

# Optical Quantum Information Program

## PROGRAM MANAGER

A/Prof Geoff Pryde – GU

## OPTICAL QUANTUM INFORMATION RESEARCHERS

**Staff** Dr Guo-Yong Xiang  
**Students** Mr Brendon Higgins (PhD),  
Mr Dylan Saunders (Honours),  
Mr Adam Bennet (Undergraduate),  
Mr Anthony Laing (Visiting PhD)

## COLLABORATING CENTRE RESEARCHERS

**Griffith University, Australia**  
Prof Howard Wiseman, Dr Joan Vaccaro,  
Dr Austin Lund  
**University of Queensland, Australia**  
Prof Andrew White, Prof Tim Ralph,  
Mr Benjamin Lanyon, Dr Marco Barbieri,  
Dr Marcelo Pereira de Almeida  
**Macquarie University, Australia**  
A/Prof Alexei Gilchrist  
**UNSW@ADFA, Australia**  
A/Prof Elanor Huntington  
**University of Toronto, Canada**  
Prof Daniel James

## OTHER COLLABORATORS

**University of Cambridge, UK / Perimeter Institute, Canada** Dr Rob Spekkens  
**University of Bristol, UK**  
Prof Jeremy O'Brien  
**University of Waterloo, Canada**  
Dr Kevin Resch  
**University of Illinois, USA** Prof Paul Kwiat  
**University of Sydney, Australia**  
Dr Stephen Bartlett  
**Australian National University**  
Dr Matthew Sellars

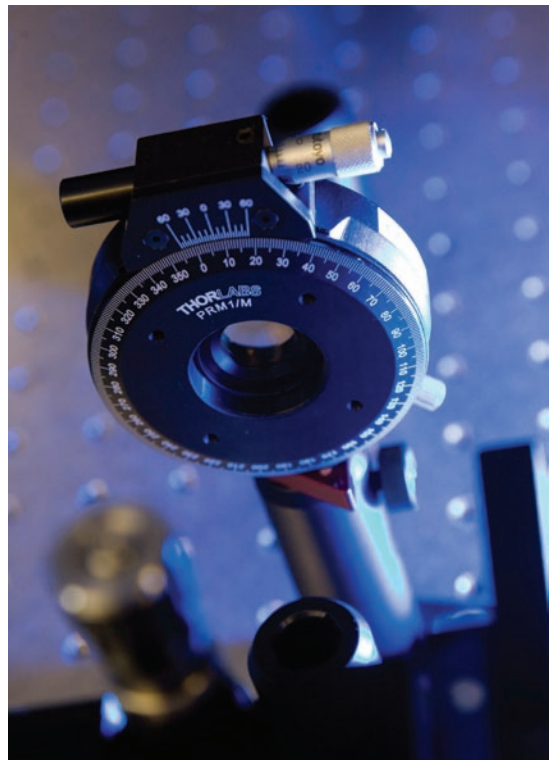
## PROGRAM DESCRIPTION

The objective of this program is to develop experimental quantum optics tools for quantum information tasks and quantum computing. This involves the development of novel quantum measurement techniques, preparation of new types of quantum states, and implementation of alternative methods of characterizing quantum systems. As well as experimental demonstrations, we are focussed on performance characterizations that test the practicality of these new approaches. The ability to create more complex quantum resources is an important step for enhancing quantum technologies, and represents a forward-looking approach to developing quantum devices. The program also aims to understand the role of the fundamental laws of quantum physics in information-based tasks.

One of the goals of this program is to develop new types of quantum resources based on states with multiple photons per mode, e.g. path entangled states and superpositions of Fock states. En route to this goal, it is necessary to develop advanced measurement techniques on simpler optical systems, such as entangled states of multiple single qubits.

FIGURE 1

Precision polarization control in the Quantum Optics and Information Laboratory.



The Optical Quantum Information program was founded at the end of 2005. Laboratory renovations were completed at Griffith University in July 2006, and experimental operations commenced in the newly-founded Quantum Optics and Information Laboratory. We began a significant expansion in 2008, commensurate with the program's increased research funding after Centre renewal.

