The Center for Quantum Information

Cornell University
Harvard University
University of Rochester
Rutgers University
Stanford University

Interim Progress Report

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ARO-MURI Center for Quantum Information

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http://www.optics.rochester.edu:8080/~stroud/cqi

ARO-MURI Center for Quantum Information

Overview

The Center for Quantum Information is a multidisciplinary research center for the study of the processing and transmittal of information using quantum systems. The major goals of the center are to develop a toolbox of quantum procedures and protocols in a variety of elementary systems, ranging from atoms and molecules to photons and electronic nanostructures, and to formulate the elements of a quantum theory of information. Since information is itself one of the basic physical properties of quantum theory, its role must be characterized for each microscopic system before it can be applied to more complex entities. The focus of our research therefore lies between the distinctive fundamental features of quantum mechanics and their application. To achieve these aims, CQI is based upon the interaction of several highly interdisciplinary research projects. The Center is a collaborative effort of nine professors from five universities (Rochester, Harvard, Stanford, Cornell, and Rutgers). Expertise ranges from quantum optics and atomic physics, through mesoscopic electronics, to information theory and its applications in commercial optical telecommunications systems.

Center for Quantum Information Website

The CQI website provides an Overview of the Center as well as information on personnel, publications (links provided), links to other universities involved in the Center, and details on seminars and meetings sponsored by the Center.

www.optics.rochester.edu:8080/~stroud/cqi.

Section 1: Papers and Presentations

Condensed Matter Projects

Manuscripts Submitted

1. "Field effect transistors on rubrene single crystals with parylene gate insulator," V. Podzorov, V. M. Pudalov, and M. E. Gershenson, cond-mat/0210555, submitted to Appl. Phys. Lett.

2. "Hopping conductivity beyond the percolation regime probed by shot-noise measurements," F. E. Camino, V. V. Kuznetsov, E. E. Mendez, M. E. Gershenson, D. Reuter, P. Schafmeister, and A. D. Weick, , cond-mat/0210167, submitted to Phys. Rev. B.

3. "SubMM wave superconducting hot-electron direct detectors," B. S. Karasik, B. Delaet, W. R. McGrath, H. G. LeDuc, J. Wei, M. E. Gershenson, and A. V. Sergeev, Proc. FIR, SubMM & MM Detector Technology Workshop, 1-3 April 2002, Monterey, CA, in press

Papers Published (Peer-Reviewed)

1. "Electron-phonon scattering in disordered metallic films," A. Sergeev, B. S. Karasik, M. Gershenson, and V. Mitin, Physica B, 316-317, 328 (2002).

2. "Reply to *Pudalov et al*," V. M. Pudalov, M. Gershenson, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett., 89, 219702 (2002).

3. "Low-density spin susceptibility and effective mass of mobile electrons in Si inversion layers," V. M. Pudalov, M. E. Gershenson, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Phys. Rev. Lett., 88, 196404 (2002).

4. "Crossed magnetic fields technique for studying spin and orbital properties of 2d electrons in the dilute regime," M. E. Gershenson, V. M. Pudalov, H. Kojima, N. Butch, E. M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, Physica E, 12, 585 (2002).

5. "Electron-phonon relaxation in hot-electron detectors below 1 K," B. S. Karasik, A. V. Sergeev, and M. E. Gershenson, *Low Temperature Detectors* - Proc. 9th Int. Workshop on Low Temperature Detectors, Madison, WI, 2001, AIP Conf. Proc 605, pp. 75-78.

6. "Rashba effect within the coherent scattering formalism," G. Feve, W. D. Oliver, M. Aranzana, and Y. Yamamoto, Phys. Rev. B, 66, 155328 (2002).

7. "Electron entanglement via a quantum dot," W. D. Oliver, F. Yamaguchi, and Y. Yamamoto, Phys. Rev. Lett., 88, 037901 (2002).

8. "Indistinguishable photons from a single-photon device," C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon, and Y. Yamamoto, Nature, 419, 594 (2002).

9. “Low-temperature fate of the 0.7 structure in a point contact: A Kondo-like correlated state in an open system,” S. M. Cronenwett, H. J. Lynch, D. Goldhaber-Gordon, L. P. Kouwenhoven, C. M. Marcus, K. Hirose, N. S. Wingreen, and V. Umansky, Phys. Rev. Lett., 88, 226805 (2002).

10. “Adiabatic quantum pump of spin-polarized current,” E. R. Mucciolo, C. Chamon, and C. M. Marcus, Phys. Rev. Lett., 89, 146802 (2002).

11. “Detecting spin-polarized currents in ballistic nanostructures,” R. M. Potok, J. A. Folk, C. M. Marcus, and V. Umansky, Phys. Rev. Lett., 89, 266602 (2002).

12. “Spin-orbit coupling, antilocalization, and parallel magnetic fields in quantum dots,” D. M. Zumbühl, J. B. Miller, C. M. Marcus, K. Campman, and A. C. Gossard, Phys. Rev. Lett., 89, 276803 (2002).

13. “A gate-controlled bidirectional spin filter using quantum coherence,” J. A. Folk, R. M. Potok, C. M. Marcus, andV. Umansky, Science, 299, 679 (2003).

14. “Gate-controlled spin-orbit quantum interference effects in lateral transport,” J. B. Miller, D. M. Zumbühl, C. M. Marcus, Y. B. Lyanda-Geller, D. Goldhaber-Gordon, K. Campman, and A. C. Gossard, Phys. Rev. Lett., 90, 076807 (2003).

Presentations / Invited Lectures

1. “Interaction effects in conductivity of Si MOSFETs at intermediate temperatures,” Michael Gershenson, Invited, NEC Research Workshop on 2D MIT, May 2002.

2. “Interaction Effects in Electron Transport in Si Inversion Layers at Intermediate Temperatures,” Michael Gershenson, Invited, Int. Conference on Localization and Interaction Effects in Disordered Solids (Localization-02), Kyoto, August 2002.

3. “Interaction Effects in Conductivity of High-Mobility Si MOSFETs at Intermediate Temperatures,” Michael Gershenson, Invited, Brown University, November 2002.

Section 1: Papers and Presentations

Information Theory Projects

Manuscripts Submitted

1. "Geometric programming duals of channel capacity and rate distortion," M. Chiang and S. Boyd, submitted to IEEE Trans. Info. Theory.

Papers Published (Peer-Reviewed)

1. "Quantum rate-distortion theory for memoryless sources," I. Devetak and T. Berger, IEEE Transactions on Information Theory (Special Issue in Memory of Aaron D. Wyner), 48, 1580 (2002).

2. "Duality between channel capacity and rate distortion with two-sided state information," T. M. Cover and M. Chiang, IEEE Trans. Info. Theory, 48, 1629 (2002).

3. "Security of quantum key distribution with entangled photons against individual attacks," E. Waks, A. Zeevi, and, Y. Yamamoto, Phys. Rev. A, 65, 052310 (2002).

