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QUANTUM OPTICAL IMPLEMENTATIONS OF CURRENT QUANTUM COMPUTING PARADIGMS

Texas Engineering Experiment Station

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13. ABSTRACT *(Maximum 200 Words)*

We have taken a systematic study of the use of the tools of quantum optics for the implementation of tasks relevant to quantum information and computing. As is widely recognized, the maturation of the field may lead to dramatic improvements in current abilities to process data, communicate securely, and simulate natural processes. Applications range from decoding cryptographic codes and secure key distribution to reducing the complexity of computational problems such as database search and pattern recognition. The key tools we use to accomplish quantum information tasks are coherence in atomic and photonic systems, and the entanglement between correlated subsystems, both of which have been extensively studied in this report.

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Abstract

In this work, we have undertaken a systematic study of the use of the tools of quantum optics for the implementation of tasks relevant to quantum information and computing. As is widely recognized, the maturation of the field may lead to dramatic improvements in current abilities to process data, communicate securely, and simulate natural processes. Applications range from decoding cryptographic codes and secure key distribution to reducing the complexity of computational problems such as database search and pattern recognition. The key tools we use to accomplish quantum information tasks are coherence in atomic and photonic systems, and the entanglement between correlated subsystems, both of which have been extensively studied in this report.

To be specific, the problems we have undertaken include the implementation of the discrete quantum Fourier transform, quantum error correction, quantum circuit design, quenching of quantum noise, quantum thermodynamics, enhancement of two-qubit nonlinearities, quantum database searching, quantum teleportation, quantum state measurement, and entanglement control through quantum coherence, etc. We have proposed schemes for new and/or improved protocols for the above tasks using cavity quantum electrodynamics, atomic arrays, correlated emission lasers, and laser spectroscopy.

Taken together, these tools and applications have revealed a strong connection between the fundamental aspects of quantum mechanics that governs physical systems and the informational/computational paradigms that have underscored the superiority of quantum systems over classical counterparts. These investigations have led us into new directions in quantum informatics, currently actively pursued in our group, and reinforced our understanding of basic science. In the following report, we outline the main accomplishments by our group in the above areas in the last three years.

Table of Contents

List of Figures

1. Introduction

A computer that would manipulate quantum objects as the elementary information carriers can take benefit of the superposition principle. This type of computer can solve some problems exponentially faster than any classical counterpart. For example, Shor showed that the specific problem of factorizing, which for known algorithms takes exponentially increasing time on a classical computer, could be solved in polynomial time using quantum computers. Another set of problems where quantum mechanics can carry out computations substantially faster than their classical counterparts lies in the search of unsorted data. For example, it was shown by Grover that, by using the same amount of hardware as in the classical case, but by having the input and output in superpositions of states, we can find an object in $O(N^{1/2})$ quantum mechanical steps instead of $O(N)$ steps. Quantum superpositions and entanglement make novel concepts such as quantum cryptography and quantum teleportation real possibilities.

A key feature of quantum mechanics is quantum coherence, which derives from the ability of a system to exist in a superposition of two distinct states simultaneously. This gives rise to the concept of phase coherence between different states, which is distinct from the probability amplitudes associated with each state. These off-diagonal coherences in the density matrix of a quantum system have been successfully applied by our group in the past to problems such as electromagnetically induced transparency, lasing without inversion, and slow light propagation. Here, we study the use of quantum coherence to enhance quantum information tasks, namely the generation of controlled logic gates between different qubits (quantum bits), and quenching of spontaneous emission noise that decoheres a quantum computer. In addition, the use of coherence can also lead us to new paradigms in thermodynamics, as discussed below.

Correlations between quantum systems are the key to the efficiency gain in quantum algorithms. Entanglement is a quantum resource that has enabled quantum information tasks such as quantum computing, quantum teleportation and sub-natural resolution in state measurement and optical imaging, as we discuss below. We study physical realizations of entanglement in quantum optics – in cavity QED systems, and atomic sources of entangled photons – to open a new window into the physical mechanisms for improvement of information theoretic tasks. Our studies have led us to new paradigms for teleporting quantum systems, for measuring the quantum state of atoms and photons, and for going beyond the Rayleigh diffraction limit of optical imaging systems, leading to applications such as quantum microscopy and lithography.

2. Research Summary

During the report period (Sep. 13, 2001-Dec. 31 2004) we carried out a number of studies in accordance with the tasks proposed in the project. In this section, we describe the results of our research with references to publications in the following section.

A. Quantum computing in cavity QED systems

Computations with a future quantum computer will be implemented through the operations by elementary quantum gates. It is now well known that the collection of 1-bit and 2-bit quantum gates are universal for quantum computation, i.e., any n-bit unitary operation can be carried out by concatenations of 1-bit and 2-bit elementary quantum gates. Three contemporary quantum devices – cavity QED, ion traps and quantum dots – have been widely regarded as perhaps the most promising candidates for the construction of elementary quantum gates. In a review [1], we describe the physical properties of these devices, and show the mathematical derivations based on the interaction of the laser field as control with atoms, ions or electron spins, leading to the following:

(i) the 1-bit unitary rotation gates; and

(ii) the 2-bit quantum phase gates and the controlled-not gate.

This review is aimed at providing a sufficiently self-contained survey account of analytical nature for mathematicians, physicists and computer scientists to aid interdisciplinary understanding in the research of quantum computation.

