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13. ABSTRACT (Maximum 200 words)

The principle goal of our program is the demonstration of scalable quantum logic between qubits encoded in the internal states of neutral atoms sharing the quantum field of an optical cavity. This requires successful integration of two leading quantum information technologies — atom-based quantum memories and cavity QED-based entanglement generation and manipulation. We have developed methods for trapping atoms inside high-finesse optical resonators for scalable quantum logic. Our configuration employs infrared (CO_2) laser traps for individual atoms that will permit us to store many individually addressable atoms and to manipulate these atoms in arbitrary combinations using the quantum field of the optical cavity. Importantly, the use of infrared trapping lasers virtually eliminates decoherence due to atomic spontaneous emission, which hinders many AMO-based systems.

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Statement of Problem

The principle goal of our program is the demonstration of scalable quantum logic between qubits encoded in the internal states of neutral atoms sharing the quantum field of an optical cavity. This requires successful integration of two leading quantum information technologies — atom-based quantum memories and cavity QED-based entanglement generation and manipulation. We have developed methods for trapping atoms inside high-finesse optical resonators for scalable quantum logic. Our configuration employs infrared (CO_2) laser traps for individual atoms that will permit us to store many individually addressable atoms and to manipulate these atoms in arbitrary combinations using the quantum field of the optical cavity. Importantly, the use of infrared trapping lasers virtually eliminates decoherence due to atomic spontaneous emission, which hinders many AMO-based systems.

Summary of Important Results

During this grant, we constructed an entirely new apparatus for performing cavity QED experiments with ultracold atoms and used it successfully to perform several important experiments in the field. Our theoretical program made many contributions to the understanding of the underlying physical systems of our proposal. In addition, several new schemes for generating entanglements in atomic based systems were proposed. The report is organized as follows: first, the development of the apparatus is described, followed by a discussion of our principal experimental results. Finally, the theoretical achievements are described.

Apparatus development

Laser cooling and atom trapping system

The atom trapping system will ultimately consist of individual rubidium atoms trapped in an array of far off-resonant laser traps (FORT) formed at the antinodes of a standing wave of laser light. The FORT is a relatively shallow trap, and atoms must be first pre-cooled in a magneto-optical trap (MOT). We have developed the MOT laser and vacuum systems for these purposes, and we have realized and carefully characterized the MOT.

We have developed a versatile frequency-stabilized diode laser system for atom cooling and trapping. The MOT laser system consists of 5 diode lasers. The main trapping laser is based on a grating-stabilized diode laser featuring intensity and frequency control to permit sub-Doppler laser cooling. This master laser is then injected into three other diode lasers to provide the necessary total laser power for the MOT. Additionally, there is a second grating-stabilized diode laser tuned to the lower hyperfine transition of Rb to provide repumping. All the laser beams can be frequency shifted and intensity modulated via lock off-sets and acousto-optic modulators and shutters. This control is necessary for sub-Doppler cooling and trap diagnostics.

The UHV chamber consists of a multi-port stainless steel conflat chamber with 16 intersecting viewports at the trap center. Aside from the 6 ports used for the MOT beams, the other ports are used for the CO_2 laser beam, cameras and detectors, and auxiliary laser probe beams. The principle pumping of the chamber is provided by an 50 l/s ion pump and a Ti:sublimation pump. We achieve vacuum levels of ~10^{-10} torr after a mild bake to 200 C^o.

The trap control and CCD image acquisition is computer-based, using the Labview software system by National Instruments. This provides complete control and flexibility of the experiment parameters. Using these systems, we have constructed a MOT that will be used to provide a cold dense reservoir of atoms from which to distill the qubits. Because the MOT is the starting point of all of our investigations, we have taken time to carefully characterize the trap, measuring including number of atoms, density and temperature of the trap atoms for different operating conditions. We routinely trap 10^7 atoms at densities of 10^{10} cm^{-3} and temperatures of 10 μK.

