**REPORT DOCUMENTATION PAGE**

1. AGENCY USE ONLY (Leave Blank)
3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE Quantum Computing Graduate Fellowship

5. FUNDING NUMBERS DAAD190210213
6. AUTHORS Ivan H. Deutsch and Carlton M. Caves

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
   University of New Mexico
   Contracts & Grants, Office Of Research Services
   1 University of New Mexico
   Albuquerque, NM 87131 -0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
   U.S. Army Research Office
   P.O. Box 12211
   Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER 44060-PH-QC.1

11. SUPPLEMENTARY NOTES
   The views, opinions and/or findings contained in this report are those of the author(s) and should not contrude as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12. DISTRIBUTION AVAILABILITY STATEMENT
   Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
   The abstract is below since many authors do not follow the 200 word limit

14. SUBJECT TERMS
   Quantum Computation

15. NUMBER OF PAGES
   Unknown due to possible attachments

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED
18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED
19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED

20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500
Quantum Computing Graduate Fellowship

ABSTRACT
A variety of projects are carried out by 2 graduate students under the “Quantum Computing and Graduate Research Fellowship” program. The students are United States citizens, with undergraduate degrees from the California Institute of Technology. The grant complemented award DAAD19-01-1-0648, "Fundamental Studies of Quantum Information Processing with Neutral Atoms" and award W911NF-04-1-0242, "Entanglement and the Power of Quantum Computation".

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

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

Number of Papers published in peer-reviewed journals: 8.00

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

Number of Papers published in non peer-reviewed journals: 0.00

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)
5. Andrew Silberfarb, APS DAMOP, 6/2003, "Continuous Measurement and Entanglement with Traveling wave probes"
6. Andrew Silberfarb, Optical Society of America, 10/2003, "Quantum State Reconstruction via Continuous Measurement".
7. Andrew Silberfarb, PRAQSYS Caltech Quantum Control Workshop, 8/2004, "Quantum State Reconstruction via Continuous Measurement".
10. Andrew Silberfarb, Caltech Institute for Quantum Information, 3/2005, "Quantum State Reconstruction via Continuous Measurement".
(d) Manuscripts


Number of Manuscripts: 4.00

Number of Inventions:

Graduate Students

Andrew Silberfarb, 50%
Bryan Eastin, 50%

Number of Graduate Students supported: 2.00
Total number of FTE graduate students: 1.00

Names of Post Doctorates

Number of Post Docs supported: 0.00
Total number of FTE Post Doctors: 0.00

List of faculty supported by the grant that are National Academy Members

Names of Faculty Supported

Ivan H. Deutsch
Carlton M. Caves

Number of Faculty: 2.00

Names of Under Graduate students supported

Number of under graduate students: 0.00

Names of Personnel receiving masters degrees
Number of Masters Awarded: 0.00

Names of personnel receiving PHDs

Number of PHDs awarded: 0.00

Names of other research staff

Sub Contractors (DD882)

Inventions (DD882)
Scientific Accomplishments:

Two students, Andrew Silberfarb and Bryan Eastin, were supported by this QuaCGr fellowship, complementing two ARO grants: award DAAD19-01-1-0648, "Fundamental Studies of Quantum Information Processing with Neutral Atoms" and award W911NF-04-1-0242, "Entanglement and the Power of Quantum Computation". These students have published 8 refereed articles in high ranking journals, have 4 more in preparation, and have delivered 11 invited talks on their work. Andrew should defend his thesis and obtain his PhD in February 2006. Bryan should complete his studies before August 2006.

Andrew performed studies of quantum control, back-action and errors, and quantum state reconstruction. His first accomplishment was to analyze the measurement strength associated with a coherent laser beam interacting with a two-level atom. The measurement strength determined the rate of decoherence (and thus errors in a quantum logic operation) due to the laser mode. The physical origin of the measurement is spontaneous emission by the atom into the paraxial modes that define the beam. While a small fraction of the total spontaneous emission, those of photons emitted into the beam mode are correlated with the state of the atom. Thus, the atom and laser become entangled. This sets a benchmark for entanglement generation of atoms and photons in free space to which other geometries (e.g. cavity QED) can be compared. The entanglement generation, calculated with our full traveling wave multi-mode formalism, was compared to simplifying models used in previous analyses, showing surprise agreement. This was explained by a deeper understanding of the nature of multipartite entanglement. Using the basic formalism he developed, Andrew turned his attention to the use of continuous measurement of atomic ensembles for real-time quantum state reconstruction. This is his most significant work. Andrew developed a complete new paradigm whereby weak, but continuous, observation of an ensemble can be used to create a measurement history that can be inverted to yield the initial quantum state. In principle this can be accomplished with negligible quantum backaction on the members of the ensemble, and in real-time. Such a protocol is a new tool for quantum feedback control. Andrew has not only worked on the theoretical foundation, but has worked closely with our experimental collaborators to perform data analysis. We hope to publish the experimental findings in the near future. In addition to his main project, Andrew was a key collaborator in other projects supported under the ARO grants. Specifically, he helped to develop the pseudopotential model for ultracold collisions which was a key component of the protocol for quantum logic with neutral atoms in optical traps.

Bryan Eastin’s work has focused on error correction. First, he explored fault-tolerant thresholds for particular error models that might arise in a physical implementation. The model for which he has explicit results is one where all errors are assumed to be associated with two-qubit gates, specifically XX, YY, or ZZ errors, and these two-qubit errors occur with equal probability. For this model, he is able to show that the fault-tolerant threshold is about a factor of 10 better than for an error model based on the depolarizing channel. Second, he has developed a general method for calculating upper
bounds on the error threshold for the most widely used class of fault-tolerant protocols applied to essentially arbitrary error models. This work was motivated by his first effort, which for the examples investigated, showed that almost all of the improvement in error threshold was due to the restricted error model and not to matching the fault-tolerant protocol to the error model, thus suggesting that the threshold is largely a function of the error model and not of the fault-tolerant protocol. Third, he has worked with graduate student Steve Flammia to explore quantum error-correcting codes based on so-called low-density parity-check classical codes. The goal is to find codes that have good rate and good distance, while at the same time having syndrome detection circuits that are both highly parallelizable and have efficient syndrome decodings. It is not yet clear whether this work will lead to codes with the desired properties or to a series of proofs that they do not exist.