4. "On the classical capacity of a quantum multiple-access channel," G. Klimovitch, Proceedings of the IEEE International Symposium on Information Theory, Washington, D.C., June 2001, pg. 278.

Presentations

1. "Continuum Quantum Rate-Distortion," T. Berger, Invited seminar, University of Rochester, Rochester, New York, August 20, 2002.

2. "Geometric programming duals of channel capacity and rate distortion," submitted to IEEE Trans. Info. Theory. Partially presented as "Shannon duality through Lagrange Duality," M. Chiang and S. Boyd, Allerton Conference 2002.

Section 1: Papers and Presentations

Quantum Optics Projects

Manuscripts Submitted

1. “Efficient implementation of the Bernstein-Vazirani algorithm,” C. Dorrer, M. Anderson, P. Londero, K. Banaszek and I. A. Walmsley, submitted to Phys. Rev. Lett., 2003.

2. “Photon engineering for quantum information processing,” A. U’Ren, K. Banaszek and I. A. Walmsley, submitted to Quantum Information and Computation (invited paper), 2003.

3. “Managing photons for quantum information processing,” A. U’Ren, E. Mukamel, K. Banaszek and I. A. Walmsley, submitted to Proc. Roy. Soc. (invited paper), 2003.

4. “Reverse decoherence and photon wave functions,” J. H. Eberly, K. W. Chan, and C. K. Law, invited article in Chaos, Solitons and Fractals (to be submitted).

5. “Quantifying control of photon-atom entanglement in spontaneous emission,” K.W. Chan, C. K. Law, and J. H. Eberly, Proc. of International Conf. on Quantum Information, edited by I. A. Walmsley, et al., OSA Publications.

6. “Schmidt-mode analysis of entanglement for quantum information studies,” J. H. Eberly, in Proc. of NATO-ASI on Quantum Communication and Information Technologies, edited by A. Shumovsky (Springer-Verlag, 2003).

7. “Experimental phase-sensitive cloning,” John C. Howell, Irfan A. Khan, D. Bouwmeester, and N. P. Bigelow, Phys. Rev. Lett., in review.

8. “Forbidden transitions in a MOT,” M. Bhattacharya, C. Haimberger, and N. P. Bigelow, Phys. Rev. Lett., in review.

9. “Calculation of the interspecies s-wave scattering length in an ultracold Na-Rb vapor,” S. B. Weiss, M. Bhattacharya, and N. P. Bigelow, Phys. Rev. A, in review.

10. “Compressible vortex matter,” L. Baksmaty, S. Woo, S. Choi, and N. P. Bigelow, Nature, in review.

11. “Quasi-particle excitations of a vortex lattice in a Bose-Einstein condensate,” S. Woo, L. Baksmaty, and N. P. Bigelow, Phys. Rev. Lett., in review.

12. “Quasi-particle excitations of a vortex lattice in a Bose-Einstein condensate,” H. Pu, W. Zhang, L. O. Baksmaty, N. P. Bigelow, and P. Meystre, Phys. Rev. A, accepted.

Papers Published (Peer-Reviewed)

1. “Rotationally induced collapse and revivals of molecular vibrational wavepackets: Model for environment-induced decoherence,” S. Wallentowitz, I. A. Walmsley, L. J. Waxer and Th. Richter, J. Phys. B: At. Mol. Opt. Phys. 35, 1967 (2002)

2. “Photon counting with a loop detector,” K. Banaszek and I. A. Walmsley, Opt. Lett., 28, 52 (2003)

3. “Localized single-photon wave functions in free space,” K. W. Chan, C. K. Law, and J. H. Eberly, Phys. Rev. Lett., 88, 100402 (2002).

4. “Bell inequalities and quantum mechanics,” J. H. Eberly, Am. J. Phys., 70, 276 (2002).

5. “Phonon decoherence of quantum entanglement: Robust and fragile states,” T. Yu and J. H. Eberly, Phys. Rev. B, 66, 193306 (2002).

6. “Spontaneous-noise entanglement and photon wave functions,” J. H. Eberly, K. W. Chan, and C. K. Law, Chaos Solitons and Fractals 16, 399 (2003).

7. “Quantum fast Fourier transform using multilevel atoms,” Ashok Muthukrishnan and C. R. Stroud, Jr., J. Mod. Opt., 49, 2115 (2002).

8. “Entanglement of internal and external angular momenta of a single atom,” Ashok Muthukrishnan and C. R. Stroud, Jr., J. Opt. B: Quantum Semiclass. Opt., 4, S73 (2002).

9. “Entanglement of a gas of atomic spins,” N. P. Bigelow, Acta Phys. Pol. **101**, 307 (2001).

10. “Spin squeezing in degenerate and non-degenerate atomic vapors,” N. P. Bigelow, Zeitschrift Naturforsch. 56a, 35 (2001).

11. “Creation of topological states in spinor condensates,” H. Pu, S. Raghavan, and N. P. Bigelow, Phys. Rev. A,, 63 063603 (2001).

12. “Comment on ``Observation of superluminal behaviors in wave propagation", N. P. Bigelow and C. R. Hagan, Phys. Rev. Lett 87, 059401 (2001).

13. “Two-dimensional matrix continued fraction and the time-independent Schrödinger equation,” H. Y. Ling, J. Michaelson, H. Pu, L. Baksmaty, and N. P. Bigelow, J. Comp. Phys., accepted.

14. “Theory of a collective atomic laser,” H. Ling, H. Pu. L. Baksmaty, and N. P. Bigelow, Phys. Rev. A 63, 053810 (2001).

15. “Rotational states in ultracold collisions,” J. Shaffer, W. Chalupczak, and N. P. Bigelow, Phys. Rev. A, Rapid. Comm., 63, 021401(R) (2001).

16. “An all optical dynamical dark trap for neutral atoms,” P. Rudy, R. Ejnisman, A. Rahman, S. Lee, and N. P. Bigelow, Optics Express, 8, 159 (2001).

17. “Generation of arbitrary Dicke states in spinor Bose-Einstein condensates,” S. Raghavan, H. Pu, P. Meystre, and N. P. Bigelow, Optics Comm. 188, 149 (2001)

18. “ Quantum Engineering: Squeezing Entanglement,”N. Bigelow, Nature, 409, 27 (2001).

Presentations

1. “Entanglement and Memory-Force Bound States,” J. H. Eberly, ARO-MURI Review, Harvard University, Boston, MA, February 2002.

2. “A New Look at ‘Spooky Action at a Distance’,” J. H. Eberly, Physics Colloquium, Queen’s University, Kingston, Ontario, Canada, March 2002.

3. “Continuum Entanglement Bound States and Quantum Memory Force (QMF),” J. H . Eberly, Invited, Quiprocone Workshop, University of Durham, Durham, UK, April 2002.

4. “Robust vs. Fragile Entanglement and Decoherence vs. Local Dephasing,” J. H. Eberly, Quantum Optics Colloquium, NASA-JPL, Pasadena, CA, May 2002.

