# Optical Quantum Computation Program - Experimental

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**PROGRAM DESCRIPTION**

The aim of this program is to construct the basic building block of a photonic quantum processor, focussing on the key 2-qubit entangling gate, and to develop the foundations for a scaleable architecture. Our strategy involves both experimental and theoretical research, including: developing measurement techniques for characterising the relevant quantum states and processes; improving photon source and optical circuitry performance; development and application of measures of gate performance; and the realisation of simple quantum circuits.

## 1. Background

Modern optical technology allows very precise manipulation and measurement of light; the basic particles of light, photons, experience very little intrinsic decoherence, as the electromagnetic environment at optical frequencies is a vacuum. These two features combine to make photonic qubits very appealing, as single qubits can be produced, manipulated and measured with low error rates. Quantum computation also requires that two photonic qubits be able to interact and influence one another, the typical example being via the entangling controlled-NOT, or CNOT, gate. This cannot be achieved via normal nonlinear optical methods, as available materials produce interactions that are 10 million times weaker than required. However, in 2001 Knill, Laflamme & Milburn (KLM) proposed a scheme for efficient quantum computation combining linear optics and measurement [1] – the gate is non-deterministic, but can be made deterministic by using teleportation.

In this scheme a single photon is used to encode each qubit. Attenuating a standard laser beam produces low average photon numbers, but this is not sufficient for quantum computation as we require exactly one photon in a given time period to avoid error. The current gold standard for photon sources is spontaneous parametric downconversion (SPDC), which produces photon pairs in well defined spatial and frequency modes, albeit non-deterministically. When used as a two-photon source, SPDC yields high rates, typically tens of thousands of photon pairs per second; when used as a four-photon source, the rates are much lower, typically a thousand counts per hour. High count rates are desirable both because they allow good statistical analysis in a reasonable time frame, and because they minimise the effect of long-term drift in the apparatus. The original KLM proposal required ancillary photon for each logical photonic qubit: a two-qubit gate required four photons. In 2001 both our and a Japanese group [2,3] published proposals to realise a CNOT gate with only two photons, suggesting that comprehensive optical quantum computing experimentation could be achieved using high count-rate (bright) two-photon sources. The final stage in any quantum computation scheme is measuring the logical state, 0 or 1, of the output qubits. However during development of a quantum computer it is necessary to be able to fully characterise output states – and even better gate processes – to determine gate behaviour in terms of noise and entangling capability. Methods for measuring qubit states are now well developed: qubit state tomography with photonic qubits was demonstrated in [4], and a comprehensive theoretical analysis that allows for the effects of measurement uncertainty was given in [5].

In 2003 we constructed and observed quantum operation of a non-deterministic CNOT gate. Key design features were the use of polarisation displacers to produce a stable interferometric arrangement [6] and the use of wave-plates to produce beam mixing in a precise ratio. The operation of the gate was unambiguously quantum. This was determined by measuring the output density matrices for the logical-input data (i.e. the 00, 01, 10, and 11 inputs), and, more significantly, for superposition inputs – in the latter case the outputs are entangled [7]. In 2004 we investigated important principles of characterising real-world quantum circuits, fully characterised our two-photon CNOT gate using quantum process tomography [8,9]. The CNOT gate, as well as being a key processing device in quantum computation, is also a key measurement device. At the simplest level it allows an ideal projective or quantum non-demolition (QND) measurement to be made on a single qubit. We simply modified our gate so that the strength of the measurement was smoothly varied from weak to strong [10,11]. This generalised measurement demonstrated that the QND measurement is coherent – a key requirement for quantum computation applications. In 2005, simultaneously with groups in Germany and Japan, we proposed and demonstrated a new architecture for entangling optical gates [12-14]. The key advantage being its simplicity and suitability for scaling – it requires only one nonclassical mode matching condition, and no classical interferometers. In 2007, we used this architecture to implement a compiled version of Shor's algorithm in a photonic system, demonstrating for the first time – in any architecture – the core processes, coherent control, and resultant entangled states required in a full-scale implementation [15]. We presented two different implementations of the order-finding routine at the heart of Shor's algorithm, characterising the algorithmic and circuit performances. Order-finding routines are a specific case of phase-estimation routines, which in turn underpin a wide variety of quantum algorithms, such as those in quantum chemistry [16]. In 2008 we showed applied a new architecture, described below, to demonstrate that a computational speed-up is possible, for certain algorithms, even in the total absence of entanglement [17].

## II. Quantum computing using shortcuts through higher-dimensions

Recently, universal quantum logic-gate sets – the elemental building blocks for a quantum computer – have been demonstrated in several physical architectures. A serious obstacle to a full-scale implementation is the large number of these gates required to build even small quantum circuits. Here, we present and demonstrate a general technique that harnesses multi-level information carriers to significantly reduce this number, enabling the construction of key quantum circuits with existing technology [18]. We present implementations of two key quantum circuits: the three-qubit Toffoli gate and the general two-qubit controlled-unitary gate. Although our experiment is carried out in a photonic architecture, the technique is independent of the particular physical encoding of quantum information, and has the potential for wider application.

