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) and an industrial partner (Lucent Technologies). Expertise ranges from quantum optics and atomic physics, through mesoscopic electronics and superconductivity, to information theory and its applications in commercial optical telecommunications systems.

Section 1: Papers and Presentations

Condensed Matter Projects

Manuscripts Submitted

1. “Absence of spontaneous spin and valley polarization at the metal-insulator transition in Si-inversion layers,” cond-mat/0110160, V.M. Pudalov, M.E. Gershenson, and H. Kojima, 2001.

2. “The low-density spin susceptibility and effective mass of mobile electrons in Si inversion layers. cond-mat/0105081, V.M. Pudalov, M.E. Gershenson, H. Kojima, N. Butch, E.M. Dizhur, G. Brunthaler, A. Prinz, and G. Bauer, submitted to *Phys. Rev. Lett*. (2001).

3. “Duality between channel capacity and rate distortion with state information and the Wyner-Ziv formula,” Y. Yamamoto, to appear in a special issue on Shannon theory, IEEE Transactions on Information Theory, April 2002.

4. “The Rashba effect within the coherent scattering formalism,” G. Feve, W.D. Oliver, M. Aranzana, and Y. Yamamoto, submitted to Physical Review B (2002).

5. “Multiple reflection effects in an electron beam splitter device,” M. Aranzana, W.D. Oliver, G. Feve, N.Y. Kim, submitted to Physical Review B (2002).

6. “The 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, submitted to *Science*.

7. “Electron entanglement via a quantum dot,” W. Oliver, F. Yamaguchi, and Y. Yamamoto, accepted for publication in Phys. Rev. Lett.

Papers Published (Peer-Reviewed)

1. “Multiphoton detection using visible light photon counter,” J. Kim, S. Takeuchi, Y. Yamamoto, and H.H. Hogue, Appl. Phys. Lett., 74, 902 (1999).

2. “Development of a high-quantum-efficiency single-photon counting system,” S. Takeuchi, J. Kim, Y. Yamamoto, and H.H. Hogue, Appl. Phys. Lett., 74, 1063 (1999).

3. “A single-photon turnstile device,” J. Kim, O. Benson, H. Kan, and Y. Yamamoto, Nature, 397, 500 (1999).

4. “Ultralow threshold laser using a single quantum dot and a microsphere cavity," M. Pelton and Y. Yamamoto, Phys. Rev. A, 59, 2418 (1999).

5. “Hanbury Brown and Twiss-type experiment with electrons," W.D. Oliver, J. Kim, R.C. Liu, and Y. Yamamoto, Science, 284, 299 (1999).

6. “Master-equation model of a single-quantum-dot microsphere laser,” O. Benson and Y. Yamamoto, Phys. Rev. A, 59, 4756 (1999).

7. “Generation of phase states by two-photon absorption,” H. Ezaki, E. Hanamura, and Y. Yamamoto, Phys. Rev. Lett., 83, 3558, (1999).

8. “Manipulation of quantum statistics in mesoscopic experiments,” Y. Yamamoto, *in Quantum Coherence and Decoherence*, Y.A. Ono and K. Fujikawa, eds., pp.83-90, North-Holland, Amsterdam (1999).

9. “Hot-electron effects in two-dimensional hopping with a large localization length,” M.E. Geshenson, Yu. B. Khavin, D. Reuter, and P. Schafmeister, Phys. Rev. Lett. **85**, 1718 (2000).

10. “Entanglement in 2DEG systems: Towards a detection loophole-free test of Bell's inequality,” X. Maitre, W.D. Oliver, and Y. Yamamoto, Physica, E6, 301 (2000).

11. “Regulated and entangled photons from a single quantum dot," O. Benson, C. Santori, M. Pelton, and Y.Yamamoto, Phys. Rev. Lett., 84, 2513 (2000).

12. “Quantum point contacts in a density-tunable two-dimensional electron gas,” S. Nuttinck, K. Hashimoto, S. Miyashita, T. Saku, Y. Yamamoto, and Y. Hirayama, Jpn. J. Appl. Phys., 39, L655 (2000).

13. Reply to comment on “Generation of phase states by two-photon absorption,” H. Ezaki, E. Hanamura, and Y. Yamamoto, Phys. Rev. Lett., 85, 1137 (2000).

14. “Single photon turnstile device, Y. Yamamoto, in *Quantum Optics of Small Structures*, D.~Lenstra et al., eds., pp.111-121, Royal Netherlands Academy of Arts and Science, Amsterdam (2000).

15. “Triggered single photons from a quantum dot,” C. Santori, M. Pelton, G. Solomon, Y. Dale, and Y. Yamamoto, Phys. Rev. Lett., 86, 1502 (2000).

16. “Single-mode spontaneous emission from a single quantum dot in a three-dimensional microcavity," G.S Solomon, M. Pelton, and Y. Yamamoto, Phys. Rev. Lett., 86, 3903 (2000).

17. “Millisecond electron-phonon relaxation in ultrathin disordered metal films at millikelvin temperatures,” M.E. Gershenson, D. Gong, T. Sato, B.S. Karasik, and A.V. Sergeev, Appl. Phys. Lett. **79**, 2049 (2001).

18. “Decoherence in nearly isolated quantum dots,” J.A. Folk, C.M. Marcus, and J.S. Harris, Jr., Phys. Rev. Lett. 87, 206802 (2001).

19. “Coulomb blockade and electron spin in quantum dots,” C.M. Marcus, J.A. folk, R.M. Potok, A.C. Johnson, L.P. Kouwenhoven, R. Berkovits, I.L. Kurland, I.L. Aleiner, and B.L. Altshuler, Proceedings of the XXXVIth Rencontres de Moriond ‘Electronic Correlations: From Meso- to Nano-physics’ Les Arcs, France (2001).

20. “Spin degeneracy and conductance fluctuations in open quantum dots,” J.A. Falk, S.R. Patel, K.M. Birnbaum, C.M. Marcus, C.I. Duruoz, and J.S. Harris, Jr., Phys. Rev. Lett. 86, 2102 (2001).

21. “Spin-orbit effects in a GaAs quantum dot in a parallel magnetic field,” B.I. Halpern, Ady Stern, Y. Oreg, J.H. Cremers, J. Folk, and C.M. Marcus, Phys. Rev. Lett. 86, 2106 (2001).

Presentations

1. "The crossover from weak to strong localization and hopping conductivity in conductors with a large localization length", M. Gershenson, Workshop on Physics of Ultrathin Films Near the Metal-Insulator Transition, Brown University, December 1999.

2. “Quantum indistinguishability in two-dimensional electron gas systems,” Y. Yamamoto, R. Liu, W. Oliver, J. Kim, and X. Maitre, Proceedings of 15th International Symposium on Advanced Physical Fields, pp. 417-426, March 2000.