## 1. Studies of advanced quantum measurement

This part of the research program deals with investigating quantum measurement both from a fundamental point of view, and from the point of view of practical implementations. We have investigated the role of *quantum complementarity* in quantum information protocols and in understanding the physical universe. Previous studies of complementarity assumed the structure of quantum mechanics, and were connected with showing apparently nonsensical measurement results when particular combinations of quantum observables were measured simultaneously.

Extending a previous generalization of contextuality to arbitrary operational theories and to preparations (as opposed to simply measurements) [1], we were able to construct an inequality to test for contextuality, in the same vein as the Bell inequality for testing violations of the assumption of local realism. This work was conducted in collaboration with Dr Robert Spekkens (Cambridge University and the Perimeter Institute) and Dr Ben Toner (CWI Netherlands).

The inequality was derived by considering a key question for quantum information science: is there a protocol for which a contextual universe allows better performance than a noncontextual one? We identified a protocol which we named parity-oblivious multiplexing, and we proved a limit enforced by the assumption of noncontextuality (Figure 2). Therefore, violation of this inequality would demonstrate contextuality. The multiplexing protocol is related to the idea of random access codes, for which quantum protocols can perform better than classical ones in certain configurations [2].

Using quantum theory, we showed that it is possible to violate this contextuality inequality using a qubit realization of parity-oblivious multiplexing. Experimentally, we used photonic polarization qubits, generated using spontaneous parametric downconversion, to implement the protocol and demonstrate the violation of the contextuality inequality for both 2-bit and 3-bit parity-oblivious multiplexing [3]. A key to our experiment was careful control of polarization using high-contrast polarizing elements (calcite beam displacers

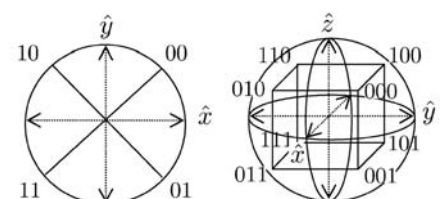
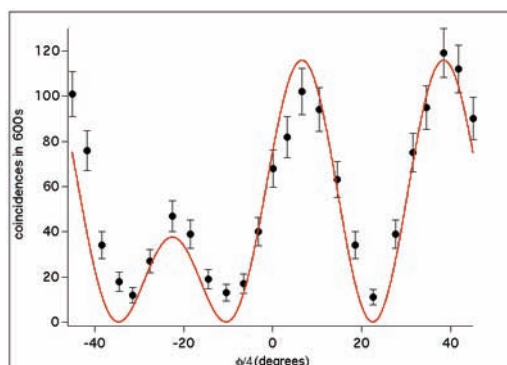


FIGURE 2

Bloch representation of states and measurements in quantum 2-bit and 3-bit parity-oblivious multiplexing.



**FIGURE 3**  
Measurement fringe corresponding to a 3-photon wedge state.

with extinction ratios of  $\sim 10^{-5}$ ), precision motorized rotation stages for polarizer rotation, along with collection of large counting statistics. We observed a 2-bit fidelity of  $0.851929 \pm 0.000030$  and a 3-bit fidelity of  $0.786476 \pm 0.000017$ . The error is calculated from the Poissonian counting error associated with the downconversion source, and settings repeatability error. These results exceed the noncontextual limits of  $3/4$  and  $2/3$  respectively for 2-bit and 3-bit parity oblivious multiplexing. This experiment also served as a demonstration of the quantum random access codes protocol [2].

An important area of future research in quantum physics is to determine the extent to which contextuality is important for quantum advantages in the broad range of quantum information protocols. In other words, in which quantum protocols is contextuality the driver of quantum advantage, and in which is it some other property such as Bell-type local realism violations?

We also continued to investigate *weak measurements*, performing preliminary investigations with theory collaborators (Wiseman, Lund) into the feasibility of experiments to test the relationship between quantum uncertainty due to the Heisenberg uncertainty principle and quantum uncertainty due to measurement back-action.

## 2. Multi-photon path-entangled states

This part of the program seeks to develop multi-photon path entangled states for quantum computing and information applications. We have performed both four-photon and six-photon experiments, generating respectively three- and five-photon path-entangled states (Figure 3). These states are created by photon subtraction from dual Fock states generated by spontaneous parametric downconversion.

