Supplemental Material for Symmetry protection of photonic entanglement in the interaction with a single nanoaperture

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Spontaneous Parametric Down-Conversion Source

To create the photon pairs, we use spontaneous parametric down-conversion with a 15 mm long, periodically poled potassium titanyl phosphate (ppKTP) crystal. The crystal has a poling period of 9.89 chosen to achieve type II, degenerate, collinear down-conversion with a pump wavelength of 404.25 nm at a crystal temperature of about 60 C. Both signal and idler thus have a wavelength of 808.5 nm and horizontal and vertical polarizations respectively. The pump laser has a spectral width of 5 MHz.

Nano-Aperture Sample

The isolated, sub-wavelength apertures were milled into a gold film of 150 nm thickness with a focused ion beam. Our sample contains apertures with a diameter between 750 nm and 280 nm, but for the experiment described we only use the largest apertures. Positioning the sample between the focusing and the collection objective is achieved by a pair of manually controlled micrometer stages and a stack of three, electronically controlled nano-positioners.

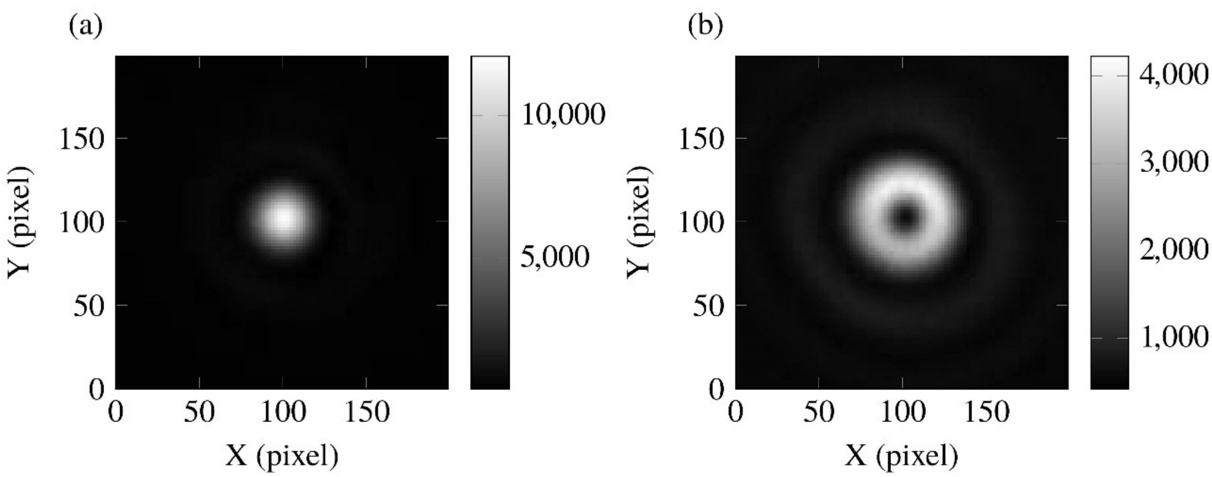

FIG. S1. Spatial mode images of single down-converted photons taken with an electron multiplying charge coupled device (EMCCD) camera. Only one photon of each pair is selected with a linear polarizer after the non-linear crystal. (a) Profile of the Gaussian mode before the q-plate transformation and (b) the orbital angular momentum eigenstate after passing through the q-plate.

State Preparation

Plus and minus states can be prepared from the orthogonally polarised SPDC pairs by a combination of wave plates and a q-plate with q=1/2. The state $|HV\rangle$ expressed in the circular polarization basis is equivalent to the polarization structure of the minus state. It can be transferred to the plus state under the action of a half-wave plate, transforming horizontal to diagonal and vertical to anti-diagonal polarization. After the polarisation state is prepared, the q-plate transfers it to the desired total angular momentum zero subspace. The spatial profile of the beam before and after it has passed through the q-plate is shown in Fig. S1. After the q-plate the beam carries one quantum of orbital angular momentum and shows the characteristic vortex structure.

The delay between the two photons was controlled through a couple of wedged birefringent crystals. By displacing the crystals we could change the path length that the photons travelled inside the crystal, thus changing the delay between the two polarizations. Also a thicker birefringent crystal could be inserted to introduce very long delays between the two polarizations and observe the effects for independent photons.

Hong-Ou-Mandel Interference

We compare the quantum interference observed through the nano-structure with the well-known quantum interference encountered in the Hong-Ou-Mandel effect. Sending a single photon into either one input port of a non-polarising beamsplitter results in a superposition of the two output modes:

$$\begin{aligned} \hat{a}_1 &\rightarrow 1/\sqrt{2}(\hat{b}_1 + \hat{b}_2) \\ \hat{a}_2 &\rightarrow 1/\sqrt{2}(\hat{b}_1 - \hat{b}_2) \end{aligned} \tag{1}$$

Here, $\hat{a}$ denotes an annihilation operator in an input port and $\hat{b}$ the annihilation operator for a photon in the output mode, while the subindex $(1,2)$ labels each of the two ports. Having one photon in each of the two inputs together leads to behaviour that can not be explained classically:

$$\hat{a}_1\hat{a}_2 \rightarrow 1/2\left(\hat{b}_1\hat{b}_1 - \hat{b}_2\hat{b}_2\right) \tag{2}$$

Namely, the two photons always leave the beamsplitter together. The cancellation of the mixed term is of course only possible if the two photons are completely indistinguishable in all their remaining degrees of freedom.

