2010 NSF EAPSI Project Description

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1 Host Researcher and Institution

The EAPSI program would give me a valuable opportunity to understand the international nature of scientific collaboration by allowing me to form new, personal connections to the research community in the Pacific Rim. If awarded this fellowship, I would travel to Australia for the first time, which is one of the world's centers for my chosen field of quantum computing. Australia is home to the ARC Centre of Excellence for Engineered Quantum Systems (EQuS), a multi-institution, international collaboration for engineering quantum systems and technology. In addition, one of the EQuS nodes is especially well-suited to hosting my fellowship, the University of Sydney. The Quantum Science Research Group there contains strong researchers including Drs. Stephen Bartlett and Andrew Doherty on the side of theory as well as Drs. Michael Biercuk and David Reilly on the side of experiment. I would be able to contribute my experience in electronics engineering and at the same time learn more about the underlying physics behind quantum computing from these experts in the field.

Dr. Michael J. Biercuk would be an ideal host due to his past experience at NIST Boulder in achieving high-fidelity quantum control over trapped ions [14]. In particular, he has developed advanced experimental techniques for suppressing decoherence-induced error rates by several orders of magnitude using any qubit technology, not just trapped ions. Dr. Biercuk is further pursuing this research at the University of Sydney where he is Senior Lecturer and head of the newly-established Quantum Control Laboratory. This is where I propose to carry out my fellowship in dealing with the central problem of suppressing quantum noise.

2 Quantum Quantum Noise

In order to realize the benefits of any quantum technology, especially quantum information processing and quantum computing, we need to deal with the practical problems of fault-tolerance and noise. Any quantum system must be shielded from unintended couplings to its environment in order to maintain a coherent quantum state that is useful for computation, among other applications. These stray couplings are known as noise, errors, or *decoherence*. Remarkable theoretical results in *fault-tolerant quantum computing* have shown that we can correct these seemingly continuous errors using discrete operations, unlike classical analog computation.

Most current approaches to fault-tolerance focus on quantum error correcting (QEC) codes, which encode each logical qubit into many physical qubits. However, every QEC code introduces an overhead of more physical qubits, which increases the probability of failure. We need to achieve a "fault-tolerant threshold" for a single qubit's error probability in order to ensure we get a net benefit from applying QEC. Threshold theorems for a variety of architectures have proven that this single qubit error is anywhere from 10^{-3} to 10^{-6} [6]. If p is the single qubit error and p_{th} is the threshold error rate, the error rate for the encoded logical qubit is $p(p/p_{th})^{2^k}$ after k levels of concatenation [6]. Therefore, to fully realize the benefits of driving down error rates with concatenated QEC codes, we need the ratio p/p_{th} to be as small as possible, and therefore our goals for p are much more stringent than for unencoded qubits.

3 Dynamical Decoupling

Dynamical decoupling is a promising approach for achieving this much lower error rate without introducing more qubits or measurement—only precise, unitary quantum control operations are needed via pulses of energy in a specific sequence, with certain durations and delays between them. (In the case of trapped ions, these are pulses of optical laser power). Based on open-loop control techniques pioneered with nuclear magnetic resonance (NMR), dynamical decoupling uses sequences of precisely timed pulses to perform quantum bit- or phase-flips, coherently averaging out fluctuations from the environment [16].

Dr. Biercuk was able to use a technique related to the famous Hahn spin-echo sequence [15], with multiple evenly-spaced pulses, to increase phase coherence times in trapped beryllium ions from 2.5 milliseconds to 700 milliseconds, an increase of *two orders of magnitude* [14]. Trapped ions have an advantage over other qubit candidates in possessing relatively long coherence times, identical energy characteristics from qubit to qubit, and a recent demonstration of a fully-programmable two-qubit trapped ion quantum processor [3]. These coherence times are inversely related to decoherence-induced error rates, where increasing the first is equivalent to reducing the second.

Unfortunately, the NMR community has long known about several limitations to a simple DD approach, for example a repeated sequence of pulses attributed to Carr, Purcell, Meiboom, and Gill (CPMG). The CPMG sequence is only effective against slowly varying phase noise (relative to the timescale of the experiment), whereas in a general quantum information setting, we may experience phase noise of arbitrary spectral density. Recent theoretical results indicate that more general kinds of noise can be further suppressed with longer and more complicated pulse sequences called Uhrig Dynamical Decoupling (UDD) [13], where the delays between various pulses in a sequence can be varied precisely.