3. "Hot-electron detectors: toward record sensitivity via controllable electron-phonon coupling", M. Gershenson, 11th Int. Symposium on Space Terahertz Technology, May 2000.

4. "Hopping with a large localization length in low-dimensional conductors", M. Gershenson, Int. Conference "Meso-2000", Chernogolovka, July 2000.

5. "Electron-phonon interaction in low-dimensional systems: old puzzles and new applications", M. Gershenson, Workshop on Quantum Transport and Mesoscopic Physics, Taiwan, January 2001.

6. “Measurements of the effective g-factor and mass of electrons in Si MOSFETs over a wide range of carrier densities”, M. Gershenson, The APS March Meeting, Seattle, March 2001.

7. “Crossed magnetic field technique for studying spin and orbital properties of 2D electrons in the dilute regime”, M. Gershenson, the 14th Int. Conf. On Electronic Properties of Two-dimensional systems, Prague, July 2001.

Section 1: Papers and Presentations

Information Theory Projects

Manuscripts Submitted

1. “Quantum rate-distortion theory for I.I.D. sources,” Igor Devetak and Toby Berger, accepted for publication in the special issue of IEEE Trans. Inf. Theory dedicated to Aaron Wyner, quant-ph/0011085 (2002).

Papers Published (Peer-Reviewed)

1. “Fidelity trade-off for finite ensembles of identically prepared quibits,” K. Banaszek and I. Devetak, Phys. Rev. A 64, 052307 (2001).
2. “Low-entanglement remote state preparation,” I. Devetak and T. Berger, Phys. Rev. Lett. 87, 197901 (2001).
3. “The union of physics and information,” I. Devetak and A.E. Staples, quant-ph/0112166 (2001).
4. “The worst additive noise under a covariance constraint,” S. Diggavi and T. Cover, IEEE Transactions on Information Theory, 47, 3072 (2001).

Presentations

1. “Duality and a proof of capacity for a class of channels with state information,” M. Chiang and T. Cover, Proceedings of IEEE International Symposium on Information Theory and Applications, Honolulu, Hawaii, November 2000.
2. “Parallel Gaussian feedback channel capacity,” M. Chiang and T. Cover, Proceedings of IEEE International Symposium on Information Theory and Applications, Honolulu, Hawaii, November 2000.
3. “Channel capacity and state estimation,” M. Chiang, A. Sutivong and T. Cover, Proceedings of the IEEE International Symposium on Information Theory and Applications, pp.838-840, Honolulu, Hawaii, November 2000.
4. “Quantum rate-distortion theory,” I. Devetak and T. Berger, poster presentation, QIP2001, 4th Workshop on Quantum Information Processing, Amsterdam, January 2001.
5. “Low-entanglement remote state preparation,” I. Devetak and T. Berger, contributed talk, International Conference on Quantum Information, Rochester, NY, June 13-16, 2001.
6. “Quantum rate-distortion theory for I.I.D. sources,” I. Devetak and T. Berger, contributed talk, 2001 IEEE International Symposium on Information Theory, Washington, DC, June 26-July 1, 2001.

7. "Writing on colored paper," W. Yu, A. Sutivong, D. Julian, T. Cover and M. Chiang, Proceedings of IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

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

9. "Unified duality of channel capacity and rate distortion with state information," M. Chiang and T. Cover, Proceedings of the IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

10. "Tradeoff between message and state information rates," A. Sutivong, T. Cover and M. Chiang, Proceedings of the IEEE International Symposium on Information Theory, Washington, D.C., June 2001.

11. "Rate distortion trade-off for channels with state information," A.Sutivong and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

12. "Multiple-access channels with state information," A. Sutivong and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

13. "Degraded broadcast channels with state information," A. Sutivong, Y. Kim, and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

14. "On the concavity of the increase in entropy in the second law of thermodynamics," D. Julian and T. Cover, submitted to IEEE International Symposium on Information Theory, Lausanne, Switzerland, June 2002.

Section 1: Papers and Presentations

Quantum Optics Projects

Manuscripts Submitted

1. "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).

2. “Quantum fast Fourier transform using multilevel atoms,” A. Muthukrishnan and C.R. Stroud, Jr., to be published in J. Mod. Opt.

3. “Entanglement of internal and external angular momenta in a single atom,” A. Muthukrishnan and C. R. Stroud, Jr., submitted to J. Opt. B: Quant. Semi. Opt., Special Issue.

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

Papers Published (Peer-Reviewed)

1. “Engineering the indistinguishability and entanglement of two photons”, D. Branning, W.P. Grice, R. Erdmann and I.A. Walmsley, Phys. Rev. Lett., 83, 955 (1999).

2. “Excitation of a three-dimensionally localized atomic electron wave packet,” J. Bromage and C.R. Stroud, Jr., Phys. Rev. Lett., 83, 4963 (1999).

3. “Multivalued logic gates for quantum computation," A. Muthukrishnan and C.R. Stroud, Jr., Phys. Rev. A 62, 052309 (2000).

4. "General series solution for finite square-well energy levels for use in wave-packet studies," D.L. Aronstein and C.R. Stroud, Jr., Am. J. Phys. 68, 943 (2000).

5. "Continuous frequency entanglement: effective finite Hilbert space and entropy control", C.K. Law, I.A. Walmsley and J.H. Eberly, Phys. Rev. Lett. 84, 5304 (2000).

6. “Interferometric technique for engineering indistinguishability and entanglement of photon pairs,” R. Erdmann , D. Branning, W.P. Grice and I.A. Walmsley, Phys. Rev. A 62, 013814 (2000).

7. “Restoring dispersion cancellation for entangled photons produced by ultrashort pulses”, R. Erdmann, D. Brannng, W. Grice, and I.A. Walmsley, Phys. Rev. A 62, 053810 (2000).

8. “Violation of Bell’s inequality by a generalized Einstein-Podolsky-Rosen state using homodyne detection”, A. Kuzmich, I.A. Walmsley and L. Mandel, Phys. Rev. Lett. 85, 1349 (2000).

9. “Temporal heterodyne detector for multitemporal mode quantum state measurement,” C. Iaconis, E. Mukamel, and I.A. Walmsley, J. Opt. B: Quantum Semiclass. Opt. 2, 510 (2000).

10. “How big is a quantum computer,” S. Wallentowitz, I.A. Walmsley, and J.H. Eberly, quant-ph/0009069, September 2000.

11. “Eliminating frequency and space-time correlations in multiphoton states,” W.P. Grice, A. U’Ren, and I.A. Walmsley, Phys. Rev. A. 64, 063815 (2001).

12. "Qubit cross talk and entanglement decay", J.S. Pratt and J.H. Eberly, Phys. Rev. B 64, 195314 (2001).

13. “Generation of correlated photons in controlled spatial modes by downconversion in nonlinear waveguides,” K. Banaszek, A.B. U’Ren, and I.A. Walmsley, Opt. Lett. 26, 1367 (2001).