Measurement of the states

In order to perform the tomography, right before the detectors, we set a beamsplitter (non-polarizing). As before, we will label with $\hat{a}$ and $\hat{b}$ the input and output ports of the beam splitter, the subindices $(1,2)$ the ports of the beamplitter, but we will now allow for a further input mode $\hat{c}$

and consequently an output mode $\hat{d}$. They can refer to either the modes we use in the paper with zero total angular momentum for right and left helicity $\hat{a} = \hat{a}_{0,+}$ or $\hat{c} = \hat{a}_{0,-}$. The transformations through the beamsplitter Eq. (3), give for the three possible input states from the same port:

$$\begin{aligned}
(\hat{a}_1\hat{a}_1 + \hat{c}_1\hat{c}_1)/\sqrt{2} &\rightarrow \left(\hat{b}_1\hat{b}_2 + \hat{d}_1\hat{d}_2\right)/2^{3/2} && + \left(\hat{b}_1\hat{b}_1 + \hat{b}_2\hat{b}_2 + \hat{d}_1\hat{d}_1 + \hat{d}_2\hat{d}_2\right)/2^{3/2} \\
(\hat{a}_1\hat{a}_1 - \hat{c}_1\hat{c}_1)/\sqrt{2} &\rightarrow \left(\hat{b}_1\hat{b}_2 - \hat{d}_1\hat{d}_2\right)/2^{3/2} && + \left(\hat{b}_1\hat{b}_1 + \hat{b}_2\hat{b}_2 - \hat{d}_1\hat{d}_1 - \hat{d}_2\hat{d}_2\right)/2^{3/2} \\
\hat{a}_1\hat{c}_1 &\rightarrow \left(\hat{b}_1\hat{d}_2 + \hat{d}_1\hat{b}_2\right)/2 && + \left(\hat{c}_1\hat{d}_1 + \hat{c}_2\hat{d}_2\right)/2
\end{aligned} \tag{3}$$

The first term after the arrow represents the possibilities where the photons go to different ports of the beamsplitter, leading to coincidences. When applying this transformations to the states in our set-up, they lead to the states we post select in our measurement. Notice that the only way of detecting a state such as $\hat{b}_1^\dagger\hat{d}_2^\dagger - \hat{d}_1^\dagger\hat{b}_2^\dagger\left|0\right\rangle$ is if the original states carry distinguishing information: $\hat{a}_1(\omega)^\dagger\hat{d}_1^\dagger(\omega') - \hat{a}_1^\dagger(\omega')\hat{b}_2^\dagger(\omega)\left|0\right\rangle$, as explained in [1].

Polarization interference

Using a set of retarders, waveplates and a polarizing beam splitter (PBS) as explained in the main text, we measured the polarization interference of the modes. We include a delay between the photons generated in the crystal to show the appearance of the visibility shown in the main text. Starting with an initial state generated from the crystal $a_H^\dagger a_V^\dagger(\tau)\left|0\right\rangle$, where both photons are generated in a Gaussian mode, in Horizontal and Vertical polarizations, and the Vertically polarized photon has a delay with respect to the Horizontal one. From this state we can generate the following one:

$$\left|\Psi_-(\tau)\right\rangle = \frac{1}{2i}\left(a_{0,+}^\dagger a_{0,+}^\dagger(\tau) - a_{0,-}^\dagger a_{0,-}^\dagger(\tau)\right)\left|0\right\rangle + \frac{1}{2i}\left(a_{0,+}^\dagger a_{0,-}^\dagger(\tau) - a_{0,+}^\dagger(\tau) a_{0,-}^\dagger\right)\left|0\right\rangle . \quad (4)$$

Notice that if the delay is zero ($\tau = 0$), we recover the $\left|\Psi_-\right\rangle$ state presented in the main text.

After a PBS, separating the $+$ and $-$ helicity components, the second term in Eq. (4) will lead to coincidence counts, while the first one won't as the photons will always go to the same port of the PBS. The same will happen with the $\left|\Psi_+\right\rangle$ state. Therefore, delaying the photons for those two states will raise the coincidence count which will drop to a minimum when the delay of the photons is zero and there is no other distinguishing information.

On the other hand, the state $\left|\Psi_0\right\rangle = a_{0,+}^\dagger a_{0,-}^\dagger\left|0\right\rangle$ will always give rise to coincidences after the beamsplitter, even with zero delay. This justifies our choice of measuring the visibilities in this polarization interference in order to quickly check the differences of the transmission of the $\left|\Psi_+\right\rangle$ and $\left|\Psi_-\right\rangle$. In our measurements we observe that the visibility of $\left|\Psi_+\right\rangle$ is very much affected in all the nanoapertures we tested, while the one of $\left|\Psi_-\right\rangle$ is preserved.

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