Dipole force trapping system

We have developed the optical system for the FORT trap system which will provide long-term confinement of the qubits. This system is based around a 25W CO_2 gas laser. The laser beam must be tightly focused at the trap center to provide confinement of the atoms. We have achieved at focused waist of <35 μm, using special aspherical lenses—this is near the diffractive limit. Additionally, the system provides the capability for multiple trapping beams, each independently controllable via computer interface.

Cavity QED system

The optical cavity system for the cavity QED aspects of the experiment consists of a dedicated, frequency-stabilized laser system, electro- and acousto-optical components for frequency manipulation, a high-finesse, UHV-compatible optical cavity, and balanced-heterodyne detectors. We have made significant progress in the area as follows.

We have developed the laser system for the cavity. This consists of a grating-feedback frequency-stabilized diode laser, some of which is passed through an acousto-optic modulator to create a frequency offset beam necessary for balanced-heterodyne detection. We have made several prototype cavities and have designed the UHV compatible cavity mount and vibration isolation system. Additionally, we have constructed low-noise, high-bandwidth optical detectors for balanced heterodyne detection of the weak cavity signals. Using these systems, we have demonstrated that we can detect less than 1 pW of cavity light in a shot-noise limited manner.

We have constructed a dedicated cavity assembly station featuring a low-particulate enclosure mounted on a low vibration optical table. This allows dust-free assembly of the cavities, and on-line monitoring of the cavity performance during assembly.

We have fabricated several cavities been developing high-finesse resonators suitable for cavity QED experiments. A photo of one of our resonators is shown in Figure 1. This cavity has a length of 200 μm, a finesse of 600,000 and strong coupling parameters $(g_0, \kappa, \Gamma) = 2\pi \bullet (13, 0.5, 2.7)$ MHz.

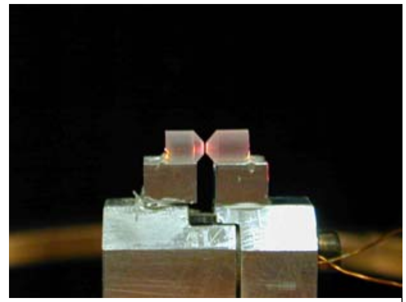

Figure 1: Photo of high-finesse optical cavity. The tapered mirrors are separated by 200 μm. The cavity finesse is 600,000.

Experimental results

CO2 laser trapping

We employ a dipole force trap formed by a focused, retro-reflected infrared (CO_2) laser beam [1, 2]. The trapping potential is given by $U(\vec{r}) \propto -\alpha_g I(\vec{r})$ where α_g is the ground state polarizability of the atom (rubidium) and $I(\vec{r})$ is the spatially varying laser intensity. The retro-reflected beam forms a standing-wave intensity pattern, $I(z) \propto \sin^2(2\pi z / \lambda_{CO_2})$, with a waist w_0 = 50 μm and a Rayleigh range z_0 = 750 μm which yields a 1-D array of miniature traps separated by $\lambda_{CO_2}/2$ = 5.3 μm. For typical parameters in our trap, the maximum potential depth is ~1 mK, which is much larger than the temperature of the laser cooled atoms (~10 μK). We load the trap from a vapor-cell magneto-optic trap (MOT), and we initially load ~10^6 atoms distributed over ~400 different anti-nodes. A typical false-color image of the trap obtained by imaging the resonant florescence of the atoms is shown in Figure 2a.

Because this trap will be the starting point of most of our future work, we have carefully characterized the properties of this trap. One of the most important parameters of these traps is the oscillation frequency of atoms in the potential wells. For the ultra cold atoms in our trap, the traps are quasi-harmonic and the expected oscillation frequencies of the atoms in the potential wells are $f_> \sim 15$ kHz and $f_< \sim 1$ kHz for motion along and transverse to the optical axis, respectively. We have directly measured these frequencies using the techniques of parametric excitation [2], whereby we modulate the trap potential depth by 20% for 1 s and measure the loss of atoms from the trap.