14. “Violation of a Bell-type inequality in the homodyne measurement of light in an Einstein-Podolsky-Rosen state,” A. Kuzmich, I.A. Walmsley, and L. Mandel, Phys. Rev. A., 64, 063804 (2001).

15. “Joint quantum state measurement using unbalanced array detection,” M. Beck, C. Dorrer,a nd I.A. Walmsley, Phys. Rev. Lett. 87, 253601 (2001).

16. “Bell’s inequalities and quantum mechanics,” J.H. Eberly, Am. J. Phys. 70, 275 (2002.)

Presentations

1. "Quantum control via classical orbits," C.R. Stroud, Jr., at Israel Science Foundation Workshop on Quantum Control and Information, Nof Genossar, Israel, November 14-19, 1999.

2. "Quantum control and quantum state measurement," I. A. Walmsley, at Israel Science Foundation Workshop on Quantum Control and Information, Nof Genossar, Israel, November 14-19, 1999.

3. "Quantifying Continuum Entanglement," J.H. Eberly, at Israel Science Foundation Workshop on Quantum Control and Information, Nof Genossar, Israel, November 14-19, 1999.

4. "Quantum control via classical orbits," C.R. Stroud, Jr. at US-Japan Workshop on Coherent Control, Honolulu, HI, December 11-15, 1999.

5. "Engineering entanglement", I.A. Walmsley, at Workshop on Quantum Communications and Information, NEC Research Institute, Princeton, NJ, December 14-16, 1999.

6. “What shape is your photon?” J.H. Eberly, Joint Atomic Physics/ITAMP Colloquium, Harvard University, April 2001.

7. “Propagation and relaxation of entanglement in Heisenberg spin chains,” J. Pratt and J. H. Eberly , Poster paper, Third Cross-Border Workshop on Laser Science, University of Toronto, May 2001.

8. “Qualifying control of photon-atom entanglement in spontaneous emission,” K. W. Chan and J. H. Eberly, Poster paper, Third Cross-Border Workshop on Laser Science, University of Toronto, May 2001.

9. “Fundamental one-photon images,” J.H. Eberly, Invited Talk, International Conference on Squeezed States and Uncertainty Relations, Boston University, June 2001.

10. “Propagation and relaxation of entanglement in Heisenberg spin chains,” J. Pratt and J. H. Eberly, Contributed Paper, International Conference on Quantum Information, University of Rochester, June 2001.

11. “Qualifying control of photon-atom entanglement in spontaneous emission,” K.W. Chan and J.H. Eberly, Contributed Paper, International Conference on Quantum Information, University of Rochester, June 2001.

12. “Control parameter for photon-atom entanglement in spontaneous emission,” K.W. Chan, C.K. Law and J.H. Eberly, Poster Paper, Quantum Optics V, Koscielisko, Poland.

13. “Even stranger than we supposed: from Max Planck to teleportation,” J.H. Eberly, Plenary Invited Talk, AAPT Annual Summer Meeting, July 2001.

14. “Reversible relaxation in quantum optics,” J.H. Eberly, three lectures, Los Alamos Summer School, Los Alamos, NM, July 2001.

15. “Control of photon-atom entanglement and photon wave functions,” K.W. Chan, C.K. Law and J.H. Eberly, Poster Paper, Workshop on Quantum Optics 2001, Jackson, WY, Aug. 2001.

16. “Reverse decoherence - Entanglement arising from quantum noise,” J.H. Eberly, Invited Paper, Conference on Mechanisms for Decoherence - Theory and Applications to Nanotechnology and Quantum Information, Austin, TX.

17. “Quantum information technology of the future?” C.R. Stroud, Jr., invited lecture, Rochester Section, Optical Society of America, November 2001.

18. “Quantum information and quantum computing,” APS-DLS Distinguished Lecture, University of Alabama, May 2001.

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)

Harvard University

Faculty

Dr. Charles M. Marcus

University of Rochester

Faculty

Dr. Carlos R. Stroud, Jr., Principal Investigator and Professor of Optics
Dr. Ian A. Walmsley, Professor of Optics
Dr. Joseph H. Eberly, Professor of Physics and Astronomy; elected Foreign Member, Academy of Sciences of Poland; recipient of Goergen Prize for creativity in Undergraduate Teaching

Postdoctoral Associates

Dr. Konrad Banaszek
Dr. Christophe Dorrer
Dr. Michael Fitch
Dr. Jin Wang

Ph.D. Students

David Aronstein (revivals and classical-motion bases of quantum wave packets)
Benjamin Brown (coherent control of cold molecular formation)
Kam Wai Chan (Schmidt-mode evolution leading to control of entanglement)
Pablo Londero (molecular dimers for quantum information studies)
Alberto Marino (entangement and teleportation of states of matter)
Ashok Muthukrishnan (quantum information and computing in multilevel systems)
Jeffrey S. Pratt (dynamical evolution of entanglement and entanglement transfer)
Alfred U'Ren (engineering entanglement using quasi phase matched nonlinear waveguides)
Sungjong Woo

Rutgers University

Faculty

Dr. Michael Gershenson, Assistant Professor of Physics and Astronomy, Rutgers University

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 and Applied Physics
Dr. Martin Morf, Senior Research Engineer, Department of Electrical Engineering

Ph.D. Students

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

Ph.D. Degrees Awarded

"Quantum information and computing in multilevel systems," Ashok Muthukrishnan, University of Rochester, The Institute of Optics, Carlos Stroud, Thesis Advisor, December 2001.

"Coherence, charging, and spin effects in quantum dots and quantum point contacts," Sara M. Cronenwett, Stanford University; Charles Marcus, Thesis Advisor, December 2001.

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

Section 3: Report of Inventions

None.

Section 4: Scientific Progress and Accomplishments

Condensed Matter Projects

Harvard University – Charles Marcus

In the past year, we have completed two studies on the use of quantum point contacts and quantum dots as elements of quantum information processing. In particular, the use of both of these elements as spin filters for a spin-based information storage and processing has been investigated.

The motivation for investigating simple constrictions in a 2D electron gas as possible spin filter is the appearance of so-called 0.7 structure, an extra plateau below the first spin-degenerate conductance plateau at g = 2e2/h, as seen in Fig. 1. The origin of this extra plateau was not known, but it appeared in early studies to be as if a spontaneous magnetization occurred in the constriction.