We developed a scheme [2] for the implementation of the discrete quantum Fourier transform using cavity quantum electrodynamics. In the proposed scheme, a series of atoms whose atomic coherence carries the input state passes through a series of cavities and classical field, and the resulting state in the cavities is the quantum Fourier transform of the input state.

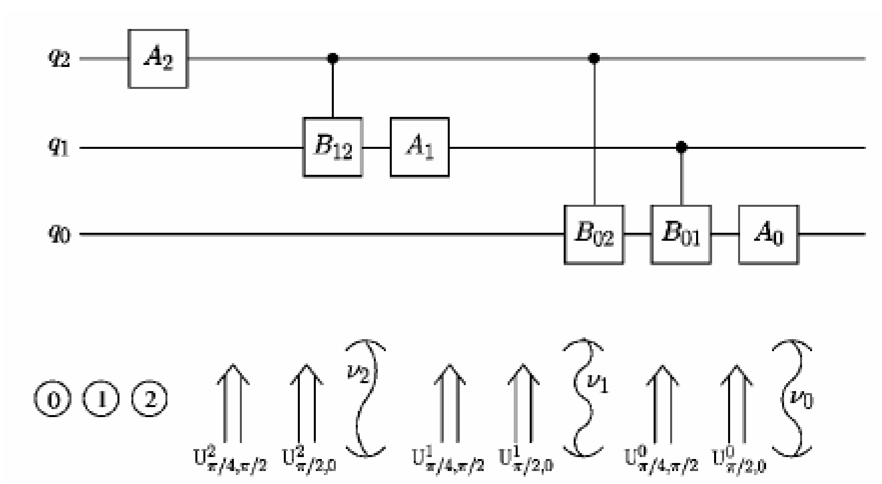

Figure 1: Cavity QED discrete Fourier transform

Figure 1: (a) Circuit diagram for the QFT with three qubits. Here A_i is the one-bit Hadamaard gate and B_{jk} is the two-bit quantum phase gate. (b) The physical implementation of the QFT. Here three atoms labeled 0, 1, and 2 interact with a sequence of classical fields and cavities. Details in Ref. [2].

An important step in the design of a computing algorithm is a circuit design composed of the basic building blocks. The basic building blocks for a quantum computing algorithm are a one-bit unitary gate and two-bit quantum phase gate. We proposed a circuit design for an arbitrary implementation for the Grover's search algorithm consisting only of these fundamental gates [3].

In many implementation schemes for the two-bit quantum logic gates, the two qubits are represented by different systems; for example one qubit could be a two-level atom and the other could be the photon state of the cavity field. We describe a quantum phase gate in which the two qubits are on equal footing and are represented by the photons in the two modes of the cavity field [4]. The gate is implemented by passing a three-level atom in a cascade configuration through the cavity. The upper levels of the atom are resonant with one of the cavity modes whereas the lower levels are appropriately detuned from the other mode of the cavity. A π phase shift is introduced when there is one photon each in the two modes and the atom is initially in the ground state. In this work, we also discuss the one-bit unitary gate in such a system and discuss potential applications.

In addition, we also presented a scheme for the generation of arbitrary two-qubit entangled states between two cavity fields via interaction of an atom resonantly interacting with classical and quantized cavity fields. The controlling parameters are the interaction times with these fields [6].

In another venue of quantum computing, we pursue the quantum equivalent of classical random walks for information processing. In this work [7], we described a possible experimental scheme for the implementation of quantum walk. The scheme is based on the passage of an atom inside a high Q cavity. The chirality is characterized by the atomic states and the displacement is characterized by the photon number inside the cavity. The quantum steps are described by appropriate interactions with a sequence of classical and quantized cavity fields.

Finally, we return to the quantum search algorithm, and note for pedagogical purposes, that a database of four elements can be accomplished in a single run with unit success probability [8]. We consider this problem in a two-qubit system and relate the one and two-qubit search transforms to Pauli spin operators. The key search operation, the inversion about mean, appears in this context as a *spatially* rotated two-qubit phase shift, which gives some physical intuition for its implementation. The classical analogy is to finding a pea hidden under one of four nut shells in a single attempt.

B. Quantum coherence applications

In an effort to use quantum coherence to improve the efficiency of multi-qubit phase gates, we showed that the effect of coherent population trapping may result in resonant enhancement of $\chi^{(5)}$ or higher order nonlinearities [9, 10]. The enhancement is accompanied by suppression of the other linear and nonlinear susceptibility terms. This effect has promise for a realistic scheme of photon phase gates necessary for practical implementation of quantum processing protocols.

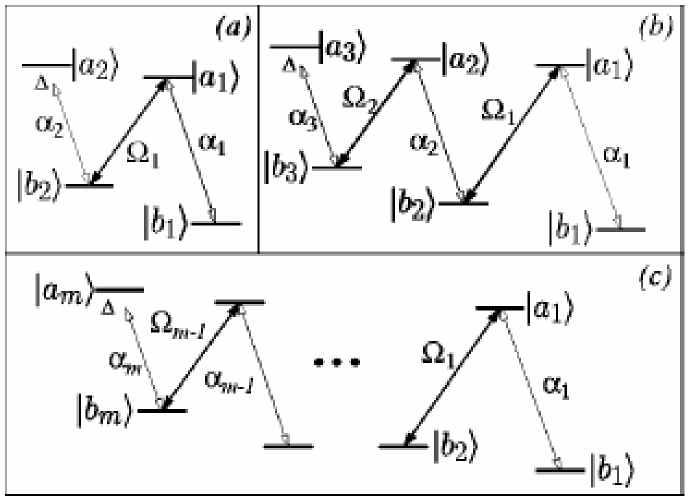

Figure 2: Resonant enhancement of Kerr nonlinearity

Figure 2: Energy level schemes for the resonant enhancement of nonlinear susceptibilities of the media: (a) $\chi^{(3)}$ nonlinearity; (b) $\chi^{(5)}$ nonlinearity; (c) $\chi^{(m)}$ nonlinearity. Details in Ref. [9].