5. “Decoherence Control via Random Matrices,” Post-deadline poster, Jin Wang and J. H. Eberly, APS/DAMOP Annual Meeting, Williamsburg, VA, May 2002.

6. “Entanglement Decoherence vs. Local Dephasing, Robust and Fragile Entangled States,” J. H. Eberly, NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

7. “Elementary Introduction to the Schmidt Theorem and Bipartite Entanglement Analysis,” J. H. Eberly, NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

8. “Entanglement in Continuous Hilbert Spaces and The ‘Memory Force’,” J. H. Eberly, NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

9. “Decoherence of Entanglement: A Toy Model,” J. H. Eberly, Poster paper, Perspectives in Decoherence Control and Quantum Computing, Ann Arbor, MI, August 2002.

10. “Information Measure of Available Entanglement in Photon-atom Scattering,” J. H. Eberly, Poster, paper # MK46, K. W. Chan and J. H. Eberly, Laser Science 18, Orlando, FL, September 2002.

11. “Robust and Fragile Entangled Quantum States in a Toy Model,” J. H. Eberly, Poster, paper # ThG2, *Ting Yu and J.H. Eberly, Laser Science 18, Orlando, FL, October 2002.

12. “Schmidt Disentanglement and Quantum Memory Force (QMF),” J. H.Eberly, AMO Physics Seminar, Seoul National University , Seoul, Korea, October 2002.

13. Inaugural Asan Memorial Lectures: “Schmidt Disentanglement and Quantum Memory Force (QMF),” J. H. Eberly, Department of Physics, Korea University, Seoul, Korea, October 2002.

14. “Control of High Entanglement and the EPR Limit,” J. H. Eberly, Invited Hot Topic, Discussion Meeting on Practical Realizations of Quantum Information Processing, The Royal Society, London, November 2002.

15. “Memory Force-a Quantum Tie that Can Bind,” J. H. Eberly, Invited, Symposium on Complexity in Optics, Lorentz Centre, Leiden University, Netherlands, November 2002.

16. “Memory Force and Quantum Entanglement,” J. H. Eberly, Informal AMO Seminar, University of Kaiserslautern, Kaiserslautern, Germany, December 2002.

17. “Quantum Mechanics in the Classical Limit,” C. R. Stroud, Jr., Invited plenary lecture, 38th Conference on the Physics of Quantum Electronics, Snowbird, Utah, January 2002.

18. “Overview MURI Center for Quantum Information,” C. R. Stroud, Jr., MURI Program Review, Harvard University, February 24, 2002.

19. “Technological Importance of Quantum Weirdness,” C. R. Stroud, Jr., Office of Naval Research, Physics Directorate Review, Arlington, VA, May 2002.

20. “Quantum Weirdness: Technology of the Future,” C. R. Stroud, Jr., Invited public lecture, SUNY Binghamton, September 2002.

21. “Rydberg Electron Wave Packets: Observing and manipulating electrons within an atom,” C. R. Stroud, Jr., Physics Colloquium, SUNY Binghamton, September 2002.

22. “Quantum Weirdness: Technology of the Future,” C. R. Stroud, Jr., Invited public lecture, University of Kansas, Lawrence, October 2002.

23. “Rydberg Electron Wave Packets: Observing and manipulating electrons within an atom,” C. R. Stroud, Jr., Physics Colloquium, University of Kansas, Lawrence, October 2002.

24. “Quantum Weirdness: Technology of the Future,” C. R. Stroud, Jr., Invited public lecture, Wichita State University, October 2002.

25. “Rydberg Electron Wave Packets: Observing and manipulating electrons within an atom,” C. R. Stroud, Jr., Physics Colloquium, Wichita State University, October 2002.

26. “Single-query all-optical 50 –element database search,” Ian A. Walmsley, QELS, Baltimore, MD, May 2001.

27. “Engineering entanglement in ultrafast parametric downconversion,” Ian A. Walmsley, ICCSUR, Boston, MA, May 2001.

28. “Single particle quantum computing and the classical limit,” Ian A. Walmsley, Atomic Physics Gordon Conference, Williamstown, MA, June 2001.

29. “Controlling decoherence in molecular vibrational dynamics,” Ian A. Walmsley, Quantum Optics V, Rochester, NY, June 2001.

30. “Controlling decoherence in molecular vibrational dynamics,” Ian A. Walmsley, Quantum Control Gordon Conference, Mt. Holyoke. MA, July 2001.

31. “Resource measures for quantum information processing,” Ian A. Walmsley, ILS-XVI, Long Beach, CA, October 2001.

32. “All-optical 50 –element database search,” Ian A. Walmsley, QUIPROCONE Torino, October 2001.

33. “Taming the Dragon: Closed-loop control of decoherence in molecular vibrations,” Ian A. Walmsley, Quantum Control Workshop, Schloss Ringberg, Bavaria, December, 2001.

34. “Managing photonic entanglement for quantum information processing,” Ian A. Walmsley, QUIPROCONE Workshop, Durham, England, April 2002.

35. “Efficient Generation of Entangled Photons by means of Parametric Downconversion in Controlled Spatio-Temporal Modes,” Ian A. Walmsley, Quantum Communications and Quantum Computation Meeting, Boston, MA, August 2002.

36. “Quantum Information Science,” Ian A. Walmsley, Near Field Optics Conference NFO-7, Rochester, NY, August 2002.

37. “Implementation of the Bernstein-Vazirani algorithm using optics,” Ian A. Walmsley, ICO Conference, Firenze, Italy, September 2002.

38. “Managing Decoherence,” Ian A. Walmsley, ESF /EU Summer School on Coherent Control, Cargese, Corsica, September 2002.

39. “Engineering photons for quantum information processing,” Ian A. Walmsley, Royal Society Meeting on Quantum Information Processing, London, November, 2002.

40. “Engineering photons for quantum information science,” Ian A. Walmsley, Max Planck Insitut für QuantenOptik, Garching, Germany, December 2002.

41. Invited speaker and session chair, Nicholas Bigelow, Institute for the Americas, University of New Mexico Workshop on BEC, February 2002.

42. Invited speaker, Nicholas Bigelow, Department of Physics Colloquium, University of Connecticut, April 2002.

43. Invited speaker, Nicholas Bigelow, Department of Physics Colloquium, University of Florida at Gainesville, April 2002.

44. “Vortex nucleation and arrangement in a stirred Bose-Einstein condensate,” L. O. Baksmaty and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

45. “Collective excitations of vortex arrays in a trapped Bose-Einstein condensate,” L. O. Baksmaty, S. Woo, and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

46. “Approaches to BEC in a two-species magnetic trap,” S. B. Weiss, M. J. Banks, J. P. Janis, and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

47. “Determination of scattering lengths in low-temperature heteronuclear collisions,” S. B. Weiss and N. Bigelow, DAMOP Meeting of the American Physical Society, Williamsburg, VA, May 2002.