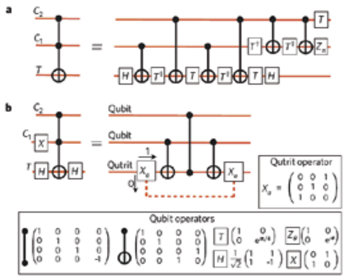

**FIGURE 1**

Simplifying the Toffoli gate. **a**, Most efficient known decomposition into the universal gate set CNOT + arbitrary one-qubit gate, when restricted to operating on qubits. **b**, Our decomposition requiring only three two-qubit gates. Here, the target is a three-level 'qutrit' with logical states 0, 1 and 2. Initially and finally, all of the quantum information is encoded in the 0 and 1 levels of each information carrier. The action of the $X_a$ gates is to swap information between the logical 0 and 2 states of the target. The target undergoes a sign shift only for the input term $(C_2,C_1,T)=(1,0,1)$. This operation is equivalent to the Toffoli under the action of only three one-qubit gates, as shown. The second gate in the decomposition is a CZ and is equivalent to a CNOT under the action of two one-qubit Hadamard (H) gates.

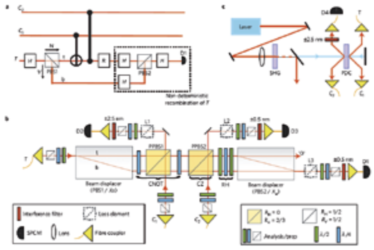

**FIGURE 2**

Toffoli and controlled-unitary experimental layout. **a**, Conceptual logic circuit. A polarizing beam splitter temporarily expands the Hilbert space of the target information carrier, from a polarisation-encoded photonic qubit to a multi-level system distributed across polarisation and longitudinal spatial modes. Information in the bottom rail (b) bypasses the two-qubit gates. Detection of a photon at D1 heralds a successful implementation. R=I (the identity) implements a Toffoli. $R=Z_\theta$ (see Figure 1) implements a $C^1U$ between $C_1$ and T (in this case, no photon is injected into $C_2$). **b,c**, Experimental circuit and optical source. We use an inherently stable polarisation interferometer using two calcite beam displacers. PPBS, partially polarizing beam splitter; SPCM, single-photon counting module; PDC, parametric downconversion; SHG, second-harmonic generation.

The realisation of a full-scale quantum computer presents one of the most challenging problems facing modern science. Even implementing small-scale quantum algorithms requires a high level of control over multiple quantum systems. Recently, much progress has been made with demonstrations of universal quantum gate sets in a number of physical architectures including ion traps [19,20], linear optics [7,21-23], superconductors [24,25] and atoms [26,27]. In theory, these gates can now be put together to implement any quantum circuit and build a scalable quantum computer. In practice, there are many significant obstacles that will require both theoretical and technological developments to overcome. One is the sheer number of elemental gates required to build quantum logic circuits.

Most approaches to quantum computing use qubits, a two-level quantum system that can be represented mathematically by a vector in a two-dimensional Hilbert space. Realizing qubits typically requires enforcing a two-level structure on systems that are naturally far more complex and which have many readily accessible degrees of freedom, such as atoms, ions or photons.

Here, we show how harnessing these extra levels during computation significantly reduces the number of elemental gates required to build key quantum circuits.

Because the technique is independent of the physical encoding of quantum information and the way in which the elemental gates are themselves constructed, it has the potential to be used in conjunction with existing gate technology in a wide variety of architectures. Our technique extends a recent proposal, and we use it to demonstrate two key quantum logic circuits: the Toffoli and controlled-unitary gates. We first outline the technique in a general context, Figure 1, then present an experimental realisation in a linear optic architecture, Figure 2, without our resource-saving technique, linear optic implementations of these gates are infeasible with current technology. Figure 3 shows the results for the controlled-unitary: we achieved gate fidelities of 94-98%.

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**FIGURE 3**

Experimentally reconstructed controlled-unitary gate process matrices. **a–d**, $U=Z_\theta$ and **a** $\theta=\pi/4$ (CT), **b** $\theta=\pi/2$ (CJ), **c** $\theta=3\pi/4$ (CL) and **d** $\theta=\pi$ (CZ). (i) Real and (ii) imaginary parts are shown. We observe high process fidelities [8-9] with the ideal {98.2±0.3, 97.7±0.4, 94.0±0.6, 95.6±0.3}% and low average output-state linear entropies {0.036±0.004, 0.047±0:004, 0.091±0:005, 0.086±0:006}, respectively. Matrices are presented in the standard Pauli basis.