Optical Quantum Information Program

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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.

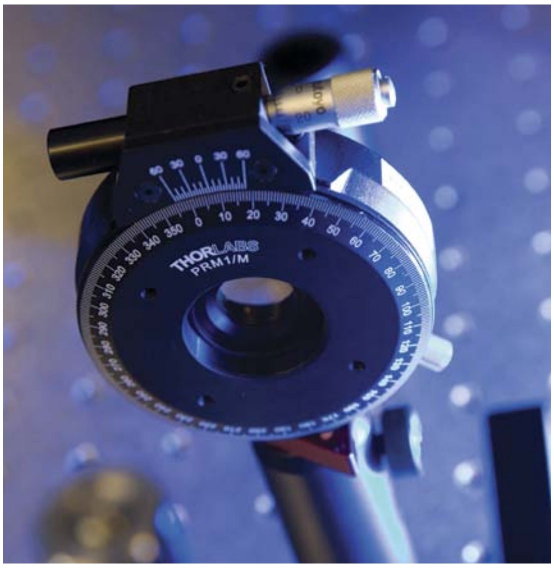

FIGURE 1

Precision polarization control in the Quantum Optics and Information Laboratory.

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 two or more single qubits.

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, and this continued in 2009.

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 finalized our studies on quantum contextuality as a property that may provide the super-classical performance in some quantum information protocols. This work, which was published in *Physical Review Letters* [1], tested the violation of a contextuality inequality (similar to a Bell inequality, but without assumptions of nonlocality). The contextuality inequality was derived from the performance of a quantum information science task (called parity-oblivious multiplexing) – this performance was bounded by assumptions of noncontextuality. Our high-confidence demonstration of the violation confirmed the importance of contextuality as the source of enhanced performance in some quantum information protocols.

In collaboration with researchers at several institutions, we demonstrated the first violation of a Leggett-Garg inequality (LGI), a relation for testing the ideas of realism and noninvasive measurement - the inequality is violated if one of these assumptions does not hold. We used a photonic variable-strength nondemolition measurement, based on a linear optics CNOT gate, in conjunction with projective measurements, to test a particular form of the LGI developed for weak measurements [2]. As well as demonstrating the LGI violation, we also demonstrated a one-to-one correlation between the violation of the LGI and the observation of "strange" weak values [3], a kind of anomalously large expectation value that can be observed in certain measurement scenarios. Weak values have previously proven useful in the resolution of a variety of quantum measurement paradoxes and enhancing measurement sensitivity in the presence of technical noise [4], but there has remained a fundamental open question over why they arise. This work demonstrates that the existence of strange weak values is tied to a violation of the assumptions encoded by the LGI.

2. Multi-photon path-entangled states

We have continued our work on making and measuring multiphoton path entangled states for applications in quantum metrology and quantum information science.

We extended our study of wedge path entangled states by working on setups for improved efficiency, to reduce the deleterious effects of loss and higher-order downconversion contributions to noise in these states. We also investigated *n,n* (Holland-Burnett [5]) states for *n* up to 3, demonstrating high-visibility fringes and a phase sensitivity well beyond the standard quantum limit. This work is presently being finalized.

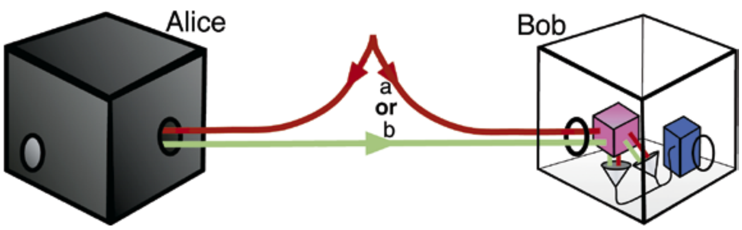

FIGURE 2

Conceptual representation of the steering task. Bob's task is to determine whether the system he receives is (a) part of an entangled state shared with Alice, or (b) an unentangled system.