When the excitation frequency matches the trap frequency or its first harmonic, the atoms are parametrically heated out of the trap. In fact, the trap frequencies vary for different anti-nodes because of the divergence of the laser field—for the larger frequency, this variation is $f_{>} \propto \sqrt{I(z)} \propto 1/w(z)$. This variation is evident in Figure 1b, where the losses are greatest at the central antinodes, and not as extreme on the wings of the lattice where

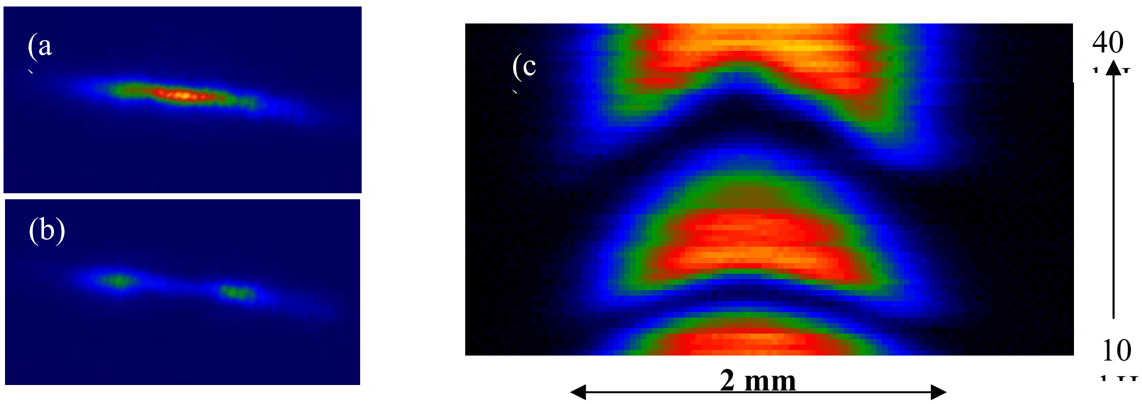

Figure 2: (a) florescent image of atom trap. (b) image of trap following parametric excitation at 15 kHz. Maximum losses occur at central antinodes (c) composite image of parametric excitation at different frequencies. In (c) each row of the image is a vertical projection of images similar to (b) taken at different excitation frequencies.

the frequencies are lower. We have measured the complete spectrum of parametric excitation of this trap, and the results are shown in the composite image in Figure 2c. The resonances at $f_{>} \sim 15$ kHz and $2f_{>} \sim 30$ kHz are clearly seen as dark bands in the composite image, and the variation of the trap frequencies along the horizontal axis is revealed by the curvature of the bands.

We have also developed more complicated trap geometries required for creating scalable entanglements in the atom-cavity scheme. Three different geometries are shown in Figure 3. Both the 2-D and the 3-D traps are new traps first developed in our laboratory. Both of these traps may be useful for other lattice-based neutral atom quantum information applications [3-5] in addition to the atom-cavity system we are pursuing.

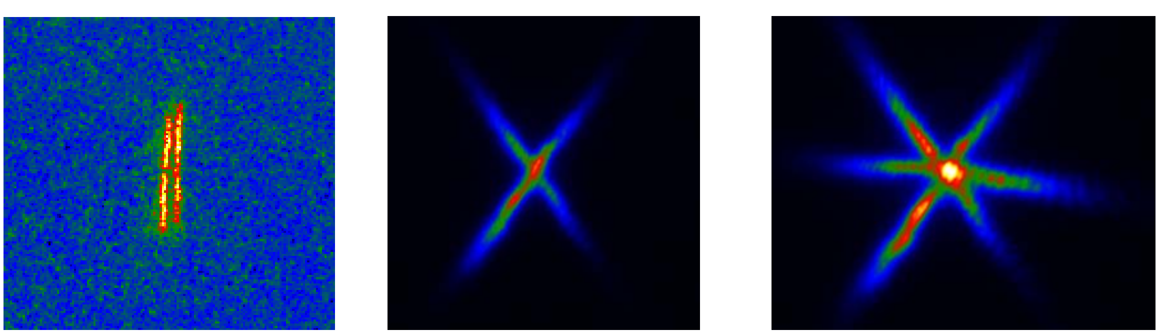

Figure 5: Images of ultracold rubidium atoms trapped in different configurations of laser beams. Left to right: dual 1-D traps, crossed 1-D traps, and 3-D lattice trap formed at trap intersections.