We proposed a new method for resonant enhancement of optical Kerr nonlinearity using multi-level atomic coherence [11]. The enhancement is accompanied by suppression of the other linear and nonlinear susceptibility terms of the medium. We discuss how this enhanced nonlinearity can be used to implement multiphoton phase gate with potential applications to quantum searching. We also predicted theoretically and demonstrate experimentally an ellipticity-dependent nonlinear magneto-optic rotation of elliptically-polarized light propagating in a medium with atomic coherence. In particular, we reported an observation of an enhancement of the polarization rotation of elliptically polarized light resonant with the $5S_{1/2}$ F=2 $\rightarrow$ $5P_{1/2}$ F=1 transition of ^{87}Rb.

Spontaneous emission represents a fundamental source of noise in any quantum mechanical system. In particular it imposes limitations on the performance on any quantum computing devices. We considered several schemes for the control of spontaneous emission [12-14].

We first considered the manipulation of spontaneous emission by 2π pulses. Such an interaction can be used for noise quenching due to spontaneous emission in quantum computing schemes involving the interaction of radiation with matter. In particular such ideas can be used for error correction in a recent scheme for quantum searching [12, 13]. We discussed [12] how to control the spontaneous decay rate via interrupting the spontaneous emission by continuous quantum measurement, which collapses the wavefunction of the atom. We presented a simple analysis of the scheme wherein the spontaneous emission is interrupted via 2π pulses between the upper level and another level. This periodic interruption can dramatically change the decay rate. The 2π pulse interruption is a unitary evolution, and does not lead to the wavefunction collapse.

In another scheme, we studied the quenching of the spontaneous emission through coherence modified and controlled via incoherent pumping [14]. The external pumping gives us a controllable handle in the manipulation of spontaneous emission. Under certain conditions, complete quenching of spontaneous emission is possible. In this work, we investigated the steady-state spontaneous emission from a three level atom, with the coherence between the two upper levels modified and controlled via incoherent pumping from these two levels to a fourth auxiliary level. The external pumping gives us an easily controllable handle in manipulating spontaneous emission to such an extent that under certain conditions complete quenching of spontaneous emission is possible.

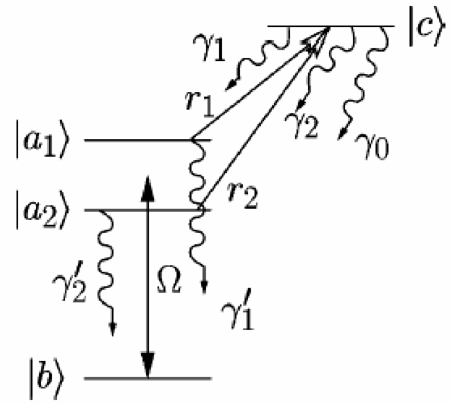

Figure 3: Manipulation of spontaneous emission

Figure 3: The level scheme. We are interested in controlling the spontaneous emission from the doublet a_1 and a_2 to level *b*. Level *c* is the auxiliary level coupled to the doublet via incoherent pumpings r_1 and r_2. Details in Ref. [14].

The use of quantum coherence to modify the group refractive index in such a way that the speed of light propagation in a medium may be controlled at will is one of the key successes of our group [15]. In a recent study [16], we demonstrate a tunable control of the group velocity of a weak probe pulse from subluminal to superluminal. The model is an extended Λ-type system with two-extra control fields and an extra energy level. Phase variation of one of the control fields imparts the tunability in the group velocity along with other interesting spectral behavior in the absorption spectrum.

C. Quantum thermodynamics

Quantum thermodynamics represents a burgeoning field at the cross roads of classical thermodynamics and quantum mechanics. We have made several key innovations in this field in recent years [17-19]. These have led us to propose new opto-mechanical devices that can produce work at high energy efficiencies. In one study, we presented a new kind of quantum Carnot engine in which the atoms in the heat bath are given a small bit of quantum coherence. The induced quantum coherence becomes vanishingly small in the high temperature limit in which we operate; and the heat bath is essentially thermal. However, the phase ϕ, associated with the atomic coherence, provides a new control parameter which can be varied to increase the temperature of the radiation field, and extract work from a single heat bath. The deep physics behind the second law of thermodynamics is not violated; nevertheless the quantum Carnot engine has certain features which are not possible in a classical engine [17, 18].

