# Quantum Algorithms Program

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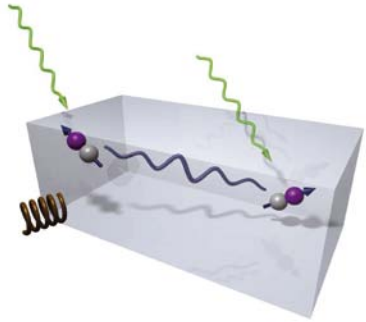

**FIGURE 1**
Schematic of experiment to demonstrate coherent coupling between two spatially separated Nitrogen Vacancy centers in Diamond. Green arrows indicate laser irradiation of the two NVs coupled via a dipole-dipole interaction (blue wiggle), and also irradiated (brown coil), by RF. [From P. Neumann *et al*.]

**PROGRAM DESCRIPTION**

This programme aims to help us understand better the ultimate capabilities of a quantum computer. In this programme we explore new applications of quantum information devices and these may range from applications that have direct benefit to scalable quantum computation through to new applications that might more immediately benefit small scale quantum processors such as simulation and metrology. In the former category the most significant of these are new quantum algorithms that out perform their classical counter part. However novel methods for quantum information transport, novel architectures for quantum computation, novel protocols for precision metrology, novel designs for fault resistant quantum computation and methods for fast and robust quantum control also benefit scalable quantum computation. Novel ways to encode quantum information, such as through topological encodings, may also lead to very robust physical implementations of quantum processors. The work of this programme combines skills from mathematical physics, computer science, and statistics, through to collaborative projects between the theory researchers and experimentalists in quantum optics and condensed matter quantum science.

One important application of quantum information science is to develop new protocols and algorithms to improve the accuracy of measurements, i.e. in metrology. A central question in metrology is the precise measurement of phase shifts. In particular, one aims for a measurement precision that scales with the Heisenberg Limit (the ultimate limit set by quantum mechanics), rather than with the weaker Standard Quantum Limit. There are a number of methods in quantum science to increase the precision of phase measurements through effectively decreasing the period of oscillation of an interference pattern due to a varying phase shift, e.g. using NOON states. However, although such a method increases the local sensitivity to small changes in phase, this protocol leaves one with an overall ambiguity in the estimated phase shift. Dr Berry and others have found phase estimation protocols that eliminate this ambiguity but still achieve a precision that scales close to the Heisenberg limit. The first such protocol, which was based on the inverse quantum Fourier transform, required adapting the quantum circuit during the protocol. However, surprisingly Dr Berry and others have recently found that the protocol can be altered to operate without feedback and can still achieve near-Heisenberg limited precision in the phase estimate. This new protocol can be much more easily implemented experimentally than the adaptive protocol.

One exciting new technology for quantum information science, invented in 2004, uses individual microwave photons trapped in superconducting coplanar resonators which interact with nearby *artificial superconducting atoms*. This technology has become known as *Circuit-QED*. One significant advantage this technology has over traditional Cavity-QED experiments is that, due to the extreme confinement of the EM fields of the trapped photons and the large dipole moments of the artificial superconducting atoms, these experiments reach far into the so-called, *strong coupling regime*, where light and matter interact so strongly that they form collective excitations known as polaritons. Circuit-QED research has demonstrated detailed experimental control of single and two qubit devices, the latter interconnected via the microwave photons held in the superconducting coplanar cavity. The very large light-matter coupling seen in these devices prompted us to explore more fundamental aspects of quantum optics in such devices. With Rebic and Milburn we examined the consequence of strongly coupling the photons held in the superconducting cavity to a nearby artificial superconducting four level system. In 1996 it was proposed by Schmidt and Immamoğlu to use such a four level system (known as an "N-System"), in Cavity-QED to generate Giant-Self-Kerr optical nonlinearities for the light trapped in the cavity. We considered forming an "N-System" by capacitive coupling two two-level charge qubits. Such an "artificial multi-level atom" suffers from the lack of well defined transition selection rules (as one can find in atomic physics), but even with this drawback, due to the very strong coupling to the light we predict that one could generate immense Self-Kerr effects within the superconducting cavity. We find that the injection of a single photon into the cavity+"N-System" would shift the cavity's resonance frequency by thousands of cavity linewidths. This surprising result has since led to experiments which fabricate pairs of coupled *superconducting flux qubits* and couple them to a superconducting cavity with a possible aim of probing this Giant-Self-Kerr effect [E. Il'ichev *et al*.

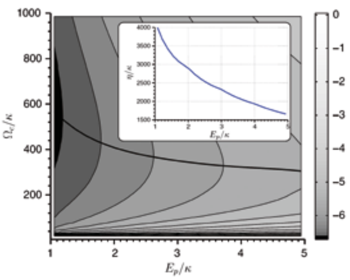

**FIGURE 2**

Plot indicated super-strong single photon blockade in a Circuit-QED system of microwave coplanar waveguide coupled to an artificial superconducting 4-level atom [From S. Rebic *et al*.]

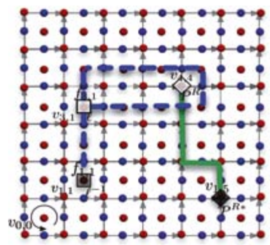

**FIGURE 3**

Schematic of a spin lattice model for a quantum double of a finite group, a physical theory possessing topological order. Entangling operations are described by braiding (physically moving), one excitation around another (dashed blue line) [From Brennen *et al*.]