All-optical Bose-Einstein condensation

This past year, we successfully created an atomic Bose-Einstein condensate using all-optical methods, and thus realized a long-term objective in the field [3]. Remarkably, our method is simpler and faster than traditional BEC experiments and offers unique capabilities for atoms and molecules not amenable to traditional methods.

All-optical methods of reaching the BEC phase transition have been pursued since the early days of laser cooling. Despite many impressive developments beyond the limits set by Doppler cooling, the best previous efforts were limited by density-dependent heating and losses in laser cooling techniques, residual heating in optical dipole force traps or the unfavorable starting conditions for evaporative cooling.

We have created a Bose condensate of ^{87}Rb atoms directly in an optical trap formed by tightly focused laser beams. Following initial loading from a laser cooled gas, evaporative cooling through the BEC transition is achieved by simply lowering the depth of the optical trap. Our success is due in part to a high initial phase space density realized in the loading of our optical dipole trap and in part to the tight confinement of the atoms that permits rapid evaporative cooling to the BEC transition in ~ 2 s. This fast evaporation relaxes considerably the requirement for extremely long trap lifetimes typical of magnetic trap BEC experiments. Additionally, in contrast to magnetic traps that only confine one or two magnetic spin projections, our technique is spin-independent and the condensates that we form are $F = 1$ three-component spinors.

This work has attracted much attention from the physics community and beyond, and was featured in write-ups in *The Economist*, *Physics Today*, *Physics World*, as well as in many trade publications. Additionally, this work was featured for the first color cover illustration in the 100+ year history of the *Physical Review*.

Magnetic guiding

We have recently demonstrated the first storage ring for neutral atoms [4]. The ring employs a two-wire magnetic guiding structure and a novel mechanism to transfer atoms to the ring from a magneto-optic trap. This experiment represents a significant step towards utilizing ultracold, guided atoms in ring-based atom interferometry experiments, and additionally, the ring geometry provides new opportunities for the creation of continuous, monochromatic atomic beams. Particularly relevant to our quantum information system, this guiding technique will be used to physically separate the production of the cold atoms from the optical trap + cavity system. This work was published in *Physical Review Letters* and has been featured in *USA Today, Discover Magazine, Physics Today, Aviation Week and Space Technology* as well as in many trade publications.

Theory Results

The theoretical component for our current program contained two main goals: (1) the development of detailed cavity QED models to interface with our ongoing experimental program, and (2) the exploration of new ideas for entanglement of atoms, molecules and photons in the context of quantum computing.

Theoreticians You and Kennedy, with assistance from visiting scientist Z. Hu have performed detailed theoretical investigations and numerical simulations of several aspects of the stimulated Raman adiabatic passage (STIRAP) proposed initially by Pellizzari et al. [5], in order to achieve the state copy and quantum CNOT gate between two atoms in cavity QED.

The effects of spontaneous emission and adiabaticity of the pulse sequence are now well understood. The original proposal of Pellizzari et al. did not address the influence of quantized motion of the atomic center of mass degrees of freedom on the atomic entanglement. Our theoretical investigations, supported by preliminary numerical simulations indicate their conclusions are limited to the Lamb-Dicke limit of atomic confinement, i.e., when the atoms are confined to the quantum ground state of center of mass motion with the ground state width much less than the resonant optical wavelength.

In a related effort, we have proposed a new scheme for implementing universal quantum computing utilizing trapped atomic spins in optical lattices [6], which has certain advantages with respect to other related lattice proposals [7, 8]. We have identified a practical regime where long range magnetic dipole-dipole coupling provides the necessary interaction for quantum entanglement through dual translating optical lattices. We have determined the theoretical limits of this new system, with reference to several alkali atom species, and identified several of its novel features.

Our investigations have clarified one specific initial concern—potential decoherence effects due to quantum motional degrees of freedom of the atoms trapped in the cavity not satisfying the Lamb-Dicke limit (LDL) [9]. The issue of motional decoherence is important in all cavity QED quantum logic implementations, and our analysis has shown that decoherence can be kept to acceptable levels for experimentally accessible systems.