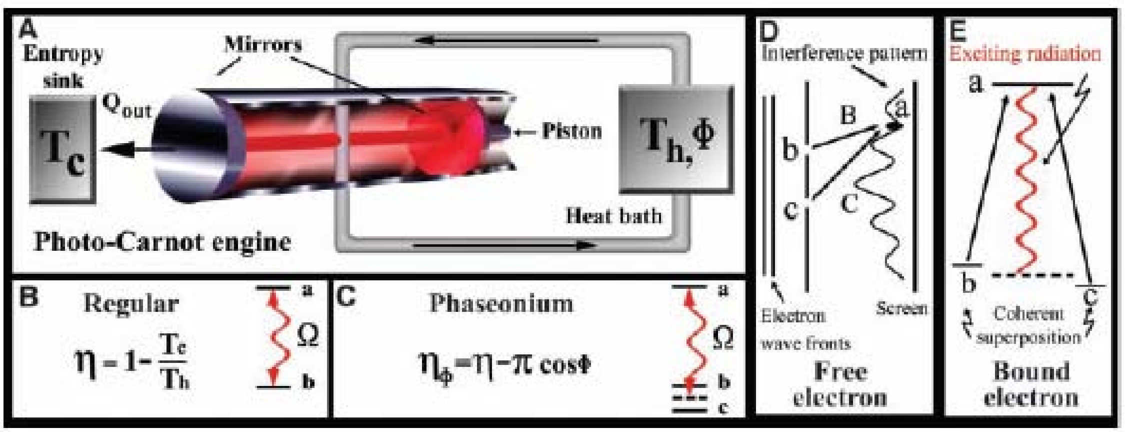

Figure 4: Photo-Carnot heat engine

Figure 4: Photo-Carnot engine in which radiation pressure from a thermally excited single-mode field drives a piston. Details in Ref. [17].

D. Quantum state measurement

Quantum state measurement is a key requirement of a quantum information processor, namely the accurate read out of the output state after unitary evolution. To this end, we undertook several studies [20-23] to measure the state of atoms and photons.

We presented a simple spectroscopic method based on Autler-Townes spectroscopy to determine the center-of-mass atomic wave function [20]. The detection of spontaneously emitted photons from a three-level atom, in which two upper levels are driven by a classical standing light, yields information about the position and momentum distribution of the atom [A. M. Herkommer, W. P. Schleich and M. S. Zubairy, J. Mod. Opt. **44**, 2507 (1997)]. We show that both the amplitude and phase information of the center-of-mass atomic wave function can be obtained from these distributions after a series of conditional measurements on the atom and the emitted photon.

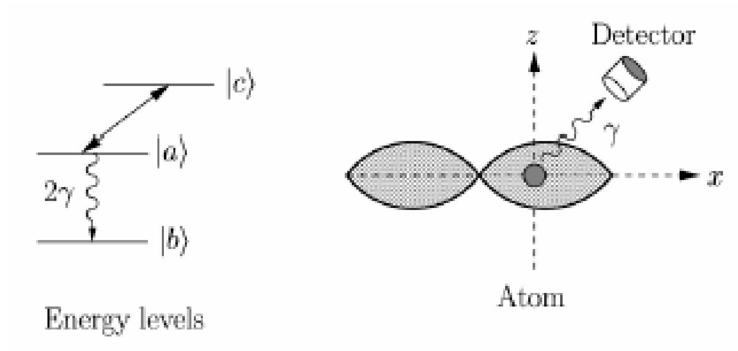

Figure 5: Measuring the atomic center-of-mass wavefunction

Figure 5: Measuring the atomic center-of-mass wavefunction. Three-level atom interacting with a classical standing light field of wave vector $\kappa = 2\pi/\lambda = \omega_{ac}/c$ aligned along the *x* direction. The transition *c-a* of the three-level atom is in resonance with the driving field and the transition *a-b* is coupled to the reservoir of vacuum modes $\{\mathbf{k}\}$, thus giving rise to spontaneously emitted photons that can be detected thereafter. Details in Ref. [20].

In a parallel study [21], the Autler-Townes spontaneous emission spectroscopy is revisited for a time-dependent case. We report the results of the spontaneous emission spectrum for nonstationary scattered light signal by using the definition of the time-dependent physical spectrum. This is a rare example of problems where time-dependent spectrum can be calculated exactly.

We proposed a model for the measurement of an arbitrary multimode entangled state of the cavity field using two-photon correlated emission laser [22]. We considered two cases: (a) The modes have different frequencies and detected separately, and (b) the modes consist of two-orthogonal polarization states and are detected using a single balanced homodyne detector. The basic idea is to amplify the initial multimode state such that there is no noise in the quadrature of interest and all the noise is fed into the conjugate quadrature component. The amplified noise-free quadrature is prepared in different phases and then the corresponding quadrature distribution is measured. The Wigner function of the initial multimode entangled state is then reconstructed by using an inverse Radon transformation. This scheme is insensitive to the noise associated with the non-unit efficiency of the detector in the homodyne detection measurement scheme.

We proposed a scheme for the measurement of joint photon statistics and Wigner function of entangled field state between two separate cavities [23]. The scheme utilizes two-level atoms of well defined momentum state. The momentum of the atoms can have only two possible states after interacting with the entangled field in Bragg regime. The probability of finding the atom in any one momentum state is the product of the joint photon statistics and an oscillatory function. The argument of the oscillatory function contains the information about the joint photon numbers in the two cavities. The photon statistics can be measured by the process of state reduction to a single set of photon number in two cavities and then measured by a quantum nondemolition method. The repeated measurement of the set of photon numbers gives the joint photon statistics of the entangled field state. The complete entangled state can be reconstructed as a Wigner function of entangled state from the knowledge of photon statistics of the coherently displaced entangled state.

E. Quantum teleportation

Quantum teleportation gives us a means to communicate the quantum state of a system across great distances without actually transmitting the system of interest. This is done by using entangled Einstein-Podolsky-Rosen (EPR) pairs of particles as an intermediate resource, aided by classical communication and post processing. Quantum teleportation is considered to be the basis of any future quantum networking system. We reviewed the field of quantum teleportation in a volume on the mathematics of quantum computation [24].

