED with monolithic microresonators and single atoms," T. Aoki, NEC: Quantum Computing Workshop (invited speaker), University of Princeton, Princeton, NJ, (9/21/07).

69. Invited speaker for the Quantum Information Science Technology Assessment Workshop, H. J. Kimble, Redondo Beach, CA (10/1/07).

Final Progress Report Publication List
Grant No.: W911NF-04-1-0201
Title: "STIC: Photonic Quantum Computation through Cavity Assisted Interaction"

1. "Scalable Photonic Quantum Computation through Cavity-Assisted Interaction," L.-M. Duan and H. J. Kimble, Phys. Rev. Lett. **92**, 127902 (2004).

2. "Deterministic Generation of Single Photons from One Atom Trapped in a Cavity," J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich, and H. J. Kimble, Science **303**, 1992 (2004).

3. "Determination of the Number of Atoms Trapped in an Optical Cavity," J. McKeever, J. R. Buck, A. D. Boozer, and H. J. Kimble, Phys. Rev. Lett. **92**, 143601 (2004).

4. "Quantum Information Processing in Cavity-QED," S. J. van Enk, H. J. Kimble, and H. Mabuchi, Q. Information Processing **3**, 75 (2004).

5. "Ultra-high-Q Toroidal Microresonators for Cavity Quantum Electrodynamics," S. M. Spillane, T. J. Kippenberg, K. J. Vahala, K. W. Goh, E. Wilcut, and H. J. Kimble, Phys. Rev. A **71**; 013817 (2005).

6. "Observation of the Vacuum-Rabi Spectrum for One Trapped Atom," A. Boca, R. Miller, K. M. Birnbaum, A. D. Boozer, J. McKeever, and H. J. Kimble, Phys. Rev. Lett. **93**, 233603 (2004).

7. "Trapped Atoms in Cavity QED: Coupling Quantized Light and Matter," R. Miller, T. E. Northup, K. M. Birnbaum, A. Boca, A. D. Boozer, and H. J. Kimble, J. Phys. B: At. Mol. Opt. Phys. **38**, S551-S565 (2005).

8. "Photon Blockade in an Optical Cavity with One Trapped Atom," K. M. Birnbaum, A. Boca, R. Miller, A. D. Boozer, T. E. Northup, and H. J. Kimble, Nature **436**, 87-90 (2005).

9. "Robust Quantum Gates on Neutral Atoms with Cavity-Assisted Photon-Scattering," L.-M. Duan, B. Wang, and H. J. Kimble, Phys. Rev. A **72**, 032333 (2005).

10. "Robust Quantum Gates on Neutral Atoms with Cavity-Assisted Photon-Scattering," L.-M. Duan, B. Wang, H. J. Kimble, Phys. Rev. A **72**, 032333 (2005).

11. "Efficient quantum computation with probabilistic quantum gates," L.-M. Duan and R. Raussendorf, Phys. Rev. Lett. **95**, 080503 (2005).

12. "Robust quantum gates on neutral atoms with cavity-assisted photon-scattering," L.-M. Duan, B. Wang, and H. J. Kimble, Phys. Rev. A **72**, 032333 (2005).

13. "Engineering Schrodinger cat states through cavity-assisted interaction of coherent optical pulses," B. Wang and L.-M. Duan, Phys. Rev. A **72**, 022320 (2005).

14. “Observation of Strong Coupling between One Atom and a Monolithic Microresonator,” Takao Aoki, B. Dayan, E. Wilcut, W. P. Bowen, A. S. Parkins, H. J. Kimble, T. J. Kippenberg, and K. J. Vahala, Nature **443**, 671-674 (2006).

15. “Cavity QED with Multiple Hyperfine Levels,” K. M. Birnbaum, A. S. Parkins, and H. J. Kimble, Phys. Rev. A **74**, 063802 (2006).

16. “Cooling to the Ground State of Axial Motion for One Atom Strongly Coupled to an Optical Cavity,” A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, Phys. Ref. Lett. **97**, 083602 (2006).

17. “Scalable Generation of Graph-State Entanglement through Realistic Linear Optics,” T. P. Bodiya and L.-M. Duan, Phys. Rev. Lett. **97**, 143601 (2006).

18. “On Experimental Procedures for Entanglement Verification,” S. J. van Enk, N. Lütkenhaus, and H. J. Kimble, Phys. Rev. A **75**, 052318 (2007).

19. “Reversible State Transfer between Light and a Single Trapped Atom,” A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, Phys. Rev. Lett. **98**, 193601 (2007).

20. “Implementation of controlled SWAP gates for quantum fingerprinting and photonic quantum computation,” B. Wang and L.-M. Duan, Phys. Rev. A **75**, 050304 (R) (2007).