Further, we demonstrated the first entanglement-enhanced phase *measurement* of an unknown optical phase. Previous demonstrations of sub-standard-quantum-limit phase sensitivity using entanglement [6] have required pre-existing knowledge of the phase an in this sense have been suitable for phase sensing (detecting small phase shifts about a known phase) as opposed to phase measurement. Although both applications are important, it is known that one of several non-trivial algorithms is required for moving from the phase sensing regime to the phase measurement regime [7]. In this present work, we combined the phase sensitivity of path-entangled states with an adaptive algorithm to measure an unknown phase with a standard deviation below the standard quantum limit. A further advance of our technique is the use of a "bottom-up" approach where we use all measurement results on entangled states that can be readily made, in order to access as much phase information as possible. This contrasts with most previous experimental demonstrations using entangled states, where the ideal entangled states are determined theoretically, and then postselection on only certain outcomes is used to obtain an approximation of this state. This "top-down" technique generally discards phase information.

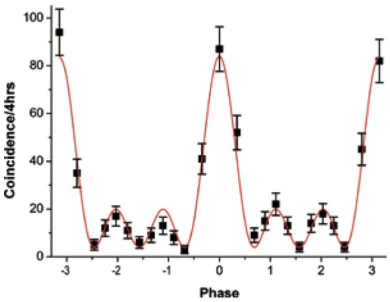

FIGURE 3

High-visibility, high-resolution measurement fringes in a 6-photon phase sensing experiment.

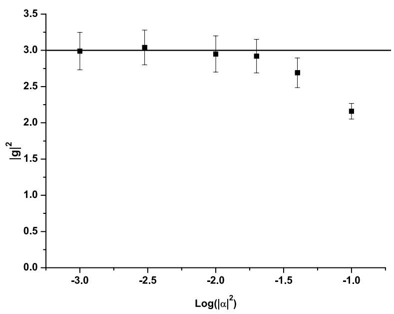

FIGURE 4

Gain of the noiseless amplifier as a function of input state size, showing linear behaviour until saturation.

In our phase measurement experiment, we used a sequence of four-, two- and one-photon path entangled states in the adaptive algorithm, to measure a random (i.e. in principle, unknown) birefringent phase shift. For the maximum total photon number we used, N = 48, we observed a phase variance nearly 2dB below the standard quantum limit. This work has been submitted for publication.

Coherent states and two-mode entangled states are useful in a number of continuous-variable quantum information protocols, including quantum computing. In collaboration with theorists Prof Tim Ralph (UQ) and Dr Austin Lund (GU), we demonstrated a noiseless linear amplifier for amplifying field-encoded states and distilling continuous-variable entanglement. Although the no-cloning theorem forbids deterministic noiseless amplification, heralded probabilistic amplification is allowed. Our device to realise this is based on measurement-induced nonlinearity in a generalized quantum scissors apparatus – the input state is nonclassically interfered with an ancilla photon in an *amplifier* stage, and conditional on a heralding signal from a detector, amplification occurs without noise. The device, as described, can be operated with low input amplitudes and moderate gains, but can be scaled to larger states by the use of multiple amplifier stages in parallel. Using the device, we demonstrated low noise operation for intensity gains of 2, 3 and 4, and used the device to distil single-photon path entanglement [8].

3. Investigating photonic entangled states

We have finalized our experimental work demonstrating steering, a concept introduced by Schrödinger as a generalization of the Einstein-Podolsky-Rosen (EPR) paradox but only recently formalized by Wiseman et al. [9]. We use two-qubit Werner states, whose creation requires adding mixture to the singlet state, to test for the different classes of entanglement. Using polarization qubits, wedge depolarizers, and local unitary operations, we have created a variety of two-qubit entangled states which we characterize using quantum state tomography, and for which we measure a steering parameter and a Bell-CHSH parameter. We demonstrated violation of the steering inequalities for certain states, and showed that, in a certain parameter regime, there exist states that are steerable but which do not violate a CHSH inequality [10]. By employing steering inequalities with measurement settings based around the vertices of platonic solids, we were able to observe that the steering phenomenon is more robust to noise as the number of measurement settings is increased.

We are also presently demonstrating error encoding against, and detection of, bit-flip errors. This 3-qubit proof-of-principle demonstration follows the scheme of Ralph [11], where a redundancy code is used to protect against the flip. The initial demonstrations use a simple 2-qubit code (which is generally a 2-qubit entangled state) and require that it be known which qubit suffers the error. However, the scheme can be scaled up to larger systems with errors on unknown qubits. The error readout circuit involves using two controlled-Z gates to correlate the encoded state with a meter (ancilla) state, which is subsequently read out. To date, we have constructed and tested the readout circuit, and produced the encoded 2-qubit states with high fidelity. Presently, we are working on improving the independent photon nonclassical interference in order to complete the demonstration.

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