Physical Review B 81, 012506 (2010)]. With flux qubits, however, the synthesis of transition selection rules may be possible and it may be that the magnitude of a Giant-Self-Kerr effect in such a flux-based system may be still larger than what we predicted in our work.

Developing methods to reduce the amount of quantum control needed in a quantum processor will have very practical consequences. As quantum processors scale up in size one will have to overcome hard technological challenges associated with designing, building, driving and delivering the complex control signals that will be needed to manipulate the qubits in the scaled-up quantum processor. An alternative approach that Twamley and others have pioneered, is to use *global addressing*, where one addresses simultaneously banks of qubits within the processor. Surprisingly, it has been proved that one can perform universal quantum computation with qubits using *global addressing* where one does not need to engineer the capability of addressing any individual qubit within the device. With PhD student Mr Paz-Silva we have developed a globally addressed scheme which can perform universal quantum computation with an array of quantum systems of arbitrary Hilbert space dimension, and in particular, infinite dimension, e.g. arrays of harmonic oscillators. With Mr Paz-Silva and others we applied these ideas to derive a protocol to spatially mirror the quantum state of a chain of harmonic oscillators, and found a way to implement this protocol in Circuit-QED where we considered a 1D chain of coplanar superconducting cavities interconnected by charge qubits. Interestingly it has been proved since 1998 [D. Aharonov & M. Ben-Or], that fault tolerant quantum error correction can also be implemented using global addressing but it was expected to possess a very small error threshold and there were no constructed circuit designs. With Dr. Fitzsimons we have developed a cellular automata scheme to implement fault tolerant globally addressed quantum error correction but, as we expected, with a very low error threshold. Work is now underway to develop higher threshold designs though at the expense of including some level of individual addressing.

Topological encoding of quantum information brings with it an inherent robustness against noise and decoherence. Many concepts in quantum information stimulate new science when one "ports" quantum information concepts into the framework of topological quantum science. In particular, when one considers the standard Bell's inequalities – such inequalities test for the existence of nonlocal quantum correlations which typically arise from some local interaction in the past which entangled the particles. In topological theories, to interact two fundamental excitations, or anyons, one must wind one anyon around the other. Such an interaction is obviously already nonlocal – and A/Prof Brennen and others revisited the formulation of Bell's inequalities in a topological theory to formulate a test which signifies the existence of quantum correlations which are not described by a local hidden variable theory. Brennen, with Aguado and Cirac also showed how to simulate 2D physical theories describing topologically ordered systems whose excitations are anionic in nature. We found how to operate on these "synthetic anyons" to perform universal topological quantum computation and we also were able to find a physical realisation of this synthetic anyons in trapped neutral atoms in a 2D optical lattice.

In many real situations one must control quantum systems even when one does not have full knowledge of either the control or the system. In the former case one can consider a control signal to have a small – but unknown – static discrepancy in power, or duration or frequency. NMR science has developed families of composite pulses that can greatly ameliorate the effects of such systematic discrepancies. However such composite pulses take long to execute and in cases where decoherence is present other, more rapid methods of defeating such systematic errors would be preferable. With PhD student Said we studied the robust execution of an entangling gate between two nuclear spins in a Nitrogen-Vacancy defect in diamond. We compared NMR-style composite pulses sequentially applied to fashion the entangling gate with numerically derived pulses which acted simultaneously on all the relevant transitions via an optimization method called GRAPE (Gradient Ascent Pulse Engineering). We found that the GRAPE derived pulses achieved a comparable level of insensitivity to small systematic discrepancies when compared with the composite pulses but achieved this in a shorter time. In the opposite case, where the control is well characterised but the quantum system is not, with PhD student Schöenfeldt we examined the coherent transport of quantum states in a three-level lambda atomic system via STIRAP: stimulated Raman adiabatic passage. STIRAP is the basis of many proposals for quantum memory where one transfers the quantum state of a light pulse into internal atomic states of an ensemble of atoms and visa versa. We examined the case when the one has an unknown but static offset in the level structure of these atoms. Such an unknown offset would break the two-photon resonance condition for the standard STIRAP process and lead to very weak light-atom conversion. Instead we investigated a similar protocol entitled SCRAP: Stark Chirped Raman adiabatic passage, where one applies a strong Stark pulse to move the atomic levels around enough so that they achieve two level resonance at some point during the process. We again used the GRAPE method to derive SCRAP pulses which would yield the best light-matter transfer over as wide a range of unknown static offsets as possible. Nitrogen-Vacancy centres in diamond is perhaps the only quantum information platform that operates effectively at room temperature. The NV possesses free electrons whose spin dephasing time can be very long in isotopically purified diamond. Experiments have demonstrated good coherent control of the NV's electronic spin but also of nearby nuclear spins coupled to the NV's electron via the hyperfine interaction. One can obtain a four spin system using three nearby nuclear spins and the electron spin but, crucially, only the electron spin can be directly read out or reset via optical fluorescence and pumping. More useful would be to achieve coherent quantum coupling between spatially separated NVs. With the group of Prof Wrachtrup we examined two NVs separated by ~10nm and were able to demonstrate coherent quantum coupling between them. Using this coupling we are able to implement basic two qubit gates between the electronic spins of the separated NVs but due to the very rapid rephasing of one of them we were unable to generate significant entanglement.