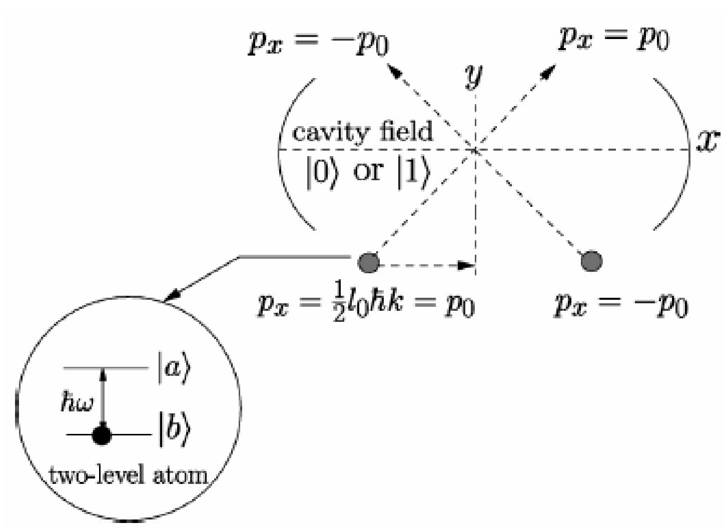

Figure 6: Atomic momentum state teleportation

Figure 6: Schematic diagram of the quantum controlled-NOT logic gate used for the atomic momentum state teleportation. If p_0 is the moment of the incoming atom along the *x* axis, then it changes into -p_0 if there is a one-photon state inside the cavity, and remains p_0 if the cavity field is in a vacuum state. Details in Ref. [25].

Most studies on quantum teleportation are directed at the study of teleporting photon states. We propose a scheme for teleporting a superposition of atomic center of mass momentum states to a superposition of the cavity field using quantum controlled

NOT gate via atomic scattering in the Bragg's regime and cavity quantum electrodynamics (QED) [25].

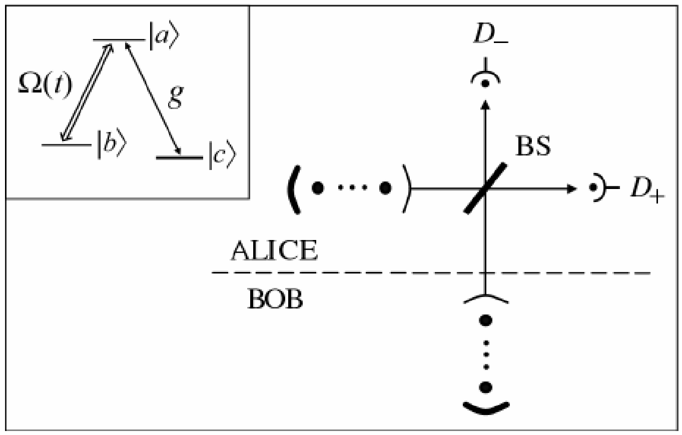

Figure 7: Atomic Dicke state teleportation

Figure 7: Setup for teleporting arbitrary atomic Dicke states between two cavities. Details in Ref. [26].

Quantum teleportation as originally conceived only applies to the information stored in a single qubit. Extensions to multiple qubits, indeed which themselves possess entangled quantum information, will be essential to distributed quantum computing. We presented a scheme for the teleportation of arbitrary superpositions of Dicke states of atoms trapped in a cavity [26]. The entangled state is teleported to the same number of atoms in a distant cavity. Rather than rely on entangled EPR pairs, our method uses the conditional detection of photons that have leaked out of both cavities, and uses the quantum jump formalism. The asymptotic fidelity of the protocol was shown to approach unity for any given Dicke state. We generalized the method to an arbitrary number of atoms in each cavity.

F. Quantum entanglement applications

Quantum entanglement is widely recognized to be the key resource for both quantum computing and communication protocols. In the former case, it gives quantum information processing a distinctive advantage over classical systems and allows for rapid solutions of complex problems. In the latter case, it enables communication protocols such as teleportation and key distribution based on EPR pairs which cannot be emulated by classical systems. Thus, it is of interest to study quantum entanglement from a physically motivated standpoint, and we have in mind the use of generalized multi-photon states for quantum information applications. Furthermore, new applications arise from this study, which we have pioneered, namely quantum microscopy and lithography, as discussed below.

The photon concept is one of the most debated issues in the history of physical science. Some thirty years ago, we published an article in Physics Today entitled “The Concept of the Photon,” in which we described the “photon” as a classical electromagnetic field plus the fluctuations associated with the vacuum. However, subsequent developments required us to envision the photon as an intrinsically quantum mechanical entity, whose basic physics is much deeper than can be explained by the simple `classical wave plus vacuum fluctuations' picture. These ideas and the extensions of our conceptual understanding are discussed in detail in our recent quantum optics book. In an invited article in Optics and Photonic News we revisit the photon concept based on examples from these sources and more [27].

Higher order correlations of the radiation field improve resolution in stellar interferometers, as in the Hanbury Brown-Twiss effect. We showed that it is also possible to improve microscopic resolution beyond the Rayleigh limit by using quantum light fields composed of entangled photons [28]. Focusing on two photons, we distinguished two types of entanglement: frequency entanglement, where the photons in different paths are correlated in frequency, and path entanglement, where the correlation between paths is in photon number. Two paradigms of quantum microscopy were presented: spectral microscopy, where path and frequency entangled photons produced in cascade decay of two atoms make possible sub-natural linewidth resolution of atomic levels, and spatial microscopy, where path entangled photons emitted by an atomic array produces sub-wavelength diffraction resolution as compared to an equivalent classical grating. These scenarios require two-photon correlation or coincidence measurements. The connection between the two paradigms, and the two types of entanglement, highlights the link between the temporal and spatial aspects of quantum interferometry.