48. Recoil effects and BEC,” Nicholas Bigelow, Invited speaker, Gargnano, Italy, June 2002.

49. “Physics of ultracold dilute atomic gasses,” Nicholas Bigelow, Invited speaker, Benasque Center for Science, Benasque, Spain, June 2002.

50. Invited speaker, Nicholas Bigelow, European Workshop on Degenerate Quantum Gasses and Ultraprecise Clocks, Luntern, the Netherlands, September 2002.

51. Invited Seminar, Nicholas Bigelow, Rice University, October 2002.

52. Invited talk, Nicholas Bigelow, Symposium on Chemical Physics and Astronomy, Univ. of Waterloo October 2002.

Section 2: Scientific Personnel

Cornell University

Faculty

Dr. Toby Berger, Professor of Electrical Engineering, Cornell University

Ph.D. Students

Igor Devetak (tradeoff problems in quantum information theory)
Ken Dennison (new directions in quantum information processing)

Harvard University

Faculty

Dr. Charles M. Marcus

University of Rochester

Faculty

Dr. Nicholas Bigelow, Lee A. DuBridge Professor of Physics
Dr. Joseph H. Eberly, Carnegie Professor of Physics
Dr. Carlos R. Stroud, Jr., Principal Investigator and Professor of Optics
Dr. Ian A. Walmsley, Professor of Optics

Postdoctoral Associates

Dr. Jin Wang

Ph.D. Students

Iman Aghilian (Stroud; entanglement of Rydberg atoms in surface MOT)
Benjamin Brown (Walmsley; coherent control of cold molecular formation)
Kam Wai Chan (Eberly; Schmidt-mode evolution leading to control of entanglement)
Pablo Londero (Walmsley; molecular dimers for quantum information studies)
Alberto Marino (Stroud; entangement and teleportation of states of matter)
Hideomi Nihira (Stroud; entanglement in three-level fluorescence)
Eric Page (Bigelow; dispersion management for applications in optical links for entanglement channels)
Jeffrey S. Pratt (Eberly; dynamical evolution of entanglement and entanglement transfer)
Alfred U'Ren (Walmsley; engineering entanglement using quasi phase matched nonlinear waveguides)

Rutgers University

Faculty

Dr. Michael Gershenson, Assistant Professor of Physics and Astronomy
Dr. Sergei Sysoev, Research Associate, Physics and Astronomy

Ph.D. Student

Vitaly Podzorov

Stanford University

Faculty

Dr. Thomas M. Cover, Kwoh-Ting Li Professor of Electrical Engineering and Statistics
Dr. Yoshihisa Yamamoto, Professor of Electrical Engineering & Applied Physics
Dr. Martin Morf, Senior Research Engineer, Department of Electrical Engineering

Ph.D. Students

William Oliver (Yamamoto; electron entanglement)
Jon Yard (Yamamoto; information theory an quantum information)
David Julian (Cover; information theory and duality of the theory of data compression)

Ph.D. Degrees Awarded

1. “Tradeoff problems in quantum information theory,” Igor Devetak, Cornell University, Department of Electrical and Computer Engineering; Toby Berger, Thesis Advisor, January 2002.

2. “The generation and detection of electron entangement,” William D. Oliver, Stanford University, Department of Electrical Engineering, Yoshihisa Yamamoto, Thesis Advisory, August 2002.

3. “Revivals and classical-motion bases of quantum wave packets,” David L. Aronstein, University of Rochester, The Institute of Optics, Carlos Stroud, Thesis Advisor, September 2002.

Section 3: Report of Inventions

1. Patent Disclosure: UR Docket No. 1-11150-03021 “Room Temperature Source of Polarized Single Photons on Demand,” S. Lukishova, R. W. Boyd, and C. R. Stroud, Jr.

Section 4: Scientific Progress and Accomplishments

Condensed Matter Projects

Rutgers University - Michael Geshenson

For the first time, we fabricated successfully the field-effect transistor (FET) with reproducible characteristics on the surface of organic single crystals. A novel idea of using the polymer parylene films as the gate insulator has been proposed. The parameters of the single-crystal organic FETs (the field-effect mobility and on/off ratio) are comparable to the parameters of the best thin-film organic FETs: the devices demonstrate the hole-type conductivity with the field-effect mobility up to 10 cm^2/Vs and the on/off ratio up to 10^6 at room temperature. The temperature dependence of the mobility depends strongly on the value of μ(300 K). Our data suggest that with further crystal purification and improvement of the single crystal surface, significant enhancement of the low-temperature mobility of the surface carriers in these devices can be expected.

The hot-electron direct detectors (HEDDs) of far-infrared radiation operating at sub-kelvin temperatures have been designed, fabricated and characterized. The deposition process for ultra-thin *Ti* and *Hf* films has been optimized and the prototype titanium HEDDs have been fabricated. These superconducting FIR HEDDS offer unique combination of sensitivity and speed at sub-Kelvin temperatures. Their robust construction suits well the purpose of large-array fabrication. Our direct measurements of the energy relaxation time due to electron-phonon coupling in thin metal films prove viability of the HEDD idea. The estimated parameters of the prototype devices: the noise-equivalent power $NEP < 1\_10^{-18}$ W/√Hz and the response time $\tau \sim 10$ ms at T = 0.3K

Section 4: Scientific Progress and Accomplishments

Condensed Matter Projects

Stanford University – Yoshihisa Yamamoto

Summary: This MURI at Stanford initiated a graduate course, Quantum Information, in the Spring of 2001. This class is being expanded to a twoquarter course taught in the Winter and Spring 2002, and will include a full set of course notes. The course continues to provide students from diverse backgrounds (electrical engineering, physics, applied physics, and computer science) with the fundamental concepts of this advanced on-going research (refer to Sec. 5 Technology Transfer for a description of this course).

The Yamamoto group under this MURI has concentrated on both theoretical and experimental implementations of the devices which are required to realize and test quantum information applications. Quantum dots serve as one key component in systems designed to investigate the quantum nature of electrons, photons, and even composite particles [1-6]. In addition to quantum dots, we investigate two-dimensional electron gas systems and single-walled carbon nanotubes.

In electron systems, the quantum optics tools required to demonstrate electron entanglement have been proposed and/or demonstrated in two-dimensional semiconductor systems [4,7,8,9,14]. We continue to pursue the noise characterization of the 0.7 and n.m structures in quantum point contacts to study spin effects of electrons in this system. We continue to perform conductance and current noise experiments with a single-walled carbon nanotubes, particularly probing the role of electron-electron correlation effects. On the theoretical side, we have incorporated the Rashba spin-orbit coupling into the coherent scattering formalism [10,16] and studied the effects of coherent multiple reflections in mesoscopic electron devices. Moreover, we proposed a means to achieve electron entanglement via a quantum dot [1].