Until recently, experimental errors were too great to allow the precise implementation of these new sequences. However, Dr. Biercuk's group at NIST were able to overcome these limitations by achieving high operational and measurement fidelities and engineering the noise environment itself [1], and thus were able to achieve the first ever experimental demonstration of UDD. This confirmed the possibility of suppressing of errors by 8 to 10 orders of magnitude for some kinds of high-frequency noise.

Dynamical decoupling in its original form can thought of as a "refreshing" process for arbitrary quantum states in a quantum memory [2]. This provides much needed volatile storage in between computational operations, similar to a DRAM for classical computers. In the future, this research could give rise to a "quantum firmware" which will provide a platform for higher-level quantum computation. However, storage is not enough for computation. How can we actually transform these states into other states, in order to compute useful functions?

A further theoretical framework has been proposed to extend DD to perform non-trivial logic functions (gates), called Dynamical Controlled Gates (DCGs) [4]. This is crucial for performing real quantum computations, as small errors in enacting individual gates may accumulate and render the overall computation useless, unless additional suppression is done. Therefore, even though DD has already demonstrated great promise, more work needs to be done to fully exploit its potential.

4 Project Description: Pulse Programming

While much of the previous discussion has been abstract, the actual work of this project will be very concrete: the construction of an electronic device called a pulse programmer to generate electrical pulses sequences for dynamical decoupling, and the implementation and testing of software to control it. The pulses are electrical signals, either analog alternating-current (AC) at some radio frequency (around 100-400 MHz) or digital signals corresponding to standard transistor-to-transistor (TTL) logic levels (0 to 5 volts) to control and synchronize other experimental equipment. The pulses in DD sequences are generally at radio frequencies (RF) and need precise and time-varying frequency, phase, and amplitude control, with low noise and in several independent channels. This can be achieved using modern direct-digital-synthesis (DDS) chips which approximate an analog waveform using digital sampling techniques. In addition, quickly changing DDS output is needed to create real-time optimized sequences for a given noise environment, thereby improving the results in [2].

In addition, the system will also need to generate arbitrary analog waveforms using a digital-to-analog converter (DAC). Finally, the system will need to be able to count input pulses from a photomultiplier tube (PMT) and perform conditional actions based on these counts, such as branching on whether a threshold has been reached in order to perform state detection. Such a device is a commonplace need for all quantum computing technologies, including trapped ions, NMR, superconducting qubits, quantum dots, and others yet to discovered [9]. Only specific features and parameters vary from technology to technology and from experiment to experiment. Therefore, it is possible to develop a set of general-purpose, reusable components (both hardware and software) which can be combined to form a pulse programmer which is tailored to a particular laboratory's requirements [7] [12].

Because Dr. Biercuk is starting a new lab, he will have the opportunity to redesign and improve the pulse programming system he used at NIST to validate the theoretical proposals above and further extend his experimental results. For example, the time resolution of the pulse programmer determines how fast a signal can change; smaller time resolutions allow pulse sequences to have more accurate delays and therefore greater fidelity in performing quantum control operations. The data given in [2] was taken at a 50 nanosecond time resolution, while the proposed system in this project will be able to achieve 10 nanosecond time resolution. Furthermore, with the new system, he will be able to optimize pulse sequences in real-time using faster hardware feedback.

The proposed project will include designing, assembling, and testing custom circuit boards, integrating them with commercial boards, and writing control software to perform the above tasks. This system will be constructed from both open source and commodity off-the-shelf components, some of which have been tested in other ion trap experiments, as described in [8], in order to decrease its cost and increase its reusability. Furthermore, the entire design and construction process will be documented on a public website [8] as a resource to the trapped ion quantum computing community. Thus, this project will form one part of a general-purpose quantum control toolkit, which is the larger goal of Dr. Biercuk's laboratory.

5 Applicant

I have extensive past experience in designing and implementing electronic pulse programming systems to control ion traps [9] [7] [12]. In addition to openly contributing to the research community for over five years, I have personally engineering systems in three different laboratories in Innsbruck, Austria [10]; Garching, Germany; and Seattle, Washington, in the U.S. I have also maintained an open source project on the internet [8] from which other researchers can learn and to which they have contributed. I have been cited by the company MagiQ in their successful Small Business Innovation Research (SBIR) grant for pulse programming systems [5] and have also been retained as a consultant for the same company.

However, what I currently lack, and what I hope to gain from this fellowship, is a deeper understanding of atomic physics and the ability to help propose and design new experiments. Dr. Biercuk would make an ideal mentor in this regard, so that in the future I can make a more intellectual contribution to the field in addition to the technical skills I will be bringing to this collaboration.