An investigation of the entanglement of the internal degrees of freedom (the qubit space) with motional states of the atoms within their respective traps was undertaken in order to assess the decoherence times produced by recoil effects associated with the absorption and emission of photons from two sources (a) the cavity field responsible for atomic entanglement, and (b) the external driving lasers which "trigger" the quantum logic. Following initial extensive numerical investigations of simplified models (e.g. one-dimensional trapping) [10] analytical studies of the complete system proved to be possible. The principal result discovered is that there is a coherence mechanism whose efficiency depends on the spatial mode matching of the cavity and laser fields, and which may in principle greatly reduce the rate of motional decoherence of atomic dark states [11]. It is a further necessary condition that the trapping potential seen by different hyperfine electronic ground states should be identical.

The coherence mechanism arises due to the nature of the two-photon coherent process in a single trapped Λ type atom, which involves absorption of one laser photon and emission of one cavity photon, or vice versa. Each single photon process in principle involves not only a change of electronic state of the atom, but also, through recoil, the motional state of the atom within the trap. On the basis of such processes we might naively expect a motional decoherence rate Γ for atoms trapped in the Lamb-Dicke limit to be of order εΩ, where ε is the Lamb-Dicke parameter, i.e., the ratio of recoil energy to trap energy level spacing, and Ω is the Rabi frequency. However, our calculations show that the probability amplitude for coupling to orthogonal states of motion induced in the coherent two photon process coupling a dark state to a motionally excited state depends on the overlap of the cavity (C) and laser (L) fields in the vicinity of the trap, and the decoherence rate approaches the value Γ $\Gamma \to |\varepsilon_L - \varepsilon_C|\Omega$ for collinear standing waves. Such overlap is very difficult in current strong coupling cavity QED implementations which involve standing wave cavities. The introduction of nearly collinear standing wave laser fields into the cavity is not readily achieved, and for lasers introduced through the side of the cavity, the overlap may be diminished to the point where the naive estimate becomes valid once more.

We have also studied quantum inseparable *entanglement/correlations* for two identical boson wavefunctions [12]. This helps to answer a pressing question in understanding the quantum information science in the context of identical particles. Recently several ideas have emerged in using pure atomic condensate for quantum information processing [5]. In this work [12], we extend the recent results on two fermion systems by J. Schliemann [13, 14] and present a unified entanglement measure in terms of the von Neumann entropy of the reduced single particle density matrix. We concluded that in all three cases: two distinguishable particles, two fermions or bosons, the reduced single particle density matrix fully characterizes their inseparable quantum correlations.

In our paper "Spin squeezing and entanglement in spinor-1 condensates," we, for the first time, proposed a mathematical formulation for studying spin-squeezing and entanglement of collections of spin-1 particles [15]. This is motivated by the experimental success of Chapman's group in optically generating spin-1 condensates [3], and may lead to interesting realization of massive atomic entanglement.

In related work, we have studied the spin squeezing of a BEC in which the effective spin up and down states are different hyperfine ground states of the atom, which are strongly coupled by an external driving field whose Rabi frequency is the largest characteristic frequency in the problem [16]. The low energy s-wave elastic collisions between atoms in the driven BEC, result in a spin squeezing, which is rather closely related to that recently discussed by the Innsbruck group [17], except that in the present case the mean spin vector undergoes a periodic motion due to the external driving, upon which the squeezed quantum fluctuations are superposed. The squeezing mechanism at play is the so-called *single axis twist*, originally discussed by Kitigawa and Ueda [18].

In our paper "Decoherence of collective atomic spin states due to inhomogeneous coupling," we addressed the important question of decoherence for atomic collective spin states [19]. In view of the recent high interest in generating and manipulating such ensemble based atomic states, our result provides a first reality check in pushing for their applications in quantum information science.