In photon systems, we have demonstrated single-photon turnstile generation from a quantum dot in a micro-cavity [3,11,12]. The indistinguishability of these photons has been demonstrated using single photons generated sequentially from a quantum dot [2]. Utilizing the single-photon source, quantum cryptographical schemes have also been implemented. In addition, we are considering the feasibility of linear optical quantum computation with such sources. We continue our efforts in improving the generation and detection efficiency of single photons and photon pairs [5,6,11-14].

Electron Entanglement (William D. Oliver): We proposed the generation and detection of electron entanglement (spin-singlet states or ying qubits) in two-dimensional electron gas systems [1]. On the detection side, the electronic analogs to the photon quantum optical tools have been developed: A Hanbury Brown and Twiss-type intensity interferometer and an electron collision analyzer [4,9,15]. A bunching/antibunching experiment with entangled electrons and a proposal for a Bells inequality test with electrons has been proposed that utilizes these electron quantum optics tools [7,8,14,16]. On the generation side, we proposed an electron entangler based on Coulomb-mediated four-wave mixing using a quantum dot [1]. In the laboratory, we explored the noise suppression at the 0.7/0.5 structures in quantum point contacts. Noise suppressions have been observed at n.m structures for multiple plateaus. We proposed a collision experiment to determine if the two channels are spin polarized or unpolarized. We have also interpreted the noise suppressions in terms of a bound-state model.

Our future work will be to extend the quantum dot entangler model and determine its efficiency. We will also continue to probe experimentally the 0.7/0.5 structure. One-dimensional systems, single-walled carbon nanotubes, will continue to be examined experimentally to determine the role of interaction effects among the charge carriers. We may consider the development of fabrication technology to connect the tubes to quantum dots.

References

1. W. D. Oliver, F. Yamaoguchi, and Y. Yamamoto, "Electron entanglement via a quantum dot," Phys. Rev. Lett. 88, 79012002.
2. C. Santori, D. Fattal, J. Vuckovic, G. S. Solomon, and Y. Yamamoto, "Indistinguishable photons from a single-photon device," Nature, 419, 594 2002.
3. C. Santori, M. Pelton, G. Solomon, Y. Dale, and Y. Yamamoto, "Triggered Single Photons from a Quantum Dot," Phys. Rev. Lett., 86, 1502-1505, February 2001.
4. W. D. Oliver, J. Kim, R. C. Liu, and Y. Yamamoto, "Hanbury Brown and Twiss-type Experiment with Electrons," Science, 284, 299-301, April 1999.
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Section 4: Scientific Progress and Accomplishments

Information Theory Projects

Cornell University – Toby Berger

Since Dr. Igor Devetak finished his Ph.D. in December 2001, output on the Cornell subcontract has diminished considerably. There is one new publication [1] which appeared in IEEE Transactions on Information Theory has now appeared. Another Physics student has been identified, Ken Dennson and he has been working on this research project since Summer 2002. Progress is being made on new directions in quantum information processing and will shortly be reaching the output stage.

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Section 4: Scientific Progress and Accomplishments

Information Theory Projects

Stanford University – Thomas Cover

Professor Thomas Cover's research group has been engaged in the exploration of how physics changes information theory. Work by Gleb Klimovitch studies the properties of multiple access quantum channels [5, 6]. In particular, this work establishes factor bounds on the relationship of the quantum multiple access channel capacity region with entanglement, the capacity region without entanglement, and the classical capacity region. The duality of source and channel coding, both with and without state information, is developed in Cover and Chiang [2]. The duality of the associated optimization algorithms is given in Chiang and Boyd [1], and dualities in statistical mechanics are studied in [3]. Jon Yard is investigating how quantum information arises in areas of physics such as string theory and condensed matter physics. Much of this group's work is influenced by a search for the most natural operational definitions of conditional states and conditional entropy. This search is directed toward finding a full quantum generalization of the Slepian-Wolf theorem. We suspect that the problem in making such a definition is largely conceptual. To this end, we have been investigating a new interpretational framework for quantum information theory. It is our desire to determine a common viewpoint of both physics and information theory.

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Section 4: Scientific Progress and Accomplishments

Quantum Optics Projects

University of Rochester – Nicholas Bigelow

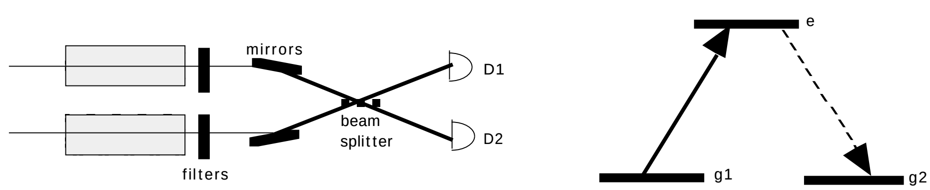
Summary of Current Research

(1) To demonstrate quantum teleportation of the state of a massive particle system composed of many millions of atoms in a simple and robust manner,

(2) To develop the current schemes for quantum communication using multi-level atomic systems, taking advantage of both spontaneous and stimulated processes and

(3) To extend our previous entanglement techniques, based on QND-type state measurement and non-local Bell measurement to include the impact of conditional measurement.

Our entanglement scheme has the attractive feature that continuous variable entanglement is realized in a vapor of many millions of atoms using simple set-ups using only coherent laser light generated from simple diode lasers. The fact that quantum entanglement is resident in the collective variables of the system means that the entangled state is robust to the loss of coherence of any individual atom and the incoherent effects of (random) processes such as spontaneous emission and other detrimental noise processes.



Schematic of anticipated experimental geometry

Here we follow a recent proposal by Duan et al. In detail, using the configuration as shown above. We note that at the University of Rochester, we have significant experience in conditional photon counting experiments. For this system, the collective atomic mode S is $\mathbf{S}=(1/\sqrt{N})\sum_j |g_{i,1}\rangle\langle g_2|$ (N is the atom number). The sample is initially prepared with all atoms in their individual $|g_{i,1}\rangle$ states. The light-atom interaction time is Δt and the experiment is carried out in the weak field limit (neglecting stimulated processes). When a single Stokes photon (the dotted line in the level diagram) is emitted in the forward direction, represented by a field operator a acting on |stokes-field-vacuum> the collective state of the atoms+field system can be written as

$$|f\rangle = |\text{atom-}g_2\text{-vacuum}\rangle\,|\text{stokes-field-vacuum}\rangle + cS^{\dagger}\,a^{\dagger}\,|\text{atom-}g_2\text{-vacuum}\rangle\,|\text{stokes-field-vacuum}\rangle$$

where c is a constant dependent on the excitation probability. When this picture is extended to the two-cell coincidence set-up, and both cells are excited simultaneously, then the state of the entire system is $|f\rangle_{UPPER}\ |f\rangle_{LOWER}$. The forward scattered light from both cells is combined on the beam splitter and a signal “click” on either photodetector reflects the combined radiation from the two samples as described by the operators $a_+^\dagger\ a_+$ or $a_-^\dagger\ a_-$ where $a_\pm = (a_{UPPER} \pm e^{i\phi}\ a_{LOWER})/\sqrt{2}$. Conditional on which detector measures a click, one applies a_+ or a_- to the entire system $|f>_{UPPER}\ \ |f>_{LOWER}$ and the projected state is nearly maximally entangled as

$$|\Psi> = (S_{LOWER}^\dagger \pm\ e^{i\phi}\ S_{UPPER}^\dagger)/\sqrt{2}[\,|\text{atom-g2-vacuum}>_{UPPER}|\text{atom-g2-vacuum}>_{LOWER}].$$

