High-dimensional entanglement is a key resource for quantum information protocols such as quantum cryptography and tests of non-locality. We present experimental results on the degree of entanglement for the case of photons entangled in the orbital angular momentum and angle degrees of freedom. In addition, we tomographically reconstruct the high-dimensionally entangled quantum state. Our results precisely characterize the entanglement, thus establishing the suitability of such states for applications in quantum information science. We present a model that accounts for the effects of the quantum efficiency, the heralding efficiency, the photon pair generation rate and finite-resolution timing electronics impact the degree of entanglement and hence the secure information capacity.

Systems entangled in high dimensions have recently been proposed as important tools for various quantum information protocols, such as multi-bit quantum key distribution and loophole-free tests of nonlocality [1]. It is therefore important to have precise knowledge of the nature of such entangled quantum states.

In this work we determine the precise quantum state of high-dimensionally entangled photon pairs generated by parametric downconversion [2]. In this process, orbital angular momentum (OAM) is conserved, resulting in two photons with equal but opposite OAM and entangled in the OAM basis [3, 4].

We use parametric downconversion to generate photon pairs entangled in the transverse degree of freedom. We use a 3-mm-long type I BBO crystal, pumped by a frequency-tripled Nd:YAG laser at 355 nm with an average power of 150 mW and a beam waist of approximately 1 mm. In each of the signal and idler arms of the experiment, spatial light modulators (SLMs) together with single mode fibers act as mode filters which allow us to measure the spatial states of light. The coincidence counting between the two APDs is performed by a National Instruments counting card with a timing resolution of 25 ns. The measured coincidence count rates are then normalized by dividing all points by the sum of the coincidence counts for the pure OAM states. This converts the coincidence count rates to probabilities so that we can construct a density matrix by minimizing Chi-squared.

We have obtained the density matrix of two entangled qudits in dimensions from \( d = 2 \) up to \( d = 8 \). Characterizing the states leads to fidelities ranging from \( F_2 = 0.96 \pm 0.01 \) to \( F_8 = 0.64 \pm 0.01 \) when compared with the maximally entangled state and linear entropies ranging from \( S_2 = 0.05 \pm 0.01 \) to \( S_8 = 0.50 \pm 0.01 \). These measurements and subsequent calculations are important for determining the upper bound on the dimension of an OAM space that is usable for secure quantum communications.


FIG. 1: The density matrices for dimensions 2 and 8. The axes for dimension 2 are labelled, and the higher dimension follow the same convention. We use the convention \( |\ell_s, \ell_i\rangle \) to be equivalent to \( |\ell\rangle_s|\ell\rangle_i \).