Press Features of Our Work:

"Trapped Atomic Spins Give Quantum Logic," *Nanotech Alert*, February, 18, 2000.
"Magnetic Forces Need Not Apply: Bose Einstein Condensates Can Be Made in an Optical Trap," *Physics Today*, July 2001, p.20-21.
"Bose-Einstein Condensates—Cold, Quickly," *The Economist*, July 7-13, 2001, p. 76
"Condensates Made Easy," *Physics World*, August 2001, p. 3
"All-Optical Technique Creates Bose-Einstein Condensates," *Photonics Spectra*, August 2001, p. 51
"Zeroing in on Absolute Zero," *The Tampa Tribune*, September 17, 2001, p.7
"All-Optical Trap Nets Bose-Einstein Condensates," *Laser Focus World*, September 2001, p. 15-16
"All-Optical Method Yields Bose-Einstein Condensates," *OE Magazine*, September 2001, p. 9-10.
"The Coldest Place in Georgia," *TechLINKS*, September/October 2001, p. 32
"Lasers Replace Magnet Trap for Condensates," *Photonics Spectra*, October 2001, p. 26
"Working at the Coldest Place in Georgia," *The Whistle*, August 27, 2001, p. 2.
"Stopping Atoms (Extremely) Cold," *Research Horizons*, Fall 2001, p. 45
"All-Optical BEC," *Physics News Update*, Number 545 #1, June 2001, www.aip.org.enews/physnews/2001/split/545-1.html
"A Storage Ring for Neutral Atoms," *Physics Today*, February 2002, p.9
"Pocket Particle Accelerator Built," *Nature Science Update*, January 2002, www.nature.com/nsu/020101/020101-4.html
"A Step Toward Atom Fiber Optics," *Research Horizons*, Winter 2002, p. 28-29
"A Nano-Electron-Volt Neutral Atom Storage Ring," *Physics News Update*, Number 569 #3, December 2001, www.aip.org.enews/physnews/2001/split/569-3.html
"Tiny Ring May Improve Guidance Systems," *USA Today*, January 2, 2002

"Neutral Atom Storage Ring," *Nature Physics Portal*, www.nature.com/physics/physics.taf?file=/physics/highlights/6867-2.html
"Inside Avionics," *Aviation Week and Space Technology*, January 14, 2002, p. 425
"Atomic Merry-Go-Round," *Discover Magazine*, April 2002, p.13

Publications

Papers Published in Peer-reviewed Journal Articles

1. You, L. and M.S. Chapman, *Quantum entanglement using trapped atomic spins.* Phys Rev A, 2000. **6205**(5): p. art. no.-052302.

2. You, L., *Motional effects of trapped atomic or ionic qubits.* Phys Rev A, 2001. **6401**(1): p. art. no.-012302.

3. Paskauskas, R. and L. You, *Quantum correlations in two-boson wave functions.* Phys Rev A, 2001. **6404**(4): p. art. no.-042310.

4. "Creating massive entanglement of Bose condensed atoms," Kristian Helmerson and L. You, Phys. Rev. Lett. **87**, 170402 (2001).

5. Barrett, M.D., J.A. Sauer, and M.S. Chapman, *All-optical formation of an atomic Bose-Einstein condensate - art. no. 010404.* Phys Rev Lett, 2001. **8701**(1): p. 0404-U14.

6. Sauer, J.A., M.D. Barrett, and M.S. Chapman, *Storage ring for neutral atoms - art. no. 270401.* Phys Rev Lett, 2001. **8727**(27): p. 0401-+.

7. Kennedy, T.A.B. and P. Zhou, *Atomic dark states and motional entanglement in cavity QED.* Phys Rev A, 2001. **6406**(6): p. art. no.-063805.

8. "Motional rotating wave approximation for harmonically trapped particles," Ozgur Mustecapliuglu and L. You, Phys. Rev. A **65**, 033412 (2002).

Submitted:

9. "Spin squeezing and entanglement in spinor-1 condensates," Ozgur Mustecapliuglu, M. Zhang, and L. You, Phys. Rev. A (submitted, 2001). quant-ph/0203015.

10. “On the single mode approximation in spinor-1 atomic condensate,” S. Yi, Ozgur Mustecapliuglu, C. P. Sun, and L. You, Phys. Rev. A (submitted, 2001), cond-mat/0201173.