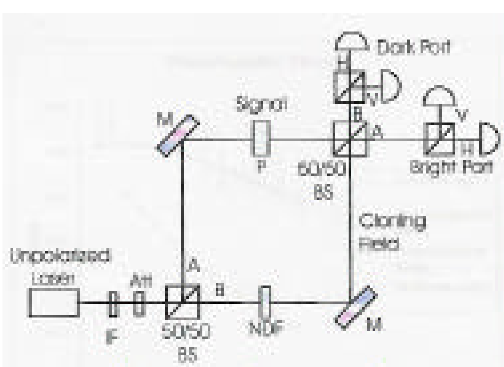
Now, in the weak field limit, the probability of a click is some small parameter p, so that the process is repeated giving an entanglement time of $\Delta t/p$. This state can be shown to be an “effective maximally entangled state” in detail, a discussion which is not appropriate here.

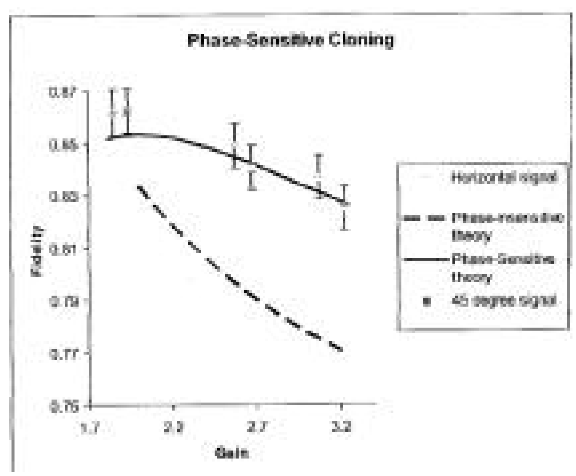
One weakness of this approach is that, like the teleportation experiments carried out in the Zeilinger group, the teleportation is probabilistic and requires posterior confirmation. This point was clearly stated in by Duan. We note that extending this scheme to the strong field limit where stimulated processes become important is motivated by a desire to effectively increase p and to move away from the limit of single photon counting.

Much as in the case of the QND/non-local Bell case, a noise study of the present conditional entanglement, Raman scattering scheme has been carried out and a detailed analysis made of a combined entanglement and entanglement swapping scheme (made by cascading two-cell conditional measurement set-ups) and efficient overall scaling and noise immunity were predicted. What is particularly striking about this scheme is that it exhibits a form of built-in entanglement purification making it nearly ideal for quantum repeater implementation.

Project 1: Experimental demonstration of phase-sensitive quantum cloning: In many quantum cryptosystems, weak coherent stares are used as substitutes for true single photon (Fock) states. An important question for photon experiments is then “what is the difference between a an attenuated coherent state and a Fock state? Our experiments probe the distinction between a weak coherent state and a true Fock state. In studies of this distinction, we have demonstrated that for an optical field, the cloning fidelity can be increased by restricting the cloning to a subset of possible polarization states. We experimentally achieved 0.86+-0.01 fidelity for 1->2 cloning of a weak coherent signal in two non-orthogonal basis states separated by 45 degrees.

Status: Complete, paper submitted to Physical Review Letters





Project 2: Unit quantum efficiency, nondestructive photon counting detector: We are in the process of constructing a high efficiency (>99%) nondestructive photon counting detector based on cross-phase modulation in electromagnetically induced transparency. In our scheme, signal photons cause a number dependent phase shift on a cw probe field in a Mach-Zender interferometer, without the use of a cumbersome cavity. We expect that this scheme will satisfy the linear optics quantum computing requirements with only pi/1000 cross-phase modulation per photon. This project is highly relevant to our proposal of combining the quantum aspects of photon statistics with the entanglement of collective quantum variables.

Status: A Rb atomic vapor cell system and stabilized diode lasers are in place and initial experiments on EIT are underway.

Project 3: Theory of a coupled nano-mechanical resonator-Cooper-Pair Box system: Second order corrections are considered for the spectrum of a nano-mechanical resonator electro-statically coupled to a Cooper-pair box. The spectrum is shown to be modified in a way that depends on the number-state of the Cooper-pair box. An analysis is underway to investigate whether frequency shifts could be utilized to prepare the nano-mechanical resonator in a number state, to perform non-demolition measurements of the resonator number state and to distinguish the phase-state of the Cooper box.

Section 4: Scientific Progress and Accomplishments

Quantum Optics Projects

University of Rochester – Joseph Eberly

Dynamics of Entanglement in Large Quantum Systems: Our main effort has been directed to predictions of time evolution of non-separable entanglement in situations where many qubits or large Hilbert spaces are involved.

(1) qubit-qubit dynamics on a lattice of N qubits, in the large-N limit, using exact results from the Heisenberg spin chain field theory model (PRB with student Jeff Pratt);

(2) photon-atom entanglement and quantum memory binding, where the ease of detection of the atom and the ease of transmission of the photon make an attractive "cross-platform" example (PRL with C.K. Law and student Cliff Chan).

Highlights of results:

(1) The decoherence over time arising from nearest neighbor cross-talk in quantum qubit arrays is not exponentially rapid.

(2) The number of "information eigenmodes" can be counted (and is often a very small integer) even for a continuous Hilbert space, giving a reliable measure of information capacity.

Dr. Jin Wang, CQI postdoc, has a goal to obtain a working theoretical model that will clearly distinguish global disentanglement from local relaxation, an open issue of importance to all proposed large-scale qubit arrays. Her progress has been hampered by her weak PhD preparation at U. Queensland.

Section 4: Scientific Progress and Accomplishments

Quantum Optics Projects

University of Rochester – Carlos Stroud

Our work on this project has been devoted to achieving two goals: (1) Developing techniques for controlling the precise superposition state of a multilevel quantum system; (2) Utilizing this control to store and manipulate quantum information.

Quantum Control: For the past decade, with the support from this MURI center and from a previous ARO sponsored URI center we have pioneered the techniques of forming and manipulation atomic Rydberg electron wave packets. These wave packets are tailored superpositions of many of many highly excited atomic states. There may be from five or six to hundreds, or even thousands of states in the superpositions. There is probably no other multilevel quantum system in all of physics that can be controlled as well. This means a Hilbert space of for example 128 states, or equivalently seven qubits, can be controlled. We have demonstrated this control in a particularly nice form by creating an approximately transform-limited three-dimensionally localized Rydberg electron wave packet travelling in a classical orbit [1]. The wave packet forms what is essentially a "quantum pixel" of the atomic wave function. Through a series of such excitations of a single atom, each pulsed excitation placing a small fraction of the total population into the excited state, an arbitrary complex wave function can be fabricated.