I frequently correspond with professors, post-docs, and grad students from groups in Germany, Denmark, England, Austria, and across the U.S. in my quest to better understand the scientific process. It is my belief that we are limited more by social and political constraints rather than technological or physical limitations. My work so far in this field is part of a new trend of applying reconfigurable computing and open source methodologies to physics research, as evidenced by NIST Boulder's decision to release their ion trap control software as open source [11]. I hope to bring this approach to the University of Sydney in Australia, and by extension other universities in East Asia and the Pacific Rim. In unifying their technical approaches to common problems, I hope this will open the door to future collaborations and a greater sense of community between the EAPSI region and the rest of the world. In the process, I hope my work with Dr. Biercuk will bring us closer to a working quantum computer.

References

[1] Michael J. Biercuk, Hermann Uys, Aaron P. VanDevender, Nobuyasu Shiga, Wayne M. Itano, and John J. Bollinger: Experimental Uhrig Dynamical Decoupling using Trapped Ions. February 2009. [arXiv:abs/0902.2957].

[2] Michael J Biercuk, Hermann Uys, Aaron P VanDevender, Nobuyasu Shiga, Wayne M Itano, and John J Bollinger: Optimized dynamical decoupling in a model quantum memory. *Nature*, 458(7241):996–1000, April 2009. [doi:10.1038/nature07951, arXiv:abs/0812.5095].

[3] D. Hanneke, J. P. Home, J. D. Jost, J. M. Amini, D. Leibfried, and D. J. Wineland: Realization of a programmable two-qubit

quantumprocessor. *Nature Physics*, 6(1):13–16, November 2009. [doi:10.1038/nphys1453, arXiv:abs/0908.3031].

[4] Kaveh Khodjasteh and Lorenza Viola: Dynamically Error-Corrected Gates for Universal Quantum Computation. *Physical Review Letters*, 102(8):5, February 2009. [doi:10.1103/PhysRevLett.102.080501, arXiv:abs/0810.0698].

[5] MagiQ: DARPA SBIR Grant SB072-002: Innovative Pulse Programmers for Quantum Computing Applications. `http://www.dodsbir.net/sitis/archives_display_topic.asp?Bookmark=30768`, 2007.

[6] Michael A. Nielsen and Isaac L. Chuang: *Quantum Computation and Quantum Information*. Cambridge University Press, Cambridge, U.K., 2000.

[7] Lutz Petersen: Quantum Simulations in Ion Traps – Towards Simulating the Early Expanding Universe. p. 154, April 2007.

[8] Paul Pham: Quantum Computing Pulse Programmer. `http://pulse-programmer.org`, 2005.

[9] Paul T. Pham: A general-purpose pulse sequencer for quantum computing. Master's thesis, Massachusetts Institute of Technology, January 2005.

[10] M. Riebe, K. Kim, P. Schindler, T. Monz, P. Schmidt, T. Körber, W. Hänsel, H. Häffner, C. Roos, and R. Blatt: Process Tomography of Ion Trap Quantum Gates. *Physical Review Letters*, 97(22), December 2006. [doi:10.1103/PhysRevLett.97.220407, arXiv:quant-ph/0609228].

[11] Till Rosenbrand: Ionizer: control-software for atomic physics experiments in ion traps. `http://ionizer.sf.net`, 2010.

[12] Philipp Schindler: *Frequency synthesis and pulse shaping for quantum information processing with trapped ions*. PhD thesis, University of Innsbruck, 2008.

[13] Götz Uhrig: Keeping a Quantum Bit Alive by Optimized π-Pulse Sequences. *Physical Review Letters*, 98(10):4, March 2007. [doi:10.1103/PhysRevLett.98.100504, arXiv:quant-ph/0609203].

[14] H. Uys, M. J. Biercuk, A. P. VanDevender, C. Ospelkaus, D. Meiser, R. Ozeri, and J. J. Bollinger: Decoherence due to elastic rayleigh scattering. *Phys. Rev. Lett.*, 105(20):200401, Nov 2010. [doi:10.1103/PhysRevLett.105.200401, arXiv:abs/0906.0398].

[15] Lieven M. K. Vandersypen and Isaac L. Chuang: NMR Techniques for Quantum Control and Computation. p. 33, April 2004. [arXiv:quant-ph/0404064].

[16] Lorenza Viola and Seth Lloyd: Dynamical suppression of decoherence in two-state quantum systems. *Physical Review A*, 58(4):2733–2744, October 1998. [doi:10.1103/PhysRevA.58.2733, arXiv:quant-ph/9803057].