The theme of controlling entanglement through physically motivated models, rather than abstract mathematical arguments, is an important near-term objective for the field of quantum information. In this regard, we have come up with a proposal based on cavity-QED to realize a delayed-choice quantum eraser [29], where the teleportation of a single qubit can be controlled by entanglement with an ancillia bit, is particularly relevant. This introduces a new window, based on path entanglement, into the complementarity principle of quantum mechanics, which is at the heart of the distinction between classical and quantum optics.

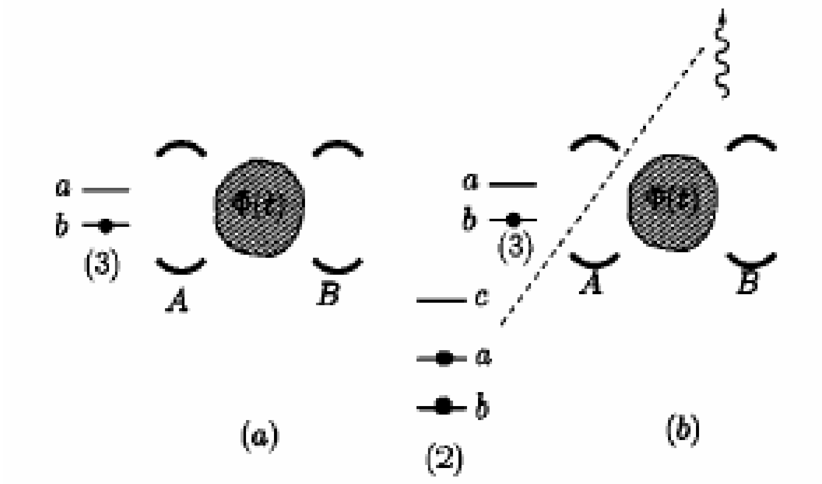

Figure 8: Quantum disentanglement eraser

Figure 8: Quantum disentanglement eraser. (a) A two-level atom initially in its ground state $|b\rangle$ passes through the entangled cavities *A* and *B*. The atom in state $|a\rangle$ acquires a phase shift while passing between the two cavities. The probability of finding the atom in the excited or ground state exhibits interference fringes. (b) The system is the same as in (a), but a tagging qubit can partially or completely erase the interference fringes via dispersive coupling of a three-level atom with cavity A. Details in Ref. [29].

Our work shows a close link between the notions of quantum eraser and entanglement. For example, in any set-up for quantum eraser, the which-path information, and therefore the disappearance of the fringes, is achieved by entangling the state of the particle with another controlling *qubit* that contains the which-path information. One can, however, restore the fringes by erasing the which-path information contained in the controlling qubit. We proposed the usage of two high quality cavities to realize a new type of quantum eraser as proposed by Garisto and Hardy. We also show how the cavities and suitably prepared atoms can be used to study the concept of induced coherence without induced emission. In our work [29], we use an auxiliary atom's passage through the first cavity to control the degree of entanglement between the two cavities. We further discuss how these changes can be studied by using a probe atom and post measurement on the auxiliary atom.

Finally, we turned to the problem of entanglement in quantum field states consisting of multiple photons. We consider a two-photon correlated emission laser as a source of an entangled radiation with a large number of photons in each mode. The system consists of three-level atomic schemes inside a doubly resonant cavity. We study the dynamics of this system in the presence of cavity losses, concluding that the creation of entangled states with photon numbers up to tens of thousands seems achievable [30].

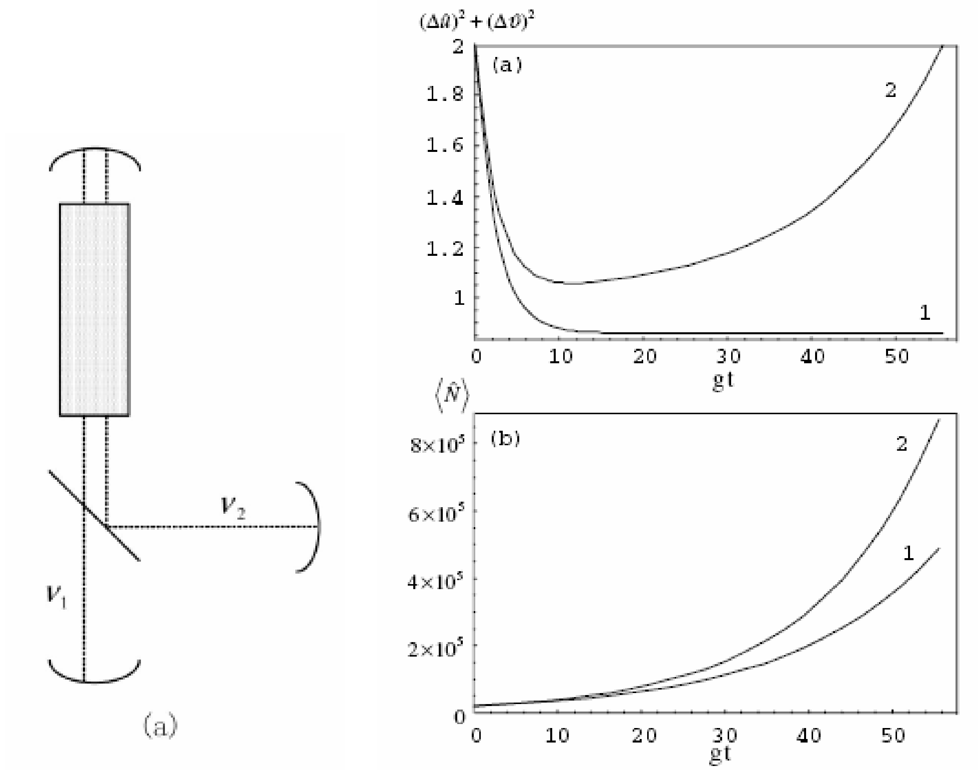

Figure 9: Quantum entanglement amplifier

Figure 9: Schematics of entanglement amplifier using a two-mode correlated emission laser. Plotted are the EPR dispersion relation and the average photon number. Details in Ref. [30].