Papers Published in Conference Proceedings

none

Papers Presented in Conference Proceedings

1. Neutral Atom Cavity QED Quantum Logic, DAMOP, Storrs, CT, May 2000
2. Investigations of CO2 Lattices, Quantum Electronics and Laser Science Conference, Baltimore, MD, May 2001 (talk given by M. Barrett)
3. Magnetic Guiding of Neutral Atoms with Simple Wire Structures, DAMOP, London, Ontario, May 2001
4. Neutral Atom Cavity QED Quantum Logic, DAMOP, London, Ontario, May 2001 “All-Optical Formation of a Bose-Einstein Condensate,” Coherence and Quantum Optics VIII, Rochester, NY 2001
5. “All-Optical Formation of Atomic BEC,” International Workshop, Quantum Gases, Insel Reichenau, July 2001.
6. “Quantum Information with Trapped Atoms in CQED,” Workshop on Beyond BEC: Ultracold Atoms Beyond Mean Field Physics, Cambridge, MA, November 2001.

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Report of Inventions

none

Bibliography

1. Takekoshi, T., J.R. Yeh, and R.J. Knize, *Quasi-Electrostatic Trap for Neutral Atoms.* Opt Commun, 1995. **114**(5-6): p. 421-424.
2. Friebel, S., et al., *CO2-laser optical lattice with cold rubidium atoms.* Phys Rev A, 1998. **57**(1): p. R20-R23.
3. Barrett, M.D., J.A. Sauer, and M.S. Chapman, *All-optical formation of an atomic Bose-Einstein condensate - art. no. 010404.* Phys Rev Lett, 2001. **8701**(1): p. 0404-U14.
4. Sauer, J.A., M.D. Barrett, and M.S. Chapman, *Storage ring for neutral atoms - art. no. 270401.* Phys Rev Lett, 2001. **8727**(27): p. 0401-+.
5. Pellizzari, T., et al., *Decoherence, Continuous Observation, and Quantum Computing - a Cavity Qed Model.* Phys Rev Lett, 1995. **75**(21): p. 3788-3791.
6. You, L. and M.S. Chapman, *Quantum entanglement using trapped atomic spins.* Phys Rev A, 2000. **6205**(5): p. art. no.-052302.
7. Brennen, G.K., et al., Phys. Rev. Lett., 1999. **82**: p. 1060.
8. Jaksch, D., et al., *Entanglement of atoms via cold controlled collisions.* Phys Rev Lett, 1999. **82**(9): p. 1975-1978.
9. You, L., *Motional effects of trapped atomic or ionic qubits.* Phys Rev A, 2001. **6401**(1): p. art. no.-012302.
10. Hu, Z., et al., *Atomic entanglement in cavity QED.* DAMOP Meeting, Santa Fe, NM, 1998.
11. Kennedy, T.A.B. and P. Zhou, *Atomic dark states and motional entanglement in cavity QED.* Phys Rev A, 2001. **6406**(6): p. art. no.-063805.
12. Paskauskas, R. and L. You, *Quantum correlations in two-boson wave functions.* Phys Rev A, 2001. **6404**(4): p. art. no.-042310.
13. Schliemann, J., D. Loss, and A.H. MacDonald, Phys. Rev. B, 2001. **63**: p. 085311.
14. Schliemann, J., et al., quant-ph/0012094.
15. Helmerson, K. and L. You, *Creating massive entanglement of Bose-Einstein condensed atoms.* Phys Rev Lett, 2001. **8717**(17): p. art. no.-170402.
16. Jenkins, S.D. and T.A.B. Kennedy, *Spin squeezing in a driven Bose-Einstein condensate.* in preparation (2002).
17. Sorenson, A., et al., Phys. Rev. Lett. **85**: p. 3991.
18. Kitigawa, M. and M. Ueda, Phys. Rev. A, 1993. **47**: p. 5138.

19. Sun, C.P., S. Yi, and L. You, *Decoherence of collective atomic spin states due to inhomogeneous coupling.* quant-ph/0203072.