In particular, we have investigated the so-called “wedge” entangled state [4], which is attractive because of its favourable state preparation efficiency. Using this state, we have demonstrated an enhanced phase sensitivity for three photons, and an enhanced

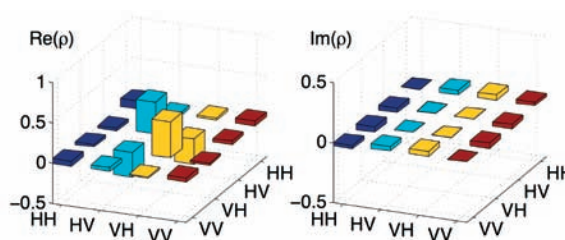
phase resolution [5] for both the 3- and 5-photon cases. A remaining challenge is to overcome the deleterious effects of background contributions from higher order downconversion terms. We are presently working on improving photon detection and collection efficiency, which should each provide significant benefits in this regard. The ability to work efficiently with 6-photon quantum states in general will enable a wide range of new quantum information demonstrations.

## 3. Investigating photonic entangled states

Entanglement is one of the key resources for quantum information science. In practice, it is very hard (if not impossible) to generate entangled states that are completely pure and also maximally entangled. Consequently, there is significant motivation to study entangled states other than maximally entangled states.

From a fundamental point of view, one may ask what really constitutes an entangled state. For two qubits, a simple definition may be provided – an entangled state is any which has a non-zero entanglement of formation. However, within this rather broad definition, not all states are equal. For instance, only a subset of such entangled states can violate a Bell inequality, or demonstrate the EPR paradox. An interesting and important fact is that there exist some entangled states that demonstrate *steering* (related to the original EPR paradox) but do not violate a Bell inequality.

In this work, we build on the theoretical work by Wiseman *et al* [6], who proposed a rigorous definition of steerable states, to demonstrate the violation of a steering inequality. We generate entangled singlet states using a nondeterministic optical controlled-NOT gate operating on photonic polarization qubits. By using a CNOT gate, we demonstrate that the present generation of gates is capable of creating highly entangled states. We use two-qubit Werner states, whose creation requires adding mixture to the singlet state, to test for the different classes of entanglement. We do



**FIGURE 4**  
Experimental density matrix of a Werner state that is suitable to demonstrate violation of a steering inequality.

this controllably using a pair of wedge depolarisers. In this way, it is possible to make states that can be transformed into Werner states by the application of a single qubit unitary operation. Using this technique, we have created a variety of two-qubit entangled states which we characterize using quantum state tomography (Figure 4). We have already shown that the entangled states so produced are capable of violating the steering inequalities and demonstrating that, in a certain parameter regime, there exist states that are steerable but which do not violate a CHSH inequality. The final remaining step is to implement the local unitary operations that will allow us to demonstrate the steering inequality violations directly, without the need for quantum state tomography.

## References

- [1] R.W. Spekkens, “Contextuality for preparations, transformations, and unsharp measurements,” *Physical Review A* **71**, 052108 (2005).
- [2] E.F. Galvao, “Foundations of quantum theory and quantum information applications,” PhD Thesis, University of Oxford (2002); quant-ph/0212124.
- [3] R.W. Spekkens, D.H. Buzacott, A.J. Keehn, B. Toner, and G.J. Pryde, “Preparation Contextuality Powers Parity-Oblivious Multiplexing,” *Physical Review Letters* **102**, 010401 (2009).
- [4] H.F. Hofmann, “Generation of a highly-phase-sensitive polarization-squeezed N-photon state by collinear parametric down-conversion and coherent photon subtraction,” *Physical Review A* **74**, 013808 (2006).
- [5] K.J. Resch, K.L. Pregnell, R. Prevedel, A. Gilchrist, G.J. Pryde, J.L. O’Brien and A.G. White, “Time-reversal and super-resolving phase measurements,” *Physical Review Letters* **98**, 223601 (2007).
- [6] H.M. Wiseman, S.J. Jones, and A.C. Doherty, “Steering, Entanglement, Nonlocality, and the Einstein-Podolsky-Rosen Paradox,” *Physical Review Letters* **98**, 140402 (2007).