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4. Conferences and Proceedings:

The results were presented at several conferences. These include:

1. M. O. Scully, "Foundations of Quantum Mechanics", in the symposium “100 Years Werner Heisenberg - Works and Impact,” September 26-30, 2001, Bamberg, Germany

2. M. O. Scully, "Quenching Spontaneous Emission and Quantum Noise via Atomic Coherence," in Mechanisms for Decoherence - Theory and Applications to Nanotechnology and Quantum Information Science: Conference, October 26-27, 2001, University of Texas at Austin, Texas

3. M. O. Scully, "Spin-Based Lattice Gas Quantum Computers in Solids using Optical Addressing," at DARPA Quantum Information Science and Technology (QuIST) Meeting, November 26-29, 2001, Dallas, Texas.

4. M. O. Scully, "FAST CARS and Anthrax detection," at 32nd Winter Colloquium on The Physics of Quantum Electronics, held at Snowbird, Utah (Jan. 6-10, 2002).

5. M. S. Zubairy, "Quantum search: with and without entanglement," at 32nd Winter Colloquium on The Physics of Quantum Electronics, held at Snowbird, Utah (Jan. 6-10, 2002).

6. Mark Pilloff, "Wigner distributions and condensate statistics in the weakly interacting Bose gas," at 32nd Winter Colloquium on The Physics of Quantum Electronics, held at Snowbird, Utah (Jan. 6-10, 2002).

7. M. O. Scully, "Quantum telecommunications: From ultra-fast computers to anthrax detectors," at Air Force II Kick-off meeting, Rome, Jan. 23, 2002.

8. M. O. Scully, "Quantum coherence and anthrax detection," MIT Seminar, Jan. 25, 2002.

9. M. O. Scully, "FAST CARS: Developing a Laser Spectroscopic Technique for Rapid Identification of Bacterial Spores," at DARPA, Jan. 29, 2002.

10. M. O. Scully, "Quantum Maxwell demons," at Texas A&M University, March 19 (2002).

11. M. O. Scully, "Quantum coherence effects from QED to DNA," at Princeton University, April 4 (2002).

12. M. O. Scully, "Novel radiation generators and detectors," at NEC, Princeton, April 5 (2002).

13. M. O. Scully, "Quantum thermodynamics: From quantum heat engines to Maxwell's demons and beyond," at MIT, April 8 (2002).

14. M. O. Scully, "Frozen light: The tip of iceberg," Eastman lecture at the University of Maryland, April 16, 2002.

15. M. S. Zubairy, “Multiphoton Phase Gate for Quantum Search,” at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, Apr. 10 and April 17, 2002.

16. M. O. Scully, “Fluctuations in the Bose Condensate: The rich interplay between optical and statistical physics,” 11th International Laser Physics Workshop 2002, Bratislava, July 1-5, 2002.

17. M. O. Scully, “Quantum thermodynamics: From quantum heat engines to Maxwell's demons and beyond,” International Conference on Quantum Information (ICQI), Oviedo, Spain, July 14-18, 2002.

18. M. O. Scully, “Stopping light with hot atoms and time reversing light,” Institute for Theoretical Physics Conference (ITPC), Santa Barbara, CA, July 22-26, 2002.

19. M. O. Scully, “Extracting work from a single heat bath via vanishing quantum coherence,” Quantum Limits to the Second Law Conference (QLSL), San Diego University, July 29-31, 2002.

20. M. S. Zubairy, “Quantum thermodynamics of a photon gas,” Quantum Limits to the Second Law Conference (QLSL), San Diego University, July 29-31, 2002.

21. M. O. Scully, “Phaseonium fuel: Superseding the Carnot limit via quantum coherence,” Feynman Festival, University of Maryland, College Park, MD, August 26-27, 2002.

22. M. S. Zubairy, “Cavity QED applications for quantum computing,” Feynman Festival, University of Maryland, College Park, MD, August 26-27, 2002.

23. M. O. Scully, “Towards ultrashort pulse detector of anthrax endospores,” Army Research Office Workshop on Relativistic and Sub-relativistic Intensity: Physics and Applications, Ann Arbor, MI, August 29-31, 2002.

24. M. O. Scully, “Quantum Thermodynamics,” colloquium, University of Electronic Communications, Tokyo, Japan, September 2002.

25. M. O. Scully, “Ultraslow and Frozen Light Applied to Quantum Computing and Quantum Noise Suppression,” Society of America Annual Conference, Orlando, FL, October 2002.

26. M. O. Scully, “EPR-Bell Correlations Do Not Require a Non-Local Interpretation of Quantum Mechanics: Recent Debate,” Symposium on Bell Theorem Conference, University of Illinois, October 2002.