In a recent invited review of this work we presented five important physical conclusions that have been demonstrated in this work [2].

a) The phase space paths contributing to the Feynman propagator describing the revivals and fractional revivals of Rydberg wave packets are quantized, and are in general Bohr-Sommerfeld orbits generalized to allow fractional quantum numbers.

b) Ehrenfest's theorem holds generally for spatially localized wave packets, even in the presence external fields, so long as the fields are not too strong.

c) Most classical states are not directly accessible from the ground state, and similarly most classical states decay to other classical states rather than to a low-lying distinctly quantum state.

d) Classical limit states provide important tools for quantum information processing. (See following section).

e) Entanglement can persist even in classical limiting states.

The detailed proofs of these statements are contained in the referenced manuscript and are too lengthy to be given here. They do provide a framework for applying quantum control of atomic electrons to problems of interest in quantum information.

Multi-level Quantum Information: Most of classical information theory, computer science, and indeed most of quantum information theory and quantum computation is based on binary logic with the associated bits and qubits. While it is certainly true that quantum systems and indeed transistors have more than two states available, one generally utilizes only two states per memory element. The reasons for this apparent waste of resources are of two types. First, the error rate is lessened by having to distinguish only two states. Second, the information capacity of the system is only increased as the logarithm of the number of states, thus offering marginal benefit for very large data sets.

We have been pursuing multilevel logic in spite of these arguments because of the following considerations: (a) While classical transistors are cheap, quantum entanglement between qubits is an expensive and fragile resource. For quantum information storage and manipulation at the level of tens or hundreds of qubits the logarithmic advantage of multilevel logic is quite significant. For example, thirty-two level logic would reduce the number of entangled systems by a factor of five. (b) The scope of this Center goes beyond quantum computing to the general subject of quantum information: the interface between information theory and quantum mechanics. Most quantum systems, even simple ones like single atoms or single photon wave packets are described by large Hilbert spaces. The information describing such systems is inherently multilevel, not efficiently reducible to a representation in terms of qubits. In particular, entanglement between two multilevel systems is not efficiently reducible to entanglement of a number of qubits.

These are reasons for extending quantum information theory to multi-state logic, and we have done so in a series of publications and a doctoral dissertation. [3-6]. The main results of those publications are the demonstration of a universal gate for multi-state logic along with a proposed physical realization of it; the description of a wave packet basis particularly suited for multilevel logical operations; the demonstration of a simple method by which a discrete Fourier transform can be performed using a single atom; and finally a proposal for a method by which the center-of-mass angular momentum and internal angular momentum states of a single atom can be entangled.

Future work will be directed towards laboratory realization of these multilevel logical systems using both atomic wave packets and photon wave packets.

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Section 4: Scientific Progress and Accomplishments

Quantum Optics Projects

University of Rochester – Ian Walmsley

Summary: Work over the past year in CQI has centered on three themes: developing efficient sources of entangled photons with controlled character; exploring implementations of quantum algorithms with linear optics and using learning control to manage decoherence and control noise for quantum logic gates.

Managing Photonic Entanglement: One of the major problems in the application of spontaneous scattering for quantum computing is the difficulty of experimentally determining whether more than one pair of photons was emitted at a given time. This hampers efficient generation of single photon states because it restricts the source to operate with extremely small parametric gain. One way of removing this restriction is to identify detectors capable of distinguishing between small numbers of photons. Such detectors do exist, and they are based on dividing the photon wavefunction among several spatially separated detectors that can each register a single photon. Then the probability that a given detector whose spatial extent is much smaller than the photon wavefunction will register more than one photon in a beam containing several is vanishingly small. Unfortunately such detectors must generally be operated at very low temperatures, making them impractical for scalable quantum information processing systems. We have recently proposed and analyzed a novel scheme for a photon-number resolving detector that can operate at room temperature. It is based on common fiber optical technology and standard avalanche photodiodes. The analysis shows that it is possible to design a system such that the photon statistics of the input pulse can be determined from the “click” registration pattern of the detector. We are currently implementing this design in our laboratory and expect to complete the initial test by the summer. This will involve determining the photon statistics of low-level coherent light pulses. The second stage will be to show that such detectors are compatible with single and pair-photon sources, and to demonstrate their ability to prepare photonic states that are useful for linear optical quantum computing (for example using the scheme proposed by Kitaev, Gottesman and Preskill).

We have also undertaken an analysis of the quantum logic gates proposed by Knill, Laflamme and Milburn, taking into account the previously ignored degrees of freedom of the input photons. Using the analytical techniques developed previously by ourselves and the Eberly group under this program, we have devised a set of criteria that must be met by any source that is to be applied to the KLM scheme. Moreover, we have shown that any source failing to meet these criteria lead to an exponential decay in the gate operation fidelity. This work shows that source engineering is a critical component of linear optical quantum computing.

Resources and Scaling Issues for Quantum Information Processing: We have implemented the Bernstein-Vazirani algorithm using linear optics. The key feature of this demonstration was the realization of the polynomial speed-up of a database search (from N queries to a single query) in an apparatus whose physical size scaled linearly with the size of the maximum number in the database. The remarkable fact is that this is possible using entirely classical physics. The interference that generates the speed-up exists only within each qubit, and not between qubits. The same apparatus can also be used for multi-level encoded cryptography, and we are planning to explore this avenue to demonstrate some of the possibilities of these protocols.

Decoherence Management: In the past year we have analyzed a model of decoherence for a simple laboratory system, and begun experiments to show how dephasing may be optimally managed in the system. The experiments show that the coherence in the system in the presence of severe dephasing may be accounted for by properly encoding the information into the system to begin with. The advantage of a multilevel encoding scheme in this regard is that it provides a degree of latitude unavailable in a qubit system.

The particular system studied was a diatomic molecule. In this system the quantum information was encoded in the vibrational degree of freedom using shaped optical pulses, and the state after some evolution measured using fluorescence tomography. The vibrations are coupled to the rotational degree of freedom in such as way that this degree of freedom acts essentially as a dephasing reservoir. The coupling admits of no decoherence-free subspaces, and as a consequence there are no coding schemes that are completely immune to “environmental” disturbances. In this case, whether there exist subspaces that are optimally resistant to dephasing is largely an experimental question.

We are continuing this project to explore the operation of a 2-bit logic gate using the electronic and vibrational degrees of freedom of the molecule as the two carriers of quantum information. This will enable us to study the effects of control field noise on the fidelity of gate operation, and to develop he concept of optimal encoding to operations, rather than simply states.

