Using a spontaneous parametric-downconversion source of photon pairs, we are working towards the creation of arbitrary 2-qubit quantum states with high fidelity. Currently, all physically allowable combinations of polarization entanglement and mixture can be produced, including maximally-entangled mixed states. The states are experimentally measured and refined via computer-automated quantum-state tomography, and this system has also been used to perform single-qubit and ancilla-assisted quantum process tomography.

Central to the long-term future of quantum information processing is the capability of performing extremely accurate and reproducible gate operations. The restrictions for fault-tolerant quantum computation are extremely demanding: the tolerable error-per-gate operation should be less than $10^{-4}$ to $10^{-6}$. Implementing such precise gate operations and preparing the requisite input states is therefore one of the key milestones for quantum information processing. Using optical realizations of qubits, e.g., polarization states of photons, we have the potential to meet these demanding tolerances. Therefore, although large-scale quantum computers will perhaps never be constructed solely using optical qubits, these systems nevertheless form a unique and convenient testbed with which to experimentally investigate the issues surrounding state creation, manipulation, and characterization, and also ways of dealing with decoherence.
Figure 2. (a) Experimental arrangement for single-photon state creation. The single-photon input to the system comes from one member of a parametric downconversion pair, with the other photon used as a herald. The operation of the decoherer – to separate orthogonal polarizations by much more than the coherence length – is indicated here using a polarizing beamsplitter to create a birefringent delay line. (b) A variety of single-qubit states have been generated and reconstructed using quantum state tomography.

Our primary tool for these investigations is a source of correlated photons produced via the process of spontaneous parametric down conversion: with small probability, a pump photon of appropriate polarization may split into two longer-wavelength daughter photons, subject to energy and momentum conservation (Fig. 1). By triggering on one of these photons, the other is prepared in a single-photon Fock state $|1\rangle$. We can apply local unitary transformations to the polarizations of these photons using a birefringent half-waveplate (HWP) and quarter-waveplate (QWP). We can also introduce decoherence (either independently or collectively) by passing the photons through birefringent delay lines.

Using these techniques for the single photon case, the initial pure horizontal state $|H\rangle$ may be precisely converted into an arbitrary pure or mixed state.
Figure 3. (a) Experimental arrangement for two-photon state creation. (b) A variety of two-qubit states have been generated and reconstructed using quantum state tomography. Also shown are the fidelity of the reconstructed density matrices with the target input states, indicating a high degree of control.

state (Fig. 2). We estimate that we can create and reliably distinguish (with fidelities of 0.998 or better) over 100,000 single-qubit states. Applying these single-qubit techniques to each output of a downconversion crystal, we can create arbitrary product states for the two photons. But these comprise only a very small part of the total two-qubit Hilbert space. To access the rest, we
must create entangled states; this is done by adding a second downconverter with an orthogonal optic axis as shown in Fig. 3a. A given pair of signal and idler photons could have been born in the first crystal, with vertical polarizations, or in the second with horizontal polarizations. These two possibilities cannot be distinguished by any measurements other than polarization, so the quantum state for these photons is a superposition of $|V\rangle\langle V|$ and $|H\rangle\langle H|$. Because each crystal responds to only one pump polarization, the relative weights of the two downconversion processes can be controlled by adjusting the input pump polarization. A birefringent phase plate is also added to one of the outputs to control the relative phase of the two contributions, so that we can create nonmaximally entangled states of the form:

$$|\psi\rangle \propto |H\rangle|H\rangle + \epsilon e^{i\phi}|V\rangle|V\rangle.$$ 

Combined with the single-photon local unitary transformations, any pure 2-qubit state can be produced. In this way, we have prepared a variety of states (Figs. 3b, 4b).

The density matrices are tomographically determined by measuring the polarization correlations in 16 bases, and performing a maximum-likelihood analysis to find the legitimate density matrix most consistent with the experimental results. In order to improve the speed and accuracy of our tomographic measurements, we have implemented a fully automated system. In addition to reducing the total time for a measurement, and significantly decreasing the uncertainty in the measurement settings, this automated system will also enable the implementation of an adaptive tomography routine – by making an initial fast estimate of the state, one could spend most of the data collection time making an optimized set of measurements. With this sort of optimal quantum tomography, we hope to reach the ultimate limit in quantum state characterization.

Our automated system has enabled the creation of a large number of states with widely varying degrees of purity and entanglement. A convenient way to display these states is the “Tangle-entropy” plane, shown in Fig. 4. Because it is impossible to have a state that is both completely mixed and completely entangled, there is an implied boundary between states that are physically possible and those that are not: this boundary is formed by the “maximally entangled mixed states” (MEMS), which possess the largest degree of entanglement possible for their entropies.

Finally, using the modification of our system shown in Fig. 5a, we can realize several methods of quantum process tomography, whose goal is to completely characterize some unknown process affecting a qubit. This process may be any combination of unitary transformations, state-dependent losses, and decoherence. One method is to send a variety of input states through the process, and tomographically determine the output states. Another technique, known as “entanglement-assisted” or “ancilla-assisted” process tomography, exploits the two-photon correlations available at the source,
and requires only a single, fixed input state to perform an entire process tomography.

In the future, we will continue to expand our abilities to create an ever-widening range of quantum states and processes, and to push the level of precision with which they are created and characterized with adaptive tomography. Ultimately, this promising set of tools should be useful for implementing and testing various protocols in quantum information processing.

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Figure 4. (a) The Tangle-Entropy plane. (b) Tomographic reconstruction of the density matrix for a MEMS (Maximally Entangled Mixed State). $F$ is the fidelity of the measured state with the target.

MEMS $F = 0.985$
Figure 5. (a) Experimental arrangement for single-qubit and entanglement-assisted quantum process tomography. (b) Tomographic reconstructions for a unitary process (left) and decoherence (right), illustrated as transformations on the Poincare sphere. The gray mesh spheres represent all possible initial single-qubit states. The dots show the initial states $|H\rangle$, $|V\rangle$, $|45^\circ\rangle$, $|-45^\circ\rangle$, $|L\rangle$, and $|R\rangle$ after the transformations. (c) Entanglement-assisted tomographic reconstructions for the same processes.

References

1. C. K. Hong and L. Mandel, Phys. Rev. Lett. 56, 58 (1986).
2. P. G. Kwiat et al., Phys. Rev. A 60, R773 (1999).
3. D. F. V. James et al., Phys. Rev. A 64, 052312 (2001); A. G. White et al., Phys. Rev. Lett. 83, 3103 (1999).
4. T. C. Wei et al., in preparation; W. J. Munro et al., Phys. Rev. A 64, 030302(R) (2001).
5. I. L. Chuang and M. A. Nielsen, J. Mod. Opt. 44, 2455 (1997); J. F. Poyatos et al., Phys. Rev. Lett. 78, 390 (1997).
6. J. B. Altepeter et al., in preparation.