27. M. O. Scully, “Quantum Thermodynamics: from Maxwell's demons and Shannon entropy to quantum coherence and relative entropy,” Quantum Information Science Seminar, University of Illinois, October 23, 2002

28. M. O. Scully, “Novel Approaches to Biological Agent Detection,” Symposium on Biotechnology and POEM Annual Research Conference, Princeton, NJ, October 2002

29. M. S. Zubairy, “A Cavity QED based Quantum Phase Gate with Applications,” seminar, Department of Computer Science, Texas A&M University, Oct 16, 2002.

30. M. S. Zubairy, “Quantum State Measurement,” colloquium, University of Arkansas, Nov. 24 (2002).

31. M. O. Scully, “Detection of large biological molecules,” at 33rd Winter Colloquium on The Physics of Quantum Electronics, held at Snowbird, Utah (Jan. 6-10, 2003).

32. M. S. Zubairy, “Cavity QED based quantum phase gate and applications” at 33rd Winter Colloquium on The Physics of Quantum Electronics held at Snowbird, Utah (Jan. 6-10, 2003).

33. M. O. Scully, “Quantum controversy,” Lecture at Utah State University (Jan. 14, 2003).

34. M. O. Scully, “The interplay between computer science and quantum thermodynamics,” Lecture at University of Arizona (Jan. 22, 2003).

35. M. O. Scully, “Raman signals, noise, and all that,” seminar at Department of Physics, Texas A&M University (Feb. 17, 2003).

36. M. S. Zubairy, “Quantum State Measurement and Sub-wavelength Atom Localization,” Colloquium at Temple University (Feb. 17, 2003).

37. M. S. Zubairy, “Atom microscopy and measurement of atom wavefunction,” at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, (March 20, 2003).

38. M. S. Zubairy, “On the implementation of Shor's algorithm,” at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, (April 10, 2003).

39. M. S. Zubairy, “Cavity QED based quantum computing,” SPIE Quantum Information and Computation Conference, Orlando (April 21-24, 2003)

40. M. S. Zubairy, “Atom microscopy and measurement of atom wavefunction,” at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, (March 20, 2003).

41. M. O. Scully, “Quantum Coherence from Anthrax to Carnot,” Special Quantum Optics Seminar, Texas A&M University (April 1, 2003).

42. M. O. Scully, “Using Quantum Coherence to Detect Anthrax,” University of Colorado (April 2, 2003).

43. M. S. Zubairy, “On the implementation of Shor's algorithm,” at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, (April 10, 2003).

44. M. O. Scully, “Extending Laser Spectroscopy via Quantum Correlation, Coherence and Control,” Princeton University (April 14, 2003).

45. M. S. Zubairy, “Cavity QED based quantum computing,” SPIE Quantum Information and Computation Conference, Orlando (April 21-24, 2003)

46. M. O. Scully, “Physics in Anthrax Detection,” Director's Colloquium, Los Alamos National Laboratory (May 27, 2003).

47. M. O. Scully, “Quantum Fluctuations and Noise,” Plenary Speaker, SPIE 2003 First International Symposium on Fluctuations and Noise (FaN 2003), Santa Fe, NM (June 2, 2003).

48. M. O. Scully, “Quantum Thermodynamics from Maxwell's Demon to the Photo Carnot Quantum Engine,” Time in Quantum Mechanics Workshop, Canary Islands, Spain (June 16, 2003).

49. M. O. Scully, “Black Hole Quantum Optics: Enhancing the Unruh Effect via Cavity QED,” Time in Quantum Mechanics Workshop, Canary Islands, Spain (June 17, 2003).

50. M. O. Scully, “Black Hole Quantum Optics: Enhancing the Unruh Effect,” 2003 TAMU-ONR-DARPA Workshop on Quantum Optics, Grand Targhee, WY (July 7-11, 2003).

51. M. S. Zubairy, “A cavity QED based quantum phase gate,” 2003 TAMU-ONR-DARPA Workshop on Quantum Optics, Grand Targhee, WY (July 7-11, 2003).

52. M. O. Scully, “Radiative quantum thermodynamics,” Hot Topics in Quantum Statistical Physics Conference, Leiden, The Netherlands (August 12, 2003).

53. M. O. Scully, “Laser Detection of Anthrax,” Homeland Security Meetings, College Station, TX (August 27, 2003).

54. M. S. Zubairy, “Quantum State Measurement,” Seminar, Center for Advanced Studies, University of New Mexico, Albuquerque (August 28, 2003).

55. M. S. Zubairy, “From correlated emission laser to an entanglement amplifier,” at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, April 15, 2004.

56. M. O. Scully, “Using Quantum Mechanics to Detect Anthrax (and much more),” NSF REU program, Chemistry Department TAMU, June 25, 2004.

57. M. O. Scully, Final Keynote Address, Fields Institute Conference on Quantum Information and Quantum Control, University of Toronto, Toronto, Canada, July 23, 2004

58. M. O. Scully, “Quantum Controversy: From Maxwell’s Demon and Quantum Eraser to Black Hole Radiation,” Frontiers of Quantum and Mesoscopic Thermodynamics Conference, Prague, Czech Republic, July 26, 2004.

59. M. S. Zubairy, “Cavity QED-based quantum computing,” SPIE Conference on Quantum Communications and Quantum Imaging II, held at Denver, Colorado (August 4-6, 2004).

60. M. S. Zubairy, “Correlated emission laser as an entanglement amplifier,” Feynman Festival, University of Maryland, Baltimore (August 20-26, 2004).