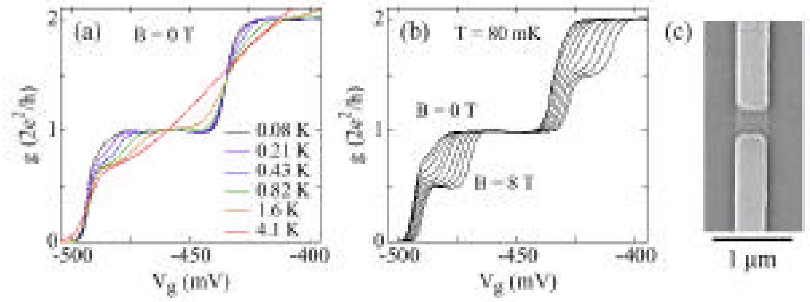

Fig. 1 a) Linear conductance (g = dI/dV, around V_{sd} ~ 0) versus gate voltage, V_g, at B = 0 for several temperatures. The extra plateau at ~ $0.7(2e^2/h)$ appears with increasing temperature while the plateaus at multiples of $2e^2/h$ become less visible due to thermal smearing. (b) Linear response g versus V_g, for in-plane field B from 0 to 8 T in 1 T steps, showing spin-resolved plateaus at odd multiples of e^2/h at high fields. (c) Electron micrograph of quantum point contact used in this study [1]. Other devices gave similar results.

A year-long investigation, resulting in a recently submitted paper to Physical Review Letters [1] and a completed Ph.D. thesis [2], now reveals the nature of the 0.7 feature. The situation is this: there is spontaneous lifting of spin modes, but without a frozen magnetization, much like the theoretical model known in the theoretical literature as the Anderson model. In this picture, there is a *free* spin that exists below the Fermi enegy, while the other spin channel is unoccupied due to interaction effects. The evidence of an Anderson-like model is the observation that the point contact forms a Kondo-like collective state at very low temperature, as seen in Fig. 2. The is the key experimental observation of Ref. 1.

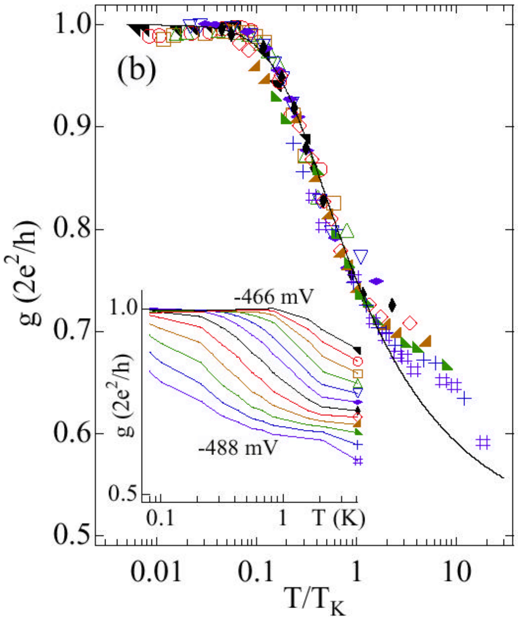

Fig. 2. Linear conductance, g, as a function of scaled temperature T/T_K where T_K is the single fit parameter to a modified Kondo form [1]. Symbols correspond to gate voltages shown in inset. Inset: Linear conductance as a function of unscaled temperature, T, at several V_g.

The formation of a Kondo-like state in a quantum point contact, in which the free spin of the point contact becomes entangled with the reservoirs, opens the possibility of entangling pairs or even arrays of quantum point contacts. Within our picture, one may think of a quantum point contact as controllable spin-1/2 impurity that is strongly coupled to its environment. The follow-up experiments, planned for the next 12 months, will involve entangling two or more quantum point contacts. These experiments are now being designed.

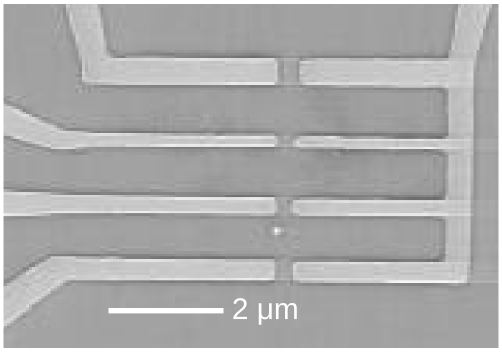

Fig. 3. SEM micrograph of independently controllable point contacts in series. Will be used to study entanglement of spin states of point contacts, like RKKY interactions.

The second set of experiments began using a pair of quantum dots in opposite arms of an Aharonov-Bohm (AB) ring, to see if the quantum dots could operate as *coherent* spin filters. The idea was to put the entire device in a strong *in-plane* magnetic field, in which case the two dots would only allow either a spin-up electron or a spin-down electron to pass, depending on whether the dot contained an even or odd number of electrons. In the Coulomb blockade regime, it is straightforward to change the number of electrons by one, and so the even or odd condition is easily changed experimentally. What we hoped to find was an alteration in the visibility of the AB oscillations around the ring as the number of electrons in one of the dots was changed. Note that to observe AB oscillations, controllable magnetic fields on the scale of millitesla perpendicular to the sample plane were needed, while field of several telsa in the plane were needed to polarize the dots. This has been accomplished using a two-magnet system developed in our lab that allows independent control of two fields.

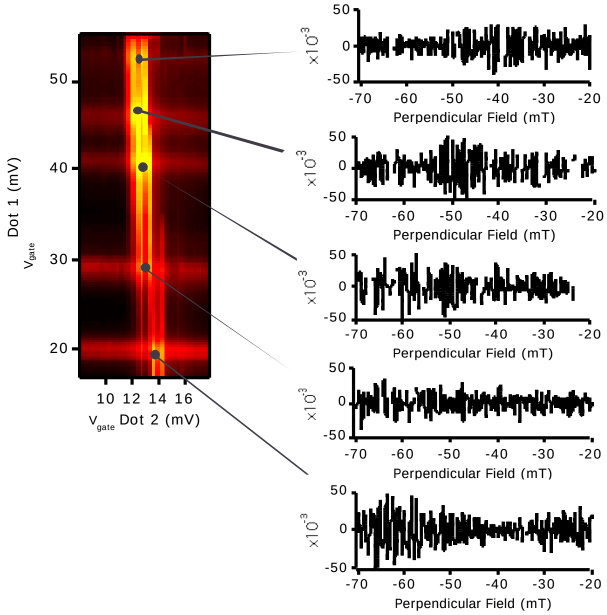

Fig. 4. (a) AFM micrograph of AB ring with dots in the two arms. In a large in-plane field, the dots should act as spin filters. (b) colorscale graph of conductance versus gate voltage on the dots. A fixed Coulomb blockade peak is seen in dot 2, while several peaks are seen on dot 1. At each peak intersection, AB measurements were made by sweeping a perpendicular magnetic field. No change in AB amplitude was observed.

The first measurements of this sort, reported in Ref. 3 and shown in Fig. 4, did not observe a difference an AB visibility as the electron number is changed. This unexpected result has motivated us to simplify the geometry, as shown in Fig. 5, to an electron focusing geometry to simply observe if the electrons coming out of a quantum dot are indeed filtered. That experiment is now underway.