Section 5: Technology Transfer

5.1 Center for Quantum Information Website

The CQI website provides an Overview of the Center as well as information on personnel, publications (links provided), links to other universities involved in the Center, and details on seminars and meetings sponsored by the Center.

www.optics.rochester.edu:8080/~stroud/cqi.

5.2 MURI Program Review by the TAC/EAB [1]

A formal program review of the MURI was held 25-26 February 2002 at Harvard University. Of the more than 50 members of the TAC and EAB of this MURI, 15 attended the critical third year program review. A listing follows:

TAC Members

H. Brandt (ARL/SEDD)	K. Deacon (ARL/CISD)
J. Dowling (NASA/JPL)	H. Everitt, Chair (ARO/Physics)
M. Foster (DARPA)	M. Kruger (NSA)
R. Meyers (ARL/CISD)	K. Miller (NSA)
S. Pethel (AMCOM)	E. Potenziani (CECOM)
P. Reynolds (ONR)	P. Shor (Lucent)

EAB Members

C. Bowden (AMCOM)	H. Everitt, Exec. Coordinator (ARO/PSD)
C. Lau, Ex Officio (DDR&E)	L. Lome, Chair (MDA)
B. West (ARO/ESD)	

Also in attendance were almost 20 faculty and graduate researchers from the MURI.

The program review contained 5 major segments:

1) An overview of the mesoscopic electronics portion of the NIP MURI program.
2) An overview of the information theory portion of the NIP MURI program.
3) An overview of the optical physics portion of the NIP MURI program.
4) A combined poster session and laboratory tour.
5) A government caucus.

Segments 1-3 identified the activity in each of the portions of the NIP MURI, preceded by an introduction by MURI director (C. Stroud) outlining the research objectives and accomplishments of the MURI. The mesoscopic electronics team is investigating decoherence, spin filters, and entanglement generation in 2D electron gas systems. The information theory team is working on the differences between classical and quantum information theory specifically for networking and data compression. The optical physics team is developing quantum components and metrics for quantifying quantum information by combining theory with experimental demonstrations in atomic and photonic systems. The tours involved visits to Marcus' labs, while posters featured students working in the respective each of the three MURI teams. Details of the activities can be obtained through printed copies of the presentations, a CD containing all the presentations was also provided, or by visiting the MURI center web site at http://www.optics.rochester.edu:8080/faculty/cqiWebsite/FRAMES/IQSframes.html.

[1] Excerpted from "Report of the TAC / EAB," 2002.

5.3 Cross-Border Workshop on Quantum Correlation and Nonlinear Photon Physics

The Cross Border Workshop is held annually bringing together scientists working in atomic, molecular and optical science and engineering from around the Great Lakes region (Canada and United States). The workshop allows graduate students and post-docs to present their research and interact with scientists in an informal setting. The 2002 Annual Cross Border Workshop was held at the University of Rochester, 24-26 May 2002. Sixty students, professors, and researchers from universities and research laboratories gathered for three days on the University of Rochester campus to hear a series of tutorials and review current research interests. The Workshop was jointly sponsored by the Center for Quantum Information and the Rochester Theory Center. The theme for 2002 focused on Quantum Correlation and Nonlinear Photon Physics. Research topics include (but are not limited to): Ultrafast and Strong-Field Physics, Quantum Information, and Nonlinear and Fiber Optics. Details on speakers and topics can be found at:

http://www.optics.rochester.edu:8080/~stroud/cqi/cbw2002speakers.html

5.4 Graduate Courses on Quantum Information

The research result output from the MURI program has generated several area specific courses for graduate students.

Stanford University: The MURI at Stanford has stimulated the creation of a graduate course, AP225 Quantum Information, Dr. Yoshi Yamamoto, Professor. Below is the course description as it appears in the Stanford Graduate Bulletin:

> **AP225: Quantum Information** - Fundamental concepts of quantum theory: linear superposition, entanglement, non-locality and projective measurement. Two photon interference and Bell's inequality. Fundamental limits in quantum measurement: quantum nondemolition measurement, non-linear measurement and quantum Zeno effect. Quantum key distribution and teleportation: information, energy dissipation and reversible computer. Quantum algorithms, physical implementations and scaling laws. Quantum hardware. Decoherence of quantum systems and quantum error correction codes.

University of Rochester: During the Spring 2003 semester, the Center for Quantum Information is hosting a series of tutorial lectures on the subject of “Physics of Matter Waves” by Professor Kasimir Rzazewski, Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland. Students attending these lectures will receive credit through OPT 592 Special Topics in Quantum Information. The lectures are proving valuable in educating the whole quantum optics community about an important area that is not currently covered in our regular curriculum. Both faculty and graduate students are attending this popular series, with the audience attendance averaging 30 person per lecture.

5.5 Center for Quantum Information (CQI) Colloquium Series

Weekly collaborative group meetings are held by Professors Bigelow, Eberly, Feldman, and Stroud at the University of Rochester. These meetings span a range of research areas and encourage collaborative efforts. Speakers from both inside and outside the University present their findings. Some typical presentations include:

University of Rochester Speakers

- Xingxiang Zhou: "Superconducting Quantum Computation: charge and flux qubits"
- Carlos Stroud: "Quantum Mechanics at the Quantum-Classical Interface, Parts 1 and 2"
- Jin Wang: "Modeling Quantum Decoherence with Random Matrices"
- Jonathan Habif: "Dephasing of an rf-SQUID qubit under the influence of sigma-x noise"
- Nicholas Bigelow: "Spin Entanglement and All That: Parts 1 and 2"
- Jeff Pratt: "Entanglement of Formation and Concurrence"
- Alberto Marino: "Spin Entanglement and All That: Microscopic Theory: Parts 1 and 2"
- Ting Yu: "Entanglement Decoherence vs. Qubit Dephasing"

Outside Speakers

- Prof. Taco D. Visser, Vrije Universitie Amsterdam
  - "Singular Optics – Light Chasing its Own Tail"
- Prof. Q-Han Park, Korea University
  - "Di-vortex formation in two-component BEC's"
- Dr. Peter Milonni, Los Alamos
  - "Effect of atmospheric turbulence on photon statistics"
- Prof. A. Sergienko, Boston University
  - "Entanglement engineering and new optical measurement techniques"

5.6 Public Lectures

Prof. J. H. Eberly presented three lectures on entanglement in quantum information at the NATO – Advanced Study Institute, Bilkent University, Ankara and Antalya, Turkey, June 2002.

- "Entanglement Decoherence vs. Local Dephasing, Robust and Fragile Entangled States"
- "Elementary Introduction to the Schmidt Theorem and Bipartite Entanglement Analysis"
- "Entanglement in Continuous Hilbert Spaces and The 'Memory Force'"

Prof. C. R. Stroud presented public lectures on "Quantum Weirdness: Technology of the Future?" at SUNY Binghamton, the University of Kansas, and Wichita State University. Attendance at the lectures by the general public was substantial, with more than 300 in Lawrence, Kansas for an evening lecture.