Tailoring photonic entanglement in high-dimensional Hilbert Spaces

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In this contribution, we present an experiment where photons can be entangled in Hilbert spaces of arbitrary discrete dimensions. The method is based on parametric down conversion with a sequence of d pump pulses with a fixed phase relation. We can thus obtain time-bin entangled qudits, i.e an entanglement between photons created in a coherent superposition of d discrete emission times, given by the successive laser pulses. The coherence between the different pulses can be obtained by using a mode-locked laser. If we pump a down-converter with a sequence of d pump pulses, after the down-converter we have the state (providing that the probability of creating more than one pair in d pulses in negligible):

$$|\Psi\rangle = \sum_{j=1}^{d} c_j |j, j\rangle \tag{1}$$

where $|j, j\rangle$ corresponds to a photon pair created in the pulse, or time-bin j, d is an integer that can be arbitrarily high and $\sum_{j=1}^{d} |c_j|^2 = 1$.

This method enables one to create any desired high-dimensional state. By selecting the number of pump pulses we can choose the dimension of the Hilbert space in which the photons are entangled. In our experiment we construct trains of exactly d pulses, where d can be varied from 1 to 20. Note that by inserting a phase and/or amplitude modulator before the down- converter, we could also in principle modulate their amplitude and phase, thus varying the coefficients c_j in order to generate non-maximally entangled states.

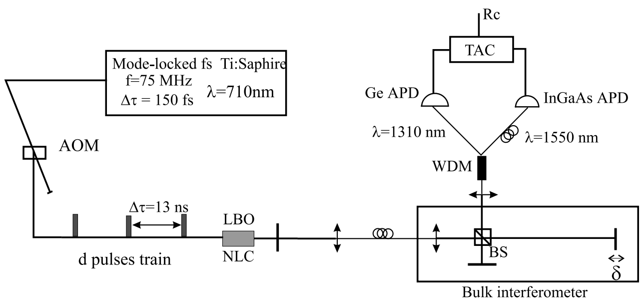

FIG. 1: Experimental setup

A complete analysis of such high dimensional entangled states would require the use of d-way interferometers, which would imply experimental difficulties as d increases. However, as we will show, an analysis with a 2 way interferometer can already show high dimensional entanglement. The long arm of the two-way interferometer we used introduces a delay $\Delta\tau$ equal to the time between 2 pump pulses, with respect to the short one (see fig. 1). This means that a photon travelling through the short arm will remain in the same time-bin while a photon travelling through the long arm will move to the next time-bin. If we restrict ourself to the events where both photons of one pair travel the same way in the interferometer, it can be shown that the coincidence count rate vary as :

$$R_c \sim 1 + V \cos(2\delta) \tag{2}$$

where δ is the phase introduced in the long arm of the interferometer and where the visibility V depends on the dimension d as:

$$V = V_{max} \frac{d-1}{d} \tag{3}$$

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where V_{max} is the maximum visibility due to experimental imperfections. From the observed visibility V, we can thus deduce the dimension in which the photons are entangled.

In our experiment, we use trains of d pump pulses, where d can be varied from 1 to 20, and we observe the visibility of the two photon interference with respect to the dimension d. A schematic of the experiment is presented in Fig 1. The pump laser is a Ti-Sapphire femtosecond mode-locked laser. The time between 2 pulses is $\Delta\tau = 13$ ns. To construct the d pulses trains, we send the pump beam through a 380MHz acousto-optic modulator (aom) which reflects the incoming beam with an efficiency of 50% when it is activated. This activation can be triggered externally, with a TTL signal of variable width synchronized with the laser pulses. The width of this signal thus determines the number of pulses per train. The reflected beam containing the pulse trains is then used to pump a non-linear LBO crystal. Non degenerate photon pairs at 1310/1550 nm are created by parametric down conversion and then sent to the analyzer, which is a 2-way bulk Michelson interferometer, where the long arm introduces a delay Δt with respect to the short one, corresponding to a path-length difference of 1.95 m. The pump power is kept low, in order to keep the probability of having more than one pair per train negligible. Photons exiting one output of the interferometer together are focused into an optical fiber, separated deterministically and sent to photon detectors (APD Ge and InGaAs), in order to be detected in coincidence. If we record the coincidence count rate as a function of the phase shift in the interferometer, we obtain sinusoidal curves with a visibility increasing with the dimension d. Net visibilities as a function of the dimension d are plotted in Fig. 2. First results with d up to ten show a good agreement with the theoretical curve with $V_{max} = 90\%$. This means that we are able to create photons pairs in a coherent superposition of a given number of emission times, and thus to create entanglement in a Hilbert space of arbitrary (up to ten) dimensions.

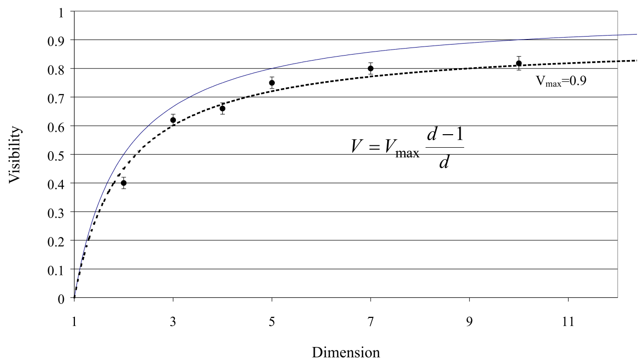

FIG. 2: Two-photon interference visibility as a function of the dimension of the Hilbert space. The black circles are experimental points. The solid line is a plot of eq. 3 with V_{max}=1, while the dotted line is the same with $V_{max} = 0.9$.