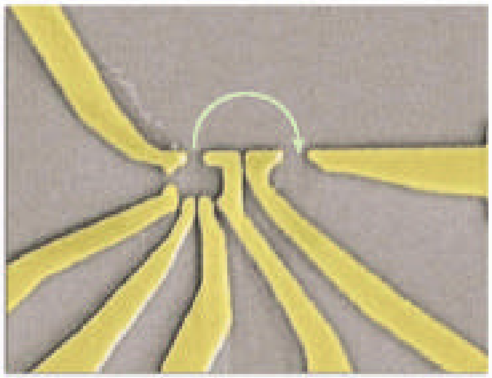

Fig. 5. A simplified geometry to test if a multielectron quantum dot will operate as a spin filter. Electrons emerging from the dot are focused on a quantum point contact set to its first plateau at e^2/h (in a large in-plane field). Changing the electron number in the dot should change the transmission. through the point contact without changing the transmission of the dot itself.

References (all available at http://marcuslab.harvard.edu/grouppubs.html)

1. S. M. Cronenwett, H. J. Lynch, D. Goldhaber-Gordon, L. P. Kouwenhoven, C. M. Marcus, K. Hirose, N. S. Wingreen, V. Umansky, The Low-Temperature Fate of the 0.7 Structure in a Point Contact: A Kondo-like Correlated State in an Open System, cond-mat/0201577 (2002).

2. Sara M. Cronenwett, Coherence, Charging, and Spin Effects in Quantum Dots and Quantum Point Contacts, Ph. D. Thesis, Stanford University, December, 2001.

3. C. M. Marcus ,J. A. Folk ,R. M. Potok ,A. C. Johnson , L. P. Kouwenhoven, R. Berkovits, I. L . Kurland, I. L. Aleiner, B. L. Altshuler, Coulomb Blockade and Electron Spin in Quantum Dots, Proceedings of the XXXVIth Rencontres de Moriond `Electronic Correlations: From Meso- to Nano-physics' Les Arcs, France (2001).

Rutgers University - Michael Geshenson

Subtleties of Quantum Decoherence in Solids: We have studied the Shubnikov-de Haas (SdH) oscillations in ultra-high-mobility Si MOSFETs over a wide range of carrier densities n = (1-50) x 10^{11} cm^{-2}, which includes the vicinity of the apparent metal-insulator transition in two dimensions (2D MIT). Using a novel technique of measuring the SdH oscillations in superimposed and independently controlled parallel and perpendicular magnetic fields, we determined the spin susceptibility χ*, the effective mass m*, and the g*-factor for mobile electrons. These quantities increase gradually with decreasing density; near the 2D MIT, we observed enhancement of x* by a factor of ~ 4.7. To test the idea of coexistence of the 2D MIT and Stoner instability, we measured the SdH oscillations in weak magnetic fields; the period of oscillations shows that the electron states remain fourfold degenerate down to n = 0.96 n_c. These data rule out spontaneous spin and valley polarization at the 2D MIT, though do not exclude such possibility for lower densities n < 8.34x10^{10} cm^{-2}.

Stanford University – Yoshihisa Yamamoto

Summary: This MURI at Stanford has stimulated the creation of a graduate course, Quantum Information (Spring 2001), by Yoshi Yamamoto, together with a full set of course notes. This has laid the foundation for dozens of students to work in this area. (Refer to Sec. 5 Technology Transfer for a description of this course.)

The primary emphasis of Yamamoto's group under this MURI has focused on the theoretical and experimental implementations of the devices necessary to realize and test quantum information applications. Our intent has been to take advantage of quantum dots as essential parts of systems for probing the physics of individual quantum particles such as electrons and photons. This work has resulted in theoretical proposals for creating entangled photons and electrons in the laboratory. Quantum dots have been used in the laboratory to trigger individual polarized photons. High efficiency coupling of a quantum dot to a single cavity mode has been achieved.

In electron systems, the quantum optics tools necessary to detect entanglement have been proposed and demonstrated [1-5]. We are continuing our efforts in the noise characterization of the 0.7 structure. Theoretical work has focused on electron entanglement via a quantum dot [6], the incorporation of the Rashba spin-orbit coupling into the coherent scattering formalism, and the effects of coherent multiple reflections in mesoscopic electron devices.

In photon systems, we have demonstrated single-photon turnstile generation from a quantum dot [7,8]. We are currently implementing quantum cryptography schemes that will utilize this source, and we are currently examining the feasibility of linear optical quantum computation. High efficiency coupling of a quantum dot to a single cavity mode has also been demonstrated recently. We continue our efforts in improving the generation and detection efficiency of single photons and photon pairs [9-14].

Electron Entanglement (William Oliver): We propose and demonstrate electron entanglement (spin-singlet states or "flying qubits") in two-dimensional electron gas systems. To this end, we have developed the fundamental quantum optical tools (a Hanbury Brown and Twiss-type intensity interferometer and an electron collision analyzer) necessary to probe entangled electrons. This leads to a proposal of a bunching/antibunching experiment with entangled electrons and a proposal for a Bell's inequality test with electrons. We also consider several systems that could act as a source of entangled electron pairs. This leads to our recent proposal for electron entanglement via a quantum dot. In addition, we consider the possibility of using the 0.7/0.5 structure in quantum point contacts as either a source of many-particle entanglement or as a polarization beamsplitter. We are able to give an experimental demonstration of noise suppression at the 0.7 structure. The degree of noise suppression is consistent with a model that has two channels split in energy through some particular interaction: one with transmission probability unity and the other transmission probability 0.4. We propose a collision experiment to determine if the two channels are spin polarized or unpolarized.

Our future work will be to extend the quantum dot entangler model and determine its efficiency. We will also continue to explore the 0.7 structure in experiments. In addition, we are beginning to explore new materials (carbon nanotubes).

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Information Theory Projects

Cornell University – Toby Berger

Our group has been dealing with various aspects of theoretical quantum information theory.

1. Quantum Rate-Distortion Theory [1,5]: The quantum lossless source coding theorem specifies the minimum rate, called the entropy and measured in code qubits per source qubit, to which a quantum source can be compressed subject to the requirement that the source qubits can be recovered perfectly from the code qubits. In realistic applications we may be able to tolerate imperfect recovery of the source qubits at the receiver, in which case we would seek to minimize the rate required to achieve a specified level of distortion. Equivalently, we may be required to use a rate less than the entropy of the source, in which case we would seek to minimize the distortion subject to this rate constraint. Here, the distortion measure is a user-defined function of the input and the reconstruction, the precise form of which depends on the nature of the application. Analysis of the tradeoff between rate and distortion is the subject matter of rate-distortion theory, and its classical counterpart is an important and fertile area of information theory. In the classical case a theorem by Shannon reduces the task to constrained minimization of mutual information between two random variables. In the quantum case no such theorem appears to exist, which renders the problem almost intractable. For the first time after the quantum formulation of the problem by Barnum we succeed in finding an exact rate-distortion function, using an important distortion measure based on entanglement fidelity.

2. Fidelity Tradeoff [2]: It is a well-known fact that given a single copy of a quantum system it is in general impossible to determine its quantum state exactly. Of course, the situation becomes different when one is given an ensemble of identically prepared quantum systems. With the increasing size of such an ensemble one can extract more and more precise information on its preparation. An important effect which usually accompanies an attempt to determine the unknown preparation of a quantum system is the disturbance of its original state -- a penalty for gaining classical information from a quantum system. This fundamental feature of quantum mechanics has been discussed from many different points of view, depending on the particular physical scenario considered, but the problem has hitherto been analytically intractable due to the choice of the information gain measure. A recent paper by Banaszek addresses the issue by finding the tradeoff function for the single copy case between the operation fidelity F, which denotes the average overlap between the state of the system after the operation and the original one, and the estimation fidelity G, which tells us how good an estimate one can provide on the basis of the knowledge of the classical outcome of a given operation. In the joint work [2] done with Banaszek, then a post-doc in the Rochester group, we discuss a more general case of the fidelity trade-off when one is given a finite ensemble of N identically prepared systems. Without imposing any restrictions on the generality of quantum operations considered, we manage to reduce the original O(2^N) dimensional constrained minimization problem to that of diagonalizing certain NxN tridiagonal matrices. We can solve the latter numerically for any N.

3. Remote State Preparation [3,5]: We all know what state preparation is: Alice has a classical description of the a state, and she makes a physical instance of it in her lab. Remote state preparation is when she again has a classical description of the the state, but now wishes to prepare it in Bob's lab, Bob being far away. We have two types of resources at our disposal: shared EPR pairs (ebits) between Alice and Bob and classical bits of forward communication from Alice to Bob. This problem may be defined with or without allowing classical back-communication from Bob to Alice. In a recent preprint Bennett et al.(Phys. Rev. Lett. 87, 077902) ask about the optimal tradeoff curve in the(bits,ebits) plane necessary for Bob to be able to produce an asymptotically perfect copy of the state, i.e. so that the average error per qubit state tends to zero as the number of states to be remotely prepared goes to infinity. One achievable point in this plane is (2,1) which corresponds to teleportation. Our work [3] concentrates on the low entanglement region where the number of ebits per state is less than one. The method used by Lo and Bennett et al. is to send partial classical informationabout the qubit state, thus reducing its posterior von Neumann entropy(i.e. the von Neumann entropy of the posterior density operator reflecting Bob'sknowledge about the qubit state having received the classical information). This may be used to Schumacher compress a block of such qubits, and teleport them at a rate corresponding to the posterior von Neumann entropy. We put this idea on a firm coding theoretical footing and use a unique blend of classical and quantum information theoretical techniques to find an expression for the optimal tradeoff curve attainable by the above method. In addition [5] contains new upper bounds on the high-entanglement region, improving on those of Bennett et al.

4. The Union of Physics and Information [4]: Coming from the perspective of quantum information theory, we have recently achieved a union of quantum mechanics, thermodynamics and Shannon's information theory. The viewpoint we take is that the totality of our conceptual experience can be described in terms of correlated random variables. Two protagonists sharing the same physical world is no more than classical correlations between the states of their knowledge regarding that world. Similarly, the observation of definite physical laws is no more than classical correlations between states of knowledge regarding two consecutive acts of measurement, or preparation and measurement, depending on the experiment. The mathematical model presented in [4] seeks a middle way between Copenhagen quantum mechanics, where the wave function does not aspire to describe reality but merely represents our knowledge of it, and Everett's many-worlds interpretation which attempts to include the observer as just another physical system, leading to the unresolved basis problem. Our model includes both physical entities P and states of knowledge K. The two have a mathematically equivalent Hilbert space description, but the latter are imbued with a preferred basis, the elements of which are labeled by the mutually exclusive possibilities. As in Everett's theory, measurement is described as entangling elements of K (the "observers") with those of P via unitary transformations. Preparation, a novel concept in Everett-like theories, is treated analogously. The joint random variable describing the correlations between the states of knowledge of the various protagonists comes about by restricting attention to the diagonal elements of their joint density matrix in the preferred basis ("diagonal vision"), and Shannon mutual information is easily calculated. This framework has already led to important contributions in quantum information theory and quantum thermodynamics. In relation to the former we have shown how both quantum and classical information processing can be seen from a unified viewpoint of entanglement transfer. Regarding the latter, we provide the long overdue quantum measure of thermodynamicentropy, having the crucial property of being able to increase in a closed system. This work will be submitted to the Young Researchers Competition in Honor of John Archibald Wheeler on "Science & Ultimate Reality".

5. Future Directions: Work in progress includes a collaboration with Konrad Banaszek (formerly a member of the MURI), and Howard Barnum on the Shannon information gain vs. operation fidelity tradeoff. Also, the thesis work on high-entanglement remote state preparation will be made into an article and submitted, most probably to IEEE IT. [1] should be extended to other distortion measures. The new unifying vision presented in [4] is yet to be fully exploited in viewing the current achievements of quantum information theory in a new light, and pointing the way to further progress. It also may have a role to play in unifying the various areas of physics into a coherent theory.

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Stanford University – Thomas Cover

Summary: Prof. Cover's group has focused on information theory and the duality of the theory of data compression and the theory of channel capacity [1,2], both classically and quantum mechanically. The search for duality leads to many insights where the results from one domain become the results in another [3,4,5]. Open problems include the amount of information that can be stored in a quantum oracle, as well as an investigation of the quantum multiple access channel [6] and the characterization of the quantum Slepian-Wolf theorem.

Information theory and quantum information (Jon Yard): Statistical thermodynamics introduced a mathematical interpretation of the entropy of a system, as well as a means of interpreting average responses of a bulk statistical mixture to external degrees of freedom. This idea was continued in two distinct directions. The first of these was the development of quantum statistical mechanics, which merged considerations of the quantum behavior of individual particles with the statistics of bulk systems. The second direction was based on the idea that information should be interpreted as an abstract entity in and of itself. This track is due to Shannon, whose intuition led the way for what has become the field of information theory. Quantum information theory ultimately represents an effort to merge these two directions on both the large and small scales.

There has been initial progress towards generalizing most of the results of classical information theory. Most of this work benefits from the correspondence between classical probability distributions and the eigenvalues of quantum density matrices. Shumacher's coding theorem, which asserts that the Von Neumann entropy $S(\rho) = -\mathrm{tr}\,\rho \log \rho$ of the density matrix corresponding to an ensemble of pure states represents a minimum average dimension of Hilbert space required to "faithfully" transmit or store a sequence of identically prepared physical systems, takes advantage of this correspondence. Indeed, if the eigenvalues of ρ are $\{\lambda_i\}$, then $S(\rho) = H(\{\lambda_i\})$.

Our notion of "faithful" above can be made more precise, but this also asks us to rethink our notion of ensemble. In one sense, we may consider a probability distribution over the set of all pure states of a prototypical system, then consider preparing a sequence of identical systems, each in a state which corresponds to a (classical) random variable. The density matrix can be thought of as the expected prepared state, where each pure state corresponds to a projection operator. We may now define the fidelity to be the average probability that a system will pass a test which checks to see if the state has changed during processing/transmission.

We may also take a dfferent viewpoint towards ensembles as arising from entanglement with some external system. Theoretically, such a system is abstracted as a "purifier." There is a sense in which the purifier can be used to generate any ensemble which respects the partial density matrix it induces. This leads to an interpretation of the purifier as an oracle. Entangled ensembles come with a "goodness criterion" as well, the entanglement fidelity F_e.

Shumacher compression gives the same rates for both of the above types of ensembles. However, this is not the case when multi-partitie ensembles are considered. Here, the analogy between probabilities and eigenvalues of ρ breaks down. Heuristically, this can be understood by the fact that the density matrix of a bipartite system can be thought of as a "matrix of matrices." Since a general ring of hermitian matrices is not guaranteed to be commutative, the naive spectral method fails to apply to all but the simplest multiuser problems.

There is an area of mathematics which falls under the vague name of "quantum groups" (group is a misnomer), which were introduced in order to study noncommutative spaces. The theory can be roughly understood as the application of formal power series to the representation theory of certain Lie algebras, which correspond to certain Hopf algebras. Hopf algebras and noncommutative geometry represent a large field of study with applications throughout physics and mathematics. Renormalization theory utilizes Hopf algebras to encode the logical structure of divergences in Feynman diagrams, allowing for computation of perturbative results to very high order. The same mathematical framework has applications in low dimensional topology, the theory of braids, exactly solvable models in statistical mechanics, conformal field theory and infinite dimensional algebras. Hopf algebras have properties which suggest that they may also be a rich language for expressing relationships between nodes at different points in spacetime in a quantum network.

There has been recent work on the foundations of quantum mechanics suggesting a unified theory of quantization/dequantization; i.e. a model for which many classical limits of a quantum theory may exist (one of which is equivalent to $h \rightarrow 0$), each of which gives the same quantum theory after (re)quantization. This theory naturally associates a symplectic space into a real infinite dimensional Hilbert space via introduction of an antihermitian operator called a complex structure, which is basically a controlled way of turning an infinite dimensional real space to an imaginary one. Operators on the Hilbert space are then associated with real valued functions on a manifold. The complex structure enables us to probe certain parameters of entanglement, such as the concurrence, which is in a sense the determinant of a pure tensor state, viewed as a matrix. It can be shown that no Hermitian observable can compute the concurrence.

We still retain a symmetric product on the underlying Hilbert space, allowing for a unified framework of linear (unitary propagation, superposition, Schrodinger/Hamiltonian flow), and nonlinear (state reduction, decoherence, measurement, Lorentzian geometry) concepts. Such work seems to be deeply tied to certain isomorphisms between the Jordan algebras of 2 x 2 hermitian matrices with elements in the Octonions. It is possible to sew together the octonionic projective plane $\mathbf{OP}^2$ near the origin in 3 parts. This topologically rich space contains symmetries which give rise to a relationship between 3 spaces known as a triality. A common example of a triality in physics is that between the representations of a left handed spinor, a right handed spinor and a vector boson, such as a vertex in the standard QED model of an electron interacting with a photon.

Trialities show potential for use in quantum, as well as classical information theory, in that to each triality is associated 3 dualities, each formed by fixing one of the three subsystems. A possible candidate for a triality in quantum information theory consists of the triple H_O, H_E, H_Q, corresponding to a cold benevolent controlling oracle, a hot malicious environment, and the quantum system under study. The oracle's controlled interaction with the quantum system could be used to model, say, the interaction of a controller for a dynamic error correction scheme with the matter in the register of a quantum computer.

The mathematical structures which give rise to and encode the structure of such maps have a well-defined theory. Division algebras, quaternions, octonions, Jordan algebras, projective geometry, Hopf fibrations of the spheres S^{15}; $S7$; $S3$, Hopf invariants. These same structures find themselves to be useful in analyzing the topology of low dimensional entangled systems. The first place in physics where these structures found themselves useful was in string theory. However, the second Hopf map $S7 \rightarrow S4$ from the projective quaternonic line to the space of unit vectors in R^5 was recently used to generalize the 2D quantum hall effect to 4D edge states on a 5D fluid of electrons.

Dualities have been an underlying theme of most of the work produced by this group. Our vision is to eventually be able to incorporate physical dualities into all of our group's work, with the hopes of understanding the physical theory of information.

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Quantum Optics Projects

University of Rochester – Joseph Eberly

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

Three examples have yielded results already. They are complementary, all dealing with quantum information in very large systems. In the order we opened our examinations, they are

(1) bi-photon entanglement in down conversion, where the Hilbert space is continuously infinite-dimensional (PRL with C.K. Law and Ian Walmsley);

(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);

(3) 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:

(3) Potentially the most interesting, and an immediate focus for further exploration. The discovery that entanglement (more specifically, quantum memory) has an interpretation as a physical "binding force" must be extended. The "exchange force" of the Pauli Principle is a special case of this more general effect existing between any pair of particles or even whole quantum systems.

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

(1) 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, a new CQI postdoc, has joined the effort to exploit better understanding of the role of dimensionality in raising or lowering decoherence rates. One goal is to obtain a working theoretical model that will clearly distinguish global decoherence decay from local relaxation, an open issue of importance to all proposed large-scale qubit arrays. She is just beginning to extend the random-environment approach of Albrecht in order to incorporate realistic environmental temperature and to determine the effect of increased dimension on decoherence-free subspaces.

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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University of Rochester – Ian Walmsley

Summary: Our work in CQI has centered on two themes: how to manage the entanglement of photons, and how to properly account for the resources needed to construct a quantum information processor. We have had some significant achievements in both of these areas, and expect to continue them for the remainder of the program.

Managing Photonic Entanglement: Our first goal in this project has been the development of novel high-brightness sources of down-converted radiation that will provide thorough control over the spatio-temporal wave functions of the produced photons. We have accomplished this goal by combining the technology of nonlinear waveguides with quasi-phase-matching to allow engineering of the two-photon wave function in the spatio-spectral domain.

The use of waveguides has two important advantages. First, the nonlinear interaction can be more efficient, so that lower pump powers can be used. Second, the spatial mode confinement means that the generated photons can be easily matched to the detectors. Spontaneous parametric down-conversion in nonlinear waveguides has been recently reported by several groups, including ours. We believe that this technology has several very promising features, especially in experiments involving multiple sources.

Specific achievements aside from this include several theoretical papers outlining how to engineer the spectral entanglement of photons, and how to characterize it, as well as how to disentangle photons, a technique that is necessary to multi-photon interference and Bell-state detection. Since the latter is the cornerstone of teleportation protocols, such engineering of the bi-photon state is important for reliable quantum communications.

In the continuation of our project, we plan to gain a much more precise control over the generated states by performing conditional detection on one of the photons in the pairs. Such a procedure removes completely the uncertainty about the number of photons, as firing of the trigger detectors implies unambiguously that the conjugate photons have been generated. Using this method, we can generate two or more photons simultaneously, and then perform collective operations that will generate entanglement. One problem related to this scheme is that the probability of generating N photon pairs simultaneously decreases in a geometrical order with the number of pairs. So far, only experiments with the simultaneous generation of two photon pairs have been realized. Our goal is to push this limit to the simultaneous generation of three photon pairs with sufficiently high count rates. This should enable us to prepare deterministic three-photon entangled states in a conditional manner. Of course, it would be rather difficult to view this direction as a straightforward route towards scalable generation of multiparticle entanglement. However, it is well recognized that three-particle entanglement exhibits a variety of novel features that are not present in bipartite quantum systems, and therefore it constitutes an important research goal by itself. Furthermore, the experimental techniques we plan to study in this project can be used as a test bed for entangling operations using linear optics and conditional detection, which in longer term have the potential of developing into fully scalable all-optical quantum computing.

Resources and Scaling Issues for Quantum Information Processing: The viability of any quantum information processor is predicated on whether it scales efficiently. That is, whether it requires fewer resources to perform a specific task than a classical computer. The notion of exactly what constitutes a resource in critical in answering the question. We have developed a procedure for quantifying resources that is based on the physical properties of the system. As quantum information processing has shown, information is physical, and physical theories therefore provide a means to answer questions of this sort.

One of the consequences of the model is that we have shown that all information processing that makes use only of quantum interference (i.e. within a single particle system) is no more efficient than a classical wave-based processor. We also performed an experiment that demonstrated this explicitly for the case of searching a database using a modified Grover algorithm. This was the all-optical analog of the quantum storage and retrieval idea of Ahn et al. An important conclusion to be drawn from this demonstration is that there appear to be things that can be done within the realm of classical physics that provide different information processing capabilities than is possible with conventional classical particle-based computers.

The next stage of the project is to determine whether it is possible to use this classical apparatus to implement some of the “quantum” algorithms that do not require entanglement. Such protocols build on the prototype proposed by Deutsch and Josza, though are geared toward more sophisticated problems that are standards for computer science. These have been analyzed by Meyer, based on ideas of Bernstein and Vazirani. If we are successful, then we shall have demonstrated a way to improve information processing without using quantum mechanics. The technological implications of this would be great. It would be possible to use much of the optical telecommunications technology to build computers that outperform standard models for computation, and to avoid the need for manipulating sensitive quantum systems at the level of individual particles.

Another path that we plan to follow is to use this starting point to better understand the role that entanglement plays in providing quantum enhancement. It is clear from our present studies that binary coding allows classical wave-based processing to achieve the same readout efficiency as an entangled-particle computer. But it is almost certainly the case that the unitary operations of the processor cannot be efficiently implemented by classical interference. But to what extent is it possible to use classically correlated subsystems with interference to achieve some of the power of quantum computers? If we can answer this, then we will have shown exactly the realm in which a full-blown quantum computer is necessary, and thereby delineated the bounds for improvements in computational power within classical physics.

Section 5: Technology Transfer

1. Center for Quantum Information Website

The Center has a very informative websitse:

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

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.

2. First International Conference on Quantum Information (ICQI)

The MURI Center at the University of Rochester was a co-sponsor of the First International Conference on Quantum Information (ICQI) held at the University of Rochester on June 10-13, 2001. It was co-sponsored by the Optical Society of America and was held in co-location with the Eighth Rochester Conference on Coherence and Quantum Optics (CQ08). The conference covered all aspects of quantum information science, including various implementations of computing, communications and cryptography, and applications as well as theoretical aspects of the subject.

The conference format was such as to encourage both pedagogy and frank discussions of the leading research in the field. One-hour long plenary tutorials were planned to cover the main sub-disciplines, as well as a liberal selection of one-half hour invited talks on current research problems from outstanding researchers in the field.

Photographs from the conference may be found at:

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

The following tutorial talks were given:

-- “Atomic physics realization of quantum logic elements in dissiplative environments,” Peter L. Knight, Imperial College, United Kingdom
--“Contemplating quantum computation,” N. David Mermin, Cornell University, Ithaca
--“Quantum error correction,” John Preskill, California Institute of Technology
-- “Characterizing entanglement,” Dagmar Bruss, University of Hannover, Germany

3. Graduate Course at Stanford on Quantum Information

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 limit in quantum measurement: quantum nondemolition measurement, non-linear measurement and quantum Zero effect. Quantum key distribution and teleportation: information, energy dissipation and reversible computer. Quantum algorithm, physical implementation and scaling law. Quantum hardware. Decoherence of quantum systems and quantum error correction codes.

4. Presentation at CLEO/QELS 2001

Dr. Ian Walmsley gave an invited talk at the CLEO/QELS 2001 in Baltimore, Maryland, May 6-11, 2001. His talk was entitled “Computing with interference: all-optical single-query 50-element database search.” This talk generated several articles from the press, which are referenced below.

--“Light shines in quantum-computing arena,” Science News
--“Quantum-light processor may thrash supercomputers,” CNN.com/Sci-Tech
--“Computer mimics quantum tricks,” MSNBC.com
--“Quantum computers get a light alternative,” Optics.org
--“Classical waves for pseudo quantum computing,” sciam.com (Scientific American)
--“Light computer runs quantum algorithm,” TRNmag.com
--“Computer runs at quantum light speed,” USATODAY.com

5. Public Lectures

Members of the Center have given several lectures to acquaint the public with the field of quantum information.

a) Professor Joseph Eberly (Univesity of Rochster) was invited by the Friends of the Rochester Public Library to speak to attendees of their regular Evening Lecture Series called Thursday Thinkers. The title to which he was asked to respond was "Beam Me Up Scotty - The New World of Quantum Physics." Speaking in layman’s terms, Prof. Eberly's talk traced highlights in the evolution of quantum physics: from Planck's introduction of a new universal constant to explain blackbody radiation, through Einstein's inspired creation of stimulated emission, to his doubts about quantum theory, as expressed in the famous EPR paper. The roles of Bohm, Bell, Clauser and Mandel in resolving the "EPR paradox" were mentioned and the process of teleportation described semi-technically. His half-hour talk generated over an hour’s worth of “questions and answers.”

b) Professor Carlos Stroud (University of Rochester) gave a lecture to industrial scientists at the Rochester Section – Optical Society of America entitled “Quantum Information: Technology of the Future,” November 2001. Prof. Stroud also gave lectures on this topic to general audiences at the University of Alabama and Truman State University as part of the Distinguished Travelling Lecturer Program of the Division of Atomic, Molecular and Atomic Physics of the American Physical Society. These